

Design, Implementation, and Field Deployment of a Real-Time Sewage Tank Level Detection and Monitoring System for Residential Facilities in A University Campus

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ABSTRACT: Sanitation hazards and environmental contamination usually result from ineffective management of wastewater systems in densely populated areas. This study presents the design, implementation, and field deployment of a real-time sewage tank level detection and monitoring system that was tailored to manage wastewater infrastructures at the Federal University of Technology, Ikot Abasi (FUTIA). The design implements a standalone, hardwired embedded architecture, unlike conventional systems that rely heavily on Internet of Things (IoT) or cloud-based platforms. The standalone design approach was informed by the erratic Wi-Fi and cellular networks within and around the university campus. The system was designed to monitor a $4m \times 4m \times 4m$ underground septic tank using a non-contact HC-SR04 ultrasonic sensor interfaced with an embedded processing unit. The designed system converts the acoustic round-trip time-of-flight (ToF) data into volumetric value. Real-time updates of the sewage tank volume are communicated to an indoor unit with LEDs that are calibrated to trigger at 20%, 40%, 60%, 80%, and 90% thresholds. At the critical 90% fill limit, the active buzzer is triggered to generate intermittent audible alarm (200 milliseconds ON / 200 milliseconds OFF) that notify facility administrators of impending structural overflow. The system design was cross-validated using Proteus Design Suite 8.13 Professional and comprehensive MATLAB simulations. The conducted field evaluation presented an impressive system execution time of one second with an average measurement deviation (E_{avg}) of 1.24%. This study provides a practical, low-maintenance, cost-effective and robust wastewater management solution for densely populated university campuses.

KEYWORDS: Smart Campus, Sewage Level Monitoring, Ultrasonic Sensing, Embedded Systems, MATLAB, Proteus Design Suite, Wastewater Management.

Nomenclature

A	Horizontal cross-sectional surface area of concrete tank (m^2)
c_0	Velocity of sound at $0^\circ C$
$c(T)$	Acoustic sound propagation velocity as a function of temperature (m/s)
V_{max}	Maximum tank volume (m^3)
$V(h)$	Instantaneous volume of wastewater
L	Length (m)
W	Width (m)
H	Height (m)
E_{avg}	Average measurement deviation
Δt	Total round-trip echo pulse flight duration time (s)
T	Enclosed ambient air temperature inside the sewage storage tank ($^\circ C$)
d	Instantaneous air gap distance measured from the ultrasonic sensor (m)
h	Instantaneous height of the sewage fluid from the bottom of tank to surface (m)
L_n	Binary electrical logic actuation state ($n = 20, 40, \dots, 90$)
P	Real-time volume fill level (%)

I. INTRODUCTION

The existing pressure on sanitation and wastewater management infrastructures within residential facilities in university campuses is on the increase, and this is a direct result of increased population density. Sewage tanks are

critical units that are required for managing domestic wastewater, improper and delayed management of same can lead to overflow which may subsequently result in environmental pollution, infrastructural degradation, and health hazards. Sewage management within many

institutions, particularly in developing countries are still performed manually by relying on physical and periodic inspection rather than employing continuous real-time measurement. The need for automated monitoring of wastewater infrastructures within university communities has become undoubtably important. Early detection of critical fill levels of sewage tanks using real-time monitoring allows for timely intervention before overflow occurs [1]. The wired embedded monitoring system being considered in this study is particularly suitable for managing critical infrastructures in university communities as they offer improved reliability, low latency, reduced operational cost, and non-dependence on the availability of communication networks, as compared to the Internet of Things (IoT)-based and cloud-dependent systems, which extensively rely on communication networks. The design of compact, low-cost monitoring systems that are capable of real-time environmental sensing, with localized decision-making capabilities have been enabled by improvements in embedded electronics and sensor systems technologies. As a result of their accuracy, affordability, and ease of integration with microcontroller platforms such as the Arduino UNO R3, the ultrasonic sensors, particularly the HC-SR04 have been widely adopted for use in non-contact liquid level measurement [2]. Ultrasonic sensors emit high-frequency acoustic waves that enables it to measure the time of flight (ToF) of reflected signals, and use same to determine distances that can be translated into sewage tank fill levels [3]. Regardless of the advancement in the development of embedded sensing technologies, most wastewater management systems are not optimized for wired deployment in medium and small-scale institutional environments but are either IoT-based or of industrial scale. The IoT-based systems, although effective, but may not be ideal for continuous critical monitoring application in residential facilities within university campuses, as they often introduce complexities, high energy requirements, and are heavily dependent on external communication networks. Presented in this study, is the design, implementation, and field deployment of a real-time sewage tank level detection system that is entirely based on a wired embedded system architecture. The system executes real-time monitoring of sewage tank level by integrating HC-SR04 ultrasonic sensor with an Arduino Uno R3 microcontroller, which eliminate the need for external cloud connectivity by providing feedback outputs through LED indicators, and audible buzzer alarm. The contribution of this system design lies in the development of a robust, cost-effective, low maintenance, and a completely standalone wired monitoring system, capable of providing real-time sewage level monitoring without relying on IoT infrastructures. This makes the system particularly suitable for deployment within residential environments at universities where simplicity, operational continuity, reliability, and affordability are critical.

II. RELATED WORKS

The growing demand for efficient and operationally effective wastewater management systems has led to increased research in automated sewage tank monitoring system designs. Recent advances in embedded systems have facilitated the development of dependable real-time monitoring solutions that are effective at providing early warning against sewage tank overflow. As a result of their high accuracy, non-contact operability, and cost-effectiveness, these technologies have been extensively embraced in high-level measurement application. [4] designed an automated water level monitoring system that protects water heater tanks on offshore platforms. The design was effective at optimizing energy consumption and preventing hazardous spill of hot water. However, the design targeted clean water in industrial heating tanks. [5] developed a water leakage detection system, capable of reducing water waste that results from overflowing tanks. The system was designed to manage an attached motor pump, installed to activate and fill the tank whenever fluid level dropped to 5% and automatically cut off at 100% fluid level capacity. However, the system was designed to be remotely controlled, as it relied on continuous internet connectivity, external ESP8266 RF transmitters, and Blynk cloud app. [6] developed a smart water level monitoring system, aimed at eliminating manual tracking in order to ensure a steady supply of drinking water. The design incorporated a SIM800L GPRS GSM module that transmitted data over cellular signals by using standard AT command. [7] constructed a sewage level monitoring device for residential septic tanks. Utilized in the prototype was an ATmega328-based Arduino Uno platform that was directly linked with an HC-SR04 ultrasonic transducer. Incorporated in the design was a SIM900D GSM transceiver module that supported the broadcast of alert to the facility administrators. [8] fabricated an open-source flowmeter for monitoring wastewater inflow and outflow profile at a wastewater treatment plant. The design featured a built-in web server using a local Wi-Fi chip that enabled operators to configure channel measurement and retrieve stored logs into smartphones. Designed by [9] was a river water level detection system, intended to provide early flood disaster warning. Paired in the design was an ATmega328P-based Arduino Uno with an HC-SR04 ultrasonic sensor, that tracked liquid elevations inside a controlled testing aquarium. The precise incremental visibility needed by facility managers was not provided by the design configuration. [10] developed a water level monitoring device for implementing outdoor irrigation in farms by tracking water movement. The design was intended for monitoring clean irrigation water in outdoor fields and does not address high concentrations of volatile gases, thick surface scum, and irregular usage spikes found in enclosed sewage tanks. The reviewed literatures revealed that majority of the existing studies on wastewater management, rely on IoT platforms,

and cloud-based monitoring infrastructures. These technologies raise implementation cost, increase system complexity and are highly dependent on stable communication networks, whereas they provide remote accessibility and data logging capabilities, this may also limit their suitability in developing region with unreliable internet connectivity. This study presents the design of a real-time sewage level monitoring system that utilizes an Arduino microcontroller in connection with HC-SR04 ultrasonic sensor that activates progressive LED indicators at predefined thresholds of 20%, 40%, 60%, 80%, and 90%, with an intermittent buzzer alarm at the critical level. The ease of deployment and maintenance of the design, makes it an economical and practical solution for residential facilities within university campuses.

III. MATERIALS AND METHODS

The real-time sewage tank level detection and monitoring system design as shown in fig. 1, is a standalone embedded system that is comprised of four key units: HC-SR04 ultrasonic unit for non-contact level measurement, Arduino UNO as embedded processing unit, LED indicators for visual indication at the different fill levels, and the alarm unit for issuing critical level warning signals. The system was designed to monitor an underground rectangular sewage tank with internal dimensions of $4m \times 4m \times 4m$, representing an underground septic tank within the campus of the Federal University of Technology, Ikot Abasi (FUTIA). The distance between the sensor and the sewage surface was continuously measured by securely mounting the ultrasonic sensor at the center of the sewage tank. The flowchart shown in fig. 2, illustrates the overall workflow of the system.

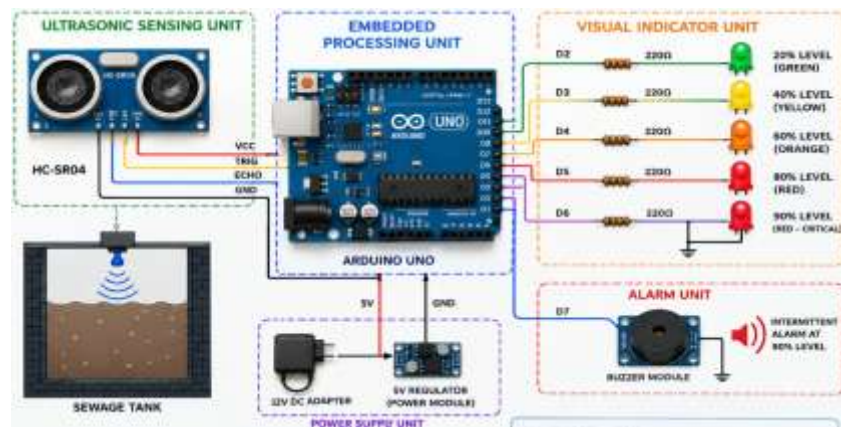


Fig. 1: Circuit diagram of the sewage tank level monitoring system architecture (Author’s design)

3.1 System Architecture

The comprehensive model of the non-IoT real-time sewage tank level monitoring system for the $4m \times 4m \times 4m$

underground residential sewage tank employed for this study is presented in this section of the study.

Table 1: Underground Sewage Tank Specifications

Parameter	Symbol	Value
Length	L	4 m
Width	W	4 m
Height	H	4 m
Cross-sectional Area	$A = L \times W$	16 m ²
Maximum Tank Volume	$V_{max} = LWH$	64 m ³

A. Tank Volumetric Capacity

$$V_{max} = L \times W \times H \quad (1)$$

$$V_{max} = 4m \times 4m \times 4m = 64 \text{ m}^3$$

Let h represent the instantaneous vertical height of the sewage tank from the floor ($0 \leq h \leq H$). Let the instantaneous volume of wastewater, $V(h)$ be given as:

$$V(h) = L \times W \times h = 16h \quad (2)$$

The percentage of wastewater in the sewage tank,

$$P = \left(\frac{V(h)}{V_{max}} \right) \times 100\% \quad (3)$$

$$P = \left(\frac{16h}{64} \right) \times 100\% = 25h \quad (4)$$

B. Ultrasonic Time-of-Flight (ToF)

The HC-SR04 ultrasonic sensor was securely mounted at the center of the sewage tank roof ($h = H$). the HC-SR04 sensor measured the vertical air gap (d) through the acoustic reflective boundary of the sewage surface. Therefore, the relationship between the sewage height (h) and the measured distance (d) is given as:

$$h = H - d = 4.0 - d \quad (5)$$

The HC-SR04 sensor emit high-frequency wave that is directed downward, through the internal vertical air gap, the high-frequency wave is reflected off the sewage boundary, and is returned to the receiver. With Δt representing the flight duration of the round-trip echo in seconds, and $c(T)$

represents the propagated speed of sound in air, the measured distance (d) is represented as:

$$d = \frac{c(T) \times \Delta t}{2} \quad (6)$$

Methane gas and carbon dioxide are generated from decomposing sewage, therefore a shift in humidity can alters the acoustic properties as well as changes in temperature, the propagated speed of sound in air can therefore be modeled as a function of temperature (T °C)

$$c(T) = c_0 \sqrt{1 + \frac{T}{273.15}} \approx 331.3 + 0.606T \text{ (m/s)} \quad (7)$$

where $c_0 = 331.3$ m/s is the velocity of sound at 0 °C. The combination of these kinematics gives rise to the dynamic height model:

$$h(\Delta t, T) = 4.0 - \frac{(331.3 + 0.606T) \times \Delta t}{2} \quad (8)$$

C. Integration of Measured Capacity

By substituting dynamic height model in eqn. (8) into the percentage of wastewater level in eqn. (4), the integrated measurement equation needed to derive the sewage tank capacity is arrived at, see eqn. (9).

$$P(\Delta t, T) = 25 \times \left[4.0 - \frac{(331.3 + 0.606T) \times \Delta t}{2} \right] \quad (9)$$

$$P(\Delta t, T) = 100 - 12.5 \times (331.3 + 0.606T) \times \Delta t \text{ (%)}$$

D. Threshold Algorithm

Detailed in fig. 2, are boundary loops, logic branches, and the systematic execution pathway of the embedded microcontroller. The computed percentage levels are compared with predefined threshold values by the Arduino UNO in order to determine the operating state of the monitoring system.

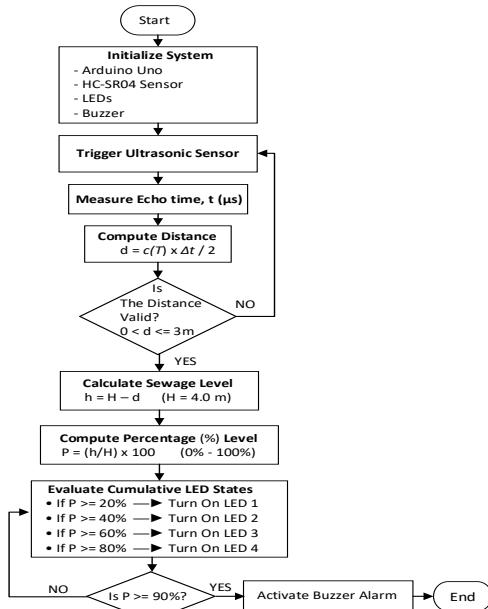


Fig. 2: Flowchart of the monitoring system model

For the 4-meter-deep sewage tank configuration, the indoor display panel interprets the calculated percentage of wastewater (P) in the sewage tank, by controlling five discrete levels of LEDs (L_{20} , L_{40} , L_{60} , L_{80} , L_{90}) using an array of microcontroller output pins.

$$L_{20}(P) = \begin{cases} 1 \text{ (ON)}, & \text{if } P \geq 20\% \\ 0 \text{ (OFF)} & \text{otherwise} \end{cases} \leftrightarrow h \geq 0.8 \text{ m} \leftrightarrow d \leq 3.2 \text{ m} \quad (10)$$

$$L_{40}(P) = \begin{cases} 1 \text{ (ON)}, & \text{if } P \geq 40\% \\ 0 \text{ (OFF)} & \text{otherwise} \end{cases} \leftrightarrow h \geq 1.6 \text{ m} \leftrightarrow d \leq 2.4 \text{ m} \quad (11)$$

$$L_{60}(P) = \begin{cases} 1 \text{ (ON)}, & \text{if } P \geq 60\% \\ 0 \text{ (OFF)} & \text{otherwise} \end{cases} \leftrightarrow h \geq 2.4 \text{ m} \leftrightarrow d \leq 1.6 \text{ m} \quad (12)$$

$$L_{80}(P) = \begin{cases} 1 \text{ (ON)}, & \text{if } P \geq 80\% \\ 0 \text{ (OFF)} & \text{otherwise} \end{cases} \leftrightarrow h \geq 3.2 \text{ m} \leftrightarrow d \leq 0.8 \text{ m} \quad (13)$$

$$L_{90}(P) = \begin{cases} 1 \text{ (ON)}, & \text{if } P \geq 90\% \\ 0 \text{ (OFF)} & \text{otherwise} \end{cases} \leftrightarrow h \geq 3.6 \text{ m} \leftrightarrow d \leq 0.4 \text{ m} \quad (14)$$

IV. RESULTS AND DISCUSSION

The monitoring circuit was designed with the least possible number of electronic components for efficient signal acquisition, processing and output control. Interfacing of HC-SR04 ultrasonic sensor with Arduino UNO was done for continuous measurement of the sewage level. The measured distance value was calculated by Arduino using the developed mathematical model to calculate the corresponding tank fill level. Five LEDs along with a current limiting resistor gave a visual indication of different fill levels and an active buzzer provided an audible warning when the sewage level reached the critical 90% level. The circuit was powered by a regulated 5 V DC supply and designed and simulated in Proteus Design Suite 8.13. MATLAB was used to model and analyze the tank dynamics, sensor distance, sewage level, tank volume, measurement error and system response. The system was subsequently deployed as a physical prototype and validated in the field after successful simulation.

A. Proteus System Design

The functionality of the real-time sewage level detection and monitoring system was verified via modeling and simulation of the circuit design using Proteus Design Suite 8.13 Professional. This helped in validating the interaction between the Arduino UNO, HC-SR04 sensor, LEDs, and active buzzer, while varying the sewage levels.

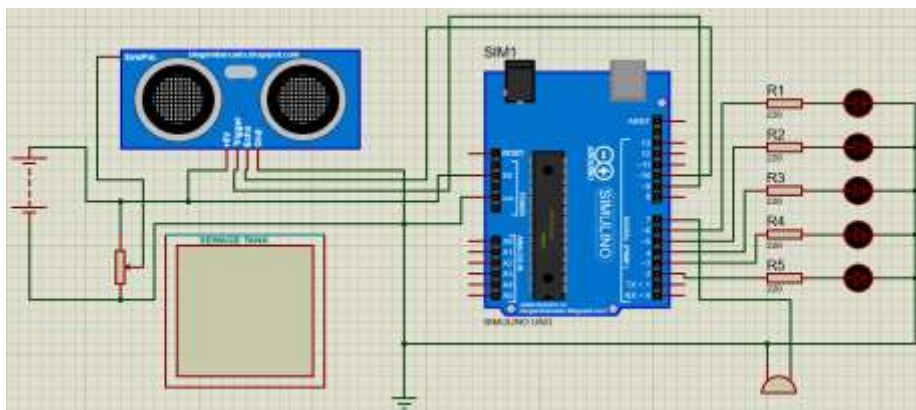


Fig. 3: Proteus Simulation Model for the Real-Time Sewage Tank Level Detection

B. MATLAB Performance Analysis

The mathematical model and firmware logic were validated by conducting MATLAB simulation. The simulated results

helped in analyzing the system response to the continuous influx of wastewater against the discrete milestone boundaries of the hardware interface.

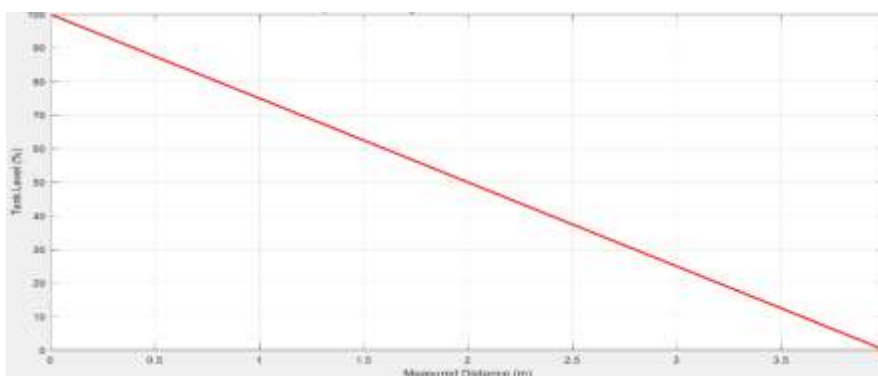


Fig. 4: Percentage Tank Level as a Function of Sensor Distance

Fig. 4 illustrates the inverse relationship employed by the controller in estimating the tank fill level. As the sensor distance decreases, the sewage level increases.

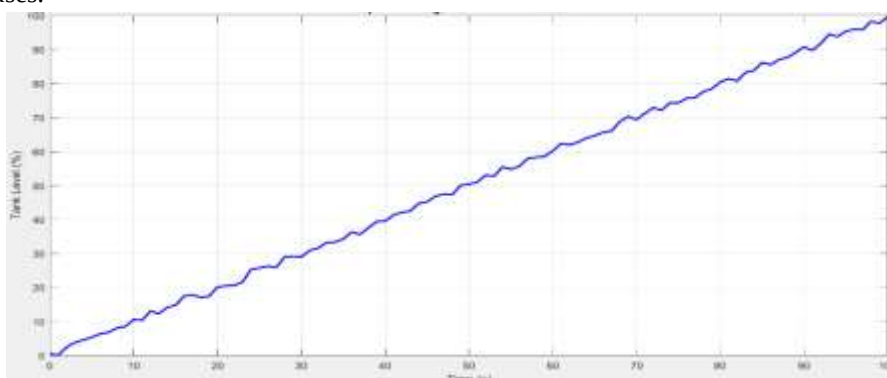


Fig. 5: Variation of Sewage Tank Level with Time

Fig. 5 illustrates the variation of the sewage tank level with time. The linear trend shows the ability of the system to monitor real-time changes in sewage level.

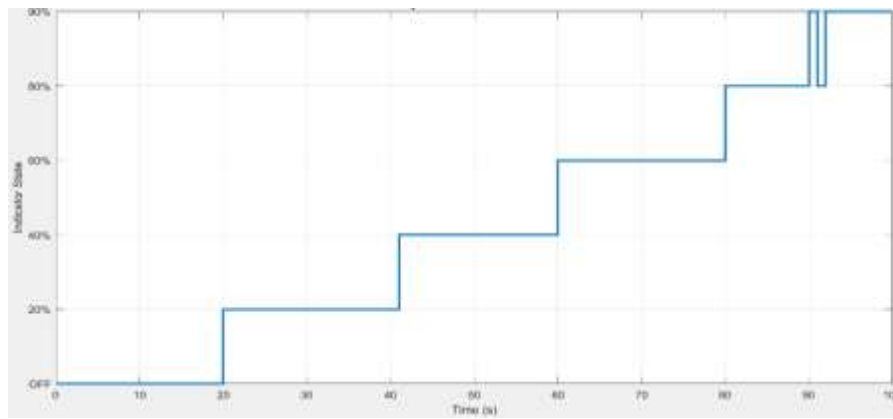


Fig. 6: LED Indicator State

Fig. 6 presents a step graph that validates the sequential activation of the different LEDs that corresponds to the predefined thresholds of 20%, 40%, 60%, 80%, and 90% respectively. Thereby, confirming the correct operability of the controller.

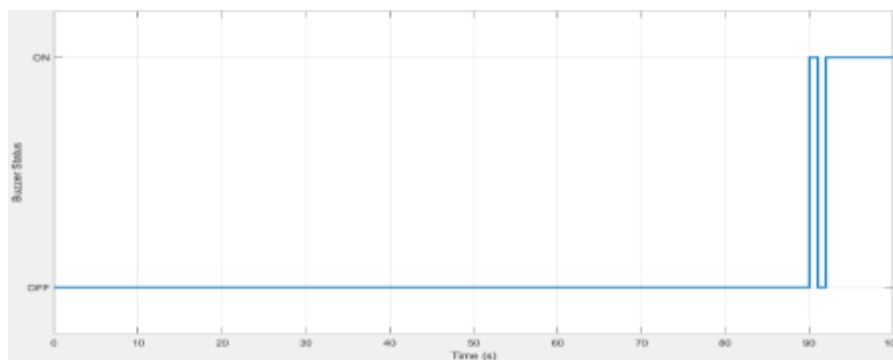


Fig. 7: Buzzer Activation Response

Fig. 7 shows the buzzer status during normal and critical state. This shows the inactiveness of the buzzer during normal operation and its activeness at critical limits of 90% and beyond, thereby validating the correct execution of the alarm logic in the control algorithm.

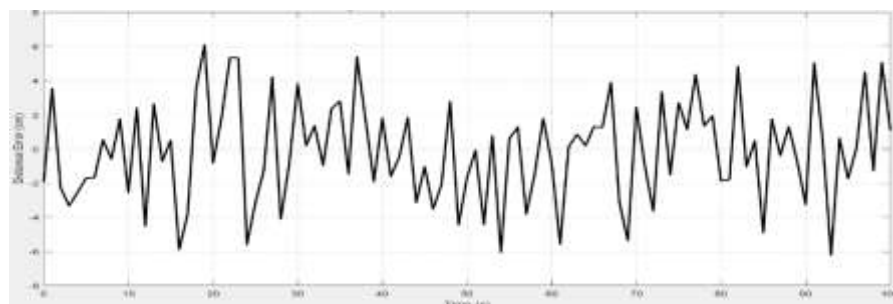


Fig. 8: Ultrasonic Sensor Measurement Error

Fig. 8 shows the measurement error of the ultrasonic sensor throughout the simulation. This illustrates the measuring accuracy of the ultrasonic sensing system by showing the anticipated uncertainty.

C. Field Deployment and Evaluation

The developed prototype was deployed at a residential facility within the Federal University of Technology, Ikot Abasi. The ultrasonic sensor was positioned at the top of the sewage tank, while the monitoring unit containing the LED

indicators and buzzer was installed indoors for convenient observation. The system was further evaluated by comparing the sensor measurement with manually determined sewage tank level.

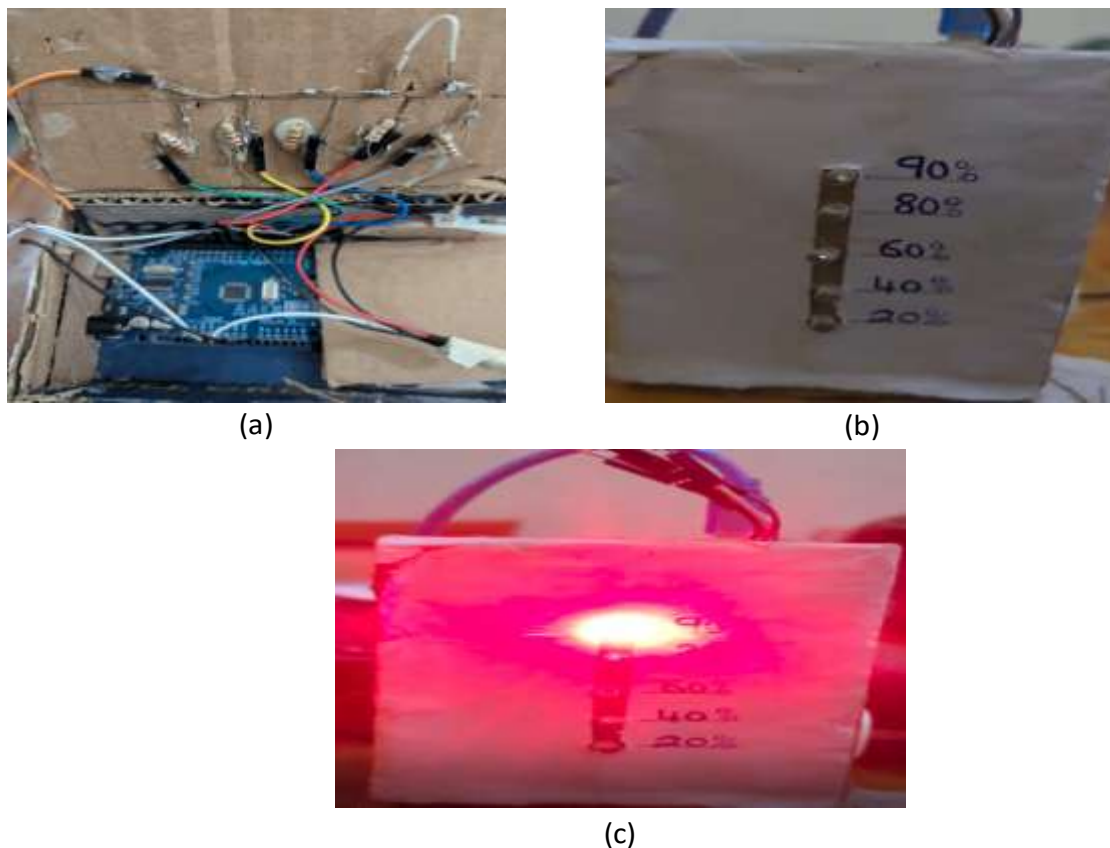


Fig. 9: Hardware Implementation and Field Testing of the Sewage Tank Level Monitoring System: (a) Internal circuit assembly showing the Arduino UNO, wiring, and LED/buzzer connections; (b) Front panel indicator layout with labeled threshold levels (20%–90%); and (c) Active LED indication during tank level testing.

Table 2: Field Performance Evaluation

Actual Level (%)	Measured Level (%)	Indicator Response	Alarm	Error (%)
20	21.2	20% LED	OFF	1.2
40	39.0	20–40% LEDs	OFF	1.0
60	61.5	20–60% LEDs	OFF	1.5
80	79.2	20–80% LEDs	OFF	0.8
90	91.3	All LEDs	ON	1.3
100	98.6	All LEDs	ON	1.4

With a system response time of approximately one second to changes in sewage level, the calculated average measurement deviation, $E_{avg} = 1.24\%$

V. DISCUSSION

The designed sewage monitoring system was highly effective under experimental evaluation and field deployment. The negligible deviation in measurement confirms the suitability of ultrasonic sensing for use in non-contact estimation of sewage level. The LED-based indication system design, provided real-time update regarding the status of the sewage tank, while the buzzer alarm effectively sounded when the tank level was at its critical point. Unlike the IoT-based sewage level monitoring system, the executed design reduced implementation complexities by eliminating its dependence on internet connectivity and availability. However, environmental conditions, foam formation, and sewage surface turbulence are factors that are capable of distorting

the effective performance of sensing devices. Future improvement on the design may incorporate additional communication capabilities.

VI. CONCLUSION

The standalone real-time sewage tank level detection and monitoring system was designed, simulated, implemented, and field-tested. The system successfully provided real-time indication of sewage level and also provided early warning by effectively integrating ultrasonic measurement and embedded processing. The designed sewage monitoring system was validated by simulating and analyzing its effectiveness for field deployment using Proteus Design Suite and MATLAB software. Evaluated results from field

deployment confirmed a response time of one second and an average error of 1.24%. The designed and implemented system provides a practical, economical and reliable solution for improving sewage and wastewater management in residential facilities across university campuses.

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