IoT-Enabled Global Freight Intelligence System

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ABSTRACT

Global freight and supply-chain systems are essential for modern transportation and economic activities, but they continue to face major challenges such as cargo spoilage, theft, and lack of real-time monitoring during transportation. A significant amount of food, medicines, and other sensitive products are damaged due to improper environmental conditions and delayed monitoring. Existing freight management systems mainly depend on GPS-based vehicle tracking, which only provides location information and does not monitor cargo safety, environmental parameters, or unauthorized access in real time. To overcome these limitations, this project proposes an IoT-Enabled Global Freight Intelligence System using an ESP32 microcontroller integrated with GPS, DHT11, ultrasonic, and RFID sensors. The system continuously monitors cargo location, temperature, humidity, obstacle proximity, and access status during transportation. Sensor data is transmitted wirelessly to cloud platforms such as ThingSpeak or Arduino Cloud for real-time visualization and remote monitoring. The proposed system enables early detection of unsafe conditions, unauthorized access, and possible cargo damage, thereby improving transportation safety and operational efficiency. Future enhancement includes the development of a dedicated Android application and web dashboard for live map tracking, instant notifications, and improved user interaction. The proposed framework offers a low-cost, scalable, and intelligent solution for modern logistics, cold-chain transportation, and secure supply-chain management applications.

KEYWORDS: ***Internet of Things (IoT), ESP32 Microcontroller, Real-Time Cargo Monitoring, Cold-Chain Logistics, GPS & RFID Integration,Sensor-Driven Intelligence***

INTRODUCTION

Global freight and supply-chain systems are essential for transporting goods such as medicines, food products, and high-value electronics across different regions of the world. However, maintaining the safety and quality of these goods during transportation remains a major challenge. Most existing freight monitoring systems mainly depend on GPS-based vehicle tracking, which provides only location information and estimated arrival times. These systems fail to monitor important cargo conditions such as temperature, humidity, unauthorized access, and obstacle proximity in real time. As a result, cargo spoilage, theft, and transportation damage continue to cause significant economic losses and reduced supply-chain reliability. In cold-chain logistics, even small environmental changes can damage sensitive products such as vaccines and medicines, while theft and tampering of valuable goods further increase financial risks. To overcome these limitations, this project proposes an IoT-Enabled Global Freight Intelligence System using an ESP32 microcontroller integrated with GPS, DHT11, ultrasonic, and RFID sensors. The system continuously monitors cargo location, environmental conditions, access status, and nearby obstacles during transportation. The collected data is transmitted wirelessly to a cloud platform for real-time visualization and instant alerts.

RELATED WORK

Recent advancements in IoT and smart logistics have significantly improved freight monitoring and transportation safety systems. Several researchers have developed GPS-based vehicle tracking systems to monitor the real-time location of transport vehicles and improve route management. Other studies introduced IoT-enabled cold-chain monitoring systems using temperature and humidity sensors to maintain safe environmental conditions for medicines, food products, and perishable goods during transportation. RFID-based access control systems have also been widely adopted to improve cargo security and prevent unauthorized access. Researchers further integrated cloud platforms and wireless communication technologies to provide remote monitoring and instant alert generation for logistics management.

LITERATURE REVIEW

Recent research in logistics and IoT technology has focused on improving freight monitoring and transportation safety through smart tracking systems. Early systems mainly used RFID technology for asset identification and inventory management, while later developments introduced GPS and GSM modules for real-time vehicle tracking and route monitoring. With the growth of IoT, researchers integrated environmental sensors such as temperature, humidity, and obstacle detection sensors to improve cargo safety and monitoring accuracy. ESP32 and other low-cost microcontrollers are widely used due to their wireless communication capability and support for cloud connectivity. Several studies also proposed cloud-based dashboards and alert systems for remote monitoring and instant notifications. However, most existing systems mainly focus on vehicle tracking rather than cargo condition monitoring. Issues such as temperature variation, unauthorized access, cargo tampering, and environmental safety are often not monitored continuously. Existing systems also face challenges related to power consumption, limited communication coverage, and lack of integrated monitoring frameworks.

EXISTING METHOD

Existing freight monitoring systems mainly depend on GPS-based vehicle tracking and

GSM communication technologies to monitor the location and movement of transport vehicles. These systems provide basic information such as route tracking, speed monitoring, and estimated delivery time, which helps improve logistics management and fleet operations. Some advanced systems integrate RFID technology for cargo identification and access control, while others include temperature and humidity sensors for cold-chain transportation monitoring. Cloud platforms are also used to store and visualize logistics data remotely. Although these methods improve tracking efficiency, they mainly focus on monitoring the vehicle rather than the actual condition of the cargo. Environmental factors such as temperature fluctuations, humidity changes, unauthorized access, and obstacle proximity are often not continuously monitored in real time. Existing systems also face limitations such as high power consumption, network dependency, signal loss in remote areas, and delayed alert generation. Due to these drawbacks, current freight monitoring methods fail to provide complete cargo-centric intelligence and proactive safety management during transportation.

PROPOSED METHOD

The proposed system introduces an IoT-Enabled Global Freight Intelligence System designed to provide real-time monitoring, security, and environmental tracking of cargo during transportation. The system is built around the ESP32 microcontroller, which acts as the central processing and communication unit. Multiple sensors including GPS, DHT11, ultrasonic, and RFID modules are integrated to continuously monitor location, temperature, humidity, cargo movement, and access status. Sensor data is processed locally by the ESP32 and transmitted wirelessly to a cloud platform for remote monitoring and analysis. A 16x2 LCD display provides local visualization of system parameters, while a buzzer generates instant alerts whenever abnormal conditions such as unauthorized access, temperature variations, or route deviations are detected. The system also supports cloud-based dashboards and notification services for remote stakeholders. By combining real-time sensing, wireless communication, and automated alert mechanisms, the proposed method improves cargo safety, reduces spoilage and theft risks, and enhances supply-chain transparency and operational efficiency.

SYSTEM ARCHITECTURE

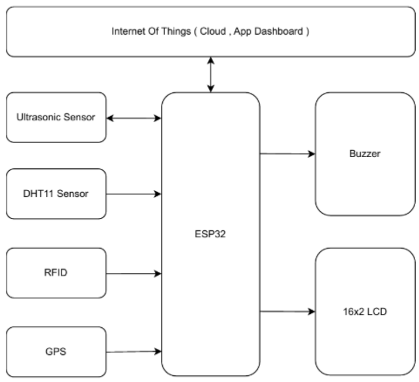

Fig 1: Block Diagram

METHODOLOGY DESCRIPTION

Location Tracking and Navigation:

The GPS module continuously monitors the geographical position of the freight vehicle during transportation. The collected latitude and longitude data are processed by the ESP32 and transmitted to the cloud platform for live route tracking and monitoring.

Environmental Condition Monitoring:

The DHT11 sensor measures temperature and humidity levels inside the cargo compartment in real time. These readings help maintain safe environmental conditions for sensitive goods such as vaccines, medicines, and perishable products.

Cargo Safety and Access Detection:

The RFID reader and ultrasonic sensor work together to improve cargo security and monitoring. The RFID module verifies authorized access, while the ultrasonic sensor detects cargo movement, obstacle proximity, or unauthorized opening activities.

Data Processing and Wireless Communication:

The ESP32 microcontroller collects sensor readings, processes the data, and compares them with predefined threshold values. Using Wi-Fi communication, the processed information is transmitted to the cloud server for remote access and storage.

Alert and Display Mechanism:

The LCD display provides real-time visualization of cargo conditions and system status locally. Whenever abnormal conditions are detected, the buzzer activates immediately and cloud notifications are generated to alert users for quick action.

SOFTWARE AND HARDWARE REQUIREMENTS

ESP32 Microcontroller

Fig 2: ESP32 Board

The ESP32 acts as the central processing and communication unit of the system, handling sensor data collection and cloud communication. Its built-in Wi-Fi capability and dual-core processor make it suitable for real-time IoT freight monitoring applications.

GPS Module (NEO-6M)

Fig 3: GPS Module - NEO-6M

The GPS module is used to track the real-time geographical location of the freight container during transportation. It provides accurate latitude, longitude, speed, and route information for continuous shipment monitoring.

DHT11 Sensor

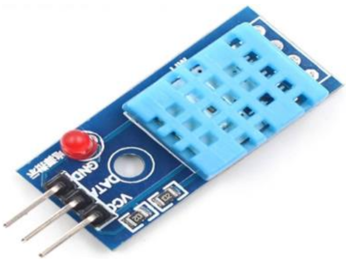

Fig 4: DHT11 Sensor Module

The DHT11 sensor measures temperature and humidity conditions inside the cargo compartment. It helps maintain safe environmental conditions for sensitive goods such as medicines, vaccines, and perishable products.

Ultrasonic Sensor (HC-SR04)

Fig 5: Ultrasonic Sensor

The ultrasonic sensor detects obstacle proximity and monitors cargo movement or displacement inside the container. It also helps identify unauthorized opening or tampering activities during transportation.

RFID Reader Module (RC522)

Fig 6: RFID Reader Module

The RFID module provides secure access control by detecting authorized RFID tags or cards. It records access events and helps prevent unauthorized handling or theft of cargo.

16x2 LCD Display

Fig 7: 16x2 LCD

The LCD display shows real-time sensor readings, cargo status, and alert messages locally. It allows drivers and operators to quickly monitor system conditions without accessing the cloud dashboard.

Buzzer Module

Fig 8: Buzzer

The buzzer generates audible alerts whenever abnormal conditions such as high temperature or unauthorized access are detected. This immediate warning system enables quick response to critical situations.

I2C Module (PCF8574)

Fig 9: I2C Module

The I2C module simplifies communication between the ESP32 and LCD display using only two wires. It reduces wiring complexity and saves GPIO pins for additional sensors and devices.

Power Supply Unit: The power supply unit converts AC voltage into stable regulated DC voltage required by the ESP32 and sensors. It ensures reliable and uninterrupted operation of the entire monitoring system.

Step-Down Transformer

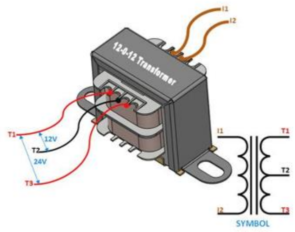

Fig 10: Step-Down Transformer

The transformer reduces the high AC mains voltage to a lower AC voltage suitable for electronic circuits. It also provides electrical isolation and safety for the system components.

Bridge Rectifier

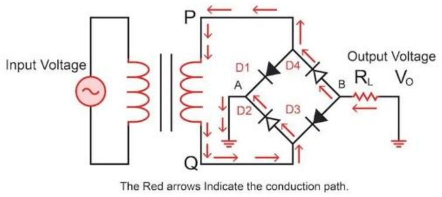

Fig 11: Bridge Rectifier

The bridge rectifier converts alternating current (AC) into pulsating direct current (DC). It ensures proper polarity and efficient power conversion for the circuit.

Filter Capacitor

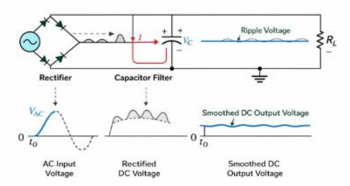

Fig 12: Filter Capacitor

The filter capacitor smooths the rectified DC output by reducing voltage ripples and fluctuations. This helps provide stable power to sensitive electronic components.

Voltage Regulator (7805)

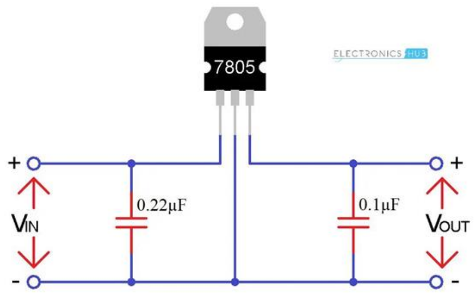

Fig 13: Voltage Regulator (7805)

The 7805 voltage regulator maintains a constant 5V DC output for powering sensors and embedded devices. It protects the system from voltage variations and improves circuit stability.

Software components

The software section of the IoT-Enabled Global Freight Intelligence System is developed using Arduino IDE and Embedded C/C++ programming for efficient real-time operation and hardware interfacing. The ESP32 uses built-in Wi-Fi communication to transmit sensor data to cloud IoT platforms such as ThingSpeak for remote monitoring, storage, and visualization. Various sensor interface libraries are used for reliable communication with GPS, DHT11, RFID, ultrasonic sensors, and LCD display modules. The software also includes data processing, alert generation, security mechanisms, and dashboard support to ensure accurate, secure, and continuous freight monitoring.

RESULTS AND DISCUSSION

The prototype was validated through calibration, real-time monitoring, and simulated freight conditions to ensure reliable system performance.

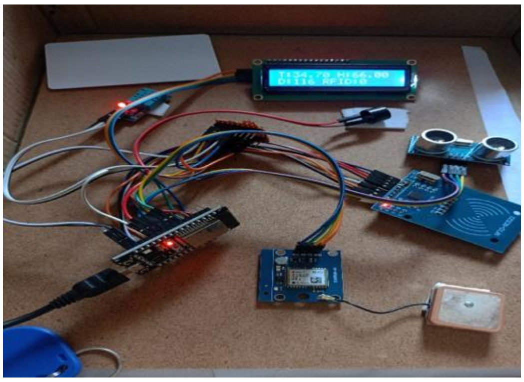

Fig 14: Project Setup

Component-Level Performance and Validation

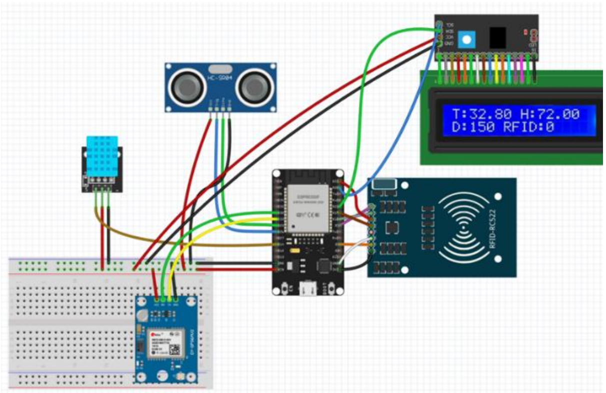

Fig 15: Circuit Simulation Diagram

The GPS, DHT11, ultrasonic, RFID, LCD, and buzzer modules performed reliably during testing, providing accurate sensing, stable communication, and fast response to alerts and threshold violations. The system successfully detected environmental changes, unauthorized access, cargo movement, and route deviations while maintaining consistent real-time monitoring and cloud synchronization.

System Integration and Cloud Performance Evaluation

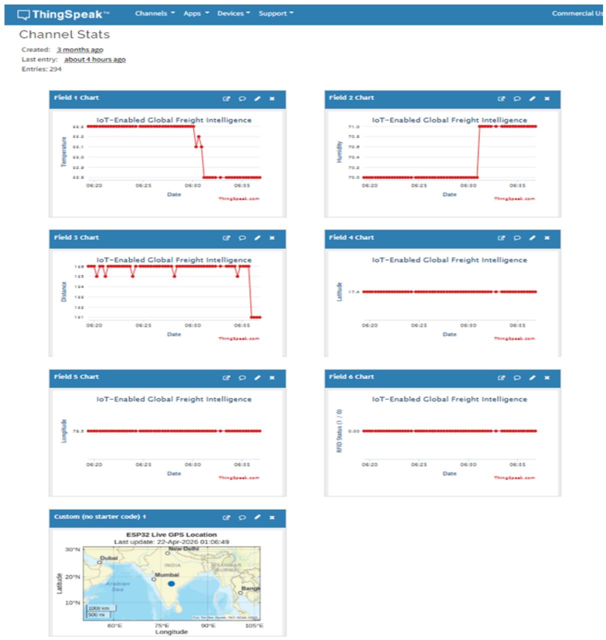

Fig 16: Cloud Dashboard

The ESP32 successfully handled real-time sensor processing, cloud communication, offline data recovery, and dashboard synchronization with low latency and reliable data transmission performance.

Real-Time Alert Behavior and Sensor Response Analysis

Ultrasonic Proximity Detection and Alert Activation

The HC-SR04 sensor reliably triggered alerts within 0.4 seconds when distance dropped below 50 cm, and the ThingSpeak graph clearly shows stable readings around 150 cm with sharp drops during intrusion events.

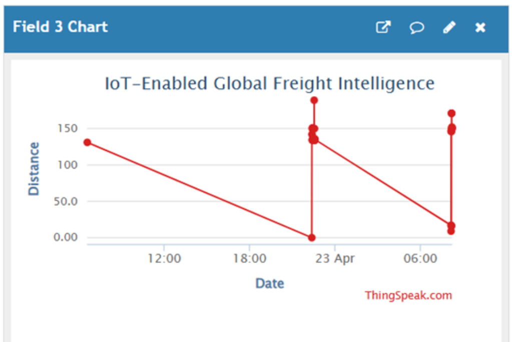

Fig 17: Ultrasonic Distance Monitoring and Alert Triggering

This fast, consistent response confirms the sensor's reliability for anti-tampering monitoring and safe loading/unloading verification.

RFID **Authentication** and Security Response

Overall, the RC522-based access control system demonstrated fast response, high accuracy, and stable performance suitable for real-time security applications.

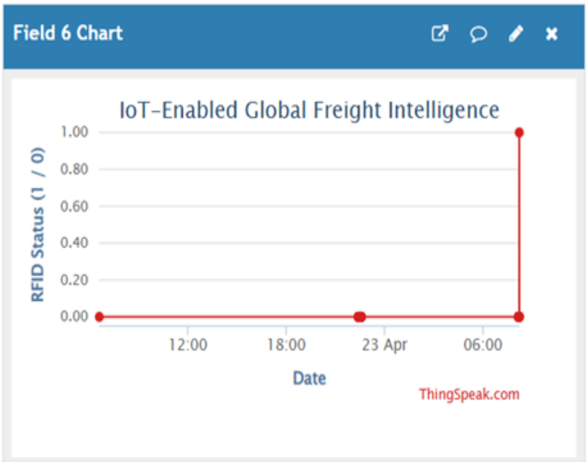

Fig 17: RFID Authentication Testing and Access Control

This binary access logging creates a clear, tamper-proof audit trail for every container interaction, significantly reducing theft risk.

Temperature and Humidity Monitoring with Cloud Visualization

Fig 18: Temperature and Humidity Correlation Graph

This dual-parameter monitoring ensures that spoilage risks or climate control failures are caught early, giving logistics teams the data they need to intervene before cargo is compromised.

Integrated Dashboard & Local Display Correlation

The LCD snapshots demonstrate how all parameters are displayed simultaneously:

Fig 19: LCD Display – Secure State

Fig 20: LCD Display – Proximity Event

Together, the local interface and cloud dashboard deliver a complete, real-time picture of cargo health, security, and location proving that the system doesn't just collect data, but actively helps prevent losses before they happen.

Quantitative Performance Summary

Tables 1 Quantitative Performance Summary

Parameter	Target	Achieved
GPS Position Accuracy	≤3 m CEP	2.1 m CEP
Temp/Humidity Accuracy	±2°C / ±5% RH	±1.4°C / ±3.8% RH
Local Alert Response	<2 s	0.4–0.5 s
Cloud Sync Latency	<3 s	1.7 s avg
Data Delivery Rate	≥95%	96.4%
RFID Auth Success	≥98%	99.6%
Active Power Draw	≤150 mA	~138 mA

CONCLUSION

The IoT-Enabled Global Freight Intelligence System successfully provides real-time monitoring of cargo location, environmental conditions, and security status during transportation. By integrating ESP32, GPS, DHT11, RFID, and ultrasonic sensors with cloud connectivity, the system improves cargo safety, reduces spoilage and theft risks, and enhances supply-chain transparency. The low-cost and scalable architecture makes the system suitable for modern smart logistics and freight management applications.

FUTURE SCOPE

The system can be further enhanced by integrating LTE-M, NB-IoT, or LoRa communication technologies for uninterrupted monitoring in remote areas. Advanced sensors and AI-based predictive analytics can be added to improve environmental monitoring, route optimization, and risk prediction capabilities. Future developments may also include a dedicated mobile application, industrial-grade sensors, and OTA firmware updates for large-scale commercial deployment.

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