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Design of End-effector for Tomato Robotic Harvesting

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Abstract: In order to improve automatic harvesting for fresh-eating tomato, a new picking end-effector was designed, which mainly consisted of three parts, such as fruit holding, stem holding, and fruit separating. In view of the convenience of stemless fruit for transport and package, the end-effector separated the tomato fruit from the plant at the abscission layer between the stem and fruit. A sleeve with three equispaced gasbags was used as the flexible fruit-holding part, so as to fit the fruit's various size and keep the holding force constant. Besides, the holding and separating force parameters were calculated based on the measuring result of the fruit material characteristics, so that the holding operation is reliable and nondestructive. Finally, the end-effector's performance was tested, and the result showed the successful picking rate was 86%.

Keywords: tomato, picking end-effector, flexible operation, automatic harvesting, agricultural robot

1. INTRODUCTION

Tomato is one of the worldwidely common vegetable due to its delicious taste, rich nutrition, convenient edible, and the output accounts for 10% of total output of vegetable. However, tomato picking basically depends on manual picking – a kind of time-consuming and labour-consuming mode. And also, the picking cost is increasing as the acceleration of urbanization. The research on automatic picking robot for releasing human labor has been a hotspot worldwide issue in recent years.

The end-effector is the critical component directly operating the fruit. Due to the complexity in working environment, irregularity and flaccidity of operation object (Chen), the end-effector should be accurate and flexible. The national and foreign research institutes have conducted a lot of research on picking robot end-effector since 1980s, and the multiple intelligent end-effectors were designed. At present, the type of robot end-effector includes sucker type (Monta, Liu), shear type (Naoshi, Ma, Zhang), spiral twisting type (Monta, Chen, Tu), multi-fingered type (Ling, Jin). Kondo designed a kind of double-fingered end-effector with soft gasket aspirator (Monta). The aspirator is used to separate the adjacent fruits. And the wrist joints of manipulator are used to twist the connection of fruit stem. The end-effector designed by Ling (USA) has four fingers in uniform distribution and the fingers will bend and hold driven by a cable (Ling). Liu achieve the separation of fruit from stalk by laser cutting (Liu).

In this paper, a new end-effector was designed on the basis of measurement of mechanical property of tomato, which could pull the stalk from the fruit to guarantee the transportation and storage quality. And the performance was tested in the final.

2. Work condition and harvesting robot

2.1 Work condition

The work condition for tomato harvesting robot is shown in Fig.1. The harvesting robot is supposed to move on the rails to pick tomatoes in its both sides. As a new cultivation model, the tomato stem is hung with the top of greenhouse by the string, so that the tomatoes could be fixed in the certain height above the rail through releasing the string.

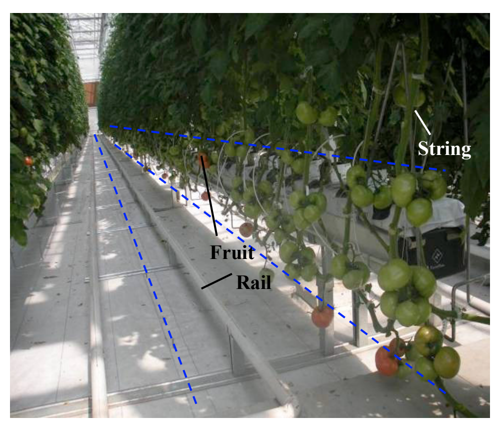

Fig.1 Work condition

2.2 Harvesting robot system

The model of tomato harvesting robot is shown in Fig.2, which contains a vision unit, a jointed manipulator, a railed vehicle, a controller and the end-effector. The vision unit is used to identify and locate the mature fruits. The controller receives and processes image data from vision unit, then sends control signal to the manipulator, the end-effector and the vehicle through CAN bus. The vehicle carries the whole system moving on the rail, until receives the stop signal from

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the controller when the mature fruits were identified in the camera field. The jointed manipulator positions the end-effector to approach the target fruit, and moves it back to the container after the fruit is picked by the end-effector.

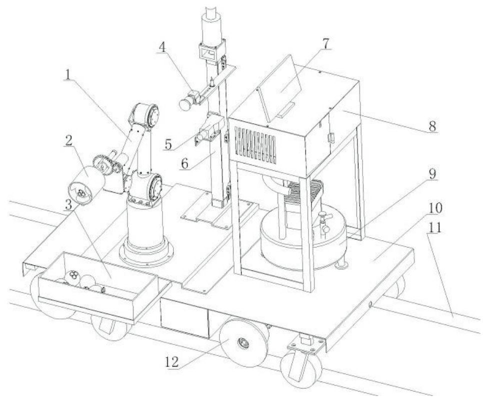


Fig.2 Tomato harvesting robot model
1.Manipulator 2.End-effector 3.Fruit container 4.Camera 5.Laser projector 6.Slider unit 7.Human interface 8.Controller 9.Air pump 10.Vihecle 11.Rail 12.Rail wheel

3. Mechanical property test

3.1 Test materials and equipment

The fruit material used in the test is Jiali No. 14 tomato. According to the ripeness of tomato, randomly select 30 fruits in green ripe stage, preliminary ripe stage, semi-ripe stage and ripe stage respectively.

3.2 Parameter measurement of fruit appearance

Analyze and summarize the measurement results to obtain the physical parameters, as shown in table 1. The friction coefficient between fruit (or stalk) and different materials is shown in table 2.

Table 1. Table of physical parameters of tomato fruit

	Maximum	Minimum	Average
Horizontal diameter(mm)	72.1	58.2	65.5
Vertical diameter(mm)	60.4	48.5	54.2

Table 2. Table of friction coefficient

	Stainless steel	Silica gel	Rubber
Fruit	0.48	0.87	0.8
Stem	0.21	0.25	0.43

3.3 Stalk tensile test

The test uses 1KN range sensor and the rate of loading is set as 1mm/s. Conducting separation layer tensile test and calyx tensile test on different ripeness of tomato respectively，get the range of pulling strength in separation layer is 9.7-28.1N and the average pulling strength is 12.2N; the range of pulling strength in calyx is 12.5-36.6N and the average pulling strength is 16.2N. Therefore, end-effector uses separation layer pulling mode to separate fruit and stalk, and the maximum pulling strength is set as 30N.

3.4 Compression characteristic test

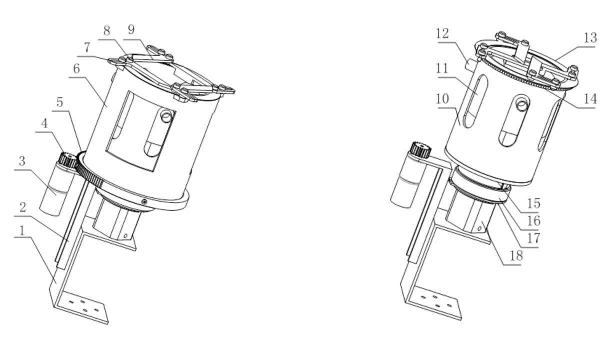
The test uses 1KN range sensor and the rate of loading is set as 5mm/s. According to the ripeness, the fruits are divided to four groups and each group has 30. Then each group is divided into 3 subgroups randomly and each subgroup has 10. The compression test of different materials will be conducted. Because the gasbag clamps fruit horizontally during picking process, horizontal compression test is conducted. From the test, we get the range of damage of pressure force is 60-314N and the average damage of pressure force is 139N. Therefore, we set the minimum damage of pressure force as 60N.

4. Design of end-effector

4.1 Major structure and working principle

The end-effector mainly consists of a fruit stalk clamping mechanism, a fruit clamping mechanism, a separating mechanism and a control unit. The major structure is shown in Fig.3, where, the base is fixed on the end of mechanical arm and the relative rotation of fixed tray and rotating tray may achieve the close and open of clamping pliers. A pressure sensor is pasted between outer layer of gasbag and fruit, which is used to detect the pressure when clamping fruit. An infrared sensor is equipped on the bottom of sleeve, which is used to detect whether the fruit is in the sleeve. Hall sensor is installed on the stroke end of the gear and cylinder, which is used to detect the clamping state of clamping pliers and the extension state of cylinder.

When the fruits access sleeve, the infrared sensor will detect the fruit and control the air compressor to inflate the gasbag, and DC motor drives clamping pliers to correctly clamp the stalk. The pressure sensor may detect the pressure between fruit and gasbag to ensure no damages on fruit on the premise of reliably clamping fruit. Until getting stability, then drive the double-acting cylinder to take the sleeve to shrink, in order to cut off and pick the fruit.



(a) Clamp mechanism opens (b) Clamp mechanism closes
Fig.3. Schematic diagram of end-effector.
1. Base 2. Motor fixed plate 3. DC motor 4. Driving gear 5. Driven gear 6. Rotating tray 7. Clamping pliers 8. Pin 9. Toggle clamp 10. Fixed tray 11. Sleeve 12. Gasbag

13. Catch 14. Steel ball bearing 15. Fixed sleeve 16. Sliding bearing 17. Clamp spring 18. Double-acting cylinder

4.2 Design of fruit stalk clamping mechanism

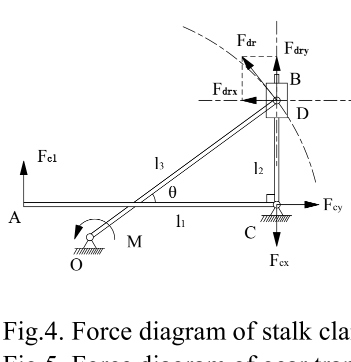
The schematic diagram of stalk clamping mechanism may be obtained through simplifying each part according to the working principle, as shown in Fig.4 and Fig.5. The fixed tray is simplified to fixed hinge C; rotation of rotating tray is simplified to pole OD and move around fixed hinge O; clamp pliers is simplified to L-shape pole ACB. The state shown in the Fig.4 and Fig.5 is stalk clamping state. Take the torque of C according to static balance relationship:

$$\begin{aligned} &F_{\mathrm{cl}} l_1 - F_{\mathrm{drx}} l_2 = 0 \\ &F_{\mathrm{drx}} = F_{\mathrm{dr}} \sin\theta \end{aligned} \quad (1)$$

Where, F_{cl} is the clamping force when clamping. The maximum pulling strength of stalk is 30N and the friction coefficient between stalk and rubber is 0.43 that is obtained from stem tensile test and friction measurement. From the formula, we may get the minimum clamping force is 35N. From the geometrical relationship, we may get θ is 35°. According to the gear rotation relationship:

$$\begin{aligned} &T_{\mathrm{dr}} = F_{\mathrm{dr}} l_3 \\ &T_2 = F_2 d_2 / 2 = T_{\mathrm{dr}} \\ &T_1 = F_2 d_1 / 2 \end{aligned} \quad (2)$$

Where, d_1 and d_2 is the pitch diagram of drive gear and driven gear respectively. After calculating, we get the driving torque of DC motor should be 1.36N•m, or 13.87kg•cm. So we select ZGA37RG deceleration DC motor. The pressure is 24V, rated rotating speed is 3.5r/min and rated torque is 15kg•cm. It may meet the design requirements.



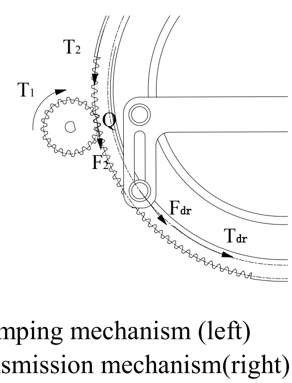


Fig.4. Force diagram of stalk clamping mechanism (left)
Fig.5. Force diagram of gear transmission mechanism(right)

4.3 Design of fruit clamping mechanism

Fruit clamping mechanism is shown in Fig.6. Three gasbags are distributed in the inner wall of sleeve evenly between 120°, which may envelop the fruits and keep even force.

The maximum pulling strength of separation layer is 30N upon the stalk tensile test and fruit friction measurement. The friction coefficient between fruit surface and rubber is 0.87. According to the fruit compression test, the maximum clamping force is 60N. Supposing the fruit does not contact the bottom of sleeve in fruit tensile process (no supporting force),

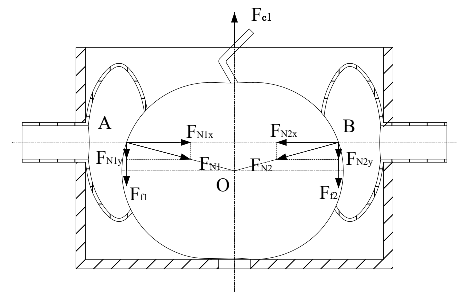


Fig.6. Force diagram of fruit clamping

the following expression according to static balance relationship is shown as,

$$\begin{aligned} &F_{\mathrm{cl}} = F_{\mathrm{Ny}} + F_{\mathrm{f}} + mg \\ &F_{\mathrm{f}} = \mu F_{\mathrm{Nx}} \\ &F_{\mathrm{Nx}} = F_{\mathrm{N}} \cos\theta \\ &F_{\mathrm{Ny}} = F_{\mathrm{N}} \sin\theta \\ &F_{\mathrm{N}} = PS \end{aligned} \quad (3)$$

The maximum pulling strength of separation layer F_{cl} takes 30N and the average quality m takes 0.11kg. The friction coefficient μ between fruit surface and rubber is 0.87. To facilitate calculation, supposing the gasbag contact area S and the displacement angle θ of each gasbag is equal. It is shown the minimum clamping force is 8.41N, which is far lower than 60N. Therefore, the minimum clamping force meets the design requirements. According to the horizontal and vertical diameter, when calculating the contact area between gasbag and fruit, the fruit may be regarded as a ball, thus the contact area scope is 0.0023-0.0034m^2. The inflation pressure of gasbag P falls between 2.6-3.84KPa. On this basis, we select CD55B25-45 thin cylinder as the driving part of pulling off the stalk. And the pulling strength reaches 42N under 0.3Mpa pressure.

4.4 Design of control system

As required in fruit picking, the control system is required to detect sensory perceptual system information and further control execution system[6]. Therefore, the control system uses the mode of combining single chip and multi-sensor. The single chip selects STC89C52 chip. Pressure sensor selects and uses FSR402 resistance pressure sensor and its pressure scope is 0.1-10kg. Because pressure sensor generates analog signal, PCF8951 chip is used for A/D conversion. The correlation-type infrared sensor selects QT30CM correlation-type PV cell. The working voltage is 5V and the induction distance is 2-30cm. Hall sensor selects YS44E hall single-pole switch. The structure of control system is as shown in Fig.7. The electrical proportional valve may adjust the voltage to control the pressure of compressed air into gasbag. The pressure sensor in gasbag may timely detect the pressure and feed the digital signal to single chip. When reaching the maximum clamping force, single chip control cylinder will pull off the stalk. It is required to calibrate the pressure monitoring system and get the relationship curve between pressure and voltage.

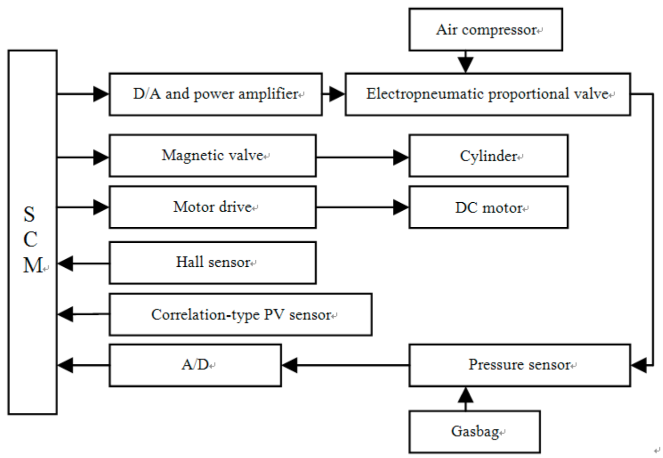


Fig.7. Structure diagram of control system

5. Test and analysis

The test was conducted in tomato cultivation greenhouse of special vegetable garden in Changping District of Beijing in January 2016. The test object is Jiali No. 14 tomato. Picking 50 fruits in preliminary ripe stage and later. During the picking process, the fruit damage, unbroken stalk and falling fruit will be deemed as failure.

The end-effector conducts test for 50 times (50 fruits), among which 43 fruits was successfully held and separated, 4 fruits unsuccessfully being held and 3 fruits separated from the calyx other than the separated-layer. So the average picking success rate is 86%. The principle of picking failure lies in: the fruit varies largely in shape and the holding force is not enough when clamping smaller fruits; the separated-layer of unripe fruits is harder broken than calyx. Therefore, accurately sensing the holding force on fruit and controlling grasping-point on the stem are the mainly future work for improving the end-effector’s performance.

6. Conclusions

Aiming at the actual demand of automatic picking fresh tomato, a flexible end-effector with holding gasbags is designed based on the fruits’ mechanics measurement. The filed test indicates the picking success of end-effector is 86%, and the constant-pressure gasbags effectively prevent soft fruits from damaging.

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