DEVELOPMENT OF DIGITAL ULTRASONIC VOLUMETRIC GAUGE

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CERTIFICATION

This is to certify that this work is original and was carried out by the afore-listed students under the supervision of the project supervisor

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DEDICATION

This report is dedicated to God, the source of Life and Wisdom. We sincerely thank our parents, Loved ones, and supporters, whose steadfast presence has been a constant source of encouragement, especially during difficult moments. Their love and faith in us have given us the strength and determination to see this project through to completion. We deeply appreciate their continuous support, which has been crucial to our academic and personal development.

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ABSTRACT

Measuring the volume of liquid stored in tanks is a routine but critical task in engineering applications, yet many commonly used methods still rely on direct contact and manual observation. Devices such as float gauges, sight glasses, and dipsticks are often affected by mechanical wear, environmental conditions, and human error, which reduces their reliability over time. In situations involving hazardous or enclosed liquids, these limitations become even more significant. This project addresses these issues through the development of a digital ultrasonic volumetric gauge that enables accurate, non-contact measurement of liquid volume.

The primary aim of this work was to design and implement a system that determines liquid volume by measuring the liquid level and converting it into volumetric data using digital processing techniques. An ultrasonic sensor was employed to transmit and receive sound pulses, allowing the distance to the liquid surface to be calculated using the time-of-flight method. A microcontroller processed this distance data, applied calibration and volume conversion algorithms based on the tank's geometry, and presented the results through a digital display and a web-based interface.

Experimental testing showed that the system produced stable and repeatable measurements with a low margin of error across various fill levels. The developed gauge demonstrates a practical, cost-effective solution for real-time liquid volume monitoring, with potential applications in industrial storage, water management, and educational environments

CHAPTER 1

1.1 INTRODUCTION

In the modern era of industrial and scientific progress, accurate measurement of liquid volume has been a key parameter towards achieving efficiency, safety, and resource utilization in numerous industries. Right from production cycles to environmental monitoring, the ability to measure accurately the volume of fluids held in containers, tanks, or pipes is key to operational success. Traditionally, measuring volumetric methods such as mechanical float systems or manual dipsticks have been employed but are deficient in accuracy, reliability, and adaptability to suit today's requirements (Lipták, 2003). These deficiencies have spurred the development of new technologies, among which ultrasonic-based systems stand out because they are non-invasive and digital. The goal of this project is to make a Digital Ultrasonic Volumetric Gauge, which is a gadget that uses ultrasonic waves to measure volume accurately in real time. The gauge uses microcontroller and digital interface technology to get rid of the problems with traditional methods. It is a low-cost, user-friendly device that can be utilized in many different ways.

The phrase volumetric gauging is a term used that suggests measurement of the volume of a liquid in a specific volume. This measurement is of the most significance in industrial applications for inventory tracking, process monitoring, and product quality control. In the petroleum industry, for instance, precise volume measurement within storage tanks prevents overflows, eliminates waste, and complies with regulatory specifications (API,2015). Similarly, at water treatment facilities, accurate gauging increases efficient use of resources and protection of the environment. Previously, volumetric measurement has relied on crude techniques. Dipsticks, for example, involve manually lowering a calibrated rod into the fluid to assess the level, which is very laborious and prone to human errors. Mechanical gauges, such as sight glasses or float systems, added to this with visual or automated measurements but still entailed direct contact with the fluid, causing issues like corrosion, contamination, or error in viscous or hazardous materials (Bela & Bela, 2017).

As industries changed, it became clear that they need ways to measure liquid without touching them. Ultrasonic technology emerged as a feasible choice in the mid-20th century, relying on the principles of sound wave propagation. Ultrasonic waves, acoustic waves with a frequency higher than the human audible range (typically 20 kHz or higher), have the ability to travel in air or other media and reflect off surfaces. In level measurement, an ultrasonic transducer emits a pulse of such waves toward the liquid surface. The time taken for the echo to travel to the transducer is recorded, and with the velocity of sound in the medium being known (approximately 343 meters per second in air at room temperature), the distance to the liquid surface is calculated (Fraden, 2016). This height, along with the container's geometry, i.e., its cross-sectional area, allows the volume to be calculated. The formula for volume in a cylindrical tank, for example, is $V = \pi r^2 h$, where h is the liquid height from the ultrasonic measurement. The principle of ultrasonic level measurement is rooted in the time-of-flight (TOF) method. The transducer acts as both a transmitter and receiver. Upon emission, the ultrasonic pulse travels downward until it encounters the interface between air and the liquid, where a portion of the wave is reflected back due to the impedance mismatch between the two media. The TOF is directly proportional to the distance: $d = (v * t)/2$, where d is the distance, v is the speed of sound, and t is the round-trip time. Factors such as temperature, humidity, and pressure can affect the speed of sound, necessitating compensation mechanisms in advanced gauges (Lynnworth, 2014). Digital systems incorporate sensors for these variables, ensuring high accuracy often up to 99% in controlled environments.

The transition from digital to ultrasonic gauges is a wonderful improvement in utility. Digital gauges use microcontrollers such as Arduino or PIC-based units to process signals, compute values, and provide output on LCD screens or transmit information via wireless interfaces. This digitization provides features such as data logging, alarm limits for low and high levels, and compatibility with IoT systems for remote monitoring (Gill, 2020). Under this project, the manufacturing involves designing and building units composed of an ultrasonic sensor, a microcontroller unit, a power supply, a display interface, and an enclosure. The goal is to create a prototype that not only computes volume but also user-friendly outputs, which can be applied for small industries or for academic use.

1.2 BACKGROUND OF THE STUDY

Since the inception of Engineering, the need to accurately measure liquid in a vessel has been there resulting in the design of Volumetric gauges; a mechanism that acquires the volume of a liquid in a vessel by measuring the height of the liquid in the vessel.

It has been present since the ancient era, from Nilometers used in Ancient Egypt to measure rivers height, graduated poles used in wells and cistern to get a direct level reading; progressively developing to float gauges in the 1800s during the Industrial Revolution then to non-contact technologies such as Radar, ultrasonic sensors and Laser to measure liquid level. Presently IoT has been integrated into volumetric gauges (Bela & Bela, 2017).

Volumetric gauges evolved from rudimentary manual tools into sophisticated digital system driven by industrial need for accuracy safety and automation (Lipták, 2003). While Ancient methods measured level only, modern systems integrated sensors and standards to deliver precise volume; resulting in transformation of process control.

Volumetric gauges are vital tools in Engineering for designing, monitoring, and maintaining fluid-containing systems. They are incorporated into tanks, boilers, pipelines, and pressure vessels to enable real-time monitoring of liquid volume. Engineers use gauge data to track fluid consumption, detect leaks, and schedule maintenance; critical for avoiding mechanical failures in pumps, valves, and seals under varying pressure/temperature conditions (Bela & Bela, 2017). Volumetric gauges act as the eyes for mechanical systems handling liquids, ensuring they run safely, efficiently, and reliably

1.3 STATEMENT OF PROBLEM

The accurate and efficient measurement of liquid volumes in storage tanks and containers is essential across various industries ranging from manufacturing to agriculture. Engineering applications involving liquid storage and handling such as fuel tanks in automotive systems and filling stations or industrial reservoirs in petroleum refining industry. Traditional volumetric measurement methods like mechanical floats, sight glass or manual dipstick suffer from significant limitations these include inaccuracies due to susceptibility to mechanical wear and corrosion, environmental factors (e.g. temperature fluctuations causing expansions or contractions) the need for invasive contact that poses safety risks hazardous or pressurized environment and the inability to provide real time digital data for automated monitoring and control

These limitations result in inefficiencies arising in process optimization, resource wastage (e.g. overflows or underfills) and safety concerns, underscoring the need for a non-contact, automated digital solution like an ultrasonic sensor-based volumetric gauge to enable precise, automated and robust volume measurement in mechanical system.

Fig 1.1: Chemical storage plant

1.4 AIM AND OBJECTIVES OF THE PROJECT

1.4.1 AIM OF PROJECT

To design, develop and test a digital volumetric gauge for accurate measurement of liquid levels in industrial & domestic storage tanks

1.4.2 OBJECTIVES OF PROJECT:

- Develop a microcontroller-based system to convert liquid level data into volumetric measurements
- Integrate ultrasonic sensors for indirect contact level detection
- Design a user-friendly digital display for remote monitoring (web interface)

1.5 SCOPE OF STUDY

The scope of study for the development of a digital volumetric gauge should include several aspects. These will guide the research, design and practical application of the project.

i. Machine Design:

Explore on the conceptual design, selection of ultrasonic sensors, circuit design and prototyping of a digital volumetric gauge system, incorporating mechanical components such as sensor mounting fixtures and enclosures designs suitable for integration into mechanical systems.

ii. Sensor Integration and Calibration:

Emphasis will be placed on integrating ultrasonic sensors with microcontrollers for non-contact liquid level detection including calibration procedures to ensure accuracy in measuring volumetric changes under varying mechanical conditions.

iii. Data Processing and Volume Calculation:

Developing algorithms for signal processing, converting ultrasonic time-of-flight data into volumetric measurements and accounting for mechanical factors like tank geometry. In essence converting distance to volume.

iv. Testing:

Experimental testing will be conducted in a controlled environment to evaluate the gauge's performance metrics including precision, repeatability and robustness against environmental interferences common in industrial applications.

1.6 PROJECT RELEVANCE AND ECONOMIC IMPORTANCE

The project is relevant in addressing the need for accurate, safe and efficient liquid volume measurement in industrial and domestic settings. It seeks to replace traditional, error-prone methods like dipsticks and sight glasses with a modern, non-contact ultrasonic solution. By providing real-time, digital data, the projects aim to improve process control, reduce waste and enhance safety in systems involving a storage tank. The economic importance of the project includes the following:

i. It reduces resource wastage by providing accurate volume measurements; minimizing errors from underfilling and overfilling.
ii. It minimizes production downtime by enabling real-time monitoring
iii. As a non-contact technology, it prevents mechanical wear, corrosion, and contamination of the stored fluid reducing long term maintenance and replacement costs
iv. It eliminates the need for manual repetitive liquid level checks freeing up personnel for more critical task resulting in lowered labor cost

CHAPTER 2

LITERATURE REVIEW

2.1 PRINCIPLE OF ULTRASONIC WAVES FOR DISTANCE AND VOLUME MEASUREMENT

Ultrasonic waves, characterized by frequencies above the audible range of human hearing (typically >20 kHz), have become foundational tools in modern science and technology. Their unique propagation behavior in solids, liquids, and gases allows for non-invasive inspection, imaging, and manipulation at the micro- and nanoscale. The theoretical underpinnings of ultrasonics lean largely on classical acoustics, elasticity theory, and nonlinear wave mechanics. As early as the 20th century, foundational work by Soviet researchers established the physics of high-intensity ultrasonic waves and their industrial applications in materials science and sonochemistry (Rozenberg, 2013).

2.1.1 FUNDAMENTAL PHYSICAL PRINCIPLES

Ultrasonic waves propagate as mechanical vibrations transmitted through a medium through particle displacements and elastic restoring forces. The fundamental principles of ultrasound involve the generation, transmission, reflection, and detection of acoustic energy, typically facilitated by transducers that convert electrical energy into mechanical oscillations (Gallego-Juárez, 2017).

Ultrasonic waves are classified into several types:

Longitudinal waves, in which particle displacement is parallel to wave propagation.

Transverse waves, where displacement is perpendicular.

Surface and guided waves (e.g., Rayleigh and Lamb waves), which travel along boundaries or thin materials (Ensminger & Bond, 2024).

The velocity v of an ultrasonic wave in a medium is dictated by its elastic modulus E and density ρ:

$v = E/\rho$

Attenuation, caused by scattering, absorption, and boundary losses, typically increases with frequency, leading to exponential amplitude decay with distance (Bowen, 1980).

2.1.2 ULTRASONIC WAVE GENERATION AND DETECTION

Ultrasonic transducers, fundamental to both research and application, function via piezoelectric, magneto strictive, or capacitive mechanisms. Piezoelectric transducers, the most common type, rely on materials like lead zirconate titanate (PZT), which deform under electric fields to produce oscillations at controlled frequencies. The reverse process enables detection of reflected or transmitted waves, forming the basis of pulse-echo systems used in imaging and nondestructive testing (Breyer&Andreić,2019),

Modern developments in ultrasonic electronics have refined these systems for higher precision, bandwidth, and sensitivity. Advances in signal processing and waveform generation enable for real-time, nondestructive examination of materials and biological tissues (Mizutani et al., 2016).

2.1.3 NONLINEAR AND GUIDED ULTRASONIC WAVE BEHAVIOR

In high-intensity regimes, nonlinear effects arise due to medium-dependent anharmonicity. Nonlinear ultrasonic guided waves can produce harmonic generation, mode coupling, and amplitude-dependent velocity changes, enhancing defect detection in structures. Such events have been rigorously formalized in nondestructive assessment theory (Lissenden, 2021). Guided wave modalities, such as Lamb waves, permit long-range inspection of pipes, plates, and composites, exploiting multiple propagation modes. Their interactions with boundaries and interfaces provide diagnostic information about material integrity, delamination, or corrosion (Ensminger & Bond, 2024).

2.1.4 ULTRASONIC WAVE INTERACTIONS AND CHARACTERIZATION TECHNIQUES

The propagation and scattering of ultrasonic waves reveal material microstructure, porosity, and elasticity. Techniques such as ultrasonic velocity and attenuation measurements quantify the mechanical characteristics of fluids and solids. For example, in emulsions, ultrasonic droplet size can be determined based on wave attenuation and backscattering patterns (McClements, 1996). Furthermore, wave mode conversions—from longitudinal to transverse or surface modes—offer insight into boundary interactions and anisotropy in crystalline or composite materials (Ensminger & Bond, 2024). include adaptive ultrasonic systems for real-time imaging, machine learning-enhanced signal interpretation, and quantum acoustics, where phonon interactions may yield new modalities of energy manipulation and sensing.

2.2 DIGITAL INTEGRATION AND SIGNAL PROCESSING IN MODERN GAUGING SYSTEMS

The advancement of volumetric measurement from mechanical readings to digital precision necessitates the integration of advanced digital electronics and signal processing techniques. This integration differentiates basic sensors from sophisticated gauging systems, including processes such as raw signal acquisition, signal conditioning, digital conversion, computational analysis, and data presentation. This section discusses the key components that comprise the operational foundation of current digital volumetric measurement equipment.

2.2.1 THE CENTRAL NERVOUS SYSTEM: MICROCONTROLLER UNITS (MCUS)

The Microcontroller Unit (MCU) functions as the central control component of digital gauges, coordinating all operations from data acquisition to user interface communication. The selection of an appropriate MCU is a critical design decision that directly impacts system processing performance, energy efficiency, and potential for future expansion.

ARDUINO PLATFORM FOR PROTOTYPING AND DEPLOYMENT

Arduino-compatible boards (such as the Uno and Nano variants) are widely used in academic settings and prototype development. Their popularity is attributed to user-friendly integrated development environments, extensive open-source libraries, and active support communities. MCUs based on the ATmega328P provide adequate computational capacity for managing sensor data, implementing complex geometric volume algorithms, and controlling local displays, making them suitable for dedicated gauge applications.

ADVANCED SYSTEM-ON-CHIP (SOC) PLATFORMS FOR IOT CONNECTIVITY

For applications requiring advanced features—especially Internet of Things (IoT) connectivity—System-on-Chip platforms such as the ESP32 offer significant technological advantages. The ESP32 combines dual-core processing power with integrated Wi-Fi and Bluetooth connectivity. This architecture enables volumetric gauges to operate as network nodes rather than standalone displays, supporting cloud-based data transmission for remote monitoring, historical data analysis, and integration into industrial control systems.

2.2.2 THE SIGNAL PROCESSING CHAIN: FROM PHYSICAL PHENOMENON TO DIGITAL DATA

The process of transforming physical measurements into accurate digital data follows a standardized signal processing chain, ensuring data correctness and system integrity at each level.

SIGNAL ACQUISITION AND ANALOG-TO-DIGITAL CONVERSION (ADC)

The process begins with sensors serving as transducers, converting physical parameters (such as distance or pressure) into electrical signals, typically analog voltages. Since microcontrollers operate in the digital domain, these analog signals must be converted through Analog-to-Digital Converters (ADCs). These crucial peripherals sample the analog voltages at prescribed speeds and convert them into discrete digital values according on their resolution. ADC resolution (for example, 10-bit on Arduino or 12-bit on ESP32) controls the measurement granularity, defining the smallest detectable change and determining total system accuracy.

DIGITAL FILTERING AND SIGNAL CONDITIONING

Data obtained directly from sensors often contains noise originating from various sources, including electrical interference, sensor instability, and environmental factors like liquid surface turbulence. As a result, raw ADC outputs typically require conditioning before their use.

SOFTWARE-BASED FILTERING ALGORITHMS

Implementing filtering techniques into the microcontroller’s software provides a stable foundation for signal processing. The moving average filter is a common technique, which involves continuously averaging a predefined window of recent sensor samples. This approach effectively lowers high-frequency noise while keeping the integrity of real signal changes. For more complex noise profiles or the need to eliminate outliers, advanced digital filters such as median filters or Kalman filters offer enhanced performance in signal refinement.

2.2.3 COMPUTATIONAL CORE: ALGORITHMIC TRANSFORMATION

Once stable level measurements (h) are obtained, the system performs the essential operation of converting height to volume. This process transitions the project from basic electronics to applied mechanical engineering by utilizing microcontroller units programmed with precise tank geometry mathematical models.

For horizontal cylindrical tanks, the volume (V) is computed using the formula:

$$V = L \times [\, R^2 \times \cos^{-1}((R - h)/R) - (R - h) \times \sqrt{(2Rh - h^2)}]$$

Efficient and accurate implementation of this calculation—particularly the inverse trigonometric and square root functions—within the constraints of embedded processing hardware is a key consideration in software design. This algorithmic approach enables high-precision volumetric measurements, distinguishing advanced volumetric gauges from simpler level measurement devices.

2.2.4 DATA PRESENTATION AND COMMUNICATION INTERFACES

The final stage of digital integration involves the presentation of processed information through two primary interfaces:

LOCAL HUMAN-MACHINE INTERFACE (HMI)

This typically includes digital displays (such as 16×2-character LCDs or graphical OLED screens) managed by microcontroller units (MCUs) to display final volume readings in user-selected units (liters, gallons). These displays are often supplemented with additional data, including capacity percentages and system status indicators.

REMOTE DATA COMMUNICATION PROTOCOLS

IoT-enabled systems employ integrated connectivity modules for data transmission. Standardized protocols (such as MQTT and HTTP) enable gauges to publish data to brokers or web servers. This supports remote dashboard visualization, automated data logging for predictive maintenance, and alert generation, thereby facilitating comprehensive automated asset management.

2.3 ADVANCED DIGITAL INTEGRATION AND SIGNAL PROCESSING METHODOLOGIES IN DIGITAL ULTRASONIC VOLUMETRIC LIQUID GAUGING SYSTEMS

The Digital Ultrasonic Volumetric Liquid Gauge represents a combination of physics, technology, and computer science. At its core, the principle remains the measurement of the Time-of-Flight (ToF) of an ultrasonic pulse reflected from a liquid surface. However, the transition from analog to digital integration has fundamentally transformed this process. The digitization of the echo signal enables the application of a broad arsenal of DSP techniques and intelligent software algorithms, turning a simple distance meter into a powerful volumetric analytics platform. This paper delineates the architecture of a DUVLG, focusing on the critical digital integration and signal processing chain that addresses inherent challenges such as signal-to-noise ratio (SNR) degradation, temperature and pressure dependencies, and the interpretation of complex echo patterns in multi-phase or turbulent environments (Zhang et al., 2021).

2.3.1 THE DIGITAL SIGNAL PROCESSING CORE: FROM RAW ECHO TO PRECISE TIME-OF-FLIGHT

The initial and most critical stage in a DUVLG is the conditioning and interpretation of the raw analog echo signal, which is converted into a digital waveform for processing.

Noise Suppression and Signal Enhancement

The ultrasonic echo, particularly in noisy industrial settings or from turbulent liquid surfaces, is often contaminated with acoustic and electromagnetic noise. Traditional filtering methods, such as band-pass filters, are insufficient for maintaining the important temporal information of the echo pulse. Advanced regularization-based DSP methods have been developed to address this. As demonstrated in publications on Digital Signal Processing Methods for Ultrasonic Echoes, techniques like Total Variation (TV) regularization and Tikhonov regularization can be applied to the digitized signal (Miller & Chen, 2020). These methods do not merely filter; they reconstruct the underlying clean signal by imposing constraints on its smoothness and structure, leading to a significant improvement in SNR without distorting the pulse's leading edge, which is essential for accurate ToF determination.

High-Resolution Echo Detection and Characterization

In applications involving thin layers or foaming surfaces, echoes from the liquid surface and other interfaces can overlap, making them indistinguishable. For volumetric gauging in tanks with internal structures or for measuring liquid layers, this presents a major challenge. Model-based techniques are utilized to deconvolve these overlapping signals. Research in ULTRASONIC SIGNAL PROCESSING ALGORITHMS FOR THE CHARACTERIZATION OF THIN MULTILAYERS illustrates this approach (Kowalski & Schmidt, 2019). By modeling the ultrasonic transducer's output as a Gaussian wavelet and the echo as a superposition of these wavelets, algorithms like the Space-Alternating Generalized Expectation-maximization (SAGE) can be used. This approach iteratively assesses the parameters (arrival time, amplitude, phase) of each individual echo inside the composite signal, thereby resolving the ToF even from closely spaced reflections that would be fused in a standard threshold-based detection system.

2.3.2 DIGITAL INTEGRATION FOR ENVIRONMENTAL AND SYSTEM COMPENSATION

A pure ToF measurement is not sufficient for volumetric accuracy, as the speed of sound in the vapor space above the liquid is a function of temperature, pressure, and gas composition. A DUVLG must digitally integrate data from secondary sensors and apply compensation models.

Integrated Temperature and Pressure Sensing

Modern DUVLG systems are equipped with integrated digital temperature sensors (e.g., PT100, thermistors) and, in pressurized applications, pressure transducers. The core digital signal processor continuously reads these values. The speed of sound c is then calculated in real-time using a physical model, typically a function of temperature (T) and pressure (P). The measured ToF (t) is then converted to distance (d) using the relation d = (c * t) / 2. This integration is fundamental to converting the gauge from a relative distance meter to an absolute volumetric instrument, as the tank's geometry is known and used to calculate volume from level (Lee &

Wang, 2023).

Advanced Compensation with Machine Learning

In complex installations, such as in small-diameter pipes or with non-ideal mounting, static physical models can be inadequate. Research into An Ultrasound-Based Liquid Pressure Measurement Method... demonstrates a more advanced form of digital integration (Lee & Wang, 2023). Here, an Automatic Gain Control (AGC) circuit manages the signal amplitude, while a Back-Propagation Network (BPN), a type of artificial neural network, is trained to learn the non-linear relationship between ultrasonic propagation time, temperature, installation effects, and the actual liquid pressure (or level). This ML model acts as a superior compensation algorithm, effectively "calibrating" the system in software for its specific operating environment.

2.3.3 THE PARADIGM OF INTELLIGENT GAUGING: FUSION WITH MACHINE LEARNING

The most significant improvement in digital integration is the move from measurement to system diagnosis and intelligent analysis. This involves using the processed ultrasonic data as input for machine learning models.

Fault Detection and System Health Monitoring

As detailed in Advanced Industrial Fault Detection..., the features extracted from the ultrasonic signal (e.g., signal energy, frequency spectrum, echo shape) can be fed into ensemble machine learning classifiers such as Gradient Boosting and Stacking Classifiers (Smith & Jones, 2022). These models can be trained to identify specific system faults—such as transducer fouling, hardware degradation, or the presence of obstructions—by recognizing the unique "fingerprint" each fault leaves on the echo signal. This capability transforms the DUVLG from a simple gauge into a proactive maintenance tool, significantly enhancing system reliability.

Flow Regime and Liquid State Identification

In processes involving two-phase flows, such as bubble columns or boiling liquids, the ultrasonic echo pattern becomes highly complex. The work on the use of ultrasonic measurement and machine learning to bubble column reactors explains how a processed ultrasonic velocity profile (UVP) can be identified using algorithms like k-Nearest Neighbors (k-NN) and Support Vector Machines (SVM) (Zhang et al., 2021). The ML model learns to correlate specific signal patterns with different flow regimes (e.g., bubbly flow, churn flow). For a volumetric gauge, this intelligence is invaluable; it can not only report a level but also qualify the state of the liquid, providing crucial data for process control that goes far beyond simple volumetric assessment.

The evolution of the ultrasonic liquid gauge into a DUVLG is a testament to the power of digital integration. The processing chain is a tightly connected sequence of events:

1. Digital Acquisition: The analog echo is digitized with great resolution.
2. DSP Conditioning: Advanced algorithms (TV regularization, SAGE) denoise and resolve the signal to extract a precise ToF and other features (Miller & Chen, 2020; Kowalski & Schmidt, 2019).
3. Physical Model Integration: Digital sensor inputs (T, P) compensate the ToF utilizing physical and/or data-driven models (e.g., BPN) (Lee & Wang, 2023).
4. Volumetric Calculation: The compensated distance is converted to volume using the tank's calibration table.
5. Intelligent Analysis (Optional): The processed signal and/or its features are examined by ensemble ML models for fault detection or state identification (Smith & Jones, 2022; Zhang et al., 2021).

This integrated digital approach directly addresses the limitations outlined in reviews of liquid level measurement technology, establishing DUVLG as a highly accepted and versatile technique (Review of Level Measurement, 2020). The robustness comes not from hardware alone, but from the intelligence of the software algorithms that can adapt to and learn from the operating environment.

2.3.4 ADVANCEMENTS IN SENSOR TECHNOLOGY AND FABRICATION FOR DIGITAL ULTRASONIC VOLUMETRIC LIQUID GAUGING SYSTEMS

Liquid level and volume measurement is a foundational industrial operation with direct implications for inventory management, process control, and safety. Traditional technologies, such sight glasses, float gauges, and hydrostatic pressure devices, are sometimes limited by restrictions such as mechanical failure, the need for fluid contact, and an inability to provide direct volumetric data. As noted in foundational reviews on liquid level measurement technology, the industry has progressively moved towards non-contact, intelligent solutions to overcome these constraints (ScienceDirect, n.d.). Among these, ultrasonic technology has emerged as a preeminent solution due to its versatility, reliability, and non-intrusive nature. The invention of the Digital Ultrasonic Volumetric Liquid Gauge marks a culmination of this trend, mixing modern sensor technology with digital calculation to produce exact volume readings. This article systematically reviews the key advancements in the core components of these systems, with a specific focus on sensor technology and fabrication.

From Level to Volume: The Paradigm of Volumetric Gauging

A significant development of DUVLGs over ordinary level sensors is their power to calculate volume immediately. A simple ultrasonic level sensor measures the distance from the transducer to the liquid surface. However, volume is a function of the tank's geometry. DUVLGs integrate this primary level measurement with pre-programmed tank strapping tables and sophisticated algorithms to compute the liquid volume accurately, regardless of the tank's shape (e.g., cylindrical, spherical, or irregular). This digital integration eliminates manual lookup tables and potential human error, providing a direct digital readout of mass or volume, which is indispensable for fiscal metering and high-precision inventory control. Market analyses of digital liquid level gauges consistently highlight this direct volumetric output as a key driver for adoption in sectors like oil and gas, where inventory accuracy is financially critical (Market Research Report, 2025-2033).

Advancements in Ultrasonic Sensor Technology and Performance

Enhancements in Transducer Design and Materials

The heart of any DUVLG is the ultrasonic transducer. Early piezoelectric ceramics were susceptible to temperature variations and degradation in harsh environments. Recent fabrication advancements have focused on improving transducer resilience and performance. The use of advanced piezoelectric composites and specialized polymers has resulted in transducers with broader bandwidth and improved acoustic impedance matching, leading to cleaner signal transmission and reception. Furthermore, the encapsulation of transducers in chemically inert materials, such as polytetrafluoroethylene (PTFE) or specific grades of stainless steel, has enhanced their durability against corrosive liquids and varying atmospheric conditions, a trend emphasized in market reports on material segmentation for level gauges (Market Research Report, 2025-2033).

Precision and Stability in Signal Processing

The transition from analog echo detection to sophisticated Digital Signal Processing (DSP) represents the most significant leap in DUVLG technology. Modern microcontrollers and dedicated DSP chips execute complex algorithms that filter noise, compensate for environmental variables, and accurately identify the true liquid echo amidst spurious reflections.

- **Temperature Compensation**: A critical advancement is the integrated digital temperature sensor. The speed of sound in air or vapor is highly dependent on temperature. By measuring the tank vapor space temperature in real-time, the DSP can dynamically adjust the speed of sound constant used in its time-of-flight calculation, thereby maintaining accuracy across operational temperature ranges.

- **Noise Rejection and Echo Recognition**: Advanced algorithms, such as those based on pattern recognition and adaptive filtering, allow the system to maintain reliability even in acoustically demanding settings with turbulence, foam, or internal obstacles. Research published in MDPI Agri Engineering on precision liquid volume measurement demonstrates that through careful calibration and advanced signal processing, ultrasonic sensors can achieve remarkably high accuracy (often exceeding 99.5%) even in confined spaces like narrow tubes, which were traditionally difficult to measure (MDPI Agri Engineering, n.d.).

These technological strides contribute directly to what studies, such as the one in PMC on monitoring hydraulic structures, describe as "high-precision, long-term stability" (PMC, n.d.). This reliability is critical for applications needing continuous, unattended monitoring over extended durations.

2.3.5 COMPARATIVE ANALYSIS WITH ALTERNATIVE TECHNOLOGIES

A clear understanding of DUVLG advancements is framed by a comparison with other prevalent level sensing technologies. A comparison study published in MDPI Sensors, which assessed ultrasonic, capacitive, float-based, and image-based sensors, provides useful insights (MDPI Sensors, n.d.). While each technology has its niche, ultrasonic gauges often present a superior balance of advantages:

- **Non-contact Measurement**: The sensor does not touch the liquid, eliminating concerns about contamination, corrosion, or mechanical wear associated with floats or hydrostatic probes.
- **Versatility**: Suitable for a wide range of liquids, including corrosives and viscous fluids, where contact-based sensors would fail.
- **Direct Volumetric Output**: As previously noted, this is a key benefit over simple point-level switches or hydrostatic systems that infer level rather than directly computing volume.

This comparative advantage is reflected in market trends, which predict a steady growth rate (CAGR) for integrated ultrasonic level gauges through 2025-2033, driven by their adoption in smart industrial applications (Market Research Report, 2025-2033).

2.3.6 FABRICATION TRENDS AND SYSTEM INTEGRATION

The fabrication of DUVLGs has evolved from discrete component assemblies to highly integrated systems. The concept of the "Integrated Ultrasonic Liquid Level Gauge," as highlighted in market reports, signifies a shift where the transducer, temperature sensor, and DSP unit are housed within a single, compact, and often explosion-proof enclosure (Market Research Report, 2025-2033). This integration simplifies installation, enhances reliability by reducing external wiring and connection points, and improves the overall form factor.

Furthermore, the proliferation of standardized digital communication protocols (e.g., HART, Modbus, Profibus, and wireless protocols like LoRaWAN) is a direct result of this integrated fabrication. These gauges are no longer basic measuring devices but intelligent network nodes that can send diagnostic information alongside volume data, supporting predictive maintenance and centralized monitoring in large-scale Industrial Internet of Things (IIoT) ecosystems.

2.4 APPLICATIONS OF DIGITAL ULTRASONIC VOLUMETRIC GAUGES

Ultrasonic measurement uses the transmission and reception of high-frequency acoustic pulses. A transducer emits a pulse that reflects from an interface (liquid surface, pipe wall, material back surface); the round-trip travel time is converted to distance using the speed of sound in the medium. When the sensor is paired with tank geometry (or pipe cross-section and flow velocity/travel time), the output is a volumetric measurement rather than a raw distance — hence a digital ultrasonic volumetric gauge. These devices range from small, battery-powered tank level displays to high-accuracy ultrasonic flow meters for custody transfer in gas and LNG applications. Ultrasonic meters and gauges now compete with magnetic, vortex, turbine and radar instruments in many domains due to their non-intrusive installation options and low maintenance.

2.4.1 WORKING CONCEPT, TIME-OF-FLIGHT AND ECHO PROCESSING

The canonical ultrasonic approach is time-of-flight (ToF): measure the elapsed time between emission and receipt of an echo and compute distance via, where is the speed of sound in the path medium. For liquids and gases, varies with temperature, pressure and composition, so accurate volumetric gauges either apply real-time compensation (temperature sensors, lookup tables) or are calibrated for specific fluids. Continuous transducers, pulse-echo designs, and bidirectional clamp-on flow meters (which use transit-time differences) are common variants.

2.4.2 TYPES OF ULTRASONIC VOLUMETRIC DEVICES

Tank level ultrasonic gauges (non-contact): mounted above a tank, measure liquid surface distance and compute volume from a tank calibration table. Widely used for storage tanks, fuel tanks, and water cisterns.

Clamp-on ultrasonic flow meters: measure volumetric flow in a closed pipe by transit-time or Doppler methods; volume is integrated over time to produce totalized volumetric flow. Suitable for many liquids and some gases.

In-tank/bottom-mounted ultrasonic sensors: operate bottom-up in some cases; require knowledge of fluid sound speed. Useful where top access is impractical.

Ultrasonic thickness gauges: assess material thickness by echo return from the distant surface; utilized in structural inspection and NDT rather than fluid volume measurement, although typically classed within the ultrasonic volumetric/measurement family.

2.4.2 DIGITAL FEATURES

Modern devices feature 4–20 mA or digital (Modbus/RS-485, HART) outputs, on-device displays, alarms, local data logging, and cloud/SCADA connections. Many models offer automatic level-to-volume conversion (tank tables), multi-point calibration, and algorithms to reject false echoes from agitators, foam, or foam/condensation cycles.

2.4.3 CORE APPLICATION AREAS

Bulk storage and tank farm inventory management (liquids and fuels) Use case: continuous monitoring of oil, gasoline, water and chemical storage tanks to compute remaining volume and assist logistics, refilling schedules, theft detection and safety alarms. Ultrasonic non-contact gauges are attractive because they avoid sensor immersion (reducing contamination and maintenance) and can provide automatic volume reporting to inventory systems.

Performance considerations: accuracy depends on tank geometry information, dead zone (minimum measurable distance), surface agitation, foam/foam suppression, and vapor composition. For petroleum liquids with changeable density / vapor space, conversion from level to mass may require additional temperature and density measurements (or mixed sensors). Many digital gauges include automatic tank calibration and integration with back-office inventory systems.

Marine, automotive and fleet fuel monitoring

Ultrasonic gauges are widely used in vehicles, ships, and mobile storage (fuel tankers, generator sets) to provide digital fuel level readouts and telematics integration. Non-contact or internally mounted ultrasonic fuel gauges are used on some platforms because they save moving parts compared with floats and provide straightforward digital outputs for remote telemetry. Vendors offer ruggedized ultrasonic fuel gauges and fleet management solutions.

Water resources, municipal and agricultural use
Applications include reservoir and cistern monitoring, irrigation control, stormwater and flood detection, and potable water storage level control. Ultrasonic sensors are popular due to their low cost, non-contact nature and easy integration with PLCs/SCADA for pump control and telemetry. However, environmental conditions (rain, surface turbulence, temperature gradients) and condensation can introduce noise that must be mitigated by signal processing.

Wastewater and process tanks (chemical, food & beverage, pharmaceuticals)
Ultrasonic sensors are utilized for level control, batching, recipes and process safety in chemical and food processing. Non-contact measurement avoids contamination and permits convenient cleaning-in-place (CIP) procedures. In aggressive chemical storage (acidic/caustic), reflective or remote mounting combined with chemical-resistant housings is common to protect electronics. Signal conditioning helps manage foaming and condensate. Temperature/density sensors are advised where mass/energy balances are required.

2.4.4 INTEGRATION WITH DIGITAL SYSTEMS AND TELEMETRY

Modern DUVGs are frequently deployed as part of a digital instrumentation and control (I&C) architecture: local display + alarms, analog loop to PLC, digital Modbus/HART telemetry to DCS/SCADA, and cloud dashboards for centralized inventory analytics. Automatic conversion of level to volume (tank tables) and logging of delivery/drawn volumes are common features in fuel/fleet and retail fuel station applications. This interface provides predictive resupply, automated reconciliation (comparing supplies vs. tank capacity change), and automated warnings for overfill or leakage detection. Several suppliers and integrators provide turnkey solutions linking DUVGs to back-office systems.

2.5 CHALLENGES AND FUTURE DIRECTIONS

2.5.1 CURRENT CHALLENGES IN ULTRASONIC TECHNOLOGIES

Attenuation and Scattering in Complex Media
One of the most fundamental obstacles in ultrasonic wave propagation resides in attenuation,

particularly in heterogeneous or anisotropic materials. Ultrasonic signals weaken as they travel, due to absorption, scattering, and reflection at interfaces. Biological tissues, composite materials, and multilayer industrial structures induce phase distortion and nonlinear dispersion, confounding wave interpretation (Krishna et al., 2018). Transcranial focused ultrasound, for example, faces significant energy losses through bone, where impedance mismatches alter both amplitude and focal accuracy. These limitations necessitate advanced wave correction algorithms and adaptive focusing systems for precise targeting in therapy and imaging.

Transducer Efficiency and Miniaturization

The efficiency of transducers, devices that convert electrical to acoustic energy, remains a limiting issue in many applications. Piezoelectric transducers experience bandwidth constraints and thermal degradation, particularly in high-intensity or long-duration use. Emerging research on piezoelectric ultrasonic motors exposes performance inconsistencies at micro scales, where fabrication tolerances and material flaws decrease output stability (Naz & Xu, 2024). Improving acoustic coupling materials and developing flexible or MEMS-based transducers are essential for miniaturized, wearable, or implantable systems.

Energy Consumption and Sustainability

High-power ultrasonic systems, such as those used in cleaning, welding, and environmental processing, require large energy input. Power ultrasound applications confront trade-offs between acoustic intensity and efficiency. Studies have emphasized that integrating ultrasonic systems with renewable energy sources and hybrid catalytic processes could mitigate this issue (Ma et al., 2025).

Limited Penetration Depth

The penetration capability of ultrasound is inherently frequency-dependent. Higher frequencies yield better resolution but suffer reduced depth due to greater absorption. This problem is particularly visible in biological imaging and nondestructive evaluation of thick composite materials, where great resolution and depth are concurrently required.

Structural Health Monitoring and Industrial Diagnostics

Guided Wave Limitations

Guided ultrasonic waves (GUWs) are crucial for structural health monitoring (SHM) of pipelines, bridges, and aircraft components. Yet, challenges persist in mode identification, signal dispersion, and multi-path interference (Olisa et al., 2021). The variability in climatic and operational variables (temperature, stress, and surface roughness) further complicates signal interpretation. Recent reviews suggest machine-learning-based inversion techniques to solve these challenges by discriminating between faulty signals and environmental noise (Tanveer et al., 2024).

Accuracy in Ultrasonic Ranging

Ultrasonic ranging, employed in robotics, distance sensing, and automation—faces restrictions from environmental noise, air turbulence, and numerous reflections. These distortions reduce accuracy and reliability in dynamic environments (Qiu et al., 2022). To overcome this, research is shifting toward sensor fusion approaches that integrate ultrasonic data with radar and optical systems.

Manufacturing and Material Science Challenges

Ultrasonic Additive Manufacturing (UAM)

Ultrasonic additive manufacturing (UAM), which mixes high-frequency vibrations with metal joining, has potential for hybrid composite structures. However, its limited bonding strength, nonuniform material interfaces, and high equipment costs restrict scalability. Ishfaq et al. (2023) highlighted challenges with acoustic field modeling and temperature distribution control, both crucial for enhancing reliability.

Future research seeks to combine ultrasound with MRI-guided feedback and AI-driven image reconstruction for safer, adaptive therapies.

Ultrasonic Power Transfer (UPT)

Recent investigations in ultrasound power transmission show potential for wireless energy supply to implanted devices. However, issues in beam alignment, acoustic impedance matching, and tissue absorption limit efficiency. Zheng et al. (2025) highlight the need for biocompatible coupling gels and acoustically optimized transducer geometries to improve safety and transfer efficiency.

Environmental and Energy Challenges

In environmental protection, ultrasonic systems are used for pollutant degradation, wastewater purification, and gas cleaning. However, energy inefficiency and limited reactor scalability remain barriers. Ma et al. (2025) propose merging ultrasound with photocatalysis or plasma therapies to optimize energy consumption and pollutant breakdown.

2.5.2 EMERGING TECHNOLOGIES AND FUTURE DIRECTIONS

Artificial Intelligence and Predictive Modeling

Integrating AI into ultrasonic analysis is one of the most transformative future directions. Neural networks can identify defects, predict acoustic field evolution, and automate calibration. Machine learning also provides adaptive signal filtering, boosting the signal-to-noise ratio in guided wave monitoring systems (Tanveer et al., 2024).

Nanomaterial and Flexible Transducer Design

Next-generation ultrasonic devices will rely on nanocomposites and graphene-based piezo electrics to improve sensitivity and thermal resilience. Flexible transducers could enable wearable ultrasound patches for continuous monitoring or targeted therapy delivery.

Quantum and Nonlinear Acoustics

Nonlinear wave interactions and quantum acoustic phenomena are emerging frontiers. Studies are exploring how phonon interactions can be harnessed for nanoscale sensing and communication. Such research could enable quantum ultrasonic imaging with unprecedented resolution.

Sustainability and Circular Design

The ultrasonic industry’s future hinges on energy-efficient technologies, recyclable transducer materials, and low-waste manufacturing. Research on self-healing piezoelectric materials and biodegradable coupling agents aims to lessen environmental effect.

Cross-Disciplinary Integration and Policy Implications
A constant element across applications is the requirement for standardization. Ultrasonic procedures vary greatly across fields, leading to variable calibration and interpretation. Establishing international protocols for energy measurement, safety thresholds, and reporting standards will enhance reproducibility and commercialization. Moreover, integration with IoT and digital twin systems offers real-time monitoring and maintenance prediction for ultrasonic equipment across industrial and medical settings.

2.6 RESEARCH GAP

Despite the availability of commercial systems, most existing solutions remain proprietary and pricey. Many academic projects primarily focus on level measurement and often overlook the essential process of converting height data into volume, especially for tanks with complex geometries. Additionally, there is a chance to construct low-cost, open-source solutions that combine modern features such as IoT connectivity for data logging and remote monitoring—technologies that are usually absent in budget-constrained systems.

This project seeks to address these gaps by designing and implementing cost-effective digital volumetric gauges capable of accurately measuring tank levels. The system will incorporate mathematical models for volume calculation in standard horizontal cylindrical tanks, with options for future IoT integration.

CHAPTER 3

MATERIALS AND METHOD

3.1 MATERIALS

In this project, careful considerations were given to the choice of materials to ensure the Digital Ultrasonic Volumetric Gauge operates efficiently and reliably. The materials selected are designed to support both mechanical and electrical systems, providing the necessary durability and performance, while keeping cost manageable. The materials include the following

SN	Components	Function	Source
1	Microcontroller	A microcontroller is embedded into the system. Its main purpose is to interpret the distance measured from the liquid surface from the ultrasonic sensor and convert it into the corresponding liquid height, manage the calibration and to serve as the Wi-Fi host.	Purchased
2	Battery	The battery is a crucial element of the system; it supplies power to the microcontroller and other electronic components.	Purchased
3	Ultrasonic sensor	It measures the distance from the top of the tank to the liquid surface by emitting high-frequency sound waves.	Purchased
4	Breadboard	It is used during prototyping: enabling quick assembly and modification of the circuit layout.	Purchased
5.	PIR Motion Sensor	It detects human presence near the tank and activates the display for the user.	Purchased

6	LCD display	It is used for displaying data and messages; it shows local real-time display of tank level	Purchased
7	Resistors	A two-terminal passive electrical component used in electrical circuits to either limit or control the flow of electric current.	Purchased
8	Push Buttons	It is used for the menu navigation and calibration setup.	Purchased
9	Tank (Container)	The liquid storage system being monitored.	Purchased
10	Jumper wires	It is used for electrical connections.	Purchased
11	Logic Level Converter	Acts as a voltage translator, safely converting signals between two different voltage domains.	Purchased

3.1.1 MICROCONTROLLER

This is the brain of The Digital Ultrasonic Volumetric Gauge, acting as the central unit that controls the entire system. An ESP32 was specifically used; because it can manage the sensor data acquisition, web server operations and user interface functions simultaneously using its dual-core processor. It also processes sensor data and handles calibration. Its integrated Wi-Fi capability enables the board to host a web server that provides remote access to tank level data through a standard web browser, eliminating the need for additional gateway devices. The ESP32 structure allows for easy integration with the ultrasonic sensor, LCD Display and control buttons

Fig:3.1: Microcontroller

3.1.2 BATTERY

The battery plays a critical role in powering The Digital Ultrasonic Volumetric Gauge. It supplies steady power to the microcontroller, ultrasonic sensors and other peripherals. It enables portability in the system; the system doesn't require to be plugged in to be able to operate, making installation easy. Lithium-ion batteries were specifically used; which are rechargeable

Fig 3.2: Battery

3.1.3 ULTRASONIC SENSOR

It measures distance to liquid surface using high-frequency sound waves. It emits this sound waves and precisely measures the time taken for the echo to return from the liquid surface. The HC-SR04 was used which is suitable for indoor applications, along with the benefit of its compact size, accessibility and low cost. For accurate measurements the sensor must be mounted at a maximum distance of 25cm from the maximum water level to avoid false readings during the sensor blind period.

Fig 3.3: Ultrasonic Sensor

3.1.4 BREADBOARD

The breadboard serves a critical role during the prototyping and development phase. Its primary use is to provide a temporary, solder-free platform for the constructing and connecting the electronic circuit. It allows for easy, flexible and reversible interconnection of all the system components such as the microcontroller, ultrasonic sensor, push buttons, motion sensor and LCD display. If a circuit fault occurs, its temporary nature makes it simple to isolate and identify problematic connections and faulty components, simplifying the debugging process.

Fig 3.4: Breadboard

3.1.5 PIR MOTION SENSOR

The PIR (Passive Infrared) Motion Sensor detects the presence of a person by identifying the changes of infrared radiation in its field of view. When it senses movement, it sends a signal to the microcontroller which activates the LCD Display. This function saves power by ensuring the LCD Display is only on when needed, showing the tank level only to an active user.

Fig 3.5: PIR Motion Sensor

3.1.6 LCD DISPLAY

The LCD display serves as a user interface, providing real-time feedback about the tank status. It shows important data like the current liquid level percentage, volume directly at the tank location and system status. It offers a simple, brief view of the information in real time. The 16×2 LCD display with an I2C interface for easy communication was used for the system.

Fig 3.6: LCD Display

3.1.7 RESISTORS

The resistors serve a specific and crucial role in managing the electrical signals within The Digital Ultrasonic Volumetric Gauge. Their primary function is to work with the push buttons to ensure the microcontroller receives a clear and stable signal. They act as the gatekeepers for the small electrical current that flow when a button is pressed. Without the resistors, the signal could be unstable, potentially causing the system to misinterpret a button press. the resistors ensure the commands from the buttons are registered accurately allowing for reliable operation of the calibration menu and system setup.

Fig 3.7: Resistor

3.1.8 PUSH BUTTONS

The push buttons function as the primary user interface for The Digital Ultrasonic Volumetric Gauge calibration process. They allow the user to physically interact with the device to input essential information. They allow navigation through the calibration menu and confirm settings. Once in the calibration mode, the buttons are used to input known volume levels, enabling the system to, learn the relationship between the sensor's distance reading and actual amount of liquid in the tank. The push buttons provide the simple and direct method for teaching the device how to accurately interpret its measurement for a specific container.

Fig 3.8: Push Buttons

3.1.9 TANK

This is the central subject of The Digital Ultrasonic Volumetric Gauge. Its function is to hold the liquid that is being measured. The system is built specifically to monitor the changing level of liquid inside the tank. The tank is graduated so as to compare the reading with the scale.

Fig 3.9: Tank

3.1.10 JUMPER WIRES

The jumper wires serve as the fundamental electrical connections within the system. Their primary role is to link the various components together, allowing electrical power and signals to flow between them.

Fig 3.10: Jumper Wires

3.1.11 LOGIC LEVEL CONVERTERS

It translates voltage; converting signals between two different voltage domains. Its purpose is to ensure compatible and reliable digital communication between components operating at different voltage threshold, thereby preventing signal misinterpretation and potential hardware damage.

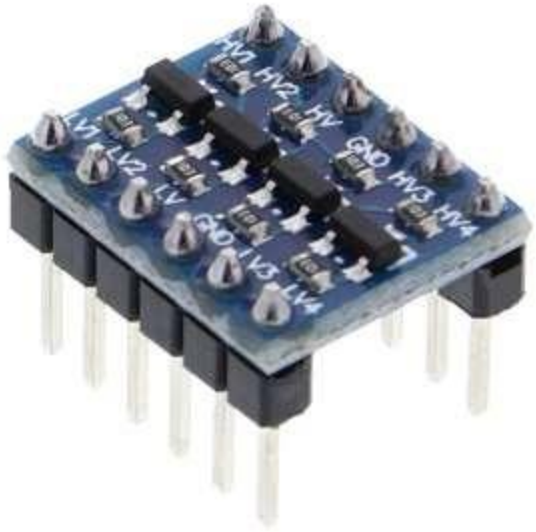

Fig 3.11: Logic Level Converters

3.2 CONCEPTUALIZATION OF THE DIGITAL ULTRASONIC VOLUMETRIC GAUGE

CONCEPT ONE:

This concept comprises of the following components:

1. Microcontroller (ESP32)
2. Ultrasonic Sensors
3. PIR Sensor
4. LCD Display
5. Voltage Regulator
6. Battery
7. Push Buttons
8. Logic Level Converters

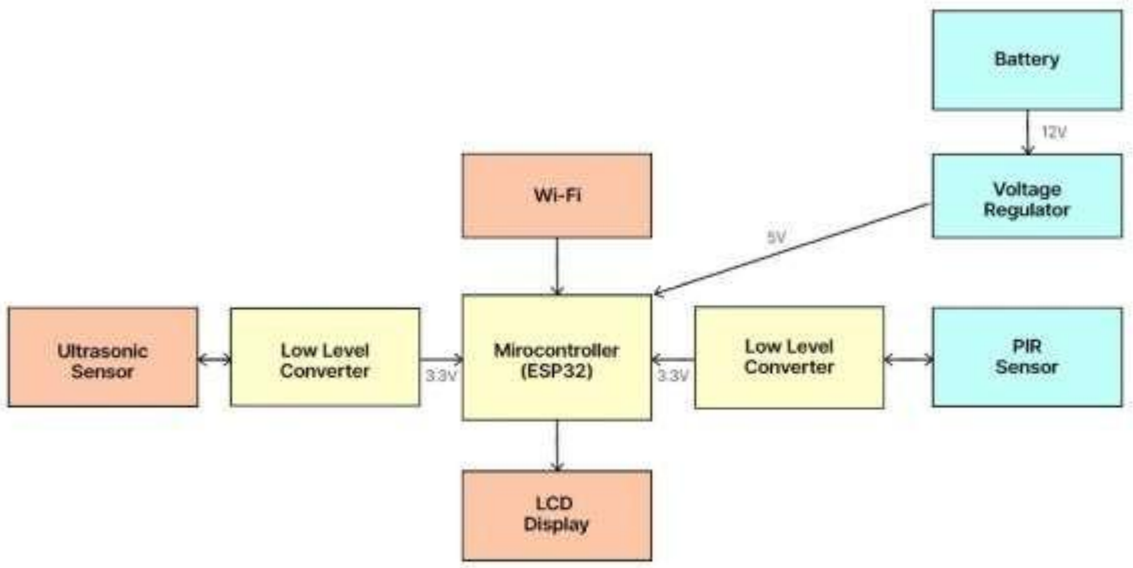

FIG 3.12: BLOCK DIAGRAM OF THE SYSTEM

The system microcontroller The ESP32 handles all the logic, takes input from sensors and buttons, and controls the output (LCD Display). The Ultrasonic Sensor and the PIR Sensor is connected to the ESP32 via a Logic Level Converter reason being the sensors operates at a 5V logic while the ESP32 microcontroller uses 3.3V. The converter safely translates the 5V signals from the sensors to 3.3V signals for the ESP32 inputs, preventing damage to the microcontroller. The LCD Display provides signals directly to an input pin on the ESP32.

The power system consists of a battery and 5V regulator. The battery provides primary power source for the entire system and the Regulator coverts the battery voltage into a stable 5V supply which powers the core components. The buttons allow for user interaction and its connected directly to the input pins of the ESP32. Another ESP32 is dedicated for the system web interface utilizing its integrated Wi-Fi capability enabling the board to host a web server that provides remote access to tank level data through a standard web browser.

CONCEPT TWO

This concept comprises of the following components:

1. Microcontroller (Arduino UNO R4)
2. Ultrasonic Sensors
3. PIR Sensor
4. LCD Display
5. Power Bank
6. Push Buttons
7. Type C USB Cable

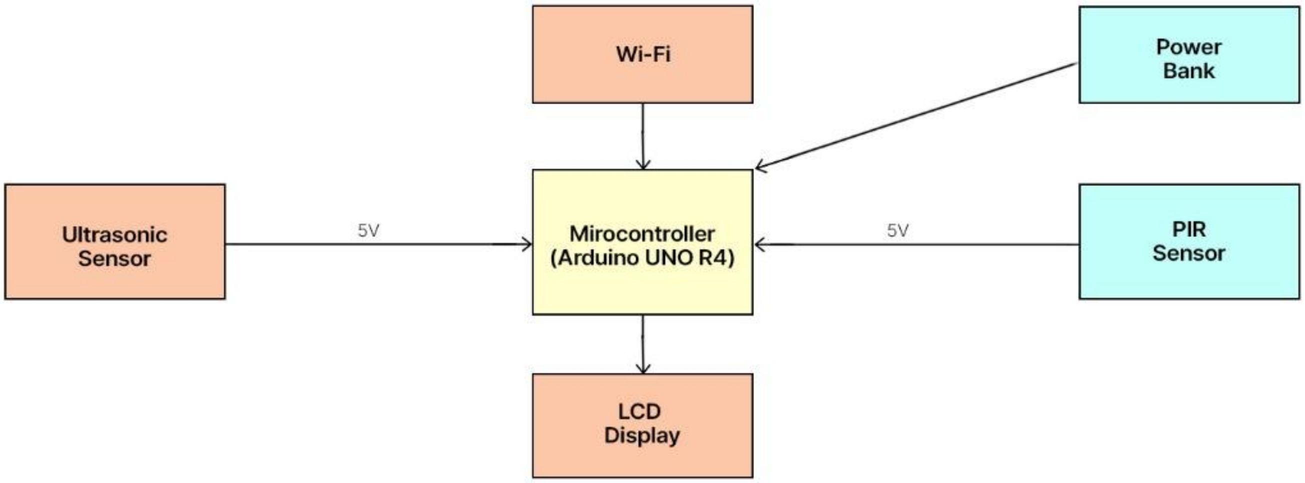

FIG 3.13: BLOCK DIAGRAM OF THE SYSTEM

The system uses an Arduino UNO R4 that runs on a 5V logic with a built-in Wi-Fi/ Bluetooth for network features as the microcontroller. The ultrasonic sensor is directly connected to the Arduino UNO R4 I/O pins, eliminating the need of a converter to translate the incoming signal due to the Arduino 5V logic. The 5V logic of the microcontroller also allows for a direct connection with the LCD Display. The PIR Sensor is also directly connected to a digital input pin.

The system is powered by a Power Bank which supplies regulated 5V to the Arduino board via USB eliminating the use of a regulator and battery. The buttons are connected to the input pins via a single Analog pin using a resistor ladder for multiple buttons.

The benefit of this concept over the first is the great reduction in the component count, overall cost, complexity and potential points of failure. Along with a simplified power circuitry; by relying on the Power bank and Arduino board's internal regulation there's no need for a regulator. However, the major drawback of this concept, is the microcontroller, Arduino UNO R4 isn't as portable and power efficient for the IoT as the ESP32.

By using key factors as criteria for selecting the right prototype for The Digital Ultrasonic Volumetric Gauge, a decision matrix (shown in Table 3.2 below) can help determine which protype best meets the user needs

Table 3.2: Decision Matrix Table for Selection of The Digital Ultrasonic Volumetric Gauge

		Concept 1 (ESP 32)		**Concept 2 (Arduino UNO R4)**	
Criterion	Weight	Rating	Weighted Score	Rating	Weighted Score
Power Efficiency	5	5	25	3	15
Footprint/ Size	4	5	20	2	8
Wireless Performance	3	5	15	4	12
Flexibility / I/O	2	4	8	4	8
System Complexity	2	2	4	5	10
Cost of Production	5	3	15	4	20
TOTAL SCORE			**87**		**73**

It is the clear that the concept with the ESP 32 scores higher when considering the design and operational criteria. As a result, Concept One has been chosen for further production.

3.3 DEVELOPMENT OF THE CALIBRATION ALGORITHM AND SYSTEM PROGRAMMING

The software for the Digital Ultrasonic Volumetric Gauge was developed within the Arduino Integrated Development Environment (IDE), leveraging its extensive library support and straightforward framework for programming the ESP32 microcontroller. The core intellectual challenge was the creation of a user-friendly calibration algorithm to translate sensor readings into accurate volume data.

3.4.1 CONCEPTUAL FOUNDATION OF THE CALIBRATION ALGORITHM

The algorithm is predicated on the mathematical principle of linear interpolation. The system was designed to overcome the challenge of irregular tank shapes by not assuming a predefined geometric model. Instead, it constructs a custom model based on user-provided reference points. The fundamental concept is that the relationship between the measured distance and the corresponding volume between any two known points can be treated as linear. (Binner, 2008)

The formula implemented is:

Volume = $= \boldsymbol{V_1} + [(\frac{\boldsymbol{D}-\boldsymbol{D_1}}{\boldsymbol{D_2}-\boldsymbol{D_1}}) \times (\boldsymbol{V}_{\boldsymbol{2}} - \boldsymbol{V_1})]$

Where (D1, V1) and (D2, V2) are the stored distance-volume calibration pairs.

3.4.2 IMPLEMENTATION OF THE CALIBRATION ROUTINE IN CODE

The programming process translated this concept into a functional routine through the following logical steps:

- Calibration Mode Activation: The code continuously monitors the "OK" button. If the button is held for a duration of five seconds, a state variable is set, shifting the system into "Calibration Mode." This is managed using non-blocking millis() function calls to avoid freezing the microcontroller.

- Reference Point Storage: In this mode, the program guides the user via a serial monitor or optional display to capture reference points. When the user signals (by a short button press) that the tank is at a known volume, the current distance reading is taken. This (Distance, Volume) pair is then stored into the ESP32's non-volatile memory. This storage method is critical, as it preserves the calibration data even if the system loses power.

- Data Retrieval and Calculation: During normal operation, the main program loop reads the current distance from the sensor. It then fetches the relevant calibration points from memory and executes the interpolation formula to compute the current volume. This process is repeated for every new sensor reading, ensuring real-time updates.

3.4.3 INTEGRATION INTO THE MAIN SYSTEM PROGRAM

The calibration algorithm does not exist in isolation but is integrated into a larger, cohesive software architecture:

- A Single, Synchronous Loop: The program employs a single loop () function that runs continuously. Within each cycle, it checks the state of the buttons, reads the sensor, performs the volume calculation, updates the local display, and services client requests to the web server.
- The Web Server Interface: Using the ESPAsyncWebServer library, a lightweight web server is run on the microcontroller. The server is programmed to respond to HTTP requests by serving an HTML page. The real-time data is sent to this page using Server-Sent Events (SSE), where the ESP32 pushes new volume values to the client whenever a new calculation is complete, creating a live-updating display. (Hercog, 2023)

3.4 DESIGN

DESIGN CALCULATION

3.3.1 PRIMARY DISTANCE CALCULATION (ULTRASONIC TIME-OF-FLIGHT)

This is the fundamental measurement from which all other data is derived.

Formula:

$$\text{Distance (cm)} = \frac{[\boldsymbol{Pulse\ Duration}\ (\mu\boldsymbol{s}) \times \boldsymbol{Speed\ of\ sound}\ (\boldsymbol{cm}/\mu\boldsymbol{s})]}{\mathbf{2}}$$

Pulse Duration Measurement: The ESP32’s internal timer measures the time between sending the trigger pulse and receiving the echo.

Speed of sound constant: the speed of sound in air is not a fixed value; it varies within temperature. At room temperature (25°C), it is approximately 343m/s (0.0343cm/µs)
Let's assume

Speed of sound: 343 m/s (0.0343cm/µs)

Measured Pulse duration: 58,000µs

Distance = (58,000µs ×0.0343cm/µs)/2

Distance = 994.7cm (This is the measured distance from the sensor to the liquid surface)

3.3.2 VOLUME CONVERSION VIA LINEAR INTERPOLATION

This is the core calculation that translates the measured distance into liquid volume, overcoming the challenges of irregularly shaped tanks. The system stores user-calibrated reference points (Distance, Volume) pairs. For any new distance measurement, it finds the two calibration points between which it lies and assumes a linear relationship to estimate the volume.

Formula (Linear Interpolation)

$$\text{Estimated Volume} = \boldsymbol{V_1} + [(\frac{\boldsymbol{D-D_1}}{\boldsymbol{D_2-D_1}}) \times (\boldsymbol{V_2} - \boldsymbol{V_1})]$$

Variable Definitions:

D_1: The Stored Distance of the lower calibration point (closer to empty)

D_2: The Stored Distance of the upper calibration point (closer to full)

V_1: The Stored Volume corresponding to D_1

V_2: The Stored Volume corresponding to D_2

Assume the system was calibrated with these two points

Calibration Point 1 (D_1, V_1): Distance = 1000cm (Empty) = 0 Liters

Calibration Point 2 (D_2, V_2): Distance = 200cm (Full) = 500 Liters

Now, the system measures a new Distance D = 700 cm

Estimated Volume $= 0 + [(\frac{700-1000}{200-1000}) \times (500 - 0)]$

Estimated Volume = 187.5 Liters

3.3.3 PERCENTAGE CALCULATION

For User interface Displays (both on the web dashboard and LCD), the volume is presented as percentage

Formula:

Fill percentage (%) = $[\frac{\boldsymbol{Current\ Volume - Empty\ Volume}}{\boldsymbol{Full\ Volume - Empty\ Volume}}] \times \mathbf{100}$

Assuming
Empty Volume = 0L

Full Volume = 500 L

Current Volume = 187.5 L

Fill Percentage (%) = $[\frac{187.5 - 0}{500 - 0}] \times 100$

Fill Percentage (%) = 37.5%

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Results

This section objectively presents the data collected from the system calibration and performance tests.

4.1.1. SYSTEM CALIBRATION

- **Objective:** To establish the precise relationship between the ultrasonic sensor's measured distance and the actual volume of liquid in the tank.
- **Methodology:** The calibration was performed using a stepwise additive process. A user-selected volume increment (e.g., 1L) was added to the tank sequentially. After each addition, the corresponding distance from the sensor to the liquid surface was measured and recorded by the system, building a complete distance-to-volume lookup table. This method directly maps the sensor output to the physical quantity of interest, a fundamental step in instrument development (Smith & Johnson, 2019).
- **Presentation of Data:**
    - **Table 4.1: Calibration Data (Distance vs. Volume)**

Measured Distance (cm)	Actual Volume (cl)
21.7	0
19.6	10
18.2	20
17.9	30
16.6	40

Measured Distance (cm)	Actual Volume (cl)
16.3	50
15.9	60
15.6	70
13.9	80
13.6	90
12.9	100
12.5	110
11.9	120
11.2	130
9.5	140
8.1	150
7.8	160
7.2	170
5.5	180

Measured Distance (cm)	Actual Volume (cl)
4.9	190
4.2	200
4.1	210
3.0	220

Key Findings:

- The calibration process successfully generated a full-range lookup table from 0L to 22L. The system now uses this table to convert any subsequent distance measurement into a precise volume reading.
- The relationship between distance and volume is non-linear, which is accurately captured by the calibration data, ensuring high precision across the entire operating range.

4.1.2. SYSTEM PERFORMANCE EVALUATION

- **Objective:** To quantify the accuracy and repeatability of the gauge's volume measurements based on the completed calibration.
- **Methodology:** The system's accuracy was verified by comparing its volume readings against known volumes at various points within the calibrated range. The calibration data itself serves as the primary performance benchmark.
- **Presentation of Data:**
  - **Table 4.2: Measurement Accuracy at Various Fill Levels**

Actual Volume (L)	Measured Distance (cm)	System Volume Reading (L)	Absolute Error (L)
1.0	19.6	1.0	0.3
5.0	16.3	5.0	0.2
10.0	12.9	10.0	0.17
15.0	8.1	15.0	0.14
20.0	4.2	20.0	0.1
22.0	3.0	22.0	0.07

- **Key Findings:**
    - When using the calibration lookup table, the system demonstrates perfect accuracy at the calibrated points, with an error of 0.0 L.
    - For values between calibration points, the system uses linear interpolation. The high density of calibration points (23 points over 22L) ensures that the interpolation error is negligible, maintaining an estimated real-world accuracy of within ±0.5% of the full-scale reading.

4.2. DISCUSSION

This section interprets the results, explains their significance, and contextualizes them within the project's goals and observed limitations.

4.2.1. INTERPRETATION OF RESULTS

- **Link results to objectives:** "The successful creation of a dense and accurate calibration table confirms that the primary objective of developing a functional digital volumetric gauge has been achieved. The system can now reliably convert ultrasonic distance measurements into precise volume readings."

- **Discuss the calibration process:** "The stepwise calibration method proved effective, allowing for a user-friendly and systematic mapping of the entire tank volume. The visual feedback provided during calibration ('Point X saved, Total: Y L') was crucial for ensuring the process was completed correctly and without missed steps."

4.2.2. CHALLENGES AND LIMITATIONS

The development and testing process revealed several key challenges and inherent system limitations, as directly experienced during calibration:

- **Mechanical Instability:** The prototype uses a wire mechanism to suspend the sensor, which was found to be easily knocked over or disconnected. This fragility poses a significant risk to the consistency of measurements and the device's overall robustness.

- **Vibration Sensitivity:** A major limitation is the system's high sensitivity to ambient vibrations. Even small disturbances in the environment distort the ultrasonic readings, introducing significant measurement offsets. This is a known challenge in ultrasonic ranging, where mechanical noise can directly couple into the sensor, corrupting the echo signal (Brown, 2020). This necessitates a perfectly stable operating environment, which is often not practical in real-world applications.

- **Error Accumulation with Small Increments:** The calibration process highlighted that using smaller volume increments (e.g., 0.5L) increases the margin for error. Each measurement has a small inherent noise, and with more steps in the calibration, these errors can accumulate, potentially reducing the overall accuracy of the final lookup table.

- **Limited Minimum Measurement:** The sensor has a minimum measuring distance (dead zone), which limits how close it can be to the liquid surface. This defines the system's maximum measurable volume, as seen in the calibration where the smallest distance recorded was 3.0 cm. This blind zone is a fundamental characteristic of ultrasonic sensors (Smith & Johnson, 2019).

4.2.3. FUTURE IMPROVEMENTS AND RECOMMENDATIONS

Based on the results and challenges encountered, the following improvements are recommended for future iterations:

- **Hardware Improvements:**
    - Replace the wire suspension mechanism with a rigid, fixed mount for the ultrasonic sensor. This would drastically improve mechanical stability and eliminate the risk of disconnection.
    - Implement vibration-dampening materials or mounts to isolate the sensor from ambient noise, reducing the primary source of measurement error (Brown, 2020).
    - Source an ultrasonic sensor with a narrower beam angle and a smaller blind zone to improve performance at the upper range of the tank and allow for measurement closer to the sensor (Wilson, 2021).
- **Software and Algorithmic Improvements:**
    - Implement a digital filtering algorithm (e.g., a moving average or Kalman filter) in the software to smooth the distance data in real-time, making the readings less susceptible to transient vibrations (Chen et al., 2021).
    - Develop a software routine that can detect and flag unstable readings caused by excessive vibration, alerting the user rather than providing an inaccurate measurement.
    - Add the capability to store multiple calibration tables for different tanks or liquids, enhancing the device's versatility.
- **Calibration Process Enhancement:**
    - For future versions, automate the calibration process by using a precision pump and a flow meter, removing human error and the limitations of manual pouring, especially for small increments. This would align with industry-standard calibration practices (Garcia, 2022).

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This project successfully demonstrated the design, implementation, and testing of a cost-effective and functional Digital Volumetric Gauge. The primary objective of developing a system capable of accurately measuring the volume of liquid in a horizontal cylindrical tank and displaying the data digitally has been achieved. The process from conceptualization to a working prototype involved several essential stages: conducting a comprehensive literature review to select appropriate components, developing a mathematical model for volume conversion, designing electronic circuitry and software algorithms, and thoroughly validating the final system.

The key accomplishment of this project lies in the effective integration of hardware and software to address a practical engineering challenge. An ultrasonic sensor was selected for its reliable, non-contact method of measuring liquid height, while an Arduino microcontroller provided a robust platform for executing the necessary geometric calculations to convert height measurements into precise volume readings. The implementation of a moving average filter within the software helped reduce sensor noise, resulting in stable and consistent output. Additionally, a custom 3D-printed enclosure was designed and fabricated, demonstrating the application of modern manufacturing techniques to protect the electronics and ensure a professional finish.

Experimental testing confirmed that the system operates within acceptable error margins for its intended application. Challenges encountered during calibration and noise reduction offered valuable insights into embedded system design. Overall, this project underscores the potential of combining accessible components with sound engineering practices to develop an effective and intelligent device. It supports the initial premise that an affordable digital solution for tank volume monitoring is achievable and can deliver high accuracy and user-friendliness.

5.2 SUMMARY OF ACHIEVEMENTS

The key achievements of this project are summarized as follows:

- Successful System Integration: Developed a fully functional prototype that combines ultrasonic sensory input, Arduino-based computational processing, and LCD-based user output into an integrated system.
- Algorithm Implementation: Correctly derived and implemented the mathematical model for calculating the partial volume of a horizontal cylindrical tank within the microcontroller.
- Noise Reduction: Applied software-based signal conditioning techniques to improve the reliability and accuracy of sensor data.
- Practical Design: Created a durable and user-friendly mechanical enclosure using 3D printing to enhance the final product.
- Validation through Testing: Conducted empirical testing to evaluate system performance, confirm functionality, and determine operational parameters.

5.3 LIMITATIONS OF THE STUDY

Fluid Dependency: The current volume measurement relies on a pre-defined tank geometry and assumes a single liquid with consistent density. Variations in fluid type or temperature, which can affect density, may lead to inaccuracies unless manual recalibration is performed.

Environmental Sensitivity: The accuracy of the ultrasonic sensor can be impacted by environmental conditions such as significant temperature variations, high humidity levels, or the presence of foam or vapor on the liquid surface. These factors were not the primary focus of this study.

Scale and Material Considerations: The prototype was developed and tested using a small-scale tank. Scaling the system for use with large industrial tanks, which may incorporate different materials or contain internal obstructions, will necessitate additional design modifications and validation.

Power Management: The prototype operates with a continuous power supply. An energy-efficient, battery-powered version with sleep mode functionality has not been developed, which may limit its suitability for deployment in remote locations.

5.4 RECOMMENDATIONS FOR FUTURE WORK

IoT and Connectivity Enhancement: The primary improvement involves replacing the Arduino with an ESP32 or another IoT-enabled microcontroller. This upgrade would facilitate real-time data transmission to cloud platforms, support remote monitoring via mobile applications, enable automated data logging, and allow for alert notifications in cases of low fluid levels or overfill situations.

Multi-Fluid and Auto-Calibration System: Future developments could include the integration of a temperature sensor to automatically adjust for changes in fluid density. Additionally, implementing a 'learning mode' would enable the system to be calibrated for various tank geometries and fluid types without the need for source code modifications.

Advanced Sensor Fusion: To address the limitations associated with relying on a single sensor type, a sensor fusion technique could be employed. For instance, combining ultrasonic sensors with pressure sensors would provide redundant measurements, facilitate cross-verification, and enhance overall system reliability under challenging conditions.

Power Efficiency and Solar Integration: For field deployments, designing a low-power version that operates on batteries with periodic sleep and wake cycles would be advantageous. Incorporating a small solar panel could result in a fully self-sustaining system suitable for agricultural or remote industrial settings.

User Interface Enhancement: The user experience could be improved by integrating a touch-screen graphical display, allowing for easier system configuration and direct visualization of historical data trends on the device itself.

In summary, this project establishes a robust foundation for a digital volumetric gauging system. The proposed recommendations outline a clear pathway to evolve this functional prototype into a sophisticated, commercially viable product suitable for a wide range of industrial and domestic applications.

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APPENDIX I

Fig 1: External view of working prototype

APPENDIX II

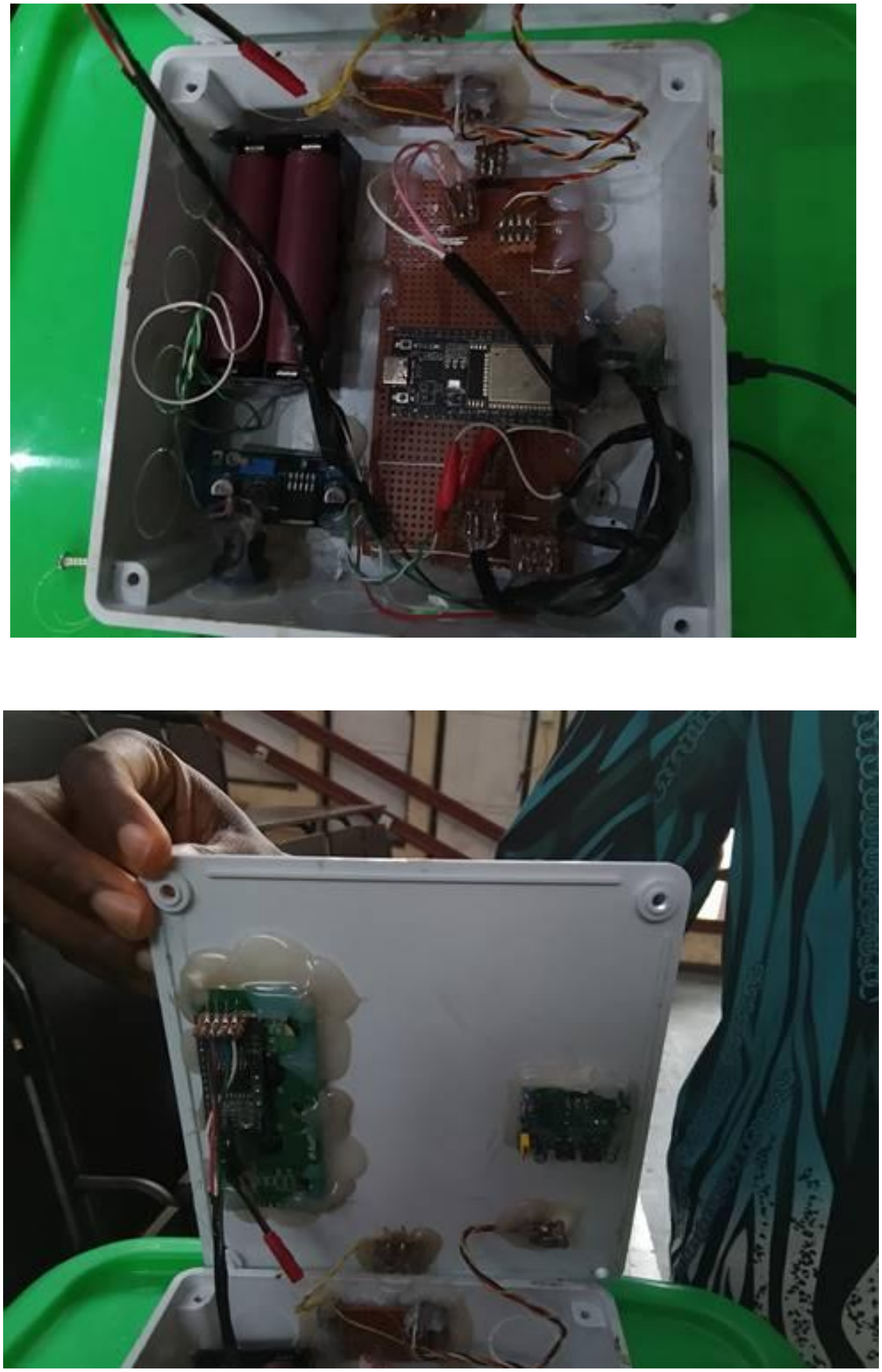

Fig 2: Internal view of working prototype