Principle Analysis and Parameter Optimization for Underactuated End-Effector Manipulator for Apple Picking

Yu Ya-xin[*,1,2], Wu Fei[1], Zhu Rong[1] and Zhang Fei[1]

[1]*Faculty of Mechanical Engineering & Automation, Zhejiang Sci-Tech University, China*

[2]*Zhejiang Province Key Laboratory of Transplanting Equipment and Technology, China*

Abstract: In this paper, the mechanical structure of an underactuated end-effector manipulator for apple-picking is presented. The structure is consisted of three identical fingers which are driven by one motor. Each finger is formed by three joints which are connected with connecting bar and gears. With operation of grasp and twist executed by the driven fingers, apple-picking action completed. Mathematical model of the mechanical structure is proposed. Kinematics simulation & optimization software which have a Human-Computer Interaction interface is developed with Visual Basic visualization platform. Parameters which affect enveloping space mostly are analyzed. With processing and analyzing data which get from the software, a set of optimum structure parameters are obtained. A sample machine of the End-effector Manipulator which is used for testing purpose is designed according to the optimum structure parameters.

**Keywords:** End-effector, envelope, kinematics, parameter design, underactuated.

1. INTRODUCTION

End-effector Manipulator is one of the core components of picking robot which grasp fruits directly [1, 2]. The grasped fruit will be damaged if the grasping force big enough [3]. Study and analysis of end-effector manipulator play an important role in automated fruit picking. The kind of manipulators mainly include suck type, barrel type, vibration type and full-driven fingers type. However, all those types have disadvantages such as poor adaptability and fruit damage in picking operation [4-12]. In recent years, underactuated end-effector manipulators working for fruit picking were proved to be a new way to solve these problems [13, 14].

Scholars from different countries have done a lot of researches about underactuated end-effector manipulator. Gosselin group, from Canada Laval University, has developed a three-fingered underactuated end-effector manipulator which has 10 DOF [15, 16] while driven by only two motors. Mao Yichu [17] has designed an integrated robot finger with high-underactuated and anthropopathic properties. Luo Minzhou [18, 19] has researched and developed a two-fingered underactuated manipulator which is driven by differential bevel gears. In the realm of fruits and vegetables picking, scholars such as Cui peng and Li Qinchuan has done a lot of researches. In order to improve manipulator's adaptability in complex environment, Cui peng [20] has developed a bio-robot manipulator driven by tendon. Li Qinchuan [21] has created a ZSTU manipulator which can grab and enclose fruits precisely. In this paper, an underactuated end-effector manipulator for apple-picking is presented.

2. THE STRUCTURE AND WORKING PRINCIPLE

The schematic diagram of the end-effector is shown in Fig. (**1**). It comprises driving portion and execution portion. In driving portion, sliding block 4 is driven by screw 1 which driven by stepmotor. Execution portion consists of three identical fingers (only 2 fingers shown in Fig. **1**) which
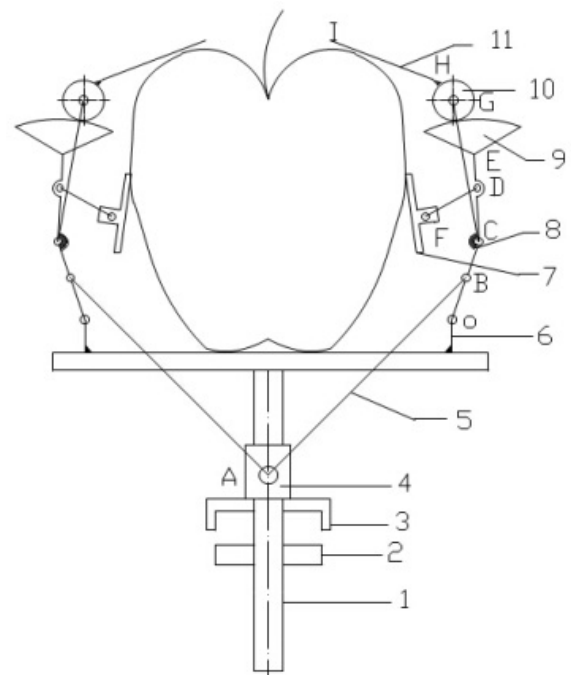
1 Screw lever, 2 Turning block, 3 Fitting block, 4 Sliding block, 5 Linkage 1, 6 The first joint 7 Plate, 8 Linkage2, 9 Sector gear, 10 Spur gear 11 The third joint

Fig. (1). Structure sketch for end actuator of an manipulator.

*Address correspondence to this author at the Faculty of Mechanical Engineering and Automation, Zhejiang Sci-Tech University, Hangzhou, 310018, China; Tel: 010-13185001173; E-mail: yyxin@zstu.edu.cn

placed evenly in peripheral direction, each finger is formed by three joints which are connected with connecting bar and gears. The first joint 6 is fixed with fixed disk. The second joint comprises a sector gear 9 (point C as rotation center), a spur gear 10 (point G as rotation center) and linkages. The third joint 11 fixed with spur gear 10. Torsion springs provide restoring force for every joint in every finger.

Working process of the manipulator as follow: The first step, linkage OC, linkage CG and joint HI driven by linkage AB, move toward surface of fruit. The second step, plate 7 contacts with the fruit. With the help of interaction between immovable linkage DF and movable linkage AB, sector gear 9 revolve around point C. Sector gear 9 drive spur gear 10 and joint HI revolving around point G. Grabbing action complete after joint HI contact with the fruit. The third step, turning block 2 embed into fitting block 3, which leading the fruit turn with whole device. With a twist action, fruit picking action complete.

3. KINEMATICS MODEL OF THE MECHANISM

3.1. Vector Equation

The structure of the manipulator is consisted of three identical fingers. In order to simplify the kinematic model, only one of finger's kinetic features is analyzed. As we can see on Fig. (**2**), coordinate Oxy be built on point O. Closed vector polygons are drawn and vector equations are established.
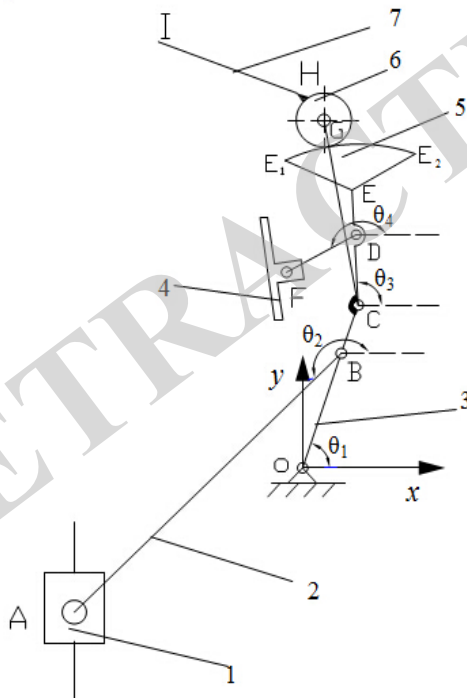
1 Sliding block, 2 Linkage AB, 3 Linkage OC, 4 Contact plate 5 Sector gear 6 Spur gear, 7 The third joint

Fig. (2). Sketch of the end actuator's finger.

$$\begin{cases} \overrightarrow{OB} + \overrightarrow{BA} = \overrightarrow{OA} \\ \overrightarrow{OF} + \overrightarrow{FD} + \overrightarrow{DC} = \overrightarrow{OC} \\ \overrightarrow{CG} + \overrightarrow{GH} = \overrightarrow{CH} \end{cases} \tag{1}$$

3.2. Displacement Model

According to vector equations, displacement equations are established.

$$\begin{cases} OB\cos\theta_1 + BA\cos\theta_2 = x_A \\ OB\sin\theta_1 + BA\sin\theta_2 = y_A \end{cases} \tag{2}$$

$$\begin{cases} x_C = OC\cos\theta_1 \\ y_C = OC\sin\theta_1 \end{cases} \tag{3}$$

Both x_A and y_A are known parameters. The first step, fingers move toward fruit, all components of the second and the third joints move as a rigid body.

$$\begin{cases} x_D = x_C + DC\cos(\pi + \theta_1 - \alpha_1) \\ y_D = y_C + DC\sin(\pi + \theta_1 - \alpha_1) \end{cases} \tag{4}$$

$$\begin{cases} x_F = x_c - FD\cos(\theta_1 - \alpha_1 - \alpha_2) - DC\cos(\pi + \theta_1 - \alpha_1) \\ y_F = y_c - FD\sin(\theta_1 - \alpha_1 - \alpha_2) - DC\sin(\pi + \theta_1 - \alpha_1) \end{cases} \tag{5}$$

$$\begin{cases} x_H = x_G + GH\cos(\theta_1 - \alpha_1 - \alpha_3) \\ y_H = y_G + GH\sin(\theta_1 - \alpha_1 - \alpha_3) \end{cases} \tag{6}$$

$$\begin{cases} x_I = x_H + HI\cos(\theta_1 - \alpha_1 - \alpha_3) \\ y_I = y_H + HI\sin(\theta_1 - \alpha_1 - \alpha_3) \end{cases} \tag{7}$$

The second step, plate 4 touches the fruit, and sector gear 9 and spur gear 10 are engaged for driving. Final positions of first step are initial positions of second step.

$$\begin{cases} x_D = x_C + DC\cos\theta_3 \\ y_D = y_C + DC\sin\theta_3 \end{cases} \tag{8}$$

$$\begin{cases} x_F = OC\cos\theta_1 - FD\cos\theta_4 - DC\cos\theta_3 \\ y_F = OC\sin\theta_1 - FD\sin\theta_4 - DC\sin\theta_3 \end{cases} \tag{9}$$

$$\begin{cases} x_H = x_G + GH\cos(\theta_1 - \alpha_1 - \alpha_3 + \Delta\theta_3 \cdot r_1/r_2) \\ y_H = y_G + GH\sin(\theta_1 - \alpha_1 - \alpha_3 + \Delta\theta_3 \cdot r_1/r_2) \end{cases} \tag{10}$$

$$\begin{cases} x_I = x_H + HI\cos(\theta_1 - \alpha_1 - \alpha_3 + \Delta\theta_3 \cdot r_1/r_2) \\ y_I = y_H + HI\sin(\theta_1 - \alpha_1 - \alpha_3 + \Delta\theta_3 \cdot r_1/r_2) \end{cases} \tag{11}$$

In those equations, α_1, α_2, α_3 represent initial installation angle, $\angle CDF = \alpha_2$, $\angle CGI = \alpha_3$, $\angle BCG = \alpha_4$. r_1 and r_2 denote reference radius of sector gear and spur gear respectively.

4. PARAMETER OPTIMIZATION BASED ON HUMAN-COMPUTER INTERACTION OPTIMIZATION METHODS

Considering the size of mature fruits has a significant difference, the manipulator needs a wide clamping margin for fruit picking. Mechanism of the end-effector has very strong coupling between the parameters, belonging to multiple targets, multivariable optimization problem and the weighting factor could not be determined. According to the kinematics model, mechanism parameters are optimized and a set of optimal solutions are obtained.

4.1. Optimization Goals and Design Variables

Red Fuji apples are chosen as picking samples. The physical properties of the apples are analyzed, data obtained as follows: diameter of the apples ranges from 60 mm to 95 mm, height of the apples ranges from 50 mm to 85 mm, weight of the apples ranges from 120.1 g to 220.4 g

According to the kinematic characteristics, setting specific parameters are as follows:

(1)   To ensure the picking stability of fingers, the first joint is fixed with fixed disk vertically; inclination range of the second joint is between 40°and 60°.

(2)   To ensure the manipulator have a good enveloping space in vertical direction, reference diameter d_1 of sector gear ranges from 60 mm to 65 mm, reference diameter d_2 of spur gear ranges from 10 mm to 12 mm.

(3)   To ensure the manipulator's picking efficiency and safety, inclination θ_3 of the third joint ranges from 90°to120°.

(4)   To ensure that the contact plate has a good performance when contact with apple, length of the contact plate stretch out is between 10 mm and 30 mm.

(5)   Range of joints' length: CD: 10 mm~26 mm; DF: 13 mm~25 mm; BC: 10 mm~20 mm; HI: 22 mm~32 mm.

4.2. Human-Computer Interaction Optimization Software Based on VB

According to kinematic models and parameter ranges listed above, in order that the manipulator has a good enveloping space, end-effector manipulator kinematics simulation software are developed on Visual Basic6.0 platform. Simulate grabbing and releasing action of the manipulator is shown on Fig. (**3a**, **b**) respectively. User interface of the software is divided into motion display area, motion control area, parameter input area and kinematic curve display area, as shown in Fig. (**4**).

(**a**)

(**b**)

Fig. (3). Trajectory of mechanism. (**a**) Trajectory of grabbing action; (**b**) Trajectory of releasing action.
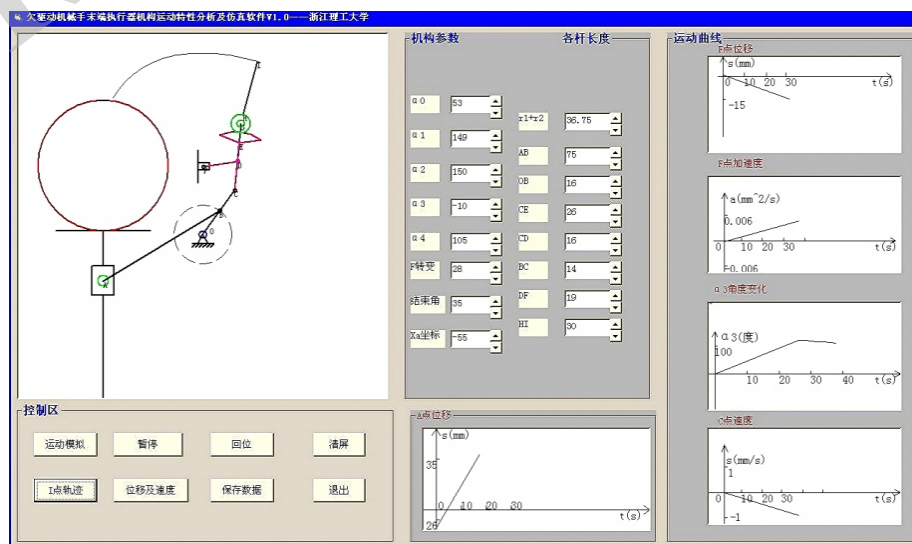

Fig. (4). Kinematics simulation and optimization software of end actuator.

4.3. Effects of Parameters on the Optimal Target

According to mathematical models established and the optimization software, parameters which affect enveloping space most are analyzed. Size of enveloping space depends on displacements of fingers' end and contact plate. The parameters have significant effects on the displacements of x-direction compare with the displacements of y-direction. Therefore, displacements referred in this paper are displacements of x-direction. Initial value of parameters are given as follow: BC=14 mm, CD=16 mm, HI=30 mm, DF=20 mm, θ_1 =53°, θ_3 =110°. Only one of the parameters will be changed during optimization in one time. The displacements and the enveloping space can be analyzed easily with the help of the software.

The relationships between displacement of point I and length of joints are shown in Fig. (**5**). With the increase in length of joint BC, displacement of point I changes apparently. In addition, inflection of the displacement curve occurs frequently (illustrated in Fig **5a**). With the increase in length of joint HI, displacement of point I changes faintly, as shown in the Fig. (**5b**). Compare with joint HI, joint BC has more effects on point I's displacement and hence length of joint BC is priority parameter.
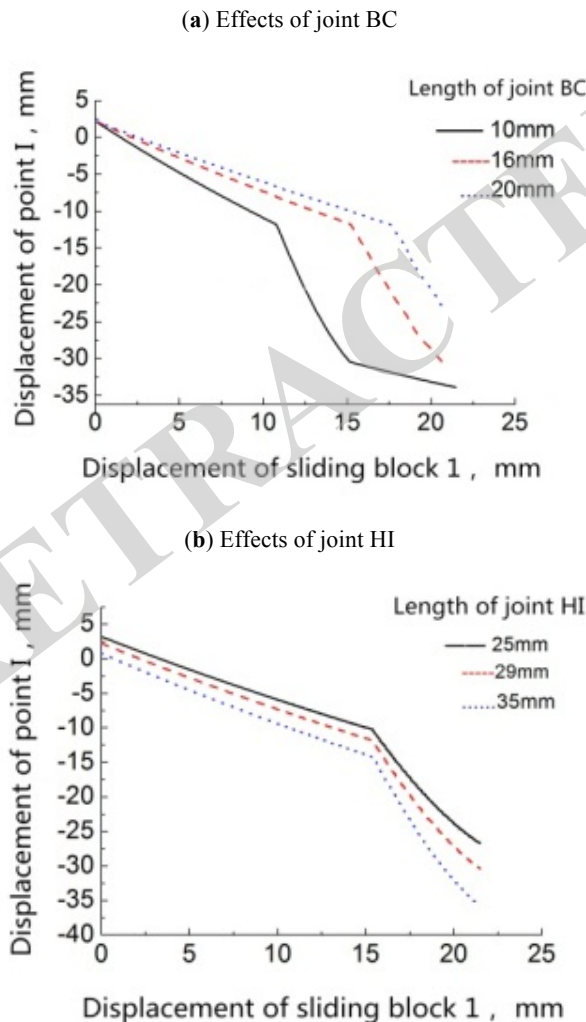
(**a**) Effects of joint BC

(**b**) Effects of joint HI

Fig. (5). Effects of length on displacement.

The relationships between displacement of point I and initial angles are shown in Fig. (**6**). Compare with θ_3 , θ_1 has more effects on point I's displacement and hence θ_1 is priority parameter.

(**a**) Effects of θ_1

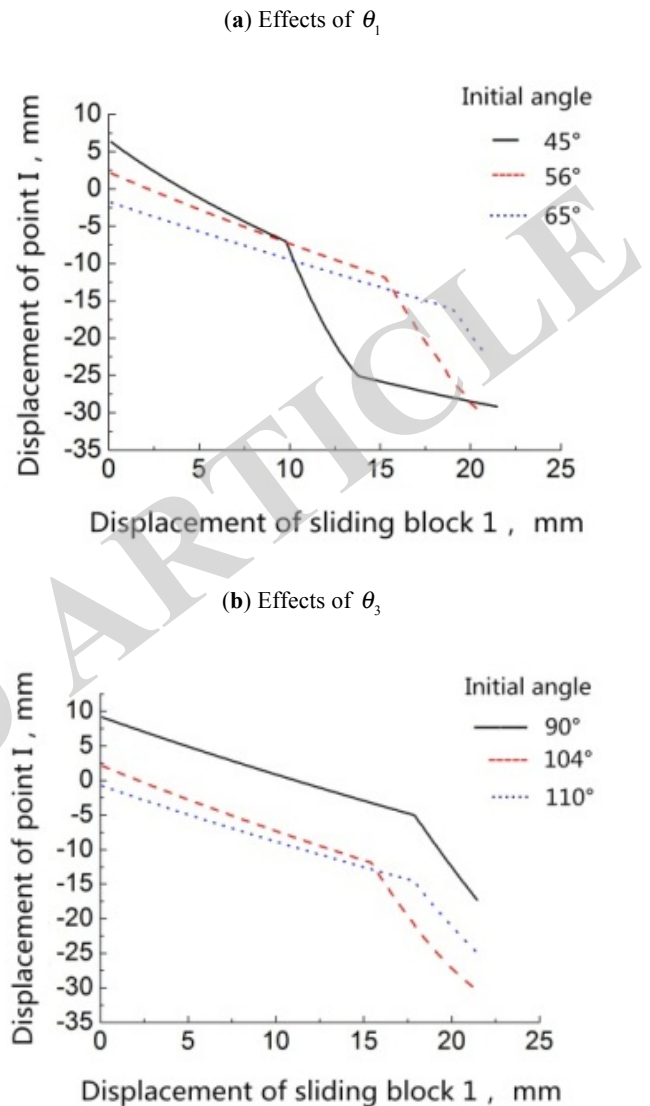(**b**) Effects of θ_3

Fig. (6). Effects of angles on displacement.

Through above analysis, effects of various parameters on endpoint's displacement are different. It also means that effects of various parameters on enveloping space are different. In order to observe the effects in a visual way, alterations of the displacements are converted into diameter of ball. From this, enveloping space can be represented as volume of ball. Stroke of sliding block 1 is a setting value. Variation curves of balls' diameter are shown in Fig. (**7**).

Diameter of enveloping ball ranges from 89.97 mm to 68.12 mm when set length CD in range of 10 mm to 26 mm.

Diameter of enveloping ball ranges from 96.28 mm to 53.25 mm when set length DF in range of 13 mm to 25 mm.

Diameter of enveloping ball ranges from 90.80 mm to 75.12 mm when set length BC in range of 10 mm to 20 mm.

Diameter of enveloping ball ranges from 89.15 mm to 77.16 mm when set length HI in range of 22 mm to 32 mm.

In the given conditions, initial angle θ_1 is set in sequence as follow: 47°, 49°, 51°, 53°, 55° and 57°. In consequence, Diameter of enveloping ball as follows: 97.63 mm, 94.59 mm, 90.73 mm, 87.59 mm, 77.97 mm and 62.00 mm.
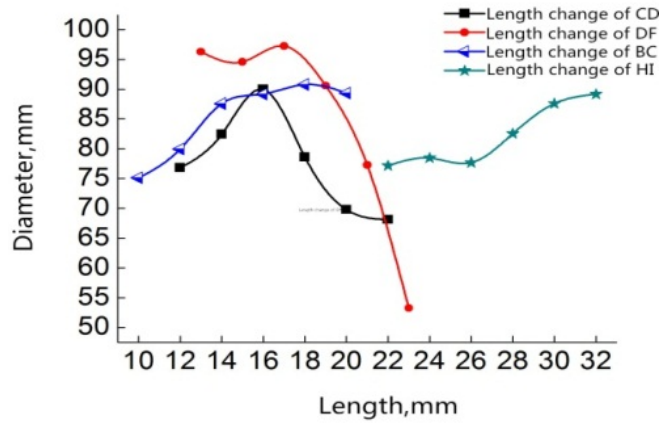

Fig. (7). Effects of length of fingers on enveloping space.

4.4. Result of Optimization

Through a comprehensive analysis of effects of various parameters, a set of optimized parameters obtained as follow: Stroke of sliding block 2 2 mm, length of joint BC 16 mm, length of joint HI 29 mm, length of CD 16 mm, length of DF 19 mm, initial angle θ_1 56°, initial angle θ_2 109°, initial angle θ_3 104°. Diameter of enveloping space ranges from 55 mm to 97 mm. Input all optimized parameters into the simulation software. The displacement curve of point I and point F obtained as shown in Fig. (**8**).
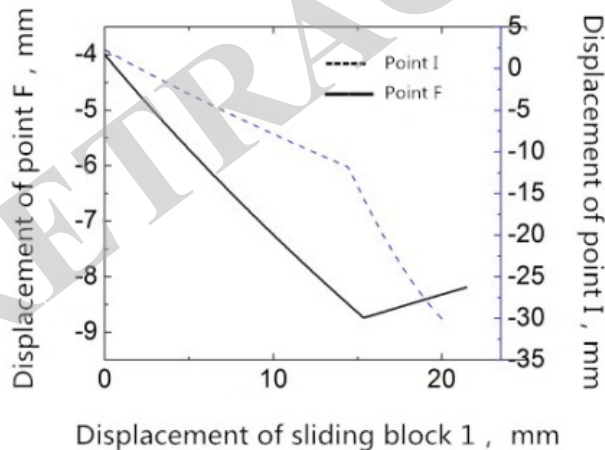

Fig. (8). Displacement of contact points by simulation.

5. PROTOTYPE OF END-EFFECTOR

Based on theoretic analysis and obtained parameters, prototype of the end-effector for testing purpose is produced. Grabbing and releasing state of end-effector are shown in Fig. (**9**).

(**a**) Grabbing state

(**b**) Releasing state

Fig. (9). Prototype of end-effector.

CONCLUSION

The mechanical structure of underactuated end-effector manipulator for apple-picking is presented. The end-effector which can execute apple-picking operation by grasping and twisting is comprised of connecting bar and gears.

Mathematical model of the mechanical structure is proposed. Kinematics simulation & optimization software which have a Human-Computer Interaction interface is developed. Mechanism Parameters of end-effector are adjusted and optimized with the help of kinematics simulation & optimization software.

With analyzing and processing data which get from the software, a set of optimum structure parameters are obtained as follow: Stroke of sliding block 22 mm, length of joint BC 16 mm, length of joint HI 29 mm, length of CD 16 mm, length of DF 19 mm, initial angle θ_1 56°, initial angle θ_2 109°, initial angle θ_3 104°.

A sample machine of the end-effector is designed according to the optimum structure parameters. Follow-up work is mainly on the experiment about enveloping effectiveness and contact force of the sample machine.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

REFERENCES

[1]   Zhao Y, Wu C, Hu X, Yu G. Research progress and problems of agricultural robot. Trans Chin Soc Agric Eng 2003; 19(1): 20-4.

[2]   Zhang L, Hu H, Ji S, Xu F. Review of non-destructive quality evaluation technology for fruit and vegetable products. Trans Chin Soc Agric Eng 2005; 21(4): 176-80.

[3]   Song J, Zhang T, Xu L, Tang X. Research actuality and prospect of picking robot for fruits and vegetables. Trans Chin Soc Agric Mach 2006; 37(5): 158-62.

[4]   Zhen Y, Zhang H, Chen W, Zhu ZC. A Full-drive Dexterous Manipulator. China. ZL201020666505, 2010.

[5]   Ma L, Yang W, Wang C, *et al*. Structure design and experiment of the end-effector for apple-harvesting robot. J Agric Mech Res 2009; (12): 65-7.

[6]   Hua D, Hua Z. Linkage mechanism design and application innovation. Beijing, China: Mechanical Industry Press 2007.

[7]   Monta M, Kondo N, Ting KC. End-effectors for tomato harvesting robot. Artif Intell Rev 1998; 12(1-3): 11-25.

[8]   Liu J, Li P, Li Z. Hardware design of the end-effector for tomato-harvesting robot. Trans Chin Soc Agric Mach 2008; 39(3): 109-12.

[9]   Xu L, Zhang T. Present situation of fruit and vegetable harvesting robot and its key problems and measures in application. Trans Chin Soc Agric Eng 2004; 20(5): 38-42.

[10]   Fon D, van Weel PA, Buwalda F. Development of a new tomato production system Research Station for Flo-riculture. Trans Chin Soc Agric Mach1995; 3(1): 15-29.

[11]   Tang Z, Meng X, Shen C, *et al*. Design and experimental investigation of mechanical vibration tree fruits and nutsharvester. J Agric Mech Res 2010; 8: 56-9.

[12]   Liu C, Zhang T, Yang L. Design of End-effecter of eggplant harvesting robot. J Agric Mech Res 2008; 12: 62-4.

[13]   Li X, Ren H. Motion analysis and application research on the nder-actuated mechanism. Mech Res Appl 2010; 23(12): 29-31.

[14]   Ying Y, Li Q, Wu C, *et al*. Underactuated Finger Device Has Properties of Preventing degradation 2007, China. ZL200710071186.

[15]   Birglen L, Gosselin CM. On the force capability of underactuated fingers. Int Conf Robotics Automat, Taipei, Taiwan 2003; pp. 1139-1145.

[16]   Birglen L, Gosselin CM. Geometric design of three-phalanx underactuated finger. ASME J Mech Des 2006; 128(2): 356-64.

[17]   Mao Y, Zhu X, Li S, Yang F. Design of a naw underactuated prosthetic hand. Mach Des Res 2008. 24(3): 33-8.

[18]   Luo M, Mei T, Wang X. Design of a shape self-adaptive underactuated robot finger with three phalanges. J Comput Aided Des Comput Graph 2005; 17(2): 353-8.

[19]   Luo M, Mei T, Lu C, Yu Y. Analysis and simulation of enveloping graspstability of the multi phalange underactuated robot hand. Optics Precis Eng 2004; 12(5): 510-7.

[20]   Cui P, Chen Z, Zhang X. Statics analysis of apple-picking robot humanoid manipulator. Trans Chin Soc Agric Mach 2011; 42(2): 149-53.

[21]   Li Q, Hu T, Wu C, Hu X, Ying Y. Review of end—effectors in fruit and vegetable harvesting robot. Trans Chin Soc Agric Mach 2008; 39(3): 175-9.