***Arab American University***

***Faculty of Engineering and Information Technology***

***Computer Systems Engineering***

**SENIOR PROJECT I**

*Cube Mind   
(Rubik's Cube solver)*

*2025/2026*

|  |
| --- |
| Supervised by: *Dr. Tareq Zanoon* |

|  |
| --- |
| **Computer Systems Engineering Dept.**  **Submitted in partial fulfillment of the requirements of B.Sc. Degree in Computer Systems Engineering**  ***Insert Date Here*** |

**Students Statement**

We, the undersigned students, certify and confirm that the work submitted in this project report is entirely our own and has not been copied from any other source. Any material that has been used from other sources has been properly cited and acknowledged in the report.

We are fully aware that any copying or improper citation of references/sources used in this report will be considered plagiarism, which is a clear violation of the Code of Ethics of the Arab American University.

|  |  |
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| Loai Hamamdeh (201811792) |  |

**Supervisor Certification**

This to certify that the work presented in this senior year project manuscript was carried out under my supervision, which is entitled:

“**SDP Title Goes Here**”

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| *Loai Hamamdeh (201811792)* |  |

I hereby that the aforementioned students have successfully finished their senior year project and by submitting this report they have fulfilled in partial the requirements of B.Sc. Degree in Engineering.

I also, hereby that I have **read, reviewed and corrected the technical content** of this report and I believe that it is adequate in scope, quality and content and it is in alignment with the ABET requirements and the department guidelines.

*Dr. Tareq Zanoon,*

**ACKNOWLEDGMENT**

We would like to express our sincere gratitude and appreciation to all those who contributed to the successful completion of this senior project.

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Finally, we thank everyone who directly or indirectly contributed to the success of this project. Their support and encouragement have made this achievement possible.

**ABSTRACT**

This project presents the design and implementation of an autonomous robot capable of solving a 3×3 Rubik's cube using Kociemba's algorithm. The primary objective of this work is to integrate and apply the knowledge and skills acquired throughout our Computer System Engineering studies while exploring new technical competencies in robotics, computer vision, and algorithm implementation.

The system consists of a Raspberry Pi as the main processing unit, coupled with cameras for cube state detection, motors for mechanical manipulation, and supporting structural components. The robot operates by first scanning and analyzing all six faces of the Rubik's cube using computer vision techniques to determine the current scrambled state. Once the cube configuration is captured and processed, the system applies Kociemba's algorithm to calculate an optimal solution sequence. The robot then executes the solution by systematically rotating the cube faces using precisely controlled motors until the puzzle is completely solved.

The project demonstrates the successful integration of multiple engineering disciplines, including embedded systems programming, computer vision, mechanical design, and algorithmic problem-solving. Developed using Python programming language, the system showcases the practical application of theoretical concepts learned during our academic program. This work contributes to the field of educational robotics and serves as a comprehensive demonstration of autonomous puzzle solving capabilities, bridging the gap between algorithmic theory and practical robotic implementation.

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*(Senior Project I chapters 1 -3),*

*(Senior Project II All chapters)*

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|  |  |
| --- | --- |
| **LIST OF SYMBOLS** | |
| **ω** | Angular velocity in rad/s |
| **ξ** | Damping ratio |
|  |  |
| **LIST OF ABBREVIATIONS** | |
| **ABET** | Accreditation Board For Engineering And Technology |
| **EC** | Examining Committee |
| **PC** | Project Committee |
| **STEM** |  **S**cience   **T**echnology   **E**ngineering   **M**athematics |
| **BFS** | Breadth First Search |
| **CNN** | Convolutional Neural Network |
| **CFOP** | CFOP: Cross, F2L (First Two Layers), OLL (Orientation of the Last Layer), PLL (Permutation of the Last Layer) |
| **DFS** | Depth First Search |
|  |  |

1. **CHAPTER 1: INTRODUCTION**

This project focuses on the design and implementation of an autonomous robot capable of solving a 3×3 Rubik's cube, integrating multiple engineering disciplines including computer vision, mechanical design, embedded systems, and algorithmic implementation. The challenge lies in creating a robust physical system capable of precise cube manipulation and reliable state detection while applying the knowledge gained throughout our Computer System Engineering studies.

We chose Kociemba's algorithm because it finds efficient solutions with a low number of moves, often under 21 steps. It's fast, well documented, and works well with the standard 3×3 cube structure. This makes it ideal for real time solving in a robotic system, where fewer moves mean less mechanical complexity and faster results. However, implementing this algorithm in a physical robotic system presents several significant technical challenges. Color detection requires accurately identifying the cube's colors using a camera under different lighting conditions, which can be particularly difficult. Mechanical control involves designing a stable and precise system to rotate the cube faces without slipping or misalignment. Integration challenges arise from ensuring that hardware components including motors and cameras work seamlessly with software systems encompassing vision processing and algorithm implementation in real time. Additionally, calibration requires precise alignment of the camera, cube positioning, and mechanical arms for consistent operation.

The scope of this project encompasses the complete design and implementation of an autonomous Rubik's cube solving robot. The main objectives include developing a robust computer vision system for accurate cube state detection, implementing Kociemba's algorithm for efficient solution generation, designing and constructing a reliable mechanical manipulation system, integrating all components using a Raspberry Pi based control system, and demonstrating successful autonomous cube solving capabilities. The expected outcomes include a fully functional robot capable of consistently solving scrambled 3×3 Rubik's cubes, comprehensive documentation of the design and implementation process, and demonstration of the practical application of Computer System Engineering principles in a real world robotics project.

* 1. Problem Statement and Purpose

This project addresses the technical challenge of designing and implementing an autonomous robotic system that can detect, analyze, and solve a scrambled 3×3 Rubik's cube without human intervention. The system must integrate computer vision for cube state recognition, Kociemba's algorithm for solution computation, and precise mechanical control for cube manipulation using Raspberry Pi based embedded systems.

The purpose of this project is to demonstrate comprehensive application of Computer System Engineering principles through a complex, multi-disciplinary robotics implementation. This project provides practical experience in embedded systems programming, computer vision, mechanical design, and real time algorithm implementation, directly preparing students for industry challenges requiring integration of hardware and software systems. The project serves as an educational platform that bridges theoretical knowledge with practical engineering skills, contributing to STEM education by showcasing how multiple engineering disciplines collaborate to achieve autonomous system functionality.

* 1. Project and Design Objectives
* Solving Speed: The robot shall solve a standard 3×3 Rubik's cube in 30 seconds or less from initial cube scanning to completion.
* Success Rate: The system shall achieve a minimum 90% success rate in correctly solving randomly scrambled 3×3 Rubik's cubes across 20 test attempts.
* Color Detection Accuracy: The computer vision system shall accurately identify all six cube face colors with 95% accuracy under standard indoor lighting conditions.
* To develop our skills in building similar and diverse robotic systems by combining various hardware and software engineering techniques.
  1. Intended Outcomes and Deliverables

We intend to build a Rubik’s Cube Solving Robot, an embedded mechatronic system capable of automatically solving a standard 3x3 Rubik’s Cube. The robot will consist of a mechanical structure operated by motors to manipulate the cube, a software interface to receive or detect the cube's state, and a solving engine that applies the Kociemba algorithm to determine the optimal move sequence. The key outcome of this project is to demonstrate how embedded systems, control algorithms, and mechanical design can be integrated into a fully automated problem solving machine. This system aims to showcase the practical application of engineering principles in robotics, optimization, and real time control.  
This project is intended as a learning platform and proof of concept for more advanced robotic manipulation systems. We aim to present it at engineering exhibitions and hope to inspire further development in educational robotics or puzzle solving automation.

* 1. Summary of Report Structure

This report is organized into seven chapters. The second chapter provides an overview of the project and discusses related work in the field. The third chapter focuses on the system design and its components, covering design specifications, standards, constraints, design alternatives, system analysis, optimization, and simulation or experimental testing. Chapter four presents and analyzes the project results. Chapter five details the management aspects of the project, including time management, cost management, and lessons learned. Chapter six examines the project's costs, production considerations, and its social and environmental impact. Finally, chapter seven reflects on the project goals achieved, evaluates the level of success, highlights the skills and experiences gained, and offers recommendations for future work.

1. **CHAPTER 2: BACKGROUND**
   1. Overview

The Rubic’s Cube was invented in 1974, it is a three-dimensional puzzle that has fascinated millions around the world, competitions are now held to solve it, attracting people of all ages to try to solve it, solving the cube independently using robots requires the integration of multiple engineering disciplines, including computer vision, mechanical design, embedded system, and algorithm optimization. The challenge lies in creating a system capable of accurately determining the state of the cube, calculating the optimal solation and performing precise mechanical operations to efficiently solve the puzzle.

In this project, we used the Kociemba’s algorithm, a two- phase algorithm that significantly reduces the cube’s solution space, enabling the puzzle to be solved efficiently with the fewest moves, this algorithm is widely known for its balance between speed and optimal solution, making it ideal for robotic applications.

* 1. Related Work

### AI Rubick Cube solver

This is the first project related to our project and this project uses artificial intelligence to solve the Rubik’s Cube puzzle automatically, this project relies on algorithm like BFS, but instead, we worked on the Kociemba’s algorithm because it’s faster and better. This project would require thousands of moves to solve the cube, whereas ours solves the cube in 21 moves or less, this project relied on CNN, but we used cameras.

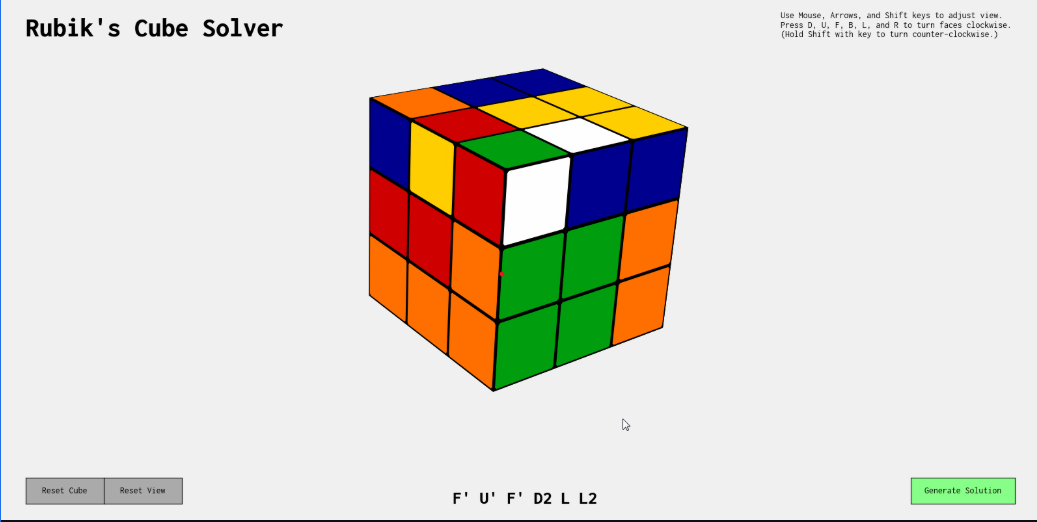


Figure 1

### Robot solves Rubic’s cube

The second project is a physical robot (not just a software simulation) that solves a Rubic’s Cube using motors and sensors. This project also aims to solve a Rubik’s Cube automatically and relies on a camera and motors, it’s similar to our project.

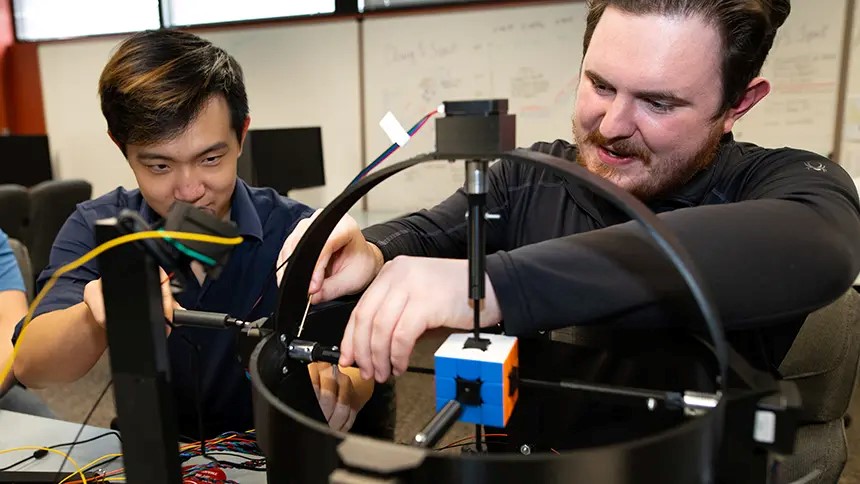


Figure 2

### CubeMoster

The third project is very similar to ours, solving the cube using several algorithms, such as CFOP, DFs and Kociemba’s, which we will use in our project. The main difference between the two projects is that they use an Arduino, a raspberry, while our project does not use an Arduino.



Figure 3

### Solving the Rubik’s cube with deep reinforcement learning and search

In this research, they created an artificial intelligence capable of solving the Rubic’s Cube without the need to study human solutions. It solves the cube in 20 moves, but it is merely a program that does not moves a real cube, this research is purely theoretical, our project is practical, and the cube will be moved by a real robot.

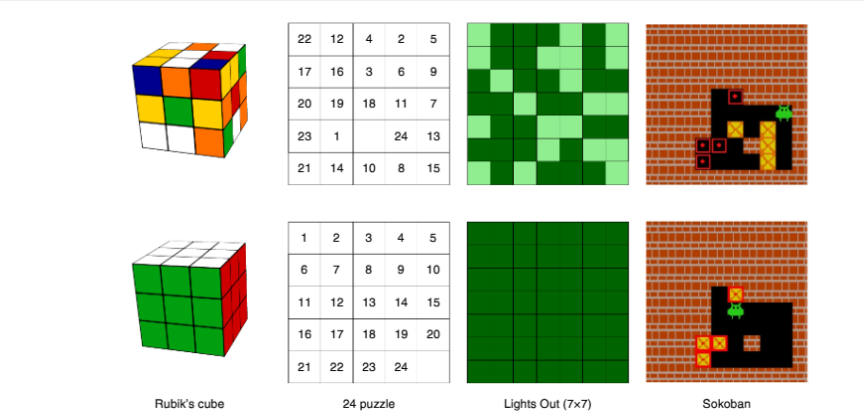


Figure 4

1. **CHAPTER 3: METHODS AND MATERIALS**
   1. System Design and Architecture

### **Project overview:**

Our senior project involves building an autonomous Rubik’s Cube solving robot that uses computer vision, servo control, and algorithmic problem-solving. The system consists of a Raspberry Pi, two cameras, six servo motors, and a mechanical base to manipulate and solve a standard 3x3 Rubik’s Cube. The solving logic is based on the Kociemba algorithm, implemented in Python.

The project was divided into four main subsystems:

* Image Acquisition and Processing

Two cameras were mounted on opposite sides of the cube to capture all six faces by rotating the cube as needed. Images are processed using OpenCV in Python to detect and map the color of each square.

* State Recognition and Solving Algorithm

The recognized cube colors are converted into a string format that represents the cube state. This state is passed into the Kociemba algorithm, which returns an optimized sequence of moves to solve the cube.

* Hardware Control and Cube Manipulation

Six servo motors are mounted around a custom base to grip and rotate each face of the cube. The Raspberry Pi generates PWM signals to control the motors based on the solution sequence.

* System Coordination and Execution

A control program on the Raspberry Pi orchestrates the full process: capturing images, interpreting the cube state, computing the solution, and commanding the servo motors to execute the moves.

### **Detailed System Architecture:**

1. Hardware Components:

* Raspberry Pi 4: Central processing unit running Python code, controlling all components.
* 2 USB Cameras: Capture images of the Rubik’s Cube from different angles.
* 6 Servo Motors: Control cube face rotations (one for each face).
* Power Supply: Supplies appropriate voltage to motors and Raspberry Pi.
* Custom Base and Grippers: Holds the cube in place and mounts all motors securely.

1. Software Components:

* OpenCV: Used for image capture and color detection.
* Python with Kociemba Module: Converts detected cube state to a solving sequence.
* GPIO Library: Sends PWM signals from Raspberry Pi to servo motors.

Main Control Script: Manages sequencing, timing, and coordination between vision, algorithm, and motor control.

### **system workflow summary:**

* Startup: The system initializes all motors and cameras.
* Image Capture: Cameras take pictures of the cube; faces are turned as needed.
* Color Mapping: The software identifies the color of each sticker.
* Solving: The current state is input into the Kociemba algorithm, which returns a solution.
* Execution: Servo motors rotate the cube step-by-step according to the solution sequence.
* Completion: The cube reaches the solved state, and the system halts or resets.

### **workflow flowchart:**

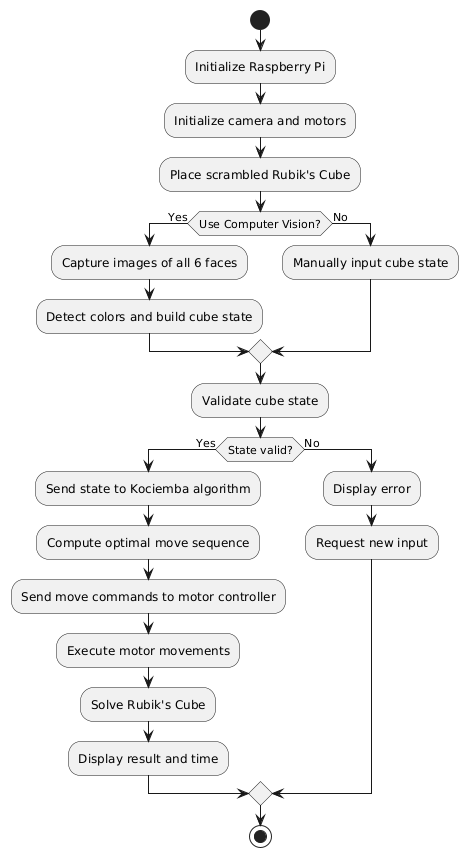


Figure 5

### **UseCase diagram:**

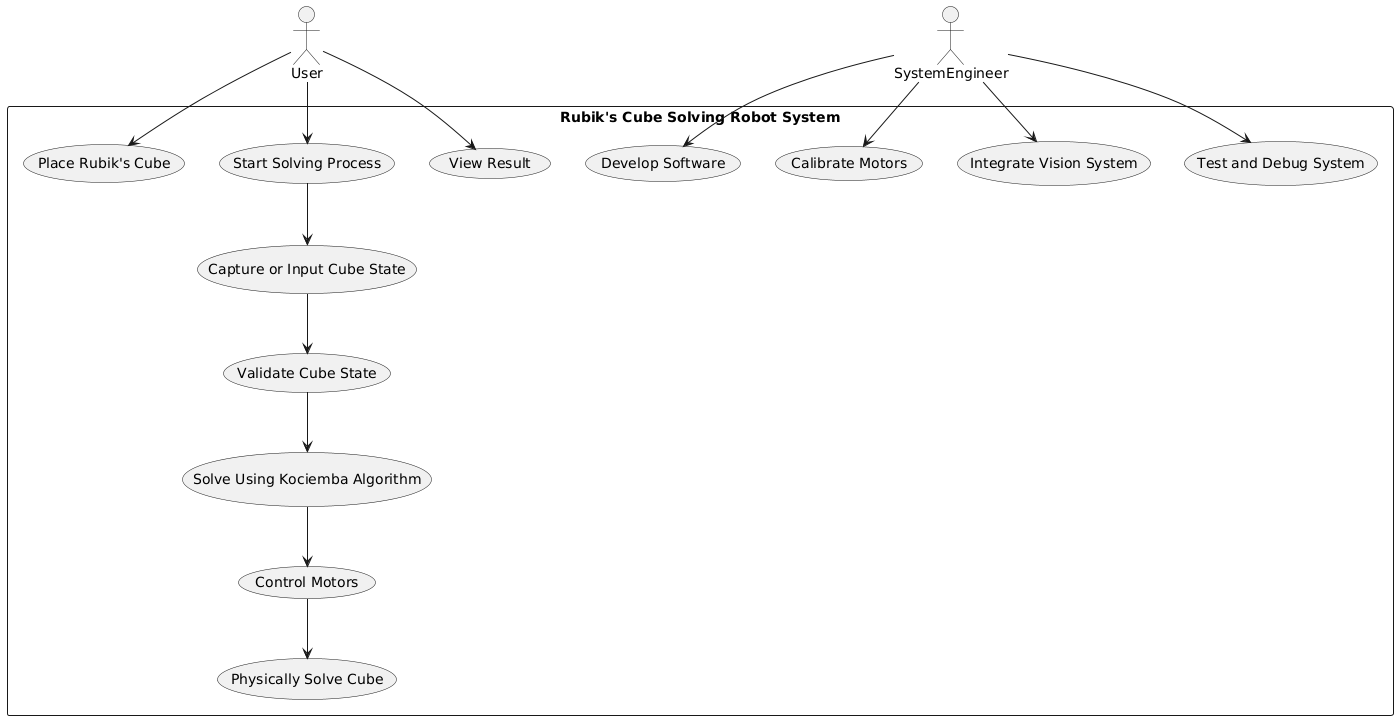


Figure 6

### **sequence diagram:**



Figure 7

* 1. System Design and Components

### **SYSTEM DESIGN**

**View #1 ( Top ) :**

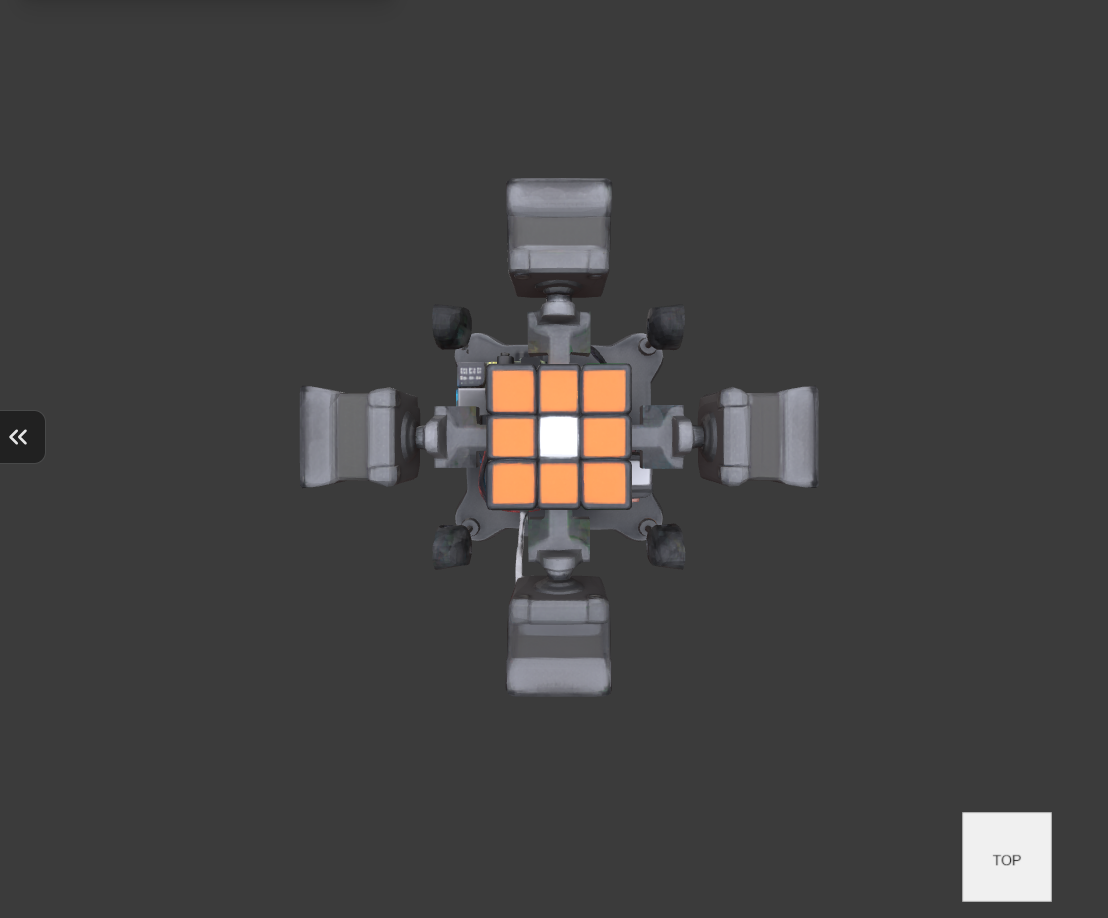


Figure 8

**View #2 :**

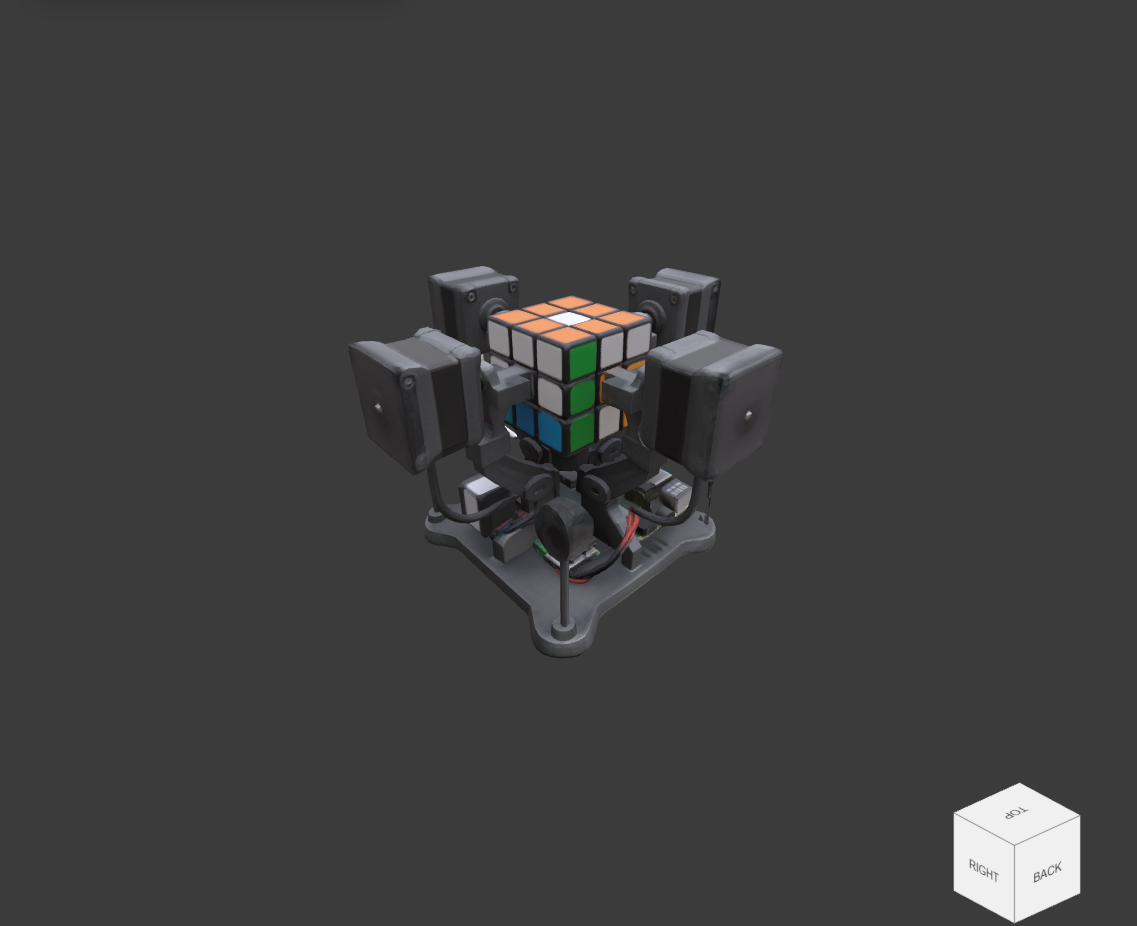


Figure 9

View #3 :



Figure 10

View #4 :

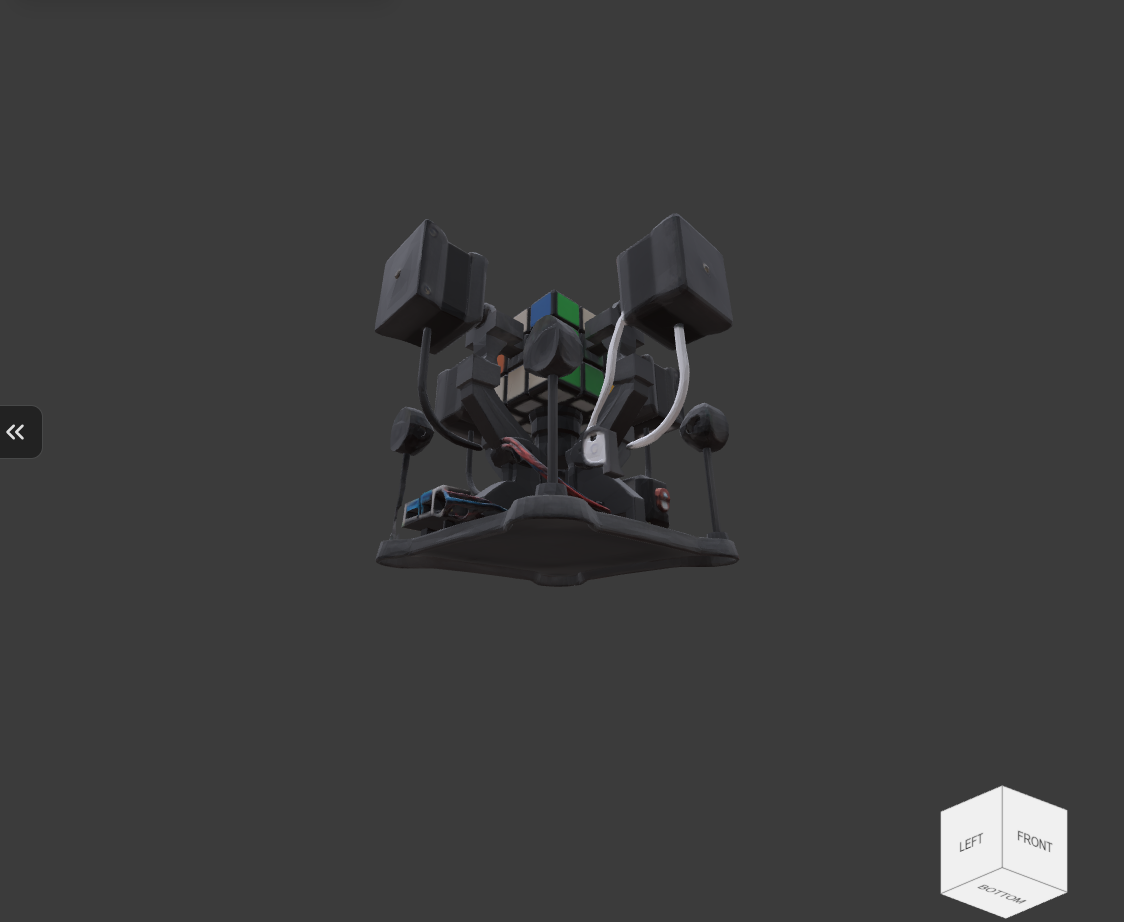


Figure 11

Note: the Design needs the sixth camera to read the upper (top) face of the cube to be completed.

### **project components:**

1. Raspberry Pi:



Figure 12

The Raspberry Pi acts as the central processing unit, coordinating all hardware and software operations of the Rubik’s Cube solving robot.  
It captures images from the two cameras, processes them using computer vision, and determines the cube's color configuration.  
Based on the solved sequence from the Kociemba's algorithm, the Raspberry Pi sends control signals to the servo motors to rotate the cube accordingly.

1. Cameras :

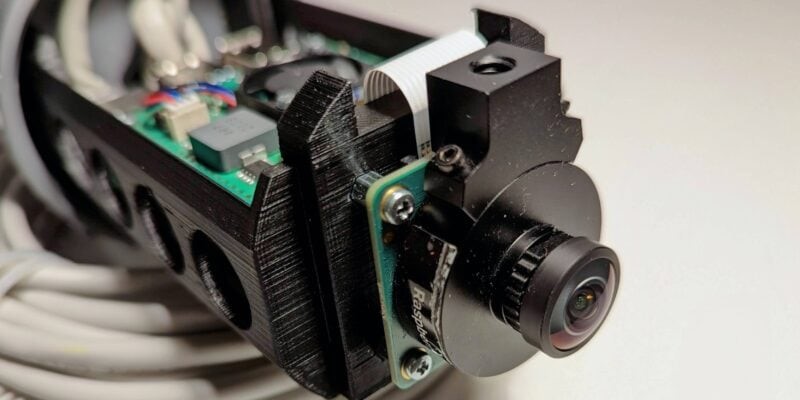


Figure 13

To determine each square's location and color, the cameras take high-resolution pictures of each face of the Rubik's Cube.  
The Raspberry Pi receives the captured images and uses OpenCV for image processing and color recognition.  
Before solving, the system can accurately reconstruct the cube's current state thanks to precise visual data from the cameras.

1. Servo Motors:



Figure 14

Commands from the Raspberry Pi cause the servo motors to physically rotate the Rubik's Cube's faces.  
With precise angular movement, each of the six servo motors is in charge of grasping and rotating a particular cube face.  
They carry out the algorithm-calculated solution steps, enabling the robot to solve the cube on its own.

1. Base :



Figure 15

The base supports the mounting of all six servo motors and offers a sturdy framework for safely holding the Rubik's Cube.

When the motors rotate each face, it makes sure the cube stays correctly aligned throughout rotation, avoiding slippage or misalignment.

Additionally, the base aids in the orderly arrangement of the parts, which makes the system small, strong, and simpler to put together and maintain.

### **software**

Kociemba's algorithm:

The Rubik's Cube can be solved from any jumbled state by using the Kociemba algorithm to determine an effective and ideal series of moves.

After image processing has identified the cube's current state, the algorithm uses this state as input in string format to produce a step-by-step solution.

The servo motors are then able to carry out each move and solve the cube by converting the output of the Kociemba algorithm into motor control commands.

* 1. Design Specifications, Standards and Constraints

### **Design specifications:**

Hardware Requirements:

* Raspberry Pi 4
* Six servo motors USB camera or Raspberry Pi Camera Module
* Power supply
* Mechanical frame supporting
* Standard 3×3 Rubik's cube compatibility

Performance Specifications:

* Cube solving time ≤30 seconds
* Success rate ≥ 90% across 20 test attempts
* Color detection accuracy ≥ 95% under standard indoor lighting
* Motor rotations : 90 , 180 , 270 or -90

### **applicable standards:**

Hardware Standards:

* USB 2.0/3.0: Used for connecting the camera to the Raspberry Pi for image capture.
* GPIO Standards: Relevant for configuring and interfacing with input/output pins on the Raspberry Pi.
* PWM Standards: Used to control servo motors for precise rotational movement.

Software Development Standards:

* Python Enhancement Proposals (PEP): Follows PEP 8 and PEP 257 for clean, readable, and maintainable Python code.
* OpenCV Standards: Computer vision library implementation for image processing

Communication Standards:

* I2C Protocol: Inter-integrated circuit communication for sensor interfaces
* UART Standards: Universal asynchronous receiver transmitter for serial communication

Open Source Standards:

* Linux Kernel Standards: Raspberry Pi OS (Debian-based) compliance
* GNU General Public License (GPL): Open source software licensing
* Python Software Foundation License: Python interpreter and libraries
* OpenCV BSD License: Computer vision library usage

Quality and Safety Standards:

* RoHS Directive: Ensures that electronic components used in the project are free from hazardous substances.

### **Design constraints:**

Physical Constraints:

* Power consumption limitation
* Operating noise level during cube manipulation

Performance Constraints:

* Real time processing requirements for computer vision algorithms
* Servo motor response time limitations
* Processing power limitations for algorithm optimization

Technical Constraints:

* Kociemba's algorithm implementation complexity and optimization requirements
* Computer vision accuracy limitations under varying lighting conditions
* Integration challenges between hardware and software components
  1. Design Alternatives

### **Solver algorithm**

Our initial alternative design for the project involved developing our own algorithm to solve the cube. However, we ultimately decided to implement Kociemba’s algorithm instead, as it offers greater efficiency and reliability. Creating a new algorithm from scratch would have required significantly more time and effort without providing any substantial benefits essentially reinventing the wheel.

### **Arduino**

The second design alternative was to use an Arduino board to handle the project. However, we replaced it with a Raspberry Pi mainly because the Raspberry Pi performs image reading and processing from the camera much faster and more efficiently. Unlike the Arduino, the Raspberry Pi has a full operating system, supports high resolution camera modules, and can run advanced image processing libraries like OpenCV. Additionally, the Raspberry Pi allows for easier integration of software components such as the solving algorithm, vision system, and control logic, all in one platform. These capabilities make it a better fit for our project's real time requirements.

### **number of cameras**

The third alternative design we considered involved the number of cameras used in the system. Initially, we planned to use six cameras one for each face of the cube. However, we later decided to use only two cameras positioned at the corners of the cube, allowing each camera to capture three faces simultaneously. This approach significantly reduced the project's cost and complexity while still providing sufficient visual coverage for our needs.

### **data mining algorithms**

The final design alternative involved our choice of motor. Initially, we planned to use a stepper motor, but we ultimately decided to switch to a servo motor. This decision was based on performance, as servo motors are significantly faster than stepper motors, aligning with our project's main goal of achieving high speed operation. Additionally, servo motors offer better position and angle control, resulting in smoother and more precise movements. They are also more energy efficient, require simpler driving circuitry, and have faster response times.

* 1. System Analysis and Optimization

The development of the Cube Mind Rubik's Cube solver involved a multi-faceted approach to system analysis and optimization, addressing various components critical to its autonomous operation. The primary analyses focused on the efficiency and reliability of the computer vision system, the precision and speed of the mechanical manipulation system, and the performance of Kociemba's algorithm within the embedded Raspberry Pi environment.

### **Computer Vision System Analysis:**

Initial analysis of the computer vision system centered on its ability to accurately detect and interpret the colors of the Rubik's Cube faces under varying lighting conditions.

### **Mechanical Manipulation System Analysis:**

The mechanical system, responsible for physically rotating the cube faces, underwent rigorous analysis to ensure precision, speed, and reliability. This involved evaluating the choice of motors, the design of the gripping mechanism to prevent slippage, and the overall structural stability of the robot, In addition to choosing a smooth moving cube that is easy to move without difficulty.

### **Kociemba's Algorithm Implementation and Performance Analysis:**

Kociemba's algorithm, chosen for its efficiency in finding solutions with a low number of moves.

1. **CHAPTER 4: RESULTS AND DISCUSSIONS**
   1. Results

Summarize the results and draw conclusions based on those results.  Detailed results (e.g., printouts) can be placed in the Appendix to improve readability of the report. experimental results.

* 1. Discussions

Discuss your result that obtains in above section.

1. **CHAPTER 5: Project Management**
   1. Tasks, Schedule and Milestones

You are required to develop the schedule of your senior project which involves identifying the main and sub tasks, investigating task sequences, resource estimations, and task duration estimates to generate the project schedule that also includes milestones which are precise points used to measure the progress toward the final goal. A sample of a project schedule represented in Gantt chart format is shown in figure 5.1.

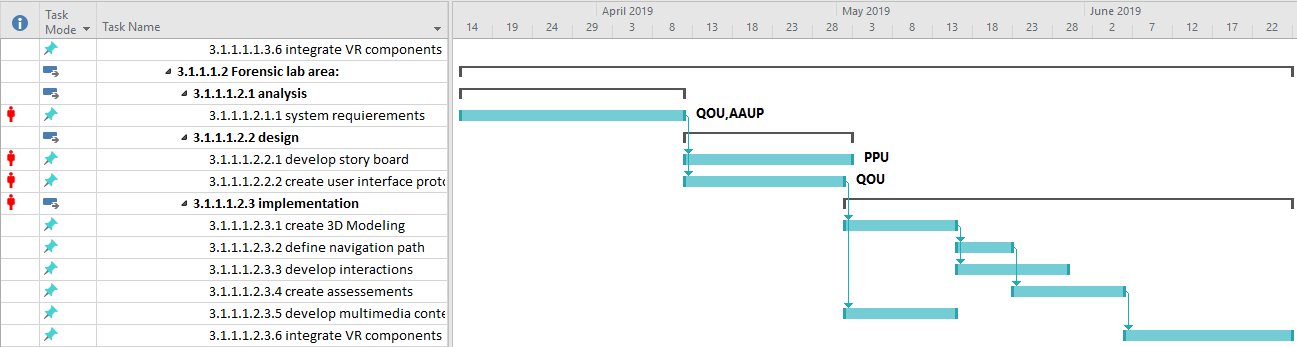


Fig. 5.1 A sample project schedule

* 1. Resources and Cost Management

In this section you have to estimate the needed project resources which involves assessing how many resources—people, tools, equipment, and materials—a project team should use to accomplish project tasks. You have to specify the cost of theses resources where you can fill these costs and calculate the budget of developing the project in a table such as the table below.

Table 5.1 Sample table to fill in total cost of senior project items

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Item | # Unit | Unit Cost | Subtotals | Comments |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |
| Total senior project estimate |  |  |  |  |

* 1. Lessons Learned

You have to document information that reproduces both the positive and negative practices of the senior project.

1. **CHAPTER 6: Impact of the engineering solution**

Sustainability consideration and constraints includes economic, environmental, and social (equity) aspects that need to be evaluated and taken into account in project research and development. There is a strong relationship between these three pillars of sustainability. These need to be considered and incorporated in this section with a discussion on their design constraint and the positive and negative effects of the project within this scope.

* 1. Economical, Societal and Global

Economics (cost) impact: should consider, when relevant,

1. Prototype design and production cost, including the manner in which production cost can be reduced, when applicable.
2. Device cost in mass production, including materials, operations, supports etc.
3. Cost saving of the product should be considered when appropriate. For example, energy savings compared with the use of other products, water saving, reduction in operation cost, etc.
4. Tax incentives to be considered towards final product cost. For example, renewable energy and energy efficient products tax incentives, carbon footprint reduction, etc.
5. Environmental aspects, such as availability of resources, may affect the product cost and therefore price and their market vulnerability.

Social impact of the product: when relevant, please consider

1. How can the developed product impact people lives. Is it a positive or negative impact?
2. What community or personal needs does it address?
3. Is the product going to change consumption patterns?
4. Is the product automating a task currently preformed manually and therefore might impact employment?
5. Does the product create new jobs or fields?
6. Safety aspects and health concerns
7. Regulation constraints that address social and environmental concerns
   1. Environmental and Ethical

Environmental impact of the product: when relevant, please consider

1. Increase or reduction in emissions obtained through modifications in processes that emit greenhouse gasses (GHG) or products that do so.
2. Change in consumption or use patterns, which effect the environment such as use of water, food, energy, wood, etc. (positive or negative affect).
3. Reliance on resources that are scarce (such as precious material) or abundant. For examples, some fuel cells technologies use rare material while other use abundant ones. This will have an impact on the availability of these materials as well as their prices.
4. Project production and operation effect on natural resources availability and competition on the planet resources. Considering their availability in nature and the impact of their consumption on the balance of nature.
5. Environmental regulation

* 1. Other Issues

1. **CHAPTER 7: CONCLUSIONS and RECOMMENDATIONS**
   1. Summary of Achievements of the Project Objectives

Draw conclusions about the level of success of your work.  Did you substantially meet your objectives?  What did you learn in the process?

* 1. New Skills and Experiences Learnt
  2. Recommendations for Future Work

This is one of the most important sections in the Final Report, at least for those who may pick up where you left off.  Knowing what you know now, given the same problem, what would you do if you had it to do all over again?  Understanding that problems of significance are rarely if ever solved perfectly the first time, what would you suggest as the next step toward finding the answer?

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**APPENDICES**

**Appendix A:**

**Appendix B:**

**Appendix C:**