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Research Article

Internet of Things Based Intravenous Fluid Level Monitoring and Alert System for Nigeria Tertiary Healthcare Centers Using Esp32 Microcontroller

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Abstract

The application of internet of things (IoT) in critical sectors of human endeavours has extended greatly to healthcare services where IoT technologies has been used to monitor several patient's vital signs such as heartbeat, glucose level, blood pressure among others and provide timely report for immediate attention to enhance patient's outcomes. In Nigeria tertiary healthcare centers, the ratio of nurses to patients is very low and most patient needs intravenous (IV) therapy as there are always several critical cases to handle hence a need for automated intravenous fluid level monitoring in our tertiary healthcare centers. Intravenous therapy is a critical component of medical care, yet most Nigeria tertiary healthcare centers rely on traditional monitoring methods that are prone to human error that could compromise patient safety. This paper aims at implementing an internet of things (IoT) based IV fluid level monitoring and alert system in Nigeria tertiary healthcare centers. The system was developed using ESP32 microcontroller, a 5kg load cell with HX711 amplifier, and a multi-channel alert mechanism (LEDs, buzzer, and 16x2 I2C liquid-crystal display (LCD), coupled with cloud connectivity via ThingSpeak and notification services (Mailjet and Twilio). It continuously tracks IV fluid levels, converting weight data into volume measurements, and triggers real-time alerts at warning (50%) and critical (15%) thresholds. The system implemented several Security features, including Transport Layer Security. (TLS) encryption and multi-tier authentication to ensure data integrity. The Arduino Integrated Development Environment (IDE) was used as the programming environment due to its cross-platform compatibility, simplicity, and robust support for ESP32 development. Its intuitive interface accelerated prototyping, enabling rapid deployment of test code for sensor calibration. It has an extensive community-driven documentation and troubleshooting resources, which simplified resolving hardware-specific challenges, such as I2C address conflicts between the HX711 and LCD. Additionally, the IDE's serial plotter tool proved invaluable for visualizing real-time weight data during load cell calibration, ensuring the accuracy of the weight-to-volume conversion algorithm. The system was tested using use case and it satisfied all test conditions making it very suitable for intravenous fluid level monitoring in our tertiary healthcare centers.

Keywords

Internet of Things, Healthcare, Intravenous Fluid, ESP32 Microcontroller, ThingSpeak

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1. Introduction

The Internet of Things (IoT) has revolutionized many sectors, including healthcare, where it facilitates remote patient monitoring, real-time data analysis, and automated alerts for critical medical services such as timely replacement of intravenous fluid. IoT solutions, particularly sensor-based monitoring systems, provide continuous surveillance of IV fluid levels and alerts medical staff when an IV fluid level approaches depletion, enhancing patient safety and reducing hospital workload. The application of Internet of Things in healthcare services has proven some capability of bridging global health equity gaps [1] particularly in underserved countries. The use of IoT in IV fluid level monitoring is particularly impactful, allowing healthcare providers to continuously track fluid levels and ensure timely fluid level replacement [2]. IoT systems integrate sensor data with cloud platforms, enabling nurses and physicians to monitor multiple patients concurrently through mobile devices or desktops, making healthcare delivery more efficient [3]. Moreover, the adoption of IoT systems aligns with the global shift towards digital health transformation. The market for healthcare IoT devices has expanded rapidly, with a projected compound annual growth rate of 24.7% between 2020 and 2024 [4]. This growth reflects the increasing demand for automated solutions that alleviate the workload on healthcare staff. Implementing IoT in IV fluid level monitoring not only improves operational efficiency but also supports more personalized patient care, as fluid administration can be optimized based on real-time patient needs [5]. Intravenous fluid administration is a vital practice in healthcare, primarily supporting patients who cannot consume fluids orally or require rapid medication delivery. Traditional IV fluid level monitoring relies on manual checks by nurses and caregivers, which is prone to oversight, particularly in busy healthcare environments where multiple patients are managed simultaneously. The Nigeria tertiary healthcare centers have nurse-to-patient-ratio of one nurse to about 1,160 patients as reported by Nigerian Association of Nurses and Midwives [6]. In this complex healthcare centers, the manual processes of monitoring IV fluid level contribute to delayed IV fluid bag replacement, potentially leading to adverse patient outcomes [7]. Statistical data highlights the efficacy of automated IV fluid level monitoring as evident in a survey of over 100 hospitals across the United State where researchers found that nearly 62% reported IV fluid level monitoring delays affecting patient care outcomes, underscoring the need for automated solutions [8]. Additionally, the utilization of IoT technology minimizes the risk of human error, with potential reductions in nursing labor costs by up to 15% [9]. Such reductions not only benefit healthcare facilities economically but also enhance patient safety by minimizing IV fluid administration errors.

As digital technology progresses, IoT-enabled healthcare devices become increasingly sophisticated. Modern IV fluid level monitoring systems integrate various sensors, such as weight and flow rate sensors, which relay data to centralized healthcare platforms. This real-time information enables predictive analytics, helping staff anticipate patient needs and reduce the risk of complications due to IV fluid exhaustion. Studies indicate that IoT-based solutions in IV fluid monitoring improve hospital response times and streamline resource allocation, demonstrating both practical and economic benefits [10]. Several studies have highlighted challenges in IV therapy management, such as staff shortages, delayed IV fluid replenishment, and the risk of IV fluid infiltration or extravasation. Manual monitoring, common in most healthcare facilities, leaves room for missed or delayed interventions, especially in high-patient-load situations. The real-time feedback offered by IoT systems presents a potential solution by continuously tracking fluid levels, alerting staff immediately when replenishment is necessary [11]. As such, IoT technology not only holds promise for timely IV fluid level replacement but also aligns with wider efforts to reduce healthcare provider burnout and improve patient safety [12]. Although researchers have developed smart IV fluid level monitoring systems that automatically track fluid levels and alert caregivers when the fluid reaches critical levels however, the existing solutions often face limitations in terms of real-time accuracy, connectivity dependency, precision and continuous reliability, rely on singular sensing methods, which may not provide a comprehensive view of fluid administration dynamics and user-friendliness that integrates with hospital systems [13]. This paper aims at implementing an IoT-based IV fluid level monitoring and alert system for Nigeria tertiary healthcare centers using an innovative hybrid sensor system that combines multiple sensing technologies for enhanced accuracy with integrated cloud base data processing that ensures effective information gathering and analysis in real-time to facilitate immediate alerts and interventions. It leverages on real-time sensor data to address the limitations of traditional IV fluid level monitoring methods, provides real-time fluid level tracking with enhanced transmission accuracy through a cloud-based platform accessible to healthcare providers, generates timely alerts, highly user-friendliness with seamless healthcare integration to improving patient outcomes and streamlining hospital workflows.

2. Review of Related Works

Several recent studies have investigated IoT applications in healthcare, focusing on the challenges and solutions for real-time monitoring, data management, and alert systems. This paper provides an insight into the development of an IoT-based IV fluid level monitoring and alert system. [14] explored an IoT-based system designed for monitoring vital signs in critically ill patients, utilizing various sensors to track heart rate, blood oxygen levels, and blood pressure. The system deployed sensors connected to a cloud platform for continuous data collection and analysis. Data was visualized in real-time on mobile applications accessible to healthcare providers. The research underscores the significance of reliable data processing techniques in real-time healthcare monitoring applications, although it did not address IV fluid level monitoring. In another related work, [15] examined the use of a load-cell sensor-based system to monitor IV fluid levels in pediatric patients. This system aimed to notify healthcare staff when IV fluid levels dropped below a specified threshold. Data from load-cell sensors was processed through a microcontroller and transmitted to a monitoring application via Wi-Fi. The system proved effective in reducing IV fluid level dry-out events, ensuring timely interventions, especially in settings with limited nursing staff. However, the study observed that sensor calibration was complex and required regular adjustment to maintain accuracy, an essential consideration in any IV monitoring paper. The study provides valuable insight into sensor use for fluid-level monitoring but also indicates the need for robust sensor calibration methods. [16] investigated a machine learning-based IoT system to predict patient deterioration by analyzing vitals such as heart rate and respiratory patterns. The system integrated data from multiple biosensors, using machine learning models to detect early signs of deterioration. Alerts were generated based on the predictive analytics, enabling preemptive action by healthcare providers. While highly effective in identifying deterioration trends, the system required extensive data processing capabilities and high computational power, which could limit scalability in resource-constrained settings. The paper exemplifies the potential of predictive analytics in healthcare but reveals limitations related to computational resource requirements. [17] conducted a study focused on designing a real-time patient monitoring system with an emphasis on network reliability. The system utilized a range of physiological sensors connected via an IoT network to ensure consistent data transfer. Real-time data analytics allowed for timely alerts in case of abnormal readings. Although successful in reducing response times, the system experienced delays in data transfer when network congestion occurred, impacting its real-time capabilities. The study highlights the necessity of reliable network infrastructure for IoT applications in healthcare, which is implementation in this IV fluid level monitoring system. [18] researched an IoT-enabled smart infusion system designed to control fluid administration rates remotely. Using flow sensors and microcontrollers, the system provided real-time data on fluid flow rates and enabled healthcare professionals to adjust flow rates through a mobile interface. The study demonstrated success in reducing medication errors and improving control over fluid administration. However, technical issues arose with the sensor alignment and accuracy over extended periods, necessitating periodic recalibration. This research contributes to understanding the role of flow sensors in IV administration but indicates challenges in ensuring long-term sensor accuracy. [19] studied an IoT-based medication reminder system designed for elderly patients, which provided visual and auditory reminders when it was time to take medications. The system was equipped with a mobile application that allowed caregivers to monitor adherence. The reminders effectively improved medication compliance, but user feedback indicated that customization options for alert types and reminder intervals were limited, impacting user satisfaction. The study showcases the role of reminders in healthcare IoT and the significance of customizable alerts, valuable for a similar approach in IV fluid monitoring alerts. Another study by [20] investigated a wearable healthcare monitoring device that transmitted patient vitals through a secure Bluetooth connection. The system's focus was on ensuring data security and patient privacy while maintaining real-time monitoring capabilities. Encryption protocols were implemented to safeguard data during transmission, enhancing the device's security profile. While effective in protecting data privacy, the system encountered connectivity issues, particularly in areas with high electronic interference. This study underscores the importance of cybersecurity in healthcare IoT, relevant to any IoT monitoring system dealing with sensitive patient data such as IV fluid level. [21] developed a patient monitoring system integrating multiple sensors for vital signs, focusing on user interface design to enhance usability among healthcare workers. The system's intuitive dashboard displayed real-time vitals and alerts, enabling quick assessment and response. Testing revealed a reduction in monitoring time and an increase in user satisfaction due to the system's user-friendly design. However, the system lacked remote accessibility, limiting its utility in situations where healthcare providers were not on-site. The study underscores the importance of a well-designed user interface, which would be valuable for an IoT IV fluid level monitoring processed locally and transmitted to the cloud for accessibility, aiding caregivers in monitoring patient respiratory health. Although the system proved useful in timely intervention, it required frequent maintenance and recalibration of sensors to maintain accuracy. This research highlights the relevance of respiratory monitoring in chronic care and the need for reliable sensor calibration, also pertinent to IV fluid monitoring. [22] Conducted a study on the use of artificial intelligence in IoT healthcare systems to predict and prevent patient deterioration. Using a predictive model trained on historical patient data, the system provided early warnings of potential complications. The model showed high accuracy, yet the system's reliance on vast data inputs for training limited its applicability in settings with scarce resources. This study emphasizes the potential of predictive analytics in healthcare IoT while revealing the challenge of scalability, which is relevant in designing a predictive element for an IV fluid level monitoring system that requires ease of access.

3. Research Methodology

In this paper, an empirical experiment was set up through modularization process where the entire system was partitioned into five interdependent components, each fulfilling specialized roles while collectively achieving autonomous IV fluid level monitoring. The architecture adopts a modular design to compartmentalize responsibilities, ensuring efficient operation and adaptability. The various modules used in the development of this system includes: Sensing module, Processing module, Communication module, Application module and power module.

1) Sensing module: The sensing module consists of a 5kg load cell and an HX711 amplifier, which work together to measure the IV fluid bag weight with a resolution of 0.1g. The load cell generates analog strain gauge signals, which the HX711 digitizes at a sampling rate of 10 samples per second (SPS) and applies noise filtering using a moving average algorithm. This digitized data is then transmitted to the Processing Module for further analysis and conversion. The load cell has a nonlinearity tolerance of ±0.5% and a sensitivity of 1mV/V, ensuring minimal measurement errors. The HX711 amplifier features a 24-bit Analog to Digital Converter (ADC), a 10Hz sampling rate, and a programmable gain of 128x, allowing it to detect minute changes in weight. This high resolution enables the system to monitor gradual fluid level reductions, making it suitable for accurate IV fluid level depletion tracking.

Figure 1. HX711 load cell sensor amplifier.

2) Processing Module: The Processing Module, managed by an ESP32 microcontroller, plays a crucial role in interpreting the raw weight data and converting it into volume measurements using the formula: Volume (mL) = Weight (g) / 1.006, it accounts for the density of saline solution to determine fluid volume accurately. In this module, a threshold-based alert logic was implemented where fluid levels were categorizing into three states: Normal (Green LED, ≥50% of the initial detectedVolume), Warning (Yellow LED, 15–50%), and Critical (Red LED + 85dB buzzer, <15%) and emergency alerts via SMS and email.. By processing real-time data, the ESP32 microcontroller ensures timely alerts and proactive fluid management. The ESP32 Microcontroller serves as the central processing unit of the system, responsible for handling sensor data acquisition, managing alert mechanisms, and facilitating IoT communication. It features a dual-core 240MHz processor, 520KB of SRAM, integrated Wi-Fi (802.11 b/g/n), and 34 programmable GPIO pins. The dual-core architecture enables efficient multitasking by dedicating Core 0 to sensor polling and real-time processing while Core 1 handles cloud communication. This division of tasks reduces system latency, ensuring timely alerts and data transmission.

Figure 1. Node MCU ESP32 development board.

3) Communication Module: The Communication Module facilitates bidirectional cloud connectivity enabling seamless data exchange with the Thingspeak cloud platform. It transmits JSON-formatted volume data, timestamps and system status updates to the Thingspeak every 15 seconds, ensuring continuous remote access to IV fluid levels. This module also integrates Mailjet and Twilio Application Programming Interface (APIs) to dispatch email and offers Short Message Service (SMS) alerts via Hypertext Transfer Protocol Secure (HTTPS) requests, embedding patient IDs and timestamps for enhanced traceability. This module also receives cloud commands, such as recalibration requests, through Message Queuing Telemetry Transport (MQTT) subscriptions, allowing remote intervention when necessary. The system incorporates both auditory and visual alerts to ensure effective notifications in clinical environments. A piezoelectric buzzer was used for critical warnings. Additionally, an red, green, and blue Light-emitting diodes (RGB LED) provides visual indications with three colors: red for critical alerts, yellow for

warning levels, and green for normal conditions. The combination of LED indicators and an audible buzzer ensures that alerts are noticeable even in high-noise environments to improving response times for healthcare personnel.

The system integrates Cloud-based services for data logging, visualization, and remote alert management. The system utilizes Thingspeak for real-time cloud storage and visualization, offering features such as Matrix Laboratory (MATLAB) analytics, private channel API keys, and a 15-second update rate to ensure continuous data synchronization. Additionally, Mailjet and Twilio handle email and SMS alerts, respectively, providing secure and reliable notifications using REST APIs, and customizable message templates. Thingspeak's integration with MATLAB enables trend analysis and predictive monitoring, while Mailjet and Twilio facilitate Health Insurance Portability and Accountability Act (HIPAA)-compliant alert delivery, ensuring secure and timely notifications to healthcare personnel.

Figure 3. Buzzer and LED.

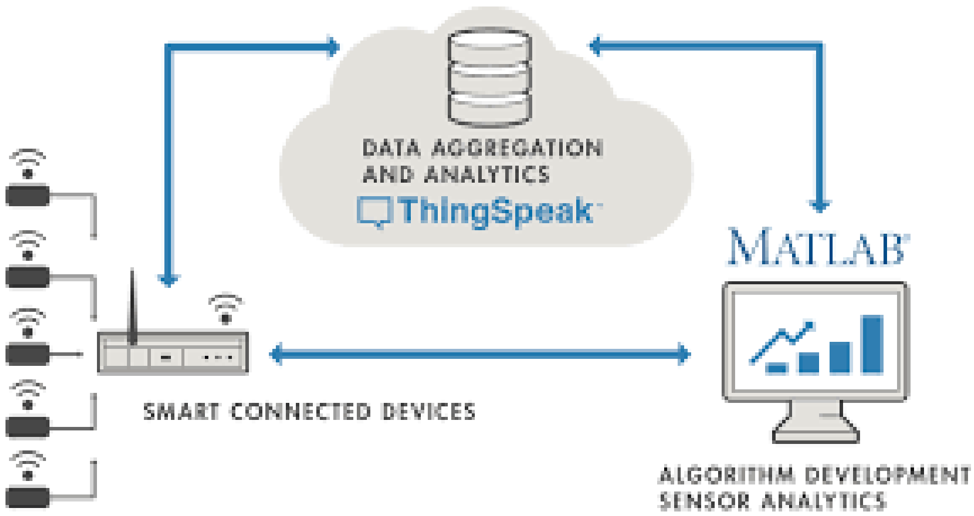

Figure 4. Network connectivity model.

For effective communication, several Libraries and communication Protocols were used to simplify implementation and improve reliability by ensuring firmware efficiency with reduced development complexity some of which include: HX711_ADC library, LiquidCrystal_I2C library, WiFiClientSecure, MQTT protocol, HTTPS protocols among others. These standardized libraries and communication protocols enhance the system's robustness, ensuring seamless integration within medical facilities while maintaining data security and compliance with healthcare regulations.

4) Application Module: The Arduino Integrated Development Environment (IDE) serves as the primary platform for software development and deployment. The IDE's integrated library manager streamlined the inclusion of dependencies such as WiFiClientSecure for encrypted cloud communication and Arduino_JSON for payload formatting. It includes essential features such as a serial monitor for real-time debugging and a Board Support Package (BSP) tailored for ESP32, enabling easy compilation and flashing of firmware and provides low-level access to hardware features, including General-Purpose Input/Output (GPIO) control and dual-core task scheduling. The Arduino IDE is chosen for its cross-platform compatibility, extensive library support, and seamless integration with the ESP32's hardware capabilities, accelerating the development and troubleshooting process. The software stack is built on the Arduino ecosystem for easy firmware execution, reliable cloud connectivity, and seamless alert management and it leverages pre-tested libraries and industry-standard communication protocols to enhance development efficiency and system stability. The User Interface was built using a 16x2 I2C LCD that displays IV fluid volume, system status, and alerts such as "Vol: 15 mL" and "CRITICAL: REPLACE FLUID BAG" during emergency situations with a tactile push-button for resetting the detected Volume

baselines measurements for new IV fluid level during manual calibration to simplifies IV fluid bag replacement workflows. The LCD operates at 5V, consumes 2mA for backlight illumination, and communicates using an I2C address of 0x27. The push button integrates an internal pull-up resistor, ensuring stable signal transitions. The combination of an LCD and a push button provides a simple yet effective user interface, allowing healthcare staff to quickly assess IV status and perform necessary adjustments. It equally has RGB LED indicators that provides intuitive status visualization, further improving user interaction and ensuring quick response to alerts. The software system was built using C++ Programming language as C++ codebase emphasized modularity, that enable the development of functionalities into distinct modules such as sensor data acquisition, alert management, cloud communication among others and the HX711_ADC library facilitated precise load cell data sampling, implementing noise reduction through a moving average filter, while the LiquidCrystal_I2C library streamlined interactions with the 16x2 LCD for real-time feedback. The final firmware integrated non-blocking code practices, allowing concurrent execution of critical tasks—sensor polling, LCD updates, and cloud synchronization—without introducing latency. For instance, timer interrupts managed periodic LCD refreshes, while FreeRTOS tasks on the ESP32's second core handled asynchronous alert delivery via Mailjet and Twilio APIs.

5) Power Module: The system is powered by a 9v battery regulated to 5v to mitigate electrical fluctuations that could interfere with sensor accuracy or disrupt system performance. This undervoltage lockout (UVLO) circuitry protects the ESP32 from potential damage during low-voltage conditions and guarantees continuous operation and reliability by mitigating power-related disruptions.

Figure 5. 9v battery power supply with connector.

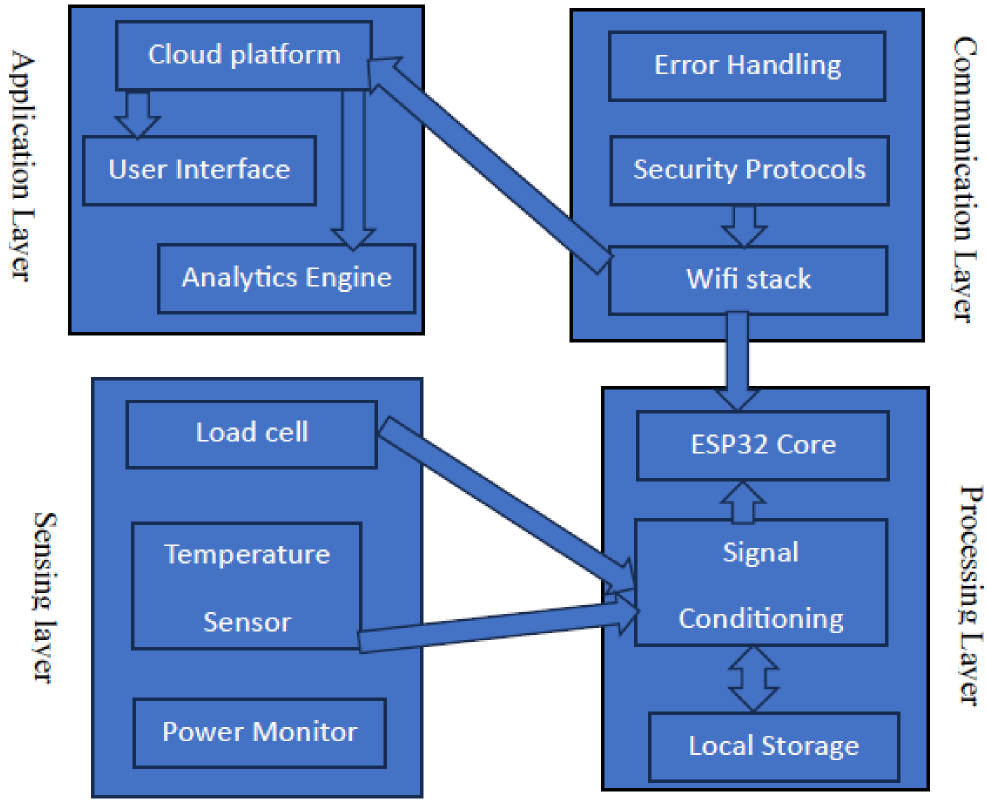

Figure 6. System Architecture Diagram.

The IV fluid level monitoring system consists of multiple components that work together to ensure accurate weight measurement, real-time status indication, seamless communication with cloud services among others. Each component is carefully selected based on precision, reliability, and integration with the system architecture. At the foundational level, the sensing module incorporates precision load cells and environmental sensors, providing accurate measurement of fluid parameters while monitoring system conditions. The processing module, centered around the ESP32 microcontroller, handles data acquisition, signal processing, and initial analysis, ensuring reliable system operation even during temporary network interruptions. The communication module manages data transmission between system components through secure WiFi connectivity, implementing robust error handling and data validation protocols. At the application level, the Thingspeak IoT platform provides the interface for system monitoring and control, while handling data storage and advanced analytics processing. This architectural approach ensures system scalability and reliability while maintaining security and performance standards essential for healthcare applications. The modular design philosophy enables system expansion and feature enhancement without fundamental architectural changes. Each module operates with defined interfaces and protocols, allowing component upgrades or modifications without impacting overall system functionality. This approach ensures the system can evolve to meet future healthcare monitoring requirements while maintaining operational reliability and performance. The hardware architecture emphasizes reliability through sophisticated power management and fail-safe mechanisms. The ESP32 module operates through carefully optimized power states, balancing monitoring accuracy with battery life.

3.1. Input and Output Design

The system adheres to standardized input/output protocols to ensure seamless interoperability between hardware components, cloud services, and user interfaces. Input data is received from multiple sources, including analog sensor readings, digital user interactions, and remote cloud-based commands. The load cell produces an analog voltage ranging from 0 to 20mV, which is digitized into a 24-bit integer by the HX711 amplifier before being processed by the ESP32. User input is facilitated through a tactile push button, which generates a digital HIGH or LOW signal for manual calibration and system reset functions. Additionally, the system processes cloud-based commands in JSON format via MQTT, enabling remote recalibration and control, such as {"command": "reset_volume"} while output data is disseminated through local and cloud-based channels. Locally, system status is conveyed using GPIO signals to control visual and auditory alerts: a green LED (3.3V) for normal conditions, a yellow LED (3.3V) for warning levels, and a red LED (3.3V) combined with a 2kHz PWM-driven buzzer for critical conditions. The LCD interface displays ASCII-formatted text, such as "CRITICAL: REPLACE FLUID BAG," providing real-time feedback to healthcare personnel. In cloud communications, JSON-formatted data, including volume measurements, status codes, and timestamps, is transmitted to Thingspeak every 15 seconds to maintain real-time synchronization. Remote notifications are dispatched via Mailjet for email alerts and Twilio for SMS notifications, ensuring continuous monitoring and timely alerts.

3.2. Algorithm Design

The monitoring algorithm operates cyclically to ensure continuous IV fluid tracking and real-time alerting. Upon initialization, the system configures all necessary GPIO pins for LEDs, buzzer, and button inputs, establishes a Wi-Fi connection, and performs a tare calibration for the HX711 amplifier to define the initial reference weight. The detectedVolume variable is set to zero, while systemStatus is initialized to indicate normal operation (0: Normal, 1: Warning, 2: Critical).

The algorithm follows the steps below:

Step 1: Start
Step 2: Initiate System Configuration
Step 3: Set up system network
Step 4: Calibration the necessary system components
Step 5: Set all Initial Values
Step 6: Establish a Continuous Monitoring Loop
Step 7: Trigger alert when necessary
Step 8: Stop

3.3. System Circuitry Design

The system's circuitry design demonstrates the seamlessly integration of hardware, software, and communication protocols into a unified circuit framework. As illustrated in Figure 7. The ESP32 microcontroller acts as the central processing unit, efficiently managing real-time data acquisition, sensor processing, and decision-making. It interfaces with key peripheral components, including the load cell, LEDs, buzzer, and the 16x2 I2C LCD, ensuring system stability and seamless cloud communication. This dual-core architecture enables concurrent execution of critical tasks, such as monitoring IV fluid levels, triggering alerts, and transmitting data to remote servers.

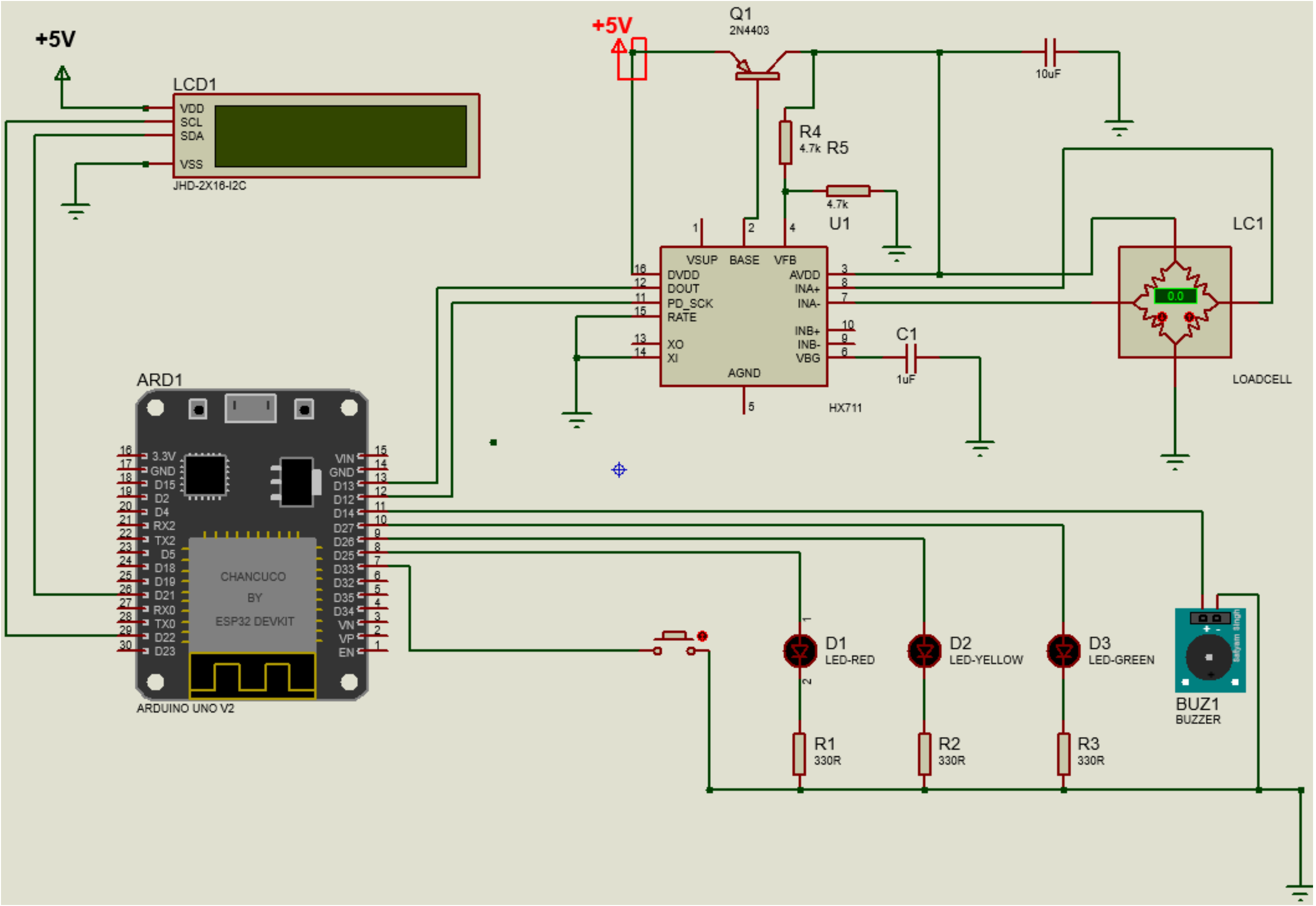

Figure 7. *The system's circuit diagram.*

Figure 8. *Wiring diagram and setup image of the circuit.*

The circuit design is optimized for reliability, with the 5kg load cell interfacing with the HX711 amplifier in a Wheatstone bridge configuration. As shown in the circuit diagram, strain gauges within the load cell generate millivolt-level signals proportional to the IV fluid level's weight. These signals are amplified and digitized by the HX711's 24-bit ADC before being transmitted to the ESP32 via GPIO pins 18 and 19. Shielded cables and a dedicated Printed Circuit Board (PCB) ground plane minimize electromagnetic interference, ensuring accurate readings. Peripheral components are mapped to specific GPIO pins for efficient functionality. The Red, Yellow, and Green LEDs, controlled by GPIO 12, 14, and 27 respectively, visually indicate fluid levels, while the buzzer on GPIO 13 provides auditory alerts. The push button on GPIO 33 facilitates manual calibration, allowing healthcare personnel to reset the system during IV fluid level replacements. Power distribution involves a 5V/2A regulated supply powering the ESP32 and a 3.3V rail supporting the HX711 and load cell. Decoupling capacitors (100nF) stabilize voltage lines, and a Schottky diode prevents damage from reverse polarity. The IoT connectivity is crucial for remote monitoring, the ESP32's Wi-Fi module securely connects to the Thingspeak cloud using Transport Layer Security (TLS) encryption. This enables secure transmission of volume metrics and system status while also supporting remote calibration commands. Local user interaction is enhanced through the 16x2 I2C LCD, which displays real-time IV fluid volume, system status, and alerts. Connected via GPIO 21 (SDA) and GPIO 22 (SCL), the LCD operates at address 0x27, minimizing GPIO usage. To mitigate backlight-induced noise, a dedicated LM7805 voltage regulator isolates the LCD's power supply, as depicted in the circuit diagram. The LCD updates every two seconds for optimal readability, while its Pulse Width Modulation (PWM)-controlled backlight, managed via GPIO 23, adjusts brightness according to ambient lighting, conserving power.

4. Performance Evaluation

The evaluation of the system is designed to validate its performance, reliability, and clinical applicability, aligning with the study's aim to enhance patient safety and reduce healthcare staff workload. The system was evaluated using usability testing technique with 10 healthcare providers in a simulated clinical setting. Participants assessed the LCD display, LED indicators, and alert notifications for clarity and ease of use and recording their observations accordingly.

Table 1. Summary of Actual Test Result versus Expected Test Result.

Test Scenario	Expected Outcome	Actual Outcome	Status
Baseline Calibration	DetectedVolume is set correctly for full IV fluid level.	Successfully detected full IV fluid level volume at 100%.	Passed
Threshold Validation (50%)	System triggers Warning Alert at 50% volume.	LED turns yellow, buzzer activates, Thingspeak logs status 1.	Passed
Threshold Validation (15%)	System triggers Critical Alert at 15% volume.	LED turns red, buzzer (2kHz) activates, email/SMS alerts sent, Thingspeak logs status 2.	Passed
Network Resilience (Wi-Fi loss)	Data temporarily stored locally, alerts continue offline.	Local alerts (LED/Buzzer) remained active, data resumed after Wi-Fi restored.	Passed
Recalibration Stability	Recalibration resets detectedVolume accurately.	Multiple recalibrations resulted in consistent detectedVolume values.	Passed
Sudden Weight Changes	System filters noise and prevents false alerts.	Small fluctuations ignored, only significant volume drops triggered alerts.	Passed
Environmental Factors (Wi-Fi, Temperature)	Performance remains stable under varying conditions.	No significant deviations in readings; network signal strength affected transmission speed.	Passed with minor delays

5. Conclusion

The architecture is designed to provide real-time IV fluid monitoring, generate timely alerts, and facilitate seamless communication between hardware components and cloud-based services. The system integrates advanced hardware components, including an ESP32 microcontroller, a 5kg load cell with HX711 amplifier, and a multi-channel alert mechanism comprising LEDs, a buzzer, and a 16x2 I2C LCD. These components work in tandem with software modules developed within the Arduino IDE, leveraging cloud platforms such as ThingSpeak for real-time data visualization, and Mailjet and Twilio for SMS and email notifications. The system continuously monitors IV fluid levels by converting weight measurements into volume data, employing a hierarchical alert structure to notify healthcare providers at warning (50% volume) and critical (15% volume) thresholds. Despite its strengths, constraints such as Wi-Fi dependency and manual calibration requirements were identified, highlighting areas for further refinement. To enhance this systems performance, redundant communication channels could be developed using other communication protocols such as LoRaWAN or Bluetooth Low Energy (BLE), to reduce reliance on Wi-Fi and enable functionality in areas with poor internet connectivity. The system calibration can equally be automated completely through the application of machine learning approach.

Abbreviations

LCD	Liquid-Crystal Display
TLS	Transport Layer Security
IDE	Integrated Development Environment
ADC	Analog to Digital Converter
SMS	Short Message Service
HTTPS	Hypertext Transfer Protocol Secure
MQTT	Message Queuing Telemetry Transport
APIs	Application Programming Interface
RGB LED	Red, Green, and Blue Light-emitting Diodes
MATLAB	Matrix Laboratory
HIPAA	Health Insurance Portability and Accountability Act
GPIO	General-Purpose Input/Output
PCB	Printed Circuit Board
TLS	Transport Layer Security
PWM	Pulse Width Modulation
IoT	Internet of Things
IV	Intravenous

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Anthony Obogo Otiko: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Supervision, Writing – review & editing

Adogwu Samuel Junior: Conceptualization, Formal Analysis, Methodology, Validation

Conflicts of Interest

The authors declare no conflicts of interest.

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