

Modular Omni-Wheel Mobile Manipulator

Manipulator Subsystem: Requirements Analysis Document

Course:

MCT333/MCT344 - Mechatronic System Design

Competition:

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1 Introduction

This document defines the system-level requirements for the Manipulator Subsystem (Arm and Gripper Module) of the Modular Omni-Wheel Mobile Manipulator developed for the Spring 2026 Mechatronics Omni-Challenge.

The Manipulator Subsystem consists of:

- A multi-degree-of-freedom (DOF) robotic arm.
- An end-effector (gripper) designed for specific competition objects.
- Local perception (camera) and dedicated arm control circuitry.
- Modular plug-and-play mechanical and electrical interfaces.

The requirements below are derived from the official competition document, focusing strictly on the manipulator's standalone functionalities and its integration with the mobile base.

2 System Overview

The Manipulator Module must operate as an independent, professionally packaged subsystem. Its primary objective is to autonomously reach, grasp $5 \times 5 \times 5$ cm cubes (encoded with QR codes) from a 40 cm elevated pedestal, identify their color via an integrated camera, and securely place them into specific onboard storage bins. It must achieve this while maintaining a lightweight profile and communicating seamlessly with the main mobile base.

3 Mechanical Requirements

3.1 Arm Structure & Kinematics

- **Degrees of Freedom (DOF):** Minimum of 4 DOF (e.g., Base Pan, Shoulder Tilt, Elbow Tilt, Wrist Pitch/Roll) to successfully pick from the pedestal and place into onboard storage bins.
- **Workspace (Reach Volume):**
 - Maximum horizontal reach: ≥ 40 cm from the center of the arm's base to the end-effector.
 - Maximum vertical reach: ≥ 45 cm from the robot's mounting plate to comfortably clear the 40 cm competition pedestal.
 - Folded State: Must fold completely into the robot's 50 cm (W) \times 50 cm (L) \times 70 cm (H) starting volume footprint.
- **Payload Capacity:**
 - Nominal Payload: ≥ 250 g (accommodates a standard $5 \times 5 \times 5$ cm plastic cube with a factor of safety).

- Maximum Payload (Stall Limit): ≥ 500 g at maximum horizontal extension.
- **Kinematic Performance:**
 - **Repeatability:** ± 5 mm at the end-effector to ensure reliable QR-code alignment and placement.
 - **End-Effector Velocity:** Capable of operational linear speeds up to 15 cm/s during autonomous trajectories.
- **Mass Constraints:** Total manipulator mass (including gripper and local electronics) must be ≤ 3 kg to preserve the mobile base’s center of gravity and respect the 10 kg global weight limit.

3.2 Gripper & End-Effector

- **Grasp Dimension (Stroke):** Maximum jaw opening must be ≥ 7 cm to comfortably approach the $5 \times 5 \times 5$ cm target cubes despite minor odometry errors.
- **Grip Force:** Must exert a sustained gripping force of ≥ 10 N (≈ 1 kg equivalent) without crushing or deforming the objects.
- **Geometric Constraints:** Must not physically obscure the face of the cube containing the QR code during the approach or grasping phases. Minimum camera viewing angle clearance ($> 60^\circ$ FOV) must be maintained.
- **Dynamic Stability:** Must maintain grip during fast omni-directional base movements (e.g., sudden braking or strafing) without dropping the payload.

3.3 Base Integration

- Must feature a standardized mechanical mounting pattern (e.g., base plate with alignment pins and quick-release fasteners).
- Must support attachment/detachment in under 5 minutes.

4 Electrical and Electronics Requirements

4.1 Control Hardware

- Must contain its own dedicated MCU/Controller (e.g., ESP32, STM32, Arduino) independent of the base’s navigation controller.
- Must include necessary motor drivers or interface logic for smart serial servos.

4.2 Sensors

- **Vision:** Must integrate a camera (RGB) positioned to clearly read QR codes on the cubes.
- **Proprioception:** Must include joint encoders (absolute or incremental) to track arm position accurately.

- **Limits:** Must include physical limit switches or hard-stops for homing and over-travel protection.

4.3 Communication

- Internal communication bus (e.g., UART, I2C, SPI) for sensors and actuators.
- External communication bus (e.g., CAN, RS-485, Ethernet) to receive high-level commands from the Integration Layer / Base.

5 Power System Requirements

5.1 Power Source Integration

- Must receive raw power from the Mobile Base Module via a standardized power connector.
- Must not require a separate dedicated battery unless explicitly justified by modularity limits.

5.2 Power Electronics

- Must include local voltage regulation (Buck converters) to provide stable 3.3V/5V for the arm's logic, MCU, and camera.
- Must distribute high-current power safely to the joint actuators.

5.3 Circuit Protection

- Must include local fusing specifically rated for the arm's maximum current draw.
- Must include reverse polarity protection at the plug-and-play power input.

6 Control and Software Requirements

- **Kinematic Engine:** Software must actively compute Forward and Inverse Kinematics to translate XYZ coordinates into joint angles.
- **Trajectory Planning:** Must implement smooth motion profiles (e.g., S-curve or trapezoidal) to prevent jerking and payload dropping.
- **State Machine:** Must possess operating states (Folded, Homing, Reaching, Grasping, Storing) controlled by the main base via the communication bus.
- **Safety Fallback:** Must automatically freeze all joint movements if the communication heartbeat from the base is lost.
- **Perception Pipeline:** Must capture camera frames and either process the QR code locally or stream the feed reliably to the main base SoC for processing.

7 Interface and Modularity Requirements

- **Electrical Interface:** Standardized power connector (e.g., XT60) and standard data connector (e.g., JST, Aviation plug) to enable plug-and-play.
- **Protocol:** Well-defined communication protocol including heartbeat, target pose commands, and current joint state feedback.
- **Wiring Management:** No exposed wires. Wires crossing joints must have strain relief and ideally be routed through drag chains or protective sleeving.
- **Assembly Time:** Full mechanical and electrical integration with the mobile base must be provable within a 5-minute window.

8 Safety Requirements

To pass the Phase 1 Safety Gate, the Manipulator Module must ensure:

- No hanging or exposed wires that could catch on the track or the robot base.
- No sharp edges or unsafe protrusions on the gripper or linkages (de-burred and covered).
- Software joint limits strictly enforced to prevent self-collision with the base or the camera.
- PCB and electronics are securely mounted within an enclosure, isolated from moving metal parts.