System Design of Tomatoes Harvesting Robot Based on Binocular Vision

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***Abstract*—Traditional manual picking is still the main picking method of fruits now. Because this method is too costly, there is an increasing interest in automatic harvest. In order to solve the problem of automatic harvest, a harvesting robot is designed for tomatoes as the research object. In this paper, a mathematical model for the mechanical arm of tomatoes harvesting robot is established, after identification and location of fruit by binocular cameras, the mechanical arm completes the task of harvesting fruits. The experimental results show that the tomatoes harvesting robot is active, accurate and efficient.**

***Keywords*—fruit recognition, binocular cameras, mechanical arm, harvesting robot**

I. Introduction

With the rapid development of modern agriculture, an increasing number of farmers use harvesting robots instead of manual harvest. However, traditional manual picking is still the main picking method of fruits [1~3]. Meanwhile, manual picking is too costly and time consuming, it greatly reduces the picking efficiency. In order to solve these problems, many scholars focus on researching harvesting robots, and have made many contributions. Wang Y et al. [4] designed an end-effector of citrus picking robot, it is based on the bionics principle. Zheng DM et al. [5] researched the motion trajectory of picking robot, realizing the trajectory tracking control of picking robot arm. Li H et al. [6] researched the identification method of green tomatoes, made the harvesting robots can detect green tomatoes.

In this paper, a robot based on binocular vision is designed to harvest tomatoes. Firstly, according to robot mechanical structure, a mathematical model for the mechanical arm is established, then the value of inverse kinematics according to forward kinematics is calculated. Secondly, an identification method combined Circular Hough transformation and RGB color space is designed, and a stereo vision model is established. Finally, we use raspberry pi, binocular cameras, mobile vehicle and mechanical arm to build a harvesting robot, and verify the ideal designed. The result shows that the tomatoes harvesting robot is flexible, accurate and efficient.

II. The Mathematical Model of Arm

In order to get the final position of the mechanical arm, the mathematical model should be established for the mechanical arm. D-H (Denavit-Hartenberg) model is the most commonly method for analyzing robot kinematics and can be applied to the robots of various structures, no matter how complex the structures is [7~9]. This paper designs a mechanical arm with 4+1 DOF (4 joints and an end-effector) for harvest tomatoes. According to the right-hand rule, the direction of each Z-axis can be determined, the corresponding X-axis is perpendicular to Z-axis. The link coordinate of the mechanical arm is shown in Fig 1.

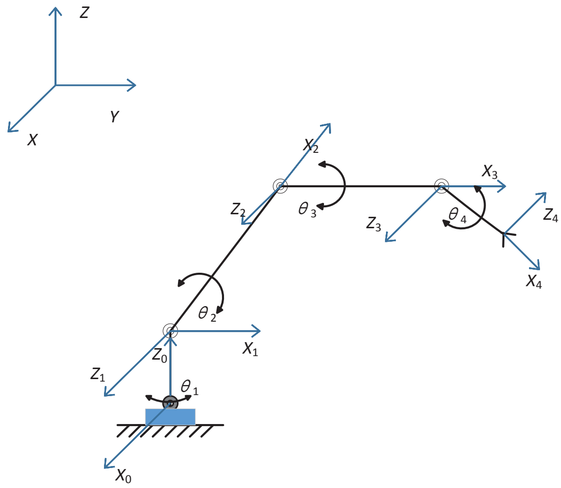

Fig. 1. Link Coordinate of Mechanical Arm

θ is the rotation angle of the joints. The D-H parameters can be obtained according to the link coordinate graph, shown in table 1, d is the offset of joint, d_{n+1} means the distance that X_n translates to X_{n+1} along Z_n, α is the torsional angle of joint, α_{n+1} means the angle that Z_n rotates to Z_{n+1}.

TABLE I. Table of D-H Parameters

#	θ	d	a	α
0-1	θ_1	l_1	0	90
1-2	θ_2	0	l_2	0
2-3	θ_3	0	l_3	0
3-4	θ_4	0	l_4	-90

According to the kinematics of the robot, the position and pose of the link $n+1$ relative to the link n can be known [10]. The formula is as follows,

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$$ {}^{n}T_{n+1} = A_{n+1} = \begin{bmatrix} C\theta_{n+1} & -S\theta_{n+1}C\alpha_{n+1} & S\theta_{n+1}S\alpha_{n+1} & a_{n+1}C\theta_{n+1} \\ S\theta_{n+1} & C\theta_{n+1}C\alpha_{n+1} & -C\theta_{n+1}S\alpha_{n+1} & a_{n+1}S\theta_{n+1} \\ 0 & S\alpha_{n+1} & C\alpha_{n+1} & d_{n+1} \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (1) $$

In the formula, $C\theta_{n+1}$ and $S\theta_{n+1}$ mean $\cos\theta_{n+1}$ and $\sin\theta_{n+1}$ respectively. Substituting the data in the D-H parameter table into formula (1), can get the value of A_1, A_2, A_3 and A_4, the position and pose of end-effector in the basic coordinate can be got by multiplying them,

$$ {}^{0}T_H = A_1A_2A_3A_4 = \begin{bmatrix} C_1C_{234} & -S_1 & -C_1S_{234} & C_1(l_3C_{23}+l_2C_2+l_4C_{234}) \\ S_1C_{234} & C_1 & -S_1S_{234} & S_1(l_3C_{23}+l_2C_2+l_4C_{234}) \\ S_{234} & 0 & C_{234} & l_1+l_2S_2+l_3S_{23}+l_4S_{234} \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (2) $$

In the formula,

$$ C_i = \cos\theta_i, $$
$$ S_i = \sin\theta_i, $$
$$ C_{234} = \cos(\theta_2+\theta_3+\theta_4), $$
$$ S_{234} = \sin(\theta_2+\theta_3+\theta_4). $$

Formula (2) is the kinematics equation for this mechanical arm [5].

III. Inverse Kinematics of Mechanical Arm

Inverse kinematics also plays an important role in robotics. The θ of the joints are calculated based on inverse kinematics so that the mechanical arm can reach the preconceived position. Assume that the preconceived position of the end-effector is

$$ P = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (3) $$

Let

$$ {}^{0}T_H = P, \quad (4) $$

then

$$ \begin{cases} p_x = C_1(l_3C_{23}+l_2C_2+l_4C_{234}) \\ p_y = S_1(l_3C_{23}+l_2C_2+l_4C_{234}) \end{cases}. \quad (5) $$

The first angle of joint can be obtained by

$$ \theta_1 = \arctan\frac{p_y}{p_x} \text{ or } \theta_1 = \theta_1 + \pi. \quad (6) $$

To calculate the other angles, the formula (4) multiplied by A^{-1} from the left,

$$ \begin{bmatrix} C_{234} & 0 & -S_{234} & l_3C_{23}+l_2C_2+l_4C_{234} \\ S_{234} & 0 & C_{234} & l_3S_{23}+l_2S_2+l_4S_{234} \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} n_xC_1+n_yS_1 & o_xC_1+o_yS_1 & a_xC_1+a_yS_1 & p_xC_1+p_yS_1 \\ n_z & o_z & a_z & p_z-l_1 \\ n_xS_1-n_yC_1 & o_xS_1-o_yC_1 & a_xS_1-a_yC_1 & p_xS_1-p_yC_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (7) $$

According to the (1,3) and (2,3) elements in the equation (7),

$$ \begin{cases} -S_{234} = a_xC_1+a_yS_1 \\ C_{234} = a_z \end{cases}, \quad (8) $$

the following can be got,

$$ \theta_{234} = \arctan(-\frac{a_xC_1+a_yS_1}{a_z}) \text{ or } \theta_{234} = \pi + \theta_{234}. \quad (9) $$

According to the (1,4) and (2,4) elements in the equation (7),

$$ \begin{cases} p_xC_1+p_yS_1 = l_3C_{23}+l_2C_2+l_4C_{234} \\ p_z-l_1 = l_3S_{23}+l_2S_2+l_4S_{234} \end{cases}. \quad (10) $$

Let

$$ \begin{cases} M = p_xC_1+p_yS_1-l_4C_{234} = l_3C_{23}+l_2C_2 \\ N = p_z-l_1-l_4S_{234} = l_3S_{23}+l_2S_2 \end{cases}, \quad (11) $$

and compute the sum of squared values of both side of equation (11),

$$ M^2+N^2 = l_3^2+l_2^2+2l_2l_3(C_2C_{23}+S_2S_{23}). \quad (12) $$

In equation (12),

$$ C_2C_{23}+S_2S_{23} = \cos[(\theta_2+\theta_3)-\theta_2] = C_3, \quad (13) $$

therefore,

$$ C_3 = \frac{M^2+N^2-l_3^2-l_2^2}{2l_2l_3}, \quad (14) $$

then

$$ S_3 = \pm\sqrt{1-C_3^2}. \quad (15) $$

Therefore, the third angle of joint can be obtained,

$$\theta_3 = \arctan \frac{S_3}{C_3}. \quad (16)$$

Transform the equation (11),

$$\begin{cases} M = l_3 C_2 C_3 - l_3 S_2 S_3 + l_2 C_2 \\ N = l_3 C_2 S_3 + l_3 S_2 C_3 + l_2 S_2 \end{cases}, \quad (17)$$

then

$$\begin{cases} S_2 = \dfrac{(l_3 C_3 + l_2)N - l_3 S_3 M}{(l_3 C_3 + l_2)^2 + l_3^{\,2} S_3^{\,2}} \\ C_2 = \dfrac{(l_3 C_3 + l_2)M + l_3 S_3 N}{(l_3 C_3 + l_2)^2 + l_3^{\,2} S_3^{\,2}} \end{cases}. \quad (18)$$

The second angle of joint can be obtained,

$$\theta_2 = \arctan \frac{(l_3 C_3 + l_2)N - l_3 S_3 M}{(l_3 C_3 + l_2)M + l_3 S_3 N}. \quad (19)$$

According to the value of θ_{234}, θ_2 and θ_3, the last angle of joint can be obtained,

$$\theta_4 = \theta_{234} - \theta_3 - \theta_2. \quad (20)$$

All four angles have been calculated. The end-effector can reach the preconceived position by rotating the corresponding angles.

IV. Recognition of Tomatoes

There are many methods to identify the target fruits. The robot can recognize whether the object is leaves, branches or fruits based on color [11], shape and texture. Color is the most intuitive feature to distinguish between target fruits and background. However, color-based recognition methods are affected by some factors such as varying illuminations, while the shape-based recognition method is not affected by varying illuminations. This paper designs an identify way of fruit that combined color and shape feature.

Circular Hough transformation is a classic method based on shape. Its basic ideal is to transform points in the measurement space into surface in the parameter space, after the transformation, points that have the same parameter feature intersect in parameter space, the feature circle is detected by judging the degree of accumulation at the intersection. Because the edge of tomatoes are arc-shaped, circular Hough transformation can be used to recognize the tomatoes. In order to get a better result, the original image should be processed. The original image is shown in the Fig.2(a), converted into a grayscale image, then median filter processing for the grayscale image is performed, shown as Fig.2(b) and Fig.2(c) respectively. Compared to Fig.2(b), Fig.2(c) looks smoother, this will get a better detect result. It is also necessary to extract edges of Fig.2(c), this paper uses canny operator edge detection method, shown as Fig.2(d). The results of detected tomatoes obtained by circular Hough transformation is shown in Fig.2(e), relevant parameters need to be adjusted to make the results more perfect.

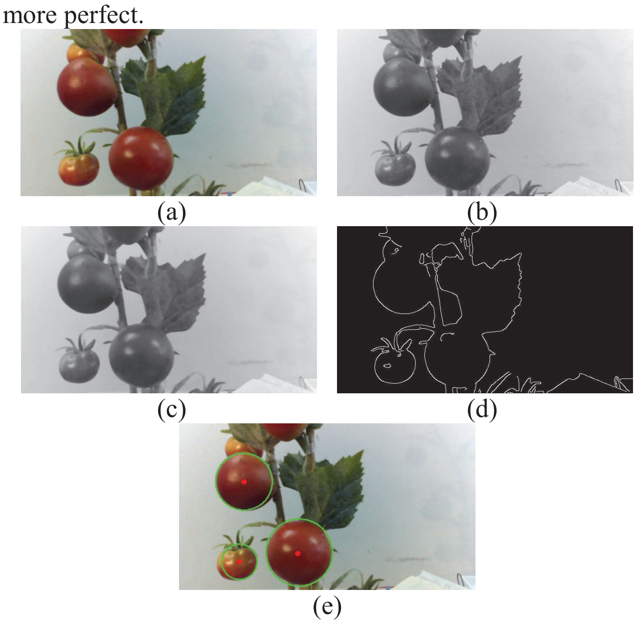

Fig. 2. Detection process using Circular Hough transformation ((a).The original image; (b).Grayscale image; (c).Median filter processing image; (d).Edge detection image; (e).Detection results of Circular Hough transformation)

However, due to some defects of this method, no parameter can make all the result perfect, sometimes there are some error detection, such as the case of Fig.3.

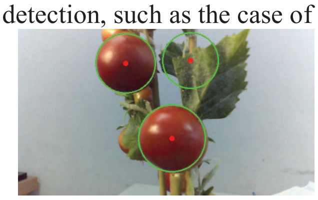

Fig. 3. Error detection

Based on this method, combined with the RGB color recognition method, the red element in the detected circle would be detected. If red element in the circle is less than a certain threshold, then it is not the target tomato. The result shown as Fig.4.

Fig. 4. Detection results combine Circular Hough transformation and RGB

V. Location of the Target Tomatoes

The principle of binocular stereo vision is that two cameras are separated by a certain angle within a certain distance, then capture the same scene in both figures. The angle between the cameras used in this paper is 180 degrees. In other words, the optical axes of two cameras are parallel [12]. The basic principle is shown in Fig 5.

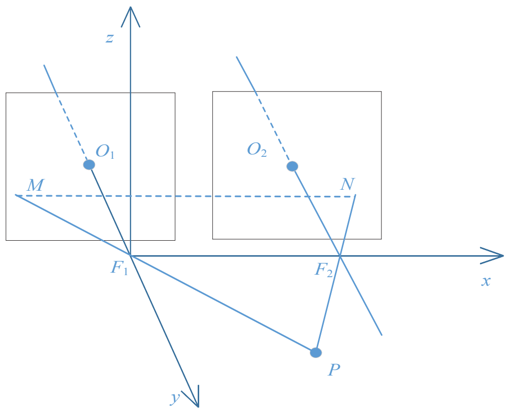

Fig. 5. The principle of binocular stereo vision

O_1F_1 and O_2F_2 are the focal length f of two cameras, the straight lines on them are the optical axis of two cameras, the distance from F_1 to F_2 is baseline b . A coordinate system with F_1 as the origin of the coordinate system is created. Assuming that the coordinates of a point P in the world are (p_x, p_y, p_z) , $M(x_1, -f, z_1)$ and $N(x_2, -f, z_2)$ are imaging points that point P maps to the imaging plane of two cameras. The coordinate of target point can be obtained according to the similarity of ΔPF_1F_2 and ΔPMN ,

$$\begin{cases} x_p = \dfrac{bx_1}{x_1 - x_2 + b} \\ y_p = \dfrac{bf}{x_2 - x_1 - b} \\ z_p = \dfrac{z_1 b}{x_1 - x_2 + b} \end{cases} \tag{21}$$

VI. EXPERIMENT

The harvesting robot is mainly composed of a Raspberry Pi 3B, a binocular camera, a mobile vehicle and a mechanical arm as shown in Block diagram Fig 6.

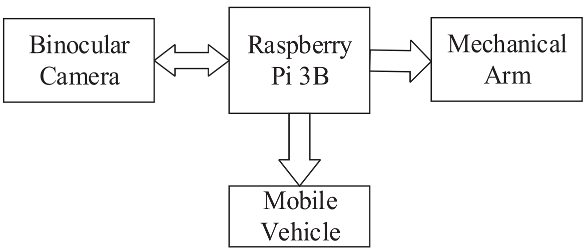

Fig. 6. Block diagram

This paper uses Raspberry Pi 3B as the main controller of the tomatoes harvesting robot. Raspberry Pi is a computer motherboard based on ARM. It has a size of a bank card only, and has the basic functions of a computer by connecting a mouse and a keyboard. HNY-CV-002 provided by LenaCV is as the binocular camera of the harvesting robot, its baseline is variable, and the frame rate can reach 30 frames per second. It can communicate with Raspberry Pi directly. The mechanical arm consists of several digital servo motors and the mobile vehicle is drove by DC motors [13]. The whole structure of the robot is shown in the Fig 7.

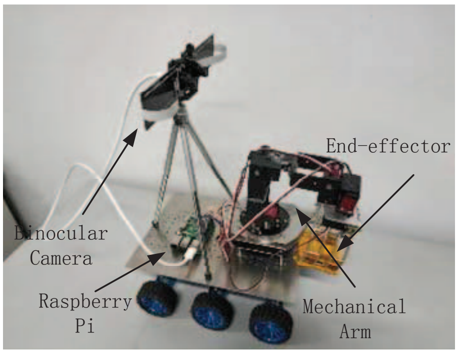

Fig. 7. The structure of the robot

In order to verify how the harvesting robot can recognize the tomatoes correctly and pick the target tomatoes successfully, the harvesting robot is tested in a simulated environment, 50 tests were performed on tomatoes in different locations. The results show that the times of the tomatoes harvesting robot picks the target tomatoes is 39, the success rate is 78%, the average time is within 15 seconds from the moment the mechanical arm reaches the working radius to pick the target tomatoes successfully.

VII. CONCLUSION

This paper designed a prototype development of tomatoes harvesting robot based on binocular vision. The prototype robot has simple structure, sensitive response, fast execution speed and high harvesting success rate. In general, it meets the requirements of design and has great significance for the realization of unmanned agriculture.

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