Overview of research on agricultural robots in China

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Abstract: As the representation of new concept agricultural machinery, agricultural robots possess great advantages of improving agricultural productivity, enhancing production environment and solving the problem of labor shortage. Therefore, the strategy for application of agricultural robots and precision agriculture to improve the intelligence and information level of agriculture is the inevitable trend for China's agriculture in the twentieth century. Based on the developmental status of agricultural robots in China, the agricultural robots are categorized and the performances, structures and characteristics of various agricultural robots such as vegetable grafting robots, transplanting robots, spraying robots, mowing robots, harvesting robots, grading and detecting robots are amply introduced. It can be seen that vegetable grafting robots, spraying robots, harvesting robots, grading and detecting robots have already been put into production while others are still at experimental stage. At present, there are several problems such as low popularization, great limitations, high cost and low intelligence, which greatly restrict the development of agricultural robots in China. Thus, open agricultural robot system with good expansibility, generality and flexibility should be developed and adopted to decrease its cost and shorten developing cycle. The mechanical structure of robots should also be designed as simply as possible. Finally, multi-robot system would become another important development direction of agricultural robots in the future.

Key words: agricultural robots; robots for facility breeding; robots for field management; robots for harvesting; robots for grading and detecting

DOI: 10.3965/j.issn.1934-6344.2008.01.012-021

Citation: Zhang Libin, Yang Qinghua, Bao Guanjun, Wang Yan, Qi Liyong, Gao Feng, et al. Overview of research on agricultural robots in China. Int J Agric & Biol Eng. 2008;1(1): 12－21.

1 Introduction

It is well known that China is an agricultural country and agriculture is the foundation of national economic and social development. Currently, China is encountering the serious problem of population aging and labor shortage, which in turn lead China's agriculture to suffer from the unbalance of economic development, resource allocation and the deterioration of environment. In order to achieve sustainable, stable and coordinated development of agriculture, Chinese government has established the policy of prospering agriculture by science and technology. And the approach of substituting resources for technology is the inevitable choice of China's agriculture of the twentieth century [1]. Since it is necessary that the precision agriculture and agricultural robots are used to improve the resource utilization and agriculture output ratio, reduce labor intensity and enhance economic benefits, research and development of agricultural robots has important significance to China's agriculture for long term development.

Agricultural robot is a kind of programmable automation or semi-automation equipment to deal with agricultural products, which has functions of human perceptions and actions. Compared with industrial robots, it exhibits the following features [2]: the first one is the fragility and complexity of the operation object; the second one is the non-structure of the operation environment; so agricultural robots not only have to own the function of handling crops, but also adapt to the variable natural environmental conditions. The third one is the complexity of the operation process; and the last one is the particularity of their cost and users. Therefore, agricultural robots should own the properties of reliability and easy operation because their users are farmers with little mechanical and electrical technology. Moreover, the cost of agricultural robots should be reduced to promote the popularization and application.

Agricultural robots have been studied in the developed countries since 1980s, some of which have

Received date: 2008-06-18 Accepted date: 2008-07-28

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been applied in agriculture production. Though research on agricultural robots in China is still at the starting stage, some favorable achievements have been obtained. At present, the agricultural robots that have been developed in China are as follows: vegetable grafting robots, transplanting robots, spraying robots, mowing robots, fruit and vegetable harvesting robots, grading robots, detecting robots, and so on. According to robots used in different growing periods of crops, agricultural robots can be divided into four categories: robots for facility breeding, robots for field management, robots for harvesting, and robots for grading and detecting.

2 Robots for facility breeding

2.1 Grafting robots

The SJZ-1 vegetable grafting robot with inarching method, designed by Weifang Agricultural Machinery Institute in 1997, consisted of motor, control system, operating mechanical and so on. It can work in continuous or discontinuous modes according to actual demands, and its maximum working rate is 310 seedlings per hour and the survival ratio is 95%[3]. Though it has properties of accurate grafting and high survival ratio, its grafting rate is only 2.5 times as much as that of manual grafting, which makes it unsuitable for large-scale production of grafting.

Compared with SJZ-1 vegetable grafting robots, the grafting rate of vegetable grafting robots jointly developed by Changchun Automation Company and Korea has enhanced a lot[4,5], which is mainly used for grafting of melon and solanaceous vegetables. Its highest working speed comes up to 540 seedlings per hour and the survival ratio is 90%. However, it cannot realize the industrialization of grafting production because it still needs operations of conveying and picking seedlings by human labor.

In 1998, Zhang Tiezhong from China Agricultural University successfully developed 2JSZ-600 vegetable grafting robots with close joining method, as shown in Figure 1. It realizes the automation of grafting robot production such as conveying, cutting, holding of stocks and scions. Its working rate can come up to 600 seedlings per hour and it can be used for grafting cucumber, watermelon, muskmelon and other melon seedlings[6]. It had been given a high appraisal for its reliable grafting performance and other superior technical indexes in China's Achievements Exhibition for the 15th Anniversary of Hi-Tech Research and Development Program of China (863 Program). Furthermore, from 2004 to 2006, students of Zhang Tiezhong did a lot of researches on the mechanical structure optimization of the traditional vegetable grafting robots, and developed grafting robots for nutritional bowl seedling of vegetables[7], grafting robots for aperture tray seedling of tomato[8], tube jointing device of grafting robots[9], respectively, which enhanced grafting accuracy, survival ratio and possessed higher automation and intelligence level, as shown in Figure 2 and Figure 3 .

Figure 1 2JSZ-600 vegetable grafting robot

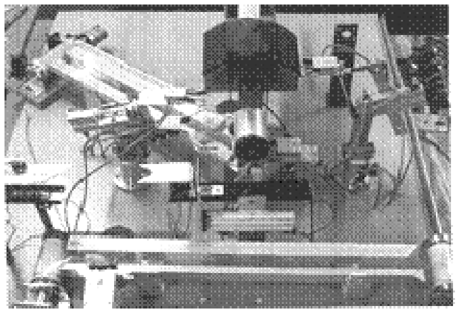

Figure 2 Grafting robot for nutritional bowl seedling of vegetables

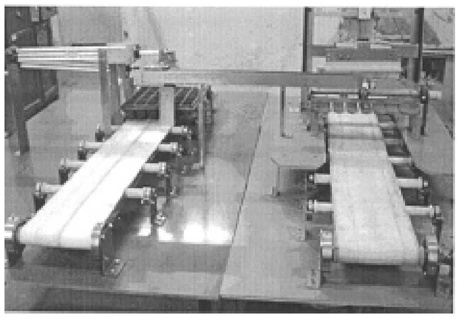

Figure 3 Grafting robot for aperture tray seedling of tomato

Nowadays, most of truck farmers and small-middle breeding centers of seedling still cannot afford to the grafting robots due to high costs. Therefore, Gu Song from Northeast Agricultural University developed the 2JC-350 semi-auto grafting machine with cut grafting method for vegetable seedling in 2006, as shown in Figure 4. It has properties of easy operation，high grafting survival ratio and so on. Moreover, the remarkable feature of 2JC-350 is its low price with only about 5000 RMB Yuan, so it has a wide application prospect among small and middle grafting centers[10].

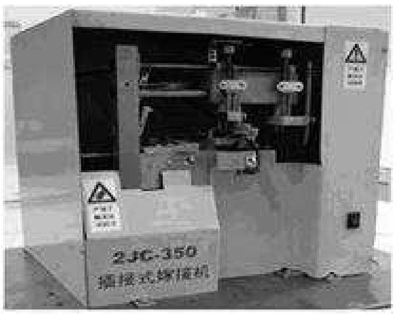

Figure 4 2JC-350 grafting robot with cut grafting method

2.2 Transplanting robots

Though the operation of vegetable transplanting is simple, it needs a lot of manual labor. The average transplanting rate of human labor is just 300～800 seedlings per hour, so it is hard to keep high efficiency if people work continuously.

The body part of transplanting robots designed by K.C.Ting and Y.Yang in 1998 consisted of 4-DOF industrial robots ADEPT-SCARA and SNS gripper, as shown in Figure 5. The vision sensor on the top of the robots is used to identify the size and position of the aperture disks and seedlings, and the force sensor ensures the gripper to hold vegetable seedlings without harming them. The time taken by transplanting one seedling is about 2.60 s to 3.25 s[11]. However, the robots cannot be widely used in pipelining production of automation because of the drawback of poor universality which is restrained by the Degree-of-Freedom(DOF) and operating space of SCARA robots.

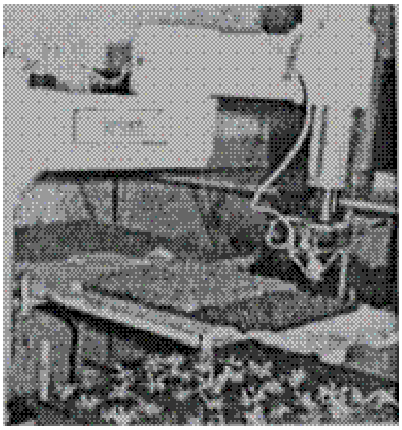

Figure 5 Transplanting robot designed by K.C.Ting and Y.Yang

In 2005, Yang Li from China Agricultural University developed a 5-DOF articulated robot which can pick up and cut tissue culture plantlets automatically, as shown in Figure 6. According to the characteristics of the plantlets in bottle, the identification algorithm based on machine vision technology was put forward. Experimental results show that the accuracy and time using the algorithm for identification of the position of every plantlet in bottle are 92% and 0.226 s, respectively. But the success ratio of picking up and cutting plantlets is just about 70% since the kinematical positioning accuracy of reaching the setting range is only about 75%[12]. Though the performance of the complete machine is not perfectly good, the study of the robots lays a foundation for realizing automatic production of cutting and transplanting tissue culture plantlets.

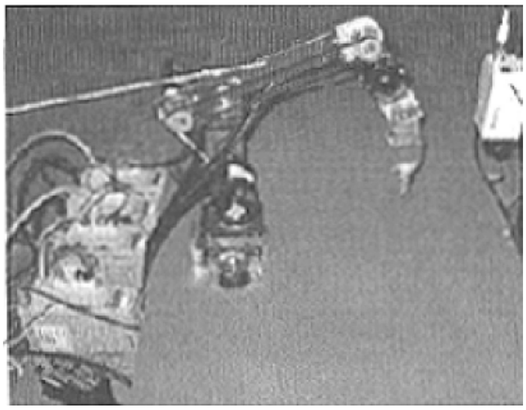

Figure 6 Transplanting robot for tissue culture plantlet

In addition, a new type of fully decoupled, three translation parallel transplanting robot was designed on the basis of 3-CRR model machine by Yu Yufeng from Jiangsu University in 2007, as shown in Figure 7. CMOS transducer camera with low-priced USB interface was used as the apparatus of vision gathering system, which reduced the systematic hardware cost and simplified the structure of the vision system, and was favorable to promote the popularization and application of machine vision in agriculture[13].

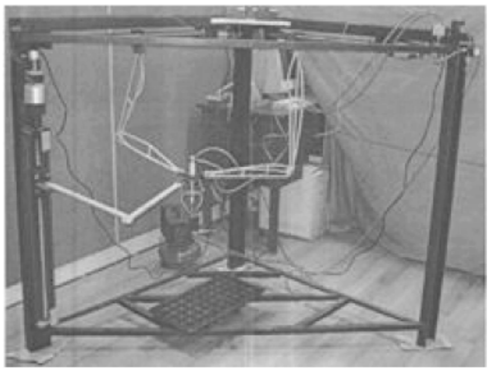

Figure 7 Three translations parallel transplanting robot

3 Robots for field management

3.1 Spraying robots

Spraying operation plays an important role in protecting agriculture because of its functions of killing weeds by herbicide and preventing diseases and pests of crops by insecticide. In order to improve labor conditions and prevent injuries for operators, spraying robots are designed to execute spraying operation instead of human beings.

Jiangsu University of Science and Technology started the research on target spraying in 1995, and then successfully designed an experimental platform of target spraying with ultrasonic wave detection technology in 1997. Later in 2001, they developed a new type of pesticide sprayer, that is, an orchard automatic target sprayer based on technologies of infrared photoelectric detecting and automatic control, by cooperating with China Agricultural University, Chinese Academy of Agricultural Mechanization Science and Suzhou Agricultural Chemicals Machinery Company, as shown in Figure 8. The sprayer can intermittently spray by detecting its target with an infrared sensor automatically, and compared with continuous spraying, it can save 50%～75% of pesticide consumption[14, 15].

Figure 8 Orchard automatic target sprayer

Thereafter, Jiangsu University continued to carry out study on sprayer, and in 2006, Qian Guojun and Qiu Baijing developed a variable spraying equipment by integrating AgGPS132 receiver, AS-RF robots with caterpillar tread and SCS450 variable spray controller, as shown in Figure 9. The robots can realize real-time collection of GPS position information and transmit the spray information to SCS450 spray controller to operate the variable spray. The error of the variable spray is less than 10%. The research of spraying robots supplied possibility for the accurate operation of variable spray and offered theoretical and practical basis to develop spray robots which could be applied in precision agriculture[16]. On the basis of the variable spraying robots, Yao Biao designed the wireless remote monitoring and control experimental system, and also designed software platform based on Customer/Server's truss by combining with the specialty of spraying robot task environment. The system adopted supervisory control mode and reoccurred the robot working circumstance and state by technology of state and visual feedback [17].

From 2005 to 2006, Yu Shufeng, Xu Haijun and Zhang Bin from China Agricultural University developed a control system for spraying robots guided by electromagnetic induced line to realize automatic spraying in greenhouses, and especially designed remote controlling and monitoring of the robots by wireless frequency-modulation, as shown in Figure 10. The system consisted of robot body, monitor and induced signal switch-group, which are connected to a wireless communication network to finish fully automatic spraying by exchanging real-time data during spraying operation [18-20].

Figure 9 Variable spraying robot

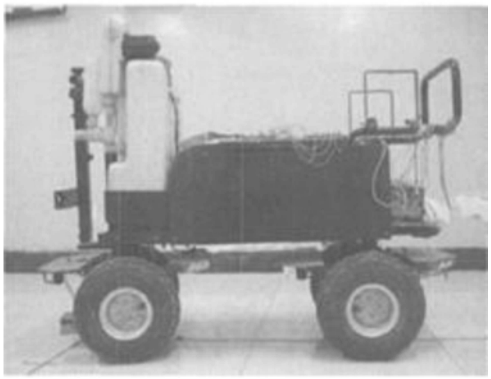

Figure 10 Spraying robot guided by electromagnetic induced line

In 2005, Chen Yong from Nanjing Forestry University developed an autonomous robot for weed control with direct herbicide delivering method which could minimize herbicide dosage and droplet drift, as shown in Figure 11. The system was composed of a digital camera, a computer, walking system, chemical delivering system and robot body. The robot manipulator would cut weeds and mop chemical onto their cutting surfaces when weeds were identified in the field by machine vision system. Experiments both in field and greenhouse showed that about 90% of herbicide could be saved [21].

3.2 Mowing robots

From 2002 to 2003, Wang Huashen, Yue Feng and Cheng Zhengjiang from Nanjing University of Science and Technology successfully developed MORO-I, MORO-II mowing robots based on a new solution of the boundary set-up and identification of unmarked work area, as shown in Figure 12 and Figure 13. Combined localization systems of photoelectric encoder and magnetic heading sensor were used to establish the digital map of boundary and acquire the current position of mobile robots to judge whether the boundary reached during the course of working. The research of MORO robots offers valuable support for region-coverage mobile robots [22-24]. Moreover, Shen Na and Wang Jinzhen applied advanced technology of robots in mowing robots, such as the control technology of robots based on Internet and the key technology of solar mower [25, 26].

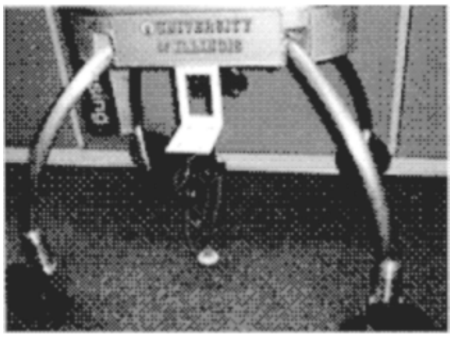

Figure 11 Autonomous robot for weed control

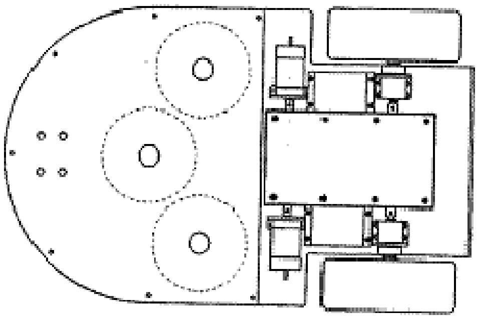

Figure 12 Structural diagram of MORO mowing robots

Different from MORO mowing robots, Zhou Ning and Ding Yi from Jiangsu University developed a mowing robot of caterpillar tread in 2005, which was composed of AS-RF robot and self-designed mowing platform, as shown in Figure 14. The combined navigation system of GPS/DR, which consisted of GPS receiver, digital compass and photoelectric encoder, was applied in the robots. Meanwhile, its adaptive Kalman filter model was also established to enhance the positioning precision of the robots[27, 28].

Figure 13 MORO mowing robots

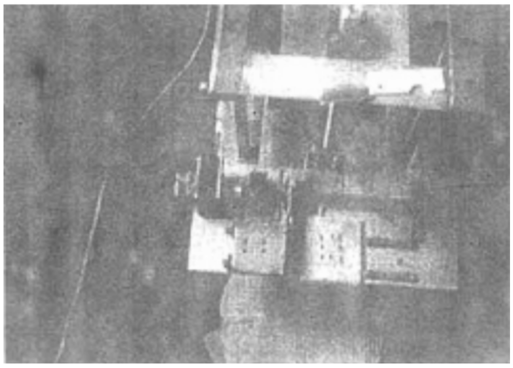

Figure 14 Mowing robot of caterpillar tread

However, the foregoing mowing robots cannot be widely applied in agriculture practice due to their high costs. Therefore, Jin Ligang from Dalian University of Technology designed an economical mowing robot with simple tricycle structure based on the successful experiences of autonomous mower robot development. And aiming at the height of different lawns, the rise and fall mowing cutter head was designed to ensure the adaptability and universality of the mowing robots [29].

4 Robots for harvesting

4.1 Strawberry harvesting robots

In 2005, a strawberry harvesting robot was developed by Zhang Tiezhong, Xu Liming, et al. from China Agricultural University [30-35], as shown in Figure 15. The robot with an open-control system uses a 3-DOF rectangular coordinate manipulator and an end-effector for picking. Its vision system consists of two CCD cameras and two digital image acquisition cards. Experimental results show that the strawberry picking point error is less than 3 mm by applying BP neural network image segmentation algorithm and using feature extraction to focus on the barycenter and picking point of strawberry. Indoor experiments show that the gripper grasp success rate is 89.1%, gripper positioning accuracy is ±1.5 mm, fruit stem cutting rate is 95.1%, and picking time per piece is 9.39s. However, the robot was designed without mobile mechanism. In order to harvest greenhouse strawberry automatically, the navigation and mobile mechanism should be designed and the picking speed should also be increased in the future.

4.2 Tomato harvesting robots

The manipulator of tomato harvesting robots has been researched by Liang Xifeng from Zhejiang University since 2004[36]. According to the characteristics of tomato harvesting, a 7-DOF manipulator for tomato harvesting has been selected, and its kinematical analysis and simulation were done to provide a foundation to develop tomato harvesting robots in the future.

In 2006, Zhao Jinying, Zhang Tiezhong et al from China Agricultural University [37] designed a 5-DOF joint manipulator and a 2-finger mechanical gripper to harvest tomatoes, as shown in Figure 16. In the laboratory environment, the absolute error of gripper positioning accuracy can be controlled within less than 10mm but the grasp success rate is only 72%. Thus the main problem needed to be solved is to improve the positioning accuracy of its end-effector.

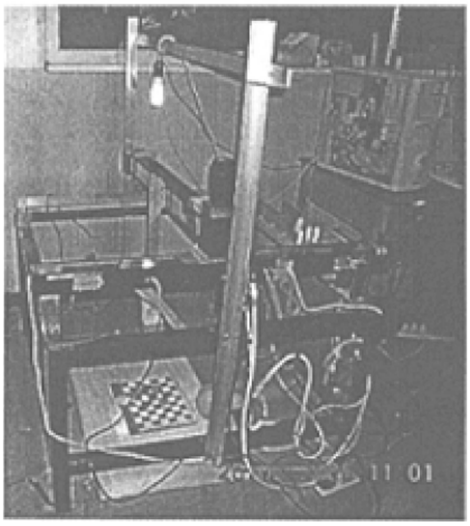

Figure 15 Strawberry harvesting robot

Figure 16 5-DOF manipulator and 2-finger mechanical gripper

Besides, the positioning of tomatoes using binocular stereo vision was researched by Zhang Ruihe, Ji Changying, et al. from Nanjing Agricultural University [38]. The results show that when the distance between the target and camera is 300~400 mm, the depth error can be controlled in the range from 3% to 4%.

The research on tomato harvesting robots in China focused on designing and analyzing manipulator, end-effector and identification and location of tomato without a complete robot, which was the main problem needed to be solved recently.

4.3 Cucumber harvesting robots

In 2007, a cucumber harvesting robot FVHR-I was developed by Tang Xiuying, Zhang Tiezhong, et al. from China Agricultural University[39,40], as shown in Figure 17. There are six degrees of freedom in the robots including one rotating and one vertical movement freedom in the body, one stretching freedom in the stern, and three rotating freedoms in the waist. The robots are driven by stepper motor with a relatively simple structure and easy to control. Its end-effector is composed of an active cutting edge and a fixed cutting edge with high efficiency. An algorithm of image segment based on G component of RGB color model is used for segment processing of cucumber images with a success rate of 70%. The picking point could be positioned by its visual system. The experimental results show that the movement positioning accuracy can be controlled in the range of ±2.5 mm, and the picking success rate is 93.3% by the end-effector. But the identification accuracy of cucumber needs to be improved in the future, and the calculation method using straight line connecting position of the picking point which gives a not-so-accurate result needs to be improved in the future too.

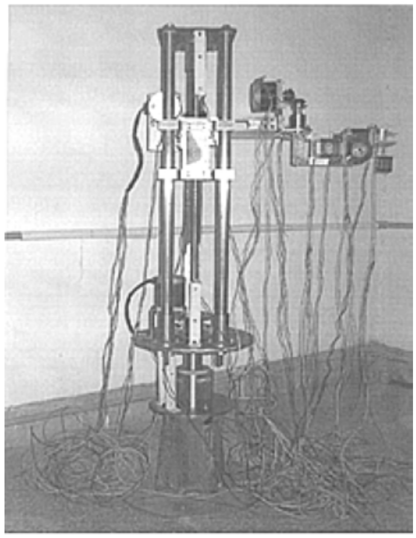

Figure 17 Cucumber harvesting robot

4.4 Eggplant harvesting robots

In 2006, a 4-DOF prototype for picking eggplant was developed by Song Jian, Zhang Tiezhong, et al. from China Agricultural University[41], as shown in Figure 18. A segmentation algorithm based on region growth was proposed by melting the G-B color mode and spatial information with a segmentation efficiency of 92%. Test results show that the repetitious orientation precision is in the range of ± 2.5 mm, and the measured error is within ±18 mm when the measured distance ranges from 275 mm to 575 mm with the method of single camera and two-step measuring distance. The picking success rate is 89% with an average time 37.4 s consumed. The robot working efficiency is not as high as expected mainly because of the limitation of image process algorithm and control algorithm. Thus, in order to improve the working efficiency, the algorithms need to be simplified.

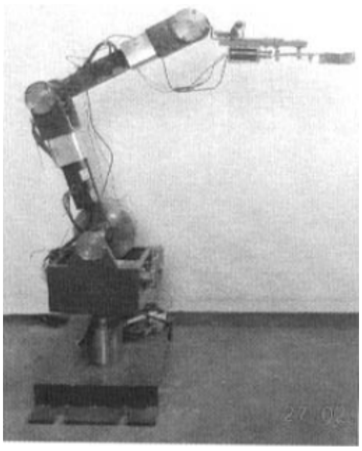

Figure 18 Prototype for eggplant harvesting

4.5 Conifer cone collection robots

In 1997, a conifer cone collection robot was developed by Lu Huaimin, Jiang Haichao et al. from Northeast Forestry University[42,43], as shown in Figure 19. It consists of a manipulator, a walking mechanism, and a hydraulic drive system. The manipulator with 6-DOF and the SCM control system is fixed on the upper body of a walking tractor. There is a collecting claw on top of the manipulator which can pick cones in the internal crown. The robots can collect about 500 kg larch cones per day and its efficiency is about 30 to 35 times higher than that of a worker who picks cones by hand. Therefore, the robot has a good prospect.

Figure 19 Conifer cone collection robot

4.6 Flexible pneumatic picking robot end-effector

From 2001, a new type of flexible pneumatic actuator (shortened as FPA) was developed in Zhejiang University of Technology[44], which featured good flexibility, high power/weight ratio, smooth movement, low noise and non-pollution. Based on FPA, a series of flexible pneumatic joints were proposed, such as bending joint[45], torsion joint[46] and spherical joint[47]. These joints are directly driven by compressed air and no transmission mechanism is needed. So they are both drivers and actuators. In 2006, the adaptive fruit picking end-effector was developed based on flexible pneumatic torsion joint and flexible pneumatic bending joint[48], as shown in Figure 20. The torsion joint works as the wrist and the bending joints serve as the fingers. The gripping model and holding model of the flexible picking end-effector are established and verified by experiments. This picking end-effector is flexible, adaptive and safe for grasping objects, which can be adopted in agricultural fruit harvesting robot research.

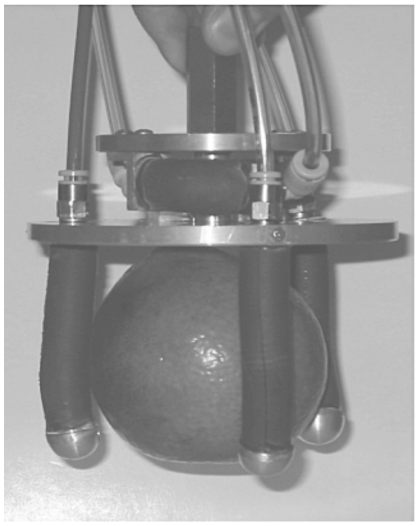

Figure 20 Flexible picking robot end-effector

5 Robots for grading and detecting

5.1 Robots for detecting and grading eggs

In 2006, an autonomous robot for detecting and grading eggs was developed by Wang Shucai, Wen Youxian from Huazhong Agricultural University[49, 50]. A vacuum sucker used as end-effector is developed taking the friability of the egg into account. The principles of the system are as follows: First, a scene video camera captures the image of massive members of eggs. Through image processing, the central coordinate and the major axis direction of each egg are obtained. Then the end-effector is guided to move to the egg centre and fetch the egg. Then the egg is moved to the knocking device to test the eggshell. After fresh testing, the robot motion controller drives the manipulator to put the eggs in corresponding eggcrate according to the grading information. Through eggshell percussion voice recognition, the recognition accurate ratios for cracked and uncracked eggs are 95% and 90%, respectively.

However, the system could only suck one egg once which caused a low efficiency that could not meet the real needs. Thus a group of suckers could be installed on the end-effector, and more eggs could be processed in one step which could greatly improve the efficiency of detection.

5.2 Robots for fruit quality detecting and grading

In 1996, research on detecting apples automatically was firstly done by Liu He and Wang Maohua from China Agricultural University[51,52]. A computer image system for automatically apple-defect detecting is established according to optical reflection characteristics of apples. As the position and size of the defects cannot be forecasted, a method to detect defects pixel monotonically based on knowledge and a method to judge the defect region are proposed. Experimental results show that the system has a high occurrence of defects detecting and can eliminate the influence of the stalk and calyx effectively.

From 1999, a lot of researches on fruit detecting and grading such as apples, Huanghua pears etc were done by Ying Yibin, et al. from Zhejiang University[53, 54]. In 2004, the first production line for fruit quality inspection and sorting based on machine vision in China was developed by the team of Ying Yibin[55], as shown in Figure 21. Its image processing software extracts the appearance characteristics of each fruit such as shape, size, color and skin roughness firstly, and then analysis and judgment are done to determine its grade. After the position sensor determines the location of the fruit, the controller gives an order to the actuator which makes the fruit fall into corresponding grade position. Thus the fruit grading is achieved. The production line can detect the appearance characteristics such as shape, size, color and skin roughness of fruit in real-time and sorting fruits which can deal with 3−6 tons of fruit per hour.

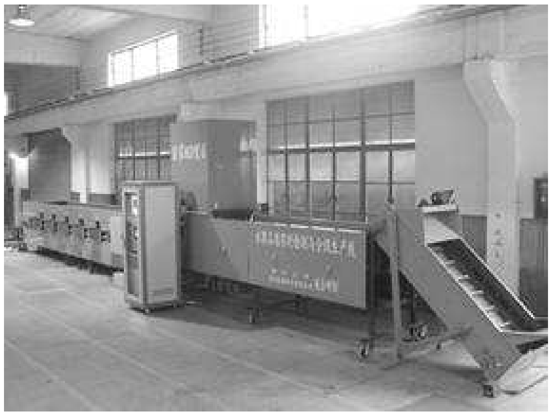

Figure 21 Production line for fruit quality inspection and sorting developed by Ying Yibin's team

It can be seen that currently this production line is the most mature fruit detecting and sorting line in China, which has achieved the commercialization successfully. The production line has been sold to Jiangxi Province, Sichuan Province and other places. However, with the development of fruit commercialization, there is still a lot of work to do, such as detecting the internal quality of the fruit and rapid detecting the security indicators of fruit, so as to solve the food safety problems.

6 Problems and prospects

From the above, it can be seen that though some achievements have been obtained in research and development of agricultural robots, there are still several problems:

1) Low popularization: although there are some agricultural robots appearing in the market, such as grafting robots and fruit quality inspection and sorting production line, etc, most of agricultural robots still stay at the laboratory stage, such as fruit harvesting robots, which are not widely used in the production.

2) Great limitations: at present, the agricultural robots in China are only applied in specific environment. They cannot meet the needs of diversity of agricultural production, the diversity of operating targets, and the complexity of the operating environment. So one robot can only be used for specific single operation of single crop, for example, strawberry harvesting robot is only used to pick strawberry in the greenhouse and cannot be used in any other environment. That makes a great limitation.

3) High cost: a large number of high-tech hardwares and softwares are used in the agricultural robots, and the researchers spend a lot of time and energy on the research, so the cost is high.

4) Low intelligence: at present, the picking rate and

picking speed of harvesting robots are not high enough, which does not achieve the desired level of intelligence.

Consequently, the research on agricultural robots in China is just at the starting stage, and there are many problems needed to be solved. In order to make the agricultural robots used widely, the robots should be developed in the following aspects in the future:

1) Simple mechanical structure and acceptable cost: the flexibility of robot movement and the complexity of control are determined directly by mechanical structure. Therefore, under the premise that the performance of robots should be met, the mechanical structure should be as simple and light as possible. The simple structure can also reduce the cost of robots. To promote popularity of agricultural robots, costs must be controlled within an acceptable range.

2) Open agricultural robot system: an open agricultural robot system has characteristics of good expansibility, generality and flexibility. A common robot consists of three major components: mechanism, sensor and controller. It becomes easier to meet the needs of different types of crops by changing the mechanical parts which have different degrees of freedom. The controller retains sufficient interface in order to control the mechanism and receive the sensor signals. One unit with multi-usages which needs to be widely used in future is a good way to improve the ratio of performance to price and the efficiency.

3) Agricultural multi-robot system: nowadays, the agricultural robots in China are all single robots, which mean that they have great limitations in information acquisition, task processing etc. This leads to the low working efficiency. Since multi-robot system can complete complex production task through coordination and collaboration, it has a broad prospect and can become an important development direction for agricultural robots.

Acknowledgements

This work is financially supported by the Natural Science Foundation of China (50575206) and the National High-Tech Research and Development (863) Program of China (2007AA04Z222).

[References]

[1] Shen Mingxia, Ji Changying. The development background and technology trend of agricultural robot. Research of Agricultural Machinery. 2000; (5):31-35.

[2] Tian Subo. Development of agricultural robots at home and abroad. Agricultural Science & Technology and Equipment. 2007; (2):3-5.

[3] Liu Fengmei, Sun Souming. Research of SJZ-1 vegetable grafting robot. Machinery for Agriculture and Food Processing. 1997; (6):27.

[4] Li Zhongqiu. Research actuality and view of grafting robot for vegetable. Contemporary Farm Machinery. 2007; (6): 61-62.

[5] Li Dengshun. Grafting robot for vegetable. Beijing Agriculture. 1997; (12):35.

[6] Song Jian, Zhang Tiezhong, Bin Zhang, et al. Research on actuality and view of picking robot for fruit and vegetable. Journal of Weifang University. 2005; 5(4): 1-5.

[7] Yan Junjie. Research on grafting robot for nutritional bowl seedling of vegetables. MD dissertation. Beijing: China Agricultural University. 2004; 55p.

[8] Chen Wengui. Research on grafting robot for aperture tray seedling of tomato. MD dissertation. Beijing: China Agricultural University. 2006; 47p.

[9] Tan Nike. Research on tube jointing device of grafting robot. MD dissertation. Beijing: China Agricultural University. 2005; 47p.

[10] Gu Song. Research on 2JC-350 automatic grafting machine with cut grafting method for vegetable seedling. Transactions of the CSAE. 2006; 22(12): 103-106.

[11] Yun Zhao, Wu Chuanyu, Hu Xudong, et al. Research progress and problems of agricultural robot. Transactions of the CSAE. 2003; 19(1): 20-24.

[12] Yang Li. The research of the cut and transplanting robot for tissue culture plantlet. PhD dissertation. Beijing: China Agricultural University. 2005; 132p.

[13] Yu Yufeng. Research on machine vision system of the three translation parallel transplanting robot. MD dissertation. Zhenjiang: Jiangsu University. 2007; 87p.

[14] Sun Hongxiang. Research on object detecting system of the orchard automatic target sprayer. MD dissertation. Zhenjiang: Jiangsu University. 2003; 57p.

[15] Yuan Xiangyue, Wu Chundu, Chu Jinyu, et al. Research of orchard automatic target sprayer. Shangdong Agricultural Machinery. 2004; (4): 9-11.

[16] Qian Guojun. Research on control system of variable sprayer. MD dissertation. Zhenjiang: Jiangsu University. 2006. 64p.

[17] Yao Biao. Research on wireless remote monitoring and control experimental system of spraying robot. MD dissertation. Zhenjiang: Jiangsu University. 2007; 56p.

[18] Yu Shufeng. Research on control system of spraying robot guided by electromagnetic induced line. MD dissertation. Beijing: China Agricultural University. 2005; 56p.

[19] Yang Shisheng, Zhang Bin, Yu Shufeng, et al. Design and implementation of the navigation system for an electromagnetic guided agricultural spraying robot. Robot. 2007; 29(1): 78-81.

[20] Xu Haijun. Research on embedded control system of spraying robot. MD dissertation. Beijing: China Agricultural University. 2006; 61p.

[21] Chen Yong. Researches on autonomous robot for weed control and smart spray based on variable rate technology. PhD dissertation. Nanjing: Nanjing Forestry University. 2005; 74p.

[22] Chen Zhengjiang. Researches on control system and architecture of out-door autonomous mobile robot. MD dissertation. Nanjing: Nanjing University of Science and Technology. 2002; 78p.

[23] Fan Mingxuan. Researches on multi-sensor system and strategies of obstacle avoidance of the region filling mobile robot. MD dissertation. Nanjing: Nanjing University of Science and Technology. 2003; 69p.

[24] Yue Feng. Researches on boundary set-up and identification of unmarked work area for region-coverage mobile robot. MD dissertation. Nanjing: Nanjing University of Science and Technology. 2003; 79p.

[25] Shen Na. Research on control of mobile robot based on Internet. MD dissertation. Nanjing: Nanjing University of Science and Technology. 2004; 69p.

[26] Wang Jinzhen. Research on key technologies of solar mower. MD dissertation. Nanjing: Nanjing University of Science and Technology. 2004; 80p.

[27] Zhou Ning. Research on motion control and mowing platform of the mowing robot. MD dissertation. Zhenjiang: Jiangsu University. 2005; 73p.

[28] Ding Yi. Research on strategies of navigation and position of mowing robot based on GPS and DR. MD dissertation. Zhenjiang: Jiangsu University. 2004; 68p.

[29] Jin Ligang. Research and development of autonomous robot lawn mower. MD dissertation. Dalian: Dalian University of Technology. 2006; 67p.

[30] Zhang Tiezhong, Zhou Tianjuan. Strawberry harvesting robot: Ⅰ. Segmentation of strawberry image by BP neural network. Journal of China Agricultural University. 2004; 9(4): 65-68.

[31] Zhang Tiezhong, Chen Libing, Song Jian. Study on strawberry harvesting robot: Ⅱ. Images based identifications of strawberry barycenter and plucking position. Journal of China Agricultural University. 2005; 10(1): 48-51.

[32] Zhou Tianjuan, Zhang Tiezhong, Yang Li. Study on strawberry harvesting robot: Ⅲ.Application of scan line filling algorithm in vacancy filling of strawberry image. Journal of China Agricultural University. 2007; 12(2): 67-71.

[33] Gao Rui. Pilot study on strawberry harvesting robot. MD dissertation. Beijing: China Agricultural University. 2004; 03. 50p.

[34] Chen Libin. Picking system study on strawberry harvesting robot. MD dissertation. Beijing: China Agricultural University. 2005; 03. 47p.

[35] Xu Liming. System study on strawberry harvesting robot. PhD dissertation. Beijing: China Agricultural University. 2006; 05. 99p.

[36] Liang Xifeng. Study on agency analysis and optimization design of tomato harvesting manipulator, PhD dissertation. Hangzhou: Zhejiang University. 2004; 05. 113p.

[37] Zhao Jinying. Study on tomato harvesting robot based on machine vision. PhD dissertation. Beijing: China Agricultural University. 2006; 05. 133p.

[38] Zhang Ruihe, Ji Changying, Shen Mingxia, et al. Application of computer vision to tomato harvesting. Transactions of the Chinese Society of Agricultural Machinery. 2001; 32(5): 51-53.

[39] Tang Xiuying, Zhang Tiezhong. Robotics for fruit and vegetable harvesting: a review. Robot. 2005; 27(1): 90-95.

[40] Tang Xiuying. Study on harvesting robot for fruit and vegetables. PhD dissertation. Beijing: China Agricultural University. 2006; 05. 119p.

[41] Song Jian. Study on key technology of open eggplant harvesting robot. PhD dissertation. Beijing: China Agricultural University. 2006; 06. 120p.

[42] Jiang Haichao. Develop collecting robot of conifer cone. MD dissertation. Harbin: Northeast Forestry University. 1997; 06. 45p.

[43] Lu Huaimin. Design and test of collecting robot of conifer cone. Transactions of the Chinese Society of Agricultural Machinery. 2001; 32(06): 52-54.

[44] Yang Qinghua, Zhang Libin, Bao Guanjun, Ruan Jian, Research on novel flexible pneumatic actuator FPA, 2004 IEEE Conference on Robotics, Automation and Mechatronics. 2004; 12: 385-389.

[45] Libin Zhang, Guanjun Bao, Qinghua Yang, Jian Ruan and Liyong Qi, Static model of flexible pneumatic bending joint, Proceeding of the 2006 9th Int. Conf. Control, Automation, Robotics and Vision. 2006; 12: 1749-1753.

[46] Libin Zhang, Guanjun Bao, Qinghua Yang, Shiming Ji, Static model of flexible pneumatic torsion joint, Chinese Journal of Mechanical Engineering, 2008, In press.

[47] Bao Guanjun, Zhang Libin, Yang Qinghua, Ruan Jian, Development of flexible pneumatic spherical joint, 2004 IEEE Conference on Robotics, Automation and Mechatronics. 2004; 12: 381-384.

[48] Bao Guanjun. Research on characteristics of flexible pneumatic actuator fpa??? and its application in multi-fingered dexterous hand design, PhD dissertation, Hangzhou, Zhejiang University of Technology. 2006; 05, 110p.

[49] Wang Shucai. A study of autonomous robot detecting and grading eggs. PhD dissertation. Wuhan: Huazhong Agricultural University. 2006; 06. 145p.

[50] Xiong Lirong, Wang Shucai, Ren Yilin, et al. The revision of grade model on egg's weight. Journal of Agricultural Mechanization Research. 2006; 2(2): 104-108.

[51] Liu He, Wang Maohua. Image segmentation in apple automatic grading. Journal of China Agricultural University. 1996; 6(19): 89-93.

[52] Liu He, Wang Maohua. Automatic detection of defects on apple with the computer image technology. Transactions of the Chinese Society of Agricultural Machinery. 1998; 29(4): 81-86.

[53] Ying Yibin, Jing Hansong, Ma Junfu, et al. Shape identification of Huanghua pear using machine vision. Transactions of the Chinese Society of Agricultural Engineering. 1999; 15(1): 192-196.

[54] Jing Hansong. Machine vision used in Huanghua pear detecting and sorting. PhD dissertation. Hangzhou: Zhejiang University. 2007; 06. 145p.

[55] Rao Xiuqin. Research on key technology of product line for fruit quality inspection and sorting based on machine vision. PhD dissertation. Hangzhou: Zhejiang University. 2007; 01. 145p.