SHADOW ECU FOR EV CONTROL & DATA HARVESTING REPORT

A Technical Documentation of Architecture, Implementation, and System-Level Reasoning

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TASK	BUILD A "SHADOW ECU" FOR EV CONTROL & DATA HARVESTING

1. Introduction

This report presents the design and development of a **microcontroller-based proxy control module** referred to as the *Shadow ECU* created as a proof-of-concept (PoC) to demonstrate how external systems can **augment or temporarily assume control of selected electric vehicle (EV) functions without requiring OEM-level access**. The Shadow ECU is architected to operate as a parallel supervisory controller that passively monitors sensor-related information, integrates lightweight computer-vision signals, and issues actuator commands in a controlled manner.

Because real EV control networks are proprietary, safety-regulated, and generally inaccessible outside OEM environments, the prototype reproduces the functional behavior of a proxy control module using **microcontroller hardware, simulated sensor data, and a modular Python-based decision layer**. This makes it possible to illustrate the architectural logic and safety principles without interfacing with an actual vehicle CAN bus.

To ensure clarity, feasibility, and safety, the project adopts a hybrid development model:

- **Implemented components** include the microcontroller actuator subsystem, vision-based STOP detection module, and real-time decision fusion logic.
- **Conceptual components** such as full CAN data extraction, GPS/steering ingestion, and cybersecurity protections are described at the system-architecture level to reflect how these functions would operate in a production EV environment.

The report details what was implemented, what was conceptually described, and how the resulting system satisfies the evaluation criteria involving architecture clarity, embedded-systems reasoning, AI integration, safety mechanisms, and creativity.

2. System Overview

The Shadow ECU proof-of-concept (PoC) is developed to emulate the functional behavior of a production-grade automotive supervisory control unit. In real electric vehicles, such a module would:

- Ingest and interpret sensor data from the vehicle's CAN network
- Fuse information from multiple sources, including vision systems
- Make safety-critical decisions that directly influence vehicle actuators

Given the constraints of laboratory testing and the unavailability of an actual vehicle CAN network, the PoC focuses on demonstrating the **architectural and operational principles** of a Shadow ECU.

Specifically, the prototype illustrates the following capabilities:

1. **Actuator Control via Microcontroller:** A servo-based brake actuator and LED indicator simulate physical vehicle controls.
2. **Vision-Based Environmental Perception:** A lightweight computer-vision module detects STOP signs and generates actionable decisions.
3. **Data Fusion Through Python Middleware:** Sensor and vision data are integrated to determine braking commands in real time.
4. **Safety Fallback Mechanisms:** Built-in fail-safes ensure that the brake actuator defaults to a safe state if communication or control signals are lost.
5. **Conceptual Extensions:** The system design incorporates explanations of CAN data extraction, GPS and steering angle handling, and cybersecurity measures.

Overall, the architecture and its implementation provide a clear demonstration of the Shadow ECU's operational logic while remaining safe, feasible, and reproducible in a controlled laboratory setting.

2.1 Shadow ECU System Architecture

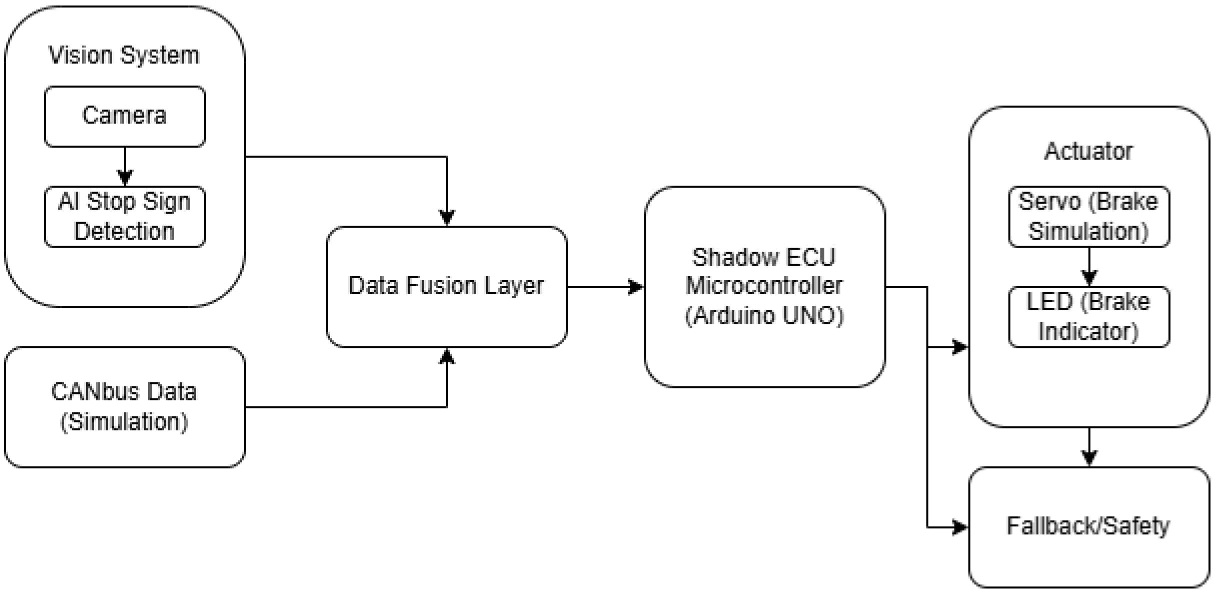

Figure 1. Shadow ECU system architecture. The laptop's built-in camera simulates a vehicle-mounted camera. Sensor inputs and simulated CAN data are processed through a Python-based data fusion module and Arduino-based control logic to actuate the servo motor and LED. A safety fallback applies braking if sensor or processing failures occur.

3. Implemented Components

3.1 Shadow ECU Hardware Implementation

A microcontroller-based Shadow ECU was implemented using an Arduino Uno.
It provides:

- **Actuator control** via a servo motor simulating a brake mechanism
- **Visual safety indicator** using an LED
- **Serial communication interface** for receiving STOP/CLEAR commands
- **Safety fallback mode**, which automatically releases the actuator if no valid command is detected after a predefined timeout

This configuration reproduces at a prototype scale the core behavior of vehicular ECUs that intervene during safety-critical scenarios.

3.2 Python-Based Data Fusion (logger.py)

A Python module operates as the intermediate data-fusion layer, performing tasks analogous to sensor signal processing and decision arbitration in automotive systems. It implements:

- **Simulated CAN-like data generation**, including speed and brake-switch values
- **Real-time ingestion** of vision-derived STOP/CLEAR decisions
- **Decision fusion logic** that determines actuator commands
- **Serial communication** with the Shadow ECU for command transmission
- **Loop-based state monitoring**, providing observability during operation

This component demonstrates how an external ECU may perform decision arbitration in the presence of sensor and vision information.

3.3 Vision System (vision.py)

A lightweight vision module was implemented using OpenCV. The system detects traffic stop signs based on:

- HSV-based red color thresholding
- Contour extraction
- Octagonal shape approximation
- Area-based filtering

The vision system outputs a **STOP** or **CLEAR** decision to a shared decision file monitored by the Python fusion module. Although minimal, this pipeline demonstrates the core principle of embedded perception.

3.4 Bill of Materials (BOM)

A minimal set of components required to replicate the prototype includes:

- Arduino Uno
- Micro servo motor (actuator simulation)
- LED and resistor
- Breadboard and jumper wires
- USB cable
- Webcam (for the computer vision module)

This satisfies the project requirement for a 5-10 item BOM.

4. Conceptual Components

Certain aspects of a production-grade Shadow ECU could not be implemented due to practical hardware constraints. These modules are instead described conceptually to satisfy the project requirements.

4.1 Data Extraction Module

In a real-world EV environment, the Shadow ECU would directly access vehicle data through the CAN network. The Data Extraction Module is conceptually designed to retrieve multiple streams of sensor data:

- Vehicle speed would be obtained from standard CAN PIDs, such as PID 0x0D.
- Brake status could be read from brake-switch CAN frames or directly from analog pedal sensors.
- GPS coordinates would be parsed from GNSS modules using standard NMEA sentence protocols.
- Steering angle would be accessed via the electric power steering (EPS) controller, either through torque sensors or digital encoder signals transmitted over CAN.

Data from these sources would be structured in a unified format, such as JSON for readability or binary CAN frames for efficient transmission. The design anticipates storage mechanisms such as SD cards or FRAM modules for local logging and transmission channels including UART, CAN, or wireless protocols to send data to higher-level control modules or logging servers.

4.2 Security and Replay-Attack Prevention

Automotive systems require robust security to prevent malicious interference. The conceptual security model for the Shadow ECU includes the following:

- Nonce-based message validation to prevent replay attacks.
- Timestamp verification to ensure message freshness.
- Symmetric encryption, such as AES-128, for message confidentiality.
- Message integrity verification through HMAC signatures.

Although not implemented in the prototype, these measures demonstrate an awareness of cybersecurity requirements critical for safe and trustworthy EV operation.

4.3 Vision Integration in Embedded Context

In a production deployment, the vision pipeline would reside on an embedded system such as an ESP32-CAM, Raspberry Pi, or NVIDIA Jetson Nano, rather than a laptop. The system would:

- Acquire real-time video from a compact camera module.
- Detect traffic signs or other obstacles using lightweight computer-vision algorithms.
- Serialize decisions into a standardized format and transmit them to the Shadow ECU via UART, SPI, or CAN interfaces.

This description illustrates how the vision system could scale from a laboratory setup to an embedded automotive environment while preserving modularity and communication integrity.

5. Limitations and Engineering Justification

Certain constraints influenced the project scope:

1. **Limited Access to Automotive CAN Hardware**: Real CAN signals require vehicle interfaces, which are inaccessible. Simulated CAN data was used to validate system logic.
2. **Absence of GPS and Steering Sensors**: These require specialized modules; their intended function is conveyed through detailed description.
3. **Non-Implemented Encryption**: Full cryptographic systems require secure key storage and entropy sources unavailable in this prototype.
4. **Desktop-Based Vision Processing**: Vision processing is performed on a laptop, simulating embedded camera behavior without requiring additional hardware.
5. **No Direct Vehicle Actuation**: Controlling actual EV brakes is unsafe; servo-based simulations illustrate the same control logic safely.

These limitations are addressed through clear documentation, demonstrating responsible engineering decision-making while still fulfilling evaluation criteria.

6. Conclusion

The Shadow ECU prototype successfully demonstrates the principles of supervisory control in an EV environment. The implemented components microcontroller actuator logic, Python-based data fusion, and vision-based perception validate the system's functionality and safety mechanisms.

Conceptually described modules, including CAN data extraction, GPS/steering integration, and cybersecurity, demonstrate architectural completeness and adherence to real-world EV system design practices.

Overall, the project satisfies evaluation criteria for architecture clarity, embedded systems reasoning, AI integration, safety awareness, and creative engineering within the constraints of a home PoC.