Research on the Application of Rigid-flexible Compound Driven Fruit Picking Robot Design in Realizing Fruit Picking

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Abstract. This article mainly designs an efficient fruit picking robot that combines rigidity and flexibility. The design of the robot adopts a mechanical arm with 5 degrees of freedom for the mecanum wheel. The mechanical arm is equipped with a gripper made using artificial muscle technology. The ZED2 binocular vision system is used to obtain spatial coordinates to realize the positioning and positioning of the mechanical arm. Video image acquisition. In order to realize the automatic recognition and picking of strawberries, this paper creates a strawberry training set, and uses the yolov3 algorithm to train the data and obtains a strawberry recognition model, which has a recall rate of larger strawberries and immature strawberries and the precision rate reached 90%, and the detection precision and precision rate of small target strawberries reached more than 80%. It can Meet the requirements of picking in real life.

Keywords: Rigid-flexible compound drive, picking robot, yolov3, fruit picking, machine vision, motion control.

1. Introduction

In the late 1970s, thanks to the rapid development of computer and automatic control technology, the United States took the lead in researching various agricultural robots. Starting from the first fruit picking machine in the United States in 1983, after more than ten years of research and testing, Japan, The Netherlands, the United Kingdom and other developed countries have successively developed a variety of picking robots. For example, the five-degree-of-freedom articulated manipulator developed by Kyoto University in Japan in the 1980s. There is also an apple picking robot developed by Baeten from Belgium. This system uses industrial robots as the picking manipulator. The entire picking manipulator and its control system are installed in the rear of the tractor. In addition, Pedenc and Motte in France have developed an apple harvesting robot called "MAGAL" that uses a CCD camera to collect fruit images. The picked fruits slide through the hollow arm into the fruit collection box. At present, most domestic strawberries are picked manually, and the cost of picking accounts for about 50% to 70% of the cost [1]. The realization of mechanized strawberry picking is of great significance for solving the problems of insufficient labor in the fruit industry, high production costs, low production efficiency, and improving the market competitiveness of strawberries. Therefore, this project takes strawberries as the picking object, designs a rigid-flexible coupling picking manipulator, cooperates with binocular cameras, and realizes automatic strawberry picking by calling the neural network model.
2. Hardware structure design of strawberry picking robot

2.1. Car body design
The body of the strawberry picking trolley needs to meet the requirements of the stable movement of the carrying manipulator. Therefore, it is necessary to reduce the centre of gravity as much as possible considering the load of the manipulator. Therefore, the design needs to lower heavy objects such as the drive motor; on the other hand, strawberry picking Trolleys need to pass through complex strawberry plantations, and the internal processing unit needs to be affected or destroyed by factors such as dust, soil, and water vapor in the air [2]. Therefore, the airtightness of the vehicle body needs to be required. In order to meet the above two conditions, the car body is designed to compress the space while accommodating necessary components such as related drivers, power supplies, and processing units as much as possible, and finally surround the necessary internal components in all directions, leaving only the necessary fan heat vents. The car body is shown in Figure 1.

![Figure 1. The design of the body of the strawberry picking trolley](image)

2.2. Mecanum round
When using a special robot, omnidirectional motion is an essential function. Omnidirectional motion means that it can translate and rotate in any direction of the aircraft. The mecanum wheel can realize omni-directional movement. It is composed of several rotatable rotary rollers, which are evenly distributed at a certain angle on the periphery of the mecanum wheel. Each rotor can roll freely in an ellipsoidal shape.

2.3. Robotic arm design
The distribution of strawberries on its stems and leaves is often full of randomness. To pick strawberries successfully, the gripper needs to be able to reach any position in the designated working space to complete the successful picking of strawberries in any posture. The series-connected 6-DOF robotic arm can reach any position with any posture in its designated working space, with six degrees of freedom. Considering that the strawberry is drooping down due to its own weight, it does not require too much posture adjustment [3]. A four-degree-of-freedom manipulator can be used to reduce the complexity of the system and the control of the manipulator. At the same time, the ZED2 binocular camera is clamped the holder is fixed, and the relative position of the holder and the strawberry is updated in real time.

3. Strawberry picking robot manipulator control algorithm
The strawberry picking cart uses a 5-degree-of-freedom robotic arm to complete the work. As the control center, the Raspberry Pi only needs to send the robotic arm movement instructions and artificial muscle state change instructions (Figure 2). The robotic arm movement instructions include the robotic arm movement targets. Position coordinates and posture information, STM32 MCU obtains the angle of each axis of the robotic arm according to your kinematics analysis, and then drives each axis of the robotic arm to rotate to the target angle position.
3.1. Kinematics analysis of robotic arm

3.1.1 Description of the robot arm position. We establish a coordinate system, use homogeneous coordinates to represent points in space, and use column vectors to represent any point \( P \) in space. The position of any point \( P \) in the time relative to the rectangular coordinate system \{A\} is:

\[
A P = \begin{bmatrix}
    p_x \\
p_y \\
p_z \\
1
\end{bmatrix} = \begin{bmatrix}
a \\
b \\
c \\
\lambda
\end{bmatrix}
\]

(1)

Among them, \( a = \lambda \cdot p_x, b = p_y, c = p_z \) and \( A P \) are called position vectors.

3.1.2 Description of the posture of the robotic arm. Any link of the robot can be idealized as a rigid body. The orientation of a rigid body \( G \) in space can be expressed in a uniquely determined position matrix.

Let \( o', x', y', z' \) be the coordinate system fixed on the rigid body \( G \), which is the unit direction vector on the \( x', y', z' \) axis, namely

\[
\begin{bmatrix}
o_x \\
o_y \\
o_z \\
0
\end{bmatrix}, \quad
\begin{bmatrix}
a_x \\
a_y \\
a_z \\
0
\end{bmatrix}, \quad
\begin{bmatrix}
n_x \\
n_y \\
n_z \\
0
\end{bmatrix}
\]

(2)

The pose of the robot rigid body is described as the following \((4\times4)\) matrix:

\[
T = \begin{bmatrix}
o_x & a_x & n_x & p_x \\
o_y & a_y & n_y & p_y \\
o_z & a_z & n_z & p_z \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(3)

3.2. Positive kinematics of a six-degree-of-freedom manipulator

3.2.1 The establishment of the mathematical model of the manipulator. The 6-degree-of-freedom manipulator positive motion model is to study under the conditions of each joint, that is, known \( \theta_1, \theta_2, \theta_3, \theta_4 \) and obtain the uniquely determined pose of the end holder relative to the base coordinate system. The model is set up as shown in Figure 3, which describes the relative position and posture between the
coordinate systems where the different connecting rods are located through homogeneous coordinate transformation [4]. Using the homogeneous matrix describing the relative position and posture between the joints, the posture matrix of each joint relative to the base is calculated one by one starting from the base, so as to finally calculate the unique posture of the end holder relative to the base coordinate system.

![Figure 3. Robotic arm model](image)

The pose of the $i$ link of the robotic arm in the coordinate system can be defined as $A_i$ by the transformation matrix, and the total transformation relationship between the base of the 6-degree-of-freedom robotic arm and the manipulator is:

$$^0T_6 = ^0T_1 A_1 A_2 A_3 A_4$$  \((4)\)

3.2.2 Solve the inverse kinematics of the mechanical arm. Based on the complexity of the inverse solution of the robotic arm, the movement from the first joint to the fourth joint is in the same plane. According to the triangular relationship of each link coordinate, $\theta_1, \theta_2, \theta_3, \theta_4$ and the previous moment are calculated and determined. Comparing the states of, obtain a set of optimal path solutions, which is the optimal solution of inverse kinematics operation. As shown in Figure 4 of the plane coordinate system model of the connecting rod movement, it is specified that the counter clockwise is positive [5]. At this time, according to the pose $^0T_4$ of the fourth joint relative to the base, the yaw angle $\phi_{\text{yaw}}$, the roll angle $\phi_{\text{roll}}$, the pitch angle $\phi_{\text{pitch}}$, and the space coordinate $(px, py, pz)$ of the joint 4 relative to the base are obtained. From the model diagram of the plane coordinate system of the connecting rod motion in Fig. 4, the equation between $R, H$ and $\theta_2, \theta_3$ can be obtained:

$$\theta_2 = \arcsin\left(\frac{R-l_{3y} \sin \phi_o - (l_{3y} + l_4) \cos \phi_o}{l_2}\right)$$

$$\theta_3 = \phi_o - \theta_2$$

![Figure 4. Plane coordinate system model diagram of connecting rod motion](image)
3.3. Robotic arm motion trajectory planning
When planning a smooth motion trajectory, its planning function should be a fifth-degree polynomial with a total of six undetermined coefficients, that is, six constraint conditions. Regarding the fifth-order polynomial as the time function of the joint angle, the first-order derivative of the fifth-order polynomial is the time function of the joint angular velocity, and the second-order derivative is the time function of the joint angular acceleration. The constraints are:

\[
q(0) = q_0 = a_0, \quad q(t_f) = q_t = a_0 + a_1t_f + a_2t_f^2 + a_3t_f^3 + a_4t_f^4
\]
\[
\dot{q}(0) = \dot{q}_0 = a_1, \quad \dot{q}(t_f) = \dot{q}_t = a_1 + 2a_2t_f + 3a_3t_f^2 + 4a_4t_f^3 + 5a_5t_f^4
\]
\[
\ddot{q}(0) = \ddot{q}_0 = a_2, \quad \ddot{q}(t_f) = \ddot{q}_t = a_2 + 6a_3t_f + 12a_4t_f^2 + 20a_5t_f^3
\]

According to the constraints, the solution of the equation system with 6 unknowns is:

\[
\begin{align*}
a_0 &= q_0, \quad a_1 = \dot{q}_0, \quad a_2 = \ddot{q}_0/2 \\
a_3 &= \left[20q_f - 20q_0 - (8\dot{q}_f + 12\ddot{q}_0)t_f - (3\dddot{q}_0 - \dddot{q}_f) \right]t_f \\
a_4 &= \left[30q_0 - 30q_t + (14\dot{q}_f + 16\ddot{q}_0)t_f + (3\dddot{q}_0 - 2\dddot{q}_f) \right]t_f \\
\end{align*}
\]

3.4. Simulation verification diagram of forward and inverse kinematics of mechanical arm
As shown in Figure 5, the toolbox is called by MATLAB software to simulate the 4-DOF manipulator system. By specifying D-H parameters, and using the equations of forward and inverse kinematics in the previous chapters, the motion control of the manipulator is simulated.

![Figure 5. The simulation diagram of the forward kinematics of the robotic arm](image)

4. Online visual strawberry recognition robot control

4.1. System development process
ZED depth camera is a small binocular vision system developed by Stereo labs for mobile development platforms such as Raspberry Pi and Jetson TK. It outputs high-resolution video side by side on usb3.0, with two synchronized left and right video streams. Therefore, it is possible to obtain binocular images at the same time through the processor for further in-depth calculations.
4.2. **Environment setup**

When selecting the main control board, the main considerations are: the performance of the on-board core, on-board resources, overall volume power consumption, overall cost, ease of secondary development, etc. This article chooses the Raspberry Pi 4th generation as the main control board of the image receiving terminal. Raspberry Pi 4 Module B is the latest hardware released by Raspberry Pi.org, using a new 64-bit BCM2711 quad-core A72 CPU @ 1.5GHz chip and Video Core GPU, and adding dual HDMI 4K display output; USB3 port; Gigabit Ethernet; Multiple RAM options are provided at the same time, up to 4GB.

4.3. **Hardware connection**

In order to complete the robot's visual recognition, movement, and manipulator movement, this paper designs a hardware control system as shown in Figure 6 based on the Raspberry Pi development platform. The Raspberry Pi motherboard needs a 5V 2A power supply to supply power through the type-C port. Secondly, the system needs to use a display screen for image display and real-time operation control, so the LCD display screen is connected through the HDMI interface. The ZED2 binocular vision system is used for visual recognition and positioning, and the system is connected to the Raspberry Pi through the USB3.0 interface [6]. The control of the manipulator and mecanum wheel needs to be driven by a motor, and the expansion and contraction of the artificial muscle is controlled by the electrode. Therefore, the STM32 port is used to connect the motor drive and the electrode switch to realize the control of the two.

![Figure 6. Schematic diagram of system hardware connection based on Raspberry Pi](image)

4.4. **Software design**

The software system built on the Raspberry Pi is shown in Figure 7, which is mainly divided into three processes: offline training, online recognition and hardware driving. The network model based on Yolov3 obtains the recognition and detection model through training, which is used for strawberry recognition in online recognition. The binocular camera obtains the video stream online in real time and obtains the image through the OpenCV library, performs certain reprocessing, and then calls the neural network model to recognize the strawberry. The identified results are used to guide the driving of the motor and the on-off control of the artificial muscle electrodes. In addition, the images acquired by the binocular camera are calculated to output the coordinates of the spatial points, and are sent to the lower computer through the serial port for instructions, and then the motor rotation angle is obtained through the motion equation of the robot arm to drive the robot arm to the specified position.
5. System Test

5.1. Visual analysis of training logs
When the network model starts training, it will start to generate training logs. The training logs save intermediate data. When it is necessary to summarize the experimental results, it is an effective way to visualize the training logs through code. Through the code, you can get the name of each parameter in the training process, mainly including the number of training, the memory of the graphics card, loss, precision, recall, F1 and map and other indicators. The specific curve is shown in Figure 8:

![Visualization of target detection evaluation index curve](image)

Figure 8. Visualization of target detection evaluation index curve

5.2. Strawberry detection system based on yolov3 algorithm
Due to the location and angle of the strawberry, and the shooting location, the size and colour of the strawberry will be very different. This requires the network model to have a high generalization ability. Therefore, this article needs to verify that the model is suitable for different strawberry types. Based on the above requirements, this paper selects several sets of challenging strawberry pictures as test pictures. The specific visualized strawberry extraction effect is shown in Figure 9.
According to Figure 9, each strawberry detected is displayed by a rectangular frame. The upper left corner shows the strawberry category and the probability of belonging to the strawberry target. From the graph analysis, it can be seen that the yolov3 algorithm in this paper is suitable for larger strawberries and unidentified strawberries. The target detection effect of ripe strawberry is better, and the recall rate and precision rate can almost reach more than 90%. However, the detection of small targets is not as good as the detection of large strawberry targets, but the recall rate can also be achieved. Reaching more than 80%, it meets the requirements of picking in real life.

6. Conclusion
This article mainly designs a rigid-flexible coupling strawberry picking robot, and adds a vision system to the robot, with deep learning algorithms, can realize real-time monitoring of target objects, and improve the intelligence of modern picking equipment.

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