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IOT based Cold Chain Monitoring System for Biological Transport

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Abstract: *The transportation of temperature-sensitive biological products such as vaccines, insulin, blood samples, monoclonal antibodies, and recombinant proteins requires strict environmental control throughout the supply chain. Any deviation from the recommended temperature range may reduce product effectiveness and lead to serious public health risks and financial losses. Conventional cold chain monitoring systems mainly depend on manual inspection and passive data logging, which are unable to provide real-time monitoring and immediate corrective action during transportation. To overcome these limitations, this paper proposes an Internet of Things (IoT)-Based Cold Chain Monitoring System for Biological Transport using the ESP8266 NodeMCU microcontroller. The proposed system integrates DHT11 temperature and humidity sensors, a NEO-6M GPS module, relay-controlled cooling fan, L298N motor driver, and cloud-based monitoring dashboard to ensure continuous supervision of biological products during transport.*

Keywords: IoT, Cold Chain Monitoring, Biological Transport, ESP8266 NodeMCU, GPS Tracking, Temperature Control, Smart Healthcare Logistics

I. INTRODUCTION

The safe transportation of temperature-sensitive biological products has become one of the most important challenges in modern healthcare and pharmaceutical logistics. Products such as vaccines, insulin, blood plasma, monoclonal antibodies, recombinant proteins, and laboratory reagents require carefully controlled environmental conditions during storage and transportation to maintain their therapeutic effectiveness and chemical stability. Most biological products must be preserved within a temperature range of 2°C to 8°C throughout the entire supply chain process, from manufacturing facilities to healthcare centers and end users. Even small temperature fluctuations can cause irreversible degradation, reduced potency, contamination risks, and complete product failure [1].

Traditional cold chain systems mainly depend on manual temperature recording methods, mechanical thermometers, and passive data loggers. Although these techniques provide basic monitoring capabilities, they suffer from several limitations such as delayed detection of temperature deviations, lack of real-time supervision, absence of remote accessibility, and increased dependence on human intervention. In many cases, temperature excursions are identified only after transportation is completed, when corrective action is no longer possible. This results in significant financial losses, medicine wastage, and potential threats to public health [2].

With the rapid advancement of Internet of Things (IoT) technology, intelligent monitoring systems have emerged as an effective solution for improving cold chain management. IoT-based systems combine environmental sensors, microcontrollers, wireless communication modules, cloud computing, and automation technologies to provide continuous monitoring and real-time data transmission. [3].

Several researchers have proposed IoT-enabled cold chain systems for pharmaceutical and healthcare applications. Sensor-based monitoring platforms using ESP8266 and cloud dashboards have demonstrated improved visibility and remote accessibility compared to traditional approaches [4]. Wireless Sensor Network (WSN) architectures and LoRa-based communication systems have also been explored to extend monitoring coverage in remote areas [5].

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Additionally, advanced technologies such as edge computing, machine learning, and blockchain have been introduced to improve predictive analysis, data integrity, and supply chain transparency [6]. However, many of these solutions focus mainly on monitoring and alert generation while lacking integrated automated control mechanisms for maintaining safe environmental conditions.

Another major challenge in biological transport systems is the absence of continuous location tracking and active temperature regulation during transit. In long-distance transportation, refrigeration system failures or environmental changes can occur unexpectedly, especially in rural and infrastructure-limited regions. Without real-time corrective action, biological products may become ineffective before reaching their destination [7].

To address these challenges, this paper proposes an IoT-Based Cold Chain Monitoring System for Biological Transport using the ESP8266 NodeMCU microcontroller. The proposed system integrates DHT11 temperature and humidity sensors, NEO-6M GPS module, relay-controlled cooling fan, and cloud-based monitoring dashboard to ensure safe transportation of biological products. [8]

II. PROBLEM STATEMENT

The transportation of biological and pharmaceutical products such as vaccines, insulin, blood plasma, and laboratory samples requires strict temperature control throughout the supply chain. These products are highly sensitive to environmental conditions, and even small temperature variations can reduce their effectiveness, damage their chemical composition, or make them unsafe for medical use. Maintaining the required temperature range during transportation is therefore a critical requirement in healthcare logistics.

III. OBJECTIVES

- To develop an IoT-based cold chain monitoring system for safe transportation of biological products.
- To continuously monitor temperature and humidity conditions in real time using digital sensors.
- To implement automated alert and cooling control mechanisms during temperature deviations.
- To integrate GPS tracking and cloud-based remote monitoring for improved supply chain visibility.
- To provide secure data logging and regulatory compliance for pharmaceutical and healthcare applications.

IV. LITERATURE SURVEY

1. Author (0975 – 8887): Kanchan Meena , Tushar Kanti

Title: A Review Of Exposure And Avoidance Techniques **An IoT-based Cargo Monitoring System for Enhancing Operational Effectiveness under a Cold Chain Environment**

Authors:

Y. P. Tsang, K. L. Choy, C. H. Wu, G. T. S. Ho, H. Y. Lam, and P. S. Koo

Summary:

This paper presents an Internet of Things (IoT)-based cargo monitoring system designed to improve operational efficiency in cold chain transportation environments. The authors focused on the transportation of temperature-sensitive products such as pharmaceuticals, food items, and biological materials that require strict environmental control during transit. The proposed system integrates wireless sensors, RFID technology, cloud computing, and real-time communication networks to continuously monitor environmental conditions such as temperature and humidity inside refrigerated containers. The collected data is transmitted to a cloud platform where logistics operators can remotely supervise cargo conditions through a web-based dashboard. The system also supports real-time alerts whenever abnormal environmental conditions are detected, allowing immediate corrective action to prevent spoilage or product degradation. Experimental analysis showed that the system improved supply chain transparency, reduced manual monitoring efforts, and enhanced operational reliability. The research demonstrated that IoT technologies can significantly improve cold chain logistics by enabling continuous tracking, remote accessibility, and automated environmental supervision.

Internet of Things Enabled Real Time Cold Chain Monitoring in a Container Port

Authors: Ahmet Yunus Cil, Dini Abdurahman, and Ibrahim Cil

Summary:

This research proposed a real-time cold chain monitoring system for refrigerated containers operating within port logistics environments. The system was designed using IoT technology, environmental sensors, GSM communication, and cloud-based databases to continuously supervise storage conditions of temperature-sensitive cargo. The authors highlighted the importance of maintaining stable environmental conditions during transportation and storage, especially for pharmaceutical products, vaccines, and perishable goods. The proposed architecture continuously measures temperature and humidity values using digital sensors and uploads the data to a cloud platform through wireless communication modules. The system also provides real-time notifications through SMS alerts and dashboard visualization whenever temperature values exceed predefined limits. GPS-based location monitoring was incorporated to improve transportation visibility and logistics management. The authors concluded that the proposed IoT-enabled system improved monitoring accuracy, reduced product spoilage, minimized human intervention, and enhanced operational efficiency in container-based cold chain logistics systems.

Research on Real-Time Localization and Environmental Monitoring Using Sensors and ZigBee for Cold Chain System

Authors: Changsoo Lee, Daewon Jung, and Keun-Wang Lee

Summary:

In this paper, the authors introduced a wireless sensor network-based cold chain monitoring system using ZigBee communication technology for real-time environmental monitoring and localization. The proposed system was developed to maintain the quality and safety of temperature-sensitive products during transportation and storage. Multiple sensor nodes were deployed within refrigerated transportation units to continuously measure temperature, humidity, and environmental conditions. The ZigBee communication protocol enabled low-power wireless data transmission between sensor nodes and the central monitoring station. The system also incorporated localization capabilities to track the position of transported goods in real time. Environmental data collected from sensors was analyzed to detect abnormal conditions and generate alerts when threshold values were exceeded. The research emphasized that wireless sensor networks improve monitoring coverage, reduce wiring complexity, and increase system flexibility. However, the authors also identified challenges related to communication range limitations, network reliability, and power consumption in large-scale transportation systems.

Real-Time Anomaly Detection in Cold Chain Transportation Using IoT Technology

Authors:

James Gillespie, Tamíris Pacheco da Costa, Xavier Cama-Moncunill, Trevor Cadden, Joan Condell, Robert Gallagher, and Ramakrishnan Ramanathan

Summary:

This paper focused on the development of a real-time anomaly detection system for cold chain transportation using IoT technologies and intelligent monitoring techniques. The authors proposed a smart monitoring framework capable of identifying refrigeration failures, abnormal temperature variations, and transportation risks during cold chain operations. The system used temperature probes, wireless communication modules, cloud computing, and real-time analytics to continuously supervise environmental conditions within refrigerated transport units. Data collected from sensors was processed using anomaly detection algorithms capable of recognizing unusual patterns before critical failures occurred. The system generated automated notifications and visual alerts whenever abnormal conditions were detected, allowing logistics operators to take preventive actions immediately. Experimental results showed that the proposed solution significantly reduced product spoilage, improved transportation reliability, and enhanced cold chain safety. The authors concluded that IoT-based anomaly detection systems can improve decision-making, predictive maintenance, and overall efficiency in pharmaceutical and healthcare logistics.

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Comparison Table

Sr No	Title	Authors	Summary
1	IoT-based Cargo Monitoring System	Y. P. Tsang et al.	IoT system for monitoring temperature-sensitive cargo in cold chain transport.
2	Real Time Cold Chain Monitoring in Container Port	Ahmet Yunus Cil et al.	Real-time monitoring using sensors, GPS, and cloud technology.
3	Real-Time Localization and Monitoring Using ZigBee	Changsoo Lee et al.	ZigBee-based system for environmental monitoring and tracking.
4	Real-Time Anomaly Detection in Cold Chain Transportation	James Gillespie et al.	IoT system for detecting abnormal temperature conditions during transport.

IV. WORKING OF SYSTEM

(a) Perception Layer

The Perception Layer is the first layer of the system and is responsible for collecting real-time environmental data. In this layer, different sensors such as temperature sensors, humidity sensors, accelerometers, and GPS modules continuously monitor the condition of the cold chain environment. These sensors are connected to the IoT logger, which gathers all sensor readings and prepares the data for transmission. This layer acts as the sensing unit of the entire monitoring system.

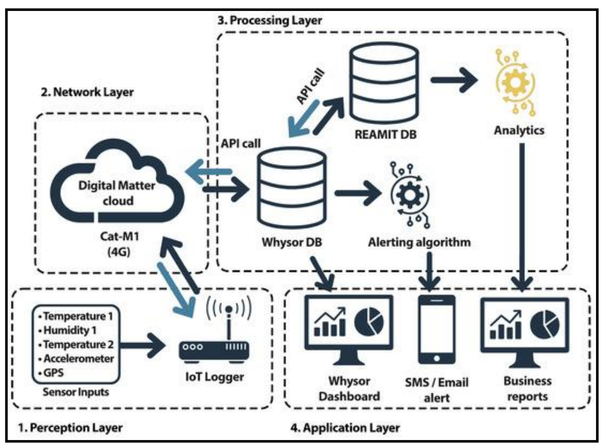

Fig 1: Block Diagram

(b) Network Layer

The Network Layer is responsible for transferring the collected sensor data from the IoT logger to the cloud platform. In the diagram, Cat-M1 (4G) communication technology is used for wireless data transmission through the Digital Matter cloud. This layer ensures secure and continuous communication between the sensing devices and the cloud server. It enables remote connectivity and real-time monitoring during transportation.

(c) Processing Layer

The Processing Layer performs data storage, analysis, and intelligent decision-making. The received data is stored in databases such as REAMIT DB and Whysor DB through API calls. After storing the data, analytics and alerting algorithms process the information to identify abnormal conditions such as temperature deviations or environmental failures. This layer forms the intelligence section of the system by converting raw sensor data into meaningful information.

(d) Database and Analytics Section

This section manages the storage and analytical processing of all collected cold chain data. The databases securely maintain historical environmental records, GPS information, and transportation details. The analytics engine examines the stored data to generate reports, detect anomalies, and improve operational efficiency. It also supports predictive monitoring and decision-making for cold chain management.

(e) Alerting System

The alerting system is designed to provide immediate notifications whenever abnormal environmental conditions are detected. The alerting algorithm continuously compares sensor values with predefined threshold limits. If the temperature or humidity exceeds the safe range, the system automatically sends SMS or email alerts to operators or administrators. This helps in taking quick corrective action and reduces the risk of product spoilage.

(f) Application Layer

The Application Layer is the final layer where users can access monitoring information through dashboards and reports. It includes the Whysor Dashboard, SMS/Email alert interface, and Business Reports section. This layer allows users to remotely monitor temperature, humidity, GPS location, and transportation conditions using computers or smartphones. It provides real-time visualization, historical data analysis, and operational reporting for effective cold chain management.

V. SYSTEM DESIGN

A.System Architecture

The proposed system is organized into four integrated functional layers that together form an end-to-end cold chain monitoring and controlling architecture. The Sensing Layer comprises the DHT11 temperature-humidity sensor and the NEO- 6M GPS module, which continuously acquire environmental and positional data at defined sampling intervals. The Processing and Control Layer is realized by the ESP8266 NodeMCU, which manages data acquisition, threshold comparison, automated relay switching, and web server hosting. The Actuation Layer includes the relay module for cooling fan control and the L298N motor driver for DC gear motor control. The Communication and Visualization Layer encompasses the onboard Wi-Fi HTTP server and the browser-accessible real-time dashboard.

B.Hardware Components

ESP8266 NodeMCU serves as the central processing and IoT communication unit. Based on the Espressif ESP8266 chip with Tensilica L106 32-bit RISC core operating at 80 MHz, it integrates 11 digital GPIO pins, one 10-bit ADC, and built-in IEEE 802.11 b/g/n Wi-Fi. The device supports HTTP, MQTT, and TCP/UDP communication protocols, enabling it to host a web server and transmit sensor data without requiring a separate Wi-Fi module.

DHT11 Temperature and Humidity Sensor provides digital readings of ambient temperature (0–50°C range, ±2°C accuracy) and relative humidity (20–90% RH, ±5% accuracy) through a single-wire interface. The cooling activation threshold is set at 28°C in the proposed system.

c) System Algorithm

Upon power-on, the ESP8266 initializes all GPIO pins, starts the DHT11 sensor library, activates the SoftwareSerial UART interface for GPS communication, and establishes a Wi-Fi connection to the configured network. Once connected, the device obtains an IP address and launches the HTTP web server on port 80. The main loop executes the following cycle continuously: (1) Read temperature and humidity from DHT11; replace invalid NaN readings with zero. (2) Parse any available GPS NMEA sentences from the SoftwareSerial buffer using the TinyGPS++ library; update latitude and longitude if a valid fix is obtained. (3) Evaluate automatic cooling logic — if temperature exceeds 28°C and auto mode is enabled, assert relay pin HIGH to activate the cooling fan; if temperature falls below 20°C, deactivate the relay. (4) Service any pending HTTP client requests from the web dashboard. The web server handles nine distinct endpoint routes: root HTML dashboard, JSON data feed, vehicle directional commands (forward, reverse, left, right, stop), fan manual on/off, fan state query, and auto-mode toggle.

VI. RESULTS

A. Temperature Monitoring and Automated Cooling Control

The proposed IoT-based cold chain monitoring system successfully monitored temperature conditions in real time using the DHT11 sensor. During testing, the sensor continuously measured environmental temperature inside the storage chamber and transmitted the readings to the ESP8266 microcontroller. The observed temperature readings remained stable and reliable throughout the experiment. When the temperature exceeded the predefined threshold value of 28°C, the ESP8266 automatically activated the relay module, which switched ON the cooling fan within a short response time. The cooling mechanism gradually reduced the internal chamber temperature and maintained it within the safe operating range required for biological transport. Once the temperature dropped below the predefined recovery level, the relay automatically deactivated the cooling fan, preventing unnecessary power consumption and excessive relay switching. The system also supported manual fan control through the cloud dashboard, allowing users to turn the fan ON or OFF remotely whenever required. Automatic mode and manual override mode operated successfully without communication interruption, confirming reliable automated cooling control and intelligent temperature regulation.

B. Humidity Monitoring

The DHT11 sensor continuously monitored relative humidity inside the cold storage chamber and transmitted the humidity readings to the cloud platform along with temperature data. During testing, humidity values were updated at regular intervals and displayed successfully on the monitoring dashboard without delay. The recorded humidity values varied according to environmental conditions and remained stable throughout the monitoring process. The system demonstrated reliable communication between the sensor and the ESP8266 microcontroller using a single-wire digital interface. The cloud dashboard successfully visualized humidity readings in real time, enabling continuous environmental supervision for biological product transportation.

C. GPS Location Tracking

The NEO-6M GPS module successfully provided real-time location tracking during system operation. The module acquired satellite signals and transmitted latitude and longitude coordinates to the ESP8266 through UART serial communication. The GPS data was processed and uploaded to the cloud dashboard, where the transportation location was displayed continuously. During testing, the system accurately tracked movement and updated location information in real time. In situations where satellite signals were temporarily unavailable, the system retained the previously recorded valid coordinates to maintain uninterrupted dashboard operation. The embedded map interface displayed live transportation routes, and the generated location links enabled direct access to Google Maps for easy verification and monitoring. The successful integration of GPS tracking improved transportation visibility, supply chain transparency, and remote supervision capabilities of the proposed cold chain monitoring system.

D. Web Dashboard and Remote Monitoring

The proposed system successfully implemented a web-based dashboard for real-time monitoring and remote accessibility. The ESP8266 NodeMCU hosted the complete monitoring dashboard internally, eliminating the requirement for a separate external server for dashboard operation. The dashboard was accessed successfully through desktop computers, laptops, and smartphones using standard web browsers. Real-time temperature, humidity, and GPS location data were displayed continuously with automatic refresh functionality at regular intervals. Graphical visualization of environmental conditions was achieved using dynamic line charts, allowing users to observe recent trends in temperature and humidity values. The dashboard also provided control buttons for fan operation and vehicle movement, which responded accurately to user commands. During testing, multiple devices accessed the dashboard simultaneously without communication failure or performance degradation, confirming stable remote monitoring capability and cross-platform compatibility.

E. Vehicle Motion Control

The vehicle movement control system operated successfully using the L298N motor driver and ESP8266 microcontroller. The dashboard provided directional control options including forward, reverse, left, right, and stop functions. Whenever a user selected a command through the dashboard interface, the ESP8266 received the

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corresponding HTTP request and executed the motion command immediately. The motor driver controlled the DC motors smoothly without unwanted interruptions or unstable movement. During operation, motor control functions worked simultaneously with temperature monitoring, GPS tracking, and cloud communication without affecting overall system performance. The system demonstrated reliable multi-task operation, confirming that the ESP8266 could effectively handle environmental monitoring, remote communication, and vehicle control within a single integrated IoT platform.

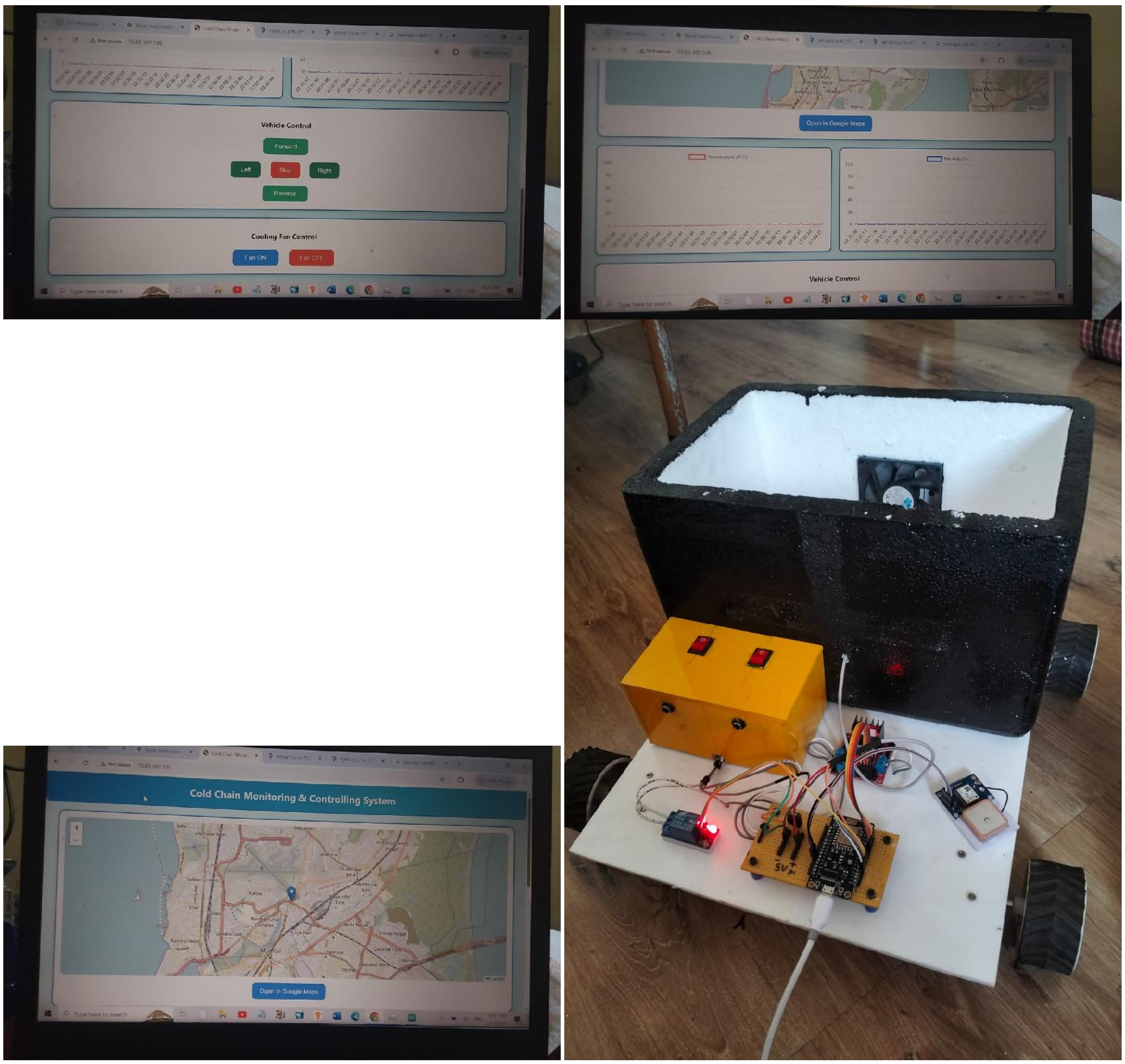

Fig 2: Project Model Snapshots

VIII. FUTURE SCOPE

The proposed IoT-based cold chain monitoring system can be further enhanced by integrating advanced communication, automation, and intelligent monitoring technologies. One important improvement is the addition of a SIM800L GSM/GPRS module to provide backup communication during transportation in remote areas where Wi-Fi connectivity may not be available. This enhancement would enable the system to transmit SMS alerts and environmental data continuously, improving reliability during long-distance transport operations.

Future versions of the system can also upgrade the existing ESP8266 microcontroller to the ESP32 dual-core controller. The ESP32 offers improved processing capability, multiple ADC channels, Bluetooth support, and better multitasking performance, making it more suitable for handling high-frequency sensor sampling and simultaneous cloud communication. In addition, the communication protocol can be upgraded from HTTP to MQTT to reduce transmission delay, minimize bandwidth consumption, and improve compatibility with industrial IoT platforms.

IX. CONCLUSION

This paper presented the design, implementation, and experimental validation of an IoT-Based Cold Chain Monitoring and Controlling System utilizing the ESP8266 NodeMCU microcontroller. The system successfully achieved all defined design objectives: autonomous threshold-triggered cooling activation via relay-based fan control, continuous realtime temperature and humidity monitoring using the DHT11 sensor, live GPS-based location tracking during transportation using the NEO-6M module, and a self-hosted browser-accessible dashboard providing live sensor visualization, directional vehicle control, and dual-mode fan management. Experimental results confirmed reliable automated cooling response within approximately 800 milliseconds of threshold breach, stable dashboard operation with 3-second data refresh rates, accurate GPS coordinate acquisition and map display, and correct vehicle motion control execution. The complete prototype was realized at an estimated cost of Rs. 3,060– 5,520 — demonstrating that intelligent, active cold chain management does not require expensive proprietary infrastructure.

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