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The Application and Future Advancement of Agricultural Harvesting Robot Technology

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Abstract

Against the trend of a reduction in agricultural labour and the scale of development of intelligent agricultural machinery, the traditional way of harvesting by hand is often ineffective and costly. The agricultural harvesting robot, endowed with technologies such as machine vision, deep learning, intelligent control, flexible manipulation, is the technical means of the intelligence automation harvesting of fruit and vegetables. In recent years, with the progress of multi-sensor fusion and three-dimensional visual perception technologies, harvesting robots' performance of the recognition of targets, positioning and grasping stability have been greatly improved. The harvesting robot has been preliminarily applied in harvesting crops such as tomatoes, strawberries and apples. In this paper, the development of agricultural harvesting robot is introduced and focused on its technical problems such as fruit recognition and fruit localization, path planning and flexible grasping. It also summarizes existing challenges, such as limited environmental flexibility and high cost, and provides insights into future trends of development.

Keywords

agricultural harvesting robots, intelligent perception, deep learning, flexible manipulation, smart agriculture

1. Introduction

Against the backdrop of population growth, labor aging, and continuous increases in the scale of agricultural production, labour-intensively used fruit and vegetable picking have indeed reached saturation limits in terms of low efficiency, high cost and poor operational stability. Especially in the fruit and vegetable harvest of high-value product types, labour-intensive production, narrow harvest windows, highly reliant labour expansion, all had become bottleneck impediments to the development of modern agriculture. This also leads to the promotion of picking robot technology to replace or serve as ancillary operators for harvest labour becoming a very key focus for smart agriculture.

Harvesting robot for agricultural harvesting belongs to an integrated intelligent robot, formed by integrating mechanical engineering, automatic control, machine vision, artificial intelligence, agricultural engineering and so on. Its primary work is target recognition, target positioning, path planning, compliant grasping, non-damaging picking work in complex natural environments, which is different from industrial robots working in mechanical and feature states. Agricultural environment changes drastically with the light intensity, is seriously affected by obstructions, has large morphological differences of different fruits and leaves as offsets. There are many difficulties to the perception ability and grasping ability of agricultural harvesting robots [1].

Recently, with the rapid development of deep learning, 3D visual perception technology, soft gripper and mobile robots, agricultural harvesting robots have seen significant advances in targeting recognition precision, efficiency and stability, and demonstrate demonstration applications for harvesting citrus, apples, tomatoes and other crops, which have entered the pilot stage. However, these demonstrations also have many drawbacks, including insufficient recognition ability, poor adaptability in complex environments, low picking speed, high prices and so on, greatly hindering its large scale industrialized application. Therefore, this article systemically reviews and analyzes the main techniques of agricultural harvesting robots, current applications and further development trends, which have significant guiding role for the research and industrialization of intelligent agricultural machinery and equipment.

2. System Composition of Agricultural Harvesting Robots

Based on most agricultural harvesting robots for sale on the market, the system consists of the mobile platform system, perception system and machine execution system.

2.1 Mobile Platform System

The mobile platform is the fundamental carrier of agricultural harvesting robots, and its performance directly affects efficiency, stability, and environmental adaptability. These robots typically operate in semi-structured environments such as greenhouses and orchards, where uneven terrain, narrow passages, and irregular crop layouts pose significant mobility challenges. Therefore, platform design must balance traversability, stability, positioning accuracy, and energy efficiency.

At present, mobile platforms are mainly classified into wheeled and tracked types. Wheeled platforms are widely used in greenhouses due to their simple structure, low energy consumption, and high maneuverability. For instance, Ackermann-steering four-wheel electric platforms have been applied to improve harvesting efficiency [2]. In contrast, tracked platforms are more suitable for orchards and rough terrain, as their larger ground contact area provides better traction and obstacle-crossing ability [3].

However, wheeled systems often suffer from poor traction on soft soil, while tracked systems tend to be more complex and energy-intensive. Future research should therefore emphasize adaptability and intelligence rather than relying solely on locomotion type. Modular chassis design, sensor-based navigation, and intelligent control algorithms can significantly improve mobility and efficiency, enabling better adaptation to diverse agricultural environments.

2.2 Perception System

The perception system forms the technological foundation of the autonomous agricultural harvesting robot, with the research focus of fruit recognition, 3D localization, mature judgement etc. Due to the agricultural environment characteristics, such as strong illumination change, large occlusion of patches and decay fruit distribution, traditional industrial vision-based method cannot be adopted directly.

With the improvement of deep learning technology, studies have proposed Strawberry R-CNN for intelligent identification and counting of strawberry in natural environment. This model attempts some special improvements to improve the accuracy of Faster R-CNN, realizing high recognition accuracy and strong anti-occlusion performance in strawberry recognition [4]. Fusion of instance segmentation technique can also accurately extract contour of fruit, giving feasible data for subsequent grasp point planning and pose estimation. The perception system of agricultural harvesting robots has evolved from traditional image processing to a stage of deep learning and multi-sensor fusion prominent, with considerable progress made in recognition accuracy and environmental adaptability.

2.3 Execution System

The mechanical execution system is the basic part that agricultural harvesting robots can accomplish the picking work. Its major role is to precisely grasp and harvest fruit under the operation of robotic arms and the end-effector. Considering the diversity of fruit shape, complicated distribution and broken fruit by mechanical force, the mechanical execution system design needs to have flexible, stable and non-injurious fruit harvesting capabilities. Robotic arm is responsible for translating and rotating the end-effector in three-dimensional space. Many agricultural harvesting robots have selected the manipulator multi- degrees-of-freedom for increasing flexible operation working in bushes and leaves. Such as a four-arm apple picking robot that is designed to do synchronous harvesting operation in an orchard environment [5]. The system integrates an automatic navigation vehicle base with multiple robotic arms and a fruit collecting device and allows harvest operation in structured orchards.

End-effector is critical to ensuring successful and damage-free harvesting. Because many fruits have delicate skins, which are easily damaged, a rigid gripper will result in bruise for fruits when harvesting. To avoid damage to fruits, researchers fabricated flexible or hybrid grippers with functions of suction, gripping and cutting. For example, a three-fingers end-effector with a retractable suction cup was designed for cluster tomato harvesting and successfully obtained a harvesting success rate more than 90% [6].

Currently, research on mechanical execution system of agricultural harvesters moves towards flexible or adaptive mechanisms from rigid mechanisms. In the future, mechanical materials of soft robot, sensor-based grippers will be the research direction to pursue higher precision grasping and lower fruit damage.

3. Key Technologies for Agricultural Harvesting Robots

3.1 Path Planning and Motion Control Technology

Path planning and motion control technology are important for agricultural harvesting robot to conduct work perfectly. The objective is to plan rational moving trajectory of robot moving around complex orchard environment and ensure that the mobile platform motion is stable and the execution of motion control is sufficiently precise, so that the harvesting task can be completed well. An improved RRT-Connect algorithm named BMGA-RRT Connect was proposed for robotic harvesting task [7]. The algorithm considered adapting step size of motion control, efficient detection of collision using bounding volume hierarchies, and gradient descent based trajectory smoothing algorithm. The experimental results showed that the algorithm can generate smooth, safe and rational trajectory of robotic harvesting tasks.

As to motion control, a four-wheeled agricultural mobile robot for information acquisition in open field addresses the shortcomings of conventional agricultural robots, which were usually built on substitutes with poor structure design and terrain capability. It has a small body structure and strong power system with hub motor and steering motor, and command four-wheel mobile robots by industrial computer and Arduino controller.

In the future, further efforts are expected to focus on the integration of multi-sensor information fusion and intelligent algorithms to improve agricultural robot operational efficiency and stability in actual agricultural fields, through the sensing of real-time environment and autonomous decision-making, thus promoting the intelligence of harvesting robot.

3.2 Fruit Target Recognition and Localization Technology

Recognition and localization of fruit are parts of the perception. The task is to recognize the matured fruit and determine the specific location of them accurately, so that the robot can carry out grasping operations accurately.

Many studies have used YOLO-based deep learning methods for fruit detection. For instance, an improved YOLOv5 framework was designed for natural environment pineapple detection [1]. It enhanced the performance of attention mechanism and loss function and received good detection rate and fast real-time performance. At present, the success rate of harvesting robot is about 90%.

Apart from recognition, accurate localization is needed. In the article, an object-feature-based method was proposed to recognize and locate the fruits and stems of wolfberry under complex lighting conditions [8]. The method effectively discriminated the fruit position with image based on different color space and image segmentation, so as to locate the fruit grasping point.

Overall, fruit recognition and localization technologies developed from image-based processing to deep learning and multi-sensor approaches. Improvements in the efficiency and robustness of these algorithms will further boost the performance of harvesting robots.

3.3 Fruit Target Recognition and Localization Technology

Flexible grasping technology is required for avoiding the damage to fruit in harvesting. Most fruits are fragile and easily squeezed, so traditional rigid grippers are not suitable. Thus, researchers have proposed many flexible end-effectors inspired by biological objects. For example, researchers adopt a biomimetic flexible gripper designed by 3D printing technology to realize greenhouse pepper harvesting [9]. Experiment results show that the flexible grippers can harvest efficiently and avoid fruit damage. Flexible grasping technologies can not only realize good harvesting quality, but also make robots more adaptable to different kinds of crops. Future work may combine soft robots with tactile sensing technologies to realize more precise manipulation.

4. Typical Applications of Crop Harvesting Robots

Based on the key technologies described above, this section presents practical applications of harvesting robots in citrus, apple, and tomato cultivation.

4.1 Citrus Harvesting Robots

Citrus is one of the largest worldwide crop fruits, with high fruit output, the harvested season being concentrated and the field cultivation often taking place in mountain hilly orchard. Therefore, citrus harvesting is labor-intensive work. With a rapid and further ageing of people and labour costs increasing in the world, citrus harvesting robots have received a lot of interest and attention from the industry and academia.

In unstructured natural citrus orchard, the artificial harvesting of citrus still has many difficulties. To meet commercial bottlenecks, one paper put forward a semi-autonomous integrated citrus harvesting robot system. The mobile platform uses a multi-sensor fusion SLAM algorithm for high precision positioning and navigation, the mobile platform can accurately guide along the run defined route and significantly improves harvesting efficiency [10].

Though the semi-autonomous robotic citrus harvesting research has achieved fruitful achievements for the path planning and motion control of the citrus harvesting robot, there still have been challenges in complex unstructured terrain such as mountainous and woody places.

4.2 Apple Harvesting Robots

Apple is one of the most important economically valuable fruit trees planted all over the world. Harvesting of apples is labor intensive and strict quality requirements for apples are placed on harvesting, making apple a hot spot for agricultural robots research.

For example, a robot consisting of a customized perception module, a 4-DOF robotic arm, an improved type vacuum flexible end-effector and a fruit picking device was designed. With integrated software algorithms, these modules of robot cooperate flexibly, facilitating efficient and automated apple picking in orchard environment. This work proposed a perception method, using improved triangulation, image processing analysis and so on, to obtain stable pick detection and accurate localization of the apple. Algorithms for better planning and control were designed to drive the robot to the target pose [11].

Great progress has been achieved in visual recognition and fruit detection for apple harvesting robots. Forapp3 there are still challenges under various illumination conditions, partial fruit occlusion and additional improvement in fruit harvesting.

4.3 Tomato Harvesting Robots

Tomato is a high-value cash crop in facility agriculture, with a short fruit ripening cycle and frequent harvesting requirements, so the harvesting requirements of tomatoes are high efficiency and fully automated.

A cherry tomato harvesting robot, which was capable of cluster harvesting by cutting peduncles, was developed and tested in real greenhouses. This robot has an end-effector based on a cam mechanism, for asynchronous grasping and cutting with a single actuator—that is, effectively avoiding damage to the fruit and also speeding up the harvesting process. It is also equipped with a vision system using dual viewpoints to determine the location of the peduncle cutting point and to adaptively determine the position of the end-effector according to the point cloud feature [12].

A lot of achievements have been accomplished for the development of fruit grasping for tomato harvesting robots. Future efforts in tomato harvesting robots should be paid more attention to the aspects of multi-sensor fusion, intelligent decision-making algorithms and multi-robot cooperation, in order to improve practicability and general use.

5. Future Development Trends

Although agricultural picking robots have reached initial applications in several kinds of fruit and vegetable crops, large-scale deployment is still constrained by the environmental complexity and the demand for system integration of picking robots. Future works will therefore focus on enhancing the adaptability, intelligence and competitiveness of the system integration through the improvement of technological level and cross disciplines integration.

First, development of mobile platform systems will pay more attention to strong adaptability to terrain and high degree of autonomous movement. Orchard terrain has uneven ground, slope and narrow working space, so robots have high requirements for mobility. Future mobile platforms will pay more attention to compound movement structure, compound suspension and improved drive structure to improve stability and passability in uncivilized spaces. At the same time, improvements in the positioning technology of multi-source positioning will improve the mobility of robot navigation. Robots can effectively navigate in environments where single sensor positioning is unreliable by combining visual SLAM, satellite positioning technology and inertial positioning. Combined with intelligent path optimization algorithm, this enables robots to actively modify their movement routes and continue completing various multi-accumulation operations for as long as possible.

Second, perception systems will evolve towards a more robust understanding of the environment using fused multi-modal information. The agricultural environment is often characterized with variable lighting, dense leaf cover and partial fruit covering, bringing challenges for a single-sensor perception system. Incorporating multi-sensor modal information such as RGB cameras, depth cameras, LiDAR and touch can greatly enhance the reliability of fruit recognition and localization. Meanwhile, development of light-weight deep learning models and the edge computing platform will improve the processing capability of real-time on-device deployment, so that robots will be able to carry out complex perception tasks on embedded devices.

Finally, mechanical execution systems will be more flexible and adaptive manipulation systems. Traditional rigid gripper is difficult to handle the fruits with different shapes, sizes and firmness. The introduction of soft robot materials, bio-mimic structures, variable stiffness can help the end effectors adapt the grasping mode for different crops. On top of that, multiclay sensor feedback, such as force and touch, may allow robots to better manipulate operations and reduce losses in the picking process. All these innovations will substantially improve the success rate and safety of robot harvesting operations.

6. Conclusion

This paper reviewed the system architecture, key technologies, and practical applications of agricultural harvesting robots. Harvesting robots typically consist of three main subsystems: mobile platforms, perception systems, and mechanical execution systems. These components work together to enable robots to move within orchards, detect fruits, and perform harvesting operations.

Recent advances in machine vision, deep learning, and flexible robotics have significantly improved the performance of harvesting robots. However, challenges such as environmental complexity, operational efficiency, and cost remain barriers to large-scale commercialization.

With the rapid development of artificial intelligence, sensor technology, and robotics, agricultural harvesting robots are expected to become increasingly intelligent, reliable, and economically viable. This paper suggests that future research should focus not only on technological breakthroughs but also on improving system integration and reducing equipment costs, which are crucial for large-scale deployment in real agricultural production. The continuous advancement of these technologies will play an important role in improving agricultural productivity and promoting the modernization of agriculture.

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Conflicts of Interest

The authors declare no conflict of interest.

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