Dual-Arm Robotic System for Cube Rotation

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1 Introduction

1.1 Objective and Background

- Goals: The primary goal of this project is to develop an integrated, bimanual robotic system capable of manipulating and solving a Rubik's cube with high precision. This system aims to overcome the limitations of traditional, single-purpose cube solvers by employing human-like manipulation, while solving the data-collection bottleneck inherent in training general bimanual policies by leveraging Sim-to-Real techniques.
- Functions: The product will perform a fully autonomous vision-scan-solve-rotate sequence. Triggered by a "One-button start," the system will visually identify the cube's state, compute the optimal solution path, and actuate dual 3-to-6 DOF robotic arms to execute the physical rotation without dropping or jamming the cube.
- Benefits: This system provides researchers and engineers with a robust physical platform to test and deploy bimanual manipulation policies trained entirely on synthetic data (via RoboTwin 2.0). It eliminates the time-consuming, expensive, and hardware-damaging process of collecting physical manipulation data in the real world [1].
- Features: Unlike existing solvers that rely on highly specialized, non-versatile mechanical enclosures, our system utilizes general-purpose bimanual arms with 3D-printed specialized end-effectors. Furthermore, it bridges simulation and reality through "Strong Domain Randomization," executing these advanced AI policies via a custom-designed PCB optimized for high-current motor drive and real-time MCU control.

1.2 High-Level Requirements

1. Visual Processing: The vision system must correctly identify the color configuration of all 6 faces of a scrambled Rubik's cube and transmit the state matrix to the central compute unit within 30 seconds, maintaining accuracy under varying ambient lighting conditions.
2. Autonomous Actuation & Stability: Upon activation via the physical start button, the dual-arm system must autonomously execute the required physical rotations to solve the cube from any scrambled state within 3 minutes, achieving a mechanical

success rate of at least 95% across test trials without dropping the cube or triggering mechanical jamming faults.

3. Hardware Integrity: The custom-designed Power Module and PCB must sustain stable power delivery to the actuation modules, ensuring that voltage drops on the 5V and 3.3V logic rails do not exceed 5% during peak simultaneous motor activity, while avoiding thermal throttling.

2 Design & Requirement

2.1 System Physical Diagram

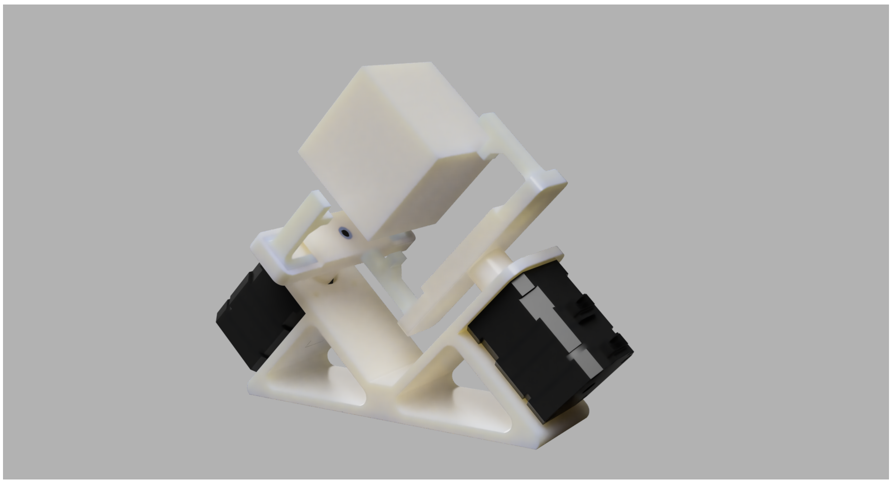

Figure 1: System physical diagram of the dual-arm Rubik's cube solving platform.

2.2 System Block Diagram

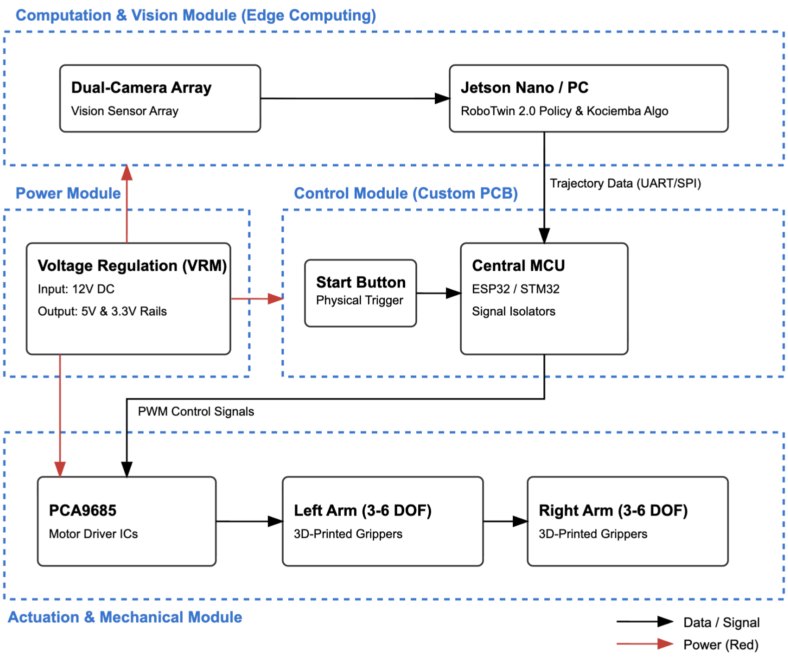

Figure 2: System block diagram of the dual-arm Rubik's cube solving platform.

2.3 Subsystem Descriptions

The dual-arm platform enables coordinated in-hand manipulation of the Rubik's cube. During a bottom-layer turn, one robotic arm maintains a stable grasp on the cube body to preserve global pose, while the other arm applies the commanded torque to rotate the bottom layer by 90 degrees. This master-support coordination minimizes slippage, avoids full re-grasp cycles between moves, and improves execution reliability for continuous multi-step solving sequences.

The Power Module is the backbone, ensuring that the high current drawn by the dual robotic arms during rapid rotation sequences does not disrupt the logic-level voltages required by the microcontrollers. The Control Module serves as the real-time execution hub, translating the high-level policy paths from the Computation Module into precise, isolated PWM signals for the Actuation Module. The Computation Module acts as the "brain," utilizing cameras to capture the cube's state and running the Kociemba algorithm and Sim-to-Real policy to generate safe, collision-free movement trajectories for the dual arms [1, 2].

2.4 Requirements and Verifications

Table 1: Power Module (Voltage Regulation) Requirements and Verification

Requirements	Verification
1. The 5V voltage regulator must step down a 12V ± 10% DC input source to 5V ± 5% DC, and be capable of sourcing a continuous current of up to 3A to power the motor drivers.	1A. Connect a DC bench power supply set to 12V to the input. 1B. Connect a programmable electronic load to the 5V output. 1C. Adjust load from 0A to 3A in 0.5A increments. 1D. Measure output using a DMM to ensure it stays between 4.75V and 5.25V.
2. The 3.3V logic voltage regulator must step down the input to 3.3V ± 3% DC and source up to 500mA for the central MCU and logic ICs.	2A. Connect an electronic load to the 3.3V output. 2B. Adjust load to 500mA. 2C. Measure output to ensure voltage is between 3.20V and 3.40V.
3. The voltage regulator ICs must maintain thermal stability and not exceed a package temperature of 85°C under peak continuous load.	3A. Run electronic loads at maximum specified currents (3A on 5V, 500mA on 3.3V) for 10 minutes. 3B. Use an IR thermometer to verify surface temperature remains below 85°C.

2.5 Tolerance Analysis: Transient Voltage Drop on Motor Rail

The most critical risk to the successful operation of our dual-arm robotic system is power instability caused by the simultaneous actuation of multiple servo motors. When the bimanual arms execute a rapid cube rotation, the motors draw a massive inrush current. If the Power Module cannot respond fast enough, the resulting transient voltage

Table 2: Control Module (Central MCU & PWM Driver) Requirements and Verification

Requirements	**Verification**
1. The central MCU must successfully transmit I2C control signals at 400 kHz without data loss or clock stretching exceeding 10%.	1A. Connect oscilloscope to SCL/SDA test points. 1B. Program MCU to send continuous byte sequences. 1C. Verify clock frequency is 400 kHz $\pm$ 5% and decode data to confirm matches.
2. The motor driver IC must output 16 PWM signals at 50 Hz $\pm$ 1% and map duty cycle commands from 2.5% to 12.5% [3].	2A. Command a 7.5% duty cycle at 50 Hz. 2B. Measure period on oscilloscope (target: 20 ms $\pm$ 0.2 ms). 2C. Verify pulse width is 1.5 ms $\pm$ 0.05 ms.

Table 3: Computation & Vision Module (Edge Computing) Requirements and Verification

Requirements	**Verification**
1. The vision system must recognize all 54 squares under 300-500 lux within 5 seconds.	1A. Place scrambled cube in workspace. 1B. Verify ambient light is $\sim$400 lux via lux meter. 1C. Use software timer to verify scan time $<$ 5s. 1D. Confirm 100% accuracy across 5 different states.
2. The Kociemba algorithm and RoboTwin policy must compute a collision-free trajectory within 5 seconds.	2A. Inject scrambled state array into the module. 2B. Check software logs for time delta $\leq$ 5s. 2C. Run trajectory in simulation to confirm no collisions.

Table 4: Actuation & Mechanical Module Requirements and Verification

Requirements	**Verification**
1. 3D-printed end-effectors must hold the cube during 90-degree rapid rotations ($<$ 0.5s) without slippage.	1A. Secure cube in end-effectors. 1B. Execute 90-degree rotation at max speed. 1C. Record with 120 fps slow-motion camera. 1D. Verify no shift in alignment across 20 trials.
2. Dual-arm mechanism must not draw peak current exceeding 2.5A from the 5V rail during simultaneous motion.	2A. Use current probe with oscilloscope on 5V main trace. 2B. Execute aggressive simultaneous motion sequence. 2C. Verify peak inrush current $\leq$ 2.5A.

drop on the 5V rail may fall below the motor driver IC's operating threshold, causing system failure or MCU resets.

To prove our custom PCB design will survive worst-case scenarios, we model the transient voltage response of our Voltage Regulation Module (VRM). The worst-case voltage drop ΔV during a sudden load step is determined by the Equivalent Series Resistance (ESR) of the bulk bypass capacitors and the total capacitance C available to supply charge before the VRM's feedback loop reacts:

$$\Delta V = \Delta I \cdot \text{ESR} + \frac{\Delta I \cdot \Delta t}{C}$$

System Parameters and Constraints:

1. Requirement: Our HLR states the 5V rail must stay within a 5% tolerance. Therefore, the maximum allowable voltage drop is:

$$\Delta V_{max} = 5 \times 0.05 = 0.25\text{V}$$

2. Transient Current (ΔI): Assuming each arm draws a 1.0A peak inrush current from a standstill, the simultaneous actuation yields $\Delta I = 2.0$A.
3. Regulator Response Time (Δt): A standard switching buck converter has a typical feedback loop response time of 10μs.
4. Capacitor ESR: By selecting low-ESR polymer Tantalum or MLCC capacitors, we limit the ESR to 0.05Ω.

Calculation: We solve for the minimum required bulk capacitance C to guarantee that $\Delta V \leq 0.25$V:

$$\begin{aligned} 0.25 &\geq 2.0 \cdot 0.05 + \frac{2.0 \cdot 10 \times 10^{-6}}{C} \\ 0.25 &\geq 0.1 + \frac{20 \times 10^{-6}}{C} \\ 0.15 &\geq \frac{20 \times 10^{-6}}{C} \\ C &\geq \frac{20 \times 10^{-6}}{0.15} \\ C &\geq 133.3\mu\text{F} \end{aligned}$$

Conclusion: Relying solely on the voltage regulator's raw output will result in failure. To maintain the required 5% voltage tolerance during bimanual high-speed rotations, our custom PCB must incorporate at least 135μF of low-ESR bulk capacitance near the motor driver power pins. We will implement a 220μF capacitor to provide a safety margin, ensuring flawless Sim-to-Real policy execution without resets.

3 Ethics and Safety

The development of an autonomous, dual-arm robotic system driven by a Sim-to-Real machine learning policy introduces unique ethical and safety challenges. We are committed to adhering to the IEEE Code of Ethics and the ACM Code of Ethics and Professional Conduct throughout the project's lifecycle [4, 5].

3.1 Ethical Considerations

- AI Predictability and Harm Prevention: Our system relies on a bimanual manipulation policy trained entirely in simulation. End-to-end neural network policies act as "black boxes" and can exhibit unpredictable behaviors when crossing the Sim-to-Real gap. To align with the IEEE imperative to hold paramount the public's safety [4], we will restrict the algorithm to output positional coordinates only within a strictly defined bounding box, preventing erratic arm movements that could cause injury.
- Data Privacy: The system utilizes a vision module to scan the Rubik's cube, risking the inadvertent capture of human faces. To uphold privacy standards, all image processing will be strictly executed locally on the edge compute device. The camera feed is temporarily held in volatile memory to extract the color matrix and immediately discarded. No images will be transmitted externally [5].
- Honest Claims and Scope: We will be honest and realistic in stating claims based on available data. We will explicitly document that the trained policy is highly specific to the geometry of a Rubik's cube, preventing misrepresentation of the system as a generalized household bimanual robot.

3.2 Safety Concerns and Mitigations

- Mechanical Hazards (Pinch Points and Collisions): The rapid 90-degree rotation of the cube requires significant torque, presenting severe pinch hazards.

  Mitigation: We will implement velocity and torque limits in software. In hardware, we will demarcate the workspace with warning tape and feature a hardwired Emergency Stop (E-Stop) button that physically interrupts the 12V power supply to the actuation module, bypassing the MCU.
- Electrical Hazards (High Inrush Currents): Simultaneous activation of motors can draw peak currents exceeding 2.5A, risking thermal runaway or wire melting.

  Mitigation: The custom PCB will feature wide copper pours and thermal vias to dissipate heat efficiently. We will use appropriately rated wire gauges and install an in-line fast-blow fuse (e.g., 5A) between the power source and the PCB to break the circuit in the event of a catastrophic short.
- Operational and Lab Safety: All assembly and testing will follow standard laboratory safety protocols. Safety glasses will be worn during high-speed mechanical testing to protect against potential 3D-printed part shattering under stress.

References

[1] Y. Sun *et al.*, "Robotwin: Dual-arm robot simulation and sim-to-real transfer for complex manipulation," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2023.

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[3] NXP Semiconductors, *PCA9685: 16-channel, 12-bit PWM Fm+ I2C-bus LED controller*, rev. 4 ed., Oct 2015. [Online; accessed 23-Mar-2026].

[4] IEEE, "Ieee code of ethics," 2020. [Online; accessed 23-Mar-2026].

[5] ACM, "Acm code of ethics and professional conduct," 2018. [Online; accessed 23-Mar-2026].