OPTIMIZATION DESIGN OF FRUIT PICKING END-EFFECTOR BASED ON ITS GRASPING MODEL
/
基于抓取模型的水果采摘末端执行器优化设计

Assoc. Prof. Ms. Lin Hanhui[1], Assoc. Prof. Ph.D. Cai Ken *[2], Assoc. Prof. Ph.D. Chen Huazhou[3], Eng. Zeng Zhaofeng[4]

[1] Center for Educational Technology, Guangdong University of Finance and Economics, Guangzhou / China;
[2] School of Information Science and Technology, Zhongkai University of Agriculture and Engineering, Guangzhou / China;
[3] College of Science, Guilin University of Technology, Guilin / China;
[4] Department of Mathematics and Computer Science, California State University, East Bay/ U.S.A
** Tel: +8634172680; Email: icken@126.com*

Abstract: *The development of intelligent fruit harvesting robots is important in improving agricultural production. In this paper, we initiated the R&D of a mechanical end-effector for fruit harvesting on the basis of the intelligence of agricultural robots. First, we provided a detailed description of the hardware components and software control of the mechanical end-effector, analyzed the mechanism of servo controlling and established a mathematical modelling of the mechanical end-effector junctions by analyzing the harvesting movement. Thereafter, the coordinates of the target fruits are disassembled and analyzed in the context of the mathematical model for precise locating and harvesting. Finally, a trail experiment of harvesting kiwifruit was conducted. The outcome implies that each module in the harvesting robot system functions well. The proposed mathematical modelling method and servo control can provide accurate harvesting movements to the mechanical end-effector.*

Keywords: *picking, end-effector, motion optimization, models*

摘要: *智能化果蔬采摘机器人的开发，对于提高农业生产力有极大的应用价值与现实意义。本论文根据农业机器人的智能化发展需要，研发了能对果实进行采摘的末端执行器。对果实采摘末端执行器的硬件构造和软件设计进行了描述，分析了舵机的控制原理，并通过对末端执行器采摘果实动作的分析，对采摘末端执行器各关节进行数学建模，然后将目标果实坐标通过数学建模进行拆解分析，使得末端执行器可以准确移动到果实的位置并进行准确采摘。最后进行了猕猴桃的采摘作业试验，试验结果表明:系统各模块运转良好，提出的建模方法与舵机控制方法可实现采摘末端执行器的精确移动和准确采摘。*

关键词: *采摘；末端执行器；运动优化；模型*

INTRODUCTION

Great efforts have been made in the past decades in the use of robots for selective harvesting, which is the most time-consuming process in agricultural operations. In natural environments, the growth of fruits depends on soil, season, and weather, which varies enormously and hinders precise locating and harvesting. Therefore, the research and development of high-end robots with accuracy and efficiency has become increasingly significant in agricultural harvesting [2,8,10,11]. Such a study has been performed for more than 40 years in many countries [16,21,18,6]. Japan, the United States, and some developed European countries have been working relentlessly on the R&D of harvesting robots. In Japan, eggplant-harvesting robots spend 64.1 s in picking one eggplant and have success rates of 62.5% [7]. Grape-harvesting robots are not only capable of harvesting but also of spraying, bagging, and clipping [1]. Kiwifruit-harvesting robots have harvesting speeds of 74.6 s for each fruit and suction attachment success rates of 95.3% [3]. Wageningen University designed cucumber-harvesting robots that utilise near-infrared visual system to identify cucumbers with success rates of approximately 70% [15]. Mushroom-harvesting robots designed in the United Kingdom can harvest one mushroom in 1.5 s with a success rate of 75% [4]. Melon-harvesting robots designed in Israel and the United States can achieve a success rate of over 85% during identification and harvesting [5]. The apple-harvesting

引言

过去的几十年里，人们在农业运作最为耗时的选择性采摘果实方面已经做出了巨大的努力。在自然环境中，水果的生长依赖于土壤、季节和天气，这些因素变化极大，阻碍了精确的定位和收获。因而，研究和开发有着高精度和高效率的农业采摘高端机器人的是非常重要的[2,8,10,11]。40 年前在许多国家已经进行这方面的研究[16,21,18,6]。日本、美国和一些发达国家一直致力于研发采摘机器人。日本茄子采摘机器人花费 64.1 秒采摘一个茄子，成功率达到 62.5%[7]。葡萄采摘机器人不仅能够采摘，而且可以喷药、套袋和裁剪[1]。猕猴桃采摘机器人对每个果实采摘速度达到 74.6 秒，成功率达到 95.3%[3]。瓦赫宁根大学设计的黄瓜收获机器人，利用近红外视觉系统，以确定黄瓜并成功采摘的概率约为 70%[15]。英国设计的磨菇采摘机器人采摘一个磨菇的时间是 1.5 秒，成功率达到 75% [4]。以色列和美国设计的甜瓜采摘机器人可

robots developed by Kyungpook National University in South Korea can identify cucumbers from the tree crown with a success rate of 85% and harvesting speed of 5 s for each cucumber [17]. The mushroom-harvesting robots by Silsoe Research Institute in the United Kingdom can harvest at the speed of 6.7 s for each mushroom with a success rate of 75% [13]. In China, the study of harvesting robots has made significant progress in recent years. China Agricultural University has developed cucumber-harvesting robots and vegetable-grafting robots [20, 9], Nanjing Agricultural University has furthered the visual navigation system to enable automatic operations [22], and Zhejiang University has designed and optimized the visual positioning and harvesting components of robots [19]. All of these studies have accelerated the development of agricultural informatics and automation in China. In the present paper, the position coordinates of fruits were obtained from a binocular system. The necessary movement at each end-effector junction was controlled according to the 3D coordinate analytic algorithm. The revolving angle of each servo was manipulated to stretch the mechanical arm to the target fruit and for harvesting.

以实现在识别和采摘，成功率达到 85%以上[5]。韩国庆北国立大学研制的苹果收获机器人，在树冠上能识别 85%的黄瓜，并用 5 秒的时间采摘一个果实[17]。由英国 Silsoe 研究院研发的磨菇采摘机器人用 6.7 秒的时间采摘一个磨菇，成功率达到 75% [13]。近年来，中国在采摘机器人方面的研究取得巨大进展。中国农业大学已经研发了黄瓜采摘机器人和蔬菜嫁接机器人[20, 9]。南京农业大学在运用自动操作的可视化导航系统方面已经取得一定成就[22]。浙江大学设计并优化了机器人的视觉定位和采摘组件[19]。所有这些研究加速中国农业的自动化和信息化。在本文，从双目系统获得水果的位置坐标。在末端执行器连接处必须的移动由 3D 坐标分析算法控制。操纵每一个伺服的旋转角度，以拉伸机械臂触及采摘目标水果。

MATERIAL AND METHODS

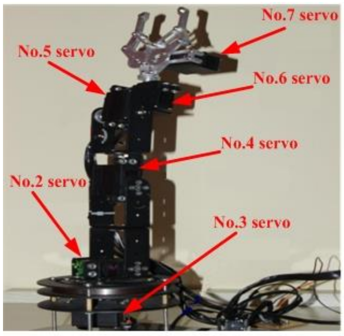
The Harvesting End-effector

The system uses an end-effector (Figure 1) that is made of aluminium alloy brackets and servos. The entire end-effector is equipped with two MG995 servos and three MG996R servos. The picking tool has a highly mimicking design. In harvesting, only No.3, No.4, No.5, No.6, and No.7 servos are involved, whereas the No.2 servo is a back-up that is temporarily immovable and is vertically upward. The No.3 servo controls the base rotation, thereby controlling the movement direction of the picking robot. The No.4 and No.5 servos control the main body of the arm, which is equivalent to the hand control of humans controlling lifting and other actions. The No.6 servo, the equivalent of a human's wrist, controls the vertical movement when picking fruits. The No.7 servo controls the opening or closing of metal pincers, similar to a human's fingers. The respective location of each servo in the harvesting end-effector is shown in Figure 1(a).

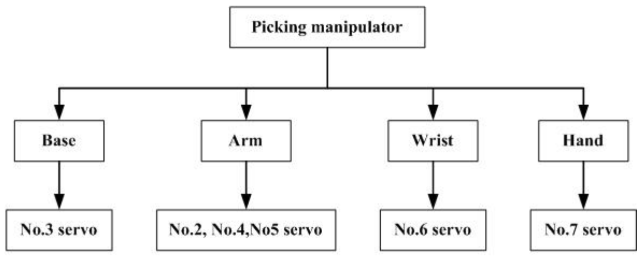
材料与方法

采摘末端执行器

系统采用的采摘末端执行器如图 1 所示，它由铝制合金结构的支架和舵机构成，整个采摘末端执行器配置了两个 MG995 与三个 MG996R 舵机。该采摘工具高度模仿人体手臂，采摘过程只涉及末端执行器的 3、4、5、6、7 号舵机，而 2 号舵机为后备移动舵机，是暂时性固定不动竖直向上的。3 号舵机控制着末端执行器的底座转动，从而控可采摘的方向；4、5 号舵机控制着末端执行器的主要躯干，相当于人体手臂部分，控制着抬举等动作；6 号舵机控制着末端执行器采摘果实的上下移动，相当于人体手腕关节；7 号舵机则控制着采摘终端金属钳子的伸张，相当于人体手部位置。末端执行器的各舵机具体位置如图 1(a)所示。



(a)



(b)

Fig.1 - Picking robot chart. (a) The specific location of each servo. (b) Picking end-effector joint control.

Control of Harvesting End-effector and Motion Analysis

Control of each joint

The servo control uses a PWM signal with a unique time width between high and low levels [12]. Given that the servo system uses a digital servo type, it has a low

采摘末端执行器的控制及动作分析

各关节控制

本系统的舵机控制采用 PWM 进行控制。PWM 信号为脉宽调制信号[12]，其特点在于它的高电平与低电平之间

requirement for PWM signal. Furthermore, the servo system does not need to receive real-time instruction and can be auto-locked and positioned. These characteristics have outperformed the ordinary stepper motor [14]. The timing diagram of the PWM signal is shown in Figure 2.

的时间宽度。鉴于伺服系统采用数字式伺服系统，其对 PWM 信号的要求较低，不需要接收实时指令，可以自动锁定和定位。这些特性都优于普通的步进电机[14]。图 2 为 PWM 信号的时序图。

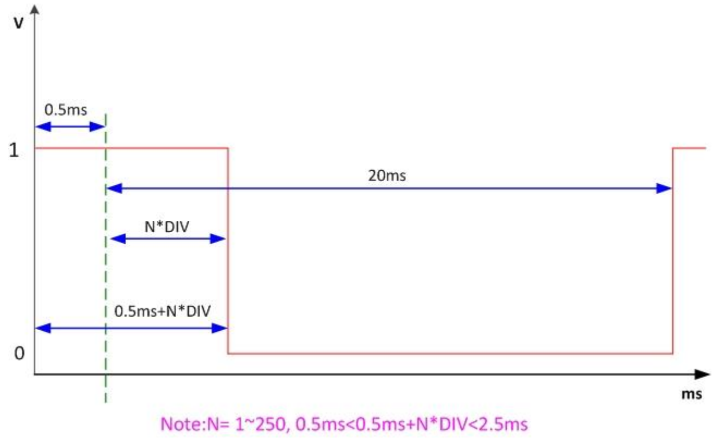


Fig.2 - PWM timing diagram at one cycle

The servo system used for the harvesting end-effector has no requirement for low-level time, thus indicating that the use of a low time of 0.5 ms is allowable and that a cycle of the PWM waveform can be 1 ms standard square wave. The system controller uses an 8-bit micro-controller and 256 data resolution, which will be divided into 250 parts after the servo limit parameter experiment. Thereafter, when the width between 0.5 ms to 2.5 ms is 2000 µs, the width will be divided into 250 parts, thus resulting to 8 µs. The PWM control precision can be used to control the revolving and positioning of the servo at an increasing basis. Given that the servo can revolve at 185°, the servo’s control precision is 0.74°. By controlling the servo’s revolving angle according to PWM wave high-level duration, we obtained the data shown in Table 1 to Table 5. The 0° angle in the Tables represents the critical point in the positive and negative directions of the space coordinates. Table 1 to Table 5 shows that the revolving angle of servo has a linear relation with PWM wave high-level duration.

系统的采摘末端执行器所使用的舵机对低电平时间并没有要求，使用 0.5ms 的低电平时间也是允许的，即 PWM 波形的一个周期可以是 1ms 的标准方波。该系统控制器采用一个 8 位微控制器，其数据分辨率为 256，那么经过舵机极限参数实验，得到应该将其划分为 250 份。那么 0.5ms 到 2.5ms 的宽度为 2000us，由 2000us/250 得 PWM 的控制精度为 8us，因此可以以 8us 为单位递增控制舵机转动与定位。鉴于舵机可旋转 185 度，控制精度为 0.74 度，根据 PWM 波高电平持续时间控制舵机转动不同的角度，进而根据实际的实验测量数据得出表 1 至表 5 中的数据。表中 0 度均表示为采摘末端执行器建立的空间坐标系中正负方向的临界点。从表 1 至表 5 可清晰看出舵机转动的角度与 PWM 波高电平持续的时间成线性关系。

Table 1

Relation between No.3 servo’s revolving angle and PWM wave high-level duration

Angle (°)	−72	−45	−30	0	60
High-level voltage (µs)	2000	1775	1588	1380	1000

Table 2

Relation between No.4 servo’s revolving angle and PWM wave high-level duration

Angle (°)	−50	−35	0	45	90
High-level voltage (µs)	2100	2000	1760	1380	1000

Table 3

Relation between No.5 servo’s revolving angle and PWM wave high-level duration

Angle (°)	−45	0	90	143
High-level voltage (µs)	500	800	1470	2100

Table 4

Relation between No.6 servo's revolving angle and PWM wave high-level duration

Angle (°)	−14	0	90	173
High-level voltage (us)	500	620	1380	2000

Table 5

Relation between No.7 servo's revolving angle and PWM wave high-level duration

Angle (°)	0	24	37	49
High-level voltage (μs)	2100	1850	1720	1600

Classification and coordinate composition of harvesting movement

In harvesting, only the No.3, No.4, No.5, No.6, and No.7 servos are involved, whereas the No.2 servo is a back-up that is temporarily immovable and is vertically upward. The No.6 and No.7 servos control the picking and stabilization of the kiwifruit, respectively. Thus, the No.6 and No.7 servos do not involve the end-effector's accurate movements to the target kiwifruit. The No.3 servo controls the base rotation, thereby controlling the revolving angle according to the X and Y space coordinates of the target kiwifruit. The flow chart of the programming is shown in Figure 3.

采摘动作的分类及其坐标分解

在采摘过程中，只有采摘末端执行器的 3、4、5、6、7 号舵机参与工作，而 2 号舵机是后备移动舵机，暂时是固定不动竖直向上的。6、7 号舵机则分别控制猕猴桃抓取与夹稳，因此 6、7 号舵机不涉及采摘末端执行器的精确移动至目标猕猴桃的过程。3 号舵机控制着采摘末端执行器基座的旋转，可以根据目标猕猴桃空间坐标的 X、Y 数据确定 3 号舵机的转动角度。程序设计流程图如图 3 所示。

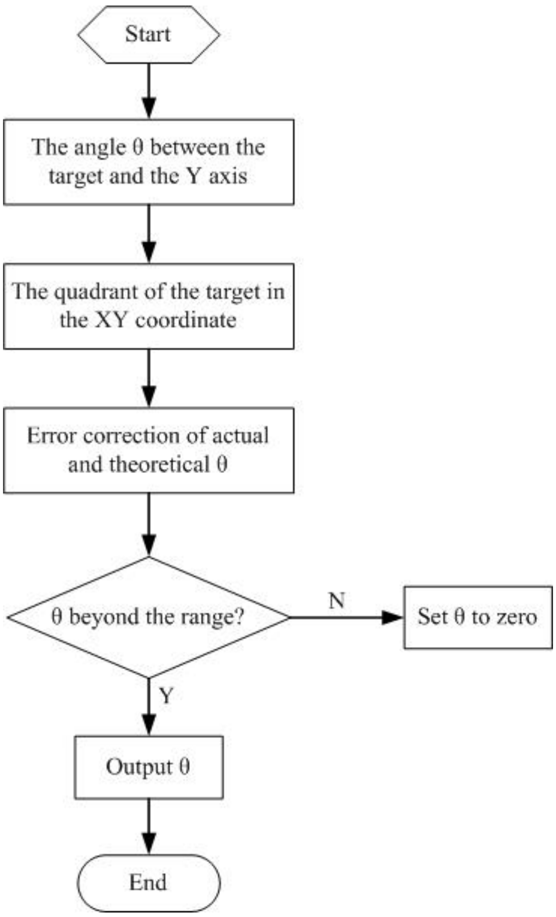


Fig.3 - Flow chart of No.3 servo's revolving angle

Only determining the rotational angle of the No.3 servo is insufficient to move the end-effector clamp to the target kiwifruit. This movement needs the analysis of the revolving angles of the No.4 and No.5 servos. The force manipulators that are controlled by the No.4 and No.5

仅确定 3 号舵机的转动角度还不能把采摘末端执行器采摘的钳子移动到目标猕猴桃的位置，还需要分析 4、5 号舵机转动的角度。在这里分别命名 4、5 号舵机控制的力臂为

servos are named as front arm and rear arm, respectively. As shown in Figure 4, the target kiwifruit is set as point A, the No.4 servo as one point, and the No.5 as another point. A triangle is formed by connecting the three points.

前臂与后臂，把目标猕猴桃设为 A 点，4 号舵机作为一个点，另外再把 5 号舵机设为一个点，然后把 A 点与 4、5 号舵机点相连接形成了三角形关系，如图 4 所示。

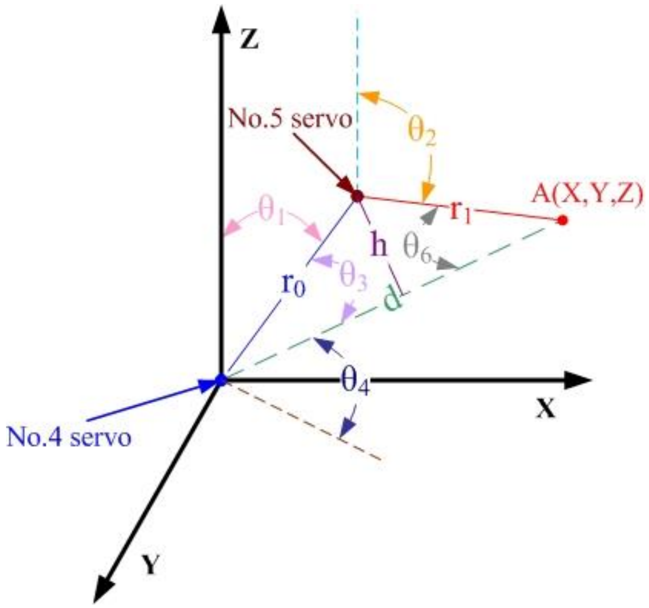


Fig.4 - Mathematical modelling of revolving angles of No.4 and No.5 servos

In Figure 4, θ_1 and θ_2 are the revolving angles of the No.4 and No.5 servos, respectively; r_0 and r_1 represent the distances from the No.4 to No.5 servos and No.5 to No.6 servos, respectively. The distance d from point A to original point "O" in Figure 4 can be obtained by using the XYZ coordinates transmitted by the binocular system.

在图 4 中，θ_1 与 θ_2 是 4、5 号舵机为采摘目标猕猴桃而需要转动的角度，r_0、r_1 分别代表末端执行器 4 号与 5 号舵机间距离、5 号与 6 号舵机间的距离，通过双目系统传送过来的 XYZ 坐标即可求出 A 点到原点“O”的距离。

$$d = \sqrt{X^2 + Y^2 + Z^2} \tag{1}$$

The triangle's height h can be calculated by Heron's formula:

通过海伦公式可以求得该三角形的高。

$$h = \frac{2\sqrt{p(p-r_0)(p-r_1)(p-d)}}{d} \tag{2}$$

where p is the half perimeter defined by the following:

在这里 p 为半径，其定义为：

$$p = \frac{1}{2}(r_0 + r_1 + d) \tag{3}$$

By using r_0, r_1, and height h with anti-trigonometric function, angles θ_3 and θ_6 in this triangle can be acquired as follows:

利用 r_0, r_1, 和高 h，通过下式求他们的反三角函数可求得 θ_3 和 θ_6。

$$\theta_3 = \arcsin(\frac{h}{r_0}) \tag{4}$$

$$\theta_6 = \arcsin(\frac{h}{r_1}) \tag{5}$$

By using the Z coordinates of the target kiwifruit, angle θ_4 of line segment OA and the horizontal plane can be calculated as follows:

根据目标猕猴桃的坐标 Z 可得出 OA 线与水平面的夹角 θ_4，如下式所示：

$$\theta_4 = \arcsin(\frac{|Z|}{d}) \tag{6}$$

Finally, according to the law of the right angle, θ_1 and θ_2 are given by the following:

最终根据直角取余法则求出 θ_1，同理可得 θ_2。

$$\theta_1 = 90^\circ - \theta_3 - \theta_4 \tag{7}$$

$$\theta_2 = 90^\circ - \theta_4 + \theta_6 \tag{8}$$

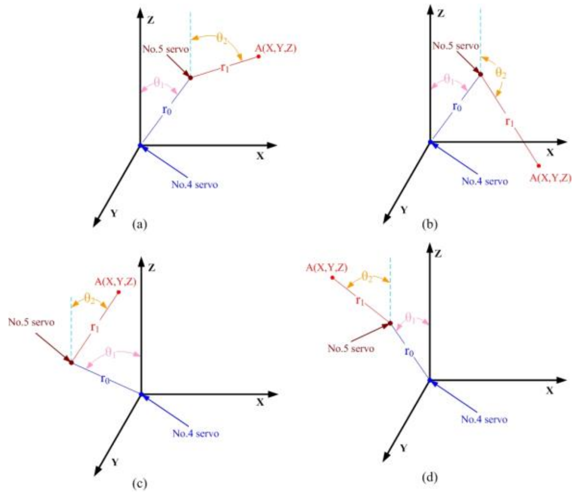


Fig.5 - Flow chart of receiving the coordinates by the end-effector's controller

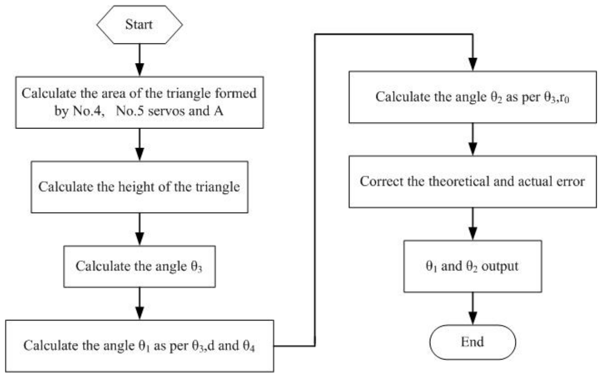


Fig.6 - Flow chart of picking feedback

The calculation algorithm of the steering revolving angle of the No.4 and No.5 servos is limited to the right ahead and above direction. Thus, θ_1 has a positive degree value and θ_2 is less than 90°. However, in actual conditions, the harvesting system is operated on the ground where complicated directions are involved such as ahead above, rear above, ahead below, and rear below. According to various experiments, the picking robot only needs four postures to achieve 360° of harvesting operation. The four postures are quite similar to a human's hand–wrist movements in all directions. As shown in Figure 5, the end-effector has four corresponding picking postures. The picking postures are distinguished on the basis of the revolving angle of over ±90°. Figure 6 shows the programming flow chart of how an end-effector controls the revolving angle of the No.4 and No.5 servos according to the space coordinates of the target fruit.

对 4、5 号舵机转动角度的计算仅限于目标猕猴桃位于采摘末端执行器三维坐标系的正前上方，即 θ_1 为正角度、θ_2 小于 90 度。然而，在实际情况下，系统的采摘过程是基于地面的，因此所有的采摘过程中猕猴桃会随机的位于末端执行器的前上方、后上方、前下方、后下方等各种情况，根据大量实验得出末端执行器只需四种采摘姿势便可采摘到 360°全方位的猕猴桃，这些姿势与人的手一样，在各个方向上都很相似，如图 5 所示，采摘末端执行器针对四种情况做出的四种采摘姿势。采摘姿势区分的依据是根据 4 号舵机和 5 号舵机转动正负角度大于 90 度而区分。采摘末端执行器根据目标果实的空间坐标控制 4 号舵机和 5 号舵机转动角度的程序设计流程图如图 6 所示。

Communication Between the End-effector and PC

The control system communicates with a PC through serial ports. When a PC detects a kiwifruit, it calculates the space coordinates of the target fruit. The PC will then transmit 9600 b/s baud rate of data to the control system of the robot end-effector. Given that the communication between the PC and the end-effector controller can only transmit one 8 bit binary data, a special algorithm needs to be applied to the data conversion to protect the data validity within the scope of 8 bit binary data and the data must be stored in the end-effector controller. The program of the specific data receiving the unit of the harvesting end-effector is shown in Figure 7. When the communication of serial ports is interrupted, RI is the zero setting and the flag denotes the flag bit of the data transmitted. The data transmitted from the PC is the X-axis coordinate, which is followed by Y and Z coordinates.

末端执行器与 PC 之间的通信

采摘末端执行器上的控制系统是通过串口与 PC 进行通信的，当 PC 检测出猕猴桃并计算出目标猕猴桃的具体空间坐标,PC 端便以 9600b/s 的波特率将数据传送到采摘末端执行器上的控制系统。由于 PC 端与采摘末端执行器上的控制器的通信一次只能传送一个 8 位的二进制数据，因此需在 PC 端通过一些特殊的数据转换算法使得数据在 8 位二进制数据的范围内以保护数据的有效性，然后在采摘末端执行器控制器中还原数据。采摘末端执行器控制器具体的数据接收程序如图 7 所示，当进入串口通信中断程序，RI 置零，flag 为数据传送个数的标记位，PC 端首先传送过来的数据是 X 轴的坐标，然后依次为 Y、Z。

When the picking end-effector completes a set of assigned actions according to the given coordinates and finally picks up the target kiwifruit, the end-effector will respond with an “OK” feedback to the PC as a signal for the picking order of the next target. The “OK” feedback procedure code is shown in Figure 8. First, ES is set to zero and “O” is placed in SBUF for data storage. Thereafter, TI is tested if it has a value of one to determine if the PC received the data. The same procedure is adopted for “K,” and ES is set to one.

当采摘末端执行器完成一组动作到达系统给定的空间坐标位置并把目标猕猴桃采摘下来后，采摘末端执行器将反馈一个“OK”给予 PC 端，从而 PC 可更有效率的传送下一个目标采摘指令。采摘末端执行器反馈“OK”的具体程序代码如图 8 所示。首先 ES 置 0，然后将数据“O”放入 SBUF 数据存储，通过检测 TI 是否为 1 即刻检测出 PC 端是否接受到数据，以同样的方法将“K”也反馈给 PC 端，最后将 ES 复位为 1。

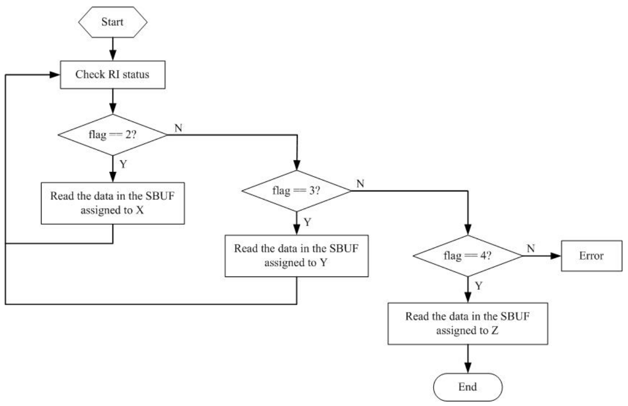


Fig.7- Flow chart of receiving the coordinates by the end-effector’s controller

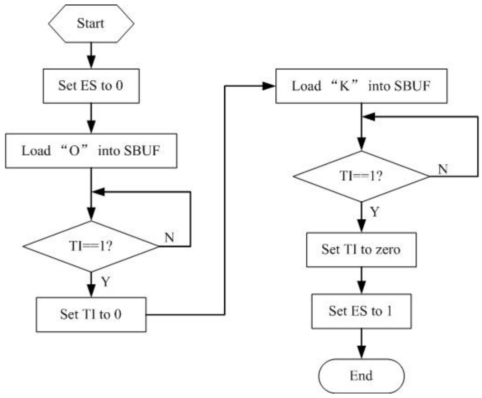


Fig.8- Flow chart of picking feedback

RESULTS

This paper selects clusters of fruits to be picked. The process is shown in Figure 9.

结果

本文选取一类水果进行采摘，其过程如图 9 所示。

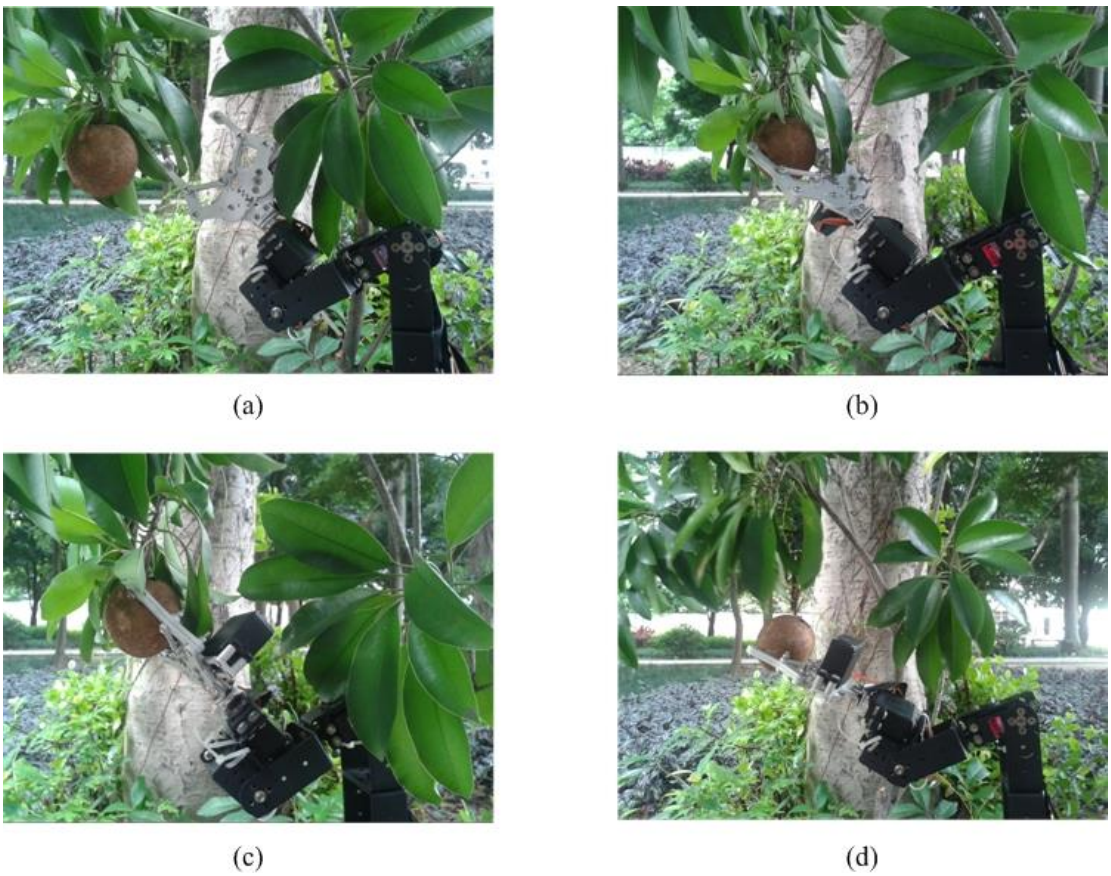


Fig.9 - Fruit picking process. (a) Start grabbing; (b) Finish grasping; (c) Start spinning; (d) Finish picking.

Table 6 shows how the PWM cycle affects the servo operation. When the PWM cycle is 2000 μs, the end-effector moves extremely fast, this is applicable for harvesting large fruits. When the cycle is 3000 μs, the speed is moderate, thus neither wearing off the machine because of the fast speed nor enabling harvesting because it is too slow. Therefore, the default PWM cycle utilized in this system is 3000 μs.

表 6 为 PWM 周期对舵机的影响，当 PWM 周期为 2000μs 的时候，末端执行器的运动极为快速，适用于大果实的采摘；当 PWM 波周期为 3000μs 的时候，末端执行器速度较为合适，不会因为速度太快而造成机械的磨损加剧，也不至于太慢导致无足够的力度采摘目标果实。因此本系统末端执行器的 PWM 周期默认为 3000μs。

Table 6

PWM cycle and servo control

PWM Cycle (us)	1500	2000	3000	7000
How the end-effector works	No movement	Extremely fast movement, normal operation	Moderately fast movement, normal operation	Slow movement, insufficient strength

Table 7 shows the test results of the precise movement of the end-effector to the target coordinates. This table shows that the end-effector is able to reach the space coordinates of the target transmitted by the binocular system, accurately analyze the direction of the coordinates, and determine the picking posture when harvesting. Moreover, picking robot can judge if the space coordinates are within the range of harvesting, which is in line with the system design. It means that the end-effector can determine if the target can be picked; if not, the end-effector will have no movement and give the feedback to the PC end.

表 7 为采摘末端执行器移动至目标坐标的测试情况。从该表不难观察出采摘末端执行器能准确到达双目系统传送过来的目标空间坐标，并且能准确分析给定坐标位于采摘末端执行器的哪个方位，从而判断出使用何种采摘姿势进行采摘。另一方面，采摘末端执行器对于空间坐标是否在采摘范围的判断符合本系统设计的结果，能准确地判断出目标坐标是否具备可采摘性，若不可采摘，末端执行器不做出任何采摘动作并且反馈给 PC 端。

Table 7

Test results of the picking end-effector

Space coordinates of the target(mm)	(150, 150, 156)	(100, 200, 156)	(100, 400, 256)	(–50, 100, 160)
Tested Results	Accurate picking	Accurate picking	Target can not be picked	Accurate picking

CONCLUSIONS

The research on fruit picking robots is thriving in China and abroad because of its significance in the development of science and technology and human civilization. The picking end-effector is a metal structure composed of five servos that control each junction of the end-effector to adapt complicated situations. The picking end-effector is more flexible and stable than other manipulators. In this paper, the movement in harvesting fruits is discussed; and each junction of the end-effector has mathematical modelling through which the coordinates of the target fruit are disassembled and analyzed so the end-effector can reach to the target precisely. Finally, experiments have verified the validity of the end-effector and its efficiency in agricultural operation.

结论

果实采摘机器人是当前国内外热门研究的课题，其发展对促进科学技术的发展与人类文明发展进程有着重大的实际意义。本论文的果实采摘末端执行器的结构为金属支架，通过控制五个舵机从而控制末端执行器的各个关节，使其能适用于各种复杂的情景，比其他采摘末端执行器更灵活、更稳定。另外本论文通过分析末端执行器采摘果实的动作，对它进行数学建模，然后将目标果实坐标通过数学建模进行拆解分析，使得末端执行器可以准确移动到果实的位置。最后通过采摘试验验证了该采摘末端执行器的有效性以及作业流程的合理性。

ACKNOWLEDGEMENT

This research was funded by the National Natural Science Foundation of China under Grant No.61505037, the National Spark Program under Grant No.2014GA780009, the State Scholarship Fund under Grant CSC No.201408440326, the Guangdong Natural Science Foundation under Grant No.S2013040014993, the Pearl River S&T Nova Program of Guangzhou under Grant No.201506010035, the University-sponsored

致谢

本论文得到国家自然科学基金项目资助（项目号：No. 61505037），国家星火计划项目资助（项目号：No. 2014GA780009），国家留学基金资助（项目号：CSC No.201408440326），广东省自然科学基金资助（项目号：No.S2013040014993），广州市珠江科技新星专项资

Research Project of Guangdong University of Finance and Economics under Grant No.14GLL63001, the Research Project of Research Institute of Education in Guangdong Province under Grant No.GDJY-2014-C-b043, the University Scientific Research Project of Guangxi Education Office under Grant No.KY2015ZL095.

REFERENCES

[1]. Berenstein R., Shahar O.B., Shapiro A., Edan Yael, (2010) - *Grape clusters and foliage detection algorithms for autonomous selective vineyard sprayer*, Intelligent Service Robotics, vol. 3, no.4, pp. 233-243;

[2]. Blanes C., Ortiz C., Mellado M., Beltrán P., (2015) - *Assessment of eggplant firmness with accelerometers on a pneumatic robot gripper*, Computers and Electronics in Agriculture, vol. 113, pp. 44-50;

[3]. Chiu Yi-Chich, Yang P.Y., Chen S., (2013) - *Development of the end-effector of a picking robot for greenhouse-grown tomatoes*, Applied Engineering in Agriculture, vol. 29, no.6, pp.1001-1009;

[4]. Chua P.Y., Ilschner T., Caldwell D.G., Van Henten E.J., (2003) - *Robotic manipulation of food products - A review*, Industrial Robot, vol. 30, no.4, pp. 345-354;

[5]. Edan Yael, Rogozin Dima, Flash Tamar, Miles Gaines E. (2000) - *Robotic melon harvesting*, IEEE Transactions on Robotics and Automation, vol. 16, no.6, pp. 831-835;

[6]. Elias Lopez-Alba, Ruben Dorado-Vicente, Jose Vasco-Olmo, Francisco Alberto Diaz-Garrido. (2012) - *Design and development of a vibration clamp for agricultural purposes*, DYNA, vol. 87, no.1, pp. 114-119;

[7]. Hayashi S, Ganno K, Ishii Y, Tanaka K. (2002) - *Robotic harvesting system for eggplants*, Japan Agricultural Research Quarterly, vol. 36, no.3, pp.163-168;

[8]. Hu Zhiyong, Zhang Xuewei, Zhang Wei, Wang Lin. (2014) - *Precise control of clamping force for watermelon picking end-effector*, Transactions of the Chinese Society of Agricultural Engineering, vol. 30, no.17, pp. 43-49;

[9]. Ji Chao, Feng Qingchun, Yuan Ting, Tan Yuzhi, Li Wei. (2011) - *Development and performance analysis on cucumber harvesting robot system in greenhouse*, Robot, vol. 33, no.6, pp.726-730;

[10]. Jin Bo, Lin Longxian. (2014) - *Design and force control of an underactuated robotic hand for fruit and vegetable picking*, Journal of Mechanical Engineering, vol. 50, no.19, pp.1-8;

[11]. Lin Hanhui, Cai Ken, Zeng Zhaofeng. (2015) - *Design of a low-cost system with built-in-gps agricultural machinery*, INMATEH - Agricultural Engineering, vol. 46, no.2, pp.25-36;

[12]. M. Mustafa Ertay, Ahmet Zengin. (2014) - *Analysis of the discontinuous PWM controlled D-STATCOM for reactive power compensation applications*, Tehnicki Vjesnik, vol. 21, no.4, pp. 825-833;

[13]. Reed J.N., Miles S.J., Butler J., Baldwin M., Noble R. (2001) - *AE-automation and emerging technologies: automatic mushroom harvester development*, Journal of Agricultural Engineering Research, vol. 78, no.1, pp. 15-23;

[14]. Shen Jian-Guang, Tao Tao, Mei Xue-Song, Xu Mu-Xun, Liu Shan-Hui. (2013) - *An improved line-drawing algorithm for arbitrary fractional frequency divider/multiplier based on FPGA*, Journal of Engineering

助（项目号：No. 201506010035），广东财经大学校级科研项目资助（项目号：No. 14GLL63001），广东省教育研究院教育研究课题资助（项目号：No. GDJY-2014-C-b043），广西教育厅高校科研项目资助（项目号：No. KY2015ZL095）。

参考文献

[1]. Berenstein R., Shahar O.B., Shapiro A., Edan Yael. (2010) - *针对自主选择葡萄园喷雾器的葡萄簇和叶检测算法*, 智能服务机器人学报, 第 3 卷, 第 4 期, 233-243;

[2]. Blanes C., Ortiz C., Mellado M., Beltrán P.,. (2015) - *使用气动机器人夹持器上的加速度计对茄子硬度进行评价*, 计算机电子技术在农业中的应用, 第 113 卷, 44-50;

[3]. Chiu Yi-Chich, Yang P.Y., Chen S.. (2013) - *设施内西红柿采收机器人爪具之研制*, 农业应用工程, 第 29 卷, 第 6 期, 1001-1009;

[4]. Chua P.Y., Ilschner T., Caldwell D.G., Van Henten E.J. (2003) - *食物产品机器人控制综述*, 工业机器人, 第 30 卷, 第 4 期, 345-354;

[5]. Edan Yael, Rogozin Dima, Flash Tamar, Miles Gaines E. (2000) – *甜瓜采摘机器人*, IEEE 机器人学与自动化杂志, 第 16 卷, 第 6 期, 831-835;

[6]. Elias Lopez-Alba, Ruben Dorado-Vicente, Jose Vasco-Olmo, Francisco Alberto Diaz-Garrido. (2012) -*农业用途的振动夹具设计与开发*, DYNA, 第 87 卷, 第 1 期, 114-119;

[7]. Hayashi S, Ganno K, Ishii Y, Tanaka K. (2002) - *茄子机器人摘取系统*, 日本农业研究季刊, 第 36 卷, 第 3 期, 163-168;

[8]. 胡志勇, 张学炜, 张伟, 王琳. (2014) - *西瓜采摘末端执行器夹持力精确控制*, 农业工程学报, 第 30 卷, 第 17 期, 43-49;

[9]. 纪超, 冯青春, 袁挺, 谭豫之, 李伟. (2011) - *温室黄瓜采摘机器人系统研制及性能分析*, 机器人, 第 33 卷, 第 6 期, 726-730;

[10].金波，林龙贤. (2014) - *果蔬采摘欠驱动机械手爪设计及其力控制*, 机械工程杂志, 第 50 卷, 第 19 期, 1-8;

[11]. Lin Hanhui, Cai Ken, Zeng Zhaofeng. (2015) - *一种基于嵌入式的低成本农业机械 GPS 导航定位系统设计*, 国际农业工程期刊, 第 46 卷, 第 2 期, 25-36;

[12]. M. Mustafa Ertay, Ahmet Zengin. (2014) - *针对无功补偿应用的不连续的 PWM 控制系统分析*, 技术公报, 第 21 卷, 第 4 期, 825-833;

[13]. Reed J.N., Miles S.J., Butler J., Baldwin M., Noble R. (2001) - *自动和新兴技术：自动蘑菇采摘机开发*, 农业工程研究杂志, 第 78 卷, 第 1 期, 15-23;

[14]. Shen Jian-Guang, Tao Tao, Mei Xue-Song, Xu Mu-Xun, Liu Shan-Hui. (2013) - *一种改进的基于 FPGA 的用*

Science and Technology Review, vol. 6, no.5, pp. 90-94;
[15]. Van Willigenburg L.G., Hol C.W.J., Van Henten E.J. (2004) - *On-line near minimum-time path planning and control of an industrial robot for picking fruits*, Computers and Electronics in Agriculture, vol. 44, no.3, pp. 223-237;
[16]. Wang Xuelin, Xiao Yongfei, Bi Shuhui, Fan Xinjian, Rao Honghui. (2015) - *Design of test platform for robot flexible grasping and grasping force tracking impedance control*, Transactions of the Chinese Society of Agricultural Engineering, vol. 31, no.1, pp. 58-63;
[17]. Xiong Juntao, Ye Min, Zou Xiangjun, Peng Hongxing, Lin Guichao, Zhu Mengsi. (2013) - *System design and performance analysis on multi-type fruit harvesting robot*, Transactions of the Chinese Society for Agricultural Machinery, vol. 44, no.1, pp. 230-235;
[18]. Yan Lei, Yu Zheng, Han Ning, Liu Jinhao. (2013) - *Improved image fusion algorithm for detecting obstacles in forests*, Journal of Digital Information Management, vol. 11, no.5, pp. 378-384;
[19]. Ying Yibin, Zhang Wenying, Jiang Yiyuan, Zhao Yun, (2000) - *Application of machine vision technique in automatic harvesting and processing of agricultural products,* Transactions of the Chinese Society of Agricultural Machinery, vol. 31, no.3, pp. 112-115;
[20]. Yuan Ting, Xu Chen-Guang, Ren Yong-Xin, Feng Qing-Chun, Tan Yu-Zhi, Li Wei, (2009) - *Detecting the information of cucumber in greenhouse for picking based on NIR image*, Spectroscopy and Spectral Analysis, vol. 29, no.8, pp. 2054-2058;
[21]. Zhang Peng, Song Jian, Gong Shenglei, Jiang Bo, Muham Polar D., (2014) - *A kinematic analysis and simulation based on ADAMS for eggplant picking robot*, INMATEH - Agricultural Engineering, vol. 43, no.2, pp. 51-60;
[22]. Zhou Jun, Ji Changying, (2003) - *Multi-resolution road recognition for vision navigation*, Transactions of the Chinese Society for Agricultural Machinery, vol. 34, no.6, pp.120-123.

于任意分频器/乘法器的直线绘制算法, 工程科学与技术综述, 第 6 卷, 第 5 期, 90-94;
[15]. Van Willigenburg L.G., Hol C.W.J., Van Henten E.J. (2004) - *水果采摘工业机器人的最小时间路径规划与控制*, 计算机电子技术在农业中的应用, 第 44 卷, 第 3 期, 223-237;
[16]. 王学林, 肖永飞, 毕淑慧, 范新建, 饶洪辉. (2015) - *机器人柔性抓取试验平台的设计与抓持力跟踪阻抗控制*, 农业工程学报, 第 31 卷, 第 1 期, 58-63;
[17]. 熊俊涛, 叶敏, 邹湘军, 彭红星, 林桂潮, 朱梦思. (2013) – *多类型水果采摘机器人系统设计与性能分析*, 农业机械学报, 第 44 卷, 第 1 期, 230-235;
[18]. Yan Lei, Yu Zheng, Han Ning, Liu Jinhao. (2013) - *用于森林障碍检测的图像融合改进算法*, 数字信息管理杂志, 第 11 卷, 第 5 期, 378-384;
[19]. 应义斌, 章文英, 蒋亦元, 赵匀. (2000) -*机器视觉技术在农产品收获和加工自动化中的应用*, 农业机械学报, 第 31 卷, 第 3 期, 112-115;
[20]. 袁挺, 许晨光, 任永新, 冯青春, 谭豫之, 李伟. (2009) - *基于近红外图像的温室环境下黄瓜果实信息获取*, 光谱学与光谱分析, 第 29 卷, 第 8 期, 2054-2058;
[21]. Zhang Peng, Song Jian, Gong Shenglei, Jiang Bo, Muham Polar D. (2014) - *基于 ADAMS 的茄子采摘机器人运动学分析与仿真*, 国际农业工程期刊, 第 43 卷, 第 2 期, 51-60;
[22]. 周俊, 姬长英. (2003) - *农业机器人视觉导航中多分辨率路径识别*, 农业机械学报, 第 34 卷, 第 6 期, 120-123.