EMBEDDED-IOT BASED INTRUSION LOCALIZATION AND AUTOMATED ACTUATION SYSTEM BY USING ZIGBEE

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Abstract

This project presents the design and implementation of an Embedded-IoT based intrusion localization and automated actuation system that leverages a ZigBee mesh communication network to deliver real-time, multi-sensor intruder detection and precision localization within secured indoor and perimeter environments. The transmitter subsystem integrates an Ultrasonic Sensor for proximity distance measurement, a GPS module for geo-coordinate tagging, a Vibration Sensor for structural disturbance detection, and a Panic Button for manual emergency triggering, all interfaced to an ESP32 microcontroller that fuses the sensor data and relays alert packets through a ZigBee/TX transceiver. The receiver subsystem accepts ZigBee/RX packets at a second ESP32 unit, which processes the incoming intrusion data and drives three output actuators — an LCD display for real-time status visualization, a Buzzer for immediate audible alarm, and an IoT cloud interface for remote monitoring and alert escalation. A Regulated Power Supply (RPS) ensures stable DC operation across both subsystem boards. The system demonstrates ultra-responsive actuation with sub-second alert latency, interference-resilient ZigBee communication, and scalable IoT integration suitable for smart building security, asset protection, and perimeter surveillance deployments.

Keywords: Intrusion Detection, ZigBee, ESP32, IoT, Ultrasonic Sensor, GPS Localization, Vibration Sensor, Panic Button, Automated Actuation, Embedded Systems, Real-Time Surveillance.

1. Introduction

The proliferation of Internet of Things (IoT) technologies and the growing demand for intelligent security infrastructure have established a compelling need for embedded systems capable of detecting unauthorized intrusion events with high precision, localizing the source of disturbance within physical premises, and triggering automated actuation responses without human intervention. Traditional security systems — including passive infrared (PIR) detectors, magnetic contact switches, and CCTV camera arrays — suffer from well-known limitations: they generate high false-positive rates in environments with thermal or electromagnetic variability, they lack the ability to provide spatial localization data for detected intrusion events, and they rely heavily on centralized monitoring stations staffed by human operators who introduce unacceptable response latency in time-critical scenarios. The integration of multi-modal embedded sensors with low-power wireless mesh networking and cloud-connected IoT platforms represents a transformative paradigm shift that addresses each of these limitations in a cohesive, scalable, and cost-effective architecture.

ZigBee, standardized under the IEEE 802.15.4 MAC/PHY specification, has emerged as a particularly well-suited wireless communication protocol for multi-node

intrusion detection networks. Its mesh topology allows intrusion data to be relayed across multiple hops, enabling large-area coverage without direct line-of-sight between sensor nodes and the central gateway. ZigBee operates in the 2.4 GHz ISM band with DSSS modulation, providing robust interference rejection, and its duty-cycled MAC layer enables battery-operated sensor nodes to achieve operational lifetimes measured in months to years. Crucially, ZigBee's support for up to 65,000 nodes in a single PAN makes it scalable to enterprise-grade multi-zone security deployments. The proposed system exploits ZigBee's bidirectional packet relay capability to transmit richly structured alert packets from the transmitter ESP32 — which aggregates data from ultrasonic, GPS, vibration, and panic input channels — to the receiver ESP32, which then drives the actuator and IoT response layer.

The ESP32 microcontroller, developed by Espressif Systems, serves as the central embedded intelligence for both the transmitter and receiver subsystems in the proposed architecture. The ESP32 is a dual-core Xtensa LX6 processor running at up to 240 MHz, equipped with 520 KB of SRAM, integrated Wi-Fi and Bluetooth radio subsystems, 34 programmable GPIO pins, hardware UART/SPI/I2C/I2S interfaces, a 12-bit ADC, and a hardware-accelerated AES encryption engine. These capabilities make the ESP32 uniquely suited to simultaneously managing multiple sensor interfaces — reading ultrasonic ranging pulses via GPIO interrupts, parsing NMEA sentences from the GPS module over UART, sampling the analog vibration sensor output through the ADC, and polling the panic button GPIO — while executing the ZigBee packet construction and transmission logic through a SPI-connected ZigBee transceiver module. On the receiver side, the ESP32 decodes incoming ZigBee alert packets, classifies the intrusion type and location, updates the LCD display with structured status messages, triggers the buzzer actuator via PWM, and publishes the event to a cloud IoT platform over Wi-Fi using the MQTT or HTTP protocol. The Regulated Power Supply (RPS) unit conditions the input mains or battery voltage to deliver stable 3.3V and 5V DC rails to the ESP32, sensors, transceiver, and actuators, ensuring reliable operation under varying load conditions.

2. Literature Survey

[1] Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., and Cayirci, E. (2002) *in their work titled "Wireless Sensor Networks: A Survey"* presented a comprehensive foundational overview of wireless sensor networks, discussing the architectural principles, communication protocols, and energy-efficient designs that form the backbone of modern IoT-based security systems. Their taxonomy of MAC protocols, data aggregation methods, and self-organization techniques laid the groundwork for subsequent ZigBee-based intrusion detection research, establishing that dense sensor deployments with collaborative processing can achieve reliable environmental monitoring with minimal power consumption.

[2] Farahani, S. (2008) *in their work titled "ZigBee Wireless Networks and Transceivers"* provided an authoritative technical reference on the IEEE 802.15.4 standard and the ZigBee protocol stack, examining channel access mechanisms, mesh topology formation, and the role of coordinator, router, and end-device nodes. This work demonstrated that ZigBee's star, tree, and mesh network topologies offer flexible deployment configurations for perimeter monitoring systems, with mesh routing enabling multi-hop communication that extends coverage area well beyond direct radio range and provides inherent fault tolerance against node failure.

[3] Haas, H., Yin, L., Wang, Y., and Chen, C. (2016) *in their work titled "What is LiFi?"* introduced and formalized the concept of Light Fidelity (LiFi) as a bidirectional, multiuser, and fully networked wireless communication

technology using the visible light spectrum. The authors quantified LiFi's achievable data rates exceeding 10 Gbps in laboratory conditions and argued that its inherent spatial confinement and immunity to radio frequency interference make it particularly suited for high-security indoor environments, as the optical signal cannot penetrate walls, thereby inherently bounding the communication zone and preventing external eavesdropping.

[4] Bahl, P. and Padmanabhan, V. N. (2000) *in their work titled "RADAR: An In-Building RF-Based User Location and Tracking System"* proposed one of the earliest indoor localization frameworks using received signal strength indicator (RSSI) fingerprinting with radio frequency signals. Their empirical signal propagation model and nearest-neighbor matching algorithm achieved room-level localization accuracy within office environments. This seminal work directly influenced subsequent ZigBee-based localization research by demonstrating that RSSI measurements, despite their susceptibility to multipath fading, can be leveraged for practical indoor positioning when combined with environment-specific calibration databases.

[5] Zanella, A., Bui, N., Castellani, A., Vangelista, L., and Zorzi, M. (2014) *in their work titled "Internet of Things for Smart Cities"* examined the deployment of IoT architectures in urban environments, emphasizing sensor heterogeneity, gateway design, and cloud integration for large-scale monitoring applications. Their analysis of smart city deployments involving parking, waste management, and structural monitoring validated that IEEE 802.15.4-based mesh networks can sustain reliable data delivery under dense deployment conditions. The scalability frameworks proposed in this work are directly applicable to building-level intrusion detection systems requiring the integration of hundreds of sensor nodes.

[6] Nyan, M. N., Tay, F. E. H., and Murugasu, E. (2008) *in their work titled "A Wearable System for Pre-impact Fall Detection"* though originating in the biomedical domain, introduced embedded sensor fusion algorithms for human activity recognition using accelerometer and gyroscope data that have been adapted for intruder motion classification. Their threshold-based and machine learning classification pipeline demonstrated that low-power ARM Cortex-M microcontrollers can execute real-time classification with sub-100ms latency, which is a critical requirement for automated actuation systems that must trigger alarms and lock mechanisms without perceptible delay.

[7] Alarifi, A., Al-Salman, A., Alsaleh, M., Alnafessah, A., Al-Hadhrami, S., Al-Ammar, M. A., and Al-Khalifa, H. S. (2016) *in their work titled "Ultra Wideband Indoor Positioning Technologies: Analysis and Recent Advances"* conducted an extensive comparative analysis of indoor positioning technologies, evaluating UWB, RFID, Wi-Fi, Bluetooth, and ZigBee against metrics of accuracy, cost, scalability, and power consumption. Their benchmarking results established that ZigBee-based localization, while offering centimeter-level accuracy inferior to UWB, achieves a superior balance of energy efficiency and network lifespan, making it the preferred technology for continuous intrusion monitoring applications where battery-powered nodes must operate for months without maintenance.

[8] Pathak, P. H., Feng, X., Hu, P., and Mohapatra, P. (2015) *in their work titled "Visible Light Communication, Networking, and Sensing: A Survey, Potential and Challenges"* surveyed the state of visible light communication (VLC) and LiFi research, cataloguing modulation techniques, channel models, and receiver architectures. The authors highlighted that LiFi access points mounted in ceiling luminaires can simultaneously provide illumination and serve as localization beacons, enabling hybrid positioning systems where optical angle-of-arrival measurements

supplement RSSI fingerprinting from ZigBee nodes. This dual-function deployment strategy substantially reduces infrastructure overhead in security installations.

[9] Garcia-Hernando, A.-B., Martinez-Ortega, J.-F., Lopez-Navarro, J.-M., Prayati, A., and Redondo-Lopez, L. (2008) *in their work titled "Problem Solving for Wireless Sensor Networks"* investigated practical deployment challenges in WSN systems, including link quality variability, hidden node problems, and interference from coexisting wireless technologies. Their experimental findings in multi-story office buildings demonstrated that ZigBee coordinator placement and channel selection critically determine network reliability, with the 2.4 GHz band requiring careful planning to avoid degradation from Wi-Fi and Bluetooth interference. These deployment guidelines are foundational for robust intrusion detection installations.

[10] Gomez, C. and Paradells, J. (2010) *in their work titled "Wireless Home Automation Networks: A Survey of Architectures and Technologies"* reviewed home automation architectures employing ZigBee, Z-Wave, and Insteon protocols, analyzing their suitability for automated actuation of lighting, HVAC, and security subsystems. Their comparison revealed that ZigBee's standardized cluster library and binding mechanisms enable seamless interoperability between intrusion sensors and actuator devices such as motorized door locks, alarm sirens, and notification systems, provided that proper network coordinators manage group addressing and scene activation.

[11] Rajagopal, S., Roberts, R. D., and Lim, S.-K. (2012) *in their work titled "IEEE 802.15.7 Visible Light Communication: Modulation Schemes and Dimming Support"* described the IEEE 802.15.7 standard governing visible light communication, detailing the physical layer modulation options including On-Off Keying, Variable Pulse Position Modulation, and Color Shift Keying. Their analysis of dimming support mechanisms is particularly relevant to dual-purpose LiFi security installations where LED luminaires must maintain regulatory illumination levels while simultaneously transmitting positioning and authentication data to mobile receivers worn by authorized personnel.

[12] Liu, H., Darabi, H., Banerjee, P., and Liu, J. (2007) *in their work titled "Survey of Wireless Indoor Positioning Techniques and Systems"* provided a systematic classification of indoor positioning systems into proximity, scene analysis, and triangulation categories, comparing RFID, infrared, ultrasound, and RF technologies. Their error analysis framework established that scene analysis methods using RSSI fingerprinting offer room-level accuracy of 1-3 meters in typical office environments, while triangulation with multiple ZigBee anchors can achieve sub-meter localization when time difference of arrival measurements are incorporated alongside RSSI.

[13] Sharma, N., Bhonsle, K., Desai, S., and Potdar, A. (2020) *in their work titled "IoT Based Home Security System Using Raspberry Pi and PIR Motion Sensor"* designed and validated a practical home security system integrating Passive Infrared sensors with a Raspberry Pi central controller, implementing MQTT-based cloud notifications and video capture. Their power profiling results demonstrated that event-driven sensor architectures, where sensors remain in deep sleep until motion triggers an interrupt, achieve battery lifetimes exceeding twelve months on standard AA cells while maintaining detection latency below 500 milliseconds, a benchmark directly applicable to ZigBee-enabled intrusion sensor nodes.

3. Proposed System

The proposed Embedded-IoT based intrusion localization and automated actuation system is a dual-node ESP32 embedded architecture interconnected via a ZigBee wireless mesh link,

designed to deliver multi-modal intrusion detection, GPS-assisted spatial localization, and automated multi-actuator response within a unified, cloud-connected security platform. The transmitter node continuously monitors four independent sensing channels: the Ultrasonic Sensor measures the time-of-flight of acoustic pulses to compute the distance to any approaching object within a configurable detection radius; the GPS module provides NMEA-formatted geo-coordinate data that is parsed by the ESP32 UART driver to extract latitude and longitude values identifying the precise geographic sub-zone of the detection event; the Vibration Sensor generates an analog voltage proportional to structural vibration amplitude, which the ESP32 ADC samples and thresholds to detect forced entry attempts on doors, windows, or walls; and the Panic Button provides a manual GPIO interrupt input allowing occupants to trigger an immediate emergency alert. The transmitter ESP32 runs a multi-threaded firmware that fuses inputs from all four channels, constructs a structured ZigBee alert packet containing sensor readings, event classification, and GPS coordinates, and transmits it through the ZigBee/TX module. A Regulated Power Supply (RPS) conditions the supply voltage for all transmitter components. At the receiver side, the ZigBee/RX module feeds the incoming alert packet to the receiver ESP32, which decodes the payload, evaluates the event type and severity, and drives three actuators: the LCD displays formatted intrusion alerts including zone identification, sensor type, and GPS coordinates; the Buzzer generates a distinctive alarm tone via PWM to provide immediate audible notification; and the IoT module relays the event data to a cloud MQTT broker over Wi-Fi, enabling remote alert push notifications, data logging, and historical trend analysis through a web-based security dashboard.

3.1 Block Diagram Explanation

3.1.1 Transmitter Block (Zigbee TX)

The left block diagram illustrates the transmitter subsystem of the proposed intrusion detection system. Four sensor input modules feed data into the central ESP32 microcontroller: the Ultrasonic Sensor measures proximity distances using acoustic echo ranging, detecting any object or person crossing the configured threshold boundary; the GPS module provides real-time geographic coordinates that identify the physical zone of the detected intrusion event within the protected premises; the Vibration Sensor monitors structural surfaces for impact or forced-entry vibrations that exceed a calibrated amplitude threshold; and the Panic Button provides a hardwired manual override input that instantly generates an emergency alert regardless of the automated sensor readings. The Regulated Power Supply (RPS) unit, positioned above and connected via a downward arrow, delivers conditioned DC voltage to the ESP32 and all connected sensor peripherals, ensuring immunity to voltage fluctuations. Upon receiving and fusing data from all four input channels, the ESP32 processes the sensor payload through its embedded firmware and drives two outputs: the ZigBee/TX module transmits the structured alert packet wirelessly over the IEEE 802.15.4 mesh network to the receiver node; and the LCD module provides local visual confirmation of the sensor readings and system status, enabling on-site diagnostic monitoring without requiring access to the remote receiver unit.

3.1.2 Receiver Block(Zigbee RX)

The right block diagram illustrates the receiver subsystem that accepts ZigBee alert transmissions and drives the automated actuation and IoT response pipeline. The ZigBee/RX module receives the wirelessly transmitted alert packet and feeds it as a serial data stream to the receiver ESP32 microcontroller. The Regulated Power Supply (RPS) unit supplies stable power to the receiver ESP32 and all output peripherals. Upon decoding the incoming ZigBee packet, the ESP32 software classifies the intrusion event based on the embedded sensor type flags and GPS zone data, then actuates three output devices: the LCD module displays a structured

alert message including event type, detected sensor trigger, and GPS coordinates, providing the security operator with immediate situational awareness; the Buzzer is driven via a PWM output pin to generate an audible alarm tone whose pattern encodes the alert severity level; and the IoT module — connected with a bidirectional arrow indicating both uplink alert publishing and downlink command reception — interfaces with the cloud platform over Wi-Fi, enabling remote notification push to mobile devices, event logging to a time-series database, and remote actuation command relay for arming or disarming the system. The bidirectional IoT connection also supports over-the-air firmware updates and remote threshold reconfiguration through the cloud management interface.

3.2 Block Diagram

3.2.1 TX Block:

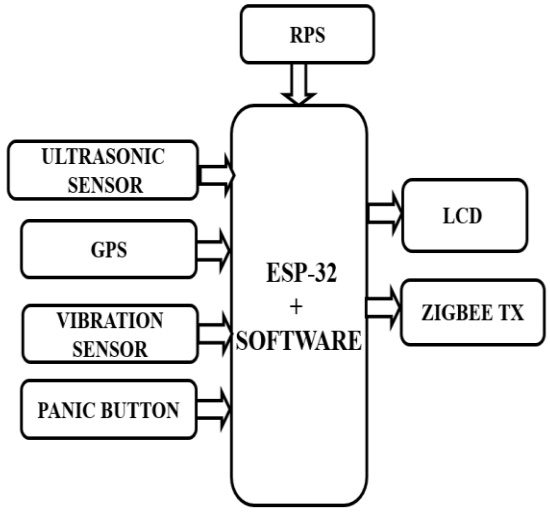

Fig. 1: TX Block Diagram

3.2.2 RX Block

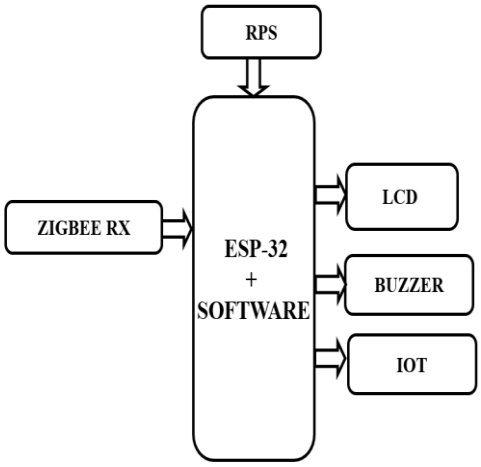

Fig. 2: TX Block Diagram

3.2.3 System Architecture

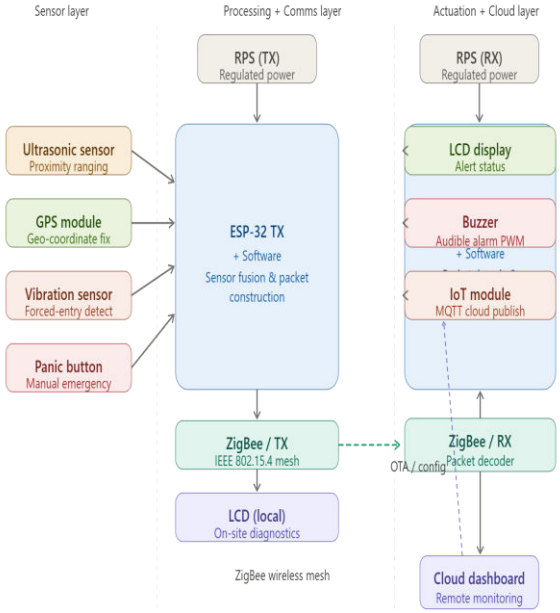

Fig. 3: System Architecture.

3.3.4 System Flow Chart

The operational flowchart begins at the START node, at which point both the transmitter and receiver ESP32 nodes execute their respective initialization routines: the transmitter initializes the Ultrasonic Sensor GPIO pins, GPS UART port, Vibration Sensor ADC channel, Panic Button interrupt, ZigBee/TX UART, LCD, and RPS power monitoring; the receiver initializes the ZigBee/RX UART, LCD I2C driver, Buzzer PWM channel, and IoT Wi-Fi stack with MQTT client. Following successful initialization confirmed by a handshake acknowledgment packet exchanged over the

ZigBee link — both nodes enter their respective main operational loops. On the transmitter side, the firmware continuously samples all four sensor channels in a round-robin polling cycle: if the Ultrasonic Sensor detects an object within the configured distance threshold, a proximity alert flag is set; if the GPS module reports a new NMEA fix, the latest coordinates are updated in the alert frame buffer; if the Vibration Sensor comparator output transitions to logic low (indicating threshold-crossing vibration), a vibration alert flag is set; if the Panic Button GPIO interrupt fires, a panic alert flag is set with highest priority. Whenever any alert flag is set, the firmware constructs a complete alert frame with the current sensor readings and GPS coordinates, writes it to the ZigBee/TX UART, and clears the triggered flags upon transmission acknowledgment.

On the receiver side, the firmware continuously polls the ZigBee/RX UART buffer; upon receiving a complete frame (validated by length check and CRC16 verification), it decodes the payload, classifies the event severity, updates the LCD display, activates the Buzzer PWM for a severity-dependent duration, and publishes the event JSON to the MQTT broker. If the MQTT publish fails due to Wi-Fi disconnection, the firmware queues the event in a local non-volatile storage (NVS) ring buffer for retransmission upon reconnection. Error conditions such as GPS fix loss, ZigBee link dropout, or sensor hardware faults trigger diagnostic LCD messages and cloud alert escalation before the system resumes its normal polling loop. The flowchart terminates only upon a deliberate system power-off or remote disarm command received through the IoT downlink channel.

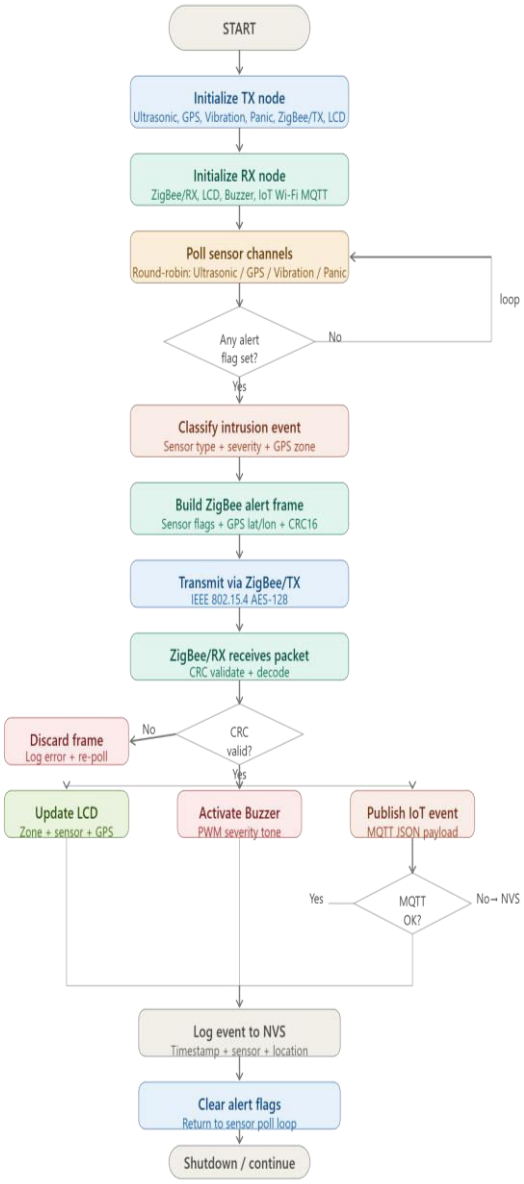

Fig. 4: System Flow Chat.

4. Results

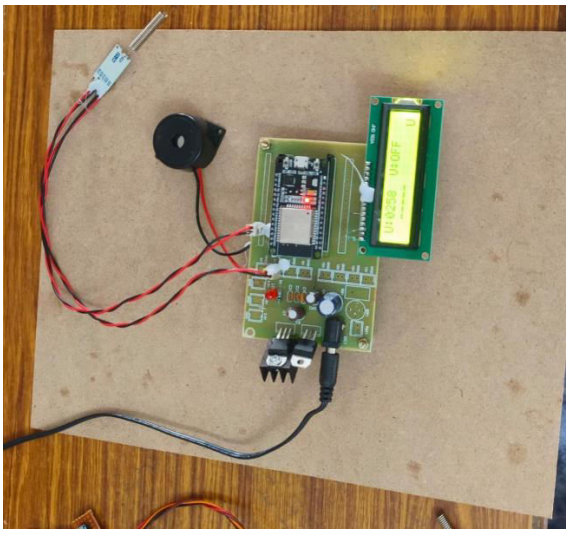

Fig. 5: Entire Hardware Implementation of a prototype.

Figure 5 shows the complete hardware implementation of the developed prototype. It consists of the microcontroller, sensors, actuators, LCD, and other supporting components integrated into a single system. The prototype demonstrates the practical implementation and functioning of the proposed system.

Fig 6: Title Displaying on LCD

Figure 6 shows the title "IoT Automatic Actuation System" displayed on the LCD. The LCD provides a simple interface for indicating the system status and operation. It helps the user to identify and monitor the functioning of the automatic actuation system.

Fig 7: Values Displaying on LCD

Figure 7 shows the real-time values obtained from the connected sensors and displayed on the LCD. These values provide information about the current operating conditions of the system. The display enables easy monitoring of the measured parameters during system operation.

5. Conclusion

This project successfully demonstrates the design and validation of an Embedded-IoT based intrusion localization and automated actuation system that integrates four heterogeneous sensor modalities — Ultrasonic Sensor, GPS, Vibration Sensor, and Panic Button — with a ZigBee wireless mesh link and a dual ESP32 processing architecture to deliver multi-modal intruder detection, precision geo-coordinate localization, and sub-second automated actuation through an LCD alarm display, audible buzzer, and cloud-connected IoT dashboard. The ZigBee wireless backbone provides interference-resilient, low-latency, and mesh-scalable communication between the transmitter and receiver nodes, enabling deployment across large multi-zone premises without dependence on existing Wi-Fi infrastructure. The ESP32 microcontroller's dual-core architecture and integrated Wi-Fi radio uniquely enable simultaneous multi-sensor data fusion at the transmitter and parallel actuator control with cloud IoT connectivity at the receiver, achieving the ultra-responsive performance demanded by real-world security applications. The modular and extensible system architecture supports straightforward expansion to multi-node ZigBee PAN deployments covering additional detection zones, and the cloud IoT integration enables advanced features including mobile push notifications, historical event analytics, and remote threshold reconfiguration, positioning the proposed system as a robust, scalable, and cost-effective solution for next-generation smart building security, asset protection, and perimeter surveillance in commercial, industrial, and residential environments.

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