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Research Paper

Design and control of an apple harvesting robot

Zhao De-An, Lv Jidong, Ji Wei, Zhang Ying, Chen Yu*

School of Electrical and Information Engineering, Jiangsu University, XueFu Road No.301, Zhenjiang, Jiangsu Province 212013, PR China

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A robotic device consisting of a manipulator, end-effector and image-based vision servo control system was developed for harvesting apple. The manipulator with 5 DOF PRRRP structure was geometrically optimised to provide quasi-linear behaviour and to simplify the control strategy. The spoon-shaped end-effector with the pneumatic actuated gripper was designed to satisfy the requirements for harvesting apple. The harvesting robot autonomously performed its harvesting task using a vision-based module. By using a support vector machine with radial basis function, the fruit recognition algorithm was developed to detect and locate the apple in the trees automatically. The control system, including industrial computer and AC servo driver, conducted the manipulator and the end-effector as it approached and picked the apples. The effectiveness of the prototype robot device was confirmed by laboratory tests and field experiments in an open field. The success rate of apple harvesting was 77%, and the average harvesting time was approximately 15 s per apple.

1. Introduction

In China, with the rapid development of the rural economy and the continuous adjustment of planting structures, fruit cultivation areas, such as apple, citrus and pear, have reached 8-9 million ha since 1993, accounting for one-quarter of the total fruit cultivation area in the world. However, fruit harvesting tasks, which take 50%–70% of the total working hours, still depend on manual labour (Xu & Zhang, 2004. Harvesting is expected to be automated because the farming population is gradually decreasing in China. In addition, since the fruit trees are tall, harvesting work has to be conducted using step ladders, which makes manual harvesting dangerous and inefficient. Therefore, there is a strong desire to mechanise and automate harvesting. Mechanical harvesting experiments have been performed on the assumption of once-over harvesting in some areas, but exploitation of this strategy is not yet widespread (Hancock, 1999). Selective harvesting, which is commonly used, requires sophisticated robotic technology. In short, it is necessary to design an intelligent robot with human-like perceptive capabilities. For instance, the machine needs to detect fruit, calculate the position of the fruit and then pick it without damaging the pericarp or the fruit tree.

Research on fruit harvesting robots took place in the 1980s. Kawamura, Namikawa, Fujiura, and Ura (1984) first developed a fruit-harvesting robot for orchards. Later, Grand, Rabatel, Pellenc, Journeau, and Aldon (1987), developed an apple-harvesting robot. Since then, their pioneering studies were followed by many research papers covering several aspects (e.g., ;Edan, Rogozin, Flash, & Miles, 2000; Foglia & Reina, 2006; Hwang & Kim, 2003; Kondo & Ting, 1998; Muscato, Prestifilippo, Abbate, & Ivan, 2005; Sakai, Osuka, Maekawa, & Umeda, 2007, 2008; Sarig, 1993; Van Henten, Hemming, Van Tuijl, Kornet, Meuleman, 2002). In addition, several relevant studies on agricultural robots in greenhouses have been carried

* *Corresponding author*. Tel.: +86 511 82028322; fax: +86 511 82028322.
E-mail address: jwhxb@163.com (J. Wei).
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Nomenclature

Symbols

C_R, C_{RU}, C_U, C_{LU}, C_L Avoidance sensors number
X_c, Y_c, Z_c The camera coordinates axes
X_o, Y_o, Z_o Robot coordinates axes
L_1, L_2, L_3 Lengths of waist, major arm and minor arm
$\theta_1, \theta_2, \theta_3$ Joint angles of waist, major arm and minor arm.
u, v Image plane coordinates horizontal and vertical axes
u_o, v_o Image centre coordinate
x_g, y_g Projection centre coordinate of target fruit
ex, ey The difference of target fruit image feature between x_g, y_g and u_o, v_o
$M \times N$ Image plane pixels of video camera
$|ex_{max}|, |ey_{max}|$ Maximum of ex and ey
$\Delta\theta_1$, $\Delta\theta_2$, $\Delta\theta_3$ Joint deviation angles of waist, major arm and minor arm
k_1, k_2 Control parameters of arms
Δd The angle to adjust for the movement of a pixel with unit of degree per pixel.

Abbreviations

AC	Alternating Current
A/D	Analog, Digital
CCD	Charge Coupled Devices
D/A	Digital, Analog
DC	Direct Current.
DOF	Degree of Freedom
GPS	Global Position System
HIS	Hue, Intensity, Saturation
IBVS	Image-Based Vision Servo
PBVS	Position-Based Vision Servo
PRRRP	Prismatic Revolute Revolute Revolute Prismatic
RBF	Radial Basis Function
RST	Rotation Scale, Translation
SVM	Support Vector Machine
USB	Universal Serial Bus
VFW	Video for Windows

out; for instance, tomato harvesting (Monta et al., 1998), cucumber harvesting (Van Henten, Van Tuijl, Hemming, Kornet, Bontsema & Van Os, 2003), cherry harvesting (Tanigaki, Fujiura, Akase, & Imagawa, 2008), strawberry harvesting (Hayashi et al., 2010). However, most of the fruit harvesting robots discussed in the literature are not currently manufactured or sold. Instead, they remain in the research and development stages. To this end, it is important to support further research and development to improve the performance and reduce the initial set-up costs of these robots.

Based on the concepts above, this study intends to develop and evaluate a competitive low price device for automatic harvesting, i.e., an apple-harvesting robot. Firstly, a detailed description on the components of the robot including the manipulator, the end-effector and the image-based vision servo control system is described. Secondly, the geometrically optimisation of the manipulator to gain a quasi-linear behaviour and simplify the control strategy is described. Thirdly, the end-effector with the pneumatic actuated gripper designed to satisfy the requirements for harvesting apple is described. Based on this design, the harvesting robot autonomously performs its harvesting task using a vision-based module to detect and locate the apple in the trees, and control system conducts the manipulator and the end-effector to approach and pick apple. To verify the validity of the developed harvesting robot, the laboratory tests and field experiments in an open field were performed. The experimental results are the important contribution of this paper.

The paper is organised as follows: in section 2 the main components of the robot are presented in detail, i.e., the manipulator, the end-effector and the image-based vision servo control system, respectively; in section 3 the experimental results are discussed to show the feasibility of the robot system proposed; finally, in section 4 conclusions are drawn and suggestions for future research are made.

2. Material and methods

2.1. Mechanical structure of apple harvesting robot

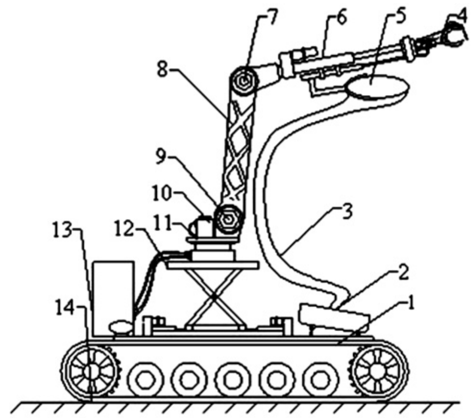
A prototype model of the apple harvesting robot is designed for both efficiency and cost effectiveness. It mainly consists of an autonomous vehicle, a 5 degree of freedom (DOF) manipulator, an end-effector, the sensors, the vision system and control system. The mechanical structure of fruit harvesting robot self-developed in this paper is shown in Fig. 1.

2.1.1. The autonomous mobile vehicle

A crawler type mobile platform was selected as the mobile vehicle. It carried the power supplies, pneumatic pump, electronic hardware for data acquisition and control, and the manipulator with the end-effector for cutting the fruit. Global position system (GPS) technology was used for autonomous navigation of the mobile vehicle, whose typical speed was 1.5 ms^{-1}.

2.1.2. The manipulator

Compared with other structures, as described in Sakai, Michihisa, Osuka, and Umeda (2008), joint structure is effective for any position and orientation in three-dimensional space. The operation of a harvesting robot is a random large space distribution, where a lot of obstacles may exist around the robot. A joint manipulator with multi-degrees of freedom has an arbitrary curve fitting function. It is therefore easy to avoid obstacles by operating the corresponding joints when the end-effector reaches the object position. Therefore, a harvesting robot manipulator with 5 DOF prismatic-revolute-revolute-revolute-prismatic (PRRRP) structure to be mounted on autonomous mobile vehicle was designed. The first DOF was used for uplifting the whole manipulator. The



1. Mobile vehicle 2.Basket 3.Flexible band 4.End-effector

5. Gathering unit 6.Electric handspike 7.Minor arm motor 8.Major arm

9. Major arm motor 10.Waist motor 11.Waist 12.Lifting platform

13. Power and control equipment

Fig. 1 – Schematic diagram of the fruit harvesting robot.

middle three DOF were for rotation, among which, the second driving arm was designed to rotate around the waist, and the third and fourth ones were rotation axes to move the terminal operator up and down. This DOF allowed the end-effector to move towards an arbitrary direction in the work space. The fifth, and last, DOF was flexible and used for elongation, which made the end-effector reach the target location according to the robot control commands, thus achieving the harvesting of fruit (Zhao, Zhao, & Ji, 2009; Zhao, Zhao, & Shen, 2009). The discussion above shows that 5 DOF manipulator designed should be sufficient to perform the harvest operation. The mechanical structure of the manipulator is shown in Fig. 2.

The lifting of manipulator was performed by the pump-driven lifting platform, which was able to cope with the special circumstances of tall fruit crops. The rotary joints and flexible joints were driven by servo motors. Motion parameters of the robot manipulator mechanical structure are shown in Table 1.

2.1.3. *The end-effector*

The mechanism of end-effector is determined by operation and biological characteristics of the target object. The operation objects of harvesting robot are mainly spherical fruit such as apple. A spoon-shaped end-effector (shown in Fig. 3) is designed according to biological characteristics of spherical fruit, which are picked by means of cutting off the stalk.

The end-effector contained the following parts: a gripper to grasp the fruit and an electric cutting device to separate the fruit from the stalk. The opening and closing of end-effector gripper was determined by some pneumatic devices, whose quick action, fast response characteristics were suitable for the switching control of the end-effector. Pressure transmission was a transferring mode using compressed gas pressure to achieve energy transference. The apple stalk was severed by an electric cutter installed in the side of gripper mechanism. When the fruit was grasped, the direct current (DC) motors transmited power by flexible wire to drive the cutter rotating around the gripper, cutting off the stalk in front of end-effector at any position.

Fig. 2 – Photograph of the manipulator.

Table 1 – Motion parameters of manipulator mechanical structure.

Joint Motion	parameters
Lift platform	0 m–0.8 m
Rotation joint of waist	−180°–180°
Rotation joint of major arm	−80°–80°
Rotation joint of minor arm	−80°–80°
Flexible joint	0 m–0.8 m

2.2. *The sensors*

The non-structural and uncertain features of the operating environment, and the individual differences and random nature of the operating objects, determines that fruit harvesting robots should have intelligent sensibility to their complex environment (Edan et al., 2000; Zhao, Zhao, & Ji, 2009; Zhao, Zhao, & Shen, 2009). During the process of clamping the fruit, the biological characteristics of fruit including its thin and fragile pericarp put a high demand on grasping force of end-effector (Monta, 1998). It required sensors to control the grasping force accurately. In addition, the rotation of arm, its traveling position and accurate capture also required the sensors to detect and locate fruit (Jiang, Cai, & Liu, 2005; Qiao, Wu, & Zhu, 1999). Furthermore, in order to avoid damaging equipment, causing injury and failing to pick fruit, collision avoidance of the arm also needs sensors to perceive the operating environment effectively.

2.2.1. *The sensors on end-effector*

The layout of sensors on end-effector, which includes a vision sensor, a position sensor, a collision sensor and a pressure sensor, is shown in Fig. 4. The vision sensor, which uses high-pixel colour charge coupled devices (CCD) video camera with universal serial bus (USB) interface and the video for windows (VFW) capture technology to form image acquisition system, plays a key role in completing image acquisition, fruit search and recognition. To obtain a wide visible-field and not influenced by end-effector, the position of the vision sensor is in an eye-in-hand mode. In Fig. 4, it can be seen that there is the photoelectric position sensor with two pairs of infrared double photoelectric cells. In addition, the switch position sensor which was usually used to limit for electric cutting knife was also mounted on the position sensor. The arm began deceleration when the end-effector moved towards the target fruit guided by the vision sensor and the first pair of photodiodes was obscured by the fruit in the holder. The arm stopped and the gripper clamped fruit when the two pairs of photocells were obscured. At this point, both the pressure and collision sensors adopted force sensitive resistance. When the pressure sensor on the gripper felt a certain pressure, the electric cutter rotated and cuts off pedicel. The cutter stopped working when the switch position sensor operated. The collision sensor was used for obstacle avoidance during the process of harvesting. Analogue signals derived from the force sensitive resistance and infrared photoelectric tubes are usually incompatible with the data acquisition module inside industrial computer. Therefore, they require modulation before transmission to the data acquisition module. Fig. 5 shows the sensors signal modulation circuit.

2.2.2. *The Sensor on manipulator for collision avoidance*

Control of the angle of the rotating joints and position control of the flexible joints was fulfilled using 8 Hall sensors, installed on the rotation joints of waist, the major arm, the minor arm and both ends of flexible joints. In the working environment, the movement space of minor arm was wide;

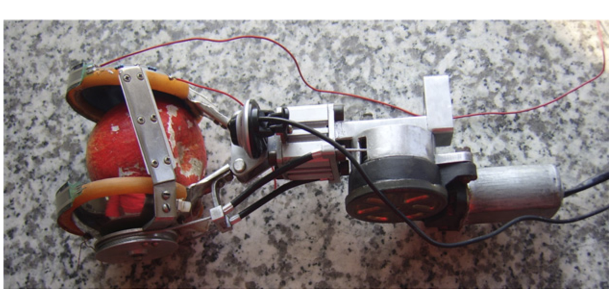


Fig. 3 – Photograph of the end-effector.

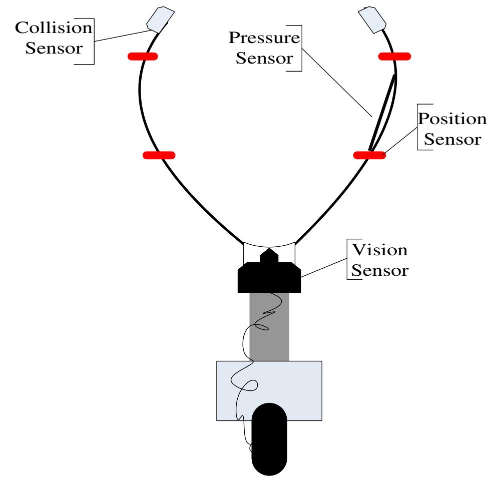


Fig. 4 – Layout of sensors on end-effector.

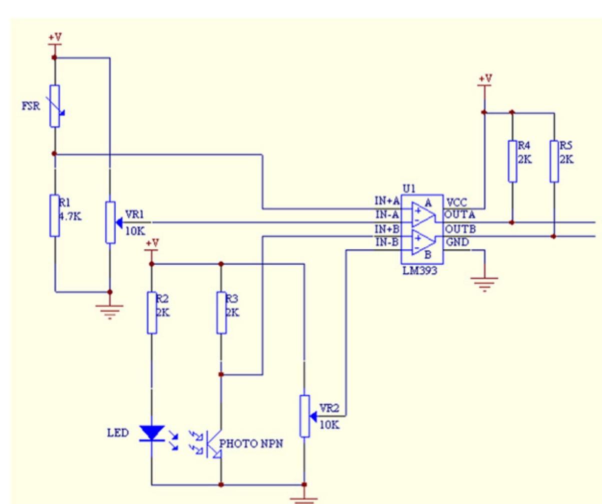


Fig. 5 – Sensors signal modulation circuit.

and the probability of collision with obstacles was high. Therefore, the collision sensor was fixed in the minor arm to detect obstacles. Five groups of micro switches were fixed on different positions in the minor arm to obtain real-time information from obstacles. Noting that software programming processes signals conveniently, the five groups of avoidance sensors were designated CR、CRU、CU、CLU、CL in accordance with their position. The distribution of the minor arm collision avoidance sensors is shown in Fig. 6.

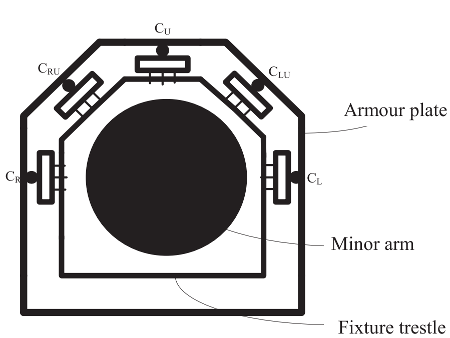


Fig. 6 – Layout of sensors on minor arm.

2.3. *The vision systems*

For the vision system of the apple harvesting robot, the key ingredient was the image processing method that recognised and located the fruit. It affects the robot's dependability and also determines its ability to directly, quickly and accurately recognise in the fruit real time (Bulanon, Kataoka, & Okamoto, 2004). However, in the earlier research (Bulanon, Kataoka, & Ota, 2002; Liu, Zhang, & Yang, 2008; Plebe & Grasso, 2001; Zhao, Yang, & Liu, 2004), there exist some unsolved issues such as low accuracy rate and time consumption, which to some extent restricted the real-time and multitasking ability of the apple harvesting robot in the natural environment.

To overcome these shortcomings, a real-time automatic recognition vision system consisting of a colour CCD camera for capturing original apple images and an industrial computer for processing images to recognise and locate the fruit was developed. Since the Fuji apples are the most popular in China, our research focused on this variety.

The recognition and location procedure is as follows.

Firstly, due to the natural environment and the image acquisition device used, the original unprocessed apple image inevitably includes noise that influences its quality. A vector median filter was applied to image enhancement preprocessing. It can not only remove noise effectively and highlights the apple fruit in foreground, but it also maintains good image edges.

Secondly, most apple images acquired in the natural conditions usually include branches and leaves which complicate matters. By using only a conventional image segmentation algorithm, it was difficult to achieve anticipated effect. Based on hue histogram statistics from the hue, intensity and saturation (HIS) model, the double threshold and region growing method was employed to develop an image segmentation algorithm for identifying apple fruit from complex background. The chromaticity component is irrelevant when lightness is extracted and this avoided the influence of different illumination levels on the images. The algorithm was simple, and required little processing time.

The apple features were extracted to determine the spatial location, and provide corresponding motion parameters for arm. For colour feature extraction, the chroma components hue and saturation, are usually extracted as colour features for recognition. However, in our study, apple fruit, branches and leaves have specific shapes, and their differences in shape are large. Therefore, the shape feature is important in apple object recognition. The selected rule of shape features was based on invariance in rotation, scale and translation (RST). Taking account of characteristics of apple fruit images, circular variance, variance ellipse, tightness, ratio between perimeter and square area were used to describe the outline shape features of apple. These four feature vectors were extracted as shape features. After the calculation of the corresponding eigenvalues, they were used as feature vectors of each sample and used for training and classification.

Finally, a new classification algorithm based on support vector machine was constructed to recognise the apple fruit. Simulation and experiment shows that the support vector machine (SVM) method with radial basis function (RBF) kernel function based on both colour features and shape features was found to be the best for apple recognition. Details of the algorithm can be found in Wang, Zhao, Ji, Tu, and Zhang (2009).

2.4. *The control system*

The hardware structure is shown in Fig. 7. At the centre of the control system was the host computer, which integrates the control interface and all of software modules to control the whole system. The sensor signal acquisition system and image acquisition system constituted the input section which was used to collect external environment information for the

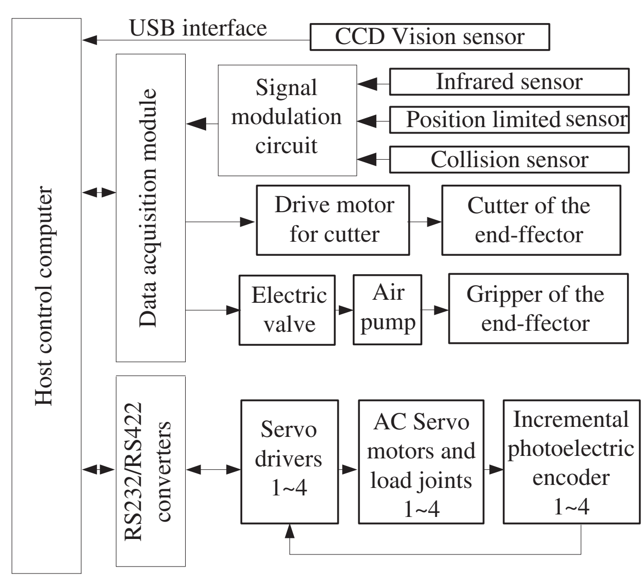


Fig. 7 – Hardware structure of apple harvesting robot control system.

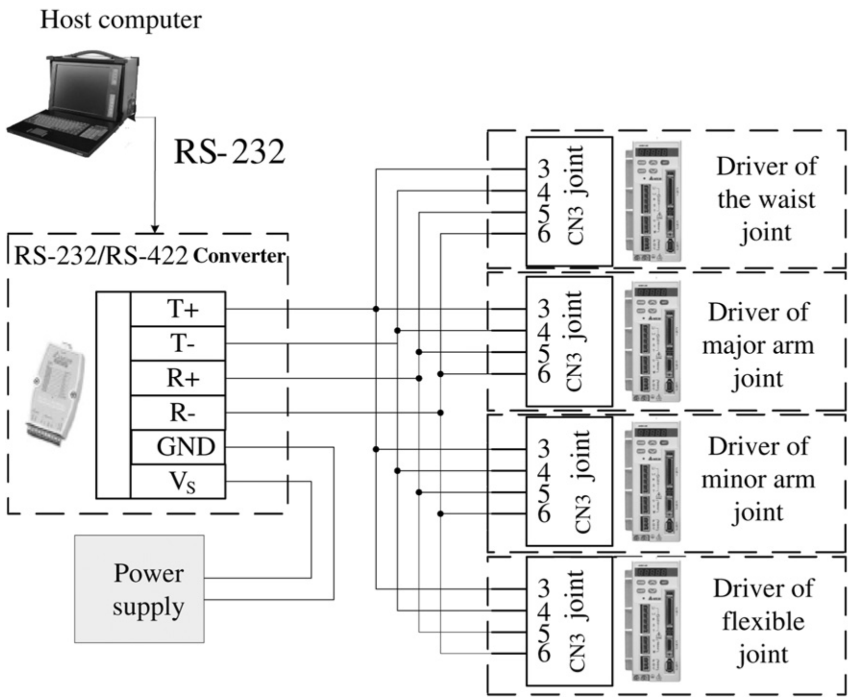


Fig. 8 – Communication link diagram of the host computer and servo drivers.

harvesting robot. The output section included a servo driven motor, air pump and end-effector.

2.4.1. *Host computer*

A Kintek KP-6420i (Kintek Electronics Co., Ltd., Miaoli Hsien, Taiwan, China) industrial computer with Intel Pentium4 1.7 GHz processor and 512 M memory was selected as the host control computer, which was responsible for collecting whole sensor signals, processing images online, calculating the inverse kinematics of manipulator and completing the control algorithm. The host computer transmitted instructions to the alternating current (AC) servo driver through a serial port to control the joint motors of waist and arms. HighTek HK-5108 (Shenzhen FangXingLiuTong Industrial Co., Ltd., Shenzhen, China) RS-232/RS-422 converters were chosen for serial communication functions. A data acquisition module installed inside host computer was responsible for data collection from all the sensors except for the vision sensor and output control of the electrical cutter. A KPCI-847H (Beijing KeRuiXingYe Technology Co., Ltd., Beijing, China)module with 16 channels A/D and D/A converter was used.

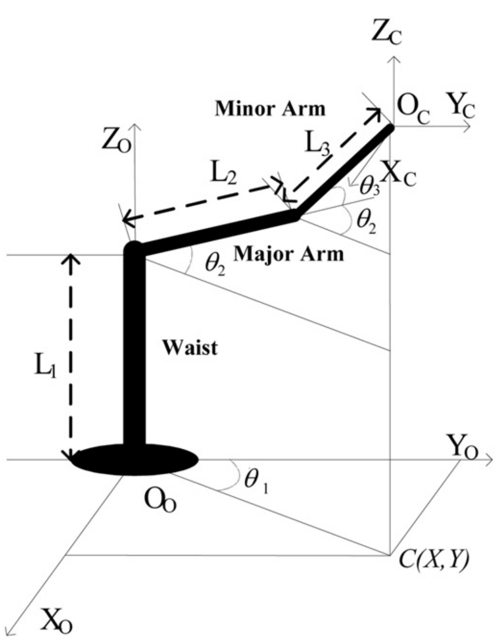


Fig. 9 – Geometrical relations of manipulator joints.

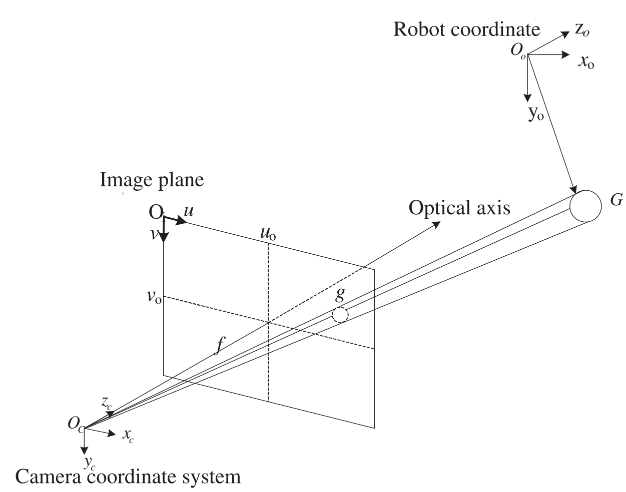


Fig. 10 – Perspective projection diagram of fruit in 3-D space.

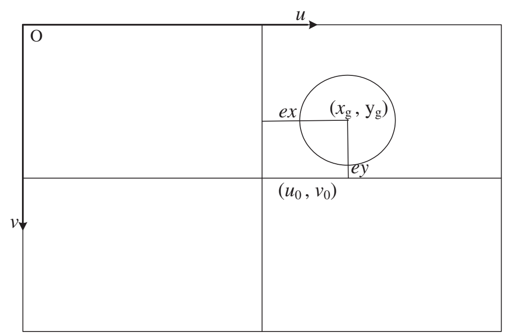


Fig. 11 – Location diagram of target fruit in image plane.

2.4.2. *Servo DriveMechanism*

The purpose of motion control was to guarantee that the fruit harvesting robot achieved movement with an arbitrary angle to grab the object fruit accurately and rapidly. Therefore the key issue was to control the drive motors of each joint. The closed-loop servo system used to control rotary joints and flexible joints, consisted of Delta ASDA-AB (Delta Electronics, Inc, Taipei, Taiwan, China) series servo drivers, ECMA (Delta Electronics, Inc, Taipei, Taiwan, China) series AC servo motors and incremental photoelectrical encoders, which included the planetary PH (Hubei Planetary Gearboxes Co., Ltd., Wuhai, China) series reduction gear and the Danaher IDC EC2 (Danaher Montion Co., Ltd., Petaluma, Cal., USA) series precise linear electric actuators. To improve the safety of operation, an electromagnetic brake was fitted to each motor. The ASDA-AB series servo driver not only has three control modes including position control, speed control and torque control, but it also included serial communication functions for RS-485, RS-232 and RS-422. Considering the practical applications of the system, the rotation joints for the waist, major arm and minor arm employed a position control mode, whilst the flexible joint of the electric pusher employed a speed control mode. The communication between host computer and servo drivers of all the joint motors employed the RS-422 mode. Therefore, the frame computer not only set the parameters and adjusted the gains, but it also monitored the operating state of the servo driver and alarm conditions. The communication link diagram for the host computer and servo drivers is shown in Fig. 8.

2.4.3. *Manipulator control strategy*

The fruit harvesting robot had an integrated system, comprising environment perception, dynamic decision-making and behaviour control. Motion control was the most basic and important ingredient. The robot vision servo control included two methods, a position-based vision servo (PBVS) and image-based vision servo (IBVS) (Lippiello, Siciliano, & Villani, 2007; Mariottini, Oriolo & Prattichizzo, 2007). IBVS was usually used to control the manipulator according to image features and separate vision reconstruction problems from robot control. This method simplifies robot control and avoids targets outside the camera visible-field. Thus, it is a commonly used as a method for robot control. To this end, in our harvesting robot manipulator control system, the IBVS control method was employed to achieve location and the picking motion for the target fruit.

The structural diagram for fruit harvesting robot manipulator is shown in Fig. 2, where the installed CCD camera is in an eye-in-hand mode. At the start of the picking process, the

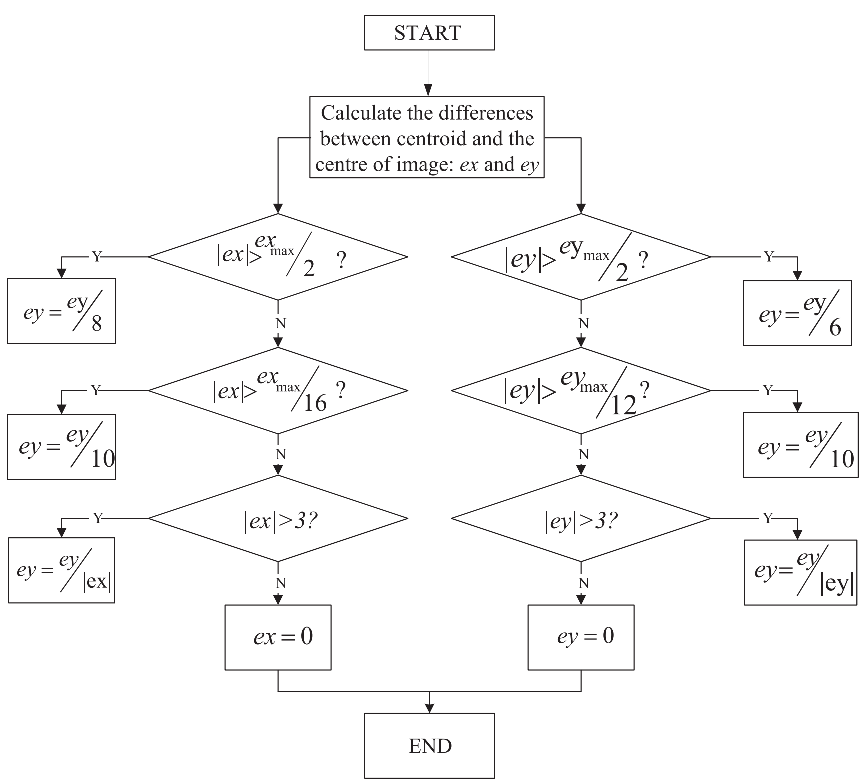


Fig. 12 – Flowchart of small step transformation algorithm.

flexible joint contracted in the minor arm during the process of searching for target fruit. Therefore, the harvesting robot manipulator can be regarded as a three-joint robot manipulator, and the relationship between camera coordinate system and robot coordinate system can be obtained according to geometrical relation shown in Fig. 9. The camera coordinates axes (X_c, Y_c, Z_c) parallel to corresponding axes in robot coordinates (X_o, Y_o, Z_o). L_1, L_2, L_3 are the lengths of the waist, major arm and minor arm respectively, and $\theta_1, \theta_2, \theta_3$ are the joint angles of the second, third and fourth DOF.

Apples with radius of 40 mm (average radius of the apples) were considered as research objectives. Their projection was a circle on the image captured by video camera. Perspective projection of a fruit in 3-D space is shown in Fig. 10, and formed in the video camera. Feature information of target fruit in image plane is shown in Fig. 11. For a two-dimensional image captured by a video camera, the origin is a point in the upper right corner. Symbols of u and v denote horizontal and vertical axes respectively. The image feature of target fruit is characterize as *ex* and *ey*, which are the errors between projection centre coordinate (x_g, y_g) and image centre coordinate (u_o, v_o). During joint control of harvesting robot manipulator, image feature of *ex* varies along with the change of waist joint angle θ_1, and image feature of *ey* varies along with the change of major arm joint angles θ_2 and minor arm joint angles θ_3.

It can be seen that the manipulator with 5 DOF PRRRP mechanical structure was geometrically optimised to simplify the control strategy, and the control algorithm designed to avoid complicated jacobian operations. At the same time, the vision systems software gave only planar information of the target fruit in our robotic system. The distance information between target fruit and camera was unknown. Hence the manipulator jacobian could not be directly used in our system.

The process of picking target fruit can be presented as follows. Firstly, each module of harvesting robot was initialised, and the manipulator made to approach the fruit trees at a proper location. Then the video obtained image information of target fruit, and the recognition and location were obtained by image processing software such that the centroid coordinate x_g, y_g of target in image and the errors *ex* and *ey* obtained by comparison with the image centre coordinate u_o and v_o.

Secondly, the robot was controlled to move with small step according to the calculated deviations *ex* and *ey*, and eventually it drove them to be zero. Assuming that image plane pixels of video camera are M × N, then $|ex_{\max}| = M/2$ and $|ey_{\max}| = N/2$. The flowchart of the small step transformation algorithm is shown in Fig. 12. When the deviations of the small step movements of the waist, major arm and minor arm were zero, then the centroid of target fruit was coincident with image centre. During the process of eliminating deviations *ex* and *ey*, each joint angle was required to move. This was calculated according to Eq. (1)

$$\begin{aligned} \Delta\theta_1 &= ex \times \Delta d \\ \Delta\theta_2 &= k_1 \times ey \times \Delta d \\ \Delta\theta_3 &= k_2 \times ey \times \Delta d \end{aligned} \tag{1}$$

where $\Delta\theta_1$, $\Delta\theta_2$, $\Delta\theta_3$ are joint angles of waist, major arm and minor arm respectively; k_1,k_2 are the control parameters of arms; Δd is the angle to be adjusted for the movement of a pixel with unit of degree per pixel.

Then, the host computer sent instructions to the flexible joint to spread. After the object fruit entered into the gripper of end-effector, the flexible joint stopped spreading. The gripper was then closed and the electrical cutter cut off the apple stalk.

Finally, the flexible joint backed to its initial position. Thereafter, the gripper was opened and fruit slid along the flexible tube into the basket.

To achieve continuous picking the above steps were repeated.

2.4.4. *System software design*

A Windows XP system was employed as an operating platform for its good stability and security. Visual C++ 6.0 was selected as programming development tool for the host computer. In the system, multiply tasks needed to be processed simultaneously. Noting that a single-thread might lead to data communication jams and not guarantee real-time control, a multi-threading event-driven approach was adopted for the program control system software. The main thread was responsible for the management of visualisation control interface, system initialisation; the sub-thread was responsible for communication and synchronisation. The sub-thread

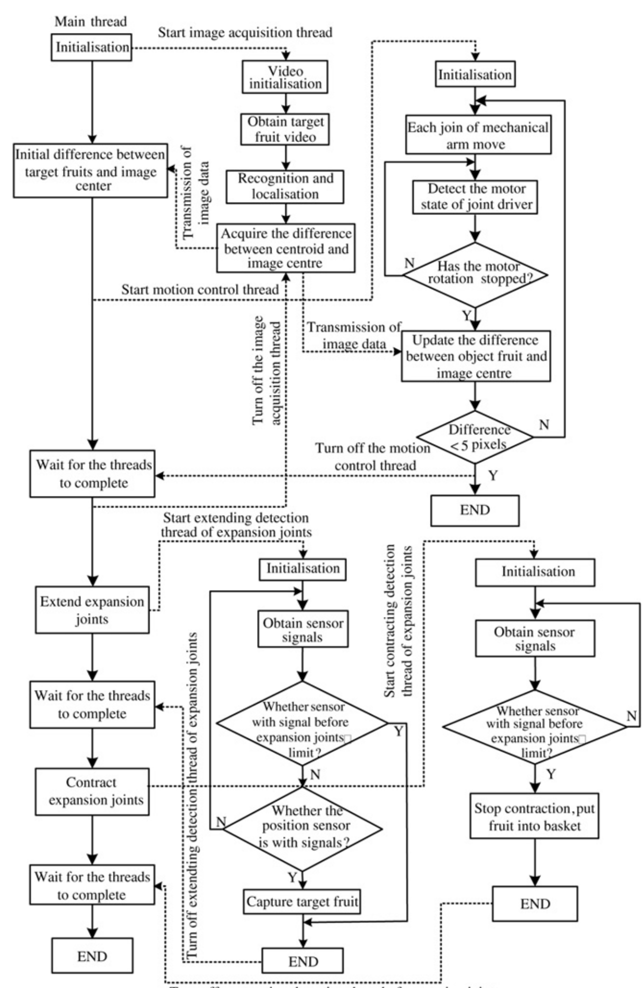


Fig. 13 – Main program flowchart of robot harvesting task.

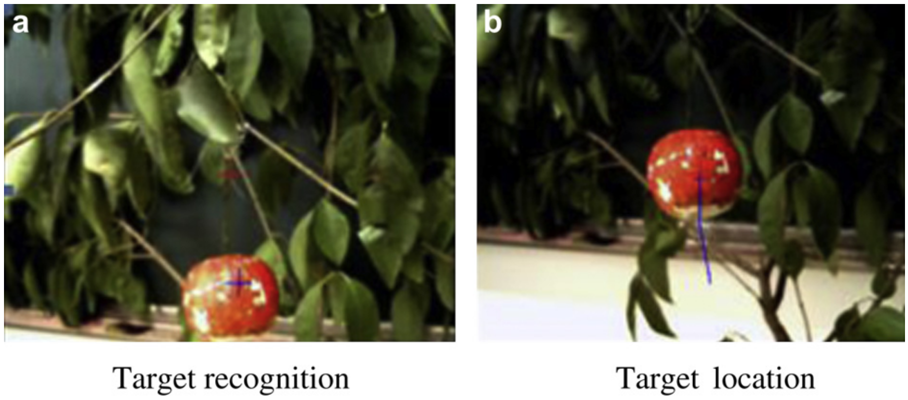


Fig. 14 – Recognition and location results in laboratory tests.

system involved video capture, motion control, elongation test of flexible joint and extraction test of prism sub-threads. The main program flowchart for the fruit harvesting robot is shown in Fig. 13.

3. Experiment results

In this section, the results of a feasibility study of the system performed through laboratory tests along with field validation are presented. The laboratory experiments were performed on the prototype operating in simulation working conditions. This stage was helpful to set up and optimise the components of our system. Finally, the performance of the harvesting robot was verified in field tests.

3.1. *Laboratory tests*

3.1.1. *Recognition and Location experiment*

For the control system of the fruit harvesting robot, live video windows on the control software interface was used to display the real-time process of picking. Target recognition windows showed the accuracy of target recognition, where red "+" implied image centre and blue "+" implied the centroid of the object fruit. The position of object fruit could be easily shown in the images. In the target location windows, the track the centroid of target fruit with regard to image centre during the location process was marked with a blue line.

Recognition and location test results of object fruit can be seen in Fig. 14. It is obvious that in the figure, accurate recognition and smooth location track made following fruit grabbing possible, which verified that the designed robot has good tracking performance to meet the requirements of accurate real-time recognition and location.

During the process of picking operations, video image signals needed to be acquired dynamically and continuously, and handled frame by frame. In the video, the size of one frame of dynamic images was 320 × 240 pixels. The recognition time for 100 continuous and dynamic images is shown in Table 2.

From Table 2, the average recognition time of 100 frame images was 352 ms. From these results, it was concluded that the developed recognition algorithm met the requirements of real-time operation and that the system could be used to guide a robot manipulator as it approached an apple in real-time.

3.1.2. *Harvesting experiments*

A photograph of the fruit harvesting robot operating during laboratory simulation harvesting tests is shown in Fig. 15. Under laboratory conditions, apples with radius about 40 mm, were hung on fresh branches in different directions. The period of image acquisition was 100 ms. 100 picking tests were carried out in 10 different positions.

The test results were as follows: successful picking occasions 86, and failed occasions 14. Therefore the success rate was 86%. Without regard to the set-up time, the average time of picking one apple is 14.3 s. This was high enough to meet

Table 2 – Dynamic images recognition time.

Image frame	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Recognition time(ms)	235	235	315	390	315	310	390	390	310	390	390	310	390	310	235	315	390	390	310	390	390	390	315	390	395
Image frame	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Recognition time(ms)	310	390	390	310	315	390	390	315	310	390	390	310	390	390	310	390	390	310	315	390	315	310	390	390	390
Image frame	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
Recognition time(ms)	315	390	395	310	390	390	310	315	390	390	315	310	390	390	310	390	390	310	390	390	310	315	390	395	310
Image frame	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
Recognition time(ms)	315	390	310	315	390	395	310	390	390	310	390	390	310	315	390	390	310	315	390	390	315	390	390	315	390

Fig. 15 – Harvesting experiments in laboratory tests.

Fig. 17 – Harvesting experiments in an orchard.

requirements of continuous harvesting operations. The main reasons for failure could be attributed to the experimental environment, where the soft foliage and apple vibration during operation resulted in a decrease in precision positioning. In addition, occasionally the cutting knife failed to cut the apple stalk.

3.2. *Field tests*

To further verify the reliability and adaptability of harvesting robot system, field tests were carried out in the Beijing Changping orchard during October 2009.

The recognition result in the orchard is shown in Fig. 16. There 7 apples were well recognised, which indicated that the recognition algorithm could identify apples efficiently. Where apples are behind branches and leaves and apples cover each other, the apples cannot be picked directly. Those without label "+" in Fig. 16, would be recognised after picking a certain number of apples.

In practice, once an image such as that in Fig. 16 was acquired, the vision system of robot located and picked the apple which had the minimum distance from the image centre of the visible-field of the camera. The vision system of robot located the next target fruit. Continuously picking

Fig. 16 – Apple recognition results in an orchard.

experiments (shown in Fig. 17) were carried out in an orchard with a complex environment. In 10 min, 39 apples were recognised, of which 30 apples were picked and put into the container successfully. Six apples failed to be picked since their image was blocked by branches. Three were picked but fell down to the ground due to their small size and the gripper not clamping tightly. After calculation, the mean recognition time for picking was 15.4 s and the picking success rate was 77%, which indicates that the prototype machine and control system could be used to carry out the picking operation outdoors.

4. Conclusions and future research

A self-developed fruit harvesting robot and its control system was developed. The main components of the robot, i.e., the manipulator, the end-effector and the image-based vision servo control system, have been described in detail. The manipulator was geometrically optimised to gain a quasi-linear behaviour and simplify the control strategy, and the end-effector with the pneumatic actuated gripper was designed to satisfy the requirements for the harvesting of apples. The harvesting robot autonomously performed its harvesting task using a vision-based module to detect and localise the apple in the trees, and control system regulated the manipulator and the end-effector to approach and pick the apples. The validity of systems was confirmed by performing laboratory tests and field experiments in an open field.

Future research needs to be focused on the following three aspects for practicability and the commercialisation of the robot: (1) optimisation of the existing software programs and algorithms to reduce computation. At the same time, improving the speed and accuracy of picking for the blocked or swinging fruits thereby increasing the practicallity of the robot; (2) considering the complexity and unknown nature of working environment, the further research should be focused on real-time obstacle avoidance, improving picking success rate and harvesting efficiency; (3) improving the mechanical structure of the robot to enhance the configuration. For example, by replacing the manipulator and end-effector with different systems or using different freedom degrees to pick fruit with different shapes and sizes, to achieve all-purposes of the robot. This would increase its versatility, lower its overall cost, and promote its commercialisation.

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