

ECE 445 SENIOR DESIGN LABORATORY
DESIGN DOCUMENT

Dual-Arm Robotic System for Cube Rotation

Team #38

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1 Introduction

1.1 Problem Statement

Developing highly dexterous, bimanual robotic systems remains a significant challenge in robotics, primarily due to the data-collection bottleneck inherent in training general manipulation policies. Traditional single-purpose Rubik’s cube solvers rely on highly specialized, non-versatile mechanical enclosures that do not translate to general robotic tasks. Furthermore, training AI policies for bimanual manipulation in the real world is time-consuming, expensive, and risks hardware damage. There is a critical need for a robust physical platform that can test and deploy manipulation policies trained entirely on synthetic data (Sim-to-Real), using a standardized dual-arm setup.

1.2 Solution Overview & Visual Aid

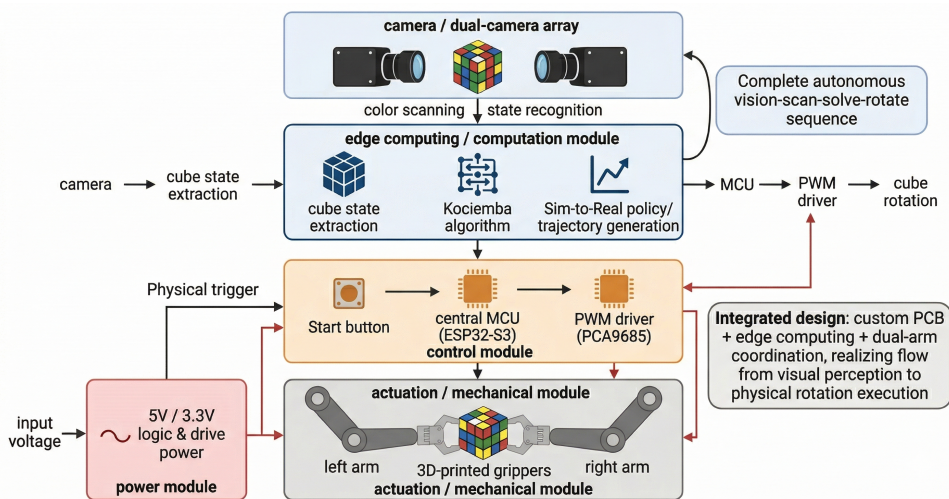


Figure 1. System Structure

Our solution is an integrated, bimanual robotic system capable of manipulating and solving a Rubik’s cube with high precision, mimicking human-like dexterity. The system performs a fully autonomous vision-scan-solve-rotate sequence. Triggered by a physical “Start” button, a top-mounted camera captures the cube’s faces while the robotic arms rotate it. The visual data is processed to extract the cube’s state matrix, which is then fed into the Kociemba algorithm to generate an optimal solution path.

To bridge simulation and reality through “Strong Domain Randomization”, the system utilizes two general-purpose 3-to-6 DOF robotic arms equipped with 3D-printed end-effectors. The hardware is driven by a custom-designed PCB carrier board featuring an ESP32-S3 microcontroller, a PCA9685 PWM driver for precise servo actuation, and a robust power management system to handle high-current transients during rapid dual-arm movements.

1.3 High-Level Requirements List

The Dual-Arm Robotic System shall meet the following 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 within 3 minutes, achieving a mechanical success rate of $\geq 95\%$ 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.

2.3 Gripper System

Using 42 Double-layer stacked stepping motor to drive a 2 DOF gripper with only one motor. Two grippers with perpendicular axes enable the rotation of all cube layers. One gripper can only rotate one later at one time and when rotating, the another gripper should catch the cube tightly.



Figure 4. 42 Double-layer stacked stepping motor

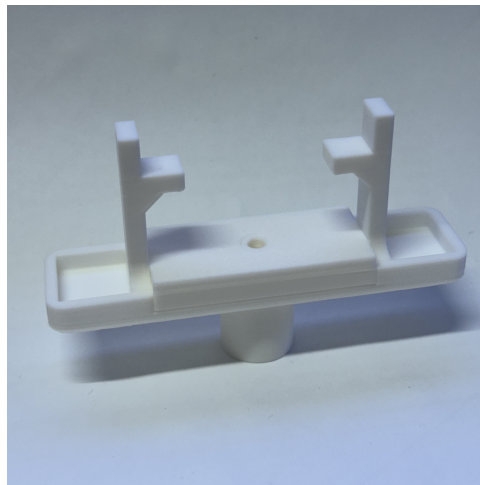


Figure 5. 3D printed gripper

2.4 Power System

The Power Subsystem is the backbone of the custom PCB, responsible for converting the 24V DC input into stable 5V and 3.3V rails. Due to the high current drawn by the dual robotic arms, a switching buck converter (XL4015) is used to step down 24V to 5V (up to 5A) specifically for the stepping motors. Two linear LDO regulators (AMS1117-5.0 and AMS1117-3.3) are used to provide clean logic-level voltages for the MCU and sensors.

Table 1: Power Subsystem Requirements and Verifications

Requirement	Verification
1. The XL4015 buck converter must output $5.0V \pm 0.25V$ under a continuous load of 4A.	1. Connect a 1.25Ω power resistor to the 5V servo rail. Measure the voltage using a multimeter to ensure it is within 4.75V - 5.25V.
2. Voltage drop on the 3.3V logic rail must not exceed 5% ($< 0.165V$) during peak servo actuation.	2. Probe the 3.3V test point with an oscilloscope. Command all servos to move simultaneously and verify the transient voltage drop remains above 3.13V.

2.5 Hardware Support

Requirements	Verification
1. The two cameras shall together detect the color arrangement of all faces of the cube	1. Run detection code with fixed camera setting to check the output.
2. Processing unit shall execute YOLOv8 at ≥ 20 fps.	2. Run test.py, average inference time ≤ 50 ms.
3. The stepping motor shall rotate without gripper confliction.	3. Run simulation to test the algorithm.

3 Cost

Table 2: Parts Cost Breakdown

Part	Unit Cost (USD)	Quantity	Total Cost (USD)
42 Double-layer stacked stepping motor	\$ 10.00	2	\$16.00
ESP32-S3-DevKitC-1	\$ 8.00	1	\$ 8.00
Custom PCB Manufacturing (JLCPCB)	\$ 5.00	5	\$ 25.00
PCB Components (PCA9685, XL4015, LDOs, passives)	\$ 15.00	1	\$ 15.00
USB Camera (1080P)	\$ 15.00	2	\$ 30.00
3D Printing Material	\$ 7.00	1	\$ 7.00
24V Power Supply Adapter	\$ 18.00	1	\$ 18.00
Total Parts Cost			\$ 119.00

4 Schedule

Table 3: Project Schedule by Team Member

Week	Zhuoyang Shen	Qixuan Huang	Yiming Xu	Rong Wang
Week 1	System Architecture	Kociemba Algorithm Test	CV Model Selection	3D Model Design (Arms)
Week 2	PCB Schematic Design	PC-ESP32 Comm Protocol	Color Recognition Script	Print End-effectors
Week 3	PCB Layout & Routing	PWM Control Logic	Camera Calibration	Assemble Robotic Arms
Week 4	Order PCB & Parts	Sim-to-Real Policy	Integration Testing	Servo Calibration
Week 5	Solder & Test PCB	Debug Cube Solving	Debug Vision-to-State	Mechanical Tuning
Week 6	Full System Integration	Full System Integration	Full System Integration	Full System Integration
Week 7	Prepare Final Demo	Polish Software	Data Analysis	Final Report Writing

5 Ethics and Safety

5.1 Ethics

In accordance with the IEEE Code of Ethics, we prioritize the safety, health, and welfare of the public. This project explores Sim-to-Real AI policies. We commit to transparency in our data reporting, ensuring that success rates and failure modes (such as cube dropping or jamming) are reported honestly without manipulation. Furthermore, the vision system utilizes a camera; we will ensure that the camera is strictly pointed downward at the Rubik's cube to avoid inadvertently capturing personally identifiable information or faces of bystanders, thus respecting privacy.

5.2 Safety

Safety is critical when dealing with autonomous robotic arms and high-current power systems.

- **Mechanical Safety:** The robotic arms pose a pinch hazard. We will implement software limits on servo ranges to prevent self-collision. A physical emergency stop (E-Stop) feature will be integrated into the main power line to immediately cut power to the servos in case of unpredictable behavior.
- **Electrical Safety:** The system operates on a 24V power supply capable of delivering high current. We have designed our PCB with a 5A PPTC resettable fuse and reverse-polarity protection (Schottky diode) to prevent fire hazards in the event of a short circuit. All power rails include LED indicators to warn users when the board is live.

References

- [1] Zhao, H., et al. "RoboTwin: Dual-Arm Robot Learning from Demonstration in Simulation." *arXiv preprint*, 2023.
- [2] Kociemba, H. "The Two-Phase-Algorithm for the Rubik's Cube." <http://kociemba.org/cube.htm>, accessed 2023.
- [3] Espressif Systems. "ESP32-S3 Series Datasheet." 2023.
- [4] NXP Semiconductors. "PCA9685: 16-channel, 12-bit PWM Fm+ I2C-bus LED controller datasheet." 2015.