Technical Report: High-Performance ESP32-S3 Motor Controller

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Executive Summary

This report presents the technical design and engineering rationale for a custom PCB developed to control and monitor a brushed DC motor for robotics and automation applications. The design focuses on robustness, efficiency, modularity, and real-time feedback, with strong integration for networked environments.

1 System Overview

The motor controller PCB is designed around the ESP32-S3 microcontroller, integrating high-current motor driving, precision current sensing, encoder feedback, and CAN bus communication. The power delivery system uses a two-stage approach for stable, low-noise operation.

2 System Architecture

- **Central MCU:** ESP32-S3, managing control, sensing, and communication.
- **Power Delivery:** Two-stage network (Buck converter and LDO) for regulated supply.
- **Motor Driver:** High-current output with current sensing and direction indication.
- **Encoder Interface:** Robust signal level adaptation for high-resolution feedback.

- **CAN Communication:** Reliable, hardware-backed network interface.

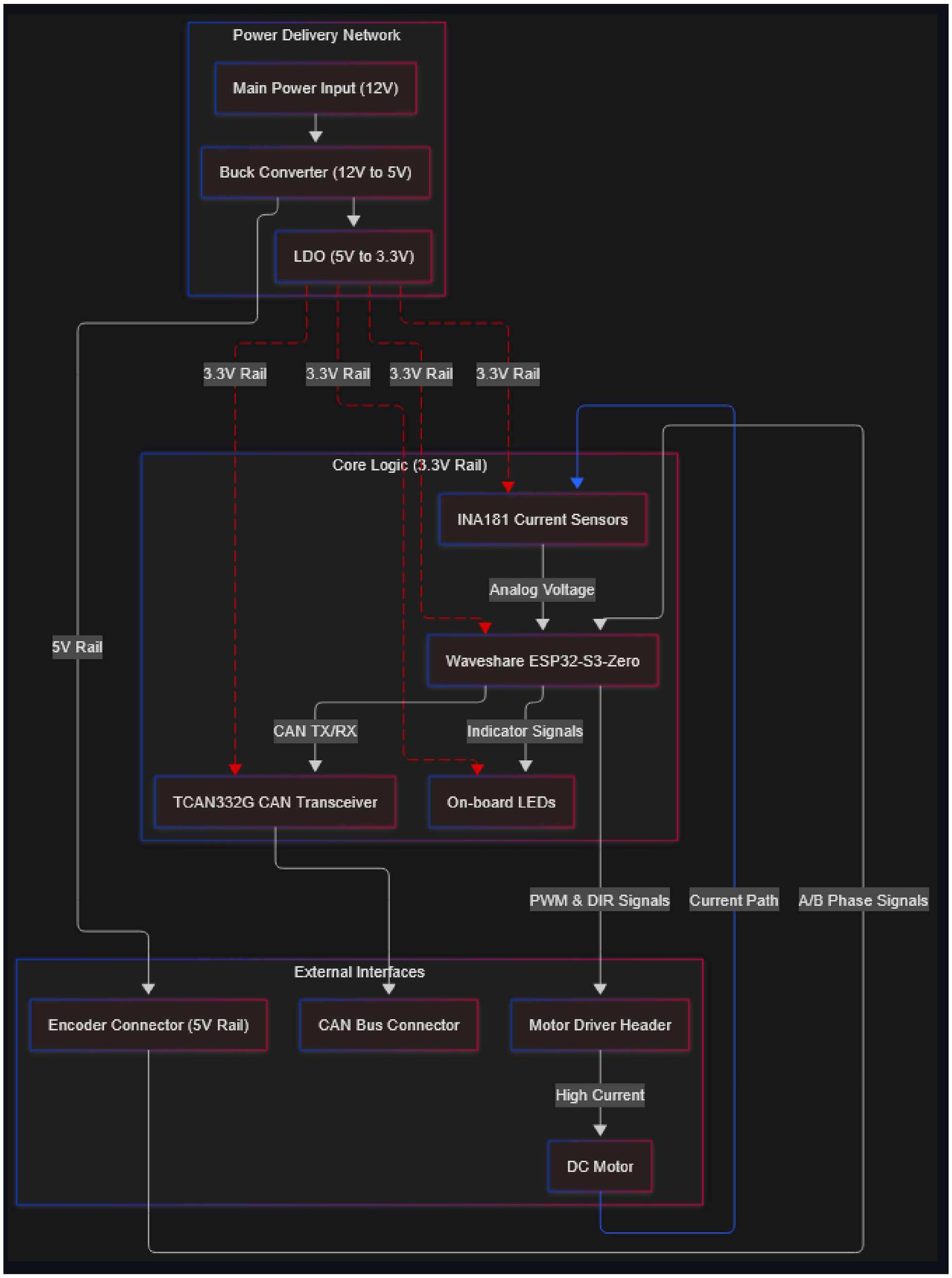

Figure 1: System Architecture Diagram

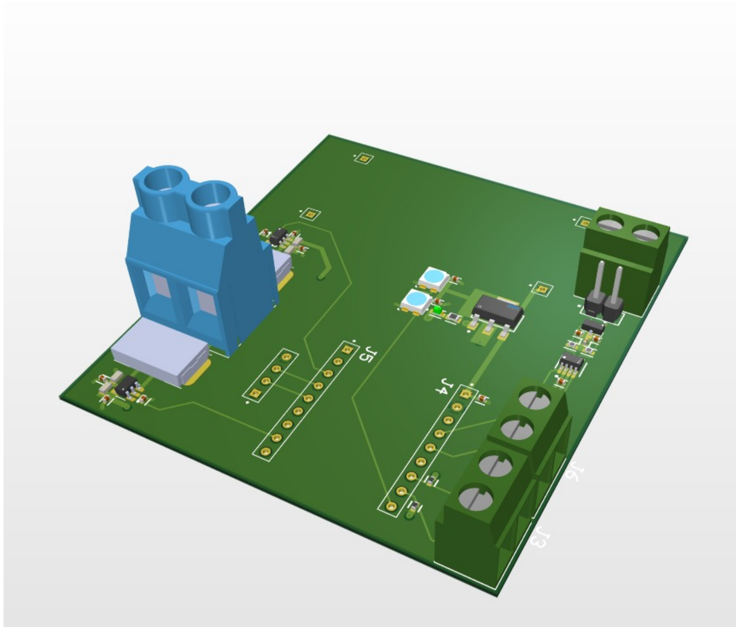

Figure 2: 3D PCB Render

3 Subsystem Deep Dive & Design Rationale

3.1 Power Delivery Network (PDN)

Stage 1: Buck Converter (12V → 5V)
Handles initial voltage drop, powering the 5V rail for the encoder. A buck converter, e.g., LM2596, is selected for high efficiency (>85%). LDOs are unsuitable due to poor thermal performance at this step.

Stage 2: LDO (5V → 3.3V)
Provides a low-noise, stable 3.3V rail for logic, sensing, and communication. The AZ1117CH-3.3TRG1 LDO offers:

- Low output noise (critical for ADC accuracy)
- Ample current capacity (1A rating vs. ∼500mA MCU peak)
- Good thermal properties (SOT-223 package with copper pour)

3.2 Microcontroller (MCU)

Component: Waveshare ESP32-S3-Zero
Chosen for its dual-core processing and rich peripherals:

- **LEDC:** Hardware PWM for motor speed control.
- **PCNT:** Hardware quadrature decoding for encoder signals.
- **ADC:** Analog input for current sense amplifier.
- **TWAI:** Native CAN controller for network integration.

3.3 CAN Communication System

The adoption of CAN bus communication over previously used I2C provides several critical advantages for our motor controller design:

- **Superior Noise Immunity:** CAN's differential signaling provides excellent resistance against electromagnetic interference, addressing the significant noise issues we previously encountered with I2C in high-current motor environments.
- **Robust Error Detection:** CAN's built-in CRC and acknowledgment mechanisms ensure data integrity in electrically noisy environments.
- **Reliable Long-Distance Communication:** Unlike I2C's limited range, CAN allows communication distances up to 1km, facilitating reliable ESP32-Jetson integration across our robot's chassis.
- **Multi-Master Capability:** CAN's inherent support for multiple nodes without master-slave limitations provides flexibility in system architecture and expansion.
- **Real-Time Performance:** CAN's deterministic collision resolution ensures timely delivery of critical motor control commands, a limitation previously observed with I2C.

The transition to CAN has eliminated the communication failures previously experienced with I2C, particularly during high-torque motor operations when communication reliability is most crucial.

3.4 Encoder Interface

Facilitates safe reading of 5V NPN open-collector encoder signals using the ESP32's 3.3V logic. A resistor pull-up network (4.7kΩ) adapts the signal, eliminating the need for level-shifter ICs.

3.5 Current Sensing

Provides real-time motor current measurement using low-side topology:

- **Shunt Resistor (WSR32L000FEA):** 2mΩ for minimal power loss.
- **Amplifier (INA181A3IDBVR):** Precision sense, fixed gain (100 V/V), mapping 13A max current to ∼2.6V ADC input.

3.6 Directional LED Indicators

Visual feedback for motor direction is provided by a complementary transistor pair (NPN: SS8050-G, PNP: SMMBT3906WT1G), enabling two LEDs to be driven by a single GPIO pin.

3.7 Programmable Status LED

Uses SK6812MINI-HS addressable RGB LEDs (3.3V native), allowing direct MCU control without level shifting. Two LEDs are chained for expanded status indication.

Conclusion

This motor controller PCB exemplifies high-performance, modular design for robotic applications, integrating robust power delivery, precise feedback, and reliable communication. Your technical review and feedback are welcomed for further refinement.