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Recent patents on intelligent automated fruit harvesting robots for sweet pepper and apple

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Abstract

Robotic harvesting offers suitable solutions for optimizing scheduling, selection enabling, increasing operation efficiency and finally reduce the labor costs. These attributes allow the users of robot harvesters to maximize production efficiency and profits. This article reviews two automated fruit harvesting systems used for sweet pepper and apple as an example to demonstrate the effectiveness of recent patents on intelligent automatic harvesting robots in horticulture.

Key words: Intelligent, efficiency, automated fruit harvesting robot

Introduction

Automation of agriculture is an innovation issue which can reduce the utilization of resources and helps to meet with increasing demand for more productivity and higher quality of food production (Bac *et al.*, 2014). Human has long strived for mechanization in crop management and harvest to reduce the labor costs. Operation of harvest usually occurs when a crop reaches its mature stage. However, harvesting a large hectarage of crop within a short period is difficult because it is labor-some and time-consuming. A solution for these problems is to develop and use some smart mechanical systems that can complete the harvesting operations efficiently and quickly. Mechanized fruit harvester is one of these systems with a conventional electro-hydraulic control mechanism to shake the nuts/fruits trees to help matured nuts or fruits drop off the trees. Such harvesters generally need to be moved to the target location of trees with a shaker head that can extend towards the tree. The shaker head includes movable jaws with pads that clamp the tree and a motor that can supply power for shaking (Needham *et al.*, 2019). The next advanced development is the "automated mechanization" which employs artificial intelligence to increase the selectivity, precision, and robustness of farming. This is especially true for harvesting high value crops, such as capsicums, since harvest operation must occur several times during a growing season. Automation of harvesting tasks can result in significant labor savings and provide gentler handling of the fruits (Russel *et al.*, 2019).

The undesirable performance of computer sensing technology is one of the major obstacles in the development of intelligent automated crop management systems. For the past decades, object localization through computer-assisted vision has been developed, resulting in the success of its application in many industry areas (Barth *et al.*, 2018). However, the application of these technologies in agriculture is still in its infancy stage (Gongal *et al.*, 2015; Nasir *et al.*, 2012). This is due to the difficulties and infeasibility of collecting a large amount of detailed and annotated agricultural data required to develop these automated crop management systems (Barth *et al.*, 2018).

Autonomous robotic harvesting is a challenging though exciting technology for modern agriculture. Developing such systems requires integration of multiple subsystems including crop detection, motion planning, and dexterous manipulation (Lehnert *et al.*, 2017). An important part of any robotic fruit picking system is the end effector. The robot uses the end effector to touch and interact with the crop. Thus, its design is critical to reliable handling and detachment of the produce (Russel *et al.*, 2019).

This article reviews the sweet pepper and apple automated fruit harvesting systems as an example to demonstrate the effectiveness of recent patents on intelligent automatic harvesting robots in horticulture.

Intelligent automated fruit-harvesting robots

Robotic harvesting of sweet pepper: An automated sweet pepper harvesting robot, named 'Harvey', has been developed recently (Lehnert *et al.*, 2017). This robot successfully addresses three key challenges: detection, grasp selection and manipulation. They developed a simple and effective vision-based algorithm for fruit detection, a three-dimensional localization and grasp selection method, and a novel end-effector design for fruit harvesting. To reduce the complexity of motion planning and minimize occlusions, Lehnert *et al.* (2017) focused on developing a system picking sweet peppers in a protected cropping environment where plants were grown on planar trellis structures (Fig. 1).

In Fig. 1, the left photo (A) is the custom mobile platform of the harvesting robot. Harvesting is performed with a custom harvesting tool and 7 Degree of Freedom (hereafter, DOF) manipulator (6-DOF articulated arm + lift joint) integrated into a custom differential drive mobile base. The right photo (B) is the custom harvesting tool attached to the robot end effector (Lehnert *et al.*, 2017).

Based on the field evaluations, this sweet pepper harvesting system resulted with 58% harvesting success rate, 81% grasping

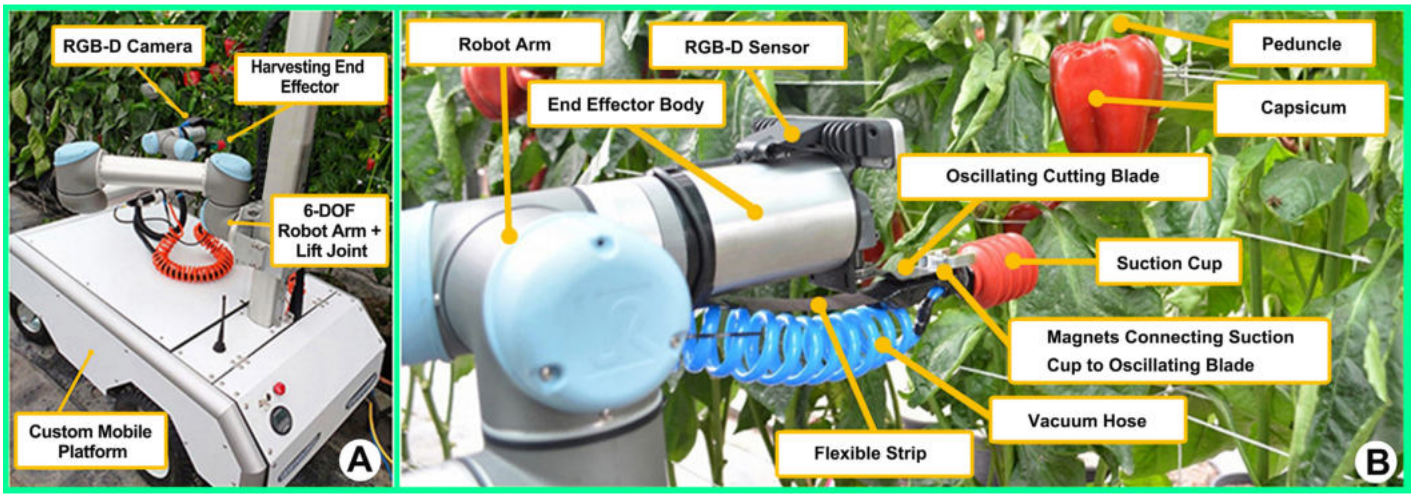

Fig. 1. The mobile harvesting robot 'Harvey' used for sweet pepper operating in a protected cropping environment.

rate, and 90% detachment rate, respectively. Such high success rates represent a significant improvement over the previous state-of-the-art technologies, demonstrating an encouraging progress towards developing a commercially viable autonomous sweet pepper harvester. Moreover, Fig. 1A shows the custom differential drive platform designed and powered by an internal 3 kWh lead-acid battery to work between crop rows for up to 8 hours. The platform has a 6-DOF revolute arm (Universal Robotics UR5) mounted on a prismatic lift joint (Thomson LM80). The differential drive mobile base houses the batteries, drive motors, gearboxes, computer hardware, robot controller and forward-facing laser scanner for mobile navigation and obstacle detection. Fig. 1B shows the custom harvesting tool that can grip sweet peppers with a suction cup and cut them free from the plant using an oscillating cutting blade. Due to variations in crop size, shape and orientation, using a single end-effector to grasp and cut each sweet pepper simultaneously is challenging and unreliable.

To overcome this difficulty, this harvesting tool is redesigned with a key feature of having a passive decoupling mechanism that allows the gripping and cutting operations to occur sequentially at independently chosen locations. The decoupling mechanism is a flexible strip that tethers the suction cup to the body of the end effector. The suction cup is also magnetically attached to the underside of the cutting blade, allowing the robot arm to guide the suction cup during the attachment phase. After attachment, the cutting blade is lifted to decouple the suction cup from the cutting blade. The suction cup is then only attached to the end effector via the flexible tether, allowing the cutting blade to move independently of the suction cup through the cutting operation. After detachment, the sweet pepper falls off the plant and hangs freely from the flexible tether. The suction cup and cutting blade can be magnetically re-coupled ready for the next harvesting cycle using gravity by simply pointing the harvesting tool downwards. The sweet pepper is released into a collection crate by releasing the vacuum.

This simple and passive decoupling method requires no additional actuators, allowing for a greater harvesting success rate. The harvesting tool also contains an RGB-D camera (Intel R Real-sense SR300 RGB-D) sensor to perceive the crop and a micro-switch to check whether the suction cup is coupled with the cutting blade. The body of the end effector contains a modified oscillating multi-tool used to cut fruit stalks. A pressure sensor on the vacuum line helps detect the success or failure of the attachment of the suction cup.

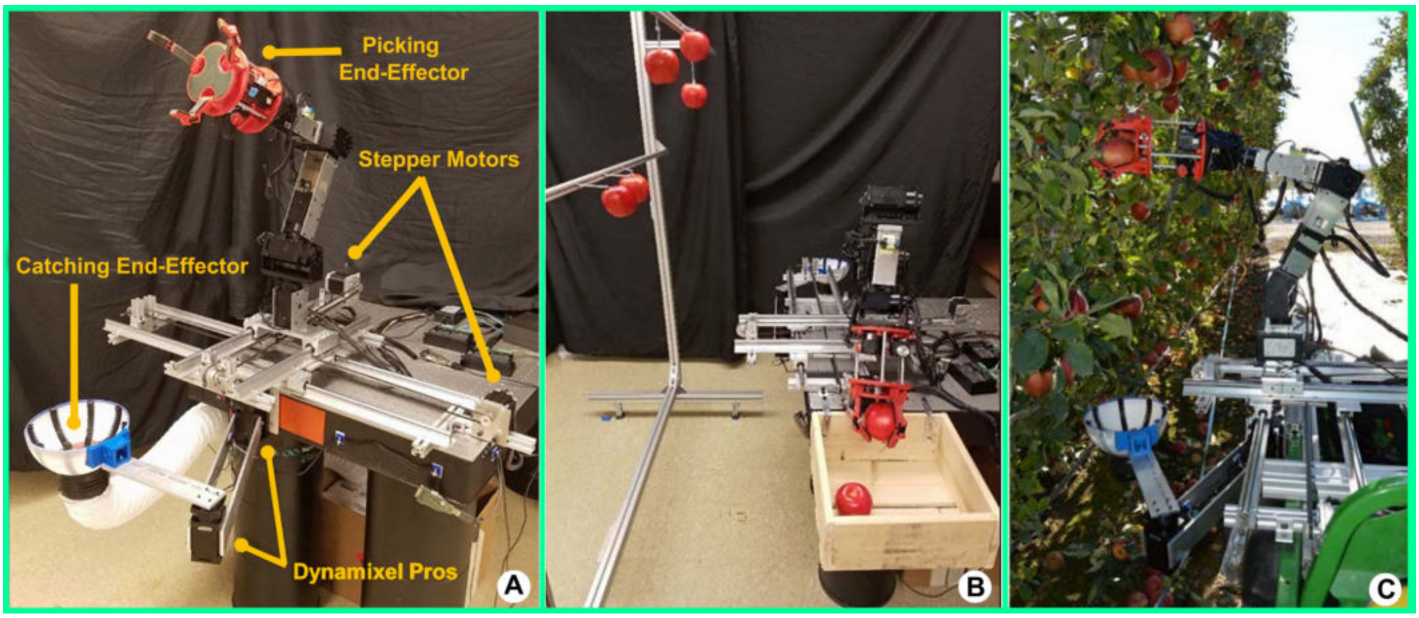

Fig. 2. The dual robot coordination used for apple harvesting.

Robotic harvesting of apple: The robotic harvesting of apple system is presented in Fig. 2. Fig. 2A shows the robotic harvesting system of apple that consists of picking the manipulator, picking end-effector, and catching manipulator.

Fig. 2 presents a kinematic redundant picking manipulator with 8-DOF for apple fruit collection. Fig. 2A shows that the 8-DOF picking manipulator includes all revolute arm with 6-DOF fastened to the base by two stepper motors. Each Dynamixel Pros actuator is placed on the redesigned catching robot at the joint location. Fig. 2B shows the experimental set-up used during the pick-and-place harvesting motion. The picking manipulator deposited the artificial apple in the container after it is detached from the replica tree. Fig. 2C shows the picking manipulator grasping fruit from the tree canopy. The machine vision system is located behind the harvesting robot (Davidson *et al.*, 2017).

The picking manipulator has 8-DOF and a 6-DOF all-revolute arm with Dynamixel Pros actuators (Robotis Inc., Irvine, CA) fastened to the base that can displace in the x-y plane. Both prismatic joints on the base are actuated by NEMA 23 stepper motors and consist of steel rails with linear bearings and timing belts. The picking end-effector design is similar to that described by Silwal *et al.* (Silwal *et al.*, 2017). The catching manipulator is a planar design with two links. Geometric parameters are selected such that the catching manipulator could reach every possible drop position in the workspace of picking manipulator. Each joint is actuated by a Dynamixel Pros model L54-50-S500-R (Robotis Inc., Irvine, CA). The stepper motors and mechanical transmissions used in the preliminary design (Davidson *et al.*, 2016) are replaced with Dynamixel Pros actuators to increase torque output, velocity, and reduce backlash.

It should be noted that although this design modification increases the overall system costs, it significantly improves its maximum end-effector velocity as well as accuracy and repeatability from reduced backlash. The manipulator's links are fabricated from aluminum plate. The catching end-effector is a plastic funnel lined with flexible baffles manufactured with a three-dimensional printer. The fruit collection system is gravity fed. A flexible hose attached to an opening at the bottom of the catching end-effector funnels fruit into a storage container.

Fig. 2B shows that a wooden storage crate is fastened to the table adjacent to the picking manipulator during harvesting cycles using the pick-and-place method. The location of the storage crate is not optimized according to the performance criteria. Rather, a convenient location for the described setup is chosen such that the crate does not obstruct robot hardware during picking. After detaching an apple from the tree, the picking manipulator deposits the fruit in the container. For each harvesting cycle, three-dimensional coordinates of all fruit positions are generated using Matlab's (Mathworks, Natick, MA) random number generator.

Both harvesting methods are then used per cycle so that total displacement between apples remains constant when comparing cycle times. Sequential fruit selection in a harvesting cycle is considered as the Traveling Salesman Problem (TSP). The TSP is an optimization problem predicated on finding the shortest path through a set of points that passes through each point once and only once (Arkin *et al.*, 1994). Matlab's k-nearest neighbor algorithm (Friedman *et al.*, 1977) is used for fruit prioritization.

The algorithm's start point for the search is the end-effector coordinates at the picking manipulator's home configuration. The algorithm selects the closest fruit as the first apple for harvesting and then, sequentially, the nearest neighbors for the remaining fruit in a cycle. Prioritization planning is completed offline before the start of each cycle. Trapezoidal velocity profiles are used for manipulator movements planned in the joint space with the maximum velocity of all revolute joints set at 60° per second. Also, the approach distance *d* is set at 15 cm. Fig. 2C shows that the integrated system is mounted on the back of an electric utility vehicle for harvesting the apple variety Envy in a V-trellis orchard system. Optimizing the collection system below the level of the catching end-effector, such as implementing a bin filling device, requires additional work. Initial observations from preliminary testing indicate that the current design requires substantial modifications prior to more extensive field evaluations.

Current and future developments

In this article, we reviewed two intelligent automated fruit harvesting robots designed to harvest sweet pepper and apple. Each harvesting robot has its unique features to complete its operation. The sweet pepper harvesting robot has a novel end-effector that facilitates an effective vision system for fruit detection, three-dimensional localization and grasp selection, resulting in a great success rate of grasping, detachment and harvesting. The apple harvesting robot has a very effective catching manipulator that can reach every possible drop position in the workspace of picking manipulator. Such design increases the end-effector velocity and accuracy and reduces the backlash for repeatability.

Due to reduced labor and rising production costs, research will increasingly focus on advanced automatic harvesting robots in agriculture, particularly horticulture. However, successful development will require interdisciplinary collaboration across agricultural engineering, mechatronics, computer science, and sensors. Intelligent systems, such as deep learning and crop management, will be crucial in software development. These tools will boost productivity and sustainability in modern agriculture.

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