Basic Concept of Manipulator Subsystem

Hardware Architecture and Specification Compliance Report

Course:
MCT333/MCT344 - Mechatronic System Design

Competition:
Spring 2026 Mechatronics Omni-Challenge

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Abstract

This document outlines the proposed hardware architecture for the Manipulator Subsystem of the Spring 2026 Mechatronics Omni-Challenge. It details the selection of Smart Serial Servos for actuation to minimize weight and wiring complexity, a 4-DOF articulated arm design for optimal reach and foldability, and an offset end-effector perception module. Furthermore, this document demonstrates how these design choices comply with the official project specifications regarding modularity, strict dimensions ($50 \times 50 \times 70$ cm starting constraint), weight limits, and safety.

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1 Actuation System Selection

1.1 Trade-off Analysis

During the concept generation phase, the team evaluated three primary actuation systems for the robotic arm joints:

1. **Stepper Motors with Drivers:** High holding torque and precision, but significantly heavier. Requires complex homing routines with external limit switches and bulky multi-wire harnesses.

2. **DC Motors with Encoders:** Fast and potentially lightweight, but requires complex custom PID tuning, large gearboxes for necessary torque, and separate heavy motor driver boards.

3. **Smart Serial Servos (e.g., Dynamixel, Feetech):** High torque-to-weight ratio, built-in absolute encoders, built-in PID control, and daisy-chainable wiring (requires only 3 or 4 wires to run through the entire arm).

1.2 Final Decision

Smart Serial Servos were selected. The daisy-chaining capability is crucial for meeting the "sub-5-minute plug-and-play" requirement, as it radically simplifies the electrical interface between the base and the arm. Furthermore, their lightweight nature ensures the manipulator mass remains well below the 3 kg target, preserving the overall 10 kg limit and keeping the robot's center of gravity low.

2 Kinematic and Arm Design Concepts

2.1 Idea 1: Anthropomorphic 5-DOF Arm

A highly flexible design capable of complex 3D maneuvers. However, the extra joints add unnecessary weight, increase the complexity of the Inverse Kinematics (IK) solver, and make it difficult to reliably fold within the $50 \times 50 \times 70$ cm starting bounding box.

2.2 Idea 2: 4-DOF Selective Articulated Arm (Selected)

A streamlined 4-DOF configuration (Base Pan, Shoulder Pitch, Elbow Pitch, Wrist Pitch/Roll) focused on reaching the 40 cm pedestal and dropping cubes into the onboard bins.

- **Reach:** Link lengths are optimized to extend ≥ 40 cm horizontally and clear the 40 cm vertical pedestal height.

- **Foldability:** The arm is designed to fold back onto itself (similar to an excavator arm) to easily fit within the $50 \times 50 \times 70$ cm constraint.

- **Material:** Links will be fabricated using lightweight 3D printed PETG/ABS reinforced with carbon fiber tubes to prevent tip deflection.

3 End-Effector and Perception Architecture

3.1 Gripper Mechanism

To handle the $5 \times 5 \times 5$ cm cubes securely without dropping them during omni-directional strafing, a **parallel jaw gripper with V-shaped interlocking fingers** is selected. The fingers will be lined with high-friction silicone pads to ensure the cubes do not slip.

3.2 Perception Integration (Eye-in-Hand)

A local RGB camera must be mounted to read the QR codes on the cubes.

- **Placement:** Mounted directly on the end-effector (Eye-in-Hand) using an offset bracket.
- **Rationale:** The offset bracket ensures the gripper fingers do not physically obstruct the camera's Field of View (FOV) when approaching the cube. An active LED ring will be added to guarantee consistent lighting for QR decoding.

4 Safety and Modularity Interface

Modularity is a core requirement of the Spring 2026 competition. The manipulator will interface with the lower base via a strictly defined layer:

- **Mechanical:** A standardized base plate utilizing chamfered alignment pins and a quick-release latch to ensure attachment in under 5 minutes.
- **Electrical:** A centralized power connector (XT60) passing fused 12V/24V power, and a single communication connector (JST/Aviation) passing the CAN or UART bus signals.
- **Safety Fallback:** The Arm MCU will implement a software heartbeat. If communication with the Base SoC is lost, the smart servos will automatically enter a torque-hold (freeze) state to prevent the arm from collapsing.

5 Compliance Matrix

The following table maps our proposed design features to the specific constraints listed in the MCT333 Project Description.

Design Feature	Project Requirement	Status
4-DOF Foldable Kinematics	Max folded dimensions: $50 \times 50 \times 70$ cm	Compliant
Link Length Optimization	Reach 40 cm elevated pedestal	Compliant
Quick-Release Base Plate	Plug-and-play integration in < 5 minutes	Compliant
Smart Serial Servos	Minimize weight (< 10 kg total system limit)	Compliant
Offset Camera Bracket	Unobstructed QR code color classification	Compliant
V-Shaped Silicone Gripper	Secure grasp of $5 \times 5 \times 5$ cm cubes	Compliant
Heartbeat & Fused Power	Phase 1 Safety Gate (No uncontrolled motion)	Compliant

6 Next Steps

1. **CAD Validation:** Verify the 4-DOF arm kinematics and confirm the folded configuration fits within the 50×50 cm footprint using CAD software.
2. **Actuator Sizing:** Calculate the maximum static holding torque required at the shoulder joint when the arm is fully extended with a 250 g payload.
3. **Interface Prototyping:** 3D print and test the quick-release mechanical mating plate.
4. **Vision Testing:** Prototype the offset camera bracket and test QR code reading reliability under various lighting conditions.