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Smart Cold Chain Monitoring System for Vaccines and Medicines

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***Abstract*— Temperature-sensitive medical products such as vaccines, insulin, blood products and certain medicines require controlled environmental conditions during transportation and storage. Conventional cold-chain monitoring often depends on manual inspection and may not identify temperature excursions, excessive vibration, unauthorized access or location deviations in real time. This paper presents the design of an AI-based smart cold-chain monitoring system for vaccines and medicines. The proposed system integrates temperature and humidity monitoring, shock and tilt detection, GPS-based location tracking, GSM-based communication, active cooling control, cloud monitoring, OTP-based access security and alert generation in a compact medicine transport box. An ESP32 microcontroller processes the sensor data, controls the cooling system and transmits information to a cloud dashboard and mobile application. A proposed Medicine Health Score combines environmental and transportation conditions into a single engineering-level monitoring indicator on a 0–100 scale. Because calibrated experimental measurements and prototype test logs were not available at the time of writing, this paper presents the system design, the underlying equations and the expected outcomes rather than measured performance results.**

Keywords: Cold Chain Monitoring, Vaccines, Medicines, IoT, ESP32, GPS Tracking, GSM, Temperature Monitoring, Medicine Health Score, Smart Medicine Box.

I. INTRODUCTION

Vaccines and temperature-sensitive medicines must be stored and transported within their specified environmental limits to preserve their intended quality. Temperature excursions, prolonged exposure to unsuitable conditions, physical shocks and delayed delivery can each increase the risk of product damage. The World Health Organization recommends continuous temperature monitoring of the vaccine supply chain because a single end-point reading cannot reveal what happened during transit [5].

Conventional cold-chain systems commonly use manual temperature checking or basic data loggers. Such methods may not provide immediate information about abnormal conditions during transportation, and a problem is often discovered only after the shipment has been inspected.

Recent IoT-based cold-chain systems have improved monitoring by combining sensors, embedded controllers, wireless communication, cloud platforms and mobile applications. IoT-enabled vaccine cold-chain frameworks emphasize continuous monitoring, device authentication and improved traceability [1], while blockchain-assisted IoT architectures have been proposed to secure pharmaceutical temperature records [2]. Low-cost microcontroller prototypes have shown that real-time vaccine cold-chain monitoring is feasible with commodity components [4], [6], and temperature-only alert systems have been demonstrated for vaccination containers [7].

The AI-Based Smart Cold Chain Monitoring System is designed to monitor temperature, humidity, shock, tilt, location, battery condition and unauthorized access during medicine transportation. A microcontroller-based design collects the sensor data, controls the cooling unit, activates alerts and transmits information to a cloud dashboard and mobile application.

The main objective is to provide a compact and low-cost monitoring solution that gives users more useful information than a conventional temperature logger. The proposed Medicine Health Score is intended as an engineering-level condition indicator. It must not be interpreted as a validated measure of vaccine potency or medicine safety without product-specific stability data and pharmaceutical validation.

II. AIMS & OBJECTIVES

Aim:

The main aim of this project is to develop an AI-based smart cold-chain monitoring system that continuously observes the environmental and transportation conditions of vaccines and medicines and provides real-time alerts during unsafe conditions.

Objectives:

- To monitor the temperature inside the medicine transport box continuously.
- To measure humidity, shock, vibration and tilt during transportation.
- To track the real-time location of the medicine box using GPS.
- To control the cooling mechanism according to the configured temperature range.
- To display important system information on an LCD or OLED display.
- To generate local alerts through a buzzer during unsafe operating conditions.
- To send alerts and sensor data using GSM/LTE or Bluetooth communication.
- To provide OTP-based security for authorized access to the medicine box.
- To record the duration of temperature excursions outside the configured range.
- To calculate a proposed Medicine Health Score based on the monitored conditions.
- To provide data access through a mobile application and cloud dashboard.
- To reduce dependence on manual monitoring during medicine transportation.

III. LITERATURE SURVEY

1. **Conventional Cold Chain Monitoring:** Traditional cold-chain monitoring records temperature values manually or through simple data loggers, and can identify a problem only after the shipment is inspected. The WHO guidance on vaccine supply-chain monitoring establishes the need for continuous temperature monitoring across all stages of storage and transport, but it is a guidance document and does not describe an implemented low-cost electronic prototype [5].

2. **IoT-Based Vaccine Cold Chain Frameworks:** Jiang, Jia and Guo developed an IoT-enabled framework for sustainable vaccine cold-chain management that uses sensing devices, cloud monitoring and device authentication to provide continuous monitoring and improved transparency [1]. Hasanat et al. presented a real-time, data-centric vaccine cold-chain monitoring system, although it focuses on storage conditions and gives limited coverage of transportation events such as shock, tilt and location [6].

3. **Blockchain-Assisted Pharmaceutical Monitoring:** Singh, Dwivedi and Srivastava combined IoT temperature sensing with blockchain-based traceability to prevent counterfeit pharmaceuticals [2]. The approach shows the value of secure records, but blockchain increases system complexity and may not be necessary for a low-cost prototype.

4. **Reviews of Monitoring Technologies:** Badia-Melis et al. reviewed monitoring technologies for cold-chain applications, including RFID, wireless sensor networks and IoT solutions, and identified the importance of connected sensing and data access [3]. The review is broad and is not specific to an AI-based medicine-box prototype.

5. **Low-Cost Microcontroller and Alert Systems:** Alshdadi et al. demonstrated an IoT smart systemthat uses low-cost sensors, a microcontroller, cloud monitoring and mobile connectivity for storage and transportation management [4]. Thiyaneswaran proposed an IoT-based temperature monitoring and alert system for vaccination containers [7]. The latter

is limited to temperature monitoring, with no multi-parameter condition assessment or scoring.

6. **Research Gap:** Existing systems commonly focus on temperature monitoring and remote data display. A medicine shipment may also be affected by shock, prolonged tilt, unauthorized access, battery failure, network interruption and route deviation, and raw sensor readings are difficult to interpret quickly during transportation. The proposed project addresses this gap by (i) integrating temperature, humidity, motion, tilt, location, security, battery, cooling and communication functions in one portable system, (ii) recording the transportation history, including the duration of excursions, rather than only instantaneous values, and (iii) introducing a Medicine Health Score that combines multiple parameters into a single indicator. The score supports monitoring and inspection decisions; it is not a substitute for medicine stability testing or pharmaceutical quality-release procedures.

IV. METHODOLOGY

The proposed AI-Based Smart Cold Chain Monitoring System is designed by combining sensing, embedded processing, cooling control, location tracking, communication, security and alert generation in a single medicine transport box. The methodology begins with sensing the conditions inside and around the box, processing the measured information using the ESP32, controlling the cooling unit, and taking appropriate action whenever an unsafe condition is detected.

1. Power Supply and Regulation

The system is powered using a rechargeable battery or a regulated DC supply. A voltage-regulation circuit provides the required supply levels for the microcontroller, sensors, GPS module, GSM module, display, buzzer, relay module and cooling system. A common ground is maintained between all modules for reliable signal communication. The battery voltage is sensed by the microcontroller so that a low-battery condition can be reported before monitoring is interrupted.

2. Temperature and Humidity Monitoring

A digital temperature and humidity sensor (SHT31, or alternatively a K-type thermocouple with a MAX6675 interface) is placed inside the insulated medicine box. The controller compares each measured temperature with configured lower and upper limits. For products requiring refrigerated storage, a 2–8 °C range may be configured only when it matches the manufacturer's authorized storage requirement for the specific medicine or vaccine being transported.

The temperature deviation of sample k from the configured safe range is expressed as:

$$D_{T,k} = \max(0,\ T_{min} - T_k,\ T_k - T_{max}) \qquad (1)$$

where T_k is the measured temperature at sample k, T_{min} and T_{max} are the lower and upper limits, and $D_{T,k}$ is the deviation (in °C). The cumulative excursion time is obtained by summing the durations of consecutive samples for which $D_{T,k} > 0$, which is the quantity recommended by WHO guidance for assessing cold-chain exposure [5].

3. Cooling System Control

The cooling systemconsists of a Peltier module, a cooling fan, a relay driver and the insulated chamber. The ESP32 controls the relay according to the sensed temperature. When the temperature rises above the upper configured limit, the controller activates the cooling system; when it returns to the selected safe range, the cooling system is switched off according to programmed hysteresis logic. Hysteresis prevents rapid relay switching (chattering) near the threshold.

4. Motion, Shock and Tilt Detection

An MPU6050 accelerometer and gyroscope module detects sudden movement, vibration, shock and tilt. The acceleration magnitude at sample k is calculated as:

$$A_k = \sqrt{(a_{x,k}^2 + a_{y,k}^2 + a_{z,k}^2)} \qquad (2)$$

A shock event is registered when:

$$A_k > A_{th} \qquad (3)$$

where A_{th} is the selected shock threshold. Tilt is computed from the accelerometer gravity components. The shock threshold and the tilt limit must be finalized through controlled prototype testing, since appropriate values

depend on the sensor mounting and the sens itivity required.

5. GPS Tracking

A NEO-6M GPS module obtains the latitude and longitude of the medicine box. The location data are sent to a cloud server, web dashboard or mobile application through the GSM/LTE module. GPS tracking allows users to monitor the shipment route and to identify the location where an abnormal event occurs. Optional geofencing can raise an alert when the box leaves an authorized route.

6. OTP-Based Security

The security system uses GSM communication, a keypad and a solenoid lock. A one-time password is generated and sent to an authorized user by SMS. The user enters the OTP through the keypad; if it is correct, the solenoid lock is activated and the box can be opened. If the OTP is incorrect, the boxremains locked and the system activates an alert. This mechanism provides a record of access attempts and deters unauthorized opening during transport.

7. Alert System

The buzzer and display provide local alerts, and remote alerts are sent through GSM/LTE communication to a mobile application or dashboard. Alert conditions include temperature outside the configured range, excessive humidity, sudden shock or vibration, excessive tilt, unauthorized opening attempt, incorrect OTP entry, low battery, loss of communication, and route deviation or geofence violation, if implemented.

8. Medicine Health Score

The proposed Medicine Health Score (MHS) combines several transport conditions into one monitoring indicator ranging from 0 to 100:

$$MHS = 100 - (w_T P_T + w_H P_H + w_S P_S + w_\theta P_\theta + w_D P_D + w_B P_B) \quad (4)$$

where P_T, P_H, P_S, P_θ, P_D and P_B are the temperature-excursion, humidity, shock-event, tilt-event, travel-duration and low-battery/monitoring-interruption penalties, and w_T to w_B are the corresponding weighting factors. Each penalty is normalized so that its maximum contribution is bounded, and the weights are constrained to sum to one. The score decreases when the system detects prolonged temperature excursions, high humidity, severe shock, excessive tilt or monitoring interruption. The weights must be decided through controlled testing and expert review; the score is therefore a proposed rule-based condition indicator, not a clinically validated AI prediction model.

9. Overall System Operation

The complete system operates continuously while the medicine box is in use. The sensors measure the internal and transport conditions, the ESP32 processes the information, controls the cooling unit and calculates the Medicine Health Score, and the data are transmitted to the cloud dashboard and mobile application. If an unsafe condition is detected, the buzzer and remote alerts are activated.

Overall Working Flow

Battery / DC Supply → Voltage Regulator → ESP32 → Cooling Control + Display

Sensors (SHT31, MPU6050, NEO-6M) → ESP32 → Health Score → GSM/LTE → Cloud + Mobile App

Unsafe Condition → ESP32 → Buzzer + SMS Alert

Keypad + OTP → ESP32 → Solenoid Lock

Thus, the methodology combines continuous multi-parameter monitoring, active cooling, location tracking, access control and alert generation in one microcontroller-based smart cold-chain system.

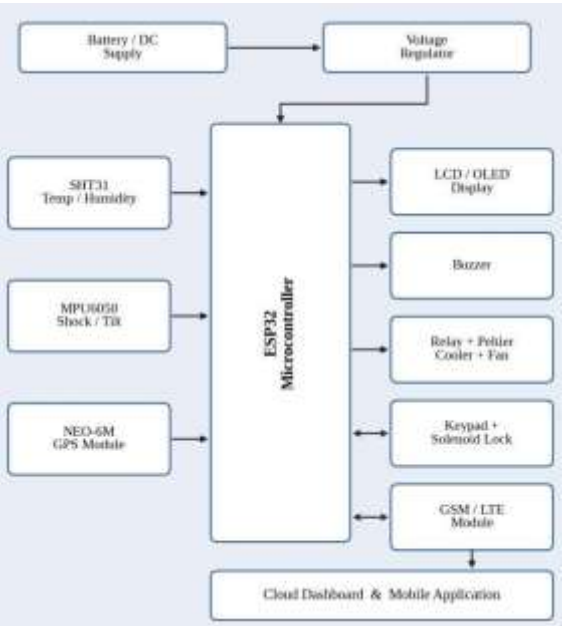


Figure 1: Block Diagram of the proposed system

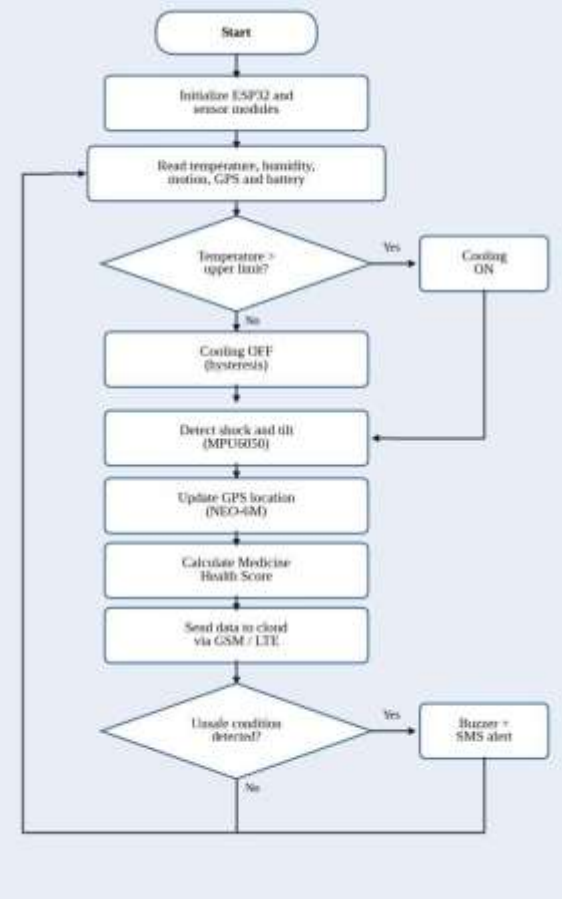


Figure 2: Flowchart of the proposed system

V. RESULTS AND DISCUSSION

No calibrated experimental data, test logs, temperature plots, battery-runtime values, communication-latency measurements or sensor-accuracy measurements were available for this paper. This section therefore presents expected outcomes rather than measured results, and Table I lists the parameters that should be measured on the completed prototype.

The proposed system is expected to monitor the internal temperature of the medicine box continuously and to activate the cooling mechanism when the measured temperature exceeds the selected upper limit. It is also expected to record temperature excursions, shock events, tilt conditions, battery level and location information.

The system should generate an audible warning through the buzzer and transmit a remote notification when an unsafe condition is detected. GPS tracking should allow users to view the location of the medicine box through a mobile application or web dashboard, and the OTP-based security mechanismshould prevent unauthorized opening of the box.

The Medicine Health Score is expected to decrease when adverse transportation events occur, such as prolonged temperature excursions, high shock values, excessive tilt and low-battery conditions. The exact score behavior can only be reported after the weights are defined and controlled testing is completed.

TABLE I

RECOMMENDED EXPERIMENTAL EVALUATION PARAMETERS

Sr.	Parameter	Measurement Method	Purpose
1	Temperature accuracy	Compare with a calibrated reference thermometer	Temperature-sensing reliability
2	Humidity accuracy	Compare with a calibrated hygrometer	Humidity-sensing reliability
3	Excursion detection time	Timebetween excursion and alert	Alert response
4	Cooling response time	Time to return to the selected range	Cooling performance
5	Shock detection	Controlled vibration or impact	MPU6050 event detection
6	Tilt detection	Test at different tilt angles	Tilt-threshold operation
7	GPS update interval	Time between location updates	Tracking performance
8	Alert latency	Delay of buzzer, SMS and dashboard alerts	Communication performance
9	Battery runtime	Continuous operation under defined conditions	Portable operating duration
10	Data-upload success rate	Successful vs. attempted cloud uploads	Communication reliability
11	OTP security response	Test valid and invalid OTP entries	Access-control operation
12	Health Score response	Introduce controlled events; record score change	Score behavior

Recommended graphs: temperature versus time with the lower and upper limits; humidity versus time; Medicine Health Score versus time under normal and deliberately induced abnormal conditions; battery voltage versus time; GPS route map; alert-latency comparison of local (buzzer) and remote (SMS/dashboard) alerts; and a sensor calibration graph of reference versus measured temperature with a linear fit.

Compared with a conventional temperature logger, the added value of the proposed design lies in the combination of multi-parameter recording, active cooling, location tracking, access control and a consolidated condition indicator. However, each added function introduces failure modes; for example, the GPS and GSM modules increase power consumption and network coverage may be interrupted in transit. The design therefore treats

communication loss and low battery as reportable conditions rather than assuming continuous connectivity. The reliability of the Medicine Health Score depends on sensor calibration, sensible penalty definitions and validation of the weighting factors, so it should be read together with the underlying temperature, humidity and event history.

VI. CONCLUSION

The AI-Based Smart Cold Chain Monitoring System provides a practical approach to improving the transportation monitoring of vaccines and medicines by combining temperature sensing, humidity monitoring, cooling control, shock and tilt detection, GPS tracking, GSM communication, OTP-based security, local alerts and cloud-based monitoring around an ESP32 microcontroller. The proposed Medicine Health Score provides a simplified way of representing multiple transport-related conditions through one engineering-level indicator, while the underlying sensor history remains available for inspection.

The system is intended to reduce dependence on manual inspection and to provide faster information when unsafe conditions occur. No numerical claims regarding sensor accuracy, cooling performance, alert latency, battery runtime, communication reliability or Medicine Health Score validity are made in this paper, because controlled prototype testing has not yet been completed.

Future work will focus on sensor calibration, measuring the evaluation parameters of Table I, real transportation trials, validation of the health-score weights, cloud and mobile-application development, and product-specific stability assessment in cooperation with pharmaceutical stakeholders.

PROJECT MODEL



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