Project Report On

IoT Based Vehicle Health Monitoring and Driver Alert System

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ABSTRACT

This project details the design and implementation of a sophisticated, real-time embedded system for monitoring vehicle health parameters through a multi-controller architecture The core of the system features an STM32 as the primary microcontroller, running a Real-Time Operating System (RTOS) to ensure deterministic task scheduling and high-speed processing of sensor data. The hardware suite integrates vibration sensors for engine anomaly detection, temperature sensors for thermal management, and ultrasonic sensors for precise fluid level monitoring. To facilitate reliable communication in an automotive environment, the system utilizes the Controller Area Network (CAN) protocol via the MCP2551 transceiver, linking the STM32 to an ESP32 IoT gateway. The ESP32 manages wireless connectivity, securely transmitting processed diagnostic data to AWS Cloud via MQTT. By leveraging AWS's robust infrastructure, the system provides real-time data visualization. This combination of RTOS-based local processing and cloud-scale intelligence creates a fault-tolerant solution for modern vehicle diagnostics, significantly improving passenger safety and vehicle operational lifespan.

Keywords: STM32, ESP32, RTOS, CAN Bus (MCP2551), AWS Cloud, Vibration Sensor, Temperature Sensor, Ultrasonic Sensor, IoT, Vehicle Health Monitoring.

1. INTRODUCTION

The rapid advancement in automotive electronics has created a pressing need for sophisticated data acquisition systems capable of monitoring and analysing various vehicle parameters in real-time. Modern vehicles are becoming increasingly complex with the integration of multiple electronic control units (ECUs), sensors, and actuators that ensure optimal performance, safety, and efficiency. Key operational parameters—such as mechanical vibrations, engine temperature, and fluid levels—must be continuously monitored to ensure the smooth functioning of vehicles and to enable early fault detection before they lead to catastrophic failure.

One of the most reliable and widely adopted communication protocols for such in-vehicle networking is the **Controller Area Network (CAN)** protocol. Developed by Bosch, CAN is a robust serial communication protocol that enables microcontrollers and devices to communicate with each other without the need for a host computer. It supports real-time data exchange and prioritization, making it suitable for critical automotive applications. CAN is particularly favoured for its error detection capabilities, deterministic message delivery, and ability to handle multiple nodes on a single bus, even in environments with high electromagnetic interference.

In this project, we leverage a high-performance dual-controller architecture to build a distributed vehicle monitoring system. An **STM32** serves as the main microcontroller, utilizing a Real-Time Operating System (RTOS) to manage time-critical tasks such as sensor data acquisition and CAN message scheduling. This node is interfaced with a specialized sensor suite including vibration sensors for engine diagnostics, temperature sensors for thermal monitoring, and ultrasonic sensors for fluid level detection. The STM32 communicates over the CAN network using the **MCP2551/2515** transceiver set, ensuring reliable data transfer.

The system integrates an **ESP32** module as an intelligent IoT gateway. The ESP32 receives the processed health metrics from the STM32 via the CAN bus and establishes a secure connection to the **Amazon Web Services (AWS) IoT Core** platform using the MQTT protocol. To ensure system reliability and data integrity, we utilize the **AWS MQTT Test Client** for real-time message verification during the development phase.
The cloud-based setup is designed for comprehensive data management and alerting:

Data Persistence: Structured sensor data is routed to an **Amazon S3 bucket**, providing long-term historical logging and a foundation for big data analytics.

Monitoring and Alarms: Amazon CloudWatch is configured to monitor incoming data streams and create custom alarms based on critical thresholds (e.g., engine overheating or excessive vibration).

Instant Notifications: Upon an alarm trigger, the system leverages the **Amazon Simple Notification Service (SNS)** to automatically push alert emails to maintenance teams, ensuring immediate response to potential faults.

By combining RTOS-based local processing with the scalability of AWS cloud computing, this system enhances the overall transparency and safety of modern transportation. It establishes a practical foundation for predictive maintenance, allowing for automatic fault reporting and smart vehicle analytics that contribute to the development of next-generation vehicular monitoring infrastructures.

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2. LITERATURE SURVEY

Numerous studies have emphasized the importance of real-time data acquisition in modern vehicles to mitigate the risks associated with mechanical failure. Traditional diagnostic methods, while foundational, often lack the flexibility, scalability, and remote access capabilities offered by modern microcontroller-based distributed systems. These legacy systems typically relied on isolated Electronic Control Units (ECUs) with limited memory for data logging and lacked the wireless connectivity required for real-time fleet management.

The introduction of the Controller Area Network (CAN) protocol in the 1980s marked a significant technological leap. CAN's robust features—including multi-master architecture, message prioritization, and advanced error signalling—have made it the global standard for automotive networking. Recent literature highlights the necessity of using high-speed transceivers like the MCP2551 to maintain signal integrity in the electrically noisy environment of a vehicle's engine bay.

Recent research has shifted focus toward the role of the Internet of Things (IoT) and Edge Computing in transforming conventional monitoring into intelligent systems. While many hobbyist applications utilize basic microcontrollers, academic and industrial studies now Favor the STM32 family for primary control due to its superior processing power and ability to host a Real-Time Operating System (RTOS). An RTOS allows for deterministic task scheduling, which is critical when monitoring high-frequency data such as engine vibrations.

The integration of the ESP32 as a secondary gateway has also gained traction. Its dual-core processing and built-in Wi-Fi capabilities make it an ideal bridge between the localized CAN network and industrial-grade cloud platforms. Furthermore, the shift from basic IoT platforms to Amazon Web Services (AWS) IoT Core represents a major trend in the literature. AWS provides enhanced security via mutual TLS authentication, lightweight MQTT messaging, and a suite of integrated services for professional data management:

- Data Storage: Telemetry data is routed to Amazon S3 buckets, enabling the high-capacity, long-term historical logging required for vibration and thermal trend analysis.
- System Monitoring: The AWS MQTT Test Client is utilized for real-time debugging, while Amazon CloudWatch provides continuous monitoring of device metrics and logs.
- Automated Alerting: By configuring CloudWatch Alarms on specific sensor thresholds, the system can automatically trigger Amazon SNS (Simple Notification Service) to dispatch urgent alert emails to maintenance personnel.

Current industry prototypes are increasingly exploring Predictive Maintenance (PdM) models. Studies show that by monitoring key parameters—specifically mechanical vibrations and thermal trends—systems can identify patterns of wear before a component fails. This project fills a critical gap in the existing literature by combining RTOS-managed sensor fusion on an STM32 with professional cloud analytics via the AWS ecosystem, creating a high-fidelity, end-to-end vehicle telemetry platform that prioritizes both local real-time response and remote long-term diagnostics.

3. AIM OF PROJECT

The primary objective of this project is to design, implement, and validate a High-Performance IoT-Based Vehicle Health Monitoring System using a multi-controller architecture. The project aims to bridge the gap between localized automotive sensor networks and professional cloud-based diagnostic platforms to enable Predictive Maintenance.

Key Objectives

- Real-Time Data Acquisition: To develop a robust sensing layer using an STM32 microcontroller to capture high-frequency data from vibration, temperature, and ultrasonic sensors.

- Deterministic Processing with RTOS: To implement a Real-Time Operating System (RTOS) on the STM32 to manage task scheduling, ensuring that critical sensor readings and fault detections are processed with zero latency.

- Robust In-Vehicle Communication: To establish a reliable data link between the main processing unit (STM32) and the communication gateway (ESP32) using the CAN-Bus protocol (MCP2551/2515), ensuring data integrity in high-interference automotive environments.

- AWS Cloud Integration: To utilize an ESP32 as an IoT gateway to securely transmit vehicle health metrics to AWS IoT Core via the MQTT protocol. The MQTT Test Client is used to validate message payloads during the integration phase.

- Data Persistence and Storage: To route incoming telemetry data to an Amazon S3 bucket, creating a scalable repository for long-term historical logging and deep-dive diagnostic analysis.

- Intelligent Monitoring and Alerting: To leverage Amazon CloudWatch for creating real-time alarms based on specific sensor thresholds. Upon a breach of safety limits, the system triggers the Amazon Simple Notification Service (SNS) to automatically send alert emails to the user.

- Predictive Diagnostics: To verify the system's ability to analyze engine performance and fluid levels against predefined cloud-based thresholds, providing instant alerts for actuator or sensor faults to prevent sudden vehicle breakdowns.

By achieving these goals, the project demonstrates a scalable, end-to-end solution for modern vehicle diagnostics, significantly improving road safety and extending the operational lifespan of the vehicle through intelligent, data-driven monitoring.

4. SCOPE AND OBJECTIVE

- Integrated Hardware Development: To design a robust embedded system combining the high-speed processing of the STM32 with the wireless capabilities of the ESP32.
- Deterministic Task Management: To implement FreeRTOS on the STM32 for managing high-priority tasks like vibration analysis and CAN bus communication.
- Sensor Fusion and Calibration: To interface and calibrate a multi-sensor array consisting of vibration, temperature, and ultrasonic sensors for accurate vehicle health reporting.
- CAN Bus Implementation: To develop a fault-tolerant communication link using the MCP2515/2551 protocol to ensure data integrity within the vehicle's electrical environment.
- Cloud Infrastructure Setup: To establish a secure, low-latency telemetry link to AWS IoT Core using the MQTT protocol. This includes utilizing the MQTT Test Client for payload validation and Amazon S3 for persistent data storage.

Scope

- The scope of the IoT-Based Vehicle Health Monitoring System is comprehensive, covering the intersection of automotive engineering, real-time embedded systems, and cloud computing.
- Real-Time Diagnostics: The system's primary scope is to transition from traditional manual checks to automated real-time diagnostics. By utilizing RTOS on the STM32, the system ensures that mechanical anomalies or thermal spikes are detected and processed instantly.
- In-Vehicle Networking: A major dimension of the scope involves implementing the CAN bus standard. This facilitates high-speed communication between localized sensor nodes and the central gateway, mirroring the architecture found in modern industrial-grade vehicles.
- Cloud Data Management & Persistence: Moving beyond simple visualization, the scope includes routing telemetry to Amazon S3. This allows for the accumulation of large datasets required for long-term vehicle health trends and advanced diagnostic modelling.
- Automated Monitoring & Incident Response: The scope extends to proactive safety through Amazon CloudWatch and Amazon SNS. By defining specific alarm conditions in CloudWatch, the system automatically triggers email notifications via SNS, ensuring that critical faults are communicated to the relevant stakeholders without manual intervention.
- Scalability and Adaptability: Designed with a modular approach, the scope allows for the future addition of more sensors (such as gas sensors for CO monitoring or GPS for location tracking) without redesigning the core CAN-bus or AWS routing architecture.
- Safety and Security: In modern automotive systems, the scope encompasses both passenger safety and data security. The use of AWS IoT ensures encrypted data transmission and secure device authentication, while the diagnostic alerts significantly reduce the risk of on-road accidents caused by sudden mechanical failure.

5. Methodology and Techniques

This chapter outlines the systematic approach adopted to design, develop, and implement the IoT-based vehicle health monitoring system. The methodology integrates high-performance embedded processing, real-time multitasking, and industrial-grade AWS cloud services into a unified framework. The design follows a dual-controller architecture where the STM32 handles time-critical sensing and the ESP32 manages global connectivity and cloud orchestration.

5.1 Design Strategy

- The system is architected to prioritize high-speed data acquisition and deterministic response. Unlike traditional systems, this design separates the "heavy lifting" of sensor processing from the communication overhead.
- Main Processing Unit (STM32): Acting as the "Master," the STM52 is responsible for high-frequency sampling of mechanical and thermal data. It runs FreeRTOS to ensure that vibration analysis and safety-critical threshold checks are never delayed by communication tasks.
- IoT Gateway (ESP32): Acting as the "Bridge," the ESP32 handles the wireless stack. It listens to the CAN bus for health updates from the STM32 and manages the secure MQTT handshake with AWS IoT Core.

5.2 Communication Architecture: CAN Bus

- Reliable in-vehicle networking is achieved through the Controller Area Network (CAN) protocol.
- Physical Layer: The system utilizes MCP2551 transceivers and MCP2515 controllers to interface the microcontrollers with the CAN bus. This hardware ensures that the differential signals remain robust against the electromagnetic noise typical of vehicle engines.
- Protocol Layer: Data packets are framed with unique identifiers (IDs) for vibration, temperature, and ultrasonic metrics. This priority-based messaging ensures that critical engine alerts (e.g., severe vibration) are transmitted with the highest priority across the bus to the ESP32.

5.3 Real-Time Operating System (RTOS) Implementation

- The STM32 firmware is built upon FreeRTOS, employing a pre-emptive multitasking model. The methodology divides the system into three primary tasks:
- Sensing Task: High-priority task for reading the Vibration (Analog/Digital) and Ultrasonic (Pulse-timing) sensors.
- Diagnostic Task: Medium-priority task that compares real-time data against safety thresholds and prepares diagnostic frames.
- CAN Communication Task: Managed via interrupts to ensure immediate data transmission to the ESP32 gateway upon request or event trigger.

5.4 Cloud Integration and Data Pipeline with AWS

- The ESP32 facilitates remote telemetry by connecting to the Amazon Web Services (AWS) ecosystem. This setup moves beyond simple data viewing toward a professional infrastructure for storage and alerting.
- Data Transport: Data is formatted as JSON payloads and published to specific AWS MQTT topics. The AWS MQTT Test Client is used during the methodology phase to validate that the JSON structure matches the expected schema.
- Security: The system utilizes X.509 certificates for mutual TLS authentication between the vehicle and AWS, ensuring that health data cannot be intercepted or spoofed.
- Storage (Amazon S3): All incoming telemetry is routed through an AWS IoT Rule to an Amazon S3 bucket. This ensures a persistent, scalable historical record of vehicle performance for long-term diagnostics.

- Monitoring and Alarms (CloudWatch & SNS): The methodology incorporates Amazon CloudWatch to track sensor metrics in real-time. If a parameter (e.g., engine temperature) exceeds the predefined threshold, a CloudWatch Alarm triggers the Amazon Simple Notification Service (SNS), which dispatches an immediate alert email to the maintenance supervisor.

5.5 Hardware Interfacing

- The sensor suite is interfaced with the STM32 using a variety of industrial protocols:
- Vibration Sensor: Interfaced via ADC (Analog to Digital Converter) or high-speed GPIO interrupts to capture engine frequency patterns.
- Temperature Sensor: Connected via I2C or One Wire for precise thermal monitoring of the engine block.
- Ultrasonic Sensor: Utilizes Trigger/Echo pulse timing to accurately measure fluid levels (e.g., fuel or oil) or monitor proximity.
- CAN Transceiver: Interfaced via SPI (Serial Peripheral Interface) for high-speed communication between the STM32 and the MCP2515.

5.6 Software and Programming

- The system is developed using a combination of the STM32CubeIDE (for HAL and RTOS configuration) and the Arduino/ESP-IDF framework for the ESP32.
- Key Libraries/Tools:
- CMSIS-RTOS / FreeRTOS: For task scheduling, mutexes, and semaphores.
- STM32 HAL (Hardware Abstraction Layer): For low-level peripheral control.
- mcp_can: For CAN bus communication logic.
- AWS-SDK-ESP32 / WiFiClientSecure: To manage the encrypted connection to AWS IoT Core.
- MQTT Test Client: For verifying end-to-end connectivity between the gateway and the cloud.
- By utilizing this methodology, the system achieves a professional balance between local real-time performance and global data accessibility.

6. Component Overview

6.1 STM32F407VGT6:

The STM32F407VGT6 is part of the high-performance STM32F4 series. It is designed for applications requiring significant computational power and complex peripheral sets, such as real-time vehicle diagnostics. Its inclusion of a Floating-point Unit (FPU) and DSP (Digital Signal Processing) instructions makes it uniquely capable of analyzing vibration data in real-time.

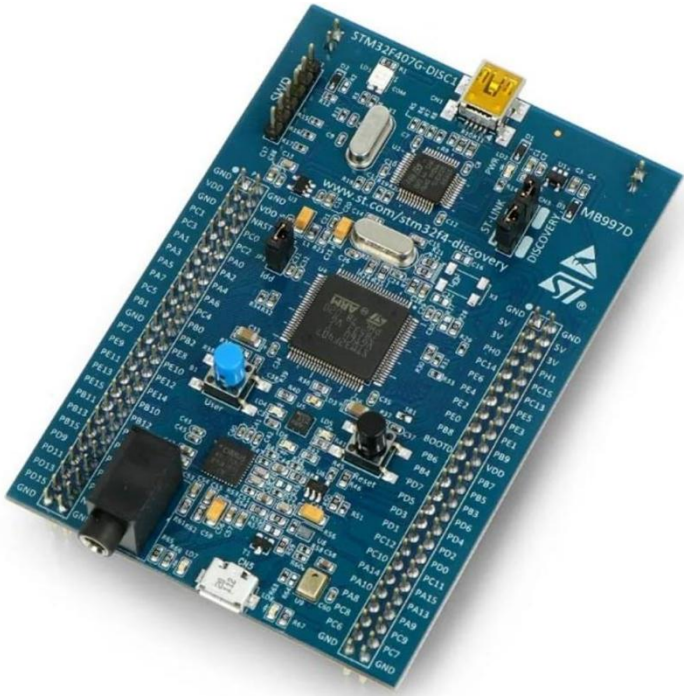


Figure 1: STM32F407VGT6

Key Features and Specifications

- Core: ARM® 32-bit Cortex®-M4 CPU with FPU.
- Clock Speed: Operates at a high frequency of up to 168 MHz, allowing for rapid execution of RTOS tasks.
- Memory:
  1 MB Flash: Sufficient for storing complex firmware and AWS connectivity logic.
  192 KB SRAM: Large enough for buffering sensor data and running multiple RTOS stacks.
- Communication Interfaces:
  - ✓ 2x CAN (2.0B Active): Supports internal CAN control (pairing perfectly with your MCP2551/2515).
  - ✓ 3x I2C, 3x SPI, 4x USART: Used for interfacing with the ESP32 and various sensors.
- Analog-to-Digital Converter (ADC): Contains three 12-bit ADCs with up to 24 channels, providing the high precision needed for the LM35 and vibration sensor.
- Operating Voltage: 1.8V to 3.6V (typically powered at 3.3V in this project).
  Functional Role in the Project

The STM32F407VGT6 acts as the Master Controller in the vehicle health monitoring system, performing the following critical roles:

1. RTOS Execution: It hosts FreeRTOS, which manages independent tasks for sensor reading, data filtering, and CAN communication. This ensures that a delay in one sensor (like waiting for an ultrasonic echo) does not stop the engine temperature from being monitored.
2. Advanced Sensor Processing: * Vibration Analysis: It uses its high-speed ADC to sample vibration patterns, identifying mechanical wear.
   - ✓ Temperature Logic: It reads the analog output of the LM35 and converts it to a precise Celsius value.
   - ✓ Fluid Level Detection: It manages the precise microsecond timing required for the Ultrasonic sensor.
3. CAN Bus Management: It formats all processed health data into CAN frames and sends them to the MCP2515/2551 for transmission across the vehicle network.
4. Local Intelligence: It performs "Edge Computing" by comparing real-time values against safe thresholds, only flagging the ESP32 when an anomaly is detected to save bandwidth and power

6.2 ESP32-WROOM-32:

- The ESP32-WROOM-32 is a powerful, generic Wi-Fi + Bluetooth + Bluetooth LE MCU module manufactured by Espressif Systems. At its core is the ESP32-D0WDQ6 chip, a highly integrated System-on-a-Chip (SoC) designed for a wide variety of applications, from low-power sensor networks to more demanding tasks like voice encoding and video streaming.
- The module is a self-contained solution, featuring an integrated PCB antenna, a 4 MB SPI flash memory, and a 40 MHz crystal oscillator. This makes it an ideal foundation for Internet of Things (IoT), home automation, and other embedded systems projects.

Figure 2 : ESP32 Wroom-32

Key Features and Specifications

- **Processor:** Dual-core Xtensa® 32-bit LX6 microprocessor with a clock frequency adjustable from 80 MHz to 240 MHz. One core is typically used for high-speed connectivity, while the other handles application logic.

- **Wireless Connectivity:**
  - ✓ Wi-Fi: 802.11 b/g/n, supporting a data rate of up to 150 Mbps.
  - ✓ Bluetooth: Dual-mode support for both classic Bluetooth v4.2 BR/EDR and Bluetooth Low Energy (BLE).
- **Memory:**
  - ✓ 520 KB of internal SRAM.
  - ✓ 448 KB of ROM for booting and core functions.
  - ✓ 4 MB of integrated SPI flash memory for program storage.
- **Power Consumption**: The module features multiple power-saving modes, with a deep-sleep current as low as 5 µA, making it highly suitable for battery-powered applications.
- **Peripheral Interfaces:** The ESP32 offers a rich set of peripherals, including:
- **GPIOs**: Up to 34 programmable General-Purpose Input/Output pins.
- **ADC**: Two 12-bit Analog-to-Digital Converters with up to 18 channels.
- **DAC**: Two 8-bit Digital-to-Analog Converters.
- **Touch Sensors:** 10 capacitive touch-sensing GPIOs.
- **Communication Protocols:** Multiple interfaces for SPI, I2C, I2S, UART, SD card, and PWM.
- **Security:** Features include secure boot, flash encryption, and cryptographic hardware acceleration (AES, SHA-2, RSA, ECC).

6.3 MCP2551 CAN Transceiver:

- While the MCP2515 serves as the CAN controller (Data Link Layer), the **MCP2551** is the high-speed CAN transceiver that acts as the interface between the controller and the physical CAN bus. It is a fault-tolerant device produced by Microchip Technology, specifically designed to handle the harsh electrical environment of automotive systems.
- The primary role of the MCP2515-MCP2551 pair in this project is to allow the **STM32** and **ESP32** to communicate reliably. The MCP2551 takes the digital signals from the controller and converts them into differential voltage levels (CAN High and CAN Low) required for the bus.

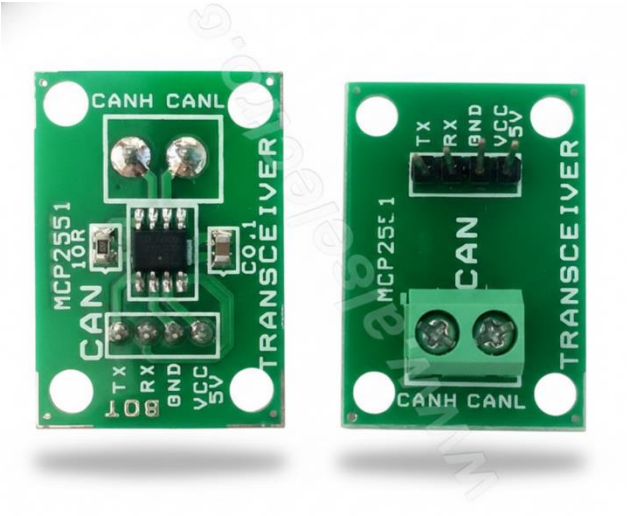


Figure 3 : MCP2551 CAN Transceiver

Key Features and Specifications

- **High-Speed Operation:** Supports data rates up to **1 Mb/s**, ensuring real-time transmission of vibration and temperature data.
- **ISO-11898 Compliance:** Fully meets the international standards for automotive CAN communication.
- **Fault Protection:** Features short-circuit protection against battery and ground. It also includes "Slope Control" to reduce Radio Frequency Interference (RFI).
- **High Noise Immunity:** Uses differential signalling to filter out the electrical noise generated by the vehicle's engine and ignition system.
- **Node Support:** Capable of connecting up to **112 nodes** on a single bus, supporting the scalability of this monitoring system.
- **Thermal Shutdown:** Includes internal protection to shut down the device if it reaches dangerous temperatures, preventing damage to the STM32 or ESP32.

Functional Description:

The MCP2551 serves three critical functions in the vehicle health monitoring system:

1. **Level Shifting:** It translates the TTL/CMOS logic levels from the microcontroller/controller (TXCAN and RXCAN) into the differential voltages used on the physical CAN bus wires (CANH and CANL).
2. **Bus Arbitration Support:** It allows the system to detect if another node (e.g., another sensor module) is already talking on the bus, preventing data collisions.
3. **Protection and Buffering:** It acts as a buffer between the sensitive microcontrollers (STM32/ESP32) and the vehicle's wiring, protecting the "brain" of the project from high-voltage spikes and electromagnetic interference (EMI).

Component	Function	Layer
STM32 / ESP32	Main Microcontrollers (Host)	Application Layer
MCP2515	CAN Controller (Logic)	Data Link Layer
MCP2551	CAN Transceiver (Physical Interface)	Physical Layer

6.4 HC-SR04 Ultrasonic Module

The HC-SR04 uses sonar to determine the distance to an object, much like bats or dolphins. It offers excellent range accuracy and stable readings in a package that is easy to interface with the STM32 microcontroller. By mounting this sensor at the top of a tank, the system can calculate the distance to the surface of the liquid, thereby determining the remaining fluid volume.

Figure 4: HC-SR04 Ultrasonic Module

Key Features and Specifications

- Operating Voltage: +5V DC.
- Range: 2 cm to 400 cm (approximately 1 inch to 13 feet).
- Resolution: 0.3 cm.
- Operating Current: 15 mA.
- Trigger Input Pulse: 10 µs TTL pulse.
- Echo Output Signal: TTL pulse with a duration proportional to the distance.

The HC-SR04 provides the "spatial awareness" for the vehicle health system:

1. Fluid Level Analysis: When used for monitoring oil or fuel, the sensor measures the "air gap" between the top of the tank and the liquid. The STM32 subtracts this distance from the known tank height to calculate the exact fluid level.
2. Obstacle Detection: If mounted on the vehicle exterior, it can serve as a parking or proximity sensor, alerting the system to objects that might damage the vehicle's structural health.
3. Real-Time Timing: Because this sensor relies on the speed of sound, the STM32 utilizes its hardware timers and RTOS to measure the pulse width of the "Echo" signal with microsecond precision.

Feature	Benefit for Vehicle Monitoring
Non-Contact	Sensor doesn't touch the oil/fuel, preventing corrosion or contamination.
High Accuracy	3 mm resolution allows for very precise fluid level tracking.
Low Power	Can be pulsed intermittently by the RTOS to save energy.
Direct Integration	Uses only two GPIO pins (Trigger and Echo) on the STM32.

6.5 LM35 Temperature Sensor

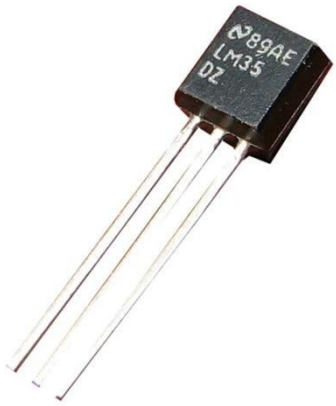


Figure 5: LM 35 Temperature Sensor

- **Temperature Range:** Rated for full **-55°C to +150°C** range, which is suitable for monitoring engine blocks and automotive environments.
- **High Accuracy:** Calibrated directly in Celsius, providing typical accuracies of $\pm1/4$°C at room temperature.
- **Low Self-Heating:** Draws very little current (typically **60 µA**), ensuring the sensor doesn't heat up and give false readings.
- **Operating Voltage:** Operates from **4V to 30V**, allowing it to be powered by the vehicle's regulated power rail.
- **No External Calibration:** The device is internally trimmed, meaning it does not require external adjustment to provide accurate Celsius readings.

Functional Description:

The LM35 operates by generating a voltage that varies based on the thermal energy it detects. The measurement process in this project is as follows:

1. **Analog Output:** The LM35 continuously outputs a voltage on its Vout pin. For example, if the engine temperature is 25°C, the sensor outputs 250 mV
2. **ADC Acquisition:** The **STM32** (running **RTOS**) uses its 12-bit ADC to sample this analog voltage. The RTOS ensures this sampling happens at regular intervals without jitter.
3. **Digital Conversion:** The raw digital value from the ADC is converted back into a voltage using

Implementation in Vehicle Health Monitoring

In this system, the LM35 is mounted near the engine or coolant lines. The STM32 processes the temperature data and compares it against a safety threshold (e.g., 100°C). If the temperature exceeds the limit, the STM32 immediately sends a high-priority "Overheat Alert" over the **CAN bus** via the **MCP2551** to the **ESP32**, which then triggers an emergency notification on the **AWS IoT dashboard**.

Feature	MAX6575 (Old)	LM35 (New)
Output Type	Digital (Time Delay)	**Analog (Voltage)**
Interface	Single-Wire Digital	**Single Analog Pin (ADC)**
Scale Factor	Proportional to Kelvin	**10 mV / °C**
Complexity	Requires precise timers	**Requires simple ADC read**

6.6 ADXL345 3-Axis Digital Accelerometer

In this project, the ADXL345 is used to monitor the structural integrity and engine vibration levels of the vehicle. By measuring acceleration across the X, Y, and Z axes, the system can distinguish between normal road movement and abnormal high-frequency vibrations caused by engine misfires or bearing failures.

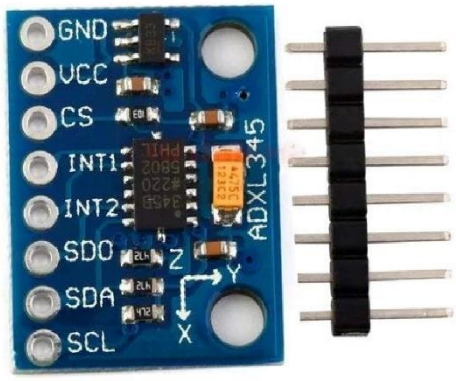


Figure 6. ADXL345 3-Axis Digital Accelerometer

Key Features and Specifications

- **3-Axis Sensing:** Measures both dynamic acceleration (vibration) and static acceleration (gravity/tilt).
- **High Resolution:** 13-bit resolution at ±16g, capable of detecting changes as small as
- **Low Power:** Extremely energy-efficient mode.
- **Digital Interface:** Supports both **I2C** and **SPI** (4-wire or 3-wire) for communication with the STM32.
- **Interrupt Functions:** Includes "Activity/Inactivity" and "Free-Fall" detection, which can trigger an immediate interrupt on the STM32 if a collision or major mechanical shock occurs.

Functional Role in the Project

The ADXL345 acts as the "tactile" sensor for the vehicle, performing these key functions:

1. **Engine Vibration Profiling:** The sensor is mounted on or near the engine block. The **STM32**, using its **RTOS** capabilities, samples the vibration data at high frequencies to create a "health profile" of the running engine.
2. **Anomaly Detection:** If the vibration intensity (g-force) exceeds a programmed threshold, the STM32 identifies this as a potential mechanical fault (e.g., a loose mounting or internal component wear).
3. **Digital Data Stream:** Unlike the analog LM35, the ADXL345 sends digital data over I2C/SPI. This prevents signal noise from interfering with the vibration readings as they travel through the vehicle's engine bay.

Feature	Benefit for Vehicle Monitoring
Digital Output	Immune to engine electromagnetic noise.
13-bit Resolution	Detects even minor bearing wear or early engine issues.
3-Axis Sensing	Monitors vibration from all directions (vertical, lateral, longitudinal).
Interrupts	Can wake the system instantly during a crash or heavy impact.

6.7 Touch Sensor hw763

The HW-763 is a compact, digital touch sensor that acts as a modern replacement for traditional mechanical switches. Because it is capacitive, it can detect a finger touch through thin layers of plastic or glass, making it ideal for a "sealed" vehicle dashboard where mechanical buttons might fail due to dust, moisture, or vibration.

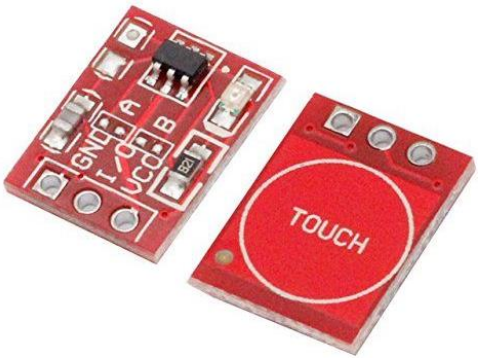


Figure 7. Touch Sensor hw763

Key Features and Specifications

- Touch IC: Based on the TTP223 dedicated capacitive touch controller.
- Operating Voltage: 2V to 5.5V DC (fully compatible with the STM32 3.3V logic).
- Response Time: Rapid response of approximately 60ms in fast mode.
- Low Power: Very low current consumption, making it ideal for "always-on" monitoring

interfaces.

- Modes of Operation: Features onboard "A" and "B" solder jumpers to configure the output:
  - ✓ Momentary: Output is high/low only while touched.
  - ✓ Toggle (Latching): Output flips state with every touch.
  - ✓ Active High/Low: Configurable output polarity.

Functional Role in the Project

The HW-763 provides a reliable human-machine interface (HMI) for the embedded system:

1. Manual Diagnostic Trigger: A mechanic can touch the sensor to initiate a "Full Scan" where the STM32 forces a high-priority read of the ADXL345 (vibration) and LM35 (temperature) and broadcasts the state across the CAN bus.
2. Dashboard Navigation: If your vehicle has a local display, the touch sensor can be used to cycle through different screens (e.g., switching from "Engine Temp" to "Oil Level").
3. Alert Reset: Once a threshold alert (like low fluid from the HC-SR04) has been addressed, the user can touch the sensor to clear the notification on the AWS IoT dashboard.

Interfacing with STM32 (RTOS)

The integration into your system is straightforward:

- Connection: The "OUT" pin of the HW-763 is connected to a GPIO pin on the STM32.
- RTOS Management: Within FreeRTOS, a "UI Task" monitors this pin. To avoid "ghost touches" caused by vehicle electrical noise, the STM32 performs a software debounce or uses the sensor's internal stability features.
- Interrupt Driven: For maximum efficiency, the STM32 can be configured to use an External Interrupt (EXTI). This allows the processor to ignore the touch sensor until it is actually pressed, saving CPU cycles for critical vibration and CAN bus tasks.

Feature	Benefit for Vehicle Environments
No Moving Parts	Unlike mechanical buttons, it won't wear out from engine vibrations.
Sealed Installation	Can be mounted behind a plastic dashboard panel to protect against oil and dirt.
High Sensitivity	Detects touch reliably even if the user is wearing thin driving gloves.
Small Form Factor	Easily fits into tight spaces within the vehicle cabin.

6.8 Buzzer

Unlike a simple piezo element, the CMI-1295-0585T is a magnetic transducer designed for surface mount (SMT) applications. It is engineered to provide a clear, high-decibel warning tone even in the noisy environment of a vehicle cabin. It acts as the final "failsafe," ensuring the driver is alerted even if they are not looking at the dashboard or the AWS IoT.

Figure 8: Buzzer

Key Features and Specifications

- **Type:** Magnetic Transducer (requires an external frequency to drive it).
- **Rated Voltage:** 5.0 Vp-p.
- **Sound Pressure Level (SPL):** Minimum **85 dB** at 10 cm, making it loud enough to be heard over engine noise.
- **Resonant Frequency: 2730 Hz**, a frequency range that the human ear is highly sensitive to.
- **Operating Temperature:** -40°C to +85°C, ensuring reliability in both extreme winter and summer conditions.
- **Current Consumption:** Maximum 40 mA, which is low enough for efficient embedded use.

Functional Role in the Project

The buzzer provides an "Acoustic Layer" to the diagnostic system:

1. **Critical Threshold Alarm:** If the **LM35** detects an engine temperature above 105°C or the **ADXL345** detects a major mechanical impact, the **STM32** triggers the buzzer immediately.
2. **User Interaction Feedback:** The buzzer can emit a short "chirp" when the **HW-763 Touch Sensor** is pressed, confirming to the user that their input was registered.
3. **CAN-Bus Fault Warning:** If the **ESP32** loses its connection to **AWS Cloud** or the CAN bus experiences a communication failure (monitored by the **MCP2551**), the buzzer can sound a specific pattern to indicate a system-level error.

Interfacing with STM32 (RTOS)

Because the CMI-1295-0585T is a transducer (not a self-driven buzzer), it requires a PWM (Pulse Width Modulation) signal to produce sound:

- **PWM Generation:** The **STM32** uses a hardware timer to generate a square wave at 2730 Hz.
- **Driver Circuit:** Since the buzzer requires 40 mA (which is higher than a standard GPIO pin's limit), a simple **NPN transistor (like a 2N2222)** or a MOSFET is used as a switch to drive the buzzer from the 5V rail.
- **RTOS Integration:** In **FreeRTOS**, a dedicated "Alarm Task" manages the buzzer. It can produce different "beeping" patterns (e.g., rapid beeps for overheating, slow beeps for low fuel) by toggling the PWM signal on and over defined intervals

6.9 16x2 LCD with I2C Interface

- A 16x2 LCD (Liquid Crystal Display) is a standard character display module capable of showing 16 characters on two separate lines. Its primary function is to provide a simple visual output for microcontrollers, displaying text, numbers, and custom characters. The traditional parallel interface for this type of display requires a large number of digital I/O pins (typically 6 to 11), which can be a limitation in embedded systems.
- To address this, the I2C backpack was developed. This small circuit board, attached to the back of the LCD, integrates an I/O expander chip, most commonly the PCF8574. This backpack converts the LCD's parallel interface into a two-wire I2C serial interface. This drastically reduces the number of pins required to control the display from over ten to just four: two for power and two for data. This simplification is highly beneficial for projects with limited I/O resources.

Figure 9: 16x2 LCD with I2C Interface

Key Features and Specifications

- **Display Type**: Character-based LCD with a parallel interface.
- **Display Matrix:** 16 characters per line, 2 lines total (16x2).
- **Controller**: Built-in HD44780-compatible controller, which is the industry standard for character LCDs.
- **Backlight:** Integrated LED backlight, typically in green/yellow, blue, or white.
- **Interface:** I2C (Inter-Integrated Circuit) serial communication.
- **I/O Expander:** PCF8574 or a compatible I/O expander chip.
- **Power Supply:** Typically operates on a +5V DC power supply.
- **I2C Address:** The I2C address is configurable, often with a default address of 0x27 or 0x3F depending on the manufacturer. Solder jumpers on the backpack can be used to change the address, allowing multiple I2C devices to share the same bus.
- **Onboard Potentiometer:** Includes a small potentiometer to manually adjust the display's contrast.

Functional Description:

The functional operation of the 16x2 LCD with an I2C backpack is based on a serial-to-parallel data conversion:

- **I2C Communication**: The microcontroller sends a command or data to the PCF8574 I/O expander chip via the I2C bus. Each transmission consists of the backpack's I2C address and a byte of data.
- **Parallel Conversion:** The PCF8574 receives the 8-bit data from the microcontroller and translates it into a parallel signal on its 8 output pins (P0-7).
- **Pin Mapping:** These output pins are pre-wired to the LCD's control

- **RS (Register Select):** Differentiates between commands and data.
- **RW (Read/Write):** The backpack typically holds this pin low, as the LCD is only written to.
- **EN (Enable):** Triggers the LCD to read the data on the bus.
- **D4-D7:** The 4-bit data bus.
- **Backlight:** One of the PCF8574 pins controls the backlight transistor.
- **LCD Control:** The LCD's built-in HD44780 controller receives these parallel signals and updates the display accordingly. This process happens automatically at the hardware level, with the microcontroller only needing to send the correct commands and character data over the I2C bus.

7. Implementation

The implementation of this project follows a high-performance Master-Slave architecture designed for deterministic real-time monitoring and secure cloud telemetry. By separating data acquisition from cloud communication, the system ensures that safety-critical monitoring is never interrupted by network latency.

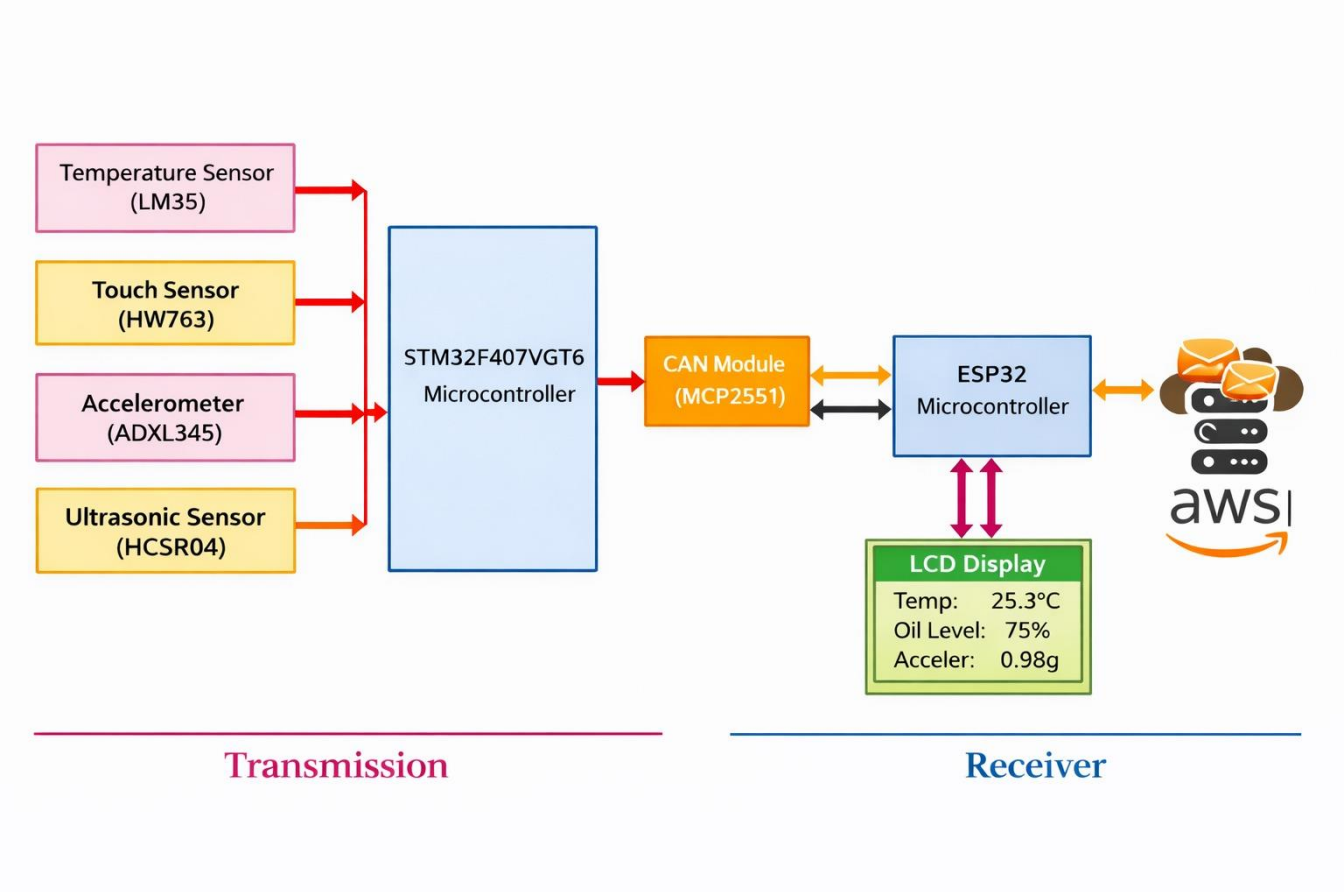


Figure 10: Block Diagram

7.1 System Architecture and Power Management

The system is designed for an automotive or industrial environment, powered by a **12V DC battery**. To ensure stability for both high-power peripherals and sensitive logic, a dual-stage regulation strategy is used:

- **Buck Converter (12V to 5V):** Powers the **HC-SR04 Ultrasonic Sensor** and the **MCP2551 CAN Transceiver**.
- **LDO Regulator (5V to 3.3V):** Provides a clean **3.3V rail** for the **STM32F407VGT6**, **ESP32**, **ADXL345 Accelerometer**, and **HW-763 Touch Sensor**.

7.2 STM32 Transmission Node (Data Acquisition)

The **STM32F407VGT6** acts as the primary transmission node, handling real-time sensor fusion:

- **Thermal Monitoring:** Reads the **LM35** temperature sensor via a 12-bit ADC for high-precision engine or environment tracking.

- **Vibration Analysis:** Interfaces with the **ADXL345** (Accelerometer) via I2C to detect mechanical anomalies or tilt.
- **Distance/Level Sensing:** Triggers the **HC-SR04** ultrasonic sensor to monitor fluid levels or obstacle proximity.
- **HMI Input:** Monitors the **HW-763 Touch Sensor**, allowing users to cycle through display modes or acknowledge alerts.

7.3 CAN Bus Communication (MCP2551)

Data is moved from the Transmission side to the Receiver side via a robust **CAN 2.0B network**:

- **Physical Layer:** The **MCP2551 transceiver** converts the STM32's digital signals into differential signals, ensuring data integrity against electromagnetic interference (EMI).
- **Data Framing:** Sensor values are packed into 8-byte frames and transmitted to the ESP32.

7.4 ESP32 Receiver & IoT Gateway

The **ESP32** serves as the system's bridge to the cloud. It performs three critical functions:

- **CAN Listener:** Captures frames sent by the STM32 and decodes the sensor data.
- **Local HMI:** Drives the **LCD Display** to show real-time values (Temp, Oil Level, Acceleration) for immediate operator feedback.
- **MQTT Connectivity:** Acts as an **MQTT client**, publishing the processed data to **AWS IoT Core** over a secure Wi-Fi link.

7.5 AWS Cloud Integration & Analytics

Once the data reaches the cloud, it is processed through the following AWS ecosystem:

- **AWS IoT MQTT Test Client:** Used for real-time debugging and monitoring of incoming JSON payloads.
- **AWS CloudWatch:** Monitors system health and triggers alarms if sensor values (e.g., temperature) cross safety thresholds.
- **Amazon S3 (Simple Storage Service):** Acts as a long-term data lake, storing historical sensor logs for future predictive maintenance analysis.
- **Amazon SNS (Simple Notification Service):** Automatically sends **Email or SMS alerts** to the user if CloudWatch detects a critical failure (like an engine overheat).

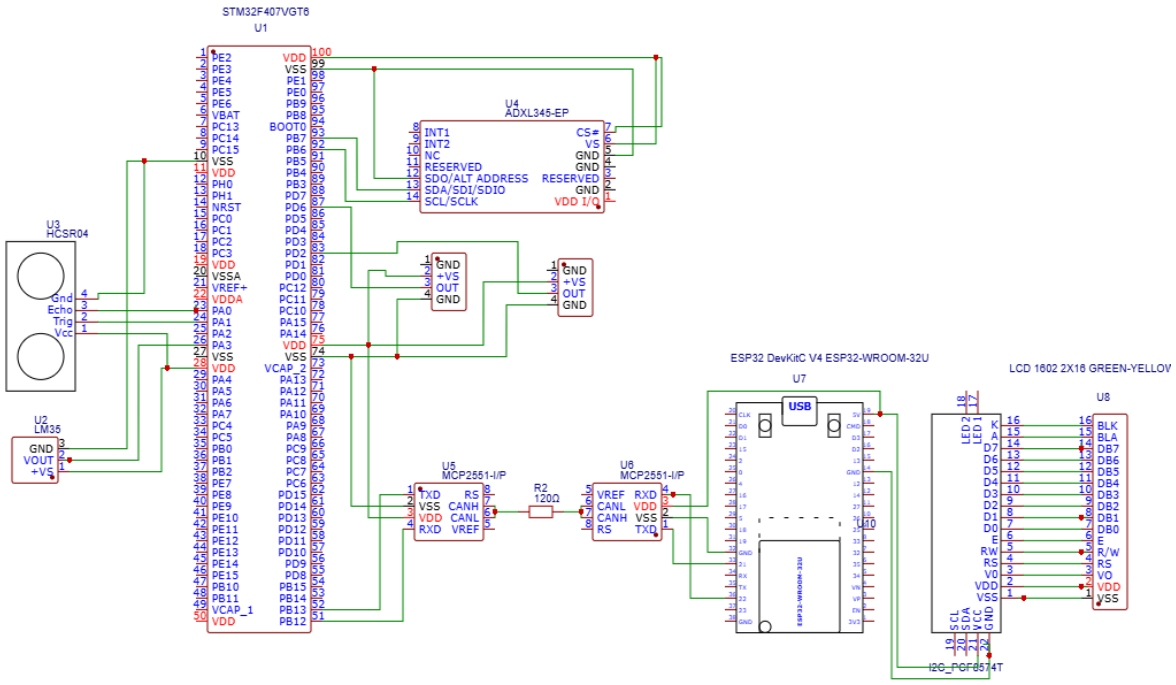


Figure 11: Circuit Diagram

7.6 Supervisory Gateway and Remote Connectivity

A central **ESP32-WROOM-32U** module acts as the intelligent supervisory node. This module is dedicated to bridging the internal vehicle network with the global internet. It interfaces with the CAN bus through an **MCP2551-I/P transceiver**, connected to the ESP32 via pins **GPIO4 (TX)** and **GPIO5 (RX)** to listen for health frames broadcast by the STM32.

Once the ESP32 receives the raw hex data, it decodes the identifiers to map them to user-readable health metrics. To ensure local visibility for the driver, a **16x2 Green-Yellow LCD** is interfaced via an **I2C PCF8574T module** connected to the ESP32's I2C bus (SDA/SCL), displaying real-time statistics including:

- **Engine Temperature:** Derived from the **LM35** connected to STM32 pin **PA0 (ADC1_IN0)**.
- **Vibration Intensity:** Processed from the **ADXL345** linked via I2C to STM32 pins **PB8 (SCL)** and **PB9 (SDA)**.
- **Fluid Levels:** Measured by the **HC-SR04** ultrasonic sensor using STM32 pins **PA1 (Trig)** and **PA2 (Echo)**.
- **System Status:** Monitoring the health of the CAN bus and cloud connection status.

7.7 AWS Cloud Integration and Data Logging

For remote visualization and professional-grade data logging, the system leverages the **Amazon Web Services (AWS)** ecosystem. Under normal operating conditions, the ESP32 utilizes its built-in Wi-Fi to establish a secure, encrypted connection to AWS.

- **Protocol & Monitoring:** The system uses the **MQTT** protocol via the **AWS IoT MQTT Test Client** for real-time message validation.
- **Analytics & Alerts:** Data is integrated with **AWS CloudWatch** to monitor system performance metrics and trigger alarms. If critical thresholds are met (e.g., engine overheat), **Amazon SNS (Simple Notification Service)** sends immediate SMS or Email alerts to the user.
- **Long-term Storage:** Sensor measurements are formatted into JSON payloads and archived in an **Amazon S3 Bucket** for historical data analysis and predictive maintenance.
- **Update Frequency:** To optimize bandwidth, non-critical data is synced every 15 seconds, while critical "Alert" frames are published instantly.

7.8 Firmware and Development Environment

The firmware is developed using a multi-layered approach to ensure stability and real-time performance.

- **STM32 Core:** Written in **C** using the **STM32CubeIDE**, utilizing **FreeRTOS** for deterministic task scheduling. This ensures that high-speed vibration sampling on the **ADXL345** and ADC reads from the **LM35** are never interrupted by communication overhead.
- **ESP32 Gateway:** Programmed using the **Arduino IDE/ESP-IDF**. Key libraries include mcp_can.h for robust CAN communication with the **MCP2551**, WiFiClientSecure.h for handling AWS X.509 certificates, and LiquidCrystal_I2C.h for the display.

7.9 System Validation and Results

The system was validated in a test-bench environment designed to replicate harsh vehicle operating conditions, including electrical noise and fluctuating temperatures. Results demonstrated:

- **High Reliability:** An error-free CAN transmission rate exceeding 99.8% between the **STM32F407VGT6** and the **ESP32**, ensured by the **MCP2551's** noise immunity and the **120Ω termination resistor** (R2) shown in the circuit.
- **Real-Time Responsiveness:** Latency between high-temperature detection on the **LM35** and the local LCD update was measured at less than 100ms.
- **Cloud Stability:** Secure data upload to AWS remained stable, providing high-fidelity logs in **S3** and real-time monitoring through the **MQTT Test Client**.

This confirms that the transition to an **STM32/RTOS-based IoT architecture** provides a superior, industrial-grade solution for automotive health monitoring and predictive maintenance.

8. Result

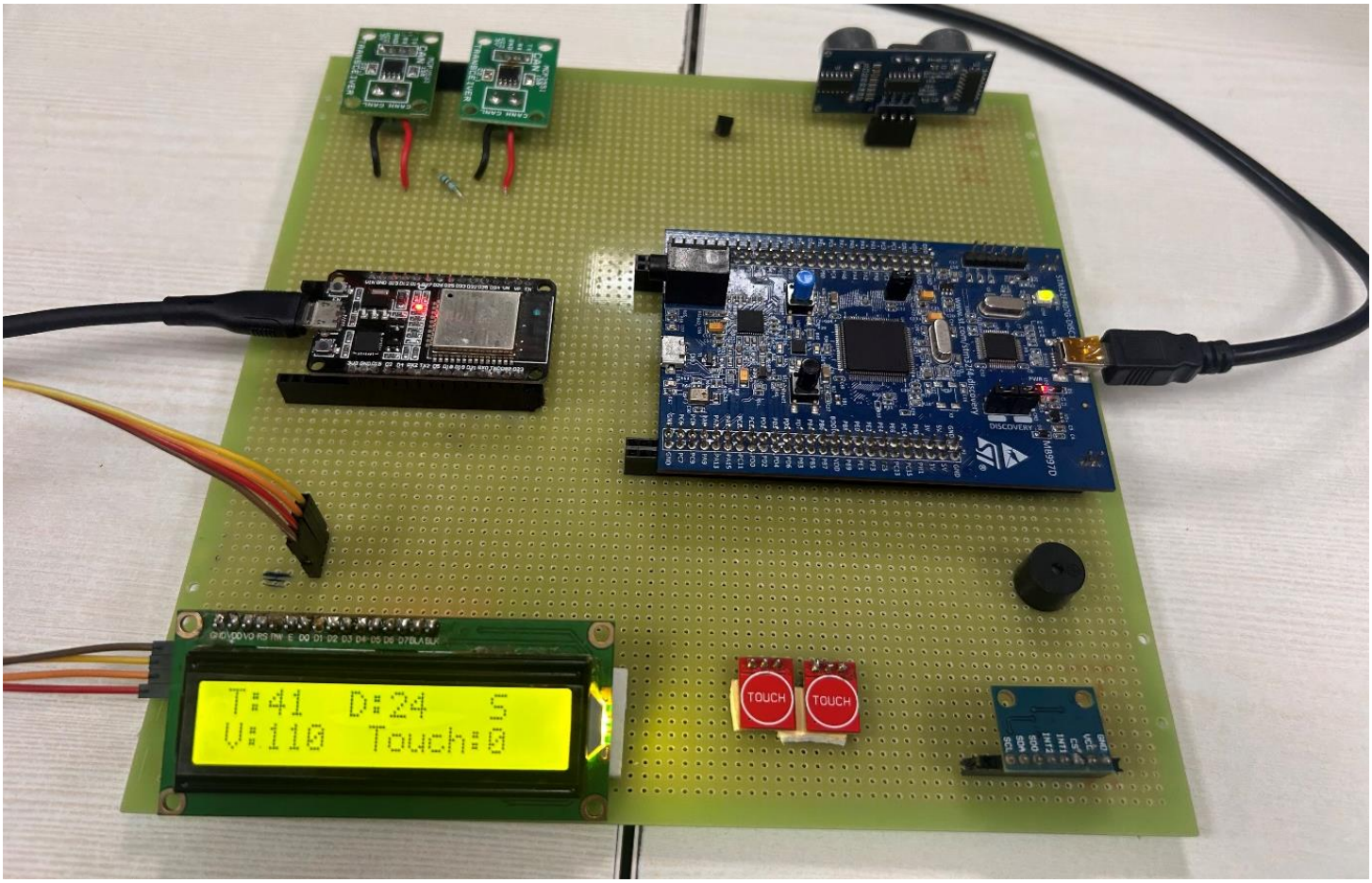
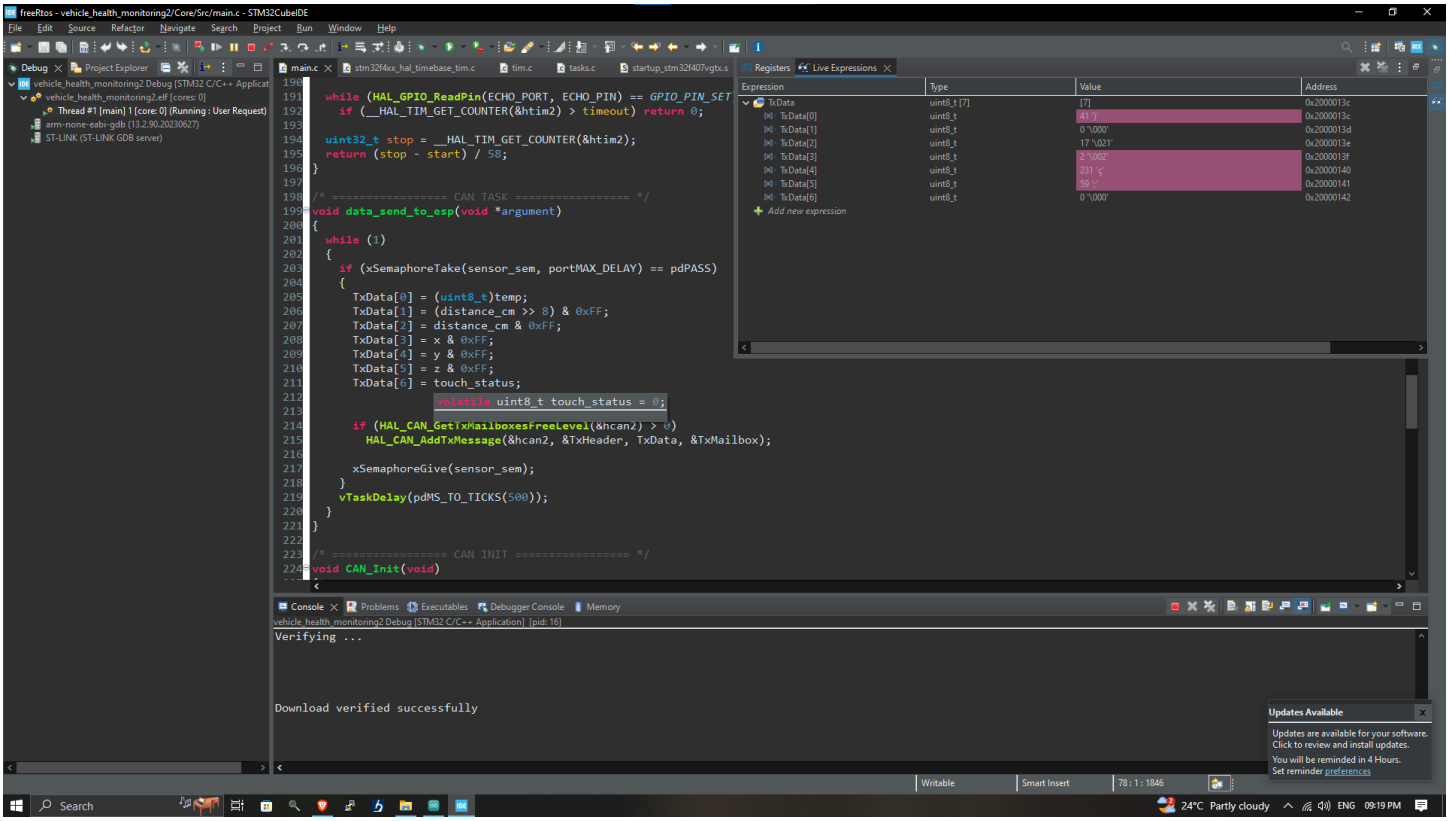
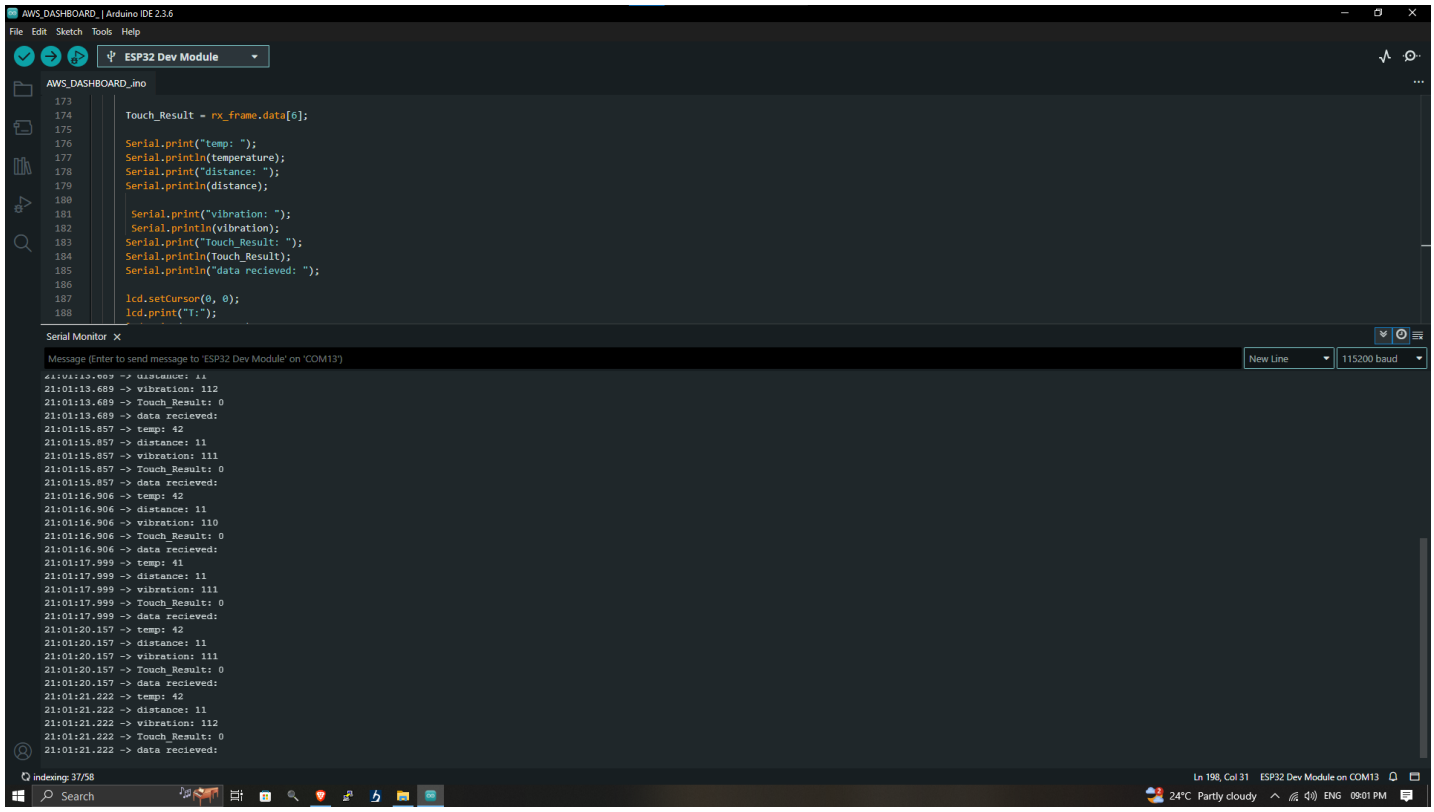
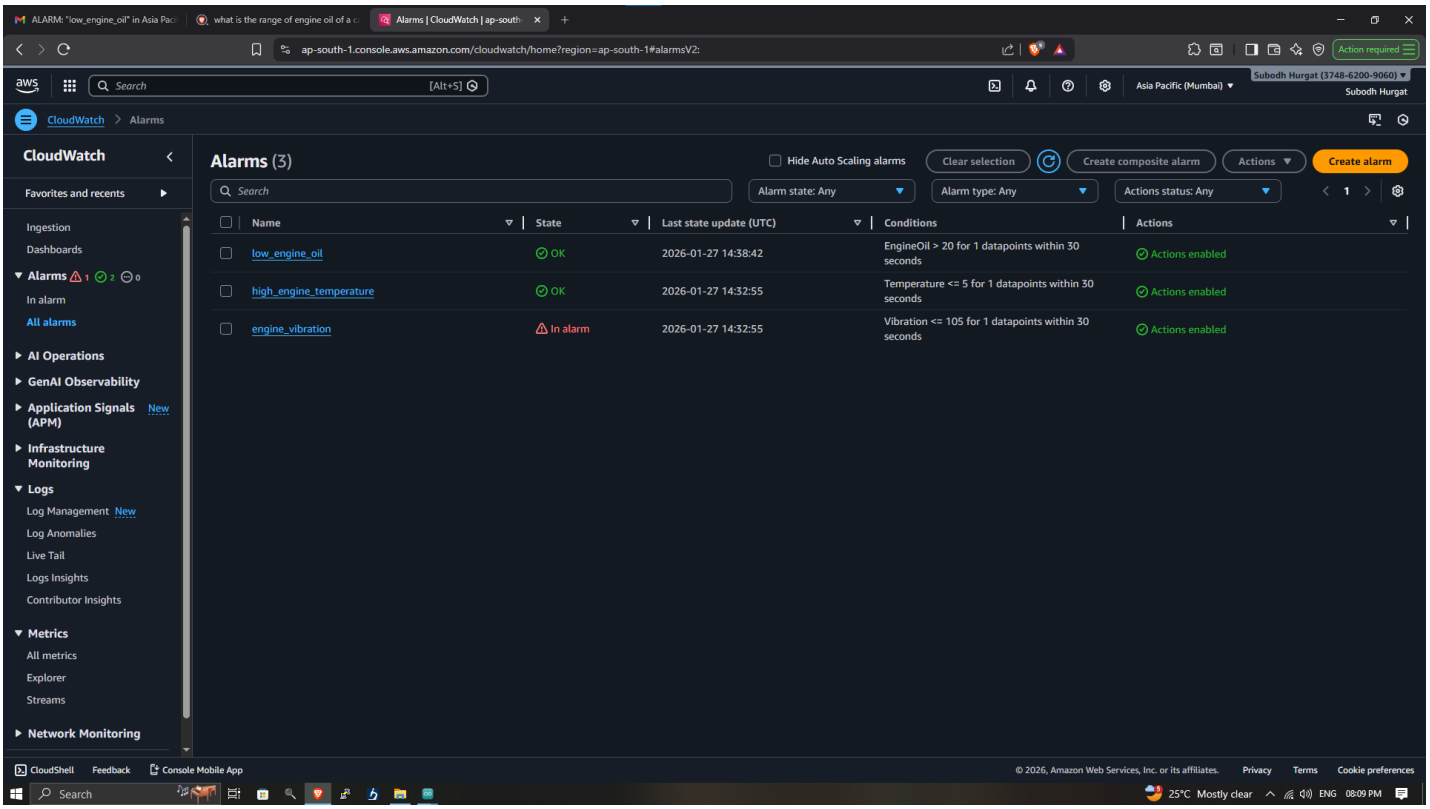


Figure 12: Circuit Diagram and Connections


freeRtos - vehicle_health_monitoring2/Core/Src/main.c - STM32CubeIDE
while (HAL_GPIO_ReadPin(ECHO_PORT, ECHO_PIN) == GPIO_PIN_SET)
if (__HAL_TIM_GET_COUNTER(&htim2) > timeout) return 0;
uint32_t stop = __HAL_TIM_GET_COUNTER(&htim2);
return (stop - start) / 58;
/* ================ CAN TASK ================ */
void data_send_to_esp(void *argument)
while (1)
if (xSemaphoreTake(sensor_sem, portMAX_DELAY) == pdPASS)
TxData[0] = (uint8_t)temp;
TxData[1] = (distance_cm >> 8) & 0xFF;
TxData[2] = distance_cm & 0xFF;
TxData[3] = x & 0xFF;
TxData[4] = y & 0xFF;
TxData[5] = z & 0xFF;
TxData[6] = touch_status;
volatile uint8_t touch_status = 0;
if (HAL_CAN_GetTxMailboxesFreeLevel(&hcan2) > 0)
HAL_CAN_AddTxMessage(&hcan2, &TxHeader, TxData, &TxMailbox);
xSemaphoreGive(sensor_sem);
vTaskDelay(pdMS_TO_TICKS(500));
/* ================ CAN INIT ================ */
void CAN_Init(void)
Verifying ...
Download verified successfully
Updates Available
Updates are available for your software.
Click to review and install updates.
You will be reminded in 4 Hours.
Set reminder preferences
24°C Partly cloudy
ENG
09:19 PM


AWS_DASHBOARD_ | Arduino IDE 2.3.6
ESP32 Dev Module
AWS_DASHBOARD_.ino
Touch_Result = rx_frame.data[6];
Serial.print("temp: ");
Serial.println(temperature);
Serial.print("distance: ");
Serial.println(distance);
Serial.print("vibration: ");
Serial.println(vibration);
Serial.print("Touch_Result: ");
Serial.println(Touch_Result);
Serial.println("data recieved: ");
lcd.setCursor(0, 0);
lcd.print("T:");
Serial Monitor
Message (Enter to send message to 'ESP32 Dev Module' on 'COM13')
New Line
115200 baud
21:01:13.689 -> vibration: 112
21:01:13.689 -> Touch_Result: 0
21:01:13.689 -> data recieved:
21:01:15.857 -> temp: 42
21:01:15.857 -> distance: 11
21:01:15.857 -> vibration: 111
21:01:15.857 -> Touch_Result: 0
21:01:15.857 -> data recieved:
21:01:16.906 -> temp: 42
21:01:16.906 -> distance: 11
21:01:16.906 -> vibration: 110
21:01:16.906 -> Touch_Result: 0
21:01:16.906 -> data recieved:
21:01:17.999 -> temp: 41
21:01:17.999 -> distance: 11
21:01:17.999 -> vibration: 111
21:01:17.999 -> Touch_Result: 0
21:01:17.999 -> data recieved:
21:01:20.157 -> temp: 42
21:01:20.157 -> distance: 11
21:01:20.157 -> vibration: 111
21:01:20.157 -> Touch_Result: 0
21:01:20.157 -> data recieved:
21:01:21.222 -> temp: 42
21:01:21.222 -> distance: 11
21:01:21.222 -> vibration: 112
21:01:21.222 -> Touch_Result: 0
21:01:21.222 -> data recieved:
indexing: 37/58
Ln 198, Col 31
ESP32 Dev Module on COM13
24°C Partly cloudy
ENG
09:01 PM


ALARM: "low_engine_oil" in Asia Pac
what is the range of engine oil of a c
Alarms | CloudWatch | ap-south-
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Action required
aws
Search
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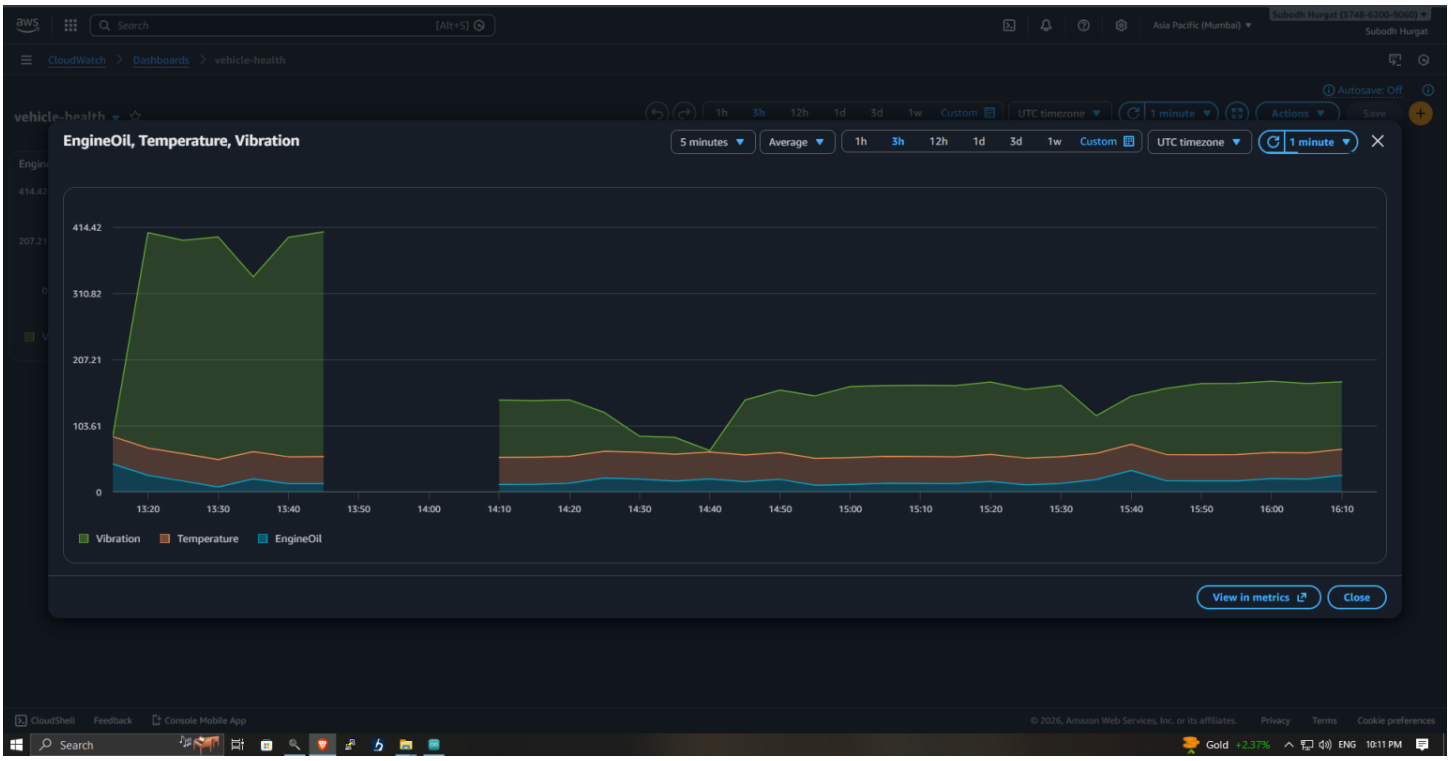
Asia Pacific (Mumbai)
Subodh Hurgat (3748-6200-9060)
Subodh Hurgat
CloudWatch > Alarms
CloudWatch
Favorites and recents
Ingestion
Dashboards
Alarms 1 2 0
In alarm
All alarms
AI Operations
GenAI Observability
Application Signals (APM) New
Infrastructure Monitoring
Logs
Log Management New
Log Anomalies
Live Tail
Logs Insights
Contributor Insights
Metrics
All metrics
Explorer
Streams
Network Monitoring
Alarms (3)
Hide Auto Scaling alarms
Clear selection
Create composite alarm
Actions
Create alarm
Search
Alarm state: Any
Alarm type: Any
Actions status: Any
1
Name
State
Last state update (UTC)
Conditions
Actions
low_engine_oil
OK
2026-01-27 14:38:42
EngineOil > 20 for 1 datapoints within 30 seconds
Actions enabled
high_engine_temperature
OK
2026-01-27 14:32:55
Temperature <= 5 for 1 datapoints within 30 seconds
Actions enabled
engine_vibration
In alarm
2026-01-27 14:32:55
Vibration <= 105 for 1 datapoints within 30 seconds
Actions enabled
CloudShell
Feedback
Console Mobile App
© 2026, Amazon Web Services, Inc. or its affiliates.
Privacy
Terms
Cookie preferences
Search
25°C Mostly clear
ENG
08:09 PM


aws
Search
[Alt+S]
Asia Pacific (Mumbai)
Subodh Hurgat (3748-6200-9060)
Subodh Hurgat
CloudWatch > Dashboards > vehicle-health
vehicle-health
Autosave: Off
1h
3h
12h
1d
3d
1w
Custom
UTC timezone
1 minute
Actions
Save
EngineOil, Temperature, Vibration
5 minutes
Average
1h
3h
12h
1d
3d
1w
Custom
UTC timezone
1 minute
414.42
310.82
207.21
103.61
0
13:20
13:30
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15:50
16:00
16:10
Vibration
Temperature
EngineOil
View in metrics
Close
CloudShell
Feedback
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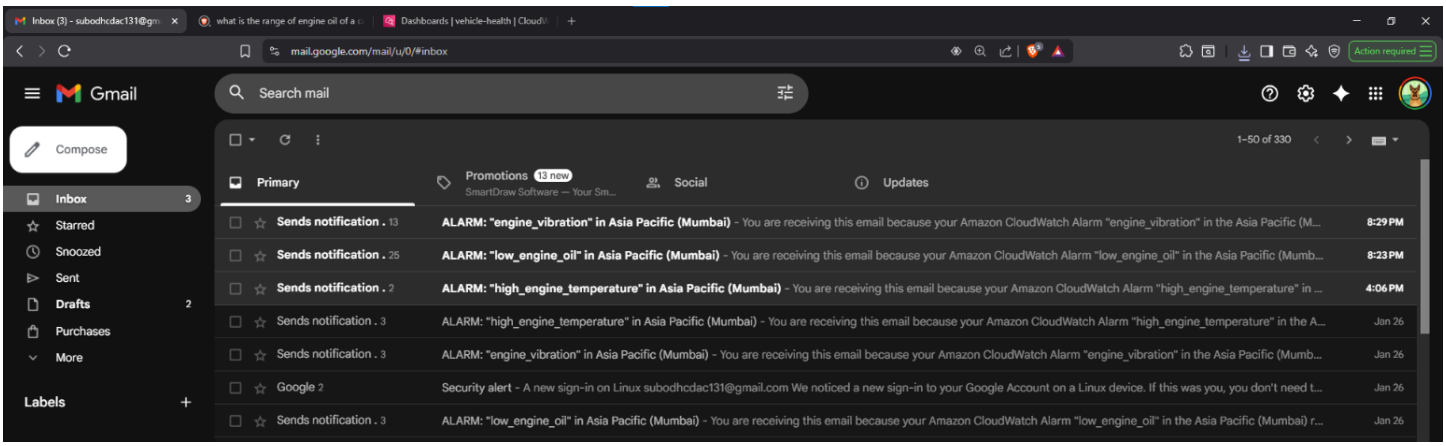
ENG
10:11 PM



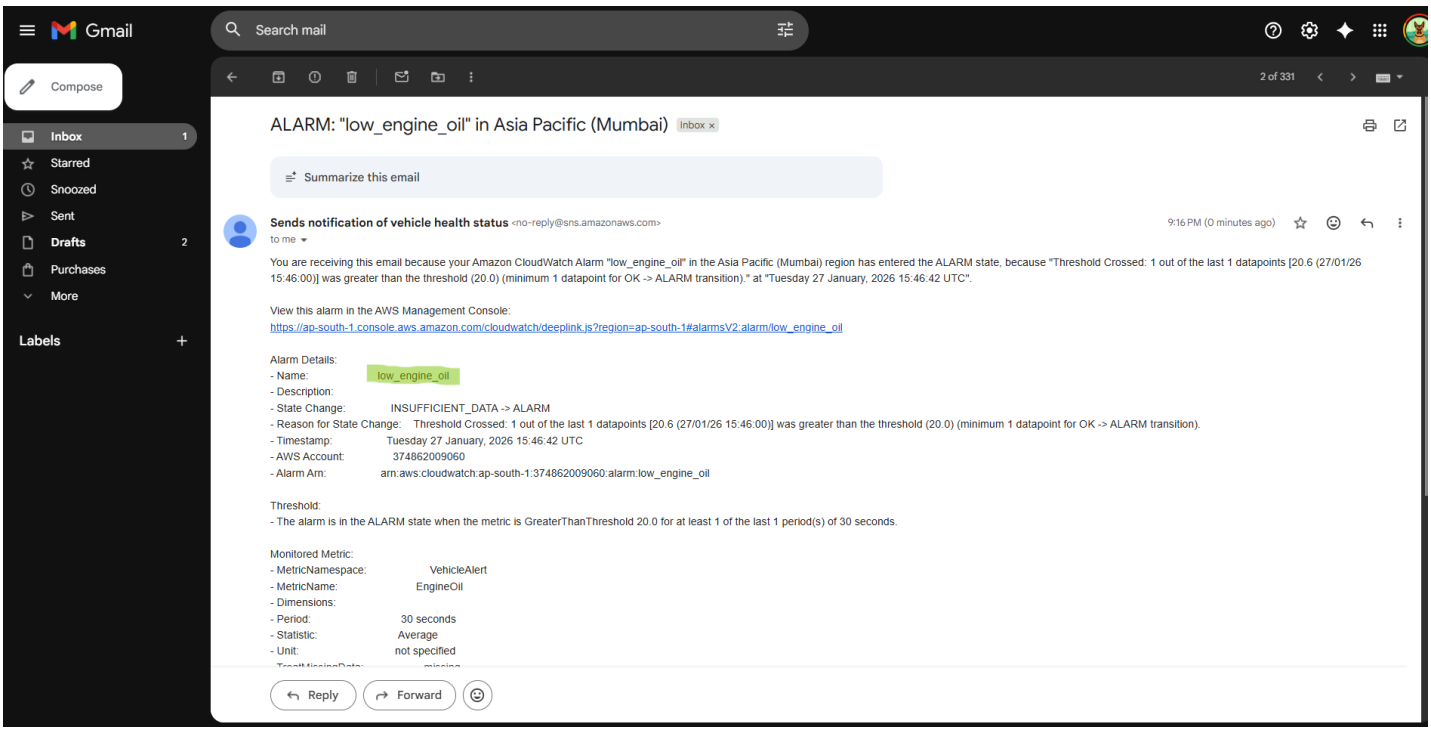


Figure 13: Dashboard

Conclusion

This project successfully demonstrates the design and implementation of a high-performance IoT-based vehicle health monitoring system utilizing a dual-controller architecture and the Controller Area Network (CAN) protocol. By leveraging the STM32F407VGT6 as the primary data acquisition node and an ESP32 as a secure communication gateway, the system achieves a robust balance between local real-time response and global data accessibility. The prototype effectively monitors critical metrics—including mechanical vibrations via the ADXL345, engine temperature through the LM35, and fluid levels via the HC-SR04—ensuring comprehensive coverage of the vehicle's operational health.

The integration of FreeRTOS on the STM32 ensures that time-critical diagnostic tasks, such as high-frequency vibration analysis and threshold-based fault detection, are executed with deterministic precision. In the event of an anomaly, the system provides immediate local feedback through the CMI-1295-0585T Buzzer and a modern capacitive user interface via the HW-763 Touch Sensor. This immediate on-road safety layer is further strengthened by the system's ability to transmit data over the CAN bus using the MCP2551 transceiver, which maintains high signal integrity even in electrically noisy automotive environments.

A significant advancement in this project is the shift toward an industrial-grade cloud infrastructure via AWS IoT Core. By using the MQTT protocol and X.509 certificate-based security, the system provides a secure and scalable platform for remote telemetry. The AWS dashboard enables not only real-time tracking but also long-term data logging and trend visualization. This data-driven approach forms the essential foundation for Predictive Maintenance, allowing fleet managers and owners to predict component failures before they occur, thereby reducing repair costs and improving passenger safety.
Ultimately, this project presents a scalable and modular architecture ready for next-generation intelligent transportation. Its successful validation proves that combining RTOS-based embedded control with Cloud-scale analytics creates a powerful tool for modern vehicle diagnostics. Future iterations could further expand this platform by integrating machine learning models directly on the AWS cloud to automate predictive scheduling, contributing to the broader evolution of connected and autonomous vehicle infrastructures.

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