International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 14, Issue 11 [November 2025] PP: 58-62

Design of Intelligent Rubik's Cube Solving Robot

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Abstract *: This paper designs a control system for a two-arm, two-finger intelligent Rubik's Cube robot. The key focus is on optimizing the basic command combinations for Rubik's Cube solving and constructing new command combinations to achieve a good balance between the execution speed and stability of the intelligent Rubik's Cube robot. By adopting a 5-segment S-shaped acceleration and deceleration curve algorithm to control the closed-loop stepper motor, continuous speed adjustment of the closed-loop stepper motor is realized. Experimental results show that the optimized basic command combinations for Rubik's Cube solving effectively reduce the number of execution steps of the robot. The average optimization rate of the new command combinations reaches 25%, and the average time for the overall Rubik's Cube solving is 13.644 seconds.*

Date of Submission: 25-10-2025 Date of acceptance: 05-11-2025

I. Brief Introduction to the Intelligent Rubik's Cube Solving Robot

1.1 Composition of the Robot System

The mechanical structure of the two-arm, two-finger intelligent Rubik's Cube robot is the key carrier for realizing Rubik's Cube solving. It mainly consists of a closed-loop stepper motor, a stepper motor base, a pneumatic rotary joint, a parallel cylinder, a Rubik's Cube claw, and other components to form a manipulator. Among them, the closed-loop stepper motor and the parallel cylinder are the core executive components: the closed-loop stepper motor is responsible for rotating the 6 faces of the Rubik's Cube and flipping the entire Rubik's Cube, while the parallel cylinder mainly realizes the clamping of the Rubik's Cube. Through combined movements, they accurately execute the Rubik's Cube solving actions.

To ensure comprehensive and accurate collection of color block information of the Rubik's Cube, the mechanical mechanism is equipped with 4 cameras, which are respectively arranged on the front, back, top, and bottom sides of the Rubik's Cube. These 4 cameras can simultaneously collect color information of 54 color blocks on the 6 faces of the Rubik's Cube. In addition, a U-shaped groove is specially designed at the clamping end of the Rubik's Cube claw to ensure that the colors of 54 color blocks can be collected smoothly at one time. Furthermore, to enhance the stability and adaptability of the visual recognition system in different environments, 6 LED light sources are added in the front, back, top, and bottom directions of the Rubik's Cube to provide sufficient and uniform supplementary lighting for the Rubik's Cube.

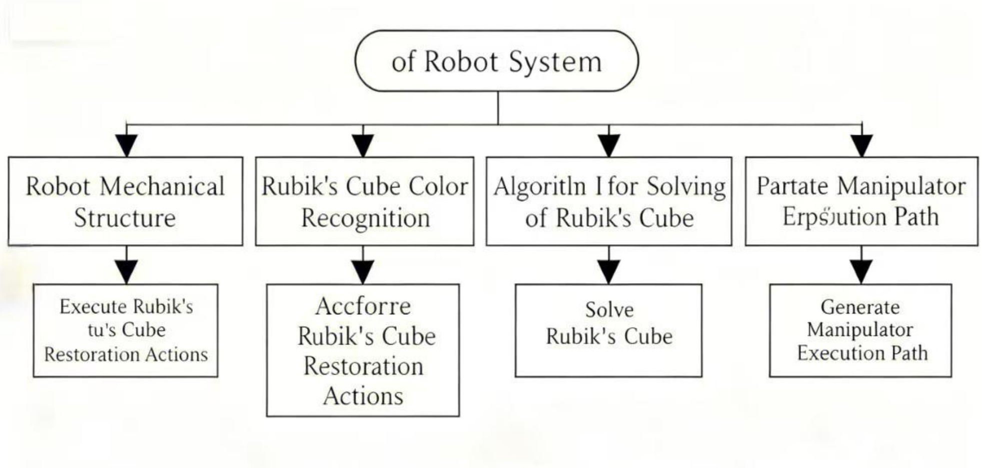

Figure 1 Composition of Intelligent Rubik's Cube Robot System

1.2 Mechanical Structure

The mechanical structure of the two-arm, two-finger intelligent Rubik's Cube robot is part of the Rubik's Cube solving system, as shown in Figure 2. The mechanical structure of the two-arm, two-finger intelligent Rubik's Cube robot mainly includes a manipulator composed of a closed-loop stepper motor, a stepper motor base, a pneumatic rotary joint, a parallel cylinder, a Rubik's Cube claw, and other components. Among them, the closed-loop stepper motor and the parallel cylinder serve as the main executive components. The closed-loop stepper motor mainly executes the rotation of the 6 faces of the Rubik's Cube and the flipping of the entire Rubik's Cube, while the parallel cylinder mainly realizes the clamping of the Rubik's Cube. Through combined movements, they execute the Rubik's Cube solving actions. The mechanical mechanism is equipped with 4 cameras, which are respectively installed on the front, back, top, and bottom sides of the Rubik's Cube. These 4 cameras simultaneously collect color information of 54 color blocks on the 6 faces of the Rubik's Cube. To collect the colors of 54 color blocks at one time, a U-shaped groove is designed at the clamping end of the Rubik's Cube claw. To enhance the stability and adaptability of the visual recognition system in various environments, 6 LED light sources are added in the front, back, top, and bottom directions of the Rubik's Cube to provide supplementary lighting for the Rubik's Cube.

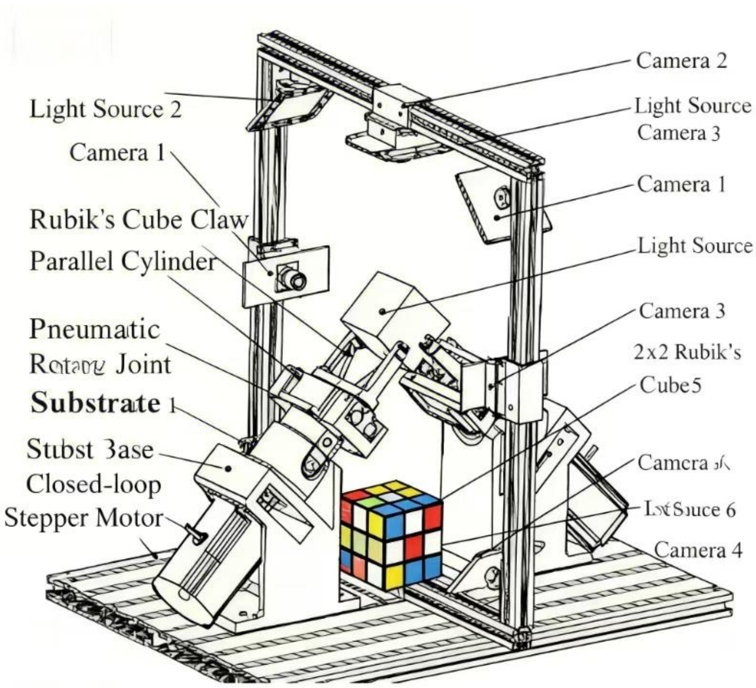

Figure 2 Mechanical Structure of Intelligent Rubik's Cube Robot

II. Transformation of Command Combinations for Rubik's Cube Robot Solving

2.1 Description of the Rubik's Cube and Origin of Command Combination Transformation

A Rubik's Cube is composed of 6 faces and 54 color blocks. To clearly describe the orientation of each face of the Rubik's Cube, a right-angle coordinate system o-xyz is established at the center of the Rubik's Cube: the face in the positive direction of the x-axis is defined as the Front face, denoted by F; the face in the negative direction of the x-axis is the Back face, denoted by B; the face in the positive direction of the y-axis is the Right face, denoted by R; the face in the negative direction of the y-axis is the Left face, denoted by L; the face in the positive direction of the z-axis is the Up face, denoted by U; and the face in the negative direction of the z-axis is the Down face, denoted by D.

The manipulator of the Rubik's Cube robot designed in this paper can only directly control 2 faces of the Rubik's Cube, which are defined as the Front face and the Left face respectively. The robot needs to indirectly control the rotation of the other 4 faces (Up, Down, Back, and Right faces) of the Rubik's Cube by flipping the entire Rubik's Cube. Compared with manual Rubik's Cube solving, the human hand has 6 degrees of freedom, while this Rubik's Cube robot lacks direct control over 4 faces due to the limitation of its mechanical structure. When the robot indirectly controls other faces by flipping the Rubik's Cube, the position of the coordinate system where some faces of the Rubik's Cube are located will change. Therefore, in the process of command design, it is necessary to consider whether the Rubik's Cube needs to be adjusted to return to its original position.

2.2 Optimization of Rubik's Cube Solving

There are two sets of command combinations for the Rubik's Cube robot to solve the Rubik's Cube. The first set of command combinations is commonly used in daily or online Rubik's Cube solving tutorials and is generated by the computer algorithm for solving the Rubik's Cube. This set of command combinations is only applicable to manual Rubik's Cube solving and 6-axis Rubik's Cube robots and cannot be directly applied to the two-arm, two-finger intelligent Rubik's Cube robot. The specific commands and step counts are shown in Table 1. To make the first set of command combinations suitable for the two-arm, two-finger intelligent Rubik's Cube robot, a Rubik's Cube solving command optimization program is used to transform it. This optimization operation not only shortens the Rubik's Cube solving time but also converts the first set of command combinations into the second set of command combinations that can be directly parsed and executed by the robot controller. The specific content of the second set of command combinations is shown in Table 2. For the convenience of distinction, the first set of command combinations is called the unoptimized command set, and the second set of command combinations is called the optimized command set. The transformation logic from the first set of command combinations to the second set can be referred to in Figure 4 and Table 3.

hable 1 First Set of Commands (Unoptimized Command Set)

Instruction	*L*	*R*	*L´*	*F´*	*R´*	*F´*	*B´*	*U´*	*R2*	*F2*	*B2*	*U2*	*D2*
Command	1	1	1	8	3	5	6	5	8	1	7	3	8
Step Count	2	2	3	4	3	5	4	5	6	7	3	3	6

Table 2 Secoond Set of Commands (Optimized Command Set)

Command	*L´*	*I2*	*F´*	*F´*	*F2*	*IL*	*FF*	*FF2*
Step	3 or 4	3 or 4	1	3 or 4	1	5 or 6	2 or 3	2 or 6
Count	3 4	3 or 5	1	3 or 4	1	2 or 3	2 or 3	5 or 6

III. Design of the Manipulator Control System

3.1 Program Design

The manipulator control system program of the Rubik's Cube robot is mainly constructed based on the 10 commands in the second set of command combinations in Table 2. Among them, each of the 6 commands (L, L', L2, F, F', F2) corresponds to 2 subprograms, and each of the 4 commands (LL, LL2, FF, FF2) corresponds to 1 subprogram. That is, the Rubik's Cube solving is realized through the combined actions of 16 subprograms.

In the normal operation state, after the manipulator executes each action, the mechanical claw is in a closed state. However, after executing the current command, the system will automatically judge whether the next command is a flipping command such as LL, LL2, FF, or FF2. If it is determined to be a flipping command, the current control mechanical claw does not need to be closed, and the subsequent actions are completed through Subprogram 2; if it is determined not to be a flipping command, Subprogram 1 is executed to ensure the orderly operation of the entire control system.

3.2 Acceleration and Deceleration Control for Motor Start and Stop

3.2.1 S-Shaped Curve Acceleration and Deceleration Model

To achieve a good balance between the mechanical execution speed and stability of the intelligent Rubik's Cube robot, an acceleration and deceleration control link is added in the start and stop control process of the closed-loop stepper motor, so that the rotation speed of the closed-loop stepper motor can be adjusted continuously and smoothly. On the premise of ensuring the smooth acceleration and deceleration of the motor, to reduce the difficulty of program design and improve the reliability of the program in controlling the stable execution of the motor, this design adopts a 5-segment S-shaped acceleration and deceleration curve, and its curve shape is shown in Figure 6.。

Assuming that the start speed vs of the closed-loop stepper motor is equal to the stop speed ve, the time parameters of each stage in the 5-segment S-shaped acceleration and deceleration curve satisfy T1=T2=T4=T5, and at this time, the acceleration and deceleration model of the S-shaped curve is symmetrically distributed. According to the relevant literature [6], the speed function of the S-shaped curve can be obtained as follows:

$$\mathbf{v(t)} = \begin{cases} \frac{a^2t^2}{2(v_m-v_n)} + \mathbf{v_n}, & \mathbf{t} \in [\mathbf{0}, \mathbf{T_1}] \\ \frac{a^2(t-T_2)^2}{2(v_n-v_m)} + \mathbf{v_m}, & \mathbf{t} \in [\mathbf{T_1}, \mathbf{T_2}] \\ \mathbf{v_m}, & \mathbf{t} \in [\mathbf{T_2}, \mathbf{T_3}] \\ \frac{a^2(t-T_3)^2}{2(v_n-v_m)} + \mathbf{v_m}, & \mathbf{t} \in [\mathbf{T_3}, \mathbf{T_4}] \\ \frac{a^2(t-T_5)^2}{2(v_m-v_n)} + \mathbf{v_n}, & \mathbf{t} \in [\mathbf{T_4}, \mathbf{T_5}] \end{cases} \quad (1)$$

In the formula: a is the acceleration of the closed-loop stepper motor; vs is the start speed of the closed-loop stepper motor; vm is the maximum speed of the closed-loop stepper motor; ve is the stop speed of the closed-loop stepper motor; T1, T2, T3, T4, T5 are the acceleration stage change times of the closed-loop stepper motor at each stage respectively. Assuming that the acceleration of the closed-loop stepper motor is set as a, and the maximum value of the acceleration curve, as well as the accelerations of the acceleration stage and deceleration stage are equal to a. Let sa and sd be the rotation displacements of the acceleration stage and deceleration stage respectively, then:

$$s = s_n = s_d = \frac{v_m^2 - v_n^2}{a} \quad (2)$$

According to the above speed function, when t=T1, we have:

$$\frac{a^2T_1^2}{2(v_m-v_n)} + v_n = \frac{a^2(T_1-T_2)^2}{2(v_n-v_m)} + v_m \quad (3)$$

Let the total running time of the acceleration stage be T, then:

$$T_1 = \frac{1}{2}T, \quad T_2 = T \quad (4)$$

Substitute Formula (4) into Formula (3), we get:

$$v_m - v_n = \frac{1}{2}aT \quad (5)$$

By combining Formula (2) and Formula (5), we can obtain:

$$\begin{cases} v_m = \frac{2s}{T} - v_n \\ a = \frac{2(v_m-v_n)}{T} \end{cases} \quad (6)$$

It can be known from the speed function and the above derivation formulas that if the start speed vs, rotation displacement s, and total running time T of the acceleration stage of the closed-loop stepper motor are determined, all parameters of the acceleration stage in the S-shaped curve can be calculated. Among them, the value of vs can be determined according to the parameter characteristics of the stepper motor and the subdivision number of the stepper motor driver. The calculation process of the deceleration stage is similar to that of the acceleration stage and will not be repeated here.

IV. System Testing and Error Analysis

4.1 Optimization Effect Test

To verify the optimization effect of the second set of command combinations (optimized command set) compared with the first set of command combinations (unoptimized command set) in the Rubik's Cube solving process, a special test program is designed in this paper, and a corresponding test platform is built, as shown in Figure 8.

During the test, the manipulator is instructed to execute the second set of command combinations and the first set of command combinations respectively, and a total of 25 groups of test data are collected. The specific data are shown in Table 4. Through the analysis of the test data, it can be seen that the optimized command combinations effectively reduce the number of execution steps of the robot, with an average optimization rate of 25%, which significantly improves the Rubik's Cube solving efficiency while ensuring the stability of the solving process.

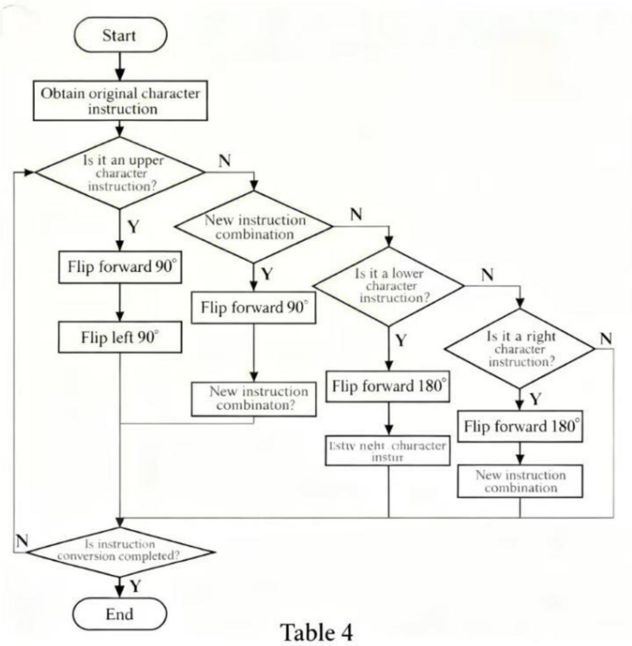

Table 4

V. Conclusion

This paper successfully designs a control system for a two-arm, two-finger intelligent Rubik's Cube robot. The system has a number of core functions: it can realize the transformation of the basic commands for Rubik's Cube solving, complete the subprogram design of the new command system after transformation, and perform accurate acceleration and deceleration control on the stepper motor.

To achieve a good balance between the mechanical execution speed and stability of the intelligent Rubik's Cube robot, the stepper motor is controlled according to the 5-segment S-shaped acceleration and deceleration curve theory. This not only realizes the continuous speed adjustment of the closed-loop stepper motor but also reduces the rigid impact of the system and ensures the flexible operation of the system. Through the optimized analysis of the basic commands for Rubik's Cube solving, the number of execution steps of the Rubik's Cube robot is effectively reduced, with an average optimization rate of 25%, and the average time for the overall Rubik's Cube solving is 13.644 seconds. This fully proves the effectiveness of the control system in improving the efficiency and stability of Rubik's Cube solving.

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