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Dual-arm Robot Design and Testing for Harvesting Tomato in Greenhouse

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Abstract: In order to improve the efficiency of robotic harvesting in unstructured environment, a modular concept of dual-arm robot for harvesting tomatoes is proposed in this paper. The objective to develop a modular robotic system which works based on human-robot collaboration is reached. Due to the complexity of working environment, an artificial recognition approach conducted by operator through marking the tomato object on the graphic user interface is used for tomato recognition and localization. A dual-arm frame equipped with two 3 DoF manipulators and two different type end-effectors used to pick tomatoes is designed and tested respectively. The cooperation of two end-effectors could improve the harvesting efficiency significantly. The EtherCAT bus based control and communication system is adopted to increases the reliability and speed of motion control and data communication. Concerning control software, a graphic user interface was designed to exchange the operator's commands and display the state information of robot. The performances of field test showed the efficiency of the developed robot system, some shortcomings of the robot were also found for future work.

Keywords: Dual-arm robot Tomato harvesting Stereo camera Field tests Human-robot collaboration

1. INTRODUCTION

As one of the most important processes in agriculture production, the harvesting work is not only a tiresome task but also requiring a large amount of skilled labour in a certain period Moreover, the tomato trees in greenhouse are tall which increases the risk of injury for farmers. Projecting into the future, the issue of labour shortage is expected to become a huge challenge to agricultural industry (Gongal et al., 2015). The harvesting robot was firstly proposed by Schertz and Brown (1968) as a potential way to combat the agricultural labour crisis. Harvesting robots are designed to sense the complex agricultural environment using various sensors and use that information, together with a goal, to perform some actions (Edan et al., 1994). These actions are to move the tool of an end-effector to grasp or pick a fruit object. Although harvesting robots hold ample promise for the future, currently the overall performance of harvesting robot is often insufficient to compete with manual operation (Grift et al. 2008). The bottlenecks to promote the commercial application of harvesting robots are the low efficiency and high cost (Edan et al., 1999).

Combining human workers and robots synergistically is a viable approach to increase the success rate of robotic harvesting. This approach for the robotic harvesting is to separate the fruit recognition stage from the harvest stage by marking the target fruit a priori. In the Agribot project, a robot prototype was designed and built for a novel artificial harvesting strategy in unstructured environments, involving a human-machine task distribution (Ceres et al., 1998). The operator performed the detection and precise location of fruits by means of a laser range finder. Ji et al. (2014) introduced an assistant-mark approach to recognize and locate the picking-point for robotic harvesting. Oren et al. (2012) also defined and implemented a collaboration of a human operator and robot applied to target fruit detection. Experimental results indicated that the fruit recognition system based on human-robot collaboration increased the success detection rate to 94% and reduce the time consumption by 20%.

Another way toward the goal of efficient robotic harvesting is to build a multi-arm robotic harvester. A number of manipulators are mounted on a mobile robot platform, and each manipulator is assigned specific fruit to harvest. Zion et al., (2014) from Israel has designed a multi-arm melons harvesting robot which enabled the maximum number of melons to be harvested. According to the idea of multi-robot cooperation for fruit harvesting, Noguchi et al. (2004) also proposed a master-slave robot system for field operations. In this multiple robot system, a high level of autonomy to the robot was achieved to allow them to cope with unexpected events and obstacles. Modular design is a practical and feasible way to reduce the investment of harvesting robot (Hwang and Kim, 2003).

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In this paper, a dual-arm robot for harvesting tomato in greenhouse scene was modular designed and field testing. Firstly, the overview and workflow of the developed dual-arm harvesting robot were described in the paper. Then, 5 major functional modules of the harvesting robot were introduced, and some shortcomings of the developed system were summarized according to the field tests. Finally, the remainder of this article present a summary about the study of dual-arm harvesting robot and outlook of this study.

2. OVERVIEW OF THE ROBOT

2.1 The Structure of Prototype Robot

The proposed robot system was designed to fit Venlo type greenhouse, in which the heating pipes was used as guided rail. The platform vehicle designed as a carrier was driven on the heating pipes. Except these auxiliary units, the dual-arm harvesting robot was composed of 5 major functional modules which are dual-arm type robotic manipulator, exchangeable modular type end-effectors, vision system equipped with stereoscope camera, EtherCAT based communication and control system, and graphic user interface. As shown in Fig. 1, a stereo camera mounted on the top of the robot platform was used to acquire the image of working scenes and provide 3D position of tomato object. The robotic dual-arm constituted by two 3 DoF manipulators was used to position the end-effector to the picking-point. A saw cutting device was designed as end-effector which could cut the stem of tomato. The other end-effector was used to grasp the tomato for avoiding tomato shaking caused by the cutting operation. The robot system adopted tele-operative concept through developing wireless remote data and signal communication and graphic user interface. The machine control system of each manipulator was built based on direct current (DC) servo motors and EtherCAT bus.

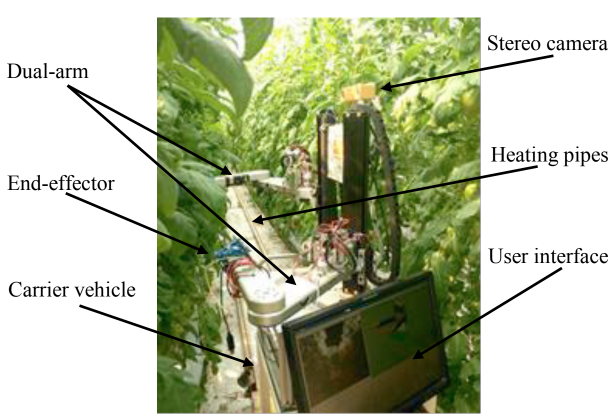


Fig. 1. Integrated dual-arm robotic system for harvesting tomato.

2.2 The Workflow of Tomato Harvesting Robot

Considering unreliability of autonomous fruit detection for various fruit harvesting robots in unstructured environment, the fruit recognition is the most difficult challenge to improve the effectively of robotic harvester. For solving the obstacles mentioned above, a human-robot collaboration strategy was introduced into the framework of proposed system. The fruit recognition task was implemented by operator through pointing out the target tomato on the screen interface which displayed the working site. Then, the spatial position of the marked tomato was obtained by stereo camera. Excepting fruit recognition, the order of carrier vehicle driving was also given by operator through user interface. The other operations were conducted by robot itself. All the task sequence of picking operation for the dual-arm robot was shown in Fig. 2.

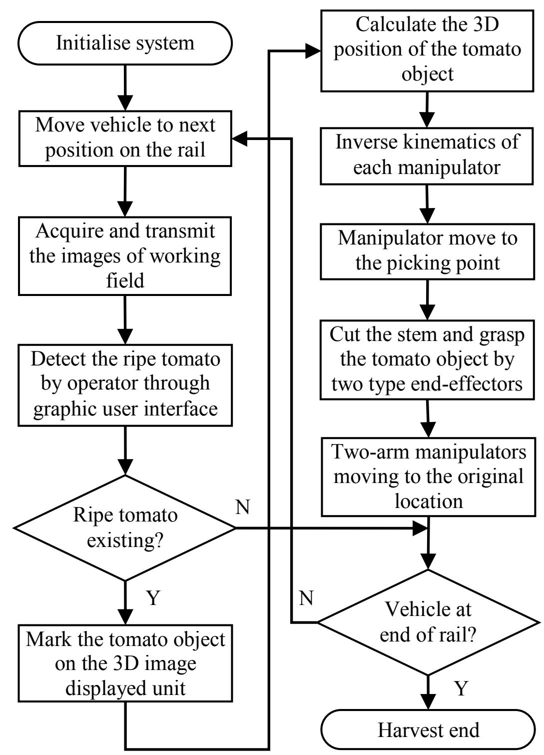


Fig. 2. The workflow of tomato harvesting robot.

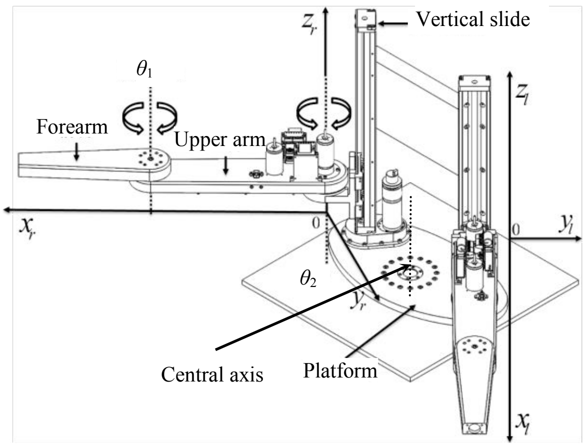
3. THE MODULAR ROBOT SYSTEM

3.1 Dual-arm Manipulator

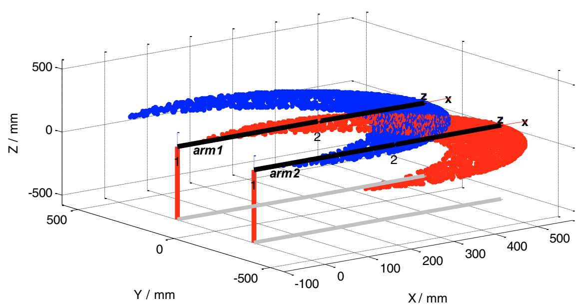
Fig. 3(a) shows the developed dual-arm robotic manipulator which was composed of two 3 degrees of freedom (DoF) Cartesian type robot manipulators. The 3 DoF Cartesian type robot manipulators were owned one prismatic joint and two rotational joints to ensure the proper workspace. Fig. 3 (b) shows the simulation results of reachable workspaces of the dual-arm robot manipulators. Totally 6000 red and blue dots were used to display the possible picking-point of each arm respectively. The common area of red and blue dots is the workspaces. According to the width of the simulation results, the distance between each picking point on heating pipes was designed as 400mm. The frame of dual-arm manipulators also can rotate 180 degrees according to the central axis. Overall geometrical and kinematic parameters of the proposed dual-arm robot manipulators were given in Table 1.

Table 1. Overall parameters of dual-arm robot manipulators

Parameter	Design value
Length Forearm, mm	250
Length Upper arm, mm	330
Distance between two arms, mm	400
Range of vertical slide, mm	[0 300]
θ_1 , deg	[-45° 45°]
θ_2 , deg	[-45° 45°]



(a) The 3D model of the dual-arm robot manipulator



(b) The simulation results of workspace for the dual-arm robot manipulators

Fig. 3. The structure of dual-arm manipulator: (a) 3D model of manipulator, (b) the possible workspace of the dual-arm robot manipulators.

3.2 End-effectors

End-effectors were developed as modular type in order to ensure two robotic arms working cooperatively. The end-effector was designed to be lightweight and simple exchangeable. As shown in Fig. 4, two different kinds of end-effectors such as cutting device for fruit separation and vacuum cup for grasping target tomato were installed on the end of each manipulator respectively. Fig. 4(a) shows the schematic drawing of saw cutting type end-effector. The actuator of saw cutting type end-effector was driven by belt pulley, and the other side of the pulley was connected to the motor's output shaft which was controlled by the micro control unit. The pose of cutter was also adjusted in two directions: X and Y. The X direction adjusting was conducted by four-bar linkage, and adjusting range was from -45 degree to 45 degree with respect to the Y direction. The Y direction adjusting was also driven by an actuator controlled by the MCU system.

The pneumatic type end-effector which is composed of vacuum suction device and plastic socket is showed in Fig. 4 (b). The plastic socket moved to the centre point of tomato object firstly, and then the vacuum suction cup gripped it to prevent shaking. The pneumatic type end-effector could approach 20mm to 50mm offset point along the stem axis of ripe tomato from the centre. The diameter of cup was 100mm and vacuum power was set up to handle 100gf to 1kgf weight. Stem cutting was performed repeatedly until pneumatic type gripper gripped the target tomato.

(a) Saw cutting type end-effector (b) Pneumatic type gripper

Fig. 4. Two kinds of the end-effectors for the dual-arm robot.

3.3 Vision System

A colour stereo camera (Bumblebee2, Point Grey, Vancouver, Canada) with a resolution of 480(H) ×640(L) at 48FPS was used as the visual system of robot. The stereo vision system consisted of two identical colour CCD sensors was attached to the top of dual-arm frame to ensure the proper view field, and the image process was performed by the host computer (Lenovo, Beijing, China, Inter(R) Core(TM) i3-370 CPU, Random Access Memory (RAM) 4.0GB). The task of ripe tomato detection and localization was completed at two different stages. Firstly, ripe tomato was detected and marked by operator in the 3D reconstructive image through graphic user interface. Then, the three dimensions position P(x, y, z) of tomato object was calculated through the principle of triangulation (Sun et al., 2011) using the two images captured by the stereo camera. Since adopting human-robot collaboration approach to detect and locate ripe tomato, the robustness and efficiency of robotic harvesting increased obviously.

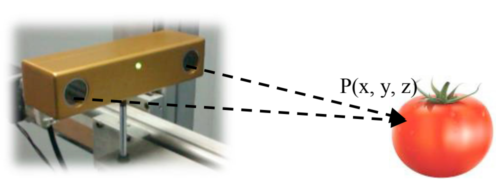


Fig. 5. The principle of 3d position measurement of tomato using stereo camera.

3.4 Motion Control and Communication System

The purpose of motion control was to ensure the developed robot to implement the picking operation accurately and rapidly. The motion control and communication system transmits the operator's command to control unit of the machinery and also receives the signal state of the task execution of machine. As shown in Fig. 6, the core unit of the control and communication system was the host computer installed with the graphic user interface and other controlling software modules. The host computer transmitted operator's command to the G-MAS through Modbus for distributing the kinematic parameter of each joint motor. Then, the control signal was transmitted through EtherCAT bus. The output section included seven DC servo motors and supporting digital drivers (G-Solo Whistle). The main characteristic of EtherCAT bus is parallel transmission, which effectively increases the reliability and speed of motion control and data communication.

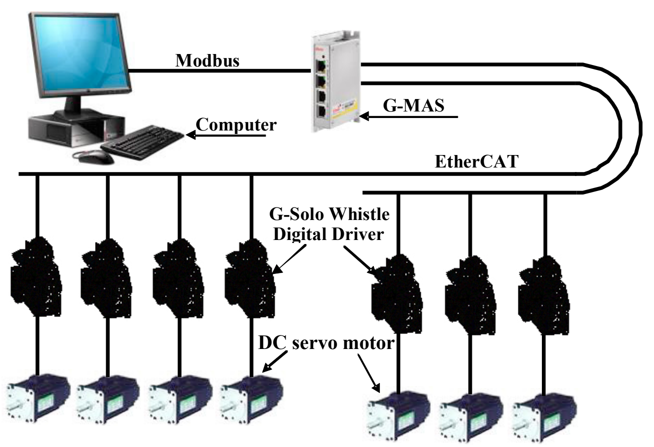


Fig. 6. Schematic diagram of controller and communication system.

3.5 Graphic User Interface

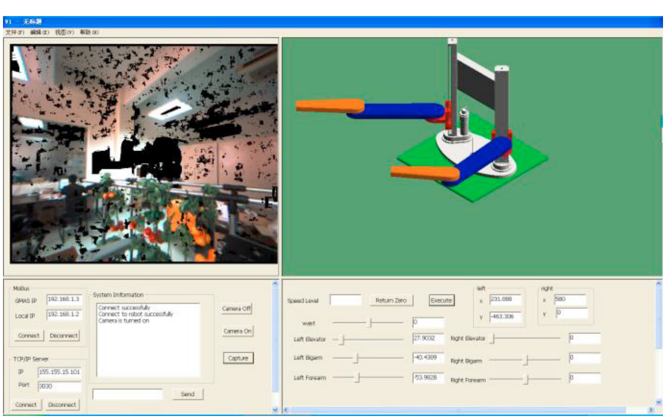


Fig. 7. The graphic user interface.

The graphic user interface is a visualisation control screen which is used to transmit the control command from operator and displayed the current state of robot. The graphic user interface consisted of four units: 3D reconstructed image display unit, robot motion simulating unit, basic command interface unit, and control command interface unit. As shown in Fig. 7, the top left of screen is the 3D reconstructed image displayed the robot working scene. The tomato object could be marked in this screen unit by operator using a small red circle, and the centre of the circle replaced the position of tomato object. The top right of the screen shows the position of the robot in virtual environment which is completely computer-generated three dimensional graphics for the simulation of human-computer interaction. The bottom left of screen is the basic command interface unit which is used to set system initialisation. The bottom right of screen is the control command interface unit which is designed to set some motion parameters of the robot. Visual C++ was selected as programming development tool for designing the graphic user interface software. Details about the developed user interface software were described by Liu et al. (2014).

4. FIELD TESTS AND ANALYSIS

4.1 Filed Tests

To further verify the reliability and adaptability of the dual-arm harvesting robot, the final integrated system was tested in the Shanghai Morden Agriculture garden during May 2015 as shown in Fig. 8. In practice, once a tomato object was marked in the 3D reconstructed image 2by operator, the robot was able to pick the marked tomato autonomously. If all the ripe tomatoes were harvested, the robot moved to the next working position controlled by operator through control command interface unit. A few shortcomings of the robot system were revealed through the field tests.

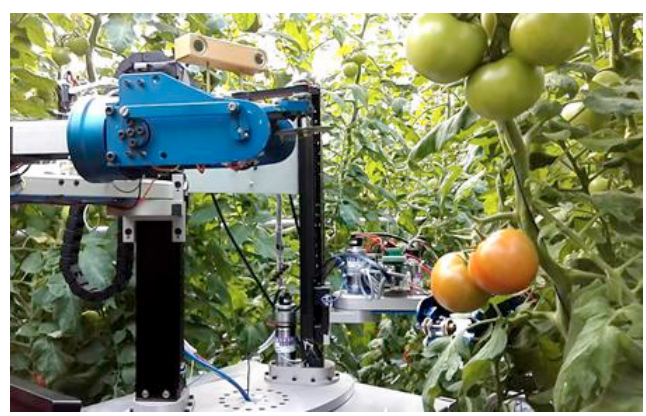


Fig. 8. Dual-arm tomato harvesting robot testing in the greenhouse

4.2 Shortcomings of Developed Robot System

The 3D image reconstruction is built on the basis of image matching. However, the complex of the natural environment caused the failure of image matching in some special conditions. As shown in Fig. 7, the black area in display unit of user interface was the result of matching failure. The varying illumination is the main factor to influence the performance of image match. On the other hand, the time consumption of 3D image reconstructing is high which directly affected to the picking cycle time.

The control strategy applied in the developed harvesting robot which is a visual open-loop control mode based on detecting the accurate position of the fruit object in 3D workspace was developed. The stereo camera can measure the space distance between target fruit and the end effector through triangulation theory. Following precision distance measurement, the movement parameter of the manipulators can be planned through calculating the kinematics equation. So, the precisions of kinematic model and calibration of vision system have great influence on the control accuracy of manipulators. Because of robot movement and working site change, the errors of vision system and manipulators might cause harvest failure.

5. CONCLUSIONS AND OUTLOOK

This paper reports on a modular concept of a dual-arm robot for harvesting tomatoes in the greenhouse scene. The objective to build a system which is able to human-robot cooperatively harvesting fruits was reached. Due to the complexity of working environment and limited visibility of the tomato objects, an artificial recognition approach which the tomato object was marked in the human interface by operator was used for tomato recognition and localization. One of the major parts of the robot system is the dual-arm manipulators with 3 DoF respectively. Two types of end-effectors to detach tomato have been developed and tested. The cooperation of two different type end-effectors could significantly improve the harvesting efficiency. The EtherCAT bus based communication system could effectively enhance the reliability of communication system and transmission speed. Concerning software, the human interface was designed to exchange the control orders and state information of robot.

According to the performance of field tests, future work is to analysis the cause of the failure and to improve the performance of the robot in terms of harvest success rate, cycle time and causes of failures. The dual-arm robot collision free motion planning and mission control are also need to research in the future.

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