Intelligent Logistics Handling Robot: Design, Control, and Recognition

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Abstract

This study aims to investigate various aspects of intelligent logistics handling robots, including mechanical design, automatic control, and image recognition. With the continuous development of the logistics industry and advancements in automation technology, intelligent logistics handling robots play a crucial role in improving logistics efficiency and reducing costs. Leveraging existing technologies, we have designed and developed an omnidirectional mobile intelligent logistics handling robot equipped with a SCARA-type robotic arm. The robot integrates functions such as task acquisition, global positioning, material detection, warehouse identification, material handling, and stacking, achieving a fully automated and streamlined logistics handling process.

Keywords: Logistics handling robots, Automatic control, Image recognition, Global positioning

1. Introduction

In modern industrial production, logistics handling is a time-consuming and labor-intensive task. The modern industry faces rapidly changing market demands and a complex and dynamic production environment, making traditional manual logistics handling methods relatively outdated. In this situation, there is an urgent need for a more flexible, efficient, and adaptive logistics handling approach to meet the requirements of modern industry. This new type of handling method should be able to adapt to changes in different factory environments and production processes, completing a large number of handling tasks in a short time to improve production efficiency. This is precisely the significant advantage that intelligent logistics handling robots can bring to modern industry.

The intelligent logistics handling robot studied in this project comprehensively designs and analyzes aspects such as mechanical structure, robotic arm control and coordinate calculation, chassis control and global positioning, image recognition, and processing. A multifunctional intelligent logistics handling robot (AGV) is designed based on the omnidirectional wheel structure chassis and planar articulated (SCARA) robotic arm [1], [2], [3], [5]. It integrates functions such as positioning, environmental perception, path planning, material recognition and grasping, material placement, and stacking. This integration significantly reduces the number of operators, enhances the speed and accuracy of logistics operations, and greatly improves the efficiency of the logistics system.

2. Intelligent Logistics Handling Robot Overall Program Design

2.1. Operational site

In this thesis, the robot's operation site is based on the 9th China University Students Engineering Practice and Innovation Competition "Intelligent +" track logistics handling robot competition. The robot drives on the gray lane, and the rest of the area is matte white or yellow. In the competition venue, the start-stop zone, raw material zone, roughing zone and temporary storage zone are set up. The start-stop zone is blue in color and is used for the robot to go back and forth. Fig. 1 shows the exact location of the given raw material area, roughing area and staging area within the competition venue.

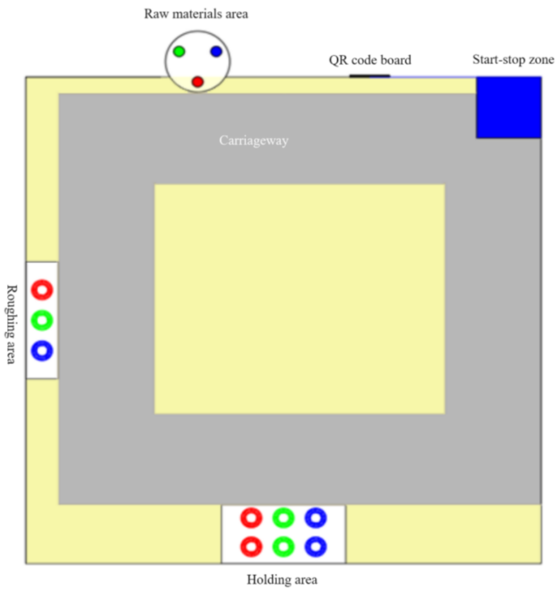


Fig. 1 Schematic diagram of the robotics field

The raw material area adopts a round electric turntable to arrange materials, and materials are identified by color. The top surface of roughing area, staging area, finishing area and finished product area are equipped with color rings and or circles for measuring the accuracy of material placement.

2.2. Mandate requirements

The robot follows a "one-key" start-up procedure, moving from the start-stop zone to the QR code panel within a specified time to read the QR code. It obtains two handling tasks (the sequence for handling materials of three different colors). According to the task requirements, the robot moves between the material area, rough processing area, and temporary storage area, carrying out placement and stacking tasks. After completing the tasks, it returns to the start-stop zone.

2.3. *Design proposal*

According to the task requirements, the overall design of the intelligent logistics handling robot is illustrated in Fig. 2. In terms of mechanical structure, the chassis adopts a Mecanum wheel [1], [5] double-layer shock-absorbing design, controlled by DJI brushless motors to achieve closed-loop control. The robotic arm employs a planar articulated (SCARA) design, driven by stepper motors and closed-loop stepper motors, allowing real-time reading of the angles of each joint for feedback control.

The electronic control system is mainly divided into three parts: chassis motion control system, robotic arm motion control system, and visual recognition system. The chassis motion control system, centered around the chassis control board, includes external devices such as a QR code recognition module, gyroscope, touchscreen, and brushless motor driver. The robotic arm motion control system integrates servos and utilizes closed-loop stepper motors for precise control of the robotic arm. The visual module, developed based on OpenCV, includes functions for material color recognition and target ring center recognition. The chassis control board, robotic arm control board, and visual module are all powered simultaneously by the power module.

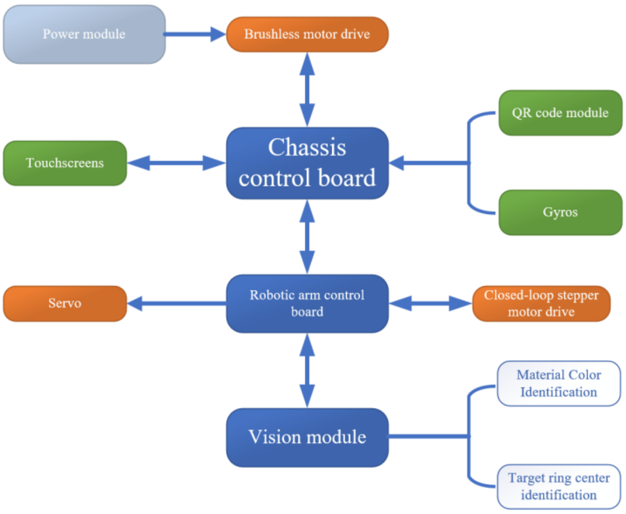


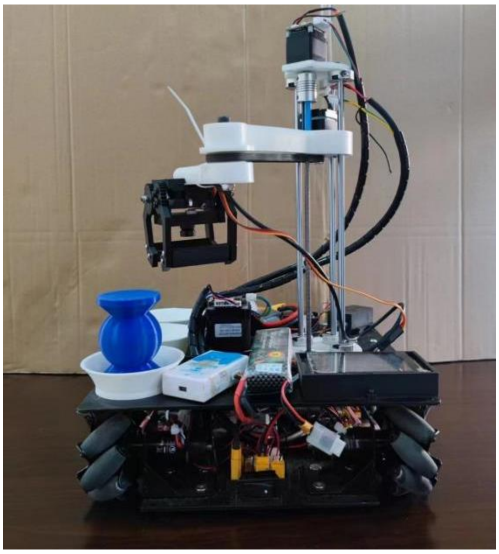
Fig. 2 Overall design schematic

3. Design of Mechanical Structural Systems

3.1. *Intelligent logistics handling robot overall mechanical structure design*

To ensure the flexibility and efficiency of the robot, the chassis adopts a Mecanum wheel chassis, and the mechanical arm structure adopts a standard three-axis SCARA structure.

a. Robot 3D drawing



b. Robot Physical Picture

Fig. 3 Image of Intelligent Logistics Handling Robot

3.2. *Chassis mechanical structure design*

The chassis adopts a double-layer design with Mecanum wheels, made of aluminum alloy with electroplating process. The lower layer of the chassis houses the electronic control system, while the upper layer accommodates the mechanical arm, material storage, and human-machine interaction module, among others. The overall structure is well-defined.

The motion system of the chassis requires a high level of grounding for the Mecanum wheels [5]. To ensure stable movement of the robot, the lower layer of the chassis adopts a double-plate coaxial structure, ensuring that all four wheels touch the ground simultaneously. This design increases shock absorption and solves the problem of Mecanum wheels slipping when not in contact with the ground [1].

a. Top view

b. Bottom view

Fig. 4 Chassis structure

3.3. *Mechanical structure design of mechanical arm*

This robotic arm is of the three-axis SCARA type [2], made of PLA material and manufactured using 3D printing technology. It is lightweight in quality.

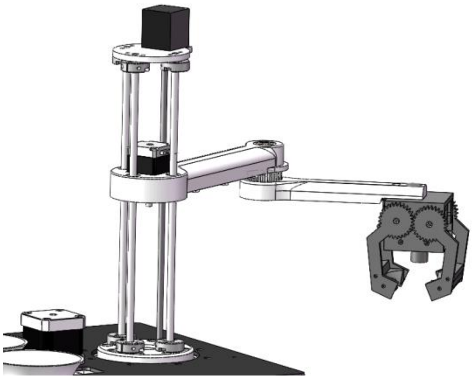
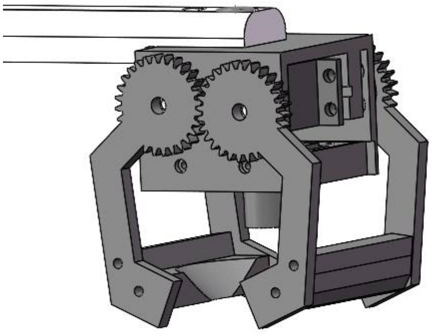


Fig. 5 3D model of the robot arm

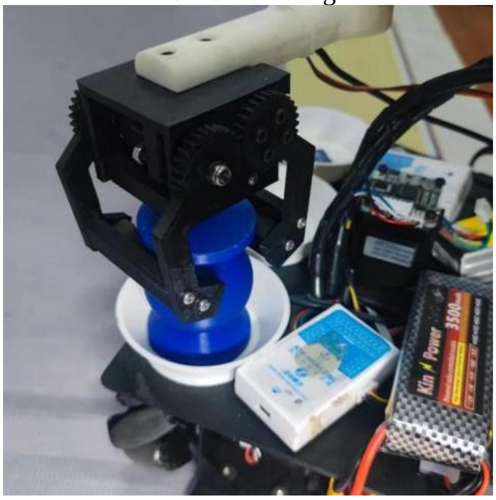
The upper arm of the robotic arm is connected to the arm axis through a linear bearing, while the lower arm is equipped with a thrust ball bearing to withstand axial forces and reduce friction between the upper and lower arms. The robotic arm can achieve three degrees of freedom through the motion of stepper motors, including vertical movement, rotation of the upper arm, and rotation of the lower arm.

3.4. *Mechanical Structure design of mechanical claw*

The mechanical claw is one of the key components of an intelligent logistics handling system. It is manufactured using 3D printing technology and made of PLA material.



a. 3D drawing



b. Concrete drawing

Fig. 6 Robotic Gripper Structure

The mechanical claw is used for grasping and identifying materials. When grasping materials, the mechanical claw needs to firmly grip the materials. The mechanical claw is divided into active and passive parts, with the active part being directly driven by a servo motor to rotate, and the active part drives the passive part to rotate through gears. The identification of materials involves the use of a camera and a visual recognition system. The camera is installed in the center of the mechanical claw.

4. Three-axis SCARA Robot Kinematic Model

4.1. *Kinematic modeling of a three-axis SCARA robotic arm*

SCARA robotic arms are usually characterized by high accuracy, high speed and repeatability [2], [3]. In this project, the SCARA robotic arm is designed as a three-degree-of-freedom, containing one rotational degree of freedom in the XY plane, one lifting degree of freedom in the Z-axis, and one moving degree of freedom in the Z-axis. The process of solving the operational science model of the three-axis SCARA robotic arm is as follows:

Determination of joints, connecting rods and their parameters. The robot arm uses a rotating chassis at the bottom, lifting and lowering using a stepper motor screw Z-axis, and a rotating arm in the XY plane, for a total of three degrees of freedom, and the analysis process is simplified by dropping the end-effector [3].

Simplify the model to set the coordinate system. With the vertical upward as the +Z-axis and the center of the Z-axis as the coordinate origin from the top view, establish a plane right-angle coordinate system with the body as the reference system.

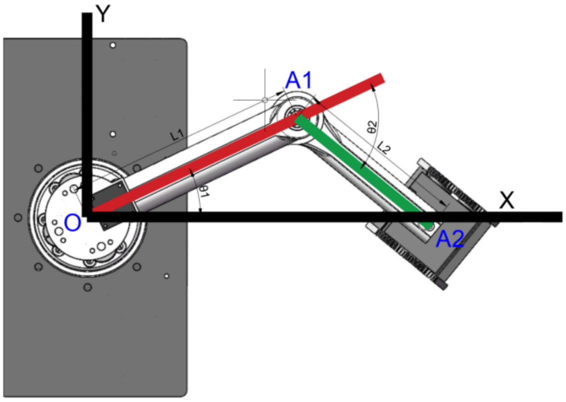


Fig. 7 Simplified coordinate system model

As shown in Fig. 7, for the big arm of the robot arm, for the small arm of the robot arm. For the rotation angle of the big arm, controlled by the bottom disk; for the rotation angle of the small arm, controlled by the stepping motor through the synchronous belt.

Inverse kinematic modeling calculations. We set the point coordinates to (x, y, z), the length of the big arm to be L1, and the length of the small arm to be L2, then the length $L3 = \sqrt{L1^2 + L2^2}$. The angle of rotation of the large arm θ_1 and the angle of rotation of the small arm θ_2 need to be solved for. This leads to Eq. (1). The rotation angle of the big arm θ_1 and the rotation angle of the small arm θ_2 can be found (Eq. (2)).

$$\begin{cases} \cos(\theta_1) = \dfrac{L2^2 + L3^2 - L1^2}{2 * L2 * L3} \\ \cos(\theta_2) = -\dfrac{L1^2 + L2^2 - L3^2}{2 * L1 * L2} \end{cases} \tag{1}$$

$$\begin{cases} \theta_1 = arccos(\dfrac{L2^2 + L3^2 - L1^2}{2 * L2 * L3}) \\ \theta_2 = arccos(-\dfrac{L1^2 + L2^2 - L3^2}{2 * L1 * L2}) \end{cases} \tag{2}$$

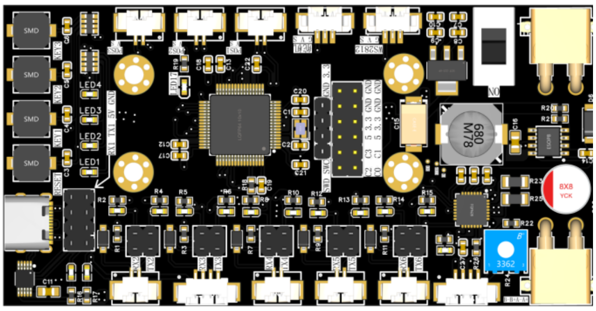
4.2. *Robotic arm electronic control system design*

(1) Robotic arm control board circuit design

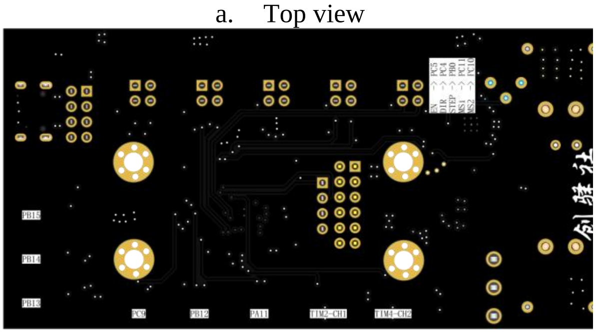
The robotic arm control board uses STM32F405RGT6 as the main control chip [4], with an externally integrated power module, stepper motor drive module and communication module. The power supply module part, the input voltage is 12V, using TPS5430 decompression to generate 5V voltage, and then through the AMS1117 on the 5V voltage regulator to generate 3.3V, thus generating all the voltages required for system operation. The control board integrates the TMC2209 stepper motor driver, which is powered by 12V and has the advantages of silence, high speed and low failure, and is used for open-loop control of the stepper motor. The closed-loop stepper motor driver is controlled using a UART interface. In order to realize a UART interface and multiple closed-loop stepper motor driver communication problems, we use a diode plus pull resistance way to enhance the serial port receiving ability, shielding the interference signal.

(2) PCB Overall Layout

The control board of the robotic arm is a four-layer board, and the shielding layer is set up to shield the power supply and signals, which improves the signal stability of the system. As Fig. 8 are the front and back of the chassis control board.



a. Top view



b. Bottom view

Fig. 8 Robotic arm control board

(3) Robotic arm software design

The robotic arm performs numerous actions, and the use of sequential execution of robotic arm actions will occupy a large amount of program storage space, and the code logic is confusing and redundant. This system uses structure variables to save the spatial coordinates of each step of the robotic arm action and information such as gripping operation, and establishes structure arrays for storing the information of the robotic arm action during the whole operation process. After the robotic arm is powered on, it initializes the peripherals and stepper motors, servos and so on. After the initialization is completed, turn on the serial port to receive interrupts and wait for the chassis controller to send task execution instructions. When the task execution instruction is received, the robotic arm starts to move, reads the action information in the structure array, and executes it step by step. The vision system will send the material color, target ring coordinates and other information to the robotic arm, and the robotic arm will calibrate and correct the position through this information. When all the actions are completed, the robotic arm task is completed and returns to the initial state. The workflow of the robotic arm motion control system is shown in Fig. 9.

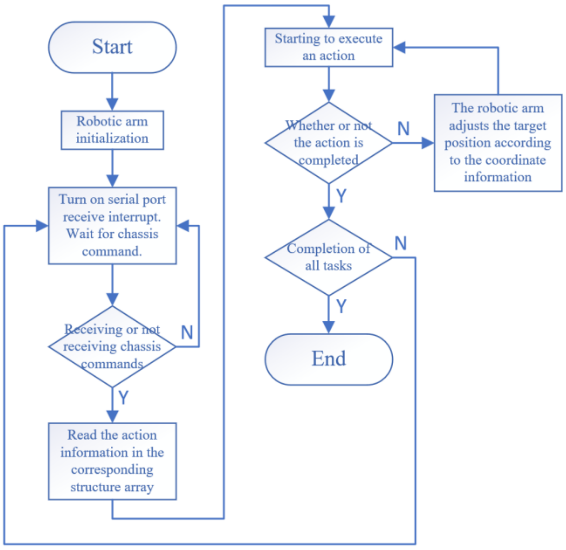


Fig. 9 Flow chart of robotic arm motion control system

5. Chassis Motion Control System Design

5.1. *Mecanum wheel chassis kinematics model*

The Mecanum wheel platform kinematic model is to establish the relationship between the rotational speed of the four Mecanum wheels and the speed of the geometric center [4]. The positive kinematics model is to know the rotational speed of the four Mecanum wheels and calculate the speed of the Mecanum wheel platform center point CENTER; the inverse kinematics model is to know the speed of the Mecanum wheel platform center point CENTER and calculate the speed of the four Mecanum wheels.

As an example, the inverse kinematics model of the Mecanum wheel is used to establish a coordinate system with the geometric center point CENTER of the top view of the chassis as the origin [5]. The distance between the CENTER point and the point of contact between the Mecanum wheel and the ground is $r. r_x$ and r_y denote the projected distances on the x-axis and y-axis, respectively, of the CENTER coordinate system (both positive). The velocity of the CENTER point is known to be $[v_c \; w_c]^T$. v_{cx} and v_{cy} are the components of a on the x and y axes, respectively.

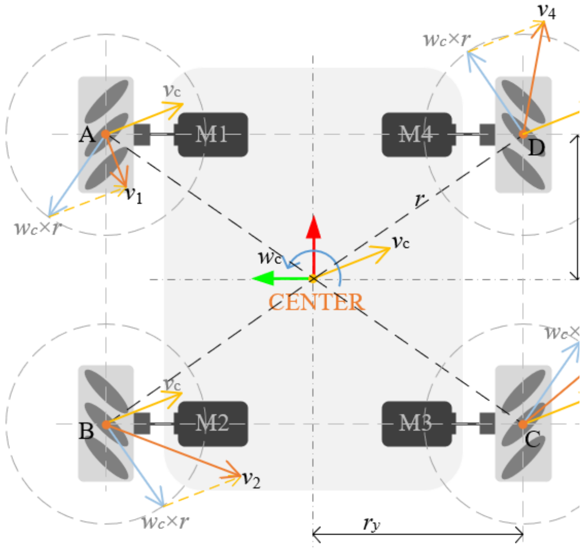


Fig.10 Decomposition of Mecanum Wheel Platform Motion

After calculation, the inverse kinematic equation of Mecanum's wheel can be obtained.

$$\begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = \frac{1}{R} \begin{bmatrix} 1 & -1 & -(r_x+r_y) \\ 1 & +1 & -(r_x+r_y) \\ 1 & -1 & +(r_x+r_y) \\ 1 & +1 & +(r_x+r_y) \end{bmatrix} \begin{bmatrix} v_{cx} \\ v_{cy} \\ w_c \end{bmatrix} \tag{3}$$

The positive kinematics equations are based on the rotational speeds of the four Mecanum wheels to calculate the velocity of the point CENTER, and the theoretical analysis is similar to the inverse kinematics, and the simplest way to do this is to invert Eq. (3), which can be expressed as Eq. (4).

$$\begin{bmatrix} v_{cx} \\ v_{cy} \\ w_c \end{bmatrix} = \frac{R}{4} \begin{bmatrix} +1 & +1 & +1 & +1 \\ -1 & +1 & -1 & +1 \\ \frac{-1}{r_x+r_y} & \frac{-1}{r_x+r_y} & \frac{1}{r_x+r_y} & \frac{1}{r_x+r_y} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} \tag{4}$$

5.2. *Full-field positioning method*

The full-field localization method studied in this project does not require the addition of the rest of the extra sensors or encoders and uses the robot's own Mecanum wheel as the encoding wheel. When the robot starts to move, the Mecanum wheel starts to shift rotation. According to the positive kinematics model of the Mecanum wheel, the velocity of the robot at the current moment can be obtained from the rotational speeds of the four wheels with respect to the current coordinate system of the robot itself [5]. Assuming that the angle between the current robot's own coordinate system and the world coordinate system is θ (Fig. 11).

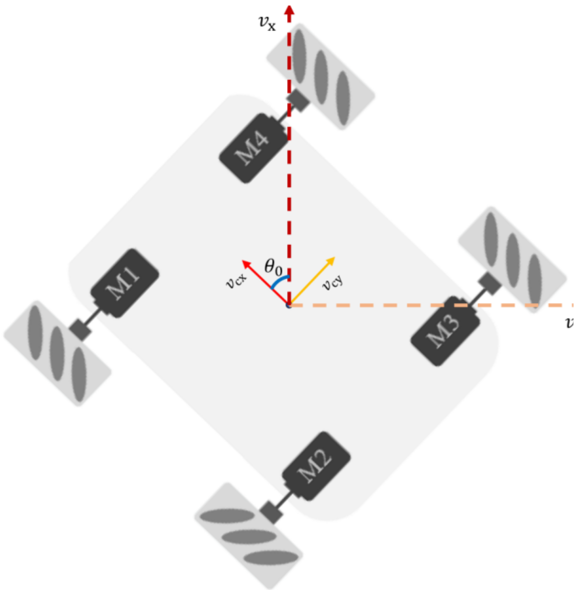


Fig.11 World Coordinate System and Own Coordinate System

The expression for converting the robot's velocity in its own coordinate system to the velocity in the world coordinate system is Eq. (5).

$$\begin{bmatrix} v_x \\ v_y \\ w_z \end{bmatrix} = \begin{bmatrix} cos\theta_0 v_{cx} + sin\theta_0 v_{cy} \\ -sin\theta_0 v_{cx} + cos\theta_0 v_{cy} \\ w_c \end{bmatrix} \tag{5}$$

With the same time units, the conversion to a displacement expression is Eq. (6).

$$\begin{bmatrix} x_x \\ x_y \\ \theta_z \end{bmatrix} = \begin{bmatrix} cos\theta_0 x_{cx} + sin\theta_0 x_{cy} \\ -sin\theta_0 x_{cx} + cos\theta_0 x_{cy} \\ \theta_c \end{bmatrix} \tag{6}$$

In this case, the calculated displacement is the relative displacement in the world coordinate system for an instantaneous moment. Since the angle between the robot's own coordinate system and the world coordinate system is always changing, therefore, to obtain the displacement of the robot in the world coordinate system over a period of time, it is necessary to integrate the displacement value calculated at any moment (discrete data summation) [6], assuming that over a period of time, a total of N times the robot's displacement relative to the world coordinate system at a given moment, the cumulative displacement expression is Eq. (7).

$$\begin{bmatrix}\Delta x_x\\ \Delta x_y\\ \Delta\theta_z\end{bmatrix}=\begin{bmatrix}\sum_{i=0}^{N}cos\theta_i x_{cxi}+sin\theta_i x_{cyi}\\ \sum_{i=0}^{N}-sin\theta_i x_{cxi}+cos\theta_i x_{cyi}\\ \Delta\theta_c\end{bmatrix}\qquad(7)$$

In Eq. (7), i represents the number of operations.

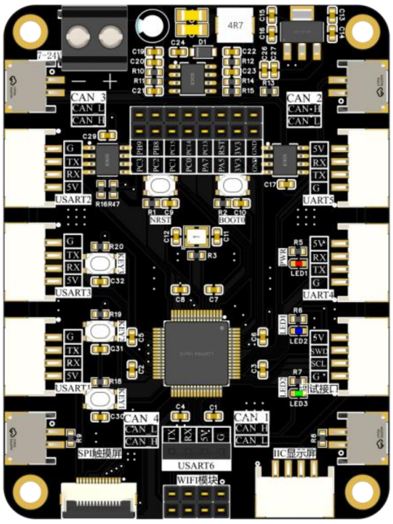
5.3. *Chassis electronic control system design*

(1) Chassis control board circuit design

The main control and power scheme of the chassis control board is the same as that of the robotic arm control board, in addition to the integrated communication module. The chassis motion control system adopts a variety of communication interfaces to communicate with various peripherals, mainly including communication with gyroscope, QR code scanning module through UART serial port, communication with touch screen through SPI and IIC, and communication with brushless motor driver through CAN [7].

(2) PCB Overall Layout

The PCB is fabricated using a two-layer board design with careful planning and design of the overall layout. As Fig. 12 show the front and back view of the chassis control board.



a. Top view

b. Bottom view

Fig.12 Chassis control board

5.4. *Chassis software design*

Prepare a chassis motion control system flowchart according to the task requirements. After the system is powered on, the program starts running and the peripherals are initialized. After the initialization is completed, the robot drives out of the start-stop area, runs to the QR code board, and starts the QR code scanning module to start scanning the QR code to receive the task code. The robot enters the next running task and proceeds to the raw material zone. When the robot runs to the raw material area, the vision system is activated to identify the color of the material according to the task code, and the robotic arm starts to grasp and place it into the bin on the robot. After completing the grasping of all materials, the robot continues to move forward. When the robot travels to the vicinity of the roughing area, the vision system starts to recognize the coordinates on the target ring in the roughing area. The chassis control board adjusts the robot position according to the coordinate data so that the robot is accurately close to the rough machining area. At this time, the vision system starts to identify the center of the target ring, and the robotic arm will place the corresponding color materials in the target ring according to the position of the target ring. After all materials have been placed, the robot will pick up the materials again in the order in which they were placed and place them in the bin on the robot. When the above operation is complete, the robot will move on to the staging area and resume the material placement operation. This operation is the same as the robot placing material in the roughing area. When all tasks are completed, the robot returns to the start-stop area.

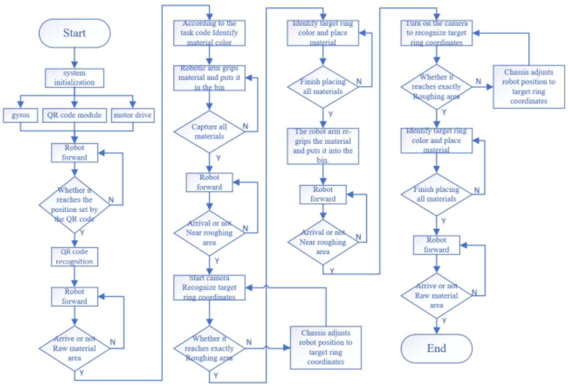


Fig.13 Chassis Motion Control System Flowchart

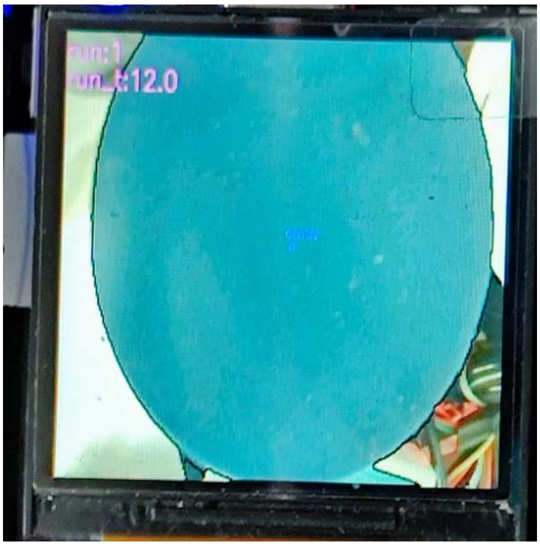
6. Visual identity system

6.1. *Material Color Identification*

The task requires the robot to be able to recognize the color of the material and grab the material in the order of the task code. This project uses OpenCV library for color recognition and detects the center of gravity of the material in the image. The idea of specific color recognition is to confirm the HSV color space threshold of the color and binarize the image with this HSV threshold to get a binary image [8]. At this point, the image is expanded so that the outline of the material in the image tends to be more like a circle. Based on this outline, it can be determined to circle the material and determine the coordinates of the center of gravity of the material.

As in Fig. 14, the robot gripper is directly above the blue material, at this time, the visual recognition system is turned on to identify the material color. The outline of the material will be wrapped by the black outline line, and the center of the material will be marked (center).

a. Identification process



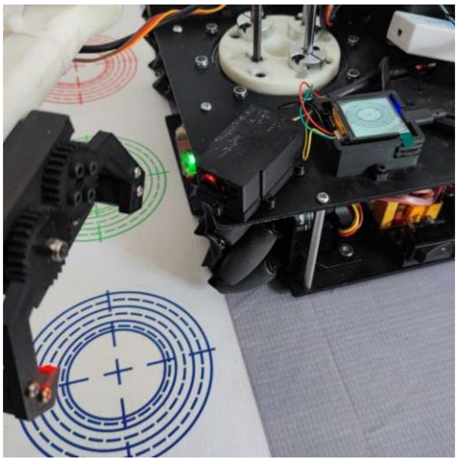
b. Identification results

Fig.14 Visual identification of material colors

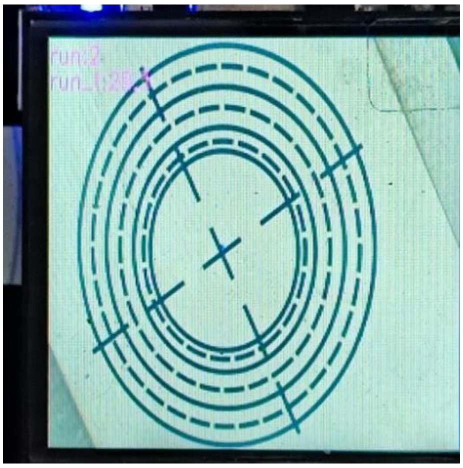
6.2. *Target ring center identification*

The task requires the robot to be able to recognize the target ring coordinates and place the material accurately into the target ring coordinates. This project uses the OpenCV library to identify the center of the target ring, which is a circle with color. When dealing with the target ring detection problem, this system does not directly detect the target ring directly by means of Hough's circle transformation, but first binarizes the image. After that, the contours in this image are searched and the contours are filtered to find the contour of the target ring. The contour of the target ring is drawn as the smallest enclosing circle, which is very close to the position and size of the target ring itself, and the circle is the center of the target ring.

As shown in Fig. 15, the robot gripper is directly above the blue target ring, and at this time, the visual recognition system is turned on to detect the center of the target ring. The center of the blue target ring will be marked by a blue dot.



a. Identification process



b. Identification results

Fig.15 Visual recognition target ring center

7. Conclusion

This project designs an intelligent logistics handling robot (AGV) for industrial logistics scenarios, which is equipped with a chassis motion control system based on an omnidirectional moving chassis with Mecanum wheels, a robotic arm motion control system based on a planar articulated (SCARA) robotic arm, and a material recognition system based on machine vision. The chassis motion control system is used to control the robot motion, pick up the task code, and perform full-field localization. The robotic arm motion control system realizes material gripping and placing operations through the movement of the robotic arm. The visual recognition system then identifies the color of the material and the center of the target ring. The chassis motion control system sends commands to the chassis motion control system to control the robotic arm to perform tasks. When the robotic arm performs the task, it needs to receive the data returned by the visual recognition system to correct the coordinate position. Each system cooperates with each other to accomplish the task.

The design simulates the handling and palletizing tasks under industrial operations, which will greatly improve the rapidity and accuracy of logistics operations and greatly improve the efficiency of the logistics system.

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