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A Comparative Analysis of Vision-Based Approaches in Autonomous Fruit Harvesting

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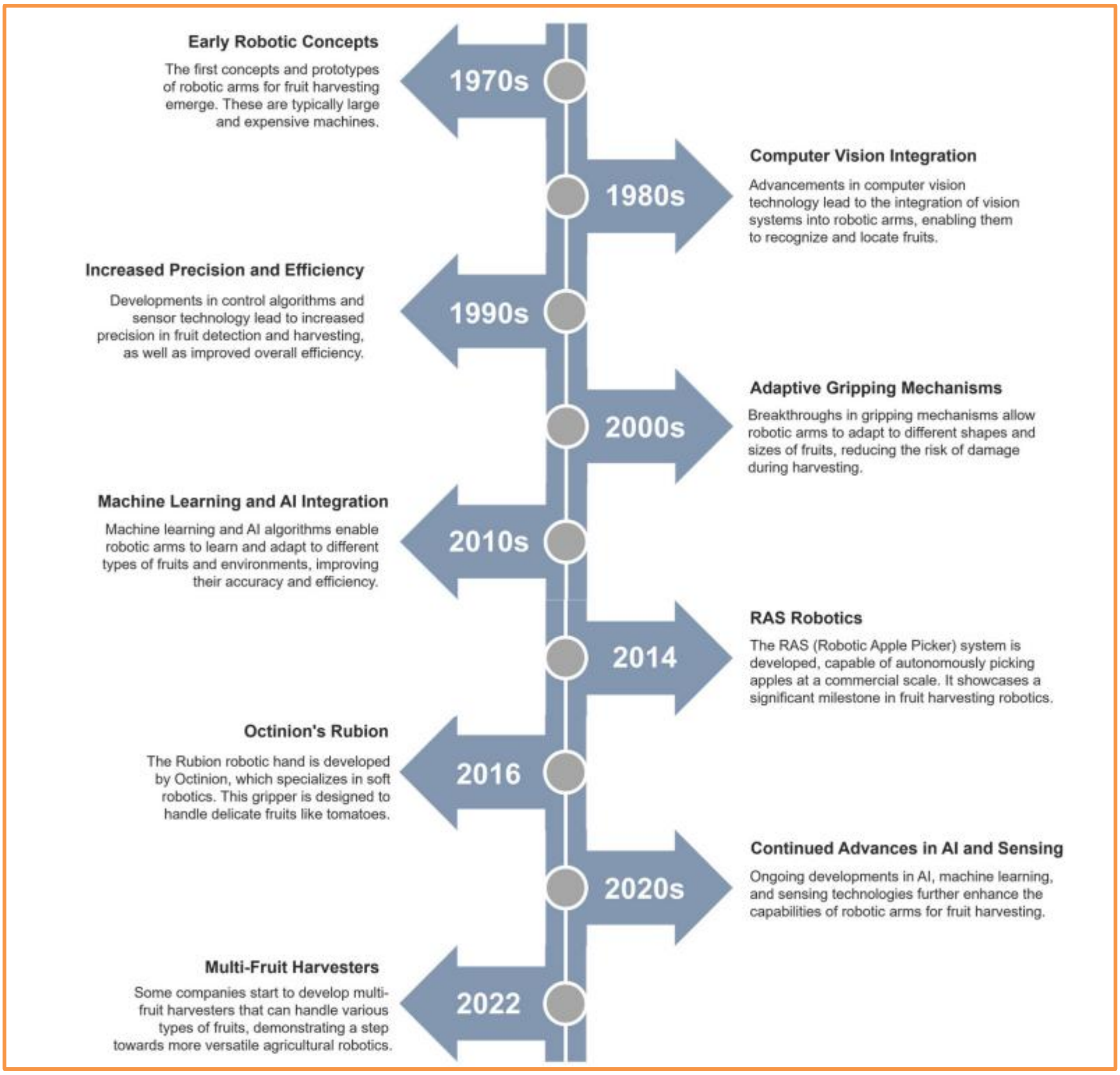
The increasing scarcity of agricultural labor, exacerbated by global crises and restrictive migration policies, has accelerated the development of robotic solutions for fruit harvesting. This paper explores the current state and evolving potential of fruit-harvesting robots, highlighting their ability to mitigate labor shortages while enhancing efficiency, precision, and sustainability in agriculture. Key technical components—such as machine vision systems, manipulators, and mobile platforms are examined within system architectures, including case studies on apple, kiwifruit, and strawberry harvesters. Each case presents specific challenges, including fruit variability, environmental complexities, and the need for non-destructive handling, which are addressed through innovations in stereo vision, bionic end-effectors, and autonomous mobility. The review also outlines future directions, emphasizing the importance of reducing environmental variability, refining sensor capabilities, and fostering human–robot collaboration. Overall, robotic harvesting technologies hold significant promise in transforming traditional horticultural practices through intelligent, adaptive, and scalable automation.

Keywords: Apple, Kiwifruit, Robatics, Strawberry

Introduction

Fruit growers are facing an increasingly severe labour shortage due to the labour workforce's diminishing interest in agriculture (Luo & Escalante, 2017). The problem is exacerbated by recent international travel restrictions in pandemic conditions, which have dramatically limited agricultural productivity due to the unavailability of migrant workers. As a result, tons of fresh produce were left unharvested and rotting on fields where farms had long relied on seasonal overseas workers (Zahniser et al., 2018; Associated Press 2020; Ieg, 2020; Chandler, 2020). Harvesting robots can counter labour shortages and provide an economically viable solution to rising labour costs. The robots can also be a tool for applying precision agriculture. Specifically, the application of the harvesting robots makes the harvesting process controllable, traceable, and customisable, meanwhile harvesting robots can gather, process and analyse temporal, spatial, and individual data of the target fruits (ripe time, harvest time, fruit position and pose, fruit ripeness and defect, etc.) as well as the environment information (branch distribution, leaves occlusion, disease infection), and combines it with other information (plant habit, plant traits, etc.) to provide support to decision-makers. The technology of robotic harvesting has been actively developed over the past three decades (Bac et al., 2014). In terms of the technology status of the harvesting robot, the robotic systems analysed can be categorized into two groups: fully integrated systems, and subsystems used in harvestings, such as vision (Tang et al. 2020), gripper (Zhang et al., 2020), and control (Zhao et al., 2016).



Timeline showing significant contributions in fruit-harvesting robotic arms development

System architecture

A harvesting robot is usually an integrated multi-disciplinary system that incorporates advanced features and functionalities from multiple fields, including sensing, perception, environment mapping and navigation, motion planning, and robotic manipulation. Thus, existing fruit harvesting robots generally consist of multiple sub-systems:

- A mobile base to carry the robot around the target,
- A machine vision system to detect and percept the environment,
- A control system to achieve overall control of the robot,
- A collector for storing the harvested fruits,
- One or several manipulators to approach the fruit while avoiding the obstacles, and.
- One or several end-effectors to detach the target fruit from the plant.

Robots in Bac et al. (2014a, 2017), Lehnert et al. (2016, 2017, 2020), Arad et al. (2020) have vertical lifting devices to extend the robot's workspace, while Traptic (2019) and FFRobotics (2019) have conveyors to prevent fruit damage in the process of collecting.

Robotic harvesting of Apple

Stereo Vision system

There are two types of stereo vision systems currently being used. The first is a binocular vision system based on optical geometry. In which we use optical principles and optimal algorithms to obtain the 3D position of the target. The second is the RGB-D camera based on the time of flight method (TOF), which uses an infrared sensor to obtain information about the target fruit. One limitation of the TOF method is that it is very sensitive to any interference and may not work if powerful light is present in the scene. Another limitation is the working distance of the infrared sensor. The optimal geometry-based system does not rely on artificial intelligence. Hence the optical geometry-based system can use in indoor and outdoor environments. To ensure stability vision system based on optimal geometry is used. On the other hand, the principle of the RGB-D camera is very simple, and the system is also very compact, which can be used for many local tasks. The optical geometry-based stereo vision system consists of two or more two cameras separated by some distance (Zou et al., 2012). First of all, cameras are calibrated. After that, two or more images of a target are obtained through the vision system. Then, obtained images are classified to identify the target object in the scene. The binocular vision-based stereo system is based on monocular vision. The early monocular-based stereo vision system used a single camera to detect a 2D image of the target. Researchers began to explore 3D images and stereoscopic machine vision (Roberts, 1965).

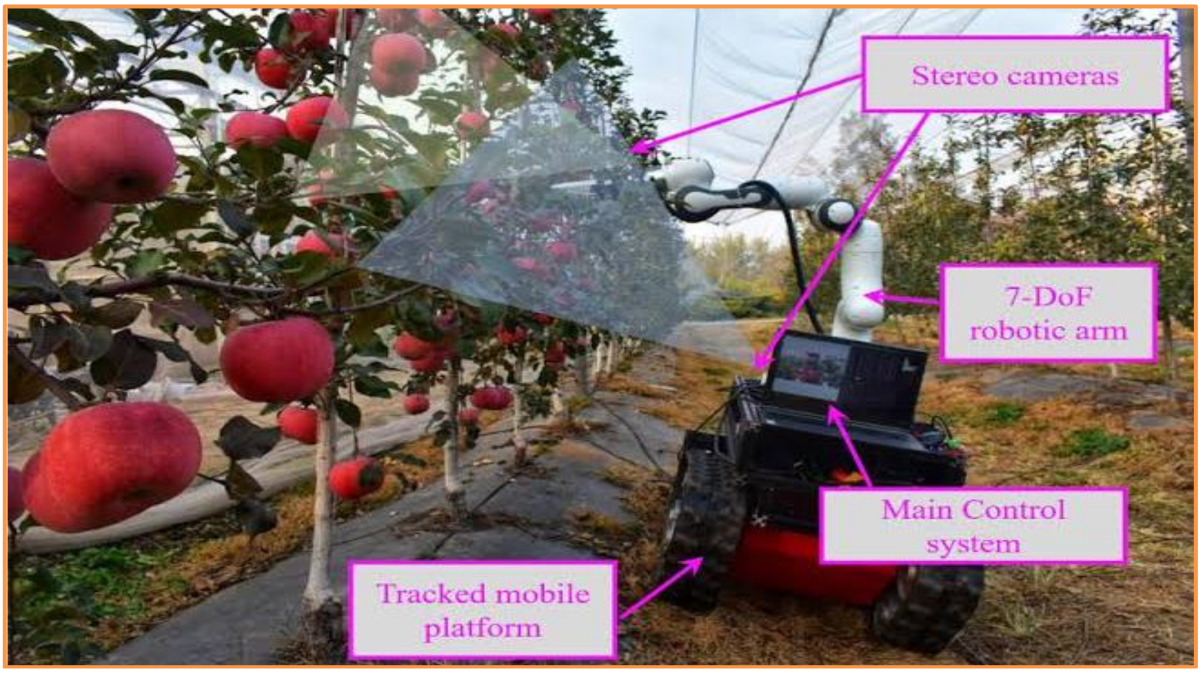


Fig.1 Apple harvesting robot

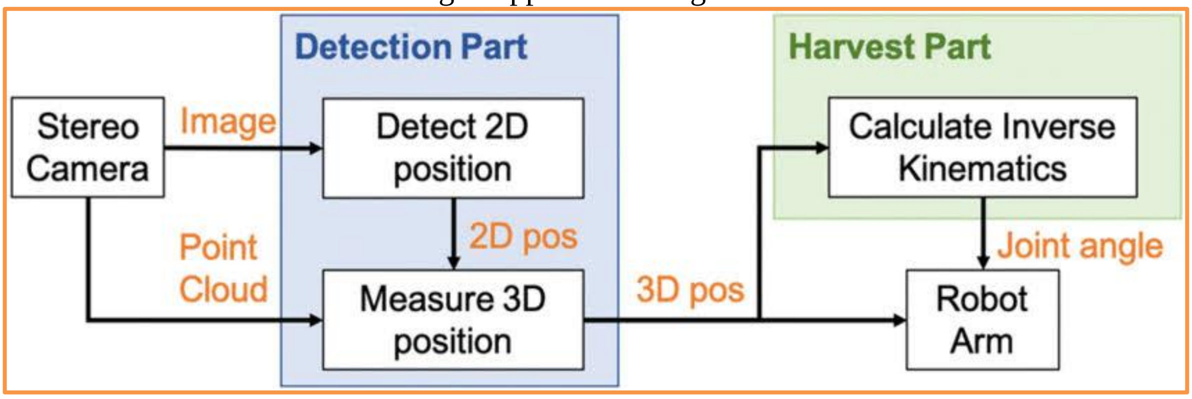


Fig.2 Flowchart for working principle of Apple harvesting robots

Robotic harvesting of Kiwi fruit

The kiwifruit picking robot consisting of five main parts: Machine vision, end-effector, coordinate manipulator, vehicle system, and control system. The picking robot can automatically undertake the tasks of fruit information recognition, positioning, picking order planning, movement to kiwifruit picking area, non-destructive picking by bionic fingers, and unloading fruit to the basket. A kiwifruit picking test being conducted with emulated fruit in an artificial shelf in farm machinery laboratory of Northwest Agriculture and Forestry University of China. Among the 30-fruit set (divided into 6 groups, 5 per group) to be harvested, 27 were successfully harvested with a success rate of 90%. The 10% failure to harvest the fruit was due to the fact that the parts with IR sensors affected the grabbing movement of the end-effector when it enveloped the adjacent fruits. The average picking time was 4 seconds, which was similar to that of manual picking but remarkably more efficient than the formerly developed end-effectors. The lab simulation test validates that the end-effector can completely fulfill all given functions in harvesting kiwifruit.

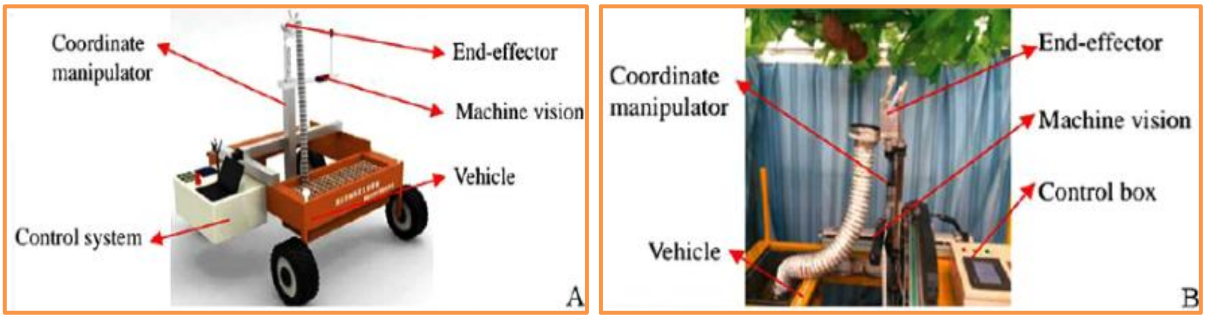


Fig. 3 Kiwi fruit harvesting robot

Robotic harvesting of Strawberry

The harvesting robot is a fully autonomous system. It does not require any human interaction or intervention during its operation, and could therefore work during day and night. The independence and effectiveness of the system relies on seven components: the electric vehicle, the localization system, the camera detection system, the custom designed robotic arm, the gripper, the logistic handling module and the quality monitoring software.

In order to have a system that is reliable and viable for commercialization, the following statistics have to be reached:

- A total picking time of 4 seconds.
- Minimum 70-95% of strawberries picked up in tabletop cultivation, depending on the variety.
- A robust detection of the location of ripe strawberries.
- Mechanical robustness for a desired lifetime of 5 years.
- Drive train components, including electric engine and battery, optimized to work for at least 8 hours continuously.

The robot's performance (picking speed, damage of the fruit, strawberries not picked, sorting) depends a lot on the on-field conditions, which depend on many parameters. In order to make a meaningful measure, the performance of the robot will be compared with the human work in the same conditions. This will make a quantitative analysis of the benefits and necessary improvements possible. The product development of the project will paramount and conclude with the implementation of the quality monitoring system. This will be performed by comparing the quality assessment by the robot with laboratory assessment. Due to the changing conditions over the year, which might impact the assessment of the robot, this also needs to be performed continuously.

Fig.4 UWB navigation anchor

Fig.5 Detection of individual strawberries

Fig.6 Gripper in action

Future scope & solution to technical problems

There is bright scope of robotics in fruit or crop harvesting. There are a lot of challenges in the operation of the harvesting robot. Here are some solutions and improvements we can make in harvesting robots.

1. Reducing variation in the work environment: The performance of the machine vision system depends on the variation in the work environment of the harvesting robot. We can enhance the productivity of the machine vision system by reducing the plant population and reducing the variation of plants by arranging in some particular sequence. We can use different plant production methods like greenhouse and orchards. To reduce the complexity of the scene, breeding for the robot is another way. Modification and standardization of the cultivation systems offer opportunities to reduce variation.

2. Enhancing robotic technology: Including more domain knowledge in the design and operation of robots to reduce the variation. For this, we have to model the world in which the robot has to operate, which will provide clues about the work environment and the presence or absence of objects. Another way is to extend the capabilities of sensors so that we can better feedback from the sensors.

3. Human-robot collaboration: The kind of variation in the agriculture field can be tackled by human-robot collaboration. They will help each other enhance the productivity of the overall operation of the harvesting robot. A human operator can guide the robot to target fruits, and the robot can harvest with its end effector.

Conclusion

The role of robotics in fruit & crop harvesting and various techniques and methods used in harvesting robots, from machine vision to fruit detachment. Various technical challenges and limitations of the system have also been discussed. For all problems, various possible solutions have also been discussed. To increase the productivity of the harvesting robot, we have to implement such solutions in the robotic system.

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