SYSTEM ARCHITECTURE

The proposed IoT-based smart freezer system follows a layered and modular architecture, designed to ensure scalability, reliability, and explainable control.
The complete system is divided into three tightly coupled layers:

1. Edge IoT Layer – Real-time sensing, control, and safety
2. Cloud IoT Layer – Data management, visualization, and alerts
3. AI / Analytics Layer – Intelligence, prediction, and optimization

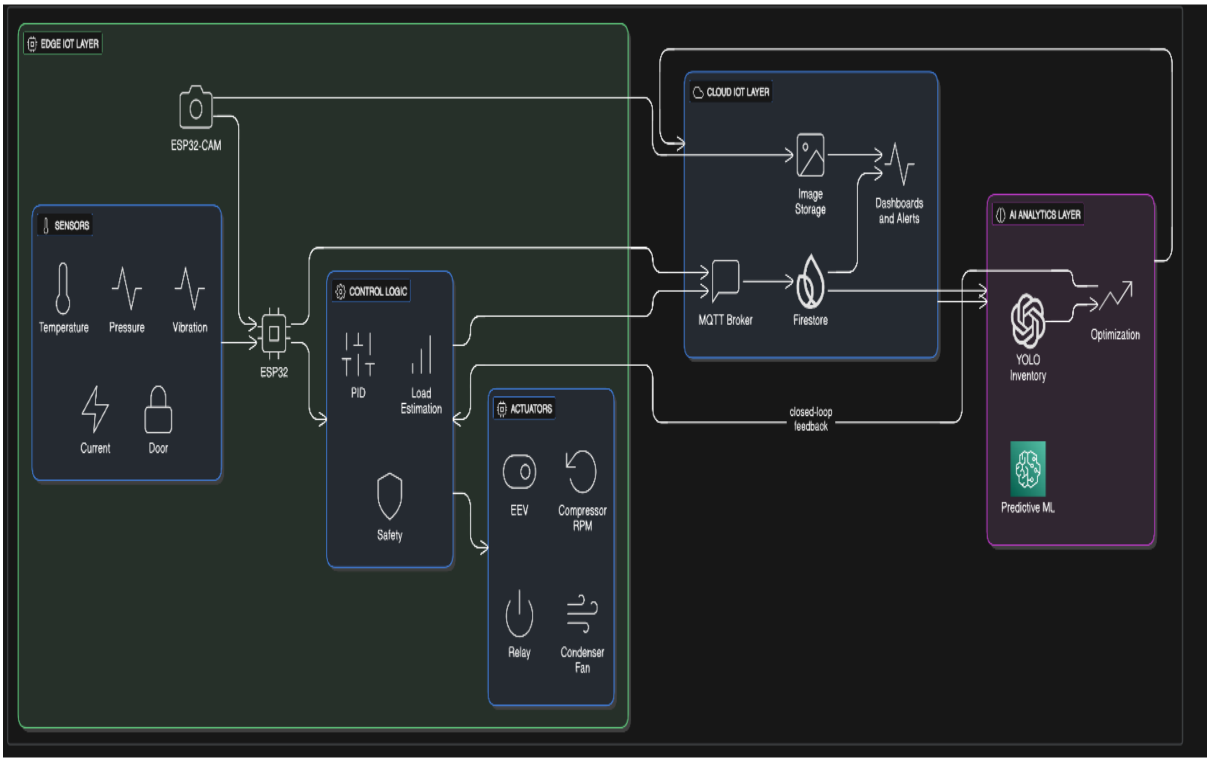
Each layer performs a clearly defined role while continuously interacting with the others through structured data and feedback loops.

Overall System Architecture

The overall architecture represents the **end-to-end flow** from physical freezer operation to intelligent decision-making and back to control execution.

Key Characteristics

- Closed-loop control with cloud and AI feedback
- Separation of real-time control and high-level intelligence
- Safe operation through supervisory monitoring



Edge IoT Layer Architecture (Inside the Freezer)

The Edge IoT Layer is responsible for real-time sensing, control, and safety, and operates independently of cloud connectivity to ensure uninterrupted freezer operation.

Hardware Architecture

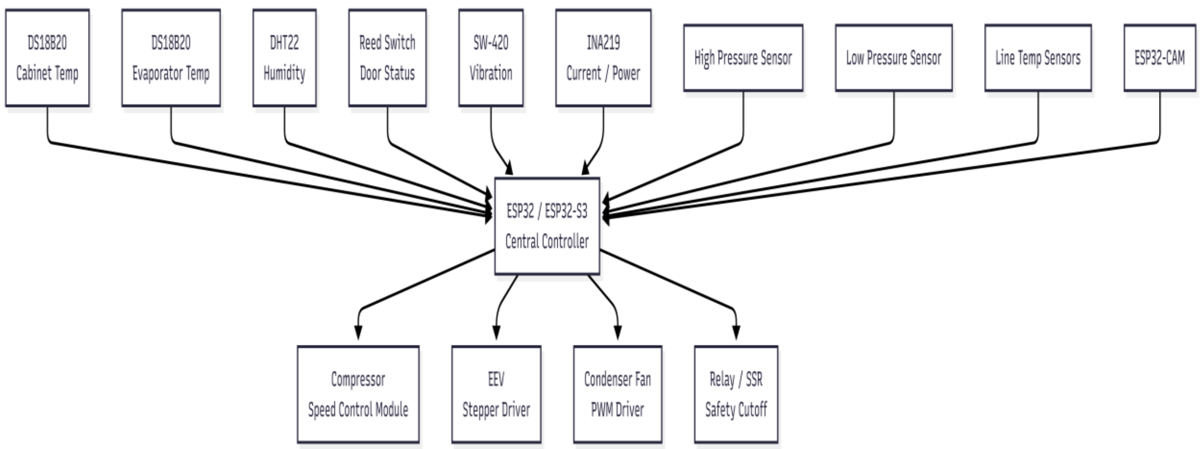
The core controller of the system is an ESP32 / ESP32-S3, interfaced with multiple sensors and actuators to monitor both thermal and mechanical behaviour of the freezer.

Sensors Integrated

- DS18B20 – Cabinet and evaporator temperature sensing
- DHT22 – Internal humidity monitoring
- Reed Switch – Door open/close detection
- SW-420 Vibration Sensor – Mechanical fault detection
- INA219 – Current and power measurement
- High-side & Low-side Pressure Sensors – Refrigeration cycle monitoring
- Line Temperature Sensors – Suction and discharge temperature tracking
- ESP32-CAM – Image capture for inventory detection

Actuators Controlled

- Compressor speed control module (RPM modulation)
- Electronic Expansion Valve (EEV) with stepper driver
- Condenser fan PWM driver
- Relay / SSR for emergency shutdown



Local Control and Safety Functions

The following functions are executed locally on the ESP32 to ensure **low-latency and safe operation**:

- Sensor fusion and data filtering
- PID-based cabinet temperature control
- Load-aware compressor speed control
- Superheat-based EEV modulation
- Door-event based compensation logic
- Safety shutdown during overcurrent, excessive vibration, or pressure faults
- TinyML-based anomaly detection
- Periodic data packaging and cloud upload

This ensures that **core freezer operation does not depend on cloud availability**.

Cloud IoT Layer Architecture

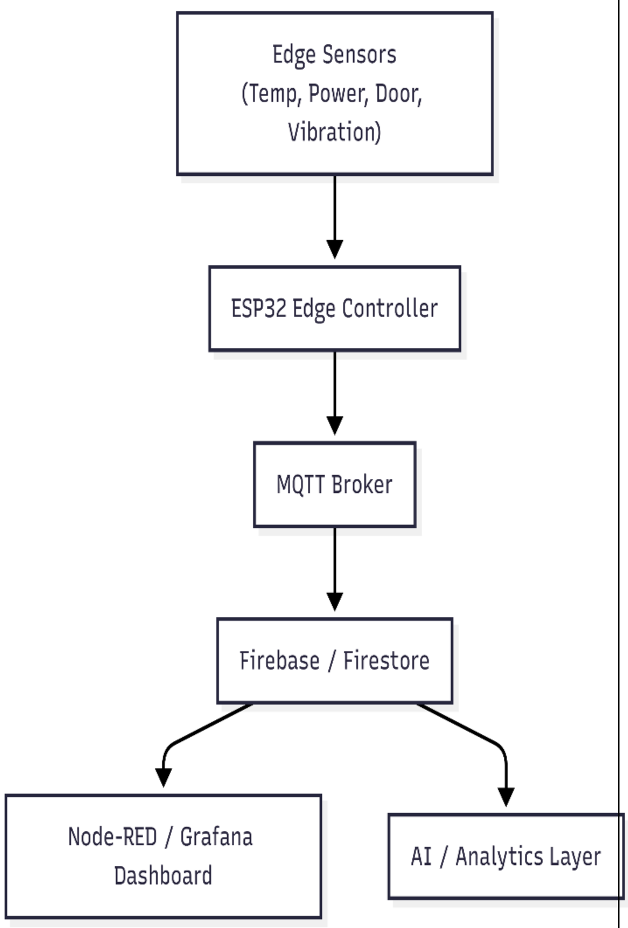
The Cloud IoT Layer acts as the central data hub, enabling monitoring, logging, and remote management.

Platforms Used

- MQTT broker (AWS IoT / Mosquitto / HiveMQ)
- Firebase (Firestore / Realtime Database)
- Cloud Storage for images
- Node-RED / Grafana dashboards

Functions Performed

- Real-time data storage and retrieval
- Dashboard visualization of freezer parameters
- Alert generation (SMS / email / push notifications)
- Multi-freezer monitoring support
- Long-term historical logging
- OTA firmware update support



.

AI and Analytics Layer Architecture

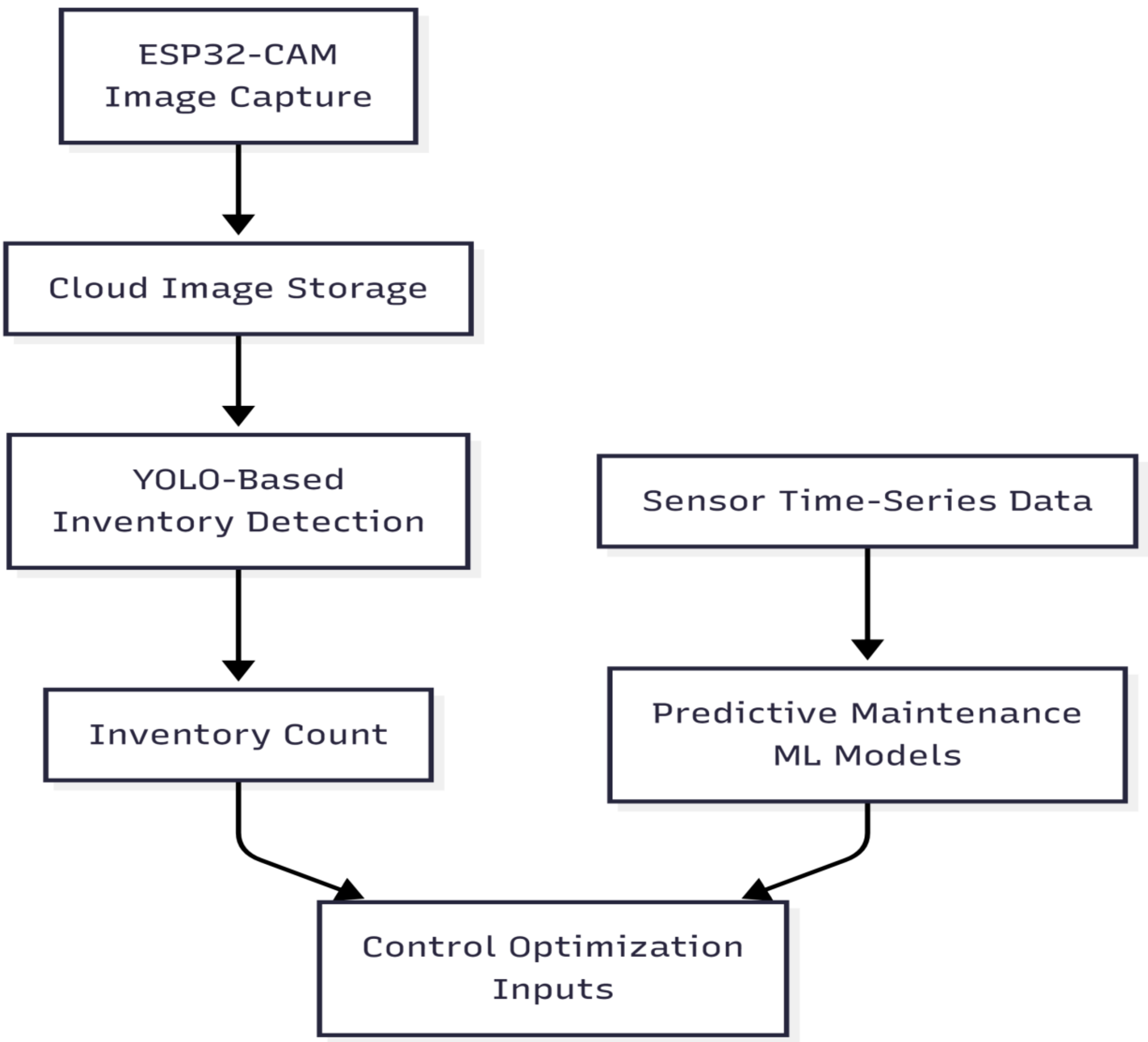
The **AI Layer** provides intelligence to the system and operates asynchronously with real-time control.

Vision-Based Inventory Detection

- Images captured by ESP32-CAM are uploaded to cloud storage
- YOLO-based object detection identifies ice-cream packs
- Inventory count is estimated and stored
- Inventory information is used as an input for load estimation

Predictive Maintenance and Analytics

- Vibration, power, and temperature trends are analyzed
- ML models detect abnormal operating patterns
- Health indicators are generated for the control layer



Load-Aware Control and ML Supervision

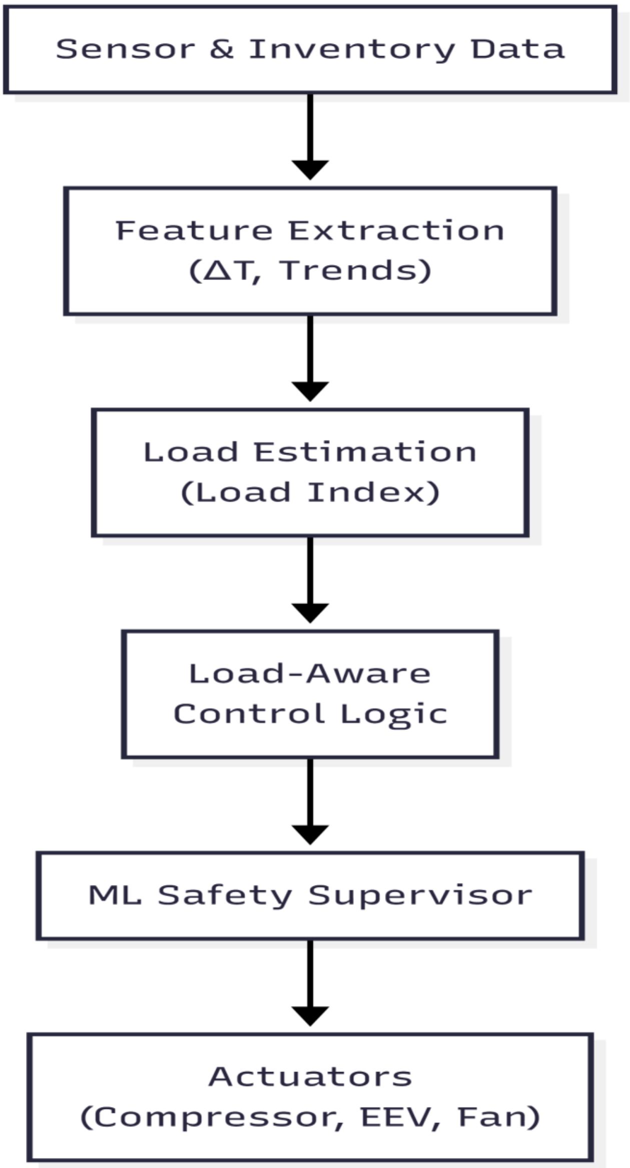
The system employs a hierarchical control strategy:

- Deterministic control logic executes compressor, EEV, and fan control
- Machine learning acts only as a supervisory safety layer

The inferred Load Index, derived from temperature dynamics, power consumption, door events, and inventory data, is used to adapt compressor speed proactively.

ML models:

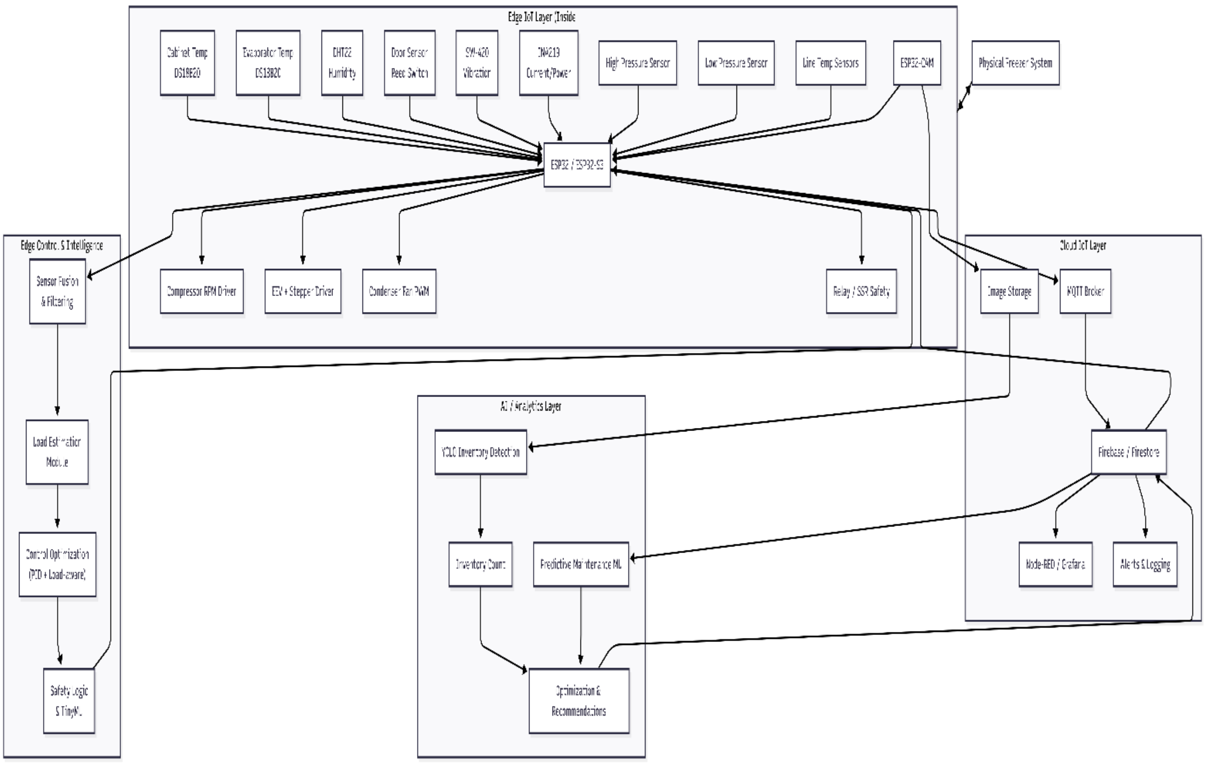
- Detect abnormal mechanical or electrical behaviour
- Restrict aggressive control actions during faults



This shows the hierarchical control architecture of the smart freezer system. Sensor measurements and inventory information are first processed to extract relevant features and estimate the refrigeration load in the form of a Load Index. The load-aware control logic uses this information to determine actuator commands for the compressor, electronic expansion valve, and condenser fan. A machine learning–based safety supervisor continuously monitors system behaviour and constrains control actions during abnormal conditions, ensuring safe and reliable operation.

Architectural Advantages

- Unified architecture combining hardware, control, cloud, and AI
- Explainable load-based control (non black-box)
- Fault-tolerant operation with local autonomy
- Scalable to multiple freezers
- Suitable for commercial and industrial refrigeration systems



In parallel, operational data is transmitted to the cloud for storage, visualization, and alerting, and further analysed by the AI layer for inventory detection and predictive maintenance. The insights generated by the AI layer are fed back through the cloud to the edge controller, enabling adaptive optimization while maintaining deterministic and safe real-time control. This layered, closed-loop architecture ensures energy-efficient, scalable, and reliable freezer operation under varying load conditions.