Design of Apple-picking End Effector

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A motor-driven end effector with 9 degrees of freedom is designed. Information of the joint position is transmitted to the potentiometer through gears, to realize the position control for the finger joint. The maximum torque of the finger joint motor is verified by imposing load to the end effector fingertip under the parabola-straight line angular velocity curve. The single-finger coordinate system and the whole-hand coordinate system are established for the end effector through D-H method. And the forward kinematics and inverse kinematics analysis of the end effector are carried out. In order to realize the stationary motion of the end effector, the basic algorithms for the starting, stopping and accelerating of the finger joint is designed, based on the analysis of the grasping space using Monte Carlo method and the analysis of the angular displacement of motor using isochronic interpolation algorithm. The control system is designed based on STM32F103RC to realize the stationary motion of the end effector. Using Tiny 6410, the remote wireless debugging system of end effector is designed to realize independent control and remote wireless debugging of each joint motor.

Keywords: Apple Picking, End Effector, Trajectory Planning, Remote Wireless Debugging, STM32F103RC, Tiny6410

Highlights:
- A motor-driven end effector with 9 degrees of freedom is designed.
- The forward kinematics and inverse kinematics analysis of the end effector are carried out.
- This end effector can be independent controlled and debugged wirelessly.
- The mechanical strength of the end effector can meet the requirement of picking.

0 INTRODUCTION

In China, apple is mostly harvested by human labor. Harvesting is expected to be automated as the farming population is gradually decreasing in China. Long He and his team have reported a new different variations of shake-and-catch harvesting system in 2017[1]. However, This method of picking is easy to cause substantial fruit damage and dropping of immature fruits. Researches have proposed that the robotic system which mimics the human hand-picking process can improve manipulation performance and reduce damage [2]. However, one of the bottlenecks in robotic apple harvester is the lack of effectively functional apple picking end-effector to meet the challenging requirements for practical application, because the picking end-effector handle plant materials directly and can potentially influence the market value of the product [3].

The automatic picking of fruit requires higher-level mechanical control and feedback of the end effector [4]. At present, many experts and scholars have carried out related researches on the end effector which is used for picking round or oval fruits such as apple [5], tomato [6], orange [7] and kiwi [8]. Up to now, the end effector used for picking round or oval fruit has such drive modes as tendon transmission, belt drive, air pressure transmission, and hydraulic transmission. But the end effector designed by adopting the abovementioned transmission modes has poor self-adaptability of grasping [9,10]. Bao, Guanjun and his team designed a type of pneumatic flexible end-effector, which can protect fruits from damaging [11]. However, the conventional off-line programming, force feedback check and other grasping posture debugging methods need to be operated by professionals, which is rather cumbersome. The flexible finger made of new materials has fairly strong adaptability and causes less damage to the fruit. But the price is expensive and the control system is rather complex. Therefore, it is imperative to design a cheaper debugging mode which allows farmers to independently set the end effector grasping posture to improve the grasping adaptability of the end effector. From the point of view of cost and efficiency, the design of such a debugging mode is conducive to the promotion of the round or oval fruit picking. Among apple, pear, peach, kiwi and
other round or oval fruit, a mature apple is representative in terms of weight and shape. Thus, this paper takes the apple picking as example to design the end effector.

1 DESIGN OF THE OVERALL SYSTEM

In the process of apple picking, the end effector is required to envelop the fruit. The number of fingers is set as three. The three fingers round together and are evenly distributed. Fig.1 shows the design of overall layout of the end effector. A direct-current dynamo is used to drive the reduction gear to drive the finger and the output shaft of the motor is connected with the potentiometer to realize the collection of the joint position information. Position-based control is used to ensure the dexterous operation of the end effector.

![Fig. 1. Overall layout of end effector](image)

The end effector has a total of nine degrees of freedom. The control system architecture of the end effector is shown in Fig. 2. The joint motor operation can be controlled after the nine-channel PWM wave inputting into the joint motor driver. In order to ensure that farmers can independently set the fruit grasping posture of the end effector, it is necessary to design a remote wireless debugging module to debug the grasping posture of the end effector. Meanwhile, the operation law for the starting, accelerating and stopping of each joint motor is made into standard modules, which is stored in the Memory of the lower computer controller. The lower computer carries out the joint trajectory planning according to the grasping posture of the end effector. Then, the joint trajectory of the end effector is constructed according to the results of trajectory planning and application of the modularized trajectory curve program of the starting, speeding and stop of each joint motor and the even operation of the subroutine of the motor.

![Fig. 2. Architecture of the control system of the end effector](image)

2 DESIGN AND VERIFICATION OF MECHANICAL STRUCTURES OF END EFFECTOR

2.1 The mechanical system design

Mature apples are usually 80mm-100mm in diameter. Each finger of the end effector is designed to consist of three knuckles whose lengths are 41mm, 41mm, 30mm. The mechanical structure of the single finger is shown in Fig. 3. At the end of the output shaft of the reduction motor, the rotating angle of the joint is transmitted to the potentiometer through the gear meshing, as shown in Fig. 4. GAM-N20 is selected as the joint deceleration motor, whose parameters are shown in Tab. 1. Fig.5 shows the end effector made of PLA material through rapid prototyping technology.

![Fig. 3. The mechanical structure of single finger](image)

![Fig. 4. Detection mechanism of joint rotation angle](image)
### Table 1. The parameters of the joint motor GAM-N20

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>6V</td>
</tr>
<tr>
<td>No load speed</td>
<td>60r/min</td>
</tr>
<tr>
<td>Load speed</td>
<td>48r/min</td>
</tr>
<tr>
<td>Rated torque</td>
<td>0.098Nm</td>
</tr>
<tr>
<td>Rated current</td>
<td>120mA</td>
</tr>
<tr>
<td>Stopping torque</td>
<td>0.686Nm</td>
</tr>
<tr>
<td>Stall current</td>
<td>200mA</td>
</tr>
<tr>
<td>Reduction ratio</td>
<td>250</td>
</tr>
</tbody>
</table>

Fig. 5. The 3D-printed end effector

The weight of an apple is 180g-250g generally. In the picking process, the distribution of the finger load is uniform without consideration of the reaction force of the fruit stem to the end effector. And the load of each knuckle is shown in equation (1).

\[ F = \frac{m \cdot g}{n} \cdot k \]  

where m is the weight of the apple, g is acceleration of gravity, n is the number of the fingers and k is the safety factor. n=3 represents that the maximum load of the finger knuckle is to bear 1/3 of the weight of the apple. Considering an apple with maximum mass of about 0.25kg, safety factor is set as 1.2, so the value of force is 0.98 N.

Fig. 6. Stress distribution of middle finger knuckle

![Stress distribution of middle finger knuckle](image)

In extreme cases, the finger tips bear all the weight of the fruits. Consider an apple with maximum mass of about 0.25kg. When distributed to each finger, the load is about 0.98N as shown in equation (1). In the picking process, the middle finger bears the largest load. In order to simulate the mechanical strength of the finger, the load of 1N is imposed on the tip of the middle finger with its basal joint fixed. The end effector is made of 1345 aluminum alloy, with shear modulus of 27000 MPa, density of 2700kg/m³, yield strength of 27.54200 MPa, and Poisson’s ratio of 0.33. The loading pattern, stress and strain stress of the middle finger are shown in Fig. 6 and Fig. 7, respectively. The simulation indicates that the minimum shear stress is 0.0000732 MPa and the maximum is 0.2671942 MPa; the minimum strain is 1.167×10⁻⁹ and the maximum is 2.453×10⁻⁶. The mechanical strength of the middle finger satisfies the requirement, and so does the mechanical strength of other fingers [12].

#### 2.2 Kinematic analysis of end effector

The single finger D-H coordinate system of the end effector is established, as shown in Fig. 8. Its parameters are shown in Tab. 2.

![Single finger D-H coordinate system](image)

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### Table 2. Parameters of single finger D-H coordinate system of end effector

<table>
<thead>
<tr>
<th>link</th>
<th>( \theta_i (°) )</th>
<th>( d_i )</th>
<th>( a_i )</th>
<th>( \alpha_i (°) )</th>
<th>Variable range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \theta_1 )</td>
<td>0</td>
<td>30</td>
<td>0</td>
<td>0~90</td>
</tr>
<tr>
<td>2</td>
<td>( \theta_2 )</td>
<td>0</td>
<td>41</td>
<td>0</td>
<td>0~90</td>
</tr>
<tr>
<td>3</td>
<td>( \theta_3 )</td>
<td>0</td>
<td>41</td>
<td>0</td>
<td>0~90</td>
</tr>
</tbody>
</table>

\[ ^0T_4 = A_1 \times A_2 \times A_3 = \begin{bmatrix} c_{123} & s_{123} & 0 & a_1c_i + a_2c_{12} + a_3c_{123} \\ s_{123} & c_{123} & 0 & a_1s_i + a_2s_{12} + a_3s_{123} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} n_x \\ o_x \\ a_x \\ p_x \end{bmatrix} = \begin{bmatrix} n_x \\ o_y \\ a_y \\ p_y \end{bmatrix} \begin{bmatrix} n_z \\ o_z \\ a_z \\ p_z \end{bmatrix} \]

(2)

The inverse kinematics of the end effector is solved by using the algebraic method [14,15]. Equation (3), (4), (5) and (6) can be obtained by equation (2). Equation (7) and (8) can be obtained by substituting equation (3) and (4) into equation (5) and (6). Though equation (7) and (8) \( \theta_2 \) can be obtained, as shown in equation (9). Then, \( \theta_1 \) can be solved by substituting (9) into (7), as shown in equation (10). Finally, \( \theta_3 \) can be obtained by equation (3) and (4). The inverse kinematics equation of the finger of the end effector has many solutions, so it is necessary to consider the actual situation of picking and the requirement of the stability of motion.

\[
\begin{align*}
c_{123} &= n_x \\
s_{123} &= n_y \\
a_i c_i + a_2 c_{12} + a_3 c_{123} &= p_n \\
a_i s_i + a_2 s_{12} + a_3 s_{123} &= p_y \\
a_i c_i + a_2 c_{12} &= p_n - a_i n_y \\
a_i s_i + a_2 s_{12} &= p_y - a_i n_x \\
\theta_2 &= \arccos \left( \frac{p_n - a_i n_y}{2a_i a_n} \right) \\
\theta_1 &= \arctan \left( \frac{p_n - a_i n_y}{p_r - a_r n_y} \right) \cdot \arctan \left( \frac{a_r \sin \theta_2}{a_r + a_\cos \theta_2} \right) \\
\theta_3 &= \arctan \left( \frac{n_z}{n_y} \right) - \theta_2 \\
\end{align*}
\]

(3) (4) (5) (6) (7) (8) (9) (10) (11)

#### 2.3 Trajectory planning and motor checking

In the starting phase of the joint motor motion, the acceleration curve is set as a parabola-straight line velocity curve planning algorithm, so that the motion of the end effector can be stabilized [16,17]. Considering the mechanical structure of the end effector, each joint of the end effector is set to rotate from 0° to 90°. The maximum acceleration of joint motor is \( a_{\text{max}} = 5 \text{ m/s}^2 \), and the maximum velocity is \( v_{\text{max}} = 10 \text{ m/s} \). The speed of the motor of each joint is planned as shown in equation (12).

The angular velocity curve of each joint motor can be obtained by equation (12), as shown in Fig. 9.

\[
\omega(t) = \begin{cases} 
\frac{a_{\text{max}} t^2}{2t_t} & 0 \leq t \leq t_t \\
-\frac{1}{2} a_{\text{max}} (t-t_t)^2 & t_t < t \leq 2t_t \\
a_{\text{max}} t_t & 2t_t < t \leq 3t_t \\
a_{\text{max}} t_l - \frac{1}{2} a_{\text{max}} (t-t_l)^2 & t_l < t \leq 4t_l \\
0 & \text{otherwise}
\end{cases}
\]

(12)

Fig. 9. Angular velocity of the joint motor

It can be seen from Fig.13 that the velocity curve of the end effector gets stable after trajectory...
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Planning. At the initial stage, the rate of change of velocity is a finite value. When the speed reaches the maximum value, it keeps uniform running, then decelerates the speed. When reaching the end point, the joint angular velocity is 0. This can reduce the damage to the fruit. And it is also conducive to the operation of the motor.

Considering the finger weight of the end effector, the no-load checking of the motor is carried out by using SolidWorks software under the motion law shown in Fig. 9. The torque variation law of each joint motor is shown in Figure 10, Figure 11 and Figure 12.

The single finger movement of the end effector is simulated through applying the parabola-straight line speed curve planning algorithm. Results of the simulation show that the end effector runs smoothly.

\[
\begin{align*}
P_{x1} &= a_1 c_1 + a_2 c_{12} + a_3 c_{123} \\
P_{y1} &= a_1 s_1 + a_2 s_{12} + a_3 s_{123}
\end{align*}
\]  

(13)

The rotation angle of each joint of the end effector is between 0° and 90°. When the rand function of MATLAB software is applied, 80,000 points in the range of the angle are generated and substitute them into equation (13). The workspace of the fingertip is calculated by using the scatter function, as shown in Figure 13. In the same way, the sports space of the middle and distal finger knuckles of the single finger in the base coordinate is shown in equation (14) and equation (15).

Combining with the mechanical mechanism of the end effector, the whole hand coordinate system is established by using the D-H method, as shown in Fig. 14. From the mechanical structure of the end effector, the D-H coordinate system parameters are learned and are shown in Tab. 3.

\[
\begin{align*}
P_{x2} &= a_1 c_1 + a_2 c_{12} \\
P_{y2} &= a_1 s_1 + a_2 s_{12}
\end{align*}
\]  

(14)

(15)

2.4 Workspace analysis of end effector

The workspace of the end effector is solved by the Monte Carlo method [18,19]. The relationship between the fingertip of the end effector and the base coordinate is \( ^{0}T_e = A1 \times A2 \times A3 \times A4 \). The motion space of the fingertip relative to the base coordinate refers to the motion space of the point at the location of (0,0,0), i.e [20].

![Fig. 10. No-load torque diagram of base joint motor](image)

![Fig. 11. No-load torque diagram of middle joint motor](image)

![Fig. 12. No-load torque diagram of distal joint motor](image)

![Fig. 13. Fingertip workspace](image)

![Fig. 14. Whole-hand D-H coordinate system](image)
Table 3. D-H parameters of finger base coordinate to palm base coordinate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>d</th>
<th>(\theta)</th>
<th>(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z01</td>
<td>0</td>
<td>-120</td>
<td>90</td>
</tr>
<tr>
<td>Z02</td>
<td>0</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>Z03</td>
<td>0</td>
<td>120</td>
<td>90</td>
</tr>
</tbody>
</table>

The transformation matrix of the Z01 coordinate system relative to the Z0 coordinate system is shown in equation (16) [21].

\[
\begin{bmatrix}
 c_{01} & -s_{01}\cos\alpha_{01} & s_{01}\sin\alpha_{01} & a_{01}c_{01} \\
 s_{01}\cos\alpha_{01} & c_{01}\cos\alpha_{01} & -c_{01}\sin\alpha_{01} & a_{01}s_{01} \\
 0 & \sin\alpha_{01} & \cos\alpha_{01} & d_{01} \\
 0 & 0 & 0 & 1
\end{bmatrix}
\]

(16)

The transformation relationship between finger 1 of the end effector and the base coordinate is \(b^T_{13} = A01 \times A1 \times A2 \times A3\). The motion space of the fingertip of finger 1 relative to the base coordinate refers to the motion space of the point at the location of (0,0,0), as shown in equation (17).

\[
\begin{align*}
 p_x &= c_{01}(a_1c_1 + a_2c_{12} + a_3c_{123} + a_{01} + a_{01}) \\
 p_y &= s_{01}(a_1c_1 + a_2c_{12} + a_3c_{123} + a_{01} + a_{01}) \\
 p_z &= \sin\alpha_{01}(a_1s_1 + a_2s_{12} + a_3s_{123})
\end{align*}
\]

(17)

Based on equation (11), the workspace of the fingertip of finger 1 relative to the base coordinate of the hand can be calculated, as shown in Fig. 15.

In the same way, the images of the fingertips of finger 2 and finger 3 relative to the palm base coordinate can be calculated. The shape is the same as that in Fig. 15, but the images have different positions in workspace. Using the fingertips of 3 fingers, the point of workspace can be obtained with the position equation of palm base coordinates. Using the cat function of MATLAB software, X coordinate, Y coordinate, and Z coordinate of the fingertip are combined. Then the whole workspace can be obtained by using the scatter3 function. Fig. 16 shows that the three fingertips can form a better envelope for the fruit from the whole hand working space.

3 DESIGN OF CONTROL SYSTEM

3.1 Design of remote wireless debugging software

STM32F103RC is selected as the controller of the end effector. According to the overall system design requirements, the grasping posture of the end effector shall be adjusted by the remote wireless debugging module and downloaded to the controller storage. Meanwhile, the well-designed motor rotation trajectory curve shall also be stored in the Memory of the controller. The controller parses the control command conveyed by the main controller of the picking robot, and then retrieves different grasping gestures of the end effector and corresponding planned trajectory curve of the joint motor to drive the joint motor, thus realizing the grasping gesture of the end effector. Chip YT5188 is selected to collect the information of the rotation angle by checking the output end of the potentiometer at the corner of motors, which constitutes the motor position feedback control system. NRF24L01 is adopted as the wireless transmission model, which can realize point-to-point transmission. It communicates with the controller via SPI port. It can send or accept as many as 32 bytes at a time after configuration.
The control mode of the end effector controller includes operation mode, debugging mode, download the initial address mode and download the final address mode.

The software procedure of the end effector controller is shown in Fig. 17. The main program has been testing the mode zone bit. When the different mode zone bits are in place, the controller runs in corresponding mode. Following a cycle of 50ms, Timer interrupt 5 tests whether the data of remote wireless debugging module have been received. When the data are received, it will determine whether it is a command or an operation data. If it is a command, corresponding zone bit will be put in place. If it is the operation data, it will be transformed and saved into the global variable, waiting for the function reference.

According to the motor control requirement, the pulse is required to be 1ms~2ms. The clock frequency of the timer is set as 1MHz and the cycling period is 20ms, and then the timer duty cycle corresponding to 1ms~2ms is 1,000~2,000. The motor rotation angle is 180 degrees, so the control accuracy of the controller is 0.18 degree. It can be seen from formula (12) that the motor rotates 0.83 degree at the beginning and accelerating period, rotates 5 degree at the uniformly accelerating period and rotates 9.1667 degree at the decelerating phase. The interpolation method is designed based on the control accuracy of the motor. 2 points are interpolated at the acceleration stage, i.e. 5t/8 and t (t ≤ 1s). At the uniformly accelerating period (1 < t ≤ 2), five points are interpolated isochronally. At the decelerating phase (2 < t ≤ 3), five points are interpolated isochronally. The interpolation point satisfying the abovementioned requests can be figured out based on the requirement of motor control, which is shown in Table 4.

The control law at the decelerating phase and the initialization phase is just on the contrary. At the uniform motion stage, the isochronal interpolation method is adopted. The interpolation point is proportional to the time of the uniform motion. There is an interpolation every 40ms and the pulse increment is 2. Based on the abovementioned control algorithm, finally, the motor displacement planning algorithm is designed, which is shown in Table 5. The motor operation process is designed based on the motor control law in Table 5.

<table>
<thead>
<tr>
<th>Time(sec)</th>
<th>A: 5t/8</th>
<th>UA: t</th>
<th>UB: t/5</th>
<th>VA: 2t/5</th>
<th>VB: 3t/5</th>
<th>VC: 4t/5</th>
<th>WD: 4t/5</th>
<th>E: t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement increment (deg)</td>
<td>0.2</td>
<td>0.63</td>
<td>0.60</td>
<td>0.80</td>
<td>1.00</td>
<td>1.20</td>
<td>1.40</td>
<td>1.59</td>
</tr>
<tr>
<td>Pulse increment</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

A: acceleration, UA: uniform acceleration, VB: variable deceleration
Table 5. Integral displacement planning and design

<table>
<thead>
<tr>
<th>Displacement S (Angle)</th>
<th>Planning algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0&lt;S&lt;=0.83</td>
<td>Run to the destination address</td>
</tr>
<tr>
<td>0.83&lt;S&lt;=6.66</td>
<td>Start acceleration planning</td>
</tr>
<tr>
<td>6.66&lt;S&lt;=15.83</td>
<td>Start acceleration planning and uniform acceleration planning</td>
</tr>
<tr>
<td>15.83&lt;S&lt;=25</td>
<td>Start acceleration planning, uniform acceleration planning and variable deceleration planning</td>
</tr>
<tr>
<td>25&lt;S&lt;=30.8</td>
<td>Start acceleration planning, uniform acceleration planning, variable deceleration planning while decelerating.</td>
</tr>
<tr>
<td>30.8&lt;S&lt;=31.65</td>
<td>Start acceleration planning, uniform acceleration planning, variable deceleration planning and variable deceleration planning while decelerating.</td>
</tr>
<tr>
<td>31.65&lt;S</td>
<td>Start phase planning, uniform velocity planning, deceleration planning</td>
</tr>
</tbody>
</table>

3.2 Design of remote wireless debugging software

For the sake of convenient and simple control of the end effector, remote wireless debugging software was designed based on Tiny6410. The development environment was established adopting Linux operation system and Qt software.

The system invokes the driving procedure using Linux, operates I/O interface and reads the command on the touch screen of Tiny 6410. The posture debug data of the end effector is sent to the transformation module via the serial port which will send the control command and data to the manipulator controller STM32F103RCT6 through the wireless communication module NRF24L01.

According to the above requirements, the software procedure of the remote wireless debugging module is designed, as shown in Fig. 18. The software interface is shown in Fig. 19. After the debugging software starts, the mode shall be selected first. When the operation mode is selected, other three modes shall be hidden. When the debugging mode is selected, the operation mode is hidden. Only under the debugging mode can the initial address and simulation address be downloaded. Control the location of the joint motor of the end effector with a slider control. When the slider slides, corresponding private slots will call a serial port to write the function. The debugging data will be sent to the controller of the end effector through the serial port.

![Software Procedure of Remote Wireless Debugging Module](image)

![Software Interface](image)

After the software runs, if the running mode or debugging mode is not selected, check the command check box or slide the slider, and the data will not be sent out. When the operation mode is chosen, the debugging mode, debugging order sending, the initial address downloading and the final address downloading will be hidden. When the debugging mode is chosen, the operation mode and operation command will be both hidden, and the check boxes of sending debugging command, downloading initial command and downloading terminal command can be switched arbitrarily.

4 EXPERIMENTS AND RESULTS

To verify the performance of end effector, design an experiment as follows. In the
experiment, three fresh market apple varieties were chosen for this study. These varieties were shaanxi "Fuji", "Luo Chuan" and "Hong Xing". The end-effector conducts test for 60 times (60 fruits) and 20 apples were selected for each variety. Before the experiment, ensure that the surface of the apple is intact so that it can be compared with the surface of the apple after the experiment to see if the force is appropriate. Then, take the apple and change the angle that manipulator grasps from $0^\circ$ to $180^\circ$ to see if the end effector can grasp the apple firmly.

**Table 5: The results of the experiment**

<table>
<thead>
<tr>
<th>Variety</th>
<th>Minimum mass (kg)</th>
<th>Maximum mass (kg)</th>
<th>Average mass (kg)</th>
<th>Success ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luo Chuan</td>
<td>0.1803</td>
<td>0.2478</td>
<td>0.2369</td>
<td>100%</td>
</tr>
<tr>
<td>Hong Xing</td>
<td>0.1803</td>
<td>0.2478</td>
<td>0.1992</td>
<td>100%</td>
</tr>
<tr>
<td>Fuji</td>
<td>0.1779</td>
<td>0.3420</td>
<td>0.2361</td>
<td>95%</td>
</tr>
</tbody>
</table>

The results of the experiment are shown in Table 5. "Luo Chuan" and "Hong Xing" apples are all successfully grasped without dropping. And the Maximum "Red Fuji" apple failed to be grasped during the experiment. Before the experiment, check the surface of the apple. The surface of the apples is smooth and the skin is intact. During the experiment, the apple was grabbed without dropping. In the process of changing grasping angle, the apple was grabbed with no dropping as shown in Fig. 20. After the experiment, check the surface of the apples with no damage. The experiment shows that the force and stability of the picking manipulator meet the requirement.

**5 CONCLUSIONS**

This paper presented the design of an end effector for apple picking with 9 degrees of freedom adopting the DC motor directly driven joints. The device can produce a grasp similar to human hand-picking process by precise control of the joint motor, greatly improving the quality and efficiency of the picking. The experiment indicates that the end effector can successfully grab an apple with a mass between 0.180kg and 0.250kg and the force of the picking manipulator meet the requirement. The position control system is established based on information of the joint position transmitted to the potentiometer through gears. The velocity curve of the end effector gets stable after trajectory planning. According to the analysis of the grasping space using Monte Carlo method and the analysis of the angular displacement of motor using isochronic interpolation algorithm, the end effector controller and remote wireless debugging module are designed, which enables the peasants to independently debug the grasping postures of the end effector and improves the grasping adaptiveness of the end effector. Other benefits of the design include its relatively low cost and simple design. Future research needs to be focused on precise control of grasping force of the end effector in order to effectively prevent fruits from damaging.

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**7 REFERENCES**


