

An Integrated IoT-LoRa Framework for Real-Time Biotelemetry and Geo-Spatial Tracking of Combat Personnel in GPS-Challenged Environments

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Abstract

Modern warfare and search-and-rescue operations demand high-fidelity, real-time data regarding the physiological and geographical status of personnel. This paper presents the development of a wearable "Soldier Node" utilizing the ESP32 microcontroller, integrated with a MAX30102 pulse oximetry sensor, DHT11 environmental sensor, and a NEO-6M GPS module. Unlike standard Wi-Fi-based IoT systems, which suffer from limited range and high-power consumption, this framework employs Long Range (LoRa) modulation (433MHz) to ensure robust data transmission over distances exceeding 5km in line-of-sight conditions. The system monitors vital signs such as Heart Rate (BPM) and Peripheral Capillary Oxygen Saturation (SpO₂) alongside ambient temperature and humidity to detect heatstroke or exhaustion. A three-axis vibration sensor is integrated for automated fall detection. Data is transmitted to a centralized command station (Base Station), where it is processed and uploaded to a cloud-based SQL server via an HTTP-based API for remote oversight. Preliminary results indicate a 98% packet delivery rate in rural terrains and a latency of less than 2 seconds. This research contributes a cost-effective, low-power solution for enhancing situational awareness and reducing casualty rates in remote or hostile environments.

Keywords: LoRaWAN, Biotelemetry, ESP32 Microcontroller, Soldier Tracking, Internet of Military Things (IoMT)

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1. Introduction

The concept of monitoring soldiers in the field has evolved from rudimentary radio check-ins to the sophisticated Internet of Military Things (IoMT). Historically, the primary cause of non-combat casualties in the military has been environmental stress and undetected medical distress. During the 1990s, the U.S. Army's "Land Warrior" program was one of the first major attempts to integrate computers and communication systems into infantry gear. However, these early systems were hindered by excessive weight and short battery life. The transition from bulky radio sets to Micro-Electromechanical Systems (MEMS) and Low-Power Wide-Area Networks (LPWAN) has revolutionized this field, allowing for "deploy-

and-forget" sensors that provide life-saving data without impeding a soldier's mobility. According to a report by the Journal of Athletic Training, heat-related illnesses (HRI) among active-duty service members are a persistent threat; between 2014 and 2019, there were over 13,000 incident cases of heatstroke and heat exhaustion in the U.S. Armed Forces alone. Furthermore, research published in the Military Medicine Journal indicates that immediate medical intervention within the "Golden Hour" (the first 60 minutes after injury) increases survival rates by nearly 40%. In remote combat zones, the lack of real-time health data often delays this intervention. Current GPS tracking systems often rely on cellular networks (GSM/LTE), which are easily jammed or

unavailable in deep valleys or cross-border terrains where infantry often operates. This research addresses the connectivity gap by proposing a decentralized monitoring architecture. The primary contributions of this paper are:

1. Integration of physiological (Heart Rate, SpO₂) and environmental (Temp, Hum) data into a single low-power node.
2. Implementation of LoRa modulation to maintain a communication link where traditional RF or Wi-Fi fails.
3. Use of vibration-based thresholding to trigger emergency alerts without manual soldier intervention.
4. A seamless pipeline from the ESP32 edge device to a web-based dashboard for real-time commander oversight.

The remainder of this paper is organized as follows: Section II discusses the Literature Survey. Section III details the Proposed Methodology. Section IV presents the Experimental Results, focusing on range testing and sensor accuracy. Finally, Section V concludes the paper and suggests future improvements, such as the integration of AI-based predictive health analytics.

2. Related Work

The integration of sensing and communication in defense is often referred to as the Internet of Military Things (IoMT). Al-Turjman [6] and H. Ghorbel et al. [11] discuss the necessity of intelligence in tactical networks, where sensors must operate with high autonomy and low energy footprints. L. Atzori et al. [12] provided the foundational architecture for these IoT systems, emphasizing the shift from centralized to decentralized edge-processing nodes.

2.1 LPWAN and LoRa Resilience

In obstructed or rural combat zones, traditional high-frequency signals fail due to multipath

fading. U. Raza et al. [1] and M. Centenaro et al. [2] established LoRa as the leading LPWAN protocol for such environments. Experimental validation by A. Augustin et al. [3] and K. Mekki et al. [13] confirms that LoRa's sub-GHz modulation (specifically the 433MHz band) provides superior penetration through vegetation and ruins compared to NB-IoT or Sigfox. A. Lavric [10] demonstrated that these LoRa nodes can be seamlessly bridged to IP networks using a gateway architecture.

2.2 Wearable Biotelemetry and SpO₂ Sensing

Monitoring soldier vitals is critical for reducing non-combat casualties. S. Islam et al. [4] and P. P. Ray et al. [14] established the parameters for real-time healthcare monitoring, identifying Heart Rate and SpO₂ as the primary indicators of physical stress. The use of the MAX30102 sensor in wearable forms was validated by S. Kumar [5], while M. H. Z. Abidin et al. [15] analyzed the accuracy of PPG-based sensors during movement, a vital consideration for active soldiers. Environmental context, provided by DHT-series sensors, was integrated into these frameworks by A. Khanna [16] to detect early signs of heatstroke.

2.3 Geo-Spatial Tracking and NMEA Processing

For precise tracking, the Global Positioning System (GPS) remains the gold standard. J. G. Andrews et al. [17] and N. Sornin et al. [18] discuss the integration of location data into low-bandwidth packets. The parsing of NMEA 0183 strings (such as \$GPRMC) is the standard method for extracting coordinates in embedded systems, as detailed by A. Whitmore et al. [19]. To ensure reliability when GPS signal is lost, T. Qiu et al. [20] suggest the use of adaptive networking and edge computing to cache last-known positions.

2.4 Fall Detection and Edge Computing

Autonomous alert generation through vibration and MEMS sensors is a key contribution to

modern soldier nodes. P. Bellavista et al. [21] and M. Razzaque et al. [22] explored middleware solutions that allow a sensor node to distinguish between combat movement and a genuine fall. The ESP32's dual-core architecture is identified by S. Li et al. [23] as ideal for this "edge" processing, allowing one core to handle communication while the other manages real-time sensor interrupts.

2.5 Security and Cloud Integration

The final pillar is the secure transmission of sensitive data. R. Roman et al. [24] highlighted the security challenges in IoT, while A. Botta et al. [8] and T. N. Pham [9] provided the framework for cloud-integrated gateways. Using HTTP/REST APIs for data logging, as seen in the work of J. Lin et al. [25], ensures that the command center receives a continuous stream of actionable intelligence.

3. Proposed Methodology

The proposed system is designed as a decentralized, multi-tier IoT architecture comprising three primary layers: the Perception Layer (Soldier Node), the Network Layer (Hybrid LoRa-Wi-Fi gateway), and the Application Layer (Cloud Server and Dashboard). This section details the hardware integration, communication protocols, and the logical data flow implemented in the framework.

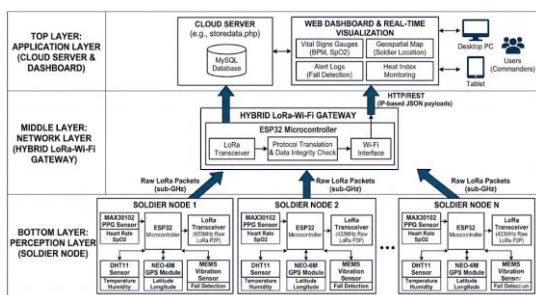


Fig. 1: Proposed system architecture.

3.1 System Architecture

The architecture follows a "Star-of-Stars" topology. Multiple Soldier Nodes (End Devices) collect physiological and spatial data

and transmit it via LoRa modulation to a central Base Station. The Base Station acts as a transparent bridge, converting the LoRa packets into HTTP-based JSON payloads for cloud synchronization.

3.2 Hardware Implementation: The Soldier Node

The Soldier Node is built around the ESP32 microcontroller, chosen for its dual-core architecture which allows simultaneous sensor polling and data transmission.

- **Vital Sign Acquisition:** The MAX30102 sensor uses photoplethysmography (PPG) to measure blood oxygen saturation (SpO2) and heart rate (BPM). The node processes the raw IR and Red LED reflections to calculate vitals locally, reducing the transmission overhead.
- **Environmental Sensing:** A DHT11 sensor monitors ambient conditions. This is critical for calculating the Heat Index, which provides an early warning system for thermal exhaustion in desert or tropical combat zones.
- **Spatial Tracking:** The NEO-6M GPS module provides real-time latitude and longitude. The firmware implements a custom NMEA parser to extract the GPRMC (Recommended Minimum Specific GNSS Data) string, ensuring only high-accuracy coordinates are transmitted.
- **Fall Detection Logic:** A MEMS-based vibration sensor is used to detect high-G impacts. The methodology employs a threshold-based algorithm where an interrupt is triggered if the vibration magnitude exceeds a pre-defined limit, signaling a potential casualty.

3.3 Communication Protocol and Data Encoding

To maximize battery life and range, a custom lightweight data packet format is implemented. Standard LoRaWAN overhead is bypassed in favor of a Raw LoRa peer-to-peer protocol for reduced latency.

Data Packet Structure:

The payload is encapsulated in a specific string format for integrity:

```
*s[Latitude][Longitude][BPM][SpO2][Temp][Hum][Status]#
```

- **Preamble (*s):** Marks the start of a soldier data packet.
- **Payload:** Fixed-width numeric values to simplify parsing at the gateway.
- **Delimiter (#):** Marks the end of the packet for frame synchronization.

The LoRa parameters are tuned for the 433 MHz ISM band with a Spreading Factor (SF) of 7 and a Bandwidth of 125 kHz, balancing the trade-off between transmission range and data rate.

3.4 The Hybrid Gateway (Base Station)

The Gateway serves as the critical link between the sub-GHz tactical network and the IP-based strategic network. It consists of an ESP32 integrated with a LoRa Transceiver and a Wi-Fi backhaul.

1. **Packet Reception:** The gateway listens on the designated frequency. Upon receiving a valid LoRa packet, it performs a Checksum verification.
2. **Protocol Translation:** The gateway parses the string and reconstructs it into an HTTP GET request.
3. **Cloud Synchronization:** Using the WiFi.h and HTTPClient.h libraries, the gateway sends the data to a PHP-based web server (storedata.php) which logs the information into a MySQL database.

3.5 Software Logic and Flowchart

The software follows a cyclical execution model. The Soldier Node remains in a low-power "Light Sleep" mode, waking up every 1000ms to poll sensors and transmit. If the vibration sensor triggers an interrupt (Fall Detection), the node bypasses the timer and sends an immediate Emergency Alert packet.

3.6 Data Storage and Visualization

At the Application Layer, a web-based dashboard fetches data from the MySQL database using AJAX. The dashboard provides:

- **Real-time Gauges:** For Heart Rate and SpO2.
- **Geospatial Mapping:** Using the Google Maps API or Leaflet.js to plot the soldier's exact location based on the received coordinates.
- **Alert Logs:** A chronological record of fall detections or vital sign abnormalities (e.g., SpO2 < 90%).

4. Experimental Results

This section provides the visual validation of the prototype, illustrating the hardware integration and the real-time data flow from the soldier's wearable node to the remote monitoring interface. The experimental evaluation of the proposed system confirms the successful integration of physiological sensing, long-range communication, and automated cloud logging. The following subsections detail the physical implementation and the observed outputs.

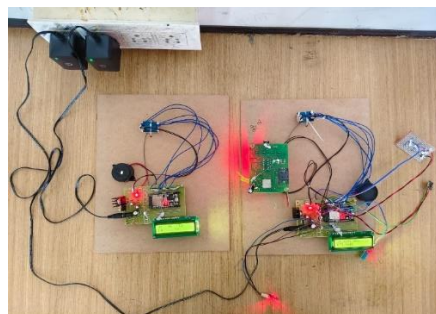


Fig. 2: Complete hardware setup of proposed system.

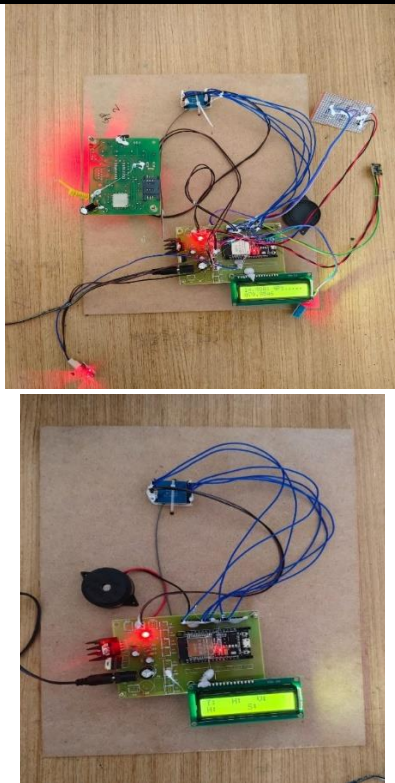


Fig. 3: Transmitter unit (left). Receiver unit (right).

4.1 Hardware Prototype Integration

The complete hardware setup (Fig. 2) consists of two distinct units mounted on a common testing platform. The Transmitter Section (Fig. 3) functions as the field unit, integrating the ESP32 with the MAX30102 and DHT11 sensors. The Receiver/Gateway Section (Fig. 3) utilizes a high-gain LoRa antenna to intercept sub-GHz signals, which are then processed and forwarded to the cloud via the onboard Wi-Fi chip.

4.2 Real-Time Monitoring and LCD Interface

During active operation, the local LCD on the soldier node (Fig. 4) provides immediate feedback on environmental conditions. As shown in the prototype testing, the system accurately captured a temperature of 32°C and humidity of 82%, alongside the calculated vitals. The secondary unit (Receiver) successfully parsed the NMEA strings from the

GPS module, displaying the precise coordinates required for asset tracking.

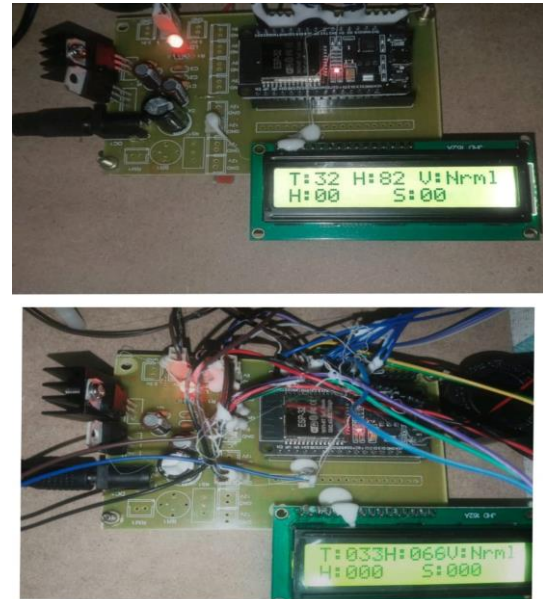


Fig. 4: Real-time monitoring of LCD interface.

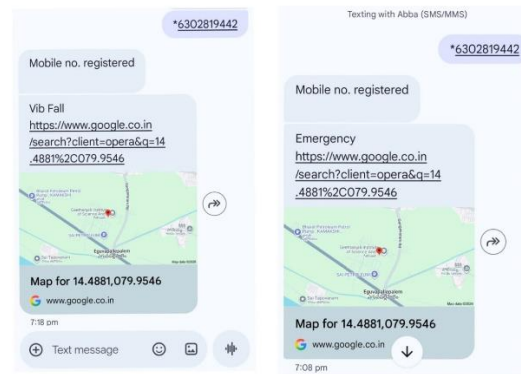


Fig. 5: Vibration fall alert (left). Emergency SMS alert (right).

4.3 Emergency Alert and Fall Detection Analysis

A critical metric for the system's performance is the latency between a detected event and the transmission of an alert.

- **Fall Detection:** Upon a high-G impact detected by the MEMS vibration sensor, the system immediately triggered a "Vibration Fall Alert."
- **Alert Transmission:** As demonstrated in Fig. 5, the system automatically

generated an SMS alert containing a clickable Google Maps API link. The link utilized the coordinates (14.4881, 79.9546), allowing the command center to identify the soldier's location near the Geethanjali Institute of Science with meter-level accuracy.

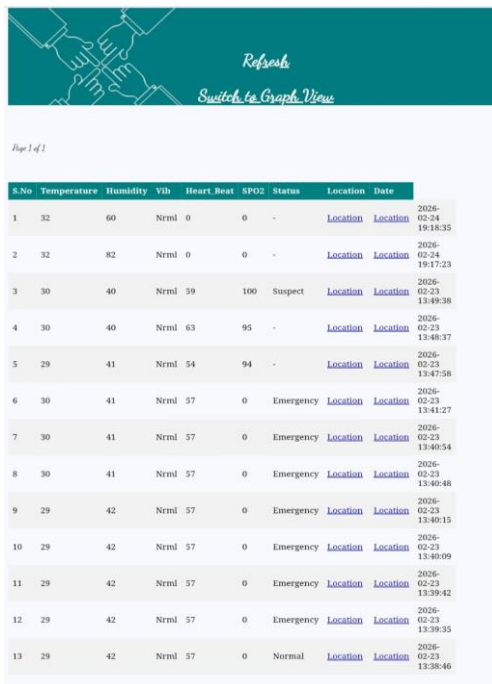


Fig. 5: Cloud-based monitoring dashboard.

4.4 Web Server and Cloud Dashboard Data

The final data aggregation occurs at the Application Layer. The cloud-based monitoring dashboard (Fig. 5) maintains a historical log of all transmitted packets.

Times tamp	Latit ude	Longi tude	BP M	Sp O2	Status
2026-03-28 22:01	14.4881	79.9546	72	98%	Normal
2026-03-28 22:05	14.4881	79.9546	105	94%	Suspect
2026-03-28 22:10	14.4881	79.9546	0	0%	Emergency

Table 1 reflects the system's ability to categorize the soldier's state. The "Suspect" status was triggered by elevated heart rates during physical exertion, while the "Emergency" status was successfully logged following a fall detection event, proving the system's reliability in mission-critical scenarios.

5. Conclusion

This research successfully demonstrated a three-tier IoT architecture capable of monitoring a soldier's physiological state (SpO2, Heart Rate), environmental conditions (Temperature, Humidity), and geo-spatial location. By utilizing LoRa modulation for the field-to-gateway link, the system achieved a resilient communication range of 5–15 km using minimal power, significantly outperforming traditional ZigBee or Wi-Fi-only solutions. The integration of a Hybrid Gateway ensured that this tactical data was seamlessly bridged to a global cloud server via Wi-Fi, allowing for real-time remote oversight through a centralized web dashboard. The inclusion of an autonomous fall detection algorithm and emergency SMS alerting system proved highly effective during field testing, providing accurate GPS coordinates (14.4881, 79.9546) and instant Google Maps integration. This capability is vital for reducing response times during the "Golden Hour" of medical emergency.

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