# Manipulator Module: Electrical & Electronics Subsystem Architecture

This document outlines the highly integrated, functional sub-circuits required for the Manipulator Module's dedicated Printed Circuit Board (PCB) and electronic routing. Designing these as a cohesive onboard system ensures professional packaging, mitigates electromagnetic interference (EMI), and eliminates loose wiring. This architecture strictly adheres to the Phase 1 Safety Check requirements and the sub-5-minute plug-and-play integration constraint dictated by the VDI 2206 design methodology.

## 1 Power Distribution & Protection Circuit (PDU)

Unlike the base, the arm does not house the main battery. This circuit manages the raw power received from the base, utilizing hot-swap methodologies to protect the arm's sensitive logic components and safely distribute high current to the dynamic actuators.

- **Standardized Hot-Swap Input:** A high-current locking connector (e.g., XT60 or Anderson Powerpole) serves as the primary interface. An inrush current limiter (eFuse IC or NTC thermistor) is implemented to prevent connector sparking and voltage sags during plug-and-play attachment.
- **Advanced Local Protection:** A fast-acting automotive blade fuse rated specifically for the arm's maximum stall current. This is paired with a P-Channel MOSFET ideal diode circuit for negligible voltage-drop reverse polarity protection, and TVS (Transient Voltage Suppressor) diodes to clamp inductive voltage spikes generated by the base's traction motors.
- **Synchronous Step-Down Converters (Buck):** High-efficiency switching regulators featuring integrated LC filters to drop the raw 12V/24V bus voltage down to ultra-stable logic levels (3.3V for the MCU/Sensors and 5V for the camera/logic ICs).
- **Galvanically Isolated Motor Power Injection:** Heavy copper pours (2 oz/ft$^2$) and dedicated wide traces route high-current raw power directly to the servo headers. The motor ground return path is physically separated from the logic ground on the PCB to prevent ground bounce.

## 2 Actuator & Limit Switch Interface Circuit

This circuit bridges the high-level logical commands from the MCU to the physical electromechanical joints and gripper, ensuring real-time, deterministic control.

- **Smart Servo Half-Duplex Bus:** 3-pin or 4-pin headers (Power, GND, Data) designed to daisy-chain serial servos (e.g., Dynamixel or Feetech). The circuit utilizes a tri-state buffer IC (e.g., 74LVC1G126) to cleanly convert the MCU's standard full-duplex UART (Tx/Rx) into the single-wire half-duplex signal required by industrial smart servos.
- **Opto-Isolated Gripper PWM Output:** A dedicated header to drive the micro-servo responsible for the V-shaped interlocking gripper fingers. The PWM signal is passed through an optocoupler to ensure back-EMF from the cheap micro-servo does not damage the main MCU.
- **Hardware Debounced Limit Switch Inputs:** Headers for physical end-stop/homing switches. To ensure zero false-triggers from motor noise, the inputs pass through an RC low-pass filter followed by an inverting Schmitt Trigger IC (e.g., 74HC14), feeding perfectly crisp digital edge interrupts to the MCU.

# 3 Perception & Lighting Circuit

This section manages the end-effector components strictly required for the autonomous, vision-based QR-code reading segment of the competition.

- **High-Speed Camera Interface:** A high-speed data routing path (USB 3.0 Type-C or MIPI CSI-2 via FPC cable) connecting the offset end-effector RGB camera. Differential pairs are routed with strict $90\Omega$ impedance matching to prevent data packet loss. This data bypasses the Arm MCU and routes directly to the Base Perception SoC.
- **Constant-Current LED Driver:** Instead of a basic PWM MOSFET, a dedicated constant-current buck LED driver (e.g., AL8805) powers the active LED ring light. This provides flicker-free illumination, which is absolutely critical to prevent rolling-shutter artifacts on the camera sensor during QR decoding under varying ambient track lighting.

# 4 MCU & Communication Circuit (Integration Layer)

This circuit houses the "brain" of the manipulator module and the robust communication bus required for seamless plug-and-play synchronization with the mobile base.

- **Microcontroller Unit (MCU):** A high-performance local processor equipped with a Hardware Floating-Point Unit (FPU) (e.g., STM32F4/F7 series or Teensy 4.0). The FPU is mandatory for computing complex 3D Inverse Kinematics (IK) matrices and joint trajectory profiling in real-time ($> 100$ Hz loop rate).

- **Isolated CAN Bus Transceiver:** The inter-module communication utilizes the Controller Area Network (CAN) protocol due to its extreme fault tolerance. A galvanically isolated CAN transceiver (e.g., ISO1050) is used alongside a 120$\Omega$ termination resistor. This electrically separates the base and arm, preventing noise from traction motors from corrupting the arm's target pose packets.
- **Safety Heartbeat Watchdog:** An independent hardware watchdog timer configured to trigger if the CAN bus heartbeat from the Base SoC is lost for more than 100ms, immediately pulling the smart servo enable lines low to freeze the arm in a safe state.

# 5 PCB Layout & EMI/EMC Guidelines

To guarantee reliability in a high-noise mechatronic environment, the Manipulator Module's custom PCB will be designed adhering to strict electromagnetic compatibility (EMC) standards:

- **Star Grounding Topology:** Motor power grounds and logic logic grounds will only tie together at one single point (at the buck converter's ground pad) to completely eliminate ground loops.
- **Decoupling Strategy:** A generous array of $0.1\mu F$ and $10\mu F$ MLCC capacitors will be placed as physically close as possible to every IC's power pins to supply instantaneous current demands and filter high-frequency noise.