A KINEMATIC ANALYSIS AND SIMULATION BASED ON ADAMS FOR EGGPLANT PICKING ROBOT
/
基于 *ADAMS* 的茄子采摘机器人运动学分析与仿真

Prof. Peng Zhang[1], Prof. Jian Song[1], Stud. Shenglei Gong[1], Prof. Bo Jiang[2] , Prof. Muham, D. Polar[3]

[1] School of Machanical-electronic and Vehicle Engineering in University of Weifang, Weifang / China; [2] College of Medicine, University of Saskatchewan, Saskatchewan / Canada; [3] Advanced Machine Engineering and Automation Center of CCB Corp, Singapore

Tel: +86-536-8785603; E-mail: sjian11@hhit.edu.cn

Abstract: *Eggplant picking robot is a type of complex optical-mechanical-electrical equipment in greenhouse environment. Its structure and control are more exigent than traditional industrial robot. Optimization design method was utilized for the design of the eggplant picking robot body structure parameters in accordance with the eggplant growth and distribution space. In order to determine the spatial position relationship between the eggplant picking robot components and the end effector, the theoretical model of robot was established by virtue of Denavit-Hartenberg approach and the positive solution of the kinematic equation is obtained. Premultiplication decoupling of* A_i^{-1} *and matrix* ${}^0T_4$ *were adopted to solve inverse kinematic solution with the help of Matlab software. Pro/E software was used to establish 3-D simulation model, and ADAMS (Automatic Dynamic Analysis of Mechanical Systems) simulation software was imported for the kinematics simulation analysis. It was indicated by the simulation results that the kinematic model established by D-H approach reflects the real motion conditions of the robot, and both the positive and inverse kinematic solutions are correct. Structure of four degrees freedom eggplant picking robot was reasonable, it could meet the requirements of eggplant picking in the greenhouse cultivation pattern.*

Keywords: *Eggplant picking robot, ADAMS, Kinematic simulation, four degrees of freedom, Agricultural machinery*

INTRODUCTION

Harvesting or picking is the most effort-requiring and time-consuming procedure in eggplant production operation, which, according to statistics, approximately accounts for from 50% to 70% of all the amount of working [7]. Moreover, it requires timely picking to guarantee the product quality, making it as the hardest work in the whole operation [5]. With the rapid development of agricultural mechanization, considering the problems with aging of population and the decrease of agricultural labor force, it is more and more significant to research and develop fruit and vegetable picking robot [8]. Since the mid 1980s, researches on automatic fruit and vegetable picking have been started in the western developed countries represented by Japan, and some vegetable picking robots with certain intelligence were experimented and developed [9,10,11]. In the intelligent tomato picking robot end effector based on multi-sensor information fusion and open control system designed by Jizhan Liu, etc, the vacuum chuck device of the execution system could separate the fruit from the fruit bunch, its finger gripper mechanism could grasp the tomato firmly, and the fruit stem disconnecting device could cut off the fruit stem with laser [4]. Peng Cui proposed a bionic manipulator which was applied to the apple picking robot end effector and the simple fixture was replaced with the tendon-driven bionic manipulator, enhancing the adaption of the end effector to grab apple in complex environment [6]. Wei Lu designed

摘要： *茄子采摘机器人是一种工作在复杂的温室中的复杂的光机电一体化设备，它的结构和控制系统比一般的工业机器人要求更加苛刻。本文根据茄子的生长分布空间，利用优化设计方法进行了茄子采摘机器人本体结构参数的设计。借助 Denavit-Hartenberg 法建立了采摘机器人的理论模型，得到机器人的运动学方程的正解，确定机器人各运动构件与末端执行器在空间位置之间的关系。采用* A_i^{-1} *与矩阵* ${}^0T_4$ *左乘解耦，借助 Matlab 软件求出运动学逆解。利用 pro/e 建立茄子采摘机器人三维模型，导入 ADAMS 仿真软件进行运动学仿真分析。仿真结果表明：D-H 法建立的运动学模型反映了采摘机器人的真实运动情况，采摘机器人运动学正逆解正确。设计开发的 4 自由度采摘机器人结构设计的合理，能够满足温室栽培模式下茄子采摘的要求。*

关键词: *茄子采摘机械手， ADAMS，运动学仿真，四自由度，农业机械化*

引言

在果蔬生产作业中，收获采摘是费力最大、耗时最多的一个环节。据统计，约占整个作业量的 50～70％[7]。而且为了保证产品的质量，必须做到适时采摘，是整个作业中最辛苦的工作[5] 。随着人口的老龄化和农业劳动力的减少，研究开发果蔬采摘机器人具有越来越重要的意义[8]。从 20 世纪 80 年代中期开始，日本等西方发达国家开始了自动化收获水果蔬菜的研究，试验开发了一些具有一定智能的蔬菜采摘机器人[9,10,11]。刘继展等设计的基于多传感器信息融合和开放式控制的智能型番茄采摘机器人末端执行器，其执行系统的真空吸盘装置使果实从果束中分离, 手指夹持机构对番茄可靠抓持,果梗切断装置利用激光对果梗进行切断[4]。崔鹏等提出了一种应用于苹果采摘机器人末端执行器的仿生机械手，采用腱传动式仿生机械手取代了简单的夹具,提高了末端执行器在复杂环境中抓取苹果的适应性[6]。卢伟等针对柑橘树冠较高,果梗木质化程度高、短且坚硬的特点,设计了新颖的柑橘采摘机器人手臂和末端

an original orange picking robot arm and end effector, considering the tall crown of citrus tree, and the high degree of lignification of its short and stiff fruit stem [12].

However, the above-described robots are still far from practical application owing to the influence factors from technology, market, and price and so on[1]. It can be seen from the analysis of literatures at home and abroad that these researches on the picking robot are mainly focused on identifying, positioning and sorting the target fruit via the vision system [14], while there are rare researches on the basic machine of the picking robot [3].

Robot kinematics is an important constituent part of robotics, whose purpose is to establish the relationships among spatial positions of the robot components and end effectors so as to provide theoretical basis and technical parameters for the optimized control of the robot [2]. However, it requires establishing mathematic model of the robot arm movements to finish most of these tasks, which have tedious process, heavy computation burden, and are error-prone [13]. In this paper, ADAMS simulation software was used for kinematics analysis and simulation study on the eggplant picking robot, which could solve the above-mentioned problem in the course of kinematics analysis in traditional multi-rigid-body system and meanwhile show intuitively the kinematic performance of the robot movement components in the diagram and simulation animation form, providing a powerful guarantee for follow-up programming of robot motion trail and verification of the structure parameter rationality.

MATERIALS AND METHODS

Structure parameter of picking robot

The articulated robot with four degrees of freedom is selected to be the basic machine of the picking robot because the picking object of the eggplant picking robot is the eggplant whose fruit is cylindrical.

The robot structure parameters mainly include the robot arm length and the rotation angle scope,etc. and these parameters determine the work space of the robot. The optimization design of the eggplant picking robot structure parameters is to use optimal method to analyze and calculate the mechanism size in accordance with the eggplant growth and distribution space.

The purpose of the optimization design is to obtain the most compact mechanical structure. The upper arm length x_1 and the forearm x_2 of picking robot are regarded as the design variables, and the actually work space of picking robot is optimization objective. The objective function is shown as follow:

执行器[12]。

但是由于技术、市场和价格等因素的影响，离实际应用还有很大距离[1]。综合国内外研究文献，对于采摘机器人的研究大多集中在视觉系统对果实采摘与分拣目标的识别和定位上[14]，而对于采摘机器人机械本体的研究较少[3]。

机器人运动学是机器人学的重要组成部分，研究机器人运动学的目的就是建立机器人各运动构件与末端执行器在空间位置之间的关系，为机器人的优化控制提供理论依据和技术参数[2]。但完成这些工作大都需要建立机器人手臂运动的数学模型，过程繁琐、计算量大、容易出错[13]。本文运用 ADAMS 仿真软件对茄子采摘机器人进行运动学分析与仿真研究，解决了传统多刚体系统运动学分析过程所产生的上述问题，同时能将机器人各个运动机构的运动性能通过图表和模拟动画的形式直观表现出来，为后续机器人的运动轨迹进行规划，结构参数的合理性验证提供有力保证。

材料与方法

采摘机器人结构参数

由于茄子采摘机器人的采摘对象是茄子，其果实呈圆柱形。所以，选用具有四自由度关节式机器人作为采摘机器人的机械本体。

机器人结构参数，主要包括机械臂的长度及其转角范围等。机器人的结构参数决定了机器人的工作空间。茄子采摘机器人结构参数的优化设计是根据茄子生长分布空间，利用优化方法进行机构尺寸分析与计算。

优化设计的目的是得到最紧凑的机械结构。优化设计变量为大臂长 x_1，小臂长 x_2，优化目标是采摘机器人的实际工作空间。目标函数如下式所示：

$$\min f(X)=\frac{1}{4}\pi(x_1+x_2)^2+\frac{1}{2}\pi x_2^2-\frac{1}{2}(x_1^2+x_2^2-2x_1x_2\cos 30^{\circ}) \tag{1}$$

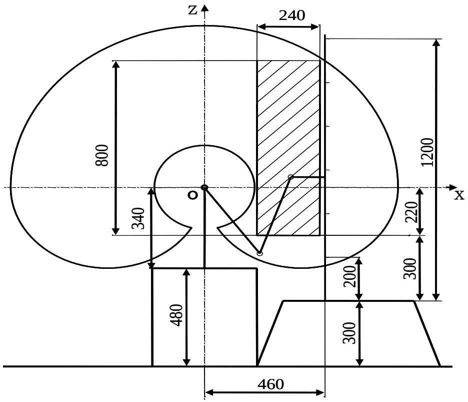


Fig. 1 - The working space of eggplant picking robot

The working space of eggplant picking robot is shown as Fig.1.The constraint condition is that it should be the minimum value under the required rectangle work space conditions, i.e., the rectangle work space required by the picking manipulator operation must be confined in the real work space. Using the optimization toolbox of Matlab software for programming, calculating and operation, the optimization result can be obtanined as follow:

图 1 表示了茄子采摘机器人实际需要的工作空间。约束条件为使其在包容所要求的矩形工作空间条件下为最小值，就是必须使采摘机械手作业要求的矩形工作空间包含在实际工作空间内。使用 Matlab 软件的优化工具箱进行编程计算，运行得到优化结果为：

$$X=[312,335] \tag{2}$$

With an overall consideration, it confirms that $x_1=x_2=350mm$. The height of pedestals is 340mm, rotation angle of the waist θ_1 is ±180° ; the upper arm length x_1 is 350mm, rotation angle θ_2 is ±90° ; the forearm length x_2 is 350mm, rotation angle θ_3 is ±150°

综合考虑，确定 $x_1=x_2=350mm$ 。最后确定底座高为 340mm，腰部回转角 θ_1 为±180°；大臂长 350mm，回转角度 θ_2 为±90°；小臂长 350mm，回转角度 θ_3 为±150°。

Model based on kinematic theory

D-H model is an approach proposed by Denavit-Hartenberg for the expression and modeling of robot joints and connecting rods, which adopts 4×4 homogeneous transformation matrix to describe the spatial position relationship of the adjacent robot rod pieces, thus translates the complicated kinematic question into 4×4 equivalence transformation matrix of the coordinate system of the end effectors and reference coordinate system. As shown in Fig.2, the coordinate system of connecting rods of 4-DOF picking robot is established according to D-H approach.

运动学理论模型

D-H 模型是 Denavit 和 Hartenberg 提出的对机器人关节和连杆进行表示和建模的方法。它采用 4×4 齐次变换矩阵来描述相邻机器人杆件的空间位置关系，将复杂的运动学问题转化为末端执行器的坐标系与参考坐标系的 4×4 等价变换矩阵。如图 2 所示，按照 D-H 法建立四自由度采摘机器人各连杆坐标系。

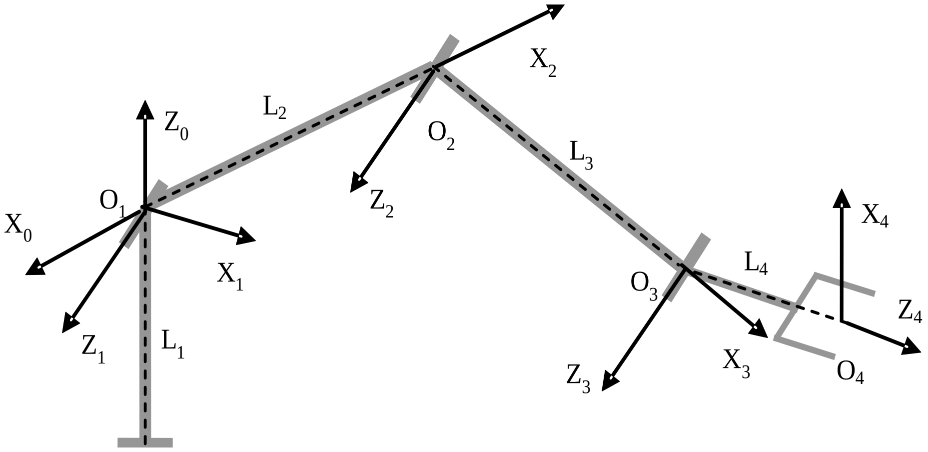


Fig. 2 - Coordinate system of connecting rods of eggplant picking robot

Matrix A_i represents 4-order homogeneous transformation matrix between the connecting rod coordinate systems, and is usually expressed as follow:

矩阵 A_i 表示连杆坐标系之间的 4 阶齐次变换矩阵，一般表达为：

$$A_i=Rot(z,\theta_i)\times Trans(a_i,0,0)\times Rot(x,\alpha_i)=\begin{bmatrix}\cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i\\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i\\ 0 & \sin\alpha_i & \cos\alpha_i & d_i\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{3}$$

The parameters of the picking robot joint connecting rods can be obtained according to the coordinate system of connecting rods of picking robot in Fig.2, as shown in Table1.

依据图 2 建立的采摘机器人各连杆坐标系可以得到各关节连杆参数，如表 1 所示。

Table 1

Connecting rod parameters of picking robot joint

i	θ_i	α_i	a_i	d_i	Variable Range	Link parameters(mm)
1	θ_1	90°	0	0	±180°	L_1=340mm
2	θ_2	0	L_2	0	±90°	L_2＝350mm
3	θ_3	0	L_3	0	±150°	L_3＝350mm
4	θ_4	90°	L_4	0	±120°	L_4＝180mm

In Table1, θ_i is the included angle between the two common perpendiculars in a plane perpendicular to joint i axis. a_i is the distance of two end joints from i to $i+1$ along the common perpendicular. α_i is the included angle between the two joint axes in a plane perpendicular to a_i . d_i is the distance of the two common perpendiculars along joint i axis. L_1 is the height of stand column of the solid of revolution pedestal, L_2 the length of the upper arm, L_3 the length of the fore arm, while L_4 is the distance from the central point of the hand gripper to the wrist reference point.

在表 1 中，θ_i 是垂直于关节 i 轴线的平面内两个公垂线的夹角。a_i 是是两端关节 i 和 $i+1$ 沿公垂线的距离。α_i 是垂直于 a_i 的平面内两个关节轴线的夹角。d_i 是沿关节 i 轴线的两个公垂线的距离。L_1 回转体底座立柱高度，L_2 为大臂的长度，L_3 为小臂长度，L_4 为手爪中心点到腕部参考点的距离。

Positive kinematic solution

The positive kinematic solution is to obtain the pose of the end effector in the given coordinate system with known joint variables and geometric parameters of the rod pieces. The expression (4) of the end effector pose of the picking robot in the reference coordinate system can be obtained when the parameters in Table 1 are substituted into formula (3).

运动学正解

机器人的运动学正问题是已知杆件的关节变量和几何参数求末端执行器在给定坐标系中的位姿。将表 1 中的参数代入公式（3）可以得到采摘机器人末端执行器在基坐标系中的位姿表示式（4）。

$$ {}^0T_4 = A_1A_2A_3A_4 = \begin{bmatrix} -C_1S_{234} & S_1 & C_1C_{234} & C_1(C_{234}L_4+C_{23}L_3+C_2L_2) \\ -S_1S_{234} & -C_1 & -S_1C_{234} & S_1(C_{234}L_4+C_{23}L_3+C_2L_2) \\ C_{234} & 0 & S_{234} & S_{234}L_4+S_{23}L_3+S_2L_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Wherein, $C_1=\cos\theta_1$, $S_1=\sin\theta_1$, $C_{23}=\cos(\theta_2+\theta_3)$, $S_{23}=\sin(\theta_2+\theta_3)$, $C_{234}=\cos(\theta_2+\theta_3+\theta_4)$, $S_{234}=(\theta_2+\theta_3+\theta_4)$.

The coordinate system of the end effector is established with the hand gripper center as the origin of coordinates. Axis Z is represented with vector $\bar{a}$ in the direction that the end effector approaches object, axis Y is represented with vector $\bar{o}$ in the direction of the connecting line of the two fingers, and axis X is determined to be represented with vector $\bar{n}$ in accordance with the right-hand rule. The end effector posture is determined by vectors $\bar{n}$, $\bar{o}$ and $\bar{a}$. The gripper's posture is ensured by the rotation vector ${}^0_TR$, as shown in expression (5).

其中，$C_1=\cos\theta_1$，$S_1=\sin\theta_1$，

$C_{23}=\cos(\theta_2+\theta_3)$，$S_{23}=\sin(\theta_2+\theta_3)$，

$C_{234}=\cos(\theta_2+\theta_3+\theta_4)$，$S_{234}=(\theta_2+\theta_3+\theta_4)$。

取手抓中心为坐标原点，建立末端执行器坐标系。Z 轴取在末端执行器接近物体方向用矢量 $\bar{a}$ 表示，Y 轴设在两手指的连线方向用矢量 $\bar{o}$ 表示，X 轴根据右手法则确定用矢量 $\bar{n}$ 表示，矢量 $\bar{n}$ 、$\bar{o}$ 和 $\bar{a}$ 确定末端执行器的姿态。手爪的姿态由旋转矩阵 ${}^0_TR$ 规定，如式（5）所示。

$$ {}^0_TR = \begin{bmatrix} \bar{n} & \bar{o} & \bar{a} \end{bmatrix} \tag{5}$$

The gripper's position is stipulated by its origin of coordinates and described with position vector $\bar{p}$. The four vectors added to scale factor are expressed in a 4×4 homogeneous matrix as shown in expression (6).

手爪的位置由其坐标系的原点规定，用位置矢量 $\bar{p}$ 描述。将这四个矢量加入比例因子写成 4×4 齐次矩阵如式（6）所示。

$$ {}^{0}T_{4}=\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6} $$

Inverse kinematic solution

The inverse question of robot kinematics is to obtain the joint variables with the known pose of the end effector in the given coordinate system and the known geometrical parameters of the rod pieces. There are many methods for inverse robot kinematic solution. In this paper, premultiplication decoupling of A_1^{-1} and matrix ${}^{0}T_{4}$ is adopted to the solution with the help of Matlab software, and hence:

运动学逆解

机器人运动学的逆问题是已知末端执行器在给定坐标系中的位姿和杆件的几何参数求关节变量。求解机器人运动学逆解的方法很多，本文采用 A_1^{-1} 与矩阵 ${}^{0}T_{4}$ 左乘解耦，借助 Matlab 软件求解得：

$$ \begin{cases} \theta_1=\arctan\left(\dfrac{P_y}{P_x}\right) \\ \quad =\arctan\left(\dfrac{P_y}{P_x}\right)+180^{\circ} \\ \theta_2=-\arctan\left(\dfrac{m}{n}\right)\pm\arctan\dfrac{m^2+n^2-L_3^{\,2}+L_2^2}{2L_2\sqrt{n^2+m^2}-\left(\dfrac{m^2+n^2-L_3^2+L_2^2}{2L_2}\right)} \\ \theta_3=\pm\arctan\dfrac{\sqrt{4L_3L_2-(n^2+m^2-L_3^2-L_2^2)}}{n^2+m^2-L_3^2-L_2^2} \\ \theta_4=-\left(\theta_3+\theta_2\right) \end{cases} \tag{7} $$

It can be observed from expression (7) that θ_1, θ_2, θ_3 have two solutions respectively, there exist 8 different sets of inverse solutions in this mechanical system, which are usually selected according to the principle of the shortest route or more small movement of joint and less movement of large joint.

由式（7）我们可以观察到 θ_1, θ_2, θ_3 分别有两个解，即此机械系统存在 8 组不同的逆解，通常根据最短行程或多移动小关节少移动大关节的原则选择。

RESULTS ANALYSIS AND DISCUSSION WITH KINEMATIC SIMULATION

Establishment of 3-D simulation model

The mechanical structure of the 4- DOF picking robot consists of the pedestal, the waist between the upper arm and electrical machine box, the elbow between the upper arm and the fore arm, the wrist between the fore arm and the end effector, and the end effector. The interconnection of the components forms the four rotating joints, namely, waist, shoulder, elbow, and wrist joints. The three preceding joints determine the position of the end effector in the work space, while the last joint determines its pose. Although ADAMS software possesses powerful kinematic and dynamic solution function, it is comparatively weak in the aspect of 3-D solid model building. Therefore, the robot virtual prototype is built in virtue of pro/E software which has powerful 3-D solid model building function in line with the picking robot structure. During the course of modeling, the main solid components are retained while such detailing components as the circular beads, chamfers, gears, bearings and electrical machine are ignored on the premise that the simulated analysis requirements are satisified, and 3-D simulation model of the eggplant picking robot is built as the following Fig.3.

结果分析与讨论

3-D 仿真模型的建立

四自由度采摘机器人机械结构由底座、大臂与电机箱体之间的腰部、大臂与小臂之间的肘部、小臂与末端执行器之间的腕部、末端执行器构成，构件之间相互连接形成的腰、肩、肘、腕 4 个旋转关节，前三个关节决定末端执行器在工作空间的位置，后一个关节决定末端执行器在工作空间的姿态。虽然 ADAMS 软件具有强大的运动学动力学求解功能但在三维实体建模方面相对薄弱，因而根据采摘机器人结构借助三维实体建模功能强大的 pro/e 软件来构建机器人虚拟样机。建模过程中在满足仿真分析要求的前提下，忽略模型的圆角、倒角、齿轮、轴承、电机等细化的部件，保留主要的实体部件，建立茄子采摘机器人三维仿真模型如下图 3。

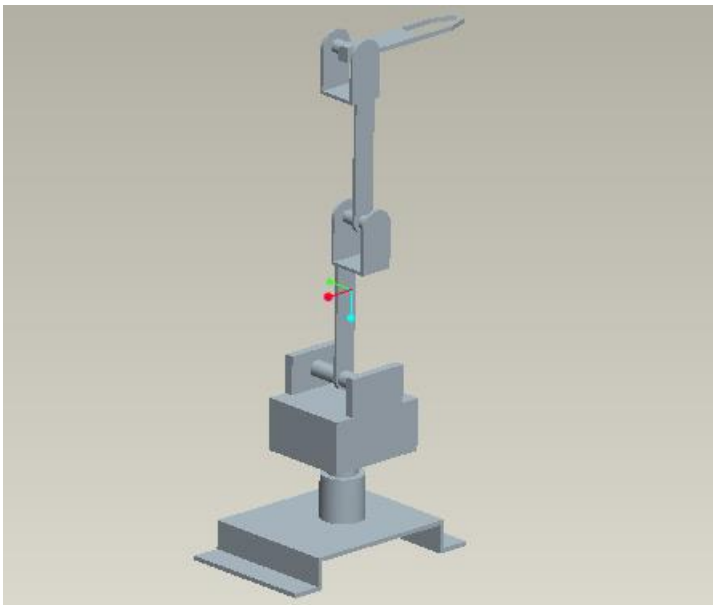


Fig. 3 - 3-D simulation model of the picking robot

Pretreatment for simulation

The model built in pro/E software is saved as intermediate format parasolid, and then is imported into ADAMS simulation software. ADAMS motion toolkit is used to add constraint to the imported 3-D simulation model as follows:

Fixed joints are added to between the bed and the ground, revolute joints are added to the waist, shoulder, and elbow and wrist part.

ADAMS drive toolkit is used to add drive to the imported 3-D simulation model as follows:

仿真预处理

将在 pro/e 中建立的模型保存为中间格式 parasolid，然后导入 ADAMS 仿真软件中。运用 ADAMS 运动工具集对导入的三维仿真模型添加约束，如下：

底座与大地之间添加固定副，腰、肩、肘、腕部添加旋转副。

运用 ADAMS 驱动工具集导入的三维仿真模型添加驱动，如下：

$$waist(time) = 180*\sin(75d*time - 90d) + 180d \tag{7}$$

$$shoulder(time) = -45*\sin(180d*time - 90d) - 45d \tag{8}$$

$$elbow(time) = -30d*\sin(145d*time - 90d) - 30d \tag{9}$$

$$wrist(time) = 80d*\sin(145d - time - 90d) + 80d \tag{10}$$

With the above mentioned tasks completed, the virtual prototype model of the picking robot is established as in Fig.4.

完成上述各项工作就建立了采摘机器人虚拟样机模型，如图 4 所示。

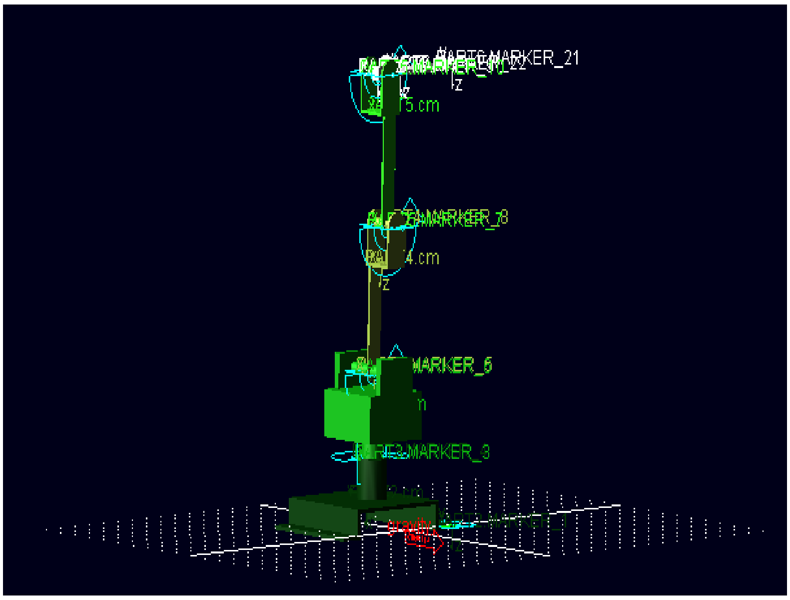


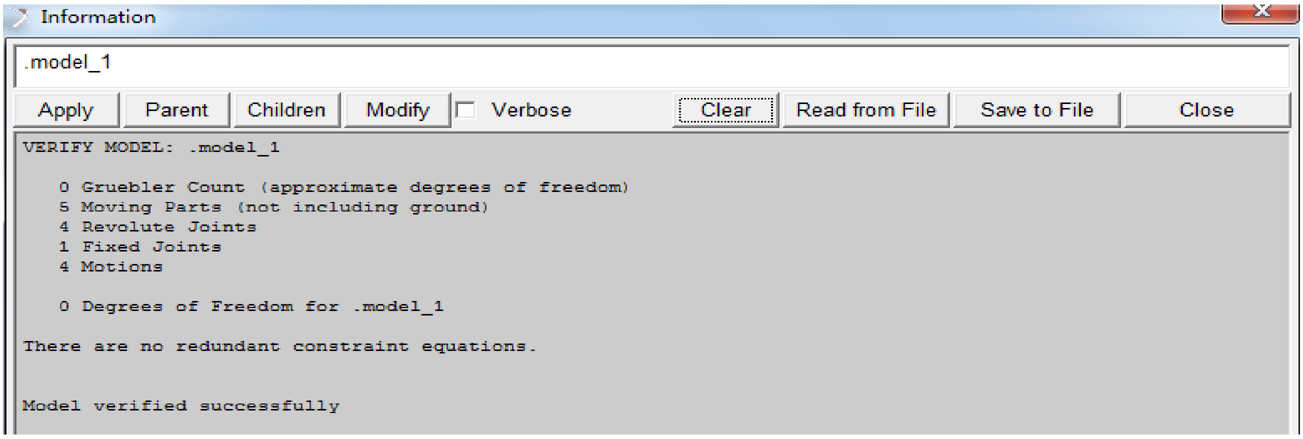
Fig. 4 - Virtual prototype model of the picking robot

Model Self-test

Before the simulating calculation, inquire the degree of freedom of the system, the components with mass undefined and over-constraint through “model verify” function in “tools” menu. Information such s as “model verified successfully” and “degrees of freedom for model..1” are displayed as shown in Fig.5, which indicates the modeling is correct and the kinematic simulation can be conducted for the next step.

模型自检

在仿真计算之前，通过 tools 菜单中的 model verify 功能对系统的自由度、未定义质量的构件和过约束情况进行查询，如图 5 信息显示“model verified successfully”和“0 degrees of freedom for model.1”说明建立模型正确，可以进行下一步的运动学仿真。



```
VERIFY MODEL: .model_1

   0 Gruebler Count (approximate degrees of freedom)
   5 Moving Parts (not including ground)
   4 Revolute Joints
   1 Fixed Joints
   4 Motions

   0 Degrees of Freedom for .model_1

There are no redundant constraint equations.


Model verified successfully
```

Fig. 5 - Self-test interface

Simulation analysis

The mark point mark-21, which is fixed joint to the centroid part6.cm of the end effector, is taken as the object of study. To study its position relative to fixed coordinate system, the rotational speed of each joint is set as $30^\circ/s$, simulation time is set as 5s, and simulation calculation is performed. After the simulation is completed, “postprocess” interface for post-processing is entered as shown in Fig.6.

仿真分析

以固连在末端执行器质心 part6.cm 上的标记点 mark-21 为研究对象，研究其相对于固定坐标系的位置，设定每个关节的转动速度为 $30^\circ/s$，设定仿真时间为 5s，进行仿真运算。仿真结束后进入 postprocess 界面后处理，如图 6 所示。

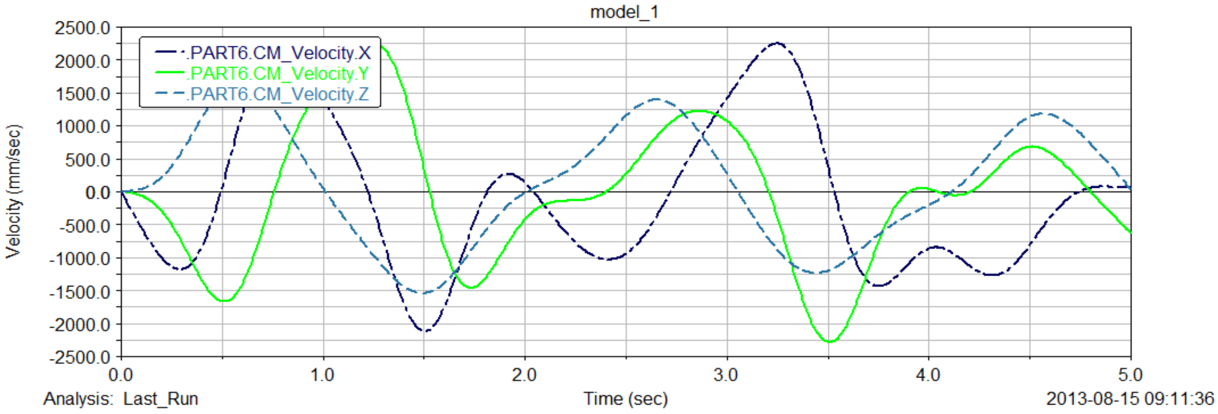


Fig. 6 - Speed graph

The solid line, the long broken line and the short broken line in the figure represent respectively the speed in the X, Y and Z directions. It is observed from Fig.6 that the change-in- speed is smooth and steady at the centroid part6.cm of the end effector, which does not generate strenuous vibration phenomenon during the whole course of movement, meeting the task requirements.

图中实线表示 X 方向的速度，长虚线表示 Y 方向速度，短虚线表示 Z 方向的速度，从图 6 中可以看出末端执行器质心 part6.cm 处速度变化相对平稳，末端执行器在整个运动过程中没有产生剧烈震动现象，达到工作要求。

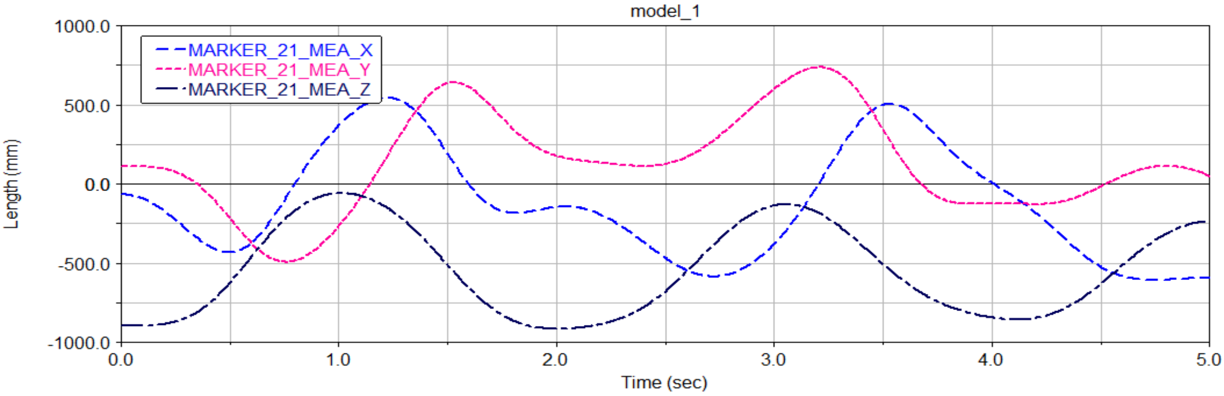


Fig. 7 - Displacement curve

As shown in Fig.7, the long broken line, the short broken line and the dot-dash line represent respectively the displacement in the X, Y and Z directions. In the postprocessing interface, it can be obtained by virtue of measurement button that the displacement of marker-21 at the initial position is x =-66mm, y=113mm, z=-897mm when t=0, which is consistent with the initial conditions of the manipulator. When the manipulator moves to the point of t=5s, the displacement of marker-21 on the three coordinates is x=-591mm, y=50, z=-236. Through test and verification, the theoretical calculation results from expression (4) and (5) in the D-H coordinate system are identical with the simulation results. The graph of Displacement and speed can reflect the real motion conditions and apply to picking robot control.

CONCLUSIONS

The application of picking robot in agricultural production can effectively reduce the number of harvest labors and increase the income of farmers, and also has great significance to improve the level of automation and intelligentization for agricultural machinery. In this paper, by applying virtual prototype technology into the design of agricultural machines, the product design cycle can be effectively shortened and product performance can be improved. As a modern design approach, the virtual design technology will have a significant impact to the development of agricultural equipment.

Eggplant picking robot with 4 degrees of freedom is developed in order to improve the economy and adaptability of the picking robot and it adopts 4-DOF open motion chain which is formed by connecting the waist, the upper arm, the fore arm and the wrist in series through the rotational joints. The robot completes the picking operation through movements of each joint. The objective of studying robot kinematics is to establish the relationship of the spatial position between the robot motion components and the end effector, to build mathematic model of the robot arm movements, and to provide theoretical basis and technical parameters for agricultural robotic control.

The optimized design of structure and path planning is based on the kinematics analysis of the manipulator. In order to determine the spatial position relationship between the robot components and the end effector, the theoretical model is established by virtue of Denavit-Hartenberg approach and the positive solution of the kinematic equation is obtained. Premultiplication

如图 7 所示，长虚线代表 X 方向的位移，短虚线代表 Y 方向的位移，点划线代表 Z 方向的位移，在后处理界面借助测量按钮出可得出当 t=0 时 marker-21 在初始位置的位移为 x =-66mm，y=113mm，z=-897mm，与机械手原始状态相吻合。当机械手运动到 t=5s 时 marker-21 在三个坐标上的位移是 x=-591mm，y=50，z=-236，经验证与 D-H 坐标系中联立式（4），（5）所得理论计算结果与仿真结果相同。位移和速度曲线图能够反映真实运动情况，可以应用于采摘机器人的控制。

结论

采摘机器人在农业生产中的应用，大量的减少了收获用工，增加了农民的收入，对于提高农业机械的自动化和智能化水平具有重要意义。本文的研究，将虚拟样机技术应用于农业机械的设计，缩短了设计周期，提高了产品质量。虚拟设计技术作为一种的现代化设计手段，必将对农业装备发展产生重要影响。

为了提高采摘机器人经济性和适应性，开发了 4 自由度茄子采摘机器人。其采用 4 自由度的开式运动链，由腰部、大臂、小臂和手腕通过转动关节串联而成。机器人是通过各个关节的运动，来完成采摘作业。研究机器人运动学的目的就是建立机器人各运动构件与末端执行器在空间位置之间的关系，建立机器人手臂运动的数学模型，为机器人的控制提供理论依据和技术参数。

机械手的运动学分析是结构优化设计、轨迹规划的基础。为了确定机器人各运动构件与末端执行器在空间位置之间的关系，借助 Denavit-Hartenberg 法建立了理论模

decoupling of A_i^{-1} and matrix ${}^0T_4$ is adopted to obtain inverse kinematic solution with the help of Matlab software. Pro/e software is used to establish 3-D simulation model of the picking robot, whose functions are experimented and tested by means of ADAMS, a dedicated virtual prototype develop tool. ADAMS simulation software is introduced for the kinematics simulation analysis. It is illustrated by the simulation results that the kinematic model established by D-H approach reflects the real motion conditions of the robot, and both the positive and inverse kinematic solutions are correct. The structural design of 4 DOF picking robot designed and developed is rational and it can meet the requirements of eggplant picking in the greenhouse cultivation pattern.

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REFERENCES

[1]. Arima S., Kondo N. (2009) – *Cucumber harvesting robot and plant training system*. Journal of Robotics and Mechatronics, vol. 11, no. 3, pp. 208-212;

[2]. Denavit, J., Hartenberg, R.S.. (1955) – *A Kinematic Notation for Lover pair Mechanisms based on matrices*. Journal of Applied Mechanics, vol. 22, no.6, pp.102-108;

[3]. Jian S., Tiezhong Z., Liming Xu. (2006) – *Research Actuality and Prospect of Picking Robot for Fruits and Vegetables*. Transactions of the Chinese Society for Agricultural Machinery, vol. 37, no.5, pp.158-162;

[4]. Jizhan L., Pingping L., Zhiguo L. (2008) – *Hardware Design of the End-effector for Tomato-harvesting Robot*. Transactions of the Chinese Society for Agricultural Machinery, Vol. 39, no.3, pp.109-112;

[5]. Kondo N., Monta M. Fujiura T.(1996) – *Fruit harvesting robot in Japan.* Advances in Space Research , vol.18, no.2, pp.181-184;

[6]. Peng C., Zhen C. Xiaochao. (2011) – *Statics Analysis of Apple-picking Robot Humanoid Manipulator*. Transactions of the Chinese Society for Agricultural Machinery, vol. 42, no. 2, pp.149-153;

[7]. Xiuying T., Tiezhong Z. (2005) – *Robotics for Fruit and Vegetable Harvesting: a Review.* Robot, vol.27, no.1, pp.90-96;

[8]. Shigehiko H., Katsunobu G., Yukitsugu I. (2002) – *Robotic Harvesting System for Eggplants*. Japan Agricultural Research Quarterly, vol.36, no.6, pp.163-168;

[9]. Song J. (2011) – *Target Identification Based on Improved Wavelet Edge Detection for Eggplant Picking Robot*. International Review on Computers and Software, Vol.6, no.5, pp.710-714;

[10]. Ting Y., Wei L., Yuzhi T. (2009) – *Information Acquisition for Cucumber Harvesting Robot in Greenhouse.* Transactions of the Chinese Society for Agricultural Machinery, vol.40, no.10, pp.151-155;

型，得到运动学方程的正解。采用 A_i^{-1} 与矩阵 ${}^0T_4$ 左乘解耦，借助 matlab 软件求出运动学逆解。利用 pro/e 建立采摘机器人三维模型，借助于专用虚拟样机开发工具 ADAMS 试验和测试功能，导入 ADAMS 仿真软件进行运动学仿真分析。仿真结果表明：D-H 法建立的运动学模型反映了机器人的真实运动情况，运动学正逆解正确。设计开发的 4 自由度采摘机器人结构设计的合理，能够满足温室栽培模式下茄子采摘的要求。

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参考文献

[1]. Arima S., Kondo N. (2009) — *黄瓜收获机器人与种植培育系统*. 机器人与机械系统期刊, 第 11 卷, 第 3 期, 208-212;

[2]. Denavit, J., Hartenberg, R.S.. (1955) —*基于矩阵的双联机构运动学方法*. 应用机械学期刊, 第 22 卷, 第 6 期, 102-108;

[3]. 宋健, 张铁中, 徐丽明. (2006) — *果蔬采摘机器人研究进展*. 农业机械学报, 第 37 卷, 第 5 期, 158-162;

[4]. 刘继展, 李萍萍, 李智国. (2008) —*番茄采摘机器人末端执行器的硬件设计*. 农业机械学报, 第 39 卷, 第 3 期, 109-112;

[5]. Kondo N., Monta M. Fujiura T.(1996) — *日本的蔬菜收获机器人*. 空间技术研究进展, 第 18 卷, 第 2 期, 181-184;

[6]. 崔鹏, 陈志, 张晓超. (2011) —*苹果采摘机器人仿生机械手静力学分析与仿真*. 农业机械学报, 第 42 卷, 第 2 期, 149-153;

[7]. 汤修映, 张铁中.(2005) —*果蔬收获机器人研究综述*. 机器人. 第27卷, 第1期, 90-96;

[8]. Shigehiko H., Katsunobu G., Yukitsugu I. (2002) — *茄子机器人采摘系统*. 日本农业研究季刊, 第 36 卷, 第 6 期, 163-168;

[9]. 宋健. (2011) — *基于改进的小波边缘提取的茄子采摘机器人目标识别*. 国际计算机和软件进展, 第 6 卷, 第 5 期, 710-714;

[10]. 袁挺,李伟,谭豫之. (2009) —西红柿采摘机器人末端执行器硬件设计. 农业机械学报, 第 40 卷, 第 10 期, 109-112;

[11]. Van Henten E.J., Van Tuijl B.A J., Hemming J. (2002) – *Field Test of an Autonomous Cucumber Picking Robot*. Biosystems Engineering, vol. 86, no.4, pp.305–313.

[12]. Wei L., Aiguo Song., Jianrong C. (2011) – *Structural design and kinematics algorithm research for orange harvesting robot*. Journal of Southeast University, vol. 41, no.1, pp.95-100;

[13]. Xifeng L., Xiangwen M., Saorong C. (2005) – *Kinematics Optimizing and Simulation Test of Tomato Picking Manipulator*. Transactions of the Chinese Society for Agricultural Machinery, vol. 36, no.7, pp.96-100.

[14]. Xu, L., You, Z., Wu, S., et al. (2013)–*Development and experiment on automatic grading equipment for kiwi*. INMATEH- Agricultural Engineering, vol. 41, no.3, pp.55-64.

[11]. Van Henten E.J., Van Tuijl B.A J., Hemming J. (2002) — *黄瓜采摘机器人现场试验*. 生物系统工程, 第 86 卷, 第 4 期,305–313;

[12]. 卢伟, 宋爱国, 蔡健荣. (2011) —*柑橘采摘机器人结构设计及运动学算法*. 东南大学学报, 第 41 卷, 第 1 期, 95-100;

[13].梁喜凤,苗香雯, 崔绍荣. (2005) — *番茄收获机械手运动学优化与仿真试验*. 农业机械学报, 第 36 卷, 第 7 期, 96-100.

[14]. 许丽佳, 尤志坤, 武胜 等. (2013) —*猕猴桃自动分级设备的研制与试验*. 国际农业工程期刊, 第 41 卷, 第 3 期, 55-64.