Kinematics analysis and experiment of a lily picking mechanical arm

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Abstract: A lily flower is a medicinal plant, which has been widely used in the Chinese medicine industry in recent years. According to the rapid picking of the lily flower, a scheme of the mechanical arm picking structure was designed, and the system with an end effector, manipulator and control system was used. The mechanical arm adopts a three-stage connecting rod structure. Through the lily plant growth of more than about 85% <50 cm characteristics of the mechanical arm were picked up from the top to bottom operation strategy. Based on this, the kinematics model of the picking robotic manipulator is designed. The kinematic equation of the manipulator is demonstrated by a DH deducing method. The kinematics simulation of the manipulator is carried out by MATLAB. The mechanical arm kinematics and picking experiments were carried out in the experimental field in a natural environment by the robotic physical machine platform. The results showed that the manipulator position error from the end of the arm was <12 mm and the picking success rate was 83.33%.

1 Introduction

Lily is rich in nutrients and its economic value in China is significantly higher than other common cut flower varieties [1]. 90% of the economic pillars in Longshan County, Hunan Province, China rely on the Lily Industry. After field research, in the production process of lily drugs, the least efficient and most labour intensive is to pick lily flowers, which accounts for 60% of the entire workload in the picking process. The labour cost accounted for 40–60% of the total cost. In the local area, as the young labourers go out to work, the agricultural labour force is reduced and the aging is serious, and the production cost last to increase. Therefore, the development of lily picking robots has important economic and market significance.

For the mechanical arm kinematics analysis problem of picking robots, domestic and foreign researchers have conducted in-depth research: Abroad, Grecia designs a simple mechanical cutting system. The movement of the mechanical arm is adjusted by the shape and size of the flower and the direction of the flower (up/down) [1]. Thomas designs a mechanical arm using industrial robots with six axes (additional linear axes) for harvesting pedigles. In the process of cutting the pedigles, a path planning module is integrated so as to ensure that the movement path of the mechanical arm does not collide [2]. Jun studied a manual and claw mechanical arm apple harvesting mode, and analyzed the degree of damage when removing flowers. The result obtained from the mechanical arm picking mode indicate that a jaw gripper requires a small gripping pressure to separate the apples and find that the mechanical arm’s jaws are more manual-like in performance [3]. Henten put forward the results of an inverse kinematics algorithm study. It is a hybrid numerical analysis solution that exploits the inverse kinematics problem of the specific structure of the P6R robot. The algorithm is successfully applied to the functional model of the flower harvester to determine if the flower was hung in the reachable workspace of the mechanical arm and to determine the collision-free picking posture for the mechanical arm’s motion control during picking [4]. In China, Feng Qingchun et al. used the parametric optimisation method to optimise the design and structure parameters of the picking mechanical arm for crop’s specific cultivation patterns, combined with the manipulator working space and structural length indicators [5]. Wang Yan develops a four degree of free joint-type picking mechanical arm for the problems existing in the existing picking mechanical arm. He proposes a general structural parameter optimisation method for a joint-type picking mechanical arm used for workspace for any cubes and establishes the mathematical model of the optimisation design with the workspace as the constraint condition [6]. In order to improve the working space and picking efficiency of picking robots, Li Wei used a parametric analysis method to discuss the relationship between the robot base height, picking distance and length, rotation angle, operating space and working space of the mechanical arm, and optimised the picking mechanical arm's structural parameters [7]. Comprehensive research at the home and abroad find that the currently designed flower picking manipulators have a long working cycle, and their structure, operating methods, and control methods are relatively complex. There are few reports on the convenient picking study of the flower picking mechanical arm.

In order to improve the target recognition and positioning accuracy of a lilium flower picking robot and reduce the mechanical damage of flowers caused by inaccurate target coordinate positioning, designed a single end actuator picking robot in this paper. The strategy of single-ended actuators of one-on-one sequential picking in the lily planting area was proposed. The kinematics model of the manipulator was established and kinematic simulation and picking experiments of the manipulators were performed. One-to-one picking was performed on all the target flowers in a planting area and centralised collection.

2 Robotic arm structure design

2.1 Mechanical arm structure designs

With China’s promotion of a village-one product policy, Longshan County, China, plants large-scale economic crop lily, and 90% of the county’s economic pillar is derived from this. The cultivation of local lilies also tends to be more regionalised. In order to ensure the yield of lily and the stable growth of plants, the local lily technician divides the field into several 2.4 m × 1.2 m small area fields. Under this lily planting field plan, the length of the mechanical arm can be...
The robot designed in this paper has one job execution claw head attached to its front end. The mechanical arm adopts the three-stage structure of the connecting rod, and the mechanical arm sends the operation execution claw head to the upper end of the target lily, and the operation execution claw head makes the adjustment of the position. The structural forms of the mechanical arm mainly include a rectangular coordinate structure, cylindrical coordinate structure, polar coordinate structure, joint-type structure etc. According to the height of the lily plant and the picking action conditions, combined with the working space characteristics of various coordinate structure manipulators, the joint-type structure is adopted in consideration of the precision and spatial range of the motion, as shown in Fig. 1. According to the growth position and posture characteristics of the target crop and the existing environment of the farmland, the mechanical arm includes a rotatable base, two main joint shafts, and three end joint shafts, and each joint range can rotate freely. Since the trajectory at the end of the movement is more, by virtue of Daheng Mercury's camera (DahengMEER 500-7UC-L, 8 megapixels, frame rate 7 frames/s) to identify the lily image, after obtaining the three-dimensional coordinates of the centre point of the lily, the end of the arm is as close as possible to the coordinates above the centre point of the lily to achieve the picking position. The plant spacing of the experimental lily plantation field is generally 7–10 cm, and the plant spacing is generally 7–10 cm. About above 85% of lily plants are below 50 cm, and the rhizome part is about 0–12 cm from the ground. Combined with the growth stage of the lily, the target horizontal working space of the picking mechanical arm can be determined to be 260–1100 mm, and the vertical working space is 0–830 mm. The flower distribution depth range is 300–500 mm. According to the target horizontal working space, the range of each joint stroke of the mechanical arm is determined, and the motion precision of the mechanical arm is deepened. During the picking operation, the mechanical arm is mounted on a moving crawler vehicle. The height of the mechanical arm base is 160 mm from the ground, the arm extension length is 740 mm, the vertical plane extending area is about 0.57, and the horizontal plane extending area is about 1.46, as shown in Fig. 2. As shown in Fig. 2a, A and B are the upper and lower limit positions of the vertical joints of the main arm. Fig. 2b is a top view of the target picking range. When the vertical distance between the main arm and the lily plant is 1100 mm, the semi-circular target area with a horizontal width of 2200 mm can be reached at the end of the sub-arm. The depth of the end effector at each angle cross section can reach a range of 300–500 mm.

2.2 End picker structure design

The main picking objects for the mechanical arm picker designed in this paper are lily flowers, and it is also applicable to spherical or quasi-spherical flowers such as roses and chrysanthemums with a circle radius of <90 mm. The objects of this type of picking are all upwards, single flowers are connected to the stem, and their stalks are located directly below the flowers and at an acute angle to the horizontal line. The structure of the lily picking mechanical arm designed in this paper is shown in Fig. 3. The picking mechanical arm is composed of a claw, a position sensor, a blade, a step motor, an asynchronous pulley, and a driven pulley. During picking, the mechanical arm enters the claw of the operation picker, the two-side smasher cut off the stalk, and the flower is in the device, along with the mechanical arm. The movement is put into the storage box for temporary storage.

3 Robot control system design

3.1 Control system hardware design

The robot adopts the upper computer and lower computer two-level control system. The hardware block diagram is shown in Fig. 4. The upper computer adopts an Advantech IPC-610L IPC. The industrial camera uses the DahengMEER500-7UC-L from Daheng Mercury, which has a resolution of 8 million pixels and a frame rate of 7 frames per second. It transmits data via the IEEE-1394 adapter card and the IPC. The lower position machine includes the controller of the track moving platform and the controller of the mechanical arm. The tracked mobile platform controller using STM32F103, the mechanical arm controller using SMC-604, and use with the MA860H driver for greater drive a larger motor torque.

3.2 Picking operation strategy

The robot uses a single point-to-point precision picking method. According to the planting distance of lily plants and the working space of the mechanical arm, the lily field is divided into a plurality
of picking areas, and the lily images are identified and collected in the corresponding picking areas and then the lily is picked up point by point precisely. First, the main arm moves to the above coordinates of the target and the end picker adjusts and picks up the target lily, which are then placed in a centralised bin. For lily plants in overlapping areas, if the target lilies were successfully picked for the first time, they would not appear in the next set of target lilies; if the target flower is not harvested successfully for the first time, the lily flower will reappear in the next set of target lilies and the system will pick it again. Each picking area corresponds to a lily picking base point, and the lily picking base point is the joint end position of the main arm base. The position of the picking point of lilies is determined from the ‘right to left’ and ‘from far and near’ principle, and the phenomenon of no omission in the picking operation of each lily is satisfied.

During the picking operation, an image of the flower in the target area is captured by an industrial camera and uploaded to the computer for processing to obtain the spatial coordinates of the target flower in the target area. The visual system captures an image size of 656 pixels × 492 pixels, as shown in Fig. 5a. First, the histogram equalisation processing is performed on the original image [8–13], and noise filter preprocessing is performed [14–16] to remove the noise influence of the original image, as shown in Fig. 5b. Then obtain the binary image of the target lily boundary by the maximum variance between classes Otsu binary method (OTSU) [17–20]. The Canny operator is used for edge detection to obtain the outline of the target lily, and then the approximate region of the target flower edge is obtained through analysis of the extracted contour images. Calculate the interval between the centre of mass and the relevant Hough line. After the shortest distance constraint, select the line with the shortest interval as the line where the picking point is located. Finally, use the midpoint coordinate of the line segment as the picking point. The robot picking control process is as follows: (i) the upper computer calculates and determines the coordinate data of the target picking point. (ii) The end of the mechanical arm moves to the target picking point. (iii) The upper machine combines the coordinates of the picker at the end of the manipulator and the coordinates of the target picking point to perform the picking path planning of the manipulator and then sends motion parameters and motion instructions to the robot controller and waits for the robotic link controller to return the job completion signal. (iv) After receiving the upper machine motion parameters and movement instructions, the mechanical arm controller controls the mechanical arm and drives the end effector to sequentially pick and recycle the target flowers in the area. (v) After the fruit in the area is picked, the end of the arm returns to the initial coordinate position.

4 Kinematic analysis of a robot arm

4.1 Coordinate system and structural parameters

The D–H method was used to establish the kinematics equation of the mechanical arm of the lilium flower picking robot. The robotic coordinate system is shown in Fig. 6, where the coordinate system [0] is the base coordinate system. The parameters of each link of the mechanical arm are shown in Table 1.

4.2 Derivation of kinematic equations

The general formula of the transformation matrix of the adjacent links under the D–H parameter of the lily flower picking manipulator is

\[
T_{i-1}^{-1} = \begin{bmatrix}
    c_\theta_i & -s_\theta_i & 0 & a_{i-1} \\
    s_\theta_i c_{\alpha_{i-1}} & c_\theta_i c_{\alpha_{i-1}} & -s_{\alpha_{i-1}} & -d_i s_{\alpha_{i-1}} \\
    s_\theta_i s_{\alpha_{i-1}} & c_\theta_i s_{\alpha_{i-1}} & c_{\alpha_{i-1}} & d_i c_{\alpha_{i-1}} \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

According to the above-mentioned mechanical arm picking operation mode, the conversion matrix of the connecting rod can be obtained through Table 1 and formula (1):
By the equality of the elements (2, 4) on both sides of (1), we get

\[\theta_i = -\arcsin\frac{p_i}{a_i}\]

Transpose \(\mathbf{T}\) and use the variable separation to solve the following equation:

\[
\begin{bmatrix}
    c_1 & s_1 & 0 & 0 \\
    -s_1 & c_1 & 0 & 0 \\
    0 & 0 & 1 & 0 \\
\end{bmatrix}
\begin{bmatrix}
    a_1 \\
    a_2 \\
    a_3 \\
\end{bmatrix}
= \begin{bmatrix}
    c_2 & s_2 & 0 & 0 \\
    -s_2 & c_2 & 0 & 0 \\
    0 & 0 & 1 & 0 \\
\end{bmatrix}
\begin{bmatrix}
    a_4 \\
    a_5 \\
    a_6 \\
\end{bmatrix}
\]

By the equality of the elements (2, 4) on both sides of (2), we get

\[a_2s_4 = -c_2s_4p_4 - s_2s_4p_4 - c_2p_4\]

The expression of \(\theta_1\) and \(\theta_2\) is obtained from (1):

\[\theta_1 = \arctan\left(\frac{-c_1s_4p_4 - s_1s_4p_4 - c_1p_4}{a_1}\right)\]

By using the elements (1, 2) and (2, 2) on both sides of formula (2), we get

\[
\begin{bmatrix}
    c_1 & c_2 & 0 & 0 \\
    -c_2 & c_1 & 0 & 0 \\
    0 & 0 & 1 & 0 \\
\end{bmatrix}
\begin{bmatrix}
    a_1 \\
    a_2 \\
    a_3 \\
\end{bmatrix}
= \begin{bmatrix}
    c_3 & s_3 & 0 & 0 \\
    -s_3 & c_3 & 0 & 0 \\
    0 & 0 & 1 & 0 \\
\end{bmatrix}
\begin{bmatrix}
    a_4 \\
    a_5 \\
    a_6 \\
\end{bmatrix}
\]

The joint 1 moves first, and the target point of the mechanical arm is moved to the same plane, and the plane set as the \(X-Y\) plane, which further simplifies the inverse kinematics:

\[\theta_1 = \arctan\frac{y}{x}\]

The step motor 1 of the 4-DOF mechanical arm is a horizontal rotary joint. Only the step motor 2, the step motor 3, and the step motor 4 are vertical rotary joints. Therefore, in the path planning of the mechanical arm, a solution to the inverse kinematics of the geometric method can be used. As shown in Fig. 7a, the distance \(P = p(x_s, y_s, z_s)\) from the coordinate \(P\) of the target point to the origin \(O(0, 0, 0)\) of the base coordinate system can be determined. If \(|PO1| \leq a_1 + a_2 + a_3\), the mechanical arm can arrive; if \(|PO1| \geq a_1 + a_2 + a_3\), then unable to reach.

When \(|PO1| \leq a_1\), the angle of rotation of the horizontal joint angle 1 can be obtained by solving according to the previous inverse equation of motion:

\[\theta_1 = \arctan\frac{y}{x}\]
problem of the mechanical arm. A spatial path planning problem is transformed into a planar three-link path planning problem.

Let the coordinates of the object in this coordinate system be $P = (x, y, z)$. Take the origin $O$ of the base coordinate system as the centre of the circle, let $a_1$ be the radius. This circle equation is

$$x^2 + y^2 = a_1^2 \tag{5}$$

Take a point $G = (g, r)$ on the circle $O$ so that $G, P$ satisfy

$$|GP| \leq a_2 + a_3$$

Let $G = (g, r)$ be the centre of the circle and $a_2$ be the radius $G$. The circle equation is

$$(x - g)^2 + (y - r)^2 = a_2^2 \tag{6}$$

Take $P = (x, y)$ as the centre and $a_3$ as the radius to draw a circle $G$. The circle equation is

$$(x - x)^2 + (y - y)^2 = a_3^2 \tag{7}$$

Since $|GP| \leq a_2 + a_3$, from the geometric meaning of (7), we know that there is at least one, there are at most two, and circle $G$ intersects circle $P$, setting the coordinates of the intersection point as $R(i, j)$.

On the other hand, as shown in Fig. 7b, using $P = (x, y)$ as the initial origin to perform the above evolution, it can be concluded that $G = (g, r)$ exists at least one, and there are at most two. Then, the solutions of the inverse equation of motion to the coordinates of the target lily flower point are at least one group, up to four groups.

Therefore, the path planning can be determined based on the minimum power consumption, that is, the sum of the rotation angles of the joints of the mechanical arm is the minimum. Since the rotation angle of the stepper motor 1 for the same coordinate point is fixed, when calculating the minimum sum of the angular displacements of the joints of the mechanical arm, only the minimum displacement of the stepper motor 2, the stepper motor 3, and the stepper motor 4 is calculated. Therefore, a function

$$f = \min (\theta_2 + \theta_3 + \theta_4)$$

is set to traverse the combination of each $\theta$ solution, and a combination $\theta$ satisfying the function $f$ is obtained.

## 5 Robotic kinematics simulation

### 5.1 Workspace simulation

In this experiment, the Monte Carlo method [21–23] was used for simulation. According to the forward kinematics analysis of the mechanical arm, the coordinate equations of the four motion joint coordinate systems in the base coordinate system were obtained. Combine the range of each joint variable given in Table 1, MATLAB software programming was used to solve and simulate the trajectory of the end of the manipulator, and get the point cloud set of the working space of the manipulator as shown in Fig. 8. As can be seen that the working points are dense in the $Z$ direction $-200$ to $1100$ mm, $X$ direction $-1100$ to $1100$ mm, and $Y$ direction $-150$ to $1100$ mm. The mechanical arm can meet the picking requirements of mature lilies.

### 5.2 Kinematics simulation verification

Using the MATLAB Robotics Toolbox [24], the kinematics model was constructed according to the $D-H$ parameters obtained in Table 1 for kinematics simulation verification. Let the initial position of the arm end $P_0 = (-704.3, 0, 0)$, and the angular displacement of each joint be in the initial state. Let the coordinates of the target lily picking point be $P_e = (-659.0, 562.2, 336.1)$. 

![Fig. 7 Schematic diagram of the connecting rod coordinate system on the vertical plane of the manipulator](image)

(a) Mechanical arm vertical plane picture 1 and (b) Mechanical arm vertical plane picture 1

![Fig. 8 Shapes of manipulator workspace](image)

(a) Motion space projection in the $XOY$ plane and (b) Motion space projection in the $ZOY$ plane
The laser distance meter was used to measure the three-dimensional coordinates of the target picking point of the mechanical arm. The upper coordinate system is marked with a reticle, and the vertical axis of the mechanical arm is the Z-axis. The initial coordinates of the mechanical arm are the same as above. Then set the coordinate system in the base coordinate system, so that the target lily collected by the camera can be located within the working area of the mechanical arm.

Picking tests were conducted according to the previous picking strategy. In order to avoid leakage of lily flowers, the following picking requirements were set.

Assume that the coordinates of four lily flowers in a lily field are 

\[
\begin{align*}
&\mathbf{p}_1^i \text{ for } i = 1, 2, \ldots, N_i \\
&\mathbf{p}_4^i \text{ for } i = 1, 2, \ldots, N_i
\end{align*}
\]

where 

\[
\begin{align*}
&\mathbf{p}_1^i \text{ is the coordinates of the lily flowers in the base coordinate system, } i = 1, 2, \ldots, N_i \\
&\text{ and } \mathbf{p}_4^i \text{ is the coordinates of the lily flowers in the base coordinate system, } i = 1, 2, \ldots, N_i
\end{align*}
\]

6 Robot picking test and analysis

6.1 Kinematic test

In this paper, the lily picking robot test sample machine was designed and manufactured and is shown in Fig. 10a. The positioning accuracy of the end effector of the mechanical arm is the key to the success or failure of lily flower picking and before the flower picking test, a positioning accuracy test was performed on the end effector of the arm end. In this test, the XOY plane of the base coordinate system is marked with a reticle, and the vertical axis of the mechanical arm is the Z-axis. The initial coordinates of the mechanical arm are the same as above. Then set the coordinate system of the target picking point of the mechanical arm. The upper computer calculates the angular displacement of each joint of the mechanical arm according to the kinematics equation and drives each joint movement through the control system so that the end effector of the mechanical arm reaches the target picking point. The laser distance meter was used to measure the three-dimensional coordinate value of the end effector of the mechanical arm under the base coordinate system. Then give the coordinate of the target picking point of the next group to the robot for the next test.

The actuator end position error of the arm is 

\[
D = \sqrt{(X - X_f)^2 + (Y - Y_f)^2 + (Z - Z_f)}
\]

where \(P(X, Y, Z)\) is the setting value and \(P(X_f, Y_f, Z_f)\) is the measured value. A total of 100 measurement experiments were conducted in this experiment and the position error data of the end effector of the mechanical arm is shown in Table 2. This can be seen from the table that the position error of the end of the manipulator is < 12 mm, which can improve the machining and assembly accuracy of the manipulator arm components and optimise the control algorithm to reduce the error.

### Table 2 Displacement of the manipulator joints

<table>
<thead>
<tr>
<th>Joints</th>
<th>Angular displacement, rad</th>
</tr>
</thead>
<tbody>
<tr>
<td>horizontal joint 1 ((\theta_1))</td>
<td>1.84597</td>
</tr>
<tr>
<td>vertical joint 2 ((\theta_2))</td>
<td>0.44880</td>
</tr>
<tr>
<td>vertical joint 3 ((\theta_3))</td>
<td>-0.74538</td>
</tr>
<tr>
<td>vertical joint 4 ((\theta_4))</td>
<td>-0.39311</td>
</tr>
</tbody>
</table>

Fig. 9 shows the displacement curve of the end picker and the angular displacement curve of the joints of the manipulators obtained during the simulation. According to the kinematics equations, the angular displacements of the joints of the mechanical arm are shown in Table 2.

Comparing Table 2 with the displacement curve, as can be seen that the angular displacement of each joint of the mechanical arm is basically the same as that in Table 2, which verifies the correctness of the established kinematic equation.

6.2 Picking tests

The picking test was conducted in the laboratory and the subject was a real lily plant, as shown in Fig. 10b. The lily plants used in the test were mature flowering plants \(~130\) mm in length. The designed end effector had a pick head diameter of \(~150\) mm and the end effector could accept a 15 mm position error. The camera is mounted on a tracked vehicle platform and the depth distance between the camera and the target lily is adjusted according to the picking working space of the mechanical arm and the camera parameters, so that the target lily collected by the camera can be located within the effective range of motion. The lily picking test, a positioning accuracy test was performed on the end effector of the end effector reaches the target picking point. The upper coordinate system is marked with a reticle, and the vertical axis of the mechanical arm is the Z-axis. The initial coordinates of the mechanical arm are the same as above. Then set the coordinate system in the base coordinate system, so that the target lily collected by the camera can be located within the working area of the mechanical arm.

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\end{align*}
\]

where 

\[
\begin{align*}
&\mathbf{p}_1^i \text{ is the coordinates of the lily flowers in the base coordinate system, } i = 1, 2, \ldots, N_i \\
&\text{ and } \mathbf{p}_4^i \text{ is the coordinates of the lily flowers in the base coordinate system, } i = 1, 2, \ldots, N_i
\end{align*}
\]

The picking test was conducted ten times. One lily image was collected each time. The crawler stopped travelling and carried out many lily flower identifications, positioning, picking and recycling. The system successfully identified and positioned 36 target flowers and successfully recovered 30 flowers. The success rate was 83.33%. The main reason for the failure of picking in the test is that the lily flower target position is inaccurate due to the obstruction of lily leaves; when the end effector picks the lily flower target, squeezing or colliding with the lily leaves causes the other lily flowers to deviate significantly from their original position, so that the end effector, which later arrives at the target position of the belonging lily flower, cannot capture the target lily. In addition, the distribution of the target lilies in the test was not clustered, and the designed end effector did not fit the picking of the clustered lily flowers.
In this paper, a lily picking mechanical arm is designed. The mechanical arm is divided into a big arm, a small arm and a front-end picker. It can achieve rapid and continuous harvesting and harvesting operations. The front-end picker developed is simple in operation, single in structure and can avoid missed and wrong picking caused by the position error of the mechanical arm, at the same time, it satisfies automated harvesting of upward-growing flower crops such as cotton, rose and chrysanthemum.

The operation strategy of point-to-point picking of lily is put forward and the continuous and accurate picking and recovery of the lily picking target areas are implemented. In this paper, kinematics analysis of the mechanical arm solves the kinematic equations. Based on the MATLAB software platform using Monte Carlo simulation to get work space description: the mechanical arm developed in this paper can meet the needs for fragment area lily picking. The robotic kinematics model is constructed using the Robotics Toolbox, and the kinematics equation is verified by kinematics simulation on this basis.

The mechanical arm develops a manipulator control system using the upper and lower machine's double-layer structure, manufactures a physical prototype of the lily picking mechanical arm and conducts kinematics and picking tests of the mechanical arm. The test results show that the picker error of the mechanical arm is <12 mm. The front-end picker developed to accommodate an error of <15 mm is tested in an open air environment and the picking success rate is 83.33%.

### 8 Acknowledgments

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### 9 References


Fig. 10 Picking experiment photos of the manipulator
(a) Robot mockup and (b) Lily growing state

Table 3  End of the mechanical arm position error

<table>
<thead>
<tr>
<th>Frequency</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>difference</td>
<td>4.5</td>
<td>5.1</td>
<td>6.4</td>
<td>3.5</td>
<td>3.3</td>
<td>5.1</td>
<td>5.4</td>
<td>6.7</td>
<td>5.9</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Fig. 11 Lily flower projection in the XOY plane


