SYSTEM DESIGN AND IMPLEMENTATION OF A NOVEL ROBOT FOR APPLE HARVEST
/
种新型苹果采摘机器人系统设计与实现

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Abstract: *The mechanical design of a novel robot system for apple harvest in orchards is introduced in this paper. A description of the working environment is first provided. The robot system is operated in a master–slave manner, which is widely used in surgical robots. The robot makes use of human judgment and the precise positioning, stable, and tireless manipulability of the slave robot to mechanize apple harvest. The slave robot is constructed with an under-actuated end effector and a modified Selective Compliance Assembly Robot Arm (SCARA) manipulator. Two passive joints are set at the end effector to adjust its capture gesture according to the branch of the target apple. An additional joint is set at the SCARA arm to point the end effector at the tree trunk during harvest period. The dexterity of the manipulator is analyzed with the geometrical method, and a preferred initial harvest position is obtained. A joystick is employed as the master device for the operator to generate the control command, which is utilized to control the motion of the slave arm and end effector. A PC-based control system is established to integrate the pieces of equipment. Initial test results validate the design concept of this apple harvest robot system.*

Keywords: *Master-slave; Under-actuated; Modified SCARA; Harvest; PC*

摘要：*本文介绍了一个用于果园中苹果采摘的新型机器人系统的机械设计。文中首先介绍了该机器人系统工作的果园环境。这个机器人系统采用的是在外科机器人中广泛采用的主-从控制模式。这个机器人综合利用人工判断与从操作机器人精确定位、稳定和不知疲倦的工作能力，以实现苹果采摘的机械化。从操作机器人由欠驱动末端工具和改进的 SCARA 机械臂构成。末端工具设置有两个被动式关节来调整其相对于目标苹果所在枝条的姿态。本文在 SCARA 构型机械臂末端增设了一个转动关节，使末端工具在采摘过程中可始终指向树干方向。本文采用几何方法分析了机械臂灵活度并得到了其优选采摘初始位置。工作人员操作控制手柄来产生控制命令用来控制从操作机械臂和末端工具的动作。控制系统采用 PC 工控机为平台集成了机器人系统的其他硬件。初步的测试结果验证了该苹果采摘机器人系统的设计概念。*

关键词：*主-从；欠驱动；改进型 SCARA；采摘；工控机*

INTRODUCTION

In China, large amounts of apples and pears are produced in orchards. These fruits play an important role in the fruit economy. Total apple production reached 35 million tons in 2014. An unavoidable social course in China at present is that a decreasing number of laborers stay in the countryside. This phenomenon affects agriculture and the fruit industry. Labor in orchards is in serious demand, especially during harvest season. Hence, mechanization of fruit harvest is required.

With the development of machine vision, robots, and artificial intelligence, many important achievements have been obtained in the automation of fruit cultivation and harvest. Schertz first proposed the concept of harvest robot in 1968 [11]. The success rate of this robot when used in harvesting was approximately 70%. Kondo developed a tomato harvest robot in 1993 [8]. The robot comprised a manipulator, an end effector, a vehicle unit, and a vision and control system. Its success rate was approximately 70%. Zhou presented a 7-DOF robot for cucumber harvest in greenhouses in 1998 [16]. A Charge-Coupled Device (CCD) was embedded inside the end effector for quick and precise positioning. The harvest speed was approximately 10 s for each target. Edan presented a robot system for melon harvesting in 2000 [2]. The robot body was set on a mobile platform, and a black and white image was utilized to locate the

引言

在中国，果园中每年生产大量的苹果和梨，这两种水果在水果经济中占据重要的地位。水果的年产量，以苹果为例在 2014 年达到了 3500 万吨。在中国社会化进程中一个不可逆的现象是农村劳动力变得越来越少，这会明显影响农业和水果业。果园中的人工劳动力会变得越来越紧缺，特别是在果实收获季节。这是水果收获机械化在近些年变得越来越迫切的一个非常重要的原因。

得益于机器视觉、机器人和人工智能的发展，在水果培育和采摘自动化方面近年来取得了许多重要的成就。舍尔茨于 1968 年首次提出了收获采摘机器人的概念[11]，他们研发的采摘机器人的收获成功率大概在 70%。近藤春雄等在 1993 年研制了番茄收获机器人[8]，该机器人包括机械臂，末端工具，车辆单元，图像和控制系统。其采摘成功率约为 70%。周在 1998 年推出了用于温室内的 7 自由度黄瓜采摘机器人[16]，机器人末端工具里面嵌入了用于快速和准确定位的 CCD 摄像头。每个目标果实的收获速度大概是 10 秒钟。埃德娜于 2000 年开发了用于收获甜瓜的机器人[2]，这个机器人安装在移动平台上，该机器人采用黑白图像来定位目标果实，采摘的成功率大概是 85%。范于 2002 年开发了在温室里自动采摘收获黄瓜的机器人

target fruit; the success rate was about 85%. Van introduced an autonomous robot for cucumber harvest in greenhouses in 2002 [14]. The robot had 7 DOF, and the end effector was equipped with a hot cut unit for antivirus. In 1994, Setiawan designed an apple gripper that is highly capable of picking up an apple without scratching its skin [12]. Foglia introduced a cost-effective robotic arm for the harvest of radicchio; the robotic arm employed visual localization of the plants in the field [3]. The harvester was composed of a double four-bar linkage manipulator and a gripper, which fulfilled the requirement for a plant cut approximately 10 mm underground. Han proposed a fruit and vegetable picking robot in 2007 [6]. The robot was jointed with 4 DOF and fulfilled the requirements for eggplant picking in greenhouses. Baur developed a redundant modular multipurpose agriculture robot for the harvest of sweet pepper, apple, and so on [1].

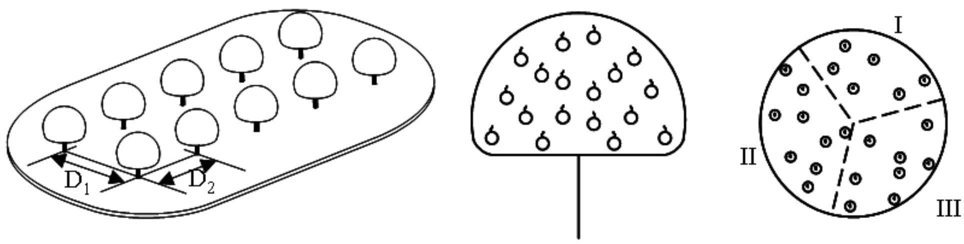
The uncertainty and non-structural environment in orchards, the random and complicated distribution of apples in a tree, illumination variation, and other factors significantly affect the efficiency of the vision system, amount of time consumed, and success rate of robot harvest. The amount of time required for a robot to harvest a single fruit varies from 7 s to 55 s [10, 13], and the success rate is approximately 43% to 95% [7, 15].

Robots for fruit harvest have been investigated for decades. Most of the studies mentioned above are based on the vision-navigated autonomous robot method. To date, no commercial products for orchards are available. The concept of master–slave robot for the mechanization of apple harvest was presented in 2013 [5]; this work is developed in the present study. The master–slave robot was first employed in a radioactive station in the 1950s in the USA [4]. It was widely used in surgery robots by the end of the 1990s [9]. The similarities of surgery and fruit harvest are the complexity of the environment and the uncertainty of target manipulation. The task for fruit harvest is less difficult compared with that in surgery; this fact may reduce the cost and difficulty involved in introducing the master–slave robot to fruit harvest.

[14]，这个机器人有 7 自由度机械臂，该机器人末端执行器上设置有高温剪切单元来消除病菌对果实切口的影响。赛蒂亚万设计了低成本的苹果采摘工具[12]，这个采摘工具可以高效率的采摘苹果，同时不会刮伤目标果实的果皮。福利亚开发了用于采摘菊苣的高效费比的机器人机械臂[3]，这个机器人采用机器视觉的方法来定位田野里的目标果实。这个机器人由双四连杆机构机械臂和特殊设计的采摘手爪构成，这个机械臂可满足地下 10mm 左右深度的植物剪断要求。韩在 2007 年推出了蔬菜和水果采摘机器人[6]，这个机器人为 4 自由度转动关节构型，可满足在温室内的茄子采摘要求。鲍尔开发了冗余式模块化多功能农业机器人[1]，可用来采摘甜椒，苹果等果实。

由于不确定性因素以及果园非结构化环境特点，以及果树上苹果分布的随机和复杂性，加之环境光线亮度变化以及其他因素影响，采摘机器人图像系统的效率会受到干扰，并进一步影响图像系统所需的处理时间以及采摘成功率。机器人采摘单个果实所需的时间大概是 7 到 55 秒[10, 13]，采摘成功率是 43%到 95%[7,15]。

采摘机器人的研究已经发展了几十年的时间，前述提到的大部分研究工作都是基于图像导航的自动化机器人，然而直到目前还没有出现可实际用于果园的商用化机器人产品。本文作者于 2013 年提出一种主-从式遥操作控制的苹果采摘机器人概念[5]，本文所述内容在此基础上深化得到。主-从式遥操作机器人技术于 1950 年代在美国核电站中得到首次应用[4]，然而最终将其大范围商业化推广却是在 1990 年代的外科医学机器人领域[9]。外科医学机器人和采摘机器人的相同点是它们作业环境的复杂性和操作目标不确定性。同时果实采摘难度不及外科手术操作，因此可降低机器人成本，也可降低将主-从遥操作技术引入果实采摘的难度。



(a) Apple tree in orchard (b) Apple distribution (c) Top view of tree

Fig.1- Orchard and apple distribution

MATERIALS AND METHODS

Working environment of a harvest robot

With several exceptions excluded, apple trees in China are typically grown in orchards with a similar layout. Apple trees are planted in lines at a distance D1 of about 4 m to 4.6 m; the trees are maintained within the same line at a distance D2 of about 3.3 m to 3.8 m, as shown in Figure 1(a). The space around the trees is for laborers to cultivate the apple trees and harvest their fruits; it also allows a vehicle to cross the orchard. Sufficient space between trees also benefits

材料和方法

采摘机器人工作环境

在中国除了一些特殊的情况外，果园里的苹果树都是以类似的布置方式种植。苹果树种植成行列形式，每列之间的行距 D_1为 4 到 4.6 米，同列中两棵树之间的间距 D_2为 3.3 到 3.8 米，如图 1（a）所示。果园工人利用树周围的空间来培育果树以及采摘果实，同时车辆可以在果树之间的空隙穿行过往。果树之间足够宽松的空间还可以使果树的光合作用更高效以提高果实产量。正常成熟苹果的直径

photosynthesis for better production. An ordinary mature apple fruit is 80 mm to 100 mm in diameter, with a weight of 0.18 kg to 0.25 kg. Fruits are distributed on almost all branches of an apple tree in different height layers, as shown in Figure 1(b). Most of the branches radially extend from the center of the tree trunk to the outer edge direction, providing an apple tree a nearly spheroid shape. The body of an apple tree is likely to point toward the ground direction because of gravity. When the apple fruits are mature, laborers pick them from around a tree along sector areas I, II, and III, as shown in top view in Figure 1(c). The preferred harvest sequence is from the bottom of a tree to its top and from the outside circle to the center tree trunk; in this manner, laborers encounter the least obstacle from radially structured branches and avoid unnecessary damage to other apples.

约为 80 至 100mm，重量约为 180 至 250g。苹果树的果实几乎分布于果树树身周围不同高度层的所有部位枝条，如图 1（b）所示。果树的多数枝条呈放射状从树干伸向外侧边缘方向，这样果树整体呈现为一个近似球形的轮廓。苹果树的果实由于重力的作用，大部分朝向地面的方向生长。当苹果成熟以后，从果树的正上方俯视果树，如图 1（c）所示，果园的工人可以沿着果树周围分别在区域 I，II，III 来采摘苹果。采摘时从果树的底部向果树的树尖方向采摘，从树的边缘部位向树干方向是比较好的顺序。这样采摘时工人不会遇到放射状分布枝条的太多阻碍，同时可以避免对其他需采摘果实的不必要伤害。

Mechanical design and analysis of the slave robot

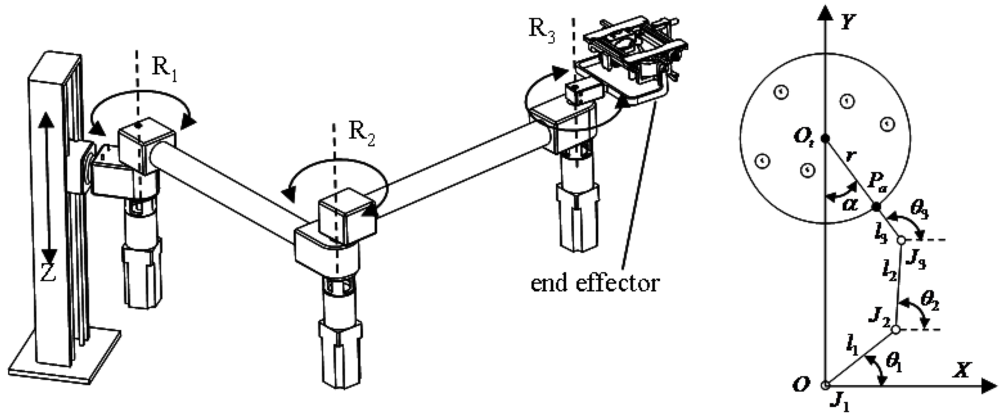
1). Manipulator of the harvest robot

A master–slave robot for apple harvest is proposed. The slave robot is meant to be set on a common vehicle in an orchard, which is not discussed in this paper. The slave robot for apple harvest is composed of a modified SCARA manipulator and an under-actuated end effector, as shown in Fig. 2(a). The manipulator of the robot is from an ordinary SCARA robot with a third rotation joint R3 added to its distal. The end effector is connected to joint R3. The manipulator has a vertical translational joint Z set inside the base column. Joint Z is driven by a screw mechanism (KA140A-C5) and lifts the robot arm up and down. Joints R1, R2, and R3 are driven by servo motors (YZ-ACSD60) to move the end effector on a plane.

从操作机器人机构设计及分析

1). 采摘机器人机械臂

本文提出主-从式苹果采摘机器人，从操作机器人装置在果园车辆上，关于车辆本文未做描述。如图 2 所示，该苹果采摘从操作机器人由改进型 SCARA 机械臂和欠驱动末端执行器构成。该机器人机械臂由一般 SCARA 机器人改进而来，如图 2（a）所示，通过在 SCARA 机械臂末端增加第三个转动关节 R_3实现。末端工具安装在关节 R_3上。该机械臂在基座立柱内部设置了竖直运动的移动关节 Z，关节 Z 由丝杠机构驱动(KA140A-C5)，带动机器人机械臂上下运动。关节 R_1，R_2 和 R_3 由伺服电机(YZ-ACSD60)驱动，使末端执行器在平面内运动。



(a) Modified SCARA manipulator (b) Pointing at tree trunk

Fig.2- Slave manipulator for apple harvest

To reduce the obstacle from branches and damage to other mature apples in sectors I, II, and III of the apple tree, joint R3 must align the end effector to the center of the tree trunk all the time during harvest, as shown in Figure 2(b). The origin of coordinate O is set on point J_1 of joint R1, and the positions of joints R2 and R3 are marked as J_2 and J_3. The coordination of the tree trunk (O_t) is $(0, L)$, and the location of the target apple is labeled with P_a by radial r and angle α of the branch, as shown in Figure 2(b). Thus, lines J_3P_a and P_aO_t are expected to be collinear all the time.

With joint angle variations $\theta_1, \theta_2, \theta_3$ and arm lengths l_1, l_2, l_3 of the manipulator, we have:

为了减少果树枝条对于机械臂的阻碍，同时为了减少对于其他成熟果实的损伤，在果树周围的区域 I，II 和 III 里，如图 2（b）所示，机械臂的关节 R_3应该让欠驱动末端工具在采摘工作的全过程中始终指向果树的树干方向。平面坐标系 O-XY 的原点O 设置在关节 R_1的 J_1 点，关节 R_2和 R_3 的位置标记为 J_2 和 J_3 。采摘对象果树的树干坐标 O_t 标记为 $(0, L)$，采摘对象苹果的位置点标记为 P_a，如图 2（b）所示，P_a 可以由所在枝条到树干的距离 r 和角度 α 确定，这样线段 J_3P_a 和 P_aO_t 应该一直保持共线。

根据关节变量 θ_1、θ_2和θ_3，以及机械臂的各段长度值 l_1、l_2和l_3，可得到：

$$\begin{cases} l_1 \cos\theta_1 + l_2 \cos\theta_1 + l_3 \cos\theta_3 = r\sin\alpha \\ l_1 \sin\theta_1 + l_2 \sin\theta_1 + l_3 \sin\theta_3 = L - r\cos\alpha \end{cases} \tag{1}$$

Incorporating $\theta_3 = \pi/2+\alpha$ into Equation (1) yields

将 $\theta_3 = \pi/2+\alpha$ 代入公式（1）可得：

$$\theta_1 = 2\arctan\frac{-4[L-(r+l_3)\cos\alpha]l_1}{2[E+2l_1(r+l_3)\sin\alpha]} + \frac{\sqrt{(4Ll_1)^2+16(r+l_3)^2l_1^2-4E^2-32L(r+l_3)l_1^2\cos\alpha}}{2[E+2l_1(r+l_3)\sin\alpha]} \tag{2}$$

where $E=(r+l_3)^2+L^2+2L(r+l_3)\cos\alpha$. Incorporating Equation (2) into Equation (1) yields

这里 $E=(r+l_3)^2+L^2+2L(r+l_3)\cos\alpha$，将公式（2）代入公式（1）可得：

$$\theta_1 = 2\arccos\frac{(r+l_3)\sin\alpha - l_1\cos\theta_1}{l_2} \tag{3}$$

To ensure that the end effector has sufficient dexterity, k is regarded as an index with

为了保证末端执行器具有足够的灵活度，这里将 k 作为一个指数：

$$k = 1-\left|\frac{\theta_3-\theta_2}{\theta_3'}\right| \tag{4}$$

where θ_3' is the angle range of joint R3 and k is distributed to r and α, as shown in Figure 3.

The result shows that dexterity is highly sensitive to angle α of a branch, and the r behaviors have a minimal effect on dexterity. The nearer to the tree trunk, the better dexterity is. The angle around $\alpha=\pi/6$ is a preferred position for the slave manipulator to have the best dexterity.

这里 θ_3' 是关节 R3 的关节活动范围，k 相对于 r 和 α 的变化情况如图 3 所示。

从结果可以看出该机器人末端执行器的灵活性受枝条角度 α 的影响较大，而 r 对于灵活性的影响较小，同时越靠近树干的采摘位置，机器人末端工具的灵活性越好。在 $\alpha=\pi/6$ 角度附近机器人灵活度最好，可以作为机器人一个优先初始位置。

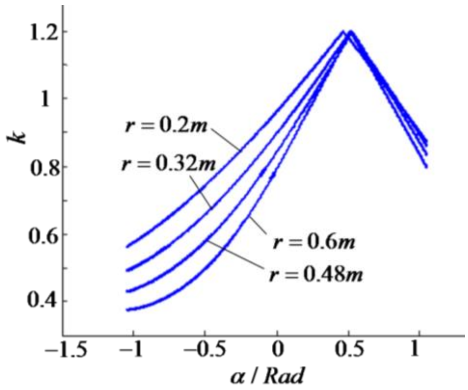


Fig.3 - Variation of k to α and r

2). Under-actuated end effector for the robot

The end effector is installed in the manipulator with two passive joints, R4 and R5, as shown in Figure 4(a). The end effector is basically constructed on a square frame. The side lengths of the frame are b and c. A local coordinate $o-xy$ is set on the frame plane, as shown in Figure 4(b). The ideal condition for harvest is that the branch is horizontal and the apple is vertical. However, in most cases, the branch is gradient oriented [marked as line L_B in Figure 4(b)]. The gradient angle of L_B relative to the frame plane is β, which is measured with a parallel auxiliary line l_B of L_B. The direction of projection line l of L_B relative to the $o-y$ axis on the

2). 机器人欠驱动末端工具

机器人欠驱动末端工具通过两个被动式关节 R4 和 R5 安装到机械臂上，如图 4（a）所示。这个末端工具基本上构建在一个长方形的框架上，该长方形的两个边长分别为 b 和 c。可在这个长方形框架上设置一个局部坐标系采摘果实的最佳情况是枝条水平生长，苹果垂直悬吊。然而，大多数时候枝条是倾斜分布，如图 4（b）中标记为 L_B 的线所示。枝条 L_B 相对于末端工具长方形框架平面倾斜的角度标记为 β，该角度值由 L_B 的平行辅助线 l_B 测得。在长方形框架平面内 L_B 的投影线 l 相对于 $o-y$ 轴的角度标记为 δ。

frame is marked as δ.

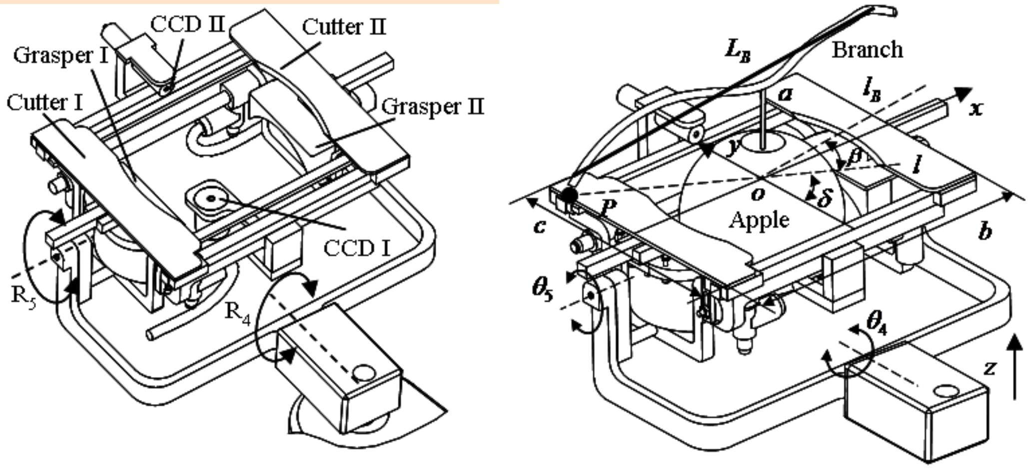
Joints R4 and R5 are expected to adjust the gesture of the end effector relative to the apple and branch, with angles labeled as θ_4 and θ_5. The end effector rises to meet the target apple, with a vertical translation by joint Z marked as z in Figure 4 (b). The frame edge of the end effector thus meets the gradient branch first at point P. The gravity of the branch and apple pushes against the frame and rotates it at joints R4 and R5 until the apple is inside the end effector, where the frame plan meets the bottom of the apple stem with vertical distance a to the branch. Thus, with displacement and moment balanced, the equations are

末端执行器相对采摘果实和枝条的姿态通过关节 R_4 和关节 R_5 调整，标记为 θ_4 和 θ_5。末端执行通过垂直升降关节 Z 上升到目标苹果，其行程标记为图 4（b）中的 z。这个过程中末端执行器的长方形框架的边缘会首先在 P 点接触到倾斜枝条。对于采摘机器人，目标苹果 L_B 和所在枝条的重力会在 P 点推着末端执行器的长方形框架边缘，使长方形框架绕着关节 R_4 和 R_5 旋转直到目标果实进入末端执行器的内部，此时长方形框架平面接触到苹果果梗的根部，果梗从果实到枝条的长度标记为 a。在这个位置，关于末端执行器的位移和力矩平衡公式为：

$$\begin{cases} \dfrac{b\sin\beta}{2\sin\delta\cos\beta} - a = \dfrac{b}{2}(\sin\theta_4 + ctg\delta\sin\theta_5\cos\theta_4) \\ \dfrac{Fb}{2\sin\delta} = (\sin\theta_4\cdot l_4 + \sin\theta_5\cdot l_5)\cdot mg \end{cases} \tag{5}$$

where m is the mass of the end effector and F is the force from the branch to the frame. l_4 and l_5 are the vertical distances of the end effector mass center to the axis of joints R4 and R5.

此处 m 为末端执行器的重量，F 为枝条作用到框架上的力。l_4 和 l_5 是末端执行器质心到关节 R_4 和 R_5 轴线的距离。



(a) Under-actuated end effector (b) Gesture adjustment

Fig.4 - End effector of the slave robot

Cutters I and II are set on two separate sliders along the axis direction of joint R5 and driven by two separate micro cylinders. Graspers I and II are installed with springs in cutters I and II separately and move together with them; they are set to an initial position where they are sure to come in contact with and grasp the apple before cutters I and II operate. With a proper capture gesture by the end effector, the cutters and graspers are driven by micro cylinders together. When graspers I and II hold the apple steadily, they stop moving. Cutters I and II keep sliding toward the center and cut the apple stem with their sharp edge when they meet each other. In this manner, the number of drive units for the cutters and graspers can be reduced for the benefit of the mechanism structure and improvement of harvest art.

沿着关节 5 的轴线方向，切刀 I 和切刀 II 分别装在两个滑块上面，这两个滑块由两个单独微型气缸驱动。夹持器 I 和夹持器 II 分别通过弹簧机构安装在切刀 I 和切刀 II 上并且各自跟随它们一起运动，夹持器 I 和夹持器 II 设置的初始位置可以确保它们在切刀 I 和切刀 II 之前先抓持苹果。当末端执行器到达合适采摘姿态后，两组微型气缸同时驱动切刀和夹持器机构向中间运动。当夹持器 I 和夹持器 II 稳定抓住苹果后它们停止移动，切刀 I 和切刀 II 继续向中心方向移动直到它们相互接触，它们各自的锋利刀刃共同挤压切断苹果果梗。利用这种结构，可以减少末端执行器的切刀和夹持器驱动单元数量，不仅可以使机械结构紧凑，同时可以优化采摘工艺。

Control method for the apple harvest robot

1) PC-based control system

The control system of the apple harvest robot is based on a PC platform, as shown in Figure 5. The

苹果采摘机器人的控制方法

1) 基于 PC 的控制系统

本文所述的苹果采摘机器人控制系统目前基于 PC 平台

operator holds the master joystick and sends control signals via the stick and a button on it to the PC and PLC controller (FX2N). PCI 1020H is a PCI-installed motion controller; it is used to receive the motion command and control the motors of the slave manipulator simultaneously. The PLC controller is employed to trigger the solenoid valves of the micro cylinders of the end effector to generate an under-actuated grasping and cutting movement. The views of the target apple are captured by CCD I and II. The video signals of CCD I and II are processed by a vision card (VCER-89) and shown on an LCD screen set in front of the operator for feedback.

集成，如图 5 所示。操作者抓持主控制手柄，通过这个手柄向 PC 和 PLC 控制器（FX2N）发送控制信号。PCI1020H 是一个 PCI 总线安装的运动控制器，本文采用它来接收运动命令然后控制从操作机械臂的驱动电机协调运动。PLC 控制器用来触发控制采摘机器人末端执行器微型气缸动作的电磁阀，微型气缸可以推动夹持器和切刀完成欠驱动运动。摄像头 CCD I 和 CCD II 用来采集目标采摘果实的图像场景信息。视频采集卡用来接收 CCD I 和 CCD II 采集的视频信号，然后将其在置于操作者面前的 LCD 显示器中显示出来。

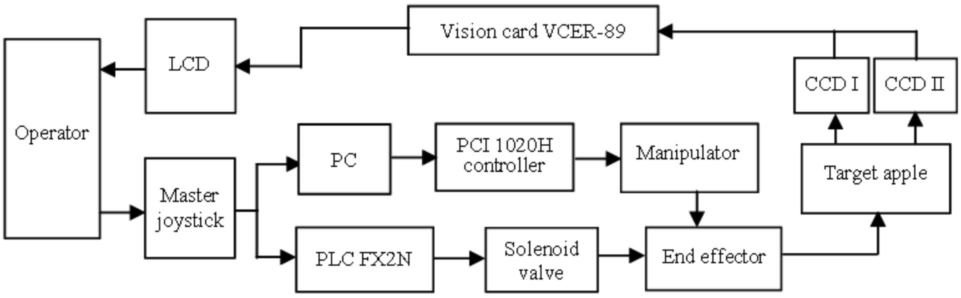


Fig.5 - Architecture of the control system

2) Vision system

CCD I (SUNWAY-500A) is vertically set at the bottom center of the end effector frame similar to the arrangement of “eye in hand,” as shown in Figure 4(a). CCD I is expected to capture views under the target apple and “guide” the apple to the center of the LCD screen, as shown in Figure 6(a). CCD II (CSTE-10) is horizontally set at the frame side of the end effector and is expected to help the operator check whether the apple has fallen into the end effector properly, as shown in Figure 6(b). The scenes captured by CCD I are the first to be shown on the LCD screen. When an apple is positioned well in CCD I, joint Z of the manipulator begins to raise the end effector. The LCD changes to show the scenes captured by CCD II to help the operator decide whether to cut the apple stem.

2) 图像系统

摄像头 CCD I (SUNWAY-500A)以“眼在手中”的方式竖直安装于末端执行器方形框架中心点的正下方，如图 4（a）所示。摄像头 CCD I 在目标苹果下方获取目标苹果图像，然后将苹果“导引”到图像中心位置，如图 6（a）所示。摄像头 CCD II(CSTE-10)水平安装于末端执行器方形框架边缘，用来帮助操作者确定苹果是否“下落”到末端执行器的合适位置，如图 6（b）所示。摄像头 CCD I 所采集的视频信息首先显示在 LCD 上。当苹果处于合适位置后，机械臂 Z 关节向上驱动末端执行器，此时 LCD 切换显示摄像头 CCD II 所采集的图像帮助操作者确定是否切断果梗。

(a) Scene of CCD I
(b) Scene of CCD II

Fig.6 - The scenes on the LCD

3) Master–slave mapping

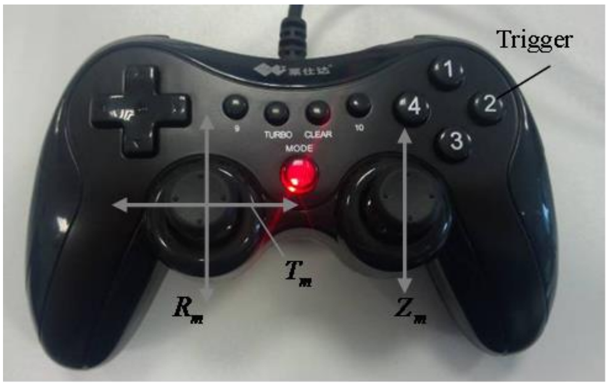
The apple harvest robot operates in a master–slave style. The master device (Litestar) is a commercial joystick, as shown in Figure 7(a). It is composed of two sticks and several buttons. The left stick can produce two

3) 主-从映射

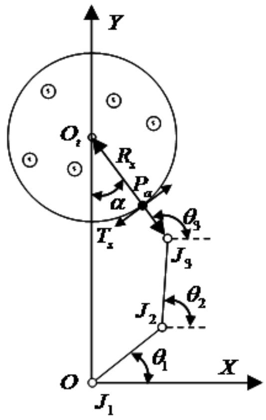
苹果采摘机器人的工作模式为主-从遥操作形式，主控制设备(Litestar)是商用手柄，如图 7（a）所示。该控制手

planar absolute values marked as R_m and T_m. The right stick is utilized to generate absolute control value Z_m. R_m used is to control the distance of P_a to O_t, which is marked as R_s, as shown in Figure 7(b). T_m is employed to control the direction of arm J_3P_a, which is labeled as T_s, and keep lines J_3P_a and P_aO_t collinear and rotating together relative to O_t. Z_m of the joystick is used to directly control the translational joint Z_s of the slave manipulator in Figure 2(a). Button 2 of the joystick functions as a switch to set off the grasper and cutter mechanism of the end effector.

柄由两个控制操纵杆和若干按钮构成，左操纵杆可输出两个平面绝对值信号，标记为 R_m 和 T_m 。右操纵杆可产生绝对控制信号 Z_m 。 R_m 可控制 P_a 到 O_t 的距离，该距离在图 7（b）中标为 R_s 。 T_m 用来控制机械臂 J_3P_a 方向，该方向标为 T_s ，这个方向应保证线段 J_3P_a 和线段 P_aO_t 处于共线，即保证它们绕着树干中心 O_t 转动。控制手柄信号 Z_m 用来控制图 2（a）中的关节 Z_s 。控制手柄的按钮 2 作为触发开关启动末端工具的夹持器和切刀机构的动作。



(a) Master joystick



(b) Slave manipulator

Fig.7 - Master-slave mapping

The master–slave control system operates in a continuous circulation mode. In the beginning of each control loop, the output of the master joystick is captured by the PC and analyzed to control joint angles θ_1, θ_2, and θ_3 of the slave manipulator as in the following equation.

主-从控制系统工作的时候处于一种连续循环状态。在每一个工作循环的初始，PC 机获取主控制手柄的输出信号，该输出信号经过处理后用来控制从操作机器人机械臂的关节角度 θ_1 、 θ_2 和 θ_3，公式为：

$$\begin{bmatrix}\Delta\theta_1\\\Delta\theta_2\\\Delta\theta_3\\\Delta z\end{bmatrix}=J\left[R_s,\alpha\right]\cdot\begin{bmatrix}\Delta R_m\\\Delta T_m\\\Delta Z_m\end{bmatrix} \tag{6}$$

where $J\left[R_s,\alpha\right]$ is a mapping function derived from Equations (2) and (3). $\left[\Delta\theta_1,\Delta\theta_2,\Delta\theta_3,\Delta z\right]^T$ are the micro displacements of slave manipulator joints; they are sent to the PCI motion controller to determine and drive the motors of the manipulator within the present control loop.

这里 $J\left[R_s,\alpha\right]$ 是由公式（2）和公式（3）得到的映射函数。$\left[\Delta\theta_1,\Delta\theta_2,\Delta\theta_3,\Delta z\right]^T$ 是从操作机器人机械臂的关节微位移，这些微小位移量传到 PCI 运动控制卡后作为本次控制周期内的目标位置，用来控制驱动机械臂的关节电机。

RESULTS AND DISSCUSSION

Before the harvest experiment in the orchard, a phantom test was conducted in a laboratory to initially evaluate the master–slave robot system. Three aspects of the system, namely, the manipulator route, gesture adjustment, and apple capture ability of the end effector, were considered.

结果分析与讨论

机器人在进行果园测试之前，为了对主-从式采摘机器人进行初步的测试，本文在实验室进行了仿体实验测试。机器人从操作臂的采摘路径，末端执行器的姿态调整和欠驱动末端工具的果实采摘是测试的三个方面。

Arc route of the manipulator

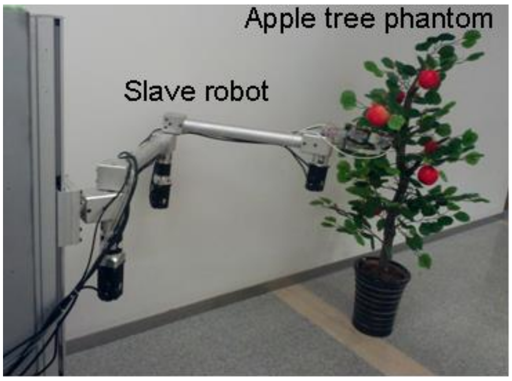
To validate the concept of the modified SCARA manipulator, a circle arc with $r=0.5m$ was set as the harvest route for the robot. Within the range of $\alpha\in[-\pi/3,\pi/3]$, the manipulator can point the end effector to the tree trunk along the arc route as expected,

机械臂弧形轨迹

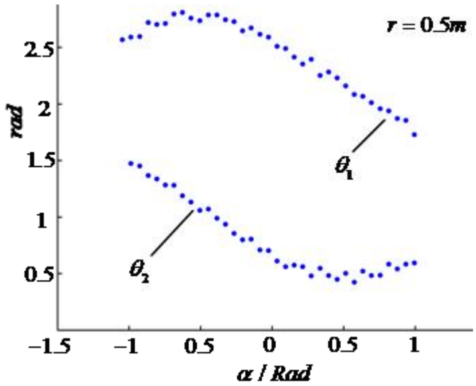
为了证明本文改进型 SCARA 机械臂的概念，本文设定了一个半径 0.5m 的圆弧段作为采摘机器人机械臂的动作路径。在 $\alpha\in[-\pi/3,\pi/3]$ 区域内，从操作机械臂可按照预期将末端执行器沿着弧形轨道移动，并保证末端工具始终

as shown in Figure 8(a). The joint angles of R1 and R2 during this process are plotted in Figure 8(b).

指向树干方向，如图 8（a）所示。在此过程中，关节 R_1和 R_2的变化情况如图 8（b）所示。



(a) Phantom test



(b) Joint variation of slave manipulator

Fig.8 - Test of the slave manipulator

Gesture adjustment of the end effector

Joints R4 and R5 are equipped with potentiometers (5kΩ) to measure the variation of joint angles θ_4 and θ_5 as the end effector approaches the target apple. With the branch of angles $\beta=\pi/6$, $\delta=\pi/4$, the plane of the end effector frame is rotated to adapt to the branch gesture.

The variations in θ_4 and θ_5 are indicated in Figure 9. The passive joints for the end effector basically achieved the expectation for gesture adjustment. Owing to a mechanical reason, the effects of the two passive joints are not similar. Joint R4 is more sensitive to rotation by the gradient branch, and joint R5 has more friction and behaves below expectations.

末端工具的姿态调整

关节 R4 和关节 R5 分别安装了电位器（5kΩ）来测量角度 θ_4 和 θ_5 在末端执行器趋近目标苹果过程中的变化情况。本实验目标苹果枝条的角度约为 $\beta=\pi/6$, $\delta=\pi/4$，机器人末端工具的方形框架平面转动以适应该枝条姿态。

图 9 显示了关节角度 θ_4 和 θ_5 的变化情况。从测试结果可看到末端执行器的被动式关节可基本达到调整其姿态的目的。由于机械系统的原因，两个关节的姿态调整效果并不完全相同。关节 R_4更为敏感容易转动，关节 R_5由于自身的摩擦较大，因此其姿态调整能力未能达到其应有的预期效果。

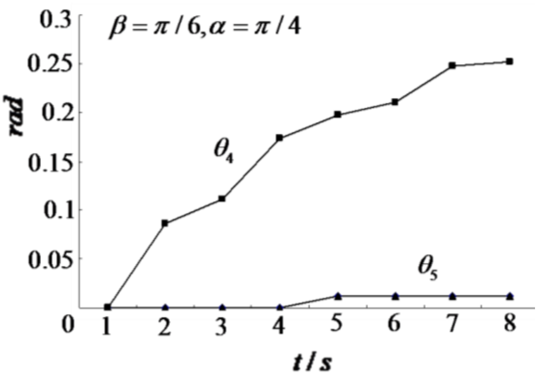


Fig.9 - Angle variation of θ_4 and θ_5

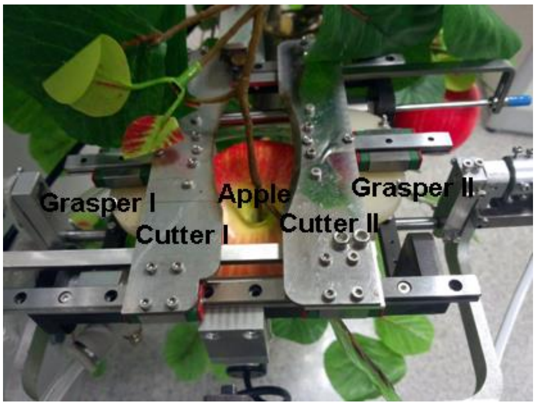


Fig.10 - Grasp and cut the apple phantom

Apple harvest with the end effector

Apple harvest is directly carried out with the end effector. The maximum diameter of the phantom target apple is approximately 80 mm. The motion of the graspers and cutters are driven pneumatically in an under-actuated mode. The cylinders for the end effector work with a pressure of 0.6 MPa, and the maximum travel distance of the cylinder is 60 mm. Given the dimension of the other mechanical parts, the maximum apple diameter that the end effector can deal with is 80 mm, as shown in Figure 10.

末端工具采摘苹果

苹果的采摘实验由机器人末端工具直接完成。仿体目标苹果的最大直径约为 80mm。末端工具的夹持器和切刀的动作由气缸以欠驱动的方式推动完成。末端工具所用的气缸正常工作压力为 0.6Mpa，该气缸的最大位移行程为 60mm。由于末端工具其他机械零件的尺寸影响，本文机器人末端工具目前可采摘的最大苹果直径为 80mm，如图 10 所示。

CONCLUSIONS

To address the reduction in available labor in orchards, a novel harvest robot system that operates in a master–slave style was comprehensively studied. The robot system integrates human judgment and the precise motion of the slave robot to mechanize apple harvest. After introducing the working environment, the mechanical design for the slave robot was presented. The slave robot is composed of an under-actuated end effector and a modified SCARA manipulator. An additional rotation joint is set to an ordinary SCARA arm to point the end effector at the tree trunk during harvest. The dexterity of the manipulator was studied, and a preferred position was obtained. The passive joints on the end effector adjust its capture gesture according to the branch of the target apple. The control system was established based on a PC platform to integrate the pieces of equipment. The operator obtains video feedback from a CCD embedded inside the end effector. A joystick is employed as the master device to generate the control command and further control the slave robot. Test results show that the new robot system meets the initial design expectation in terms of the modified SCARA manipulator, gesture adjustment of passive joints, and apple harvest with the end effector.

Nevertheless, the control system and end effector need to be improved. For the control system, a dedicated system instead of a PC platform is preferred in the field test and final usage, which will be conducted in the next stage. As for the end effector, the mechanical design needs to be modified for better weight and dimension to be capable of harvesting bigger apples than those harvested at present.

结论与研究展望

为了适应果园中劳动力越来越少的社会发展现状，本文详细研究了一种用于果实采摘的新型主-从控制模式机器人系统。这个机器人集成了人工判断和机器人精确运动能力来实现机械化采摘作业。本文首先分析了采摘的工作环境，之后介绍了从操作机器人的机械结构设计。从操作机器人由欠驱动末端工具和改进的 SCARA 机械臂构成。从操作机械臂在常规 SCARA 结构末端增加了一个转动关节以使末端工具在采摘过程中始终指向树干。本文分析了采摘机器人从操作机械臂灵活性并得到了其优选初始采摘位置。末端工具上设置的被动关节可根据苹果所在枝条方位调整末端工具的姿态。目前该采摘机器人的控制系统建立在 PC 平台上并集成了各种相关设备。操作人员从内置于末端执行器的两个 CCD 摄像头获取机器人采摘果实的实时视频信息。本文采用控制手柄作为主操作设备发送命令控制从操作机器人的动作。初步测试结果显示本文设计的新型采摘机器人系统可达到预期的目标，包括改进的 SCARA 机械臂，末端工具姿态调整及欠驱动末端工具的果实采摘动作。

目前本文机器人在控制系统及末端工具两个方面仍需改进。对于控制系统，在下一阶段进行户外测试及最终应用的时候应使用专用控制系统而不是基于 PC 平台的开放式系统。对于机器人的末端工具的机械结构设计，需在重量和尺寸等方面对其进行优化，使其可采摘比现在更大尺寸的果实。

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