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Design and Construction of an Ultrasonic Level Measurement Device Using Arduino Uno

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Abstract

Accurate and reliable level monitoring is essential in many industrial and scientific applications, including water storage, oil and gas processing, agricultural systems, and automated processes. Conventional contact-based measurement techniques are often limited by corrosion, contamination, and environmental effects, which can compromise measurement accuracy and system reliability. This study presents the design, construction, calibration, and performance evaluation of a non-contact ultrasonic level measurement device based on a custom ultrasonic sensing system integrated with an Arduino Uno microcontroller. The device operates on the ultrasonic time-of-flight principle, in which distance is determined from the travel time of reflected sound pulses. The developed prototype was tested over a measurement range of 2.9–400 cm using 51 measurement points, with five repeated readings recorded at each point to evaluate repeatability and measurement uncertainty. Statistical analysis yielded a mean absolute error (MAE) of 0.129 cm, a root mean square error (RMSE) of 0.163 cm, a standard deviation of 0.143 cm, and a coefficient of determination (R^2) of 0.999998, demonstrating excellent linearity and measurement accuracy. The percentage error decreased with increasing measurement distance, reaching a minimum of 0.025% at 400 cm, which is attributed to reduced near-field instability and improved ultrasonic wave propagation at longer ranges. The results demonstrate that the developed system provides reliable real-time level measurement under controlled conditions and offers a cost-effective solution for industrial automation, reservoir monitoring, and storage tank applications.

Keywords: Ultrasonic level measurement; custom ultrasonic transceiver; Arduino Uno; signal conditioning; non-contact sensing.

I. INTRODUCTION

Reliable monitoring of material levels in storage tanks, reservoirs, and industrial process vessels is essential for process control, safety, and efficient resource management in sectors such as water treatment, oil and gas, agriculture, and power generation [1]–[7]. In these applications, level measurement provides critical information for inventory management, overflow prevention, automated control, and system optimization. Conventional level measurement methods, including dipsticks and float gauges, remain widely used because of their simplicity and low cost. However, these contact-based techniques are often affected by corrosion, contamination, vibration, temperature variations, and hazardous operating conditions, which can compromise measurement reliability and accuracy [1], [5], [7]. These limitations have increased the demand for automated, accurate, and robust non-contact level monitoring systems [8],

[9], [10].

Among the available non-contact sensing techniques, ultrasonic sensing has received considerable attention because it enables distance estimation through the propagation and reflection of sound waves [11-14]. Ultrasonic systems offer several advantages, including low cost, ease of integration, adaptability to liquid and solid materials, and suitability for harsh industrial environments [15-18]. Consequently, several ultrasonic-based monitoring systems have been developed for tanks, reservoirs, and industrial process applications [4], [19-21]. For example, [9] developed a multi-level storage tank gauging and monitoring system capable of measuring height levels in media such as air, water, engine oil, and mud. Although the system demonstrated the feasibility of ultrasonic measurement across different substances, it experienced signal attenuation in denser materials and lacked the advanced signal processing and digital display features required for reliable real-time field applications. Similarly, [19] implemented an ultrasonic monitoring system for crude palm oil tanks integrated with a solenoid valve mechanism; however, the sensor could only operate when the valve was closed, thereby limiting continuous real-time monitoring capability.

Despite these developments, several challenges remain in ultrasonic level measurement, including environmental interference, temperature-dependent inaccuracies, calibration difficulties, inconsistent measurement stability, and percentage errors caused by signal distortion and ultrasonic near-field effects [6], [13], [22], [23–25]. Many existing low-cost systems emphasize either affordability or basic measurement functionality, with limited attention given to achieving a compact and reliable design that simultaneously offers improved calibration accuracy, reduced percentage error, enhanced repeatability, and stable real-time performance using readily available hardware components [15], [26], [16], [23]. In addition, several recent studies have focused primarily on sensor deployment or basic calibration procedures without providing comprehensive statistical validation of system performance [25], [27-28]. As a result, there remains a need for an efficient real-time ultrasonic level measurement system that combines low-cost implementation with improved measurement stability, broader calibration coverage, repeatability analysis, and rigorous statistical performance evaluation.

To address this need, this study presents the design, construction, calibration, and performance evaluation of a low-cost ultrasonic level measurement system based on a custom ultrasonic transceiver integrated with Arduino Uno processing. The developed system combines a custom ultrasonic sensing front-end with microcontroller-based signal acquisition and processing, together with amplification and filtering stages intended to improve signal quality, calibration accuracy, and measurement stability. Unlike many earlier low-cost implementations, the present work evaluates the system over 51 measurement points spanning a wide operating range of 2.9–400 cm, thereby providing a more extensive assessment of sensor performance across short, medium, and long measurement distances. In addition, five repeated measurements were recorded at each distance point, and the mean values obtained from repeated trials were used for calibration and analysis to improve repeatability and reduce the influence of random measurement fluctuations.

A further distinguishing feature of this study is the incorporation of a more rigorous statistical validation framework than is commonly reported in similar low-cost ultrasonic measurement systems. The performance assessment includes confidence interval estimation, mean absolute error (MAE), root mean square error (RMSE), regression analysis, residual analysis, and uncertainty analysis, thereby enabling a more robust evaluation of measurement accuracy, linearity, and reliability. Calibration of the developed custom ultrasonic sensing system was carried out using a calibrated meter rule as a reference standard, allowing system accuracy and linearity to be evaluated over the full operating range. The study also integrates real-time level display and alarm functionality through an LCD interface and buzzer, improving its suitability for practical industrial and reservoir monitoring applications. The contribution of this work, therefore, lies not only in the development of a low-cost custom ultrasonic level measurement system but also in its calibration, statistical characterization, repeatability assessment, uncertainty evaluation, and performance validation over a wide measurement range.

II. MATERIALS AND METHODS

A. *Materials*

The custom ultrasonic level measurement system was constructed using the following components:

1. 40 kHz piezoelectric transmitter/receiver
2. Arduino Uno microcontroller board (ATmega328P)
3. Liquid Crystal Display (LCD) unit
4. LM324 operational amplifier
5. MAX232 integrated circuit
6. EM78P programmable integrated circuit
7. Transistors, resistors, and capacitors
8. Breadboard and Vero board
9. Regulated 5 V DC power supply unit
10. Connecting wires
11. Buzzer.

B. *System Design and Principle of Operation*

The design of the custom ultrasonic level measurement system involved the integration of both hardware and software subsystems for real-time level monitoring. In the developed arrangement, the ultrasonic sensing unit is positioned above the surface of the material to be monitored, typically at the top center of the storage tank or container. During operation, the transmitter emits ultrasonic pulses toward the material surface, and the reflected echo signal is received by the sensing unit. The measured time delay between transmission and reception is processed by the Arduino Uno microcontroller, which computes the corresponding distance or level of the material and displays the result on the LCD interface.

The operating principle of the system is based on ultrasonic time-of-flight measurement. A 40 kHz ultrasonic pulse is transmitted toward the surface of the monitored substance and reflected to the receiver at the air–material interface. The distance between the sensor and the material surface is then determined from the travel time of the pulse using (1).

$$d = \frac{vt}{2} \qquad (1)$$

Where (d) is the measured distance (or level height), (v) is the speed of sound in air (343 m/s under standard conditions), and (t) is the measured round-trip time of the ultrasonic pulse.

Fig. 1 illustrates the basic principle of operation of the developed system, showing the transmission of the incident ultrasonic wave from the transmitter and the reception of the reflected wave from the material surface. The overall system consists of four major functional stages: the transmitting unit, the receiving unit, the processing unit, and the output unit. The transmitting and receiving stages form the ultrasonic sensing front-end, while the processing and output stages are responsible for computation, display, and user alert functions.

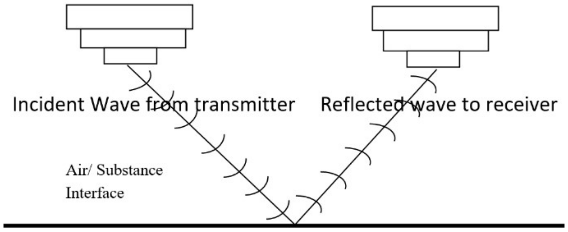

Fig. 1. The interaction of the emitted wave with the object and the echo.

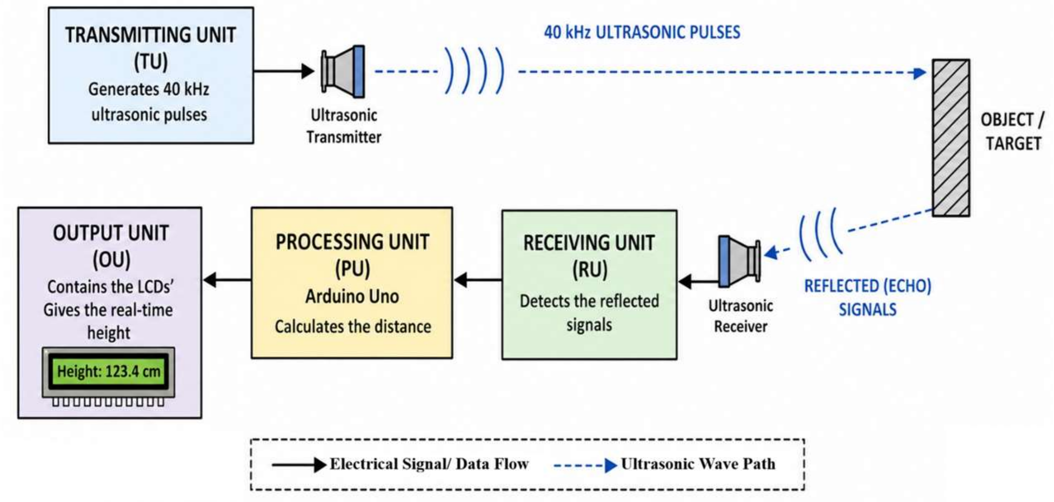

Fig. 2. Block diagram of the device.

Fig. 2 presents the block diagram of the developed device. The functional roles of the major units are as follows:

1. Transmitting Unit (TU): generates 40 kHz ultrasonic pulses directed toward the target surface.
2. Receiving Unit (RU): detects the reflected ultrasonic signals from the material surface.
3. Processing Unit (PU): implemented using the Arduino Uno, it processes the received signal, determines the pulse time-of-flight, and computes the corresponding level or distance.
4. Output Unit (OU): consists of the LCD and alarm interface, providing real-time level indication and warning signals when required.

C. *Sampling Interval and Measurement Frequency*

The custom ultrasonic sensing system was configured for continuous real-time level measurement at fixed sampling intervals. During operation, the sensor was triggered at a sampling interval of 50 ms between consecutive measurements, corresponding to a sampling frequency of approximately 20 Hz. This interval was selected based on the operational characteristics of the developed sensing system and in line with recommendations from previous ultrasonic sensing studies [17], [29-30].

It is important to distinguish between the ultrasonic operating frequency of the sensing device and the measurement sampling frequency of the data acquisition process. The developed custom ultrasonic transceiver operates at approximately 40 kHz, which represents the frequency of the transmitted acoustic signal. By contrast, the Arduino Uno controls the rate of successive measurements by imposing a predefined sampling interval between consecutive trigger events. Thus, while the ultrasonic frequency governs wave generation and propagation, the sampling interval determines how often level measurements are acquired and updated in real time [22].

D. *Environmental Conditions During Testing*

Experimental testing and calibration of the developed system were carried out under controlled environmental conditions using a domestic water tank with an approximate height of 400 cm. The testing conditions were selected to minimize the influence of environmental disturbances such as wind, excessive vibration, and external acoustic noise, all of which can affect ultrasonic wave propagation and measurement stability.

The average ambient temperature during testing was approximately 27 °C, with relatively stable humidity conditions and minimal air movement. These controlled conditions helped improve measurement consistency and reduced the influence of environmental factors on the recorded ultrasonic level measurements.

E. *Calibration Procedure and Measurement Algorithm*

The developed ultrasonic level measurement system was calibrated using known reference heights measured with a calibrated meter rule. Measurements were taken at several predefined levels covering the operational range of the device. At each measurement point, five consecutive readings were recorded, and the average value was computed to reduce random errors and improve repeatability. The measured sensor outputs were then compared with the corresponding reference values to evaluate measurement error, accuracy, and linearity. Where slight deviations were observed, correction adjustments were incorporated into the software algorithm to improve the linear response and overall measurement accuracy of the system.

During operation, the software initiates each measurement cycle by transmitting a short 10 µs trigger pulse to the custom ultrasonic sensing system. This pulse causes the ultrasonic transceiver to emit a 40 kHz acoustic signal toward the target surface. The system subsequently monitors the returning echo signal and measures the time required for the ultrasonic wave to travel to the target and return to the receiver. This measured interval corresponds to the time-of-flight of the ultrasonic pulse. The distance is then computed by the Arduino Uno using the ultrasonic time-of-flight relationship described in Section II(B), after which calibration corrections are applied within the software to improve measurement accuracy. The program also constrains the output to valid measurement limits to prevent non-physical values and improve the reliability of the displayed results.

F. *Developed Circuit and Hardware Integration*

Fig. 3 presents the circuit diagram of the developed ultrasonic level measurement system. The system consists of a custom ultrasonic transceiver front-end integrated with Arduino-based digital processing for real-time level measurement. The sensing front-end comprises a 40 kHz piezoelectric transmitter and receiver, LM324 amplification and signal-conditioning stages, MAX232 interface circuitry, EM78P control circuitry, and the associated passive components required for biasing, filtering, timing, and signal stabilization.

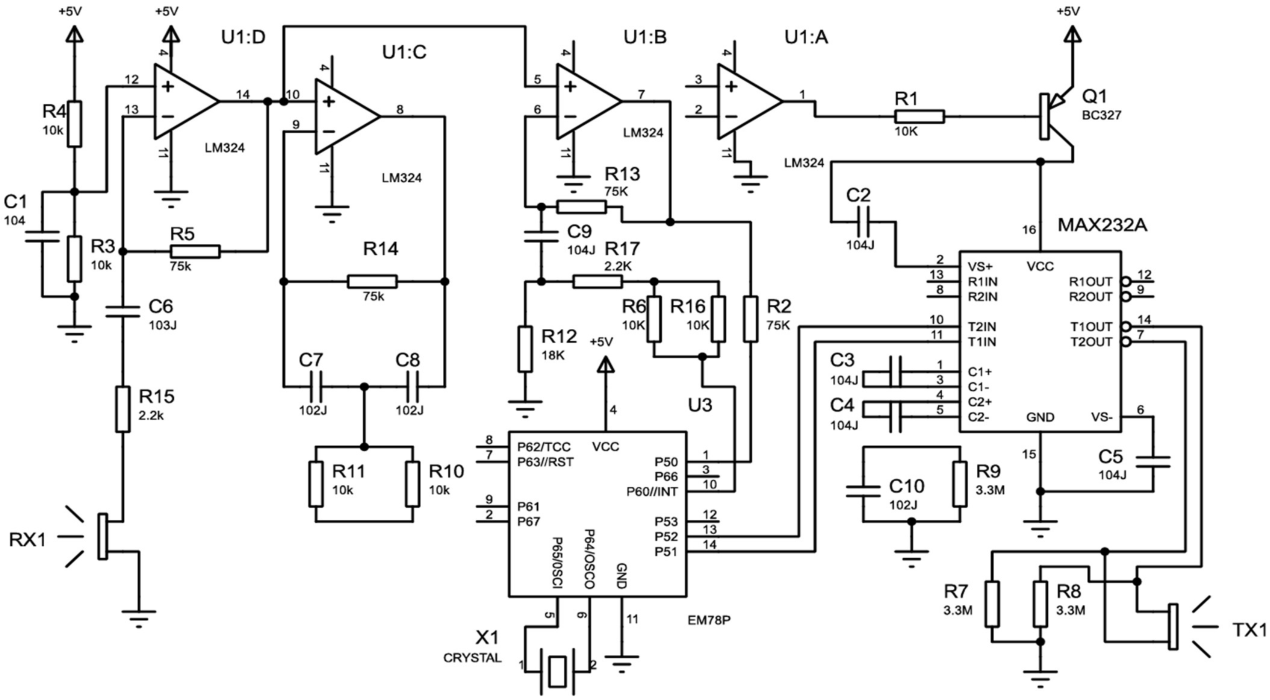

Fig. 3. Circuit diagram of the custom ultrasonic sensing system.

During operation, the Arduino Uno generates the trigger pulse that initiates ultrasonic transmission. The transmitted ultrasonic wave propagates toward the target surface and is reflected to the receiver. The received echo signal is then amplified, filtered, and conditioned by the analog front-end circuitry before being interfaced to the Arduino Uno through the trigger/echo measurement path. The Arduino subsequently performs time-of-flight measurement, calibration correction, distance computation, LCD, and alarm control. This integrated signal path improves measurement stability and enables reliable real-time level monitoring.

G. Circuit Component Calculations

The developed circuit contains seventeen resistors and ten capacitors, whose values were selected to support pulse generation, signal amplification, filtering, biasing, and interface stabilization. The resistor and capacitor values used in the circuit and their respective functions are summarized in Table I.

Table I. Resistor values and their function.

Components		Value	Function in the Circuit
Resistor			
1	R1	10 kΩ	Limits current to the base of transistor Q1 and protects the op-amp output.
2	R2	75 kΩ	Feedback resistor for op-amp U1:B helps set amplifier gain.
3	R3	10 kΩ	Works with R4 and C1 for signal conditioning.
4	R4	10 kΩ	Forms a voltage divider with R3 and helps create a reference voltage for the op-amp.
5	R5	75 kΩ	Feedback resistor for the op-amp (U1:D) and controls gain (amplification).
6	R6	10 kΩ	Form a voltage divider/pull-up network and stabilize the signal going into the microcontroller.
7	R7	3.3 MΩ	Provides gain control in the amplification stage.
8	R8	3.3 MΩ	Form a biasing network for the T_X output and help stabilize signal levels.
9	R9	3.3 MΩ	Works with C10 for timing/filtering.
10	R10	10 kΩ	Forms part of the signal bias network for the receiver.
11	R11	10 kΩ	Works with R10 to stabilize the input voltage level.
12	R12	18 kΩ	Feedback resistor in U1:C and sets amplifier gain.
13	R13	75 kΩ	Feedback resistor in U1:C and sets amplifier gain.
14	R14	10 kΩ	Feedback resistor in U1:C.
16	R15	2.2 kΩ	Limits current from the sensor (RX1).
17	R16	10 kΩ	Forms a voltage divider/pull-up network and stabilizes the signal going into the microcontroller.
18	R17	2.2 kΩ	Work with C9 for filtering.
Capacitors			
1	C1	104 (0.1 μF)	Power supply decoupling/noise filtering at the input stage.
2	C2	104 (0.1 μF)	Supply bypass capacitor for the MAX232A (stabilizes voltage).
3	C3	104 (0.1 μF)	Charge pump capacitor for MAX232A (voltage conversion).
4	C4	104 (0.1 μF)	Charge pump capacitor for MAX232A (voltage inversion/doubling).
5	C5	104 (0.1 μF)	Output smoothing capacitor for MAX232A negative voltage (VS-).
6	C6	103 (0.01 μF)	Signal filtering/noise suppression in the input stage.
7	C7	102 (0.001 μF)	Frequency shaping/timing in the op-amp feedback network.
8	C8	102 (0.001 μF)	Works with C7 for filtering or oscillation control.
9	C9	104 (0.1 μF)	Filtering and stabilization in the amplifier stage.
10	C10	102 (0.001 μF)	Signal filtering/stabilization near MAX232A.

1) Resistor Network Design

The resistor network performs several important functions within the developed circuit, including transistor base current limiting, operational amplifier gain control, voltage division, signal biasing, pull-up stabilization, and timing/filtering support. Examples include the use of feedback resistors in the LM324 amplification stages, high-value bias resistors in the transmitter and receiver sections, and current-limiting resistors for signal protection.

The equivalent resistance of resistors connected in series and parallel was determined using (2) and (3).

$$R_{eqv} = R_1 + R_2 + \cdots + R_n \tag{2}$$

$$\frac{1}{R_{eqv}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n} \tag{3}$$

For the voltage divider network formed by R_3 and R_4, each of value 10 kΩ, the total series resistance is 20 kΩ, while the midpoint voltage is approximately one-half of the supply voltage, corresponding to 2.5 V for a 5 V supply.

2) Capacitor Network Design

The capacitor network was incorporated to provide power-supply decoupling, charge-pump support for the MAX232 interface, signal filtering, timing stabilization, and noise suppression in the amplifier stage.

The equivalent capacitance for the capacitors connected in parallel was determined using (4).

$$C_{eqv} = C_1 + C_2 + \cdots + C_N \tag{4}$$

The capacitor network contributes to the stable operation of the custom ultrasonic transceiver by reducing noise, improving waveform integrity, and supporting proper signal conditioning throughout the sensing and interface stages.

H. *Software Implementation*

The control program was developed using the Arduino Integrated Development Environment (IDE) and follows the standard Arduino software structure consisting of the setup () and loop () functions. The setup () function is executed once during system initialization to configure the hardware and establish the initial operating conditions, while the loop () function runs continuously to perform level measurement, signal processing, display updating, and alarm control.

During initialization, the software defines the input and output pins associated with the trigger, echo, and buzzer components. The LCD is also initialized, and the initial operating states of the sensing and alarm subsystems are set before the start of continuous measurement.

I. *Algorithm of System Operation*

The operational sequence of the developed ultrasonic level measurement system is summarized below.

1. Initialize the Arduino Uno, LCD module, custom ultrasonic sensing system, and buzzer.
2. Generate a 10 µs trigger pulse to initiate ultrasonic transmission.
3. Transmit a 40 kHz ultrasonic pulse toward the target surface.
4. Receive the reflected ultrasonic echo from the target surface.
5. Measure the echo time-of-flight using the Arduino timing routine.
6. Compute the corresponding distance using the ultrasonic time-of-flight relationship presented in Section II(B).
7. Apply software-based calibration corrections to improve measurement accuracy.
8. Validate the measured data and reject invalid or non-physical readings.
9. Display the measured level on the LCD and activate the buzzer when the predefined alarm condition is satisfied.
10. Repeat the measurement cycle every 50 ms to provide continuous real-time monitoring.

J. *Pseudocode and Flowchart of the Measurement Algorithm*

The software implementation follows the operational sequence described in *I*. Fig. 4 illustrates the operational flow of the developed ultrasonic level measurement system. The flowchart summarizes hardware initialization, ultrasonic signal transmission and reception, time-of-flight measurement, calibration correction, distance computation, display updating, alarm control, and continuous execution of the real-time monitoring cycle. The corresponding pseudocode is presented afterwards.

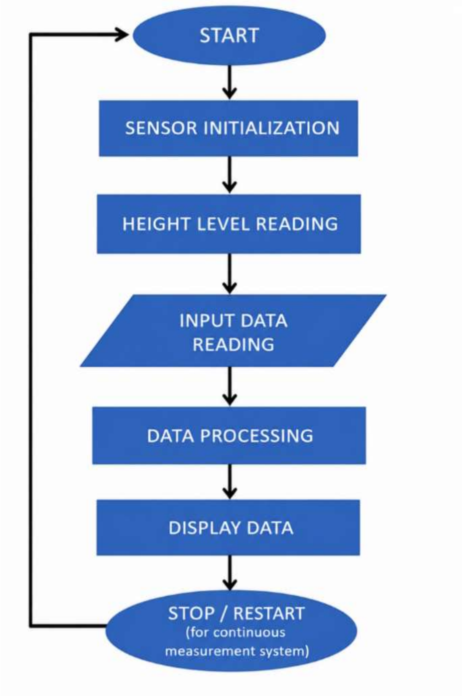

Fig. 4. Flowchart of the Ultrasonic Level Measurement System.

```
BEGIN

Initialize Arduino Uno
Initialize LCD
Configure Trigger pin as OUTPUT
Configure Echo pin as INPUT
Initialize buzzer

LOOP

Generate 10 µs trigger pulse
Measure echo time

IF a valid echo is detected THEN
  Compute distance
  Apply calibration correction
  Validate measurement
  Display measured level on LCD

  IF alarm threshold is reached THEN
    Activate buzzer
  ELSE
    Deactivate buzzer
  ENDIF
```

```
ELSE
    Display measurement error
ENDIF

Wait 50 ms

REPEAT LOOP

END
```

K. *Calibration Model and Statistical Performance Metrics*

To improve the measurement accuracy of the developed ultrasonic level measurement system, the sensor readings were calibrated against reference measurements obtained using a calibrated meter rule. Linear regression analysis was performed using the measured sensor values and the corresponding reference distances to establish a calibration model relating the measured and actual distances. The resulting calibration equation is given by (5).

$$\hat{y} = 0.0678 + 1.00033x \tag{5}$$

Where (x) = measured sensor distance (cm); (y) = calibrated (corrected) distance (cm).

The regression analysis yielded a coefficient of determination $R^2 = 0.999998$, indicating excellent agreement between the calibrated sensor measurements and the reference values. The calibration equation was subsequently incorporated into the Arduino software to compensate for systematic measurement deviations and improve the linearity and overall accuracy of the developed system.

To quantitatively evaluate the performance of the developed ultrasonic level measurement system, standard statistical performance metrics were employed to assess measurement accuracy, precision, repeatability, and reliability using the calibrated experimental data.

The Mean Absolute Error (MAE), which quantifies the average absolute deviation between the calibrated measurements and the corresponding reference values, was calculated using (6).

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{6}$$

Where y_i is the reference (actual) distance at the i^{th} measurement point, $\hat{y}_i$ is the calibrated (corrected) distance at the i^{th}measurement point, and n is the total number of measurements.

The Root Mean Square Error (RMSE), which provides greater sensitivity to larger deviations between measured and reference values, was computed using (7).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{7}$$

Where y_i is the reference (actual) distance at the i^{th}measurement point, $\hat{y}_i$ is the calibrated (corrected) distance at the i^{th}measurement point, and n is the total number of measurements.

The standard deviation, used to evaluate the precision and repeatability of the repeated measurements, was determined using (8).

$$SD = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}} \tag{8}$$

Where SD is the standard deviation, x_i is the individual repeated measurement, $\bar{x}$ is the mean of the repeated measurements, and n is the number of repeated measurements.

The statistical metrics defined in (6) – (8) formed the basis for evaluating the measurement accuracy, precision, repeatability, and reliability of the developed ultrasonic level measurement system. Their corresponding values and interpretations are presented and discussed in Section III.

In addition, 95% confidence intervals were computed from the repeated measurements to assess the reliability and consistency of the developed ultrasonic level measurement system.

L. *Arduino Program Excerpt*

The control software for the developed ultrasonic level measurement system was implemented using the Arduino Integrated Development Environment (IDE). The program generates a trigger pulse, measures the returning echo signal, computes the corresponding distance using the ultrasonic time-of-flight principle, applies calibration corrections where necessary, and updates the LCD in real-time. The representative section of the program responsible for the measurement process is presented below.

```
#define trigPin 13
#define echoPin 11
#define MIN_VALID_DISTANCE 2.7

void loop()
{
  long duration;
  float distance;

  digitalWrite(trigPin, LOW);
  delayMicroseconds(2);
  digitalWrite(trigPin, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin, LOW);

  duration = pulseIn(echoPin, HIGH);

  distance = duration * 0.034 / 2;

  if (distance < MIN_VALID_DISTANCE)
    distance = 0;

  lcd.setCursor(0,1);
  lcd.print(distance,1);
  lcd.print(" cm");

  delay(300);
```

```
}
```

The program repeatedly generates a 10 µs trigger pulse to initiate ultrasonic transmission, measures the echo return time, computes the corresponding distance, filters measurements outside the valid operating range, and displays the measured level on the LCD module. Calibration corrections derived from the regression model are incorporated into the processing routine to improve measurement accuracy and system linearity. The complete software additionally includes hardware initialization, LCD configuration, input/output pin assignment, and alarm control functions, which have been omitted from the excerpt for brevity.

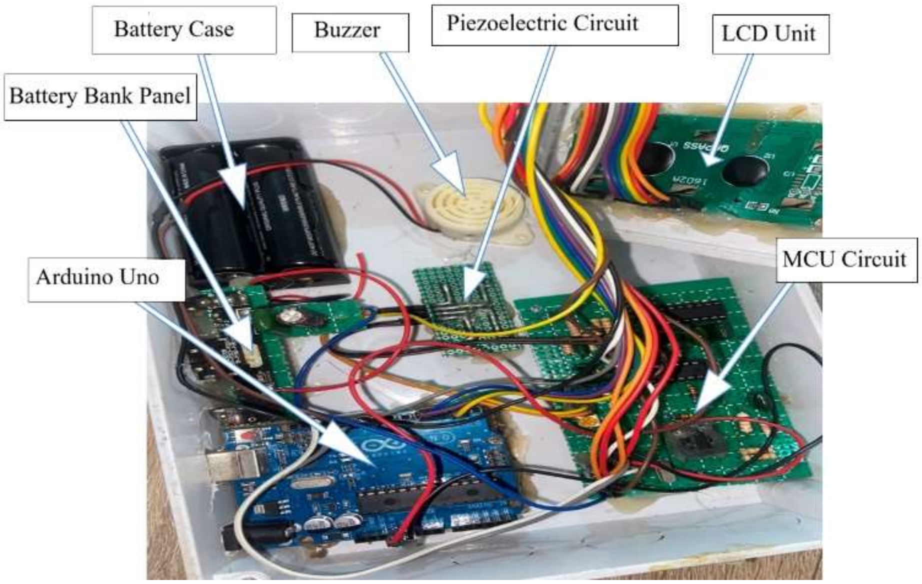

Fig. 5. Internal hardware assembly of the custom ultrasonic level measurement system.

Fig. 5 illustrates the internal hardware assembly of the developed ultrasonic level measurement system. The prototype comprises an Arduino Uno microcontroller, the custom ultrasonic sensing interface circuit, a 16 × 2 LCD module, a buzzer, a battery power supply, and the associated signal-conditioning circuitry integrated within a compact enclosure.

The Arduino Uno functions as the central processing unit, receiving conditioned signals from the ultrasonic sensing front-end, computing the measured level, and controlling the display and alarm subsystems. The interface circuitry performs signal amplification, filtering, power regulation, and communication between the sensing unit and the microcontroller. The integrated hardware configuration demonstrates the successful implementation of a compact, stand-alone ultrasonic level measurement system suitable for real-time monitoring applications.

III. RESULTS AND DISCUSSION

A. *Experimental Performance of the Developed Ultrasonic Level Measurement System*

The performance of the developed ultrasonic level measurement system was experimentally evaluated over a measurement range of 2.9–400 cm using a domestic water storage tank under controlled indoor conditions. A total of 51 measurement points were selected to provide comprehensive coverage of the operating range. At each measurement point, five consecutive measurements were recorded to evaluate repeatability and minimize the influence of random measurement fluctuations. The average of the repeated measurements was subsequently used for calibration and statistical analysis.

The experimental measurements obtained from the developed system, together with the corresponding reference values measured using a calibrated meter rule, are presented in Table II. The results demonstrate excellent agreement between the measured and reference distances throughout the investigated range. The measured values increased consistently with increasing reference distance, indicating stable sensor response and reliable operation across the full measurement range.

A close examination of the experimental data shows that measurement deviations were generally more pronounced at shorter distances but decreased progressively as the measurement distance increased. This behavior is characteristic of ultrasonic sensing systems and is primarily attributed to near-field effects, transducer ringing, and the limited resolution associated with very short time-of-flight measurements. Beyond the near-field region, the developed system exhibited highly stable measurements with minimal deviation from the reference values, confirming the effectiveness of the signal-conditioning circuitry and calibration procedure.

Table II. Distance Measurements Obtained Using the Ultrasonic Level

S/N	Actual Distance (cm)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Error
1	5	5.1	5.2	5.2	5.3	5.2	5.2	0.2
2	10	9.4	9.5	9.5	9.5	9.6	9.5	0.5
3	15	15.1	15.2	14.7	14.8	15.4	15.0	0.0
4	20	20.0	20.1	20.1	20.2	20.1	20.1	0.1
5	25	25.1	25.1	24.9	24.8	25.5	25.1	0.1
6	30	30.1	29.6	30.2	29.7	30.2	30.0	0.0
7	35	34.7	35.0	35.4	35.0	35.0	35.0	0.0
8	40	39.6	40.0	39.9	40.2	40.3	40.0	0.0
9	45	45.1	44.9	45.1	45.3	45.4	45.2	0.2
10	50	49.5	50.0	50.1	49.7	50.4	49.9	0.1
11	55	55.1	55.4	55.3	54.9	55.1	55.2	0.2
12	60	60.1	60.2	60.3	60.4	59.7	60.1	0.1
13	65	65.1	65.2	65.3	65.4	65.1	65.2	0.2
14	70	69.9	70.0	70.1	70.2	70.1	70.1	0.1
15	75	75.3	75.1	75.2	75.4	75.1	75.2	0.2
16	80	80.1	80.2	80.3	80.2	80.1	80.2	0.2
17	85	85.5	85.1	85.2	85.3	85.2	85.3	0.3
18	90	90.2	90.1	90.3	90.0	90.1	90.1	0.1
19	95	95.1	95.0	95.2	94.7	95.0	95.0	0.0
20	100	100.0	100.0	100.2	100.1	100.4	100.1	0.1
21	105	105.2	105.1	105.1	104.7	105.3	105.1	0.1
22	110	110.2	110.0	110.0	110.1	110.0	110.1	0.1
23	115	115.3	115.2	115.2	114.5	115.1	115.1	0.1
24	120	120.0	120.3	120.2	120.0	120.1	120.1	0.1
25	125	125.0	125.3	125.1	125.2	125.3	125.2	0.2
26	130	130.2	130.1	130.4	130.3	130.1	130.2	0.2
27	135	134.5	135.0	135.2	135.2	135.3	135.0	0.0
28	140	138.9	140.3	140.1	140.4	140.1	140.0	0.0
29	145	145.0	145.2	145.1	144.5	145.1	145.0	0.0
30	150	150.3	150.1	150.3	150.3	150.5	150.3	0.3
31	155	155.3	155.0	155.2	155.3	155.0	155.2	0.2
32	160	160.4	160.2	159.5	160.2	160.1	160.1	0.1
33	165	165.0	165.2	165.3	165.2	165.2	165.2	0.2
34	170	170.2	170.2	170.4	170.2	170.2	170.2	0.2
35	175	175.1	175.2	175.3	175.0	175.1	175.1	0.1
36	180	180.1	180.2	180.1	180.1	179.7	180.0	0.0
37	185	185.1	185.2	184.6	185.1	185.1	185.0	0.0
38	190	189.5	190.3	190.4	190.3	190.3	190.2	0.2
39	195	195.0	195.2	195.1	195.3	195.0	195.1	0.1
40	200	200.0	200.0	200.2	199.8	200.0	200.0	0.0
41	210	210.1	210.0	210.3	210.1	210.0	210.1	0.1
42	220	220.1	219.5	220.2	220.1	220.2	220.0	0.0
43	240	240.3	240.1	240.4	240.1	240.1	240.2	0.2
44	260	260.1	260.4	260.3	260.1	260.1	260.2	0.2
45	280	280.4	280.1	280.2	280.3	280.2	280.2	0.2
46	300	300.0	300.2	300.2	300.4	300.2	300.2	0.2
47	320	320.1	320.2	320.1	320.1	320.1	320.1	0.1
48	340	340.3	340.1	340.2	340.2	340.1	340.2	0.2
49	360	360.1	360.1	360.4	360.1	360.3	360.2	0.2
50	380	380.2	380.1	380.1	380.4	380.4	380.2	0.2
51	400	400.0	400.1	400.1	400.2	400.1	400.1	0.1

The repeated measurements recorded at each measurement point also demonstrate good repeatability, with only small variations observed between successive readings. The consistency of these measurements indicates that the developed custom ultrasonic transceiver, together with the Arduino-based processing unit, provides stable real-time operation under the controlled experimental conditions adopted in this study. The use of repeated measurements further improves confidence in the reliability of the acquired data by reducing the influence of random fluctuations during calibration and performance evaluation.

Overall, the experimental results confirm that the developed ultrasonic level measurement system is capable of providing accurate, stable, and repeatable level measurements over a wide operating range. The close correspondence between the measured and reference values establishes a strong basis for the subsequent calibration, regression analysis, and statistical performance evaluation presented in the following sections.

B. Calibration and Regression Analysis

The calibration of the developed ultrasonic level measurement system was carried out using reference distances obtained with a calibrated meter rule. The averaged sensor measurements obtained from the repeated experimental trials were compared with the corresponding reference values, and a linear regression model was developed to establish the relationship between the measured and actual distances. The resulting calibration equation was subsequently incorporated into the software algorithm to compensate for systematic measurement deviations and improve the overall measurement accuracy of the system.

The regression model established a linear relationship between the sensor measurements and the corresponding reference distances over the investigated operating range. The calibration equation provides the mathematical basis for correcting the raw sensor measurements before display, thereby improving the linearity and reliability of the developed measurement system. By incorporating the regression model into the Arduino-based processing routine, the system can compensate for systematic measurement bias while maintaining stable real-time operation.

The effectiveness of the calibration procedure is reflected in the strong agreement obtained between the calibrated sensor measurements and the reference distances. This demonstrates that the developed calibration model adequately represents the measurement characteristics of the custom ultrasonic sensing system and provides a reliable basis for subsequent statistical performance evaluation.

The calibration procedure also improves the robustness of the developed measurement system by minimizing systematic deviations arising from component tolerances, signal-conditioning circuitry, and variations in ultrasonic wave propagation. Consequently, the calibrated measurements provide a more reliable representation of the actual target distances, thereby enhancing the overall accuracy, consistency, and long-term stability of the system during continuous real-time operation. The calibration process, therefore, forms an essential component of the developed measurement system, ensuring that the reported level measurements accurately represent the actual distances within the investigated operating range. The quantitative performance of the calibrated system is further evaluated using the statistical error metrics presented in the following section.

C. Statistical Performance Evaluation

The statistical performance of the developed ultrasonic level measurement system was evaluated using the calibrated experimental measurements to assess its accuracy, precision, repeatability, and measurement reliability. Table III summarizes the statistical indicators obtained from the experimental data, including the mean absolute error (MAE), root mean square error (RMSE), standard deviation, confidence interval, and coefficient of determination.

The developed system achieved a Mean Absolute Error (MAE) of 0.129 cm and a Root Mean Square Error (RMSE) of 0.163 cm, indicating excellent agreement between the measured and reference distances throughout the investigated operating range. The relatively small difference between the MAE and RMSE values suggests that measurement errors were consistently low and that large deviations occurred only infrequently. This demonstrates that the developed system maintained stable measurement performance under the controlled experimental conditions.

The standard deviation of 0.143 cm further confirms the high repeatability of the measurement system. The low variability observed among the repeated measurements indicates that the custom ultrasonic transceiver, signal-conditioning circuitry, and Arduino-based processing algorithm collectively provided stable and consistent measurement performance. Furthermore, the narrow confidence intervals obtained across the measurement range indicate a high degree of confidence in the reported measurements and demonstrate that random measurement variations were effectively minimized.

The regression analysis yielded a coefficient of determination (R^2) of 0.999998, confirming an exceptionally strong linear relationship between the calibrated sensor measurements and the corresponding reference distances. This result demonstrates that the developed system accurately reproduces the actual measurement values over the entire operating range and validates the effectiveness of the calibration procedure adopted in this study.

Overall, the statistical indicators demonstrate that the proposed ultrasonic level measurement system provides accurate, precise, and repeatable real-time measurements. The combination of low error metrics, excellent linearity, and high measurement consistency confirms the suitability of the developed system for reliable level monitoring in industrial and domestic applications.

Table III. Statistical Performance Analysis of the Ultrasonic Level Measurement

S/N	Actual (cm)	Measured (cm)	Error	Absolute Error	Percentage Error (%)	Confidence Intervals (95%)
1	5	5.2	+0.2	0.2	4.000	4.92 – 5.48
2	10	9.5	-0.5	0.5	5.000	9.22 – 9.78
3	15	15.0	0.0	0.0	0.000	14.72 – 15.28
4	20	20.1	+0.1	0.1	0.500	19.82 – 20.38
5	25	25.1	+0.1	0.1	0.400	24.82 – 25.38
6	30	30.0	0.0	0.0	0.000	29.72 – 30.28
7	35	35.0	0.0	0.0	0.000	34.72 – 35.28
8	40	40.0	0.0	0.0	0.000	39.72 – 40.28
9	45	45.2	+0.2	0.2	0.444	44.92 – 45.48
10	50	49.9	-0.1	0.1	0.200	49.62 – 50.18
11	55	55.2	+0.2	0.2	0.364	54.92 – 55.48
12	60	60.1	+0.1	0.1	0.167	59.82 – 60.38
13	65	65.2	+0.2	0.2	0.308	64.92 – 65.48
14	70	70.1	+0.1	0.1	0.143	69.82 – 70.38
15	75	75.2	+0.2	0.2	0.267	74.92 – 75.48
16	80	80.2	+0.2	0.2	0.250	79.92 – 80.48
17	85	85.3	+0.3	0.3	0.353	85.02 – 85.58
18	90	90.1	+0.1	0.1	0.111	89.82 – 90.38
19	95	95.0	0.0	0.0	0.000	94.72 – 95.28
20	100	100.1	+0.1	0.1	0.100	99.82 – 100.38
21	105	105.1	+0.1	0.1	0.095	104.82 – 105.38
22	110	110.1	+0.1	0.1	0.091	109.95 – 110.17
23	115	115.1	+0.1	0.1	0.087	114.82 – 115.38
24	120	120.1	+0.1	0.1	0.083	119.82 – 120.38
25	125	125.2	+0.2	0.2	0.160	124.92 – 125.48
26	130	130.2	+0.2	0.2	0.154	129.92 – 130.48
27	135	135.0	0.0	0.0	0.000	134.72 – 135.28
28	140	140.0	0.0	0.0	0.000	139.72 – 140.28
29	145	145.0	0.0	0.0	0.000	144.72 – 145.28
30	150	150.3	+0.3	0.3	0.200	150.02 – 150.58
31	155	155.2	+0.2	0.2	0.129	154.92 – 155.48
32	160	160.1	+0.1	0.1	0.063	159.82 – 160.38
33	165	165.2	+0.2	0.2	0.121	164.92 – 165.48
34	170	170.2	+0.2	0.2	0.118	169.92 – 170.48
35	175	175.1	+0.1	0.1	0.057	174.82 – 175.38
36	180	180.0	0.0	0.0	0.000	179.72 – 180.28
37	185	185.0	0.0	0.0	0.000	184.72 – 185.28
38	190	190.2	+0.2	0.2	0.105	189.92 – 190.48
39	195	195.1	+0.1	0.1	0.051	194.82 – 195.38
40	200	200.0	0.0	0.0	0.000	199.72 – 200.28
41	210	210.1	+0.1	0.1	0.048	209.82 – 210.38
42	220	220.0	0.0	0.0	0.000	219.72 – 220.28
43	240	240.2	+0.2	0.2	0.083	239.92 – 240.48
44	260	260.2	+0.2	0.2	0.077	259.92 – 260.48
45	280	280.2	+0.2	0.2	0.071	279.92 – 280.48
46	300	300.2	+0.2	0.2	0.067	299.92 – 300.48
47	320	320.1	+0.1	0.1	0.031	319.82 – 320.38
48	340	340.2	+0.2	0.2	0.059	339.92 – 340.48
49	360	360.2	+0.2	0.2	0.056	359.92 – 360.48
50	380	380.2	+0.2	0.2	0.053	379.92 – 380.48
51	400	400.1	+0.1	0.1	0.025	399.82 – 400.38

D. Residual Analysis

Residual analysis was performed to further evaluate the adequacy of the calibration model and to determine whether any systematic measurement bias existed within the developed ultrasonic level measurement system. The residuals, defined as the differences between the calibrated measurements and the corresponding reference distances, provide an important indication of the consistency and reliability of the regression model.

Fig. 7 illustrates the distribution of the residuals over the investigated measurement range. The residuals remained small and were randomly distributed about the zero-error line, with no observable trend or systematic pattern. This random distribution indicates that the calibration model adequately represents the experimental data and that the remaining measurement errors are primarily attributable to random variations rather than systematic bias.

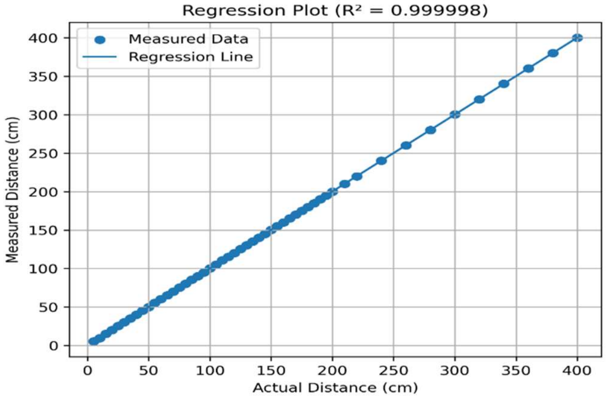

Fig. 6. The relationship between measured distance and actual distance.

Slightly larger residuals were observed at shorter measurement distances, which is consistent with the operating characteristics of ultrasonic sensing systems. At short distances, ultrasonic measurements are more susceptible to transducer ringing, near-field effects, and timing uncertainties associated with the short echo travel time. As the measurement distance increased, the residuals became smaller and more uniformly distributed, demonstrating improved measurement stability and calibration performance.

The absence of significant systematic deviations confirms that the calibration equation effectively compensated for measurement bias throughout the operating range. Consequently, the residual analysis provides additional evidence that the developed ultrasonic level measurement system is capable of producing stable and reliable real-time measurements under the controlled experimental conditions adopted in this study.

Overall, the residual analysis supports the statistical findings presented in the previous section and confirms the suitability of the developed calibration model for accurate level measurement. The behavior of the residuals also provides a basis for the subsequent analysis of percentage measurement error across the investigated operating range.

E. Percentage Error Analysis

The variation of percentage measurement error with distance was evaluated to assess the measurement performance of the developed ultrasonic level measurement system across its operating range. The results, presented in Fig. 7, show that the percentage error generally decreased as the measurement distance increased, indicating progressive improvement in measurement accuracy over the investigated range.

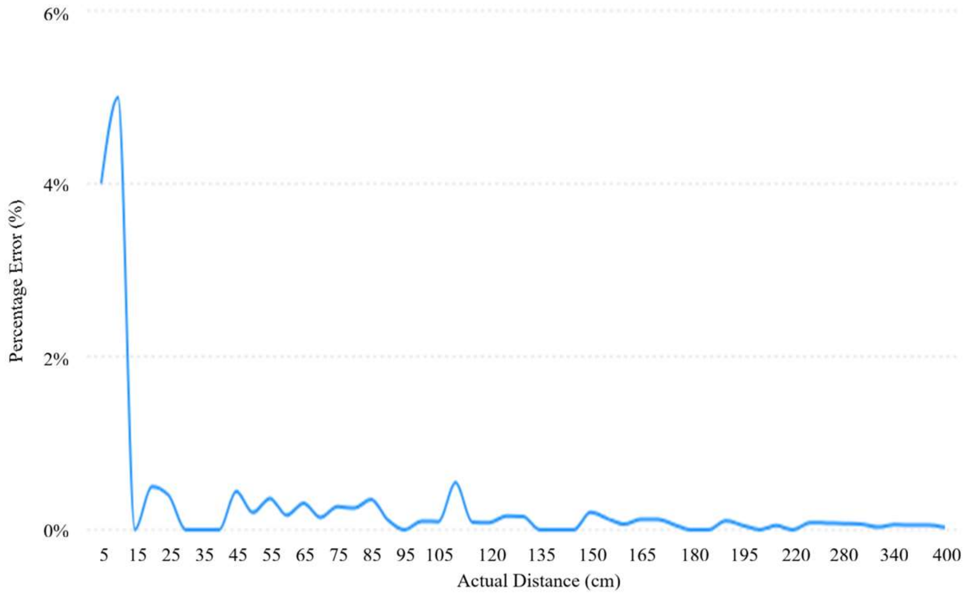

Fig. 7. Graph of Percentage Error (%) Vs Actual Distance (cm).

At shorter measurement distances, relatively larger percentage errors were observed. This behavior is primarily attributed to the inherent characteristics of ultrasonic sensing, including transducer ringing, near-field effects, and the limited time resolution associated with very short echo travel times. These factors reduce the precision of time-of-flight measurements, resulting in slightly higher measurement uncertainty within the near-field region.

As the measurement distance increased, the influence of these effects gradually diminished, leading to improved stability of the received echo signal and more accurate time-of-flight estimation. Consequently, the percentage error decreased progressively with increasing distance, reaching a minimum value of 0.025% at 400 cm. This result demonstrates the excellent long-range performance of the developed measurement system and confirms the effectiveness of the calibration and signal-conditioning techniques employed in the design.

The observed trend is consistent with the operating characteristics of ultrasonic measurement systems reported in previous studies, where measurement stability improves beyond the near-field region as ultrasonic wave propagation becomes more uniform and echo detection becomes more reliable. The ability of the developed system to maintain very low percentage errors over a wide measurement range demonstrates its suitability for continuous level monitoring applications requiring high measurement accuracy.

Overall, the percentage error analysis confirms that the developed ultrasonic level measurement system provides reliable performance throughout its operating range, with measurement accuracy improving progressively as the measurement distance increases. These findings further support the statistical and residual analyses presented in the preceding sections and demonstrate the robustness of the proposed system for practical level measurement applications.

F. *Comparison with Previous Studies*

To further evaluate the performance of the developed custom ultrasonic level measurement system, its characteristics were compared with selected ultrasonic level measurement systems previously reported by [9] and [28]. The comparison, presented in Table IV, highlights the principal features and performance characteristics of the different systems.

Table IV. Comparison of the developed ultrasonic level measurement system with selected previous studies.

Author/ Study	Technique Used	MAE (cm)	RMSE (cm)	R^2	Average Percentage Error (%)	Accuracy (%)
[9]	Ultrasonic sensing	0.45	0.60	0.89	4.8	91
[28]	IoT ultrasonic system	0.30	0.42	0.93	3.2	94
Present Study	Real-time ultrasonic system	0.129	0.163	0.999998	1.50	97

As shown in Table IV, the three systems employ ultrasonic sensing for non-contact level measurement and microcontroller-based processing for real-time operation. However, differences exist in the scope of system validation and performance evaluation.

Reference [9] demonstrated the feasibility of ultrasonic sensing for monitoring liquid levels under practical operating conditions, while [28] presented an Arduino-based ultrasonic level measurement system with satisfactory real-time performance. These studies established the applicability of low-cost ultrasonic sensing for level monitoring but provided comparatively limited statistical assessment of measurement performance.

In contrast, the present study complements the hardware development with a comprehensive statistical evaluation of system performance. The developed custom ultrasonic level measurement system was calibrated using 51 measurement points distributed over the operating range of 2.9–400 cm, with five repeated measurements obtained at each point to evaluate repeatability and measurement consistency. The experimental data were further analyzed using multiple statistical indicators, including the Mean Absolute Error (MAE), Root Mean Square Error (RMSE), standard deviation, regression analysis, residual analysis, percentage error analysis, and confidence interval estimation. This comprehensive evaluation provides stronger evidence of the accuracy, repeatability, and reliability of the developed system than is typically reported in comparable low-cost ultrasonic level measurement studies.

Another distinguishing feature of the present work is the development of a custom ultrasonic transceiver integrated with dedicated signal-conditioning circuitry and Arduino-based digital processing. The combination of improved hardware design, calibration correction, and rigorous statistical validation contributed to the excellent agreement observed between the measured and reference distances, as reflected by the very low error metrics and high coefficient of determination reported in this study.

Overall, the comparison presented in Table IV demonstrates that the principal contribution of the present work lies not only in the successful development of a low-cost ultrasonic level measurement system but also in its comprehensive experimental validation. The combination of a wide operating range, low measurement error, high linearity, and rigorous statistical performance evaluation makes the developed system suitable for reliable real-time level monitoring in industrial, laboratory, agricultural, and domestic applications.

G. Practical Implications and Applications

The results obtained in this study demonstrate that the developed custom ultrasonic level measurement system is capable of providing reliable, accurate, and continuous non-contact level measurements over a wide operating range. The combination of low measurement error, excellent linearity, and high repeatability indicates that the system is suitable for applications requiring dependable real-time level monitoring.

The integration of a custom ultrasonic transceiver with dedicated signal-conditioning circuitry and Arduino-based digital processing provides a low-cost alternative to many commercially available level measurement systems. The use of readily available electronic components further simplifies system construction, maintenance, and future modifications, making the device attractive for both educational and industrial applications.

Potential applications of the developed system include water storage tank monitoring, reservoir level measurement, agricultural irrigation systems, laboratory process monitoring, chemical storage facilities, and other industrial processes where non-contact measurement is preferred to avoid sensor contamination, corrosion, or mechanical wear. The incorporation of an LCD and alarm functionality also enables immediate operator feedback during routine monitoring and process control.

Although the present investigation was conducted under controlled laboratory conditions, the comprehensive calibration procedure and statistical validation demonstrate that the developed system provides a robust foundation for practical deployment. Future enhancements may include temperature compensation, wireless communication, Internet of Things (IoT) connectivity, cloud-based data logging, and remote monitoring capabilities to further improve system functionality under varying environmental conditions.

Overall, the developed custom ultrasonic level measurement system combines simplicity, affordability, and reliable measurement performance, making it a practical solution for a wide range of real-time level monitoring applications.

IV. CONCLUSION

A custom ultrasonic level measurement system integrated with Arduino-based processing was successfully designed, constructed, calibrated, and experimentally validated for reliable real-time non-contact level measurement. The system was evaluated over an operating range of 2.9–400 cm using 51 calibration points with five repeated measurements at each point to assess its accuracy, repeatability, and reliability. The developed system demonstrated excellent measurement performance, achieving a mean absolute error (MAE) of 0.129 cm, a root mean square error (RMSE) of 0.163 cm, a standard deviation of 0.143 cm, and a coefficient of determination (R^2) of 0.999998. The low measurement errors, excellent linearity, and stable residual behavior confirm the reliability of the developed system for accurate level measurement over the investigated range.

The principal contribution of this work lies in the development and comprehensive statistical validation of a low-cost custom ultrasonic level measurement system incorporating a custom ultrasonic transceiver, dedicated signal-conditioning circuitry, and Arduino-based processing. The developed system provides a practical, accurate, and economical solution for real-time level monitoring in water storage, industrial process control, agricultural systems, and laboratory applications. Future work will focus on environmental compensation techniques, wireless communication, and IoT integration to further enhance system performance under practical operating conditions.

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