IoT-Based Smart Freezer

Abstract

Cold storage systems require continuous monitoring to ensure reliable operation and prevent product spoilage. This paper presents an IoT-based smart freezer monitoring system that integrates real-time sensor data acquisition, cloud storage, anomaly detection, and dashboard visualization. The proposed system monitors critical freezer parameters such as temperature, vibration, power consumption, and door status using an ESP32 microcontroller. Data is transmitted to a cloud platform through Node-RED and stored for analysis. Anomaly detection logic is applied to identify abnormal operating conditions and trigger alerts. Additionally, a camera-based inventory monitoring approach using YOLO object detection is proposed. The system improves operational reliability, supports predictive maintenance, and enhances cold-chain management efficiency.

I. Introduction

Cold storage and freezer systems are widely used in food preservation, pharmaceutical storage, and industrial cold-chain applications. Failures in freezer operation due to temperature deviation, compressor malfunction, power instability, or improper usage can lead to significant economic losses. Traditional monitoring systems lack real-time intelligence and predictive capabilities.

Recent advancements in the Internet of Things (IoT) and machine learning (ML) enable intelligent monitoring and automation of refrigeration systems. This paper proposes an IoT-based freezer monitoring system capable of continuous sensing, real-time alerting, anomaly detection, and cloud-based visualization. The system aims to improve reliability, energy efficiency, and maintenance effectiveness.

II. System Architecture

The proposed system follows a multi-layered architecture, as shown below.

A. Hardware Layer

The hardware layer consists of an ESP32 microcontroller interfaced with multiple sensors including cabinet and evaporator temperature sensors, a vibration sensor for compressor health monitoring, a power and current sensor (INA219), a door status sensor, and an ESP32-CAM module for visual monitoring.

B. Communication Layer

Wi-Fi connectivity is used to transmit sensor data from the ESP32 to the backend server. MQTT and HTTP protocols are employed for efficient and reliable data transfer.

C. Cloud and Processing Layer

Node-RED is used as the central data processing engine to route sensor data, apply anomaly detection logic, and manage alert workflows. Firebase Firestore is utilized for cloud-based data storage and retrieval.

D. Application Layer

A web-based dashboard developed using Node-RED Dashboard 2.0 provides real-time visualization, alert notifications, and system status monitoring.

III. Working Principle

The ESP32 periodically acquires sensor readings and transmits them to the Node-RED server. Incoming data is validated, formatted, and processed in real time. Threshold-based and statistical anomaly detection logic is applied to identify abnormal operating conditions. Processed data is stored in the cloud database and displayed on the dashboard. Alert notifications are triggered when predefined conditions are violated.

IV. Data Collection and Cloud Integration

Sensor data is collected at fixed intervals and timestamped for traceability. Each parameter is stored as an individual field in the cloud database, enabling structured storage and easy data export. The collected dataset can be used for historical analysis, system optimization, and future ML model training.

V. Anomaly Detection Methodology

Anomaly detection is implemented using rule-based and ML-inspired approaches. Temperature anomalies indicate cooling failure or excessive load. Vibration anomalies reflect compressor wear or imbalance. Power consumption deviations suggest electrical faults or inefficiencies. Door open duration analysis identifies improper usage patterns. These methods enable early fault detection and preventive maintenance.

VI. AI-Based Inventory Monitoring

To enhance freezer intelligence, a camera-based inventory monitoring approach is proposed. The ESP32-CAM captures images of stored items, and YOLO object detection is used to identify inventory categories. Although a custom-trained model was not fully implemented, experimental results demonstrate the feasibility of AI-based freezer inventory monitoring.

VII. Dashboard and Alert System

The dashboard displays real-time sensor values, anomaly status indicators, and historical trends. Alert mechanisms notify users during critical events such as temperature violations, excessive vibration, power anomalies, and prolonged door openings. Notifications are delivered through dashboard alerts and email services.

VIII. Testing and Results

The system was tested under normal and abnormal operating conditions. Simulated temperature rise, vibration spikes, door events, and power fluctuations were introduced. The system successfully detected anomalies, triggered alerts, and logged data accurately. The results confirm reliable real-time monitoring and fault detection.

IX. Future Work

Future enhancements include integration of real pressure sensors, deployment of advanced ML models for predictive maintenance, training a custom YOLO model for specific inventory items, edge AI implementation for low-latency inference, and mobile application integration.

X. Conclusion

This paper presented an IoT-based smart freezer monitoring system that combines real-time sensing, cloud integration, anomaly detection, and dashboard visualization. The proposed solution enhances freezer reliability, supports preventive maintenance, and demonstrates the potential of AI-enabled cold-chain monitoring systems.