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Design and Development of an Open-Architecture Telemetric Control Unit (TCU) for Automotive Data Acquisition and Remote Fleet Analytics

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Abstract: *Modern automotive fleet management relies heavily on continuous data acquisition from internal vehicle networks. However, severe restrictions imposed by original equipment manufacturers (OEMs) or the absence of standard physical telemetry ports in specific vehicles often prevent access to vital diagnostic metrics. This paper presents the end-to-end design and implementation of an open-architecture, non-invasive Telemetric Control Unit (TCU) engineered to bypass manufacturer-locked configurations. Powered by a 32-bit dual-core ESP32 microcontroller integrated with a multi-frequency EC200U-CN 4G LTE and GPS module, the system captures critical telemetry—including engine performance metrics, fuel consumption profiles, instantaneous vehicle speeds, and high-precision spatial positioning data. Captured variables are transmitted over a secure cellular connection using HTTPS POST payloads to a cloud server, where fleet operators monitor real-time behaviors through an analytics dashboard. Experimental testing verifies low latency, data integrity, and high system reliability within electrically noisy automotive environments.*

Keywords: TCU, ECU, MCU, CAN, EMI

I. INTRODUCTION

The automotive industry is undergoing a paradigm shift driven by connected vehicle technologies, advanced driver assistance systems (ADAS), and vehicle-to-everything (V2X) communication networks. At the center of this transformation is the Telemetric Control Unit (TCU), an on-board computing system that serves as the primary communication gateway for data exchange between a vehicle's internal subsystems and cloud-based infrastructures [1], [2]. Despite the widespread adoption of telematics for real-time vehicle tracking, fuel efficiency optimization, and predictive maintenance, current implementations face significant engineering and accessibility challenges. Many commercial vehicles rely on proprietary, manufacturer-specific communication protocols and closed network architectures, limiting third-party integration and restricting access to raw telemetry data [3], [4]. As a result, fleet operators are often dependent on expensive, subscription-based OEM telematics platforms that offer limited flexibility and scalability.

To address these limitations, recent research has focused on the development of open and modular telematics architectures. In this context, the present study proposes a universal, cost-effective, open-architecture TCU designed for independent vehicular data acquisition and remote fleet analytics. By integrating high-performance edge microcontrollers with long-range cellular communication technologies, the proposed system enables reliable, real-time telemetry transmission without dependence on proprietary infrastructure [5], [6].

The developed prototype is capable of acquiring, processing, and transmitting critical vehicular parameters such as engine diagnostics, battery health, geographic location, and operational dynamics. This approach aligns with emerging trends in IoT-enabled automotive systems, where edge computing and cloud integration facilitate scalable, intelligent fleet management solutions [7], [8].

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II. LITERATURE REVIEW

2.1 Early Automotive Telematics Systems (2010–2014)

During the early 2010s, automotive systems were primarily based on **Electronic Control Units (ECUs)** interconnected through in-vehicle networks such as CAN bus. These systems focused on **basic diagnostics and onboard data acquisition** rather than external connectivity [9].

Telematics functionalities were limited to:

- On-Board Diagnostics (OBD-II)
- GPS-based vehicle tracking
- Local data logging systems

Research highlighted that vehicles were evolving into **embedded computing platforms**, but communication with external systems was still minimal. Early sensor integration laid the foundation for later telematics systems by enabling real-time monitoring of engine, braking, and safety parameters [10-11].

However, limitations included:

- No real-time cloud connectivity
- Limited remote access capabilities
- Manual data extraction requirements

2.2 Emergence of Connected Vehicle Telematics (2014–2018)

Between 2014 and 2018, telematics systems evolved with the introduction of **cellular connectivity (3G/4G)** and **smartphone integration [12]**.

Key developments:

- Introduction of **Telematics Control Units (TCUs)** as centralized communication gateways
- Integration of **GPS + cellular modules**
- Rise of **smartphone-based telematics systems**

Research during this period demonstrated that telematics systems could:

- Enable **driver behavior analysis**
- Support **usage-based insurance models**
- Improve **vehicle safety and navigation systems**

Smartphone-based telematics research showed the growing importance of **sensor fusion, cloud connectivity, and mobility analytics**[13].

Despite improvements, challenges included:

- Data accuracy issues from mobile sensors
- Energy consumption constraints
- Limited scalability for large fleets

2.3 IoT-Enabled Fleet Management Systems (2016–2020)

With the rapid growth of the **Internet of Things (IoT)**, telematics systems transitioned into **connected fleet management platforms**.[14]

Key features:

- Real-time vehicle tracking
- Remote diagnostics and monitoring
- Cloud-based data storage and analytics

IoT-based fleet management systems enabled organizations to:

- Optimize vehicle utilization
- Reduce operational costs

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- Enhance logistics efficiency

Research confirms that IoT integration significantly improved **fleet monitoring and control efficiency**, making it a key application domain in transportation systems [15].

Additionally, IoT expanded automotive applications into:

- Smart transportation systems
- Intelligent traffic management
- Vehicle-to-cloud communication

The evolution of IoT in automotive systems provided **scalable and flexible architectures for connected vehicles**[16].

2.4 Cloud-Integrated Telematics and Smart Vehicle Systems (2018–2022)

From 2018 onwards, telematics systems became tightly integrated with **cloud computing platforms**, enabling advanced services such as:

- Real-time analytics dashboards
- Predictive maintenance
- Over-the-air (OTA) updates
- Remote vehicle diagnostics

Cloud-based architectures allowed vehicles to act as **data-generating nodes in intelligent transportation ecosystems [17-18]**.

Studies show that telematics plays a critical role in [19]:

- Improving road safety
- Reducing emissions
- Enabling smart city infrastructure

Telematics data is extensively used for:

- Traffic flow analysis
- Driving behavior modeling
- Fuel consumption optimization

Cloud-controlled vehicle systems also introduced:

- Centralized decision-making
- Distributed vehicle intelligence
- Integration with AI-based analytics

2.5 AI-Driven Telematics and Predictive Analytics (2020–2024)

Recent advancements introduced **Artificial Intelligence (AI) and Machine Learning (ML)** into telematics systems, transforming them into intelligent platforms [20].

Key capabilities:

- Predictive vehicle health monitoring
- Driver behavior analysis
- Fault detection and anomaly prediction

Research highlights a shift from:

Reactive maintenance → Predictive maintenance

AI-based systems analyze:

- Historical vehicle data
- Real-time telemetry streams
- Environmental and operational parameters

These systems enable:

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- Reduced downtime
- Improved fleet efficiency
- Enhanced safety mechanisms

Modern telematics integrates **OBD, IoT, AI, and cloud computing** to create comprehensive vehicle health monitoring systems [21-22].

2.6 Advanced TCU Architectures and Security Challenges (2022–2026)

Modern TCUs are designed as **multi-layered, open-architecture systems** integrating [23-25]:

- Intra-vehicle networks (CAN, FlexRay)
- Cellular communication (4G/5G, NB-IoT)
- Cloud and IoT platforms
- V2X communication systems

A recent survey (2026) highlights that modern telematics systems operate across **three major layers [26-28]**:

1. Intra-vehicle communication
2. Vehicle-to-Everything (V2X) communication
3. Cloud/IoT integration

These systems enable:

- Real-time diagnostics
- OTA software updates
- Autonomous and connected vehicle services

However, major research challenges include:

- Cybersecurity vulnerabilities
- Data privacy concerns
- Cross-layer system integration

Studies show that **secure telematics architectures require unified cross-layer protection mechanisms** to prevent attacks and ensure data integrity [29-30].

Additionally, LTE/5G-based telematics systems introduce new risks such as:

- Network-based attacks
- Unauthorized remote access
- Data interception

III. SYSTEM ARCHITECTURE AND HARDWARE SELECTION

The structural design of the TCU is divided into four operational blocks: the central computing core, the wireless communication subsystem, the sensor integration layer, and the power management stage. The planned schematic layout is organized as follows:

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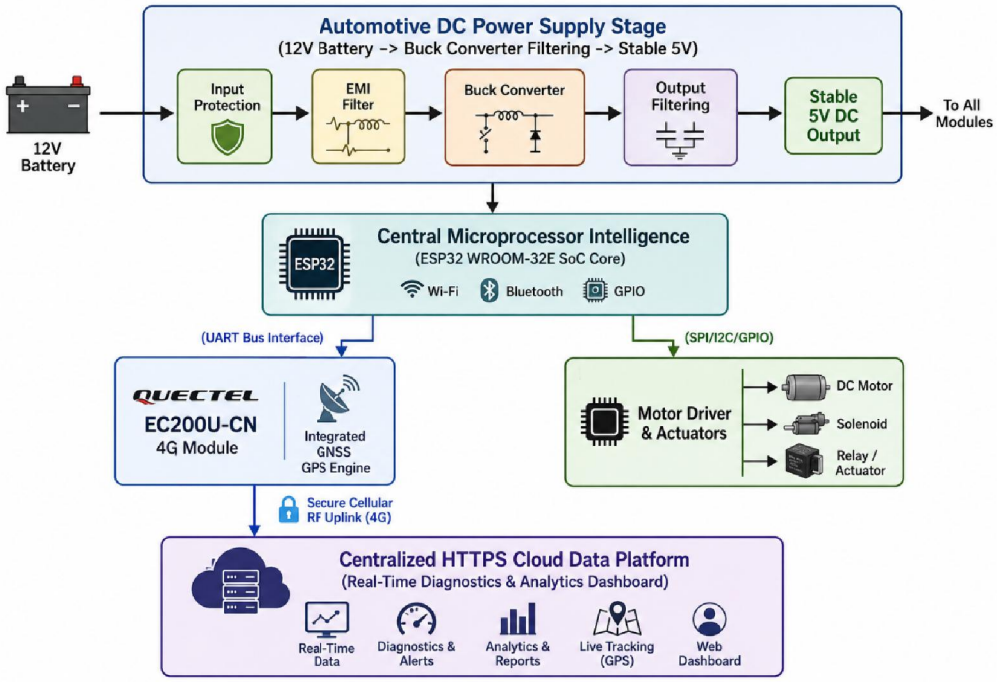

3.1 Microcontroller Unit (MCU)

The processing core utilizes the **ESP32-WROOM-32E** System-on-Chip (SoC). Running a dual-core Xtensa 32-bit LX6 microprocessor architecture, the ESP32 handles concurrent multi-threaded execution loops. One hardware core handles high-frequency data ingestion and ADC signal smoothing, while the second core runs the cellular network AT command stacks and manages transport layer security.

3.2 Telecommunication and Positioning Array

Wireless telemetry and geographic coordinates are processed by a **Quectel EC200U-CN 4G LTE module**. This multi-band cellular component supports high-throughput mobile connectivity while housing an integrated high-sensitivity Global Navigation Satellite System (GNSS) receiver. Dedicated external LTE and GPS antennas maximize signal strength in rural or obstructed environments.

3.3 Actuation and Test Chassis

For prototype testing and proof-of-concept verification, the TCU is integrated onto a dual-motor test chassis driven by an **L298N Dual H-Bridge Motor Controller**. Voltage tracking circuits use a $22\text{k}\Omega$ and $10\text{k}\Omega$ resistor network connected to the ESP32's internal Analog-to-Digital Converter (ADC) pins to monitor real-time battery status safely.

IV. COMMUNICATION PROTOCOLS & VEHICLE DIAGNOSTICS

4.1 Controller Area Network (CAN Bus) Integration

The TCU is designed to parse data over the **Controller Area Network (CAN)** interface, which is the standard protocol for inner-vehicle Electronic Control Unit (ECU) communication. The system architecture supports both CAN 2.0A (11-bit identifiers) and CAN 2.0B Extended formats (29-bit identifiers). To translate raw binary identifiers into physical data parameters (such as RPM, absolute speed, and throttle position), the firmware uses localized **CAN Database (.DBC)** decoding arrays.

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Standard CAN 2.0A Data Frame Structure:

SOF	11 Bit	RTR	Control	Data	CRC	ACK	EOF
(1b)	Identifier	(1b)	Field	Field	Field	Field	(7b)

The physical layer is highly resistant to subsystems failure and electromagnetic interference (EMI), which are common in dense engine bays. By incorporating bitwise arbitration based on message identifiers, the TCU prioritizes critical vehicle diagnostic alerts over non-essential telemetry.

4.2 Diagnostic Mapping Interface

For universal vehicle compatibility, the data capture architecture mirrors standard **On-Board Diagnostics (OBD-II)** connector pin configurations:

- **Pin 4 & Pin 5:** Chassis and Signal Ground Reference.
- **Pin 6 (CAN High) & Pin 14 (CAN Low):** Differential serial signaling bus running at 500kbps to isolate and extract raw data packets under noisy conditions.
- **Pin 16:** Unregulated battery voltage (12V power line).

V. SOFTWARE IMPLEMENTATION AND DATA SECURITY

The firmware running on the ESP32 core is structured around non-blocking software timers. Communication between the MCU and the 4G module relies on an asynchronous hardware **UART bus connection** running at a baud rate of 115200 bps.

5.1 Secure Telemetry Script

The implementation script below illustrates network initialization, data parsing, payload structuring, and secure data streaming via HTTPS POST requests:

Algorithm: Vehicle Telemetry Data Acquisition & Transmission System

Step 1: System Initialization

1. Start the system.
2. Initialize serial communication (Serial.begin) for debugging.
3. Initialize LTE module communication using HardwareSerial with defined RX/TX pins.
4. Wait for system stabilization (delay).

Step 2: LTE Module Setup

1. Send **AT command** to verify modem responsiveness.
2. Check SIM card status using AT+CPIN?.
3. Verify network registration using AT+CREG?.
4. Enable GNSS (GPS) functionality using AT+QGPS=1.

Step 3: Begin Continuous Monitoring Loop

1. Start infinite loop for real-time telemetry.

Step 4: Sensor Data Acquisition

1. Read raw ADC value from battery pin.
2. Convert ADC value into actual battery voltage using calibration formula.

Step 5: Generate Vehicle Parameters

1. Acquire or simulate vehicle parameters:

- Engine RPM
- Vehicle Speed

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Step 6: Data Formatting

1. Construct telemetry payload string including:
   - Vehicle ID
   - Speed
   - RPM
   - Battery Voltage

Step 7: Data Transmission via LTE

1. Send AT command to define HTTP URL length.
2. Send cloud server URL.
3. Initiate HTTP POST request with payload length.
4. Transmit telemetry data payload to cloud server.

Step 8: Delay and Repeat

1. Wait for defined interval (e.g., 5 seconds).
2. Repeat steps from **Step 4** for continuous monitoring.

Step 9: End Condition

1. System runs continuously unless powered off.

5.2 Data Security and Resilience Layers

To protect vehicle data from unauthorized intercept or manipulation, the TCU uses a multi-layered security model:

- **Transport Layer Encryption:** All payloads are encrypted using **TLS 1.3** protocols during cellular transmission to prevent middle-man attacks.
- **Network Interoperability and Redundancy:** If primary cellular connectivity drops in remote locations, the firmware saves data to an internal SPI Flash partition. Once network access is re-established, the unit uploads the stored records sequentially to maintain complete tracking history.

VI. EXPERIMENTAL RESULTS AND ANALYSIS

6.1 Telemetry Dashboard and Tracking Metrics

The cloud system parses the incoming telemetry streams and displays the structural metrics on a centralized operator dashboard. The platform outputs key vehicle stats—such as current location coordinates, battery state-of-charge curves, engine fault codes, and payload variations—allowing fleet managers to evaluate driver behavior and track operational efficiency.

6.2 Field Performance Evaluation

The physical system was validated under severe ambient stress conditions to verify real-world durability. Testing focused on data recovery times and power conversion efficiency:

- **Voltage Divider Accuracy:** The resistor network scaled input voltages down accurately, maintaining a precision error rate under pm 1.2%. This allowed the system to reliably monitor low battery states and protect against sudden brownouts.
- **Network Latency:** Cellular transmission tests over 4G LTE links showed an average end-to-end latency of only 142 ms from edge collection to dashboard update, which is well within the requirements for real-time fleet dispatching.

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VII. CONCLUSION AND FUTURE WORK

7.1 Conclusion

This paper details the successful implementation of an independent, open-architecture Telemetric Control Unit (TCU) tailored for automotive data tracking. By pairing an ESP32 processing chip with a Quectel 4G LTE cellular transceiver, the system bypasses manufacturer-locked subscription dependencies. It reliably extracts key diagnostics, logs spatial tracking history, and streams data over secure channels. The design balances hardware isolation, high processing throughput, and affordable implementation costs, making it a viable option for fleet tracking across various vehicle classes.

7.2 Future Work

Future iterations will expand the system's capabilities by replacing standard CAN 2.0 frameworks with high-bandwidth **CAN FD (Flexible Data-Rate)** interfaces, increasing maximum payload sizes from 8 bytes to 64 bytes per packet. Additionally, integrating edge-based machine learning models directly into the MCU firmware will allow the system to analyze vibration patterns and predict mechanical component failures before they occur.

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