# Overview of control systems for robotic harvesting of sweet peppers and apples

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**Abstract:** Automated harvesting systems are becoming a crucial part of digital agriculture. Substituting time-consuming and laborious manual harvesting with a continuously automated operation would result in reduced human efforts, which contribute to higher field efficiency. This could be achieved by means of robotic harvesting which comprises robot manipulators, gripping and grasping mechanisms, software implementations. However, the inadequate design of control strategies could cause the agricultural production loss. This paper reviews some of the latest achievements in control systems of agricultural robotics and more specifically in robotic harvesting. The employed robot arms, their degrees of freedom (DOF), and the crops are also considered in this review study. While the control algorithms are being developed with high robustness and fast-response properties, our conclusion is that the performance of controllers could be drastically affected by different parameters such as the number of DOF, estimation accuracy of the robot pose during visual servoing and failure of robot's inverse kinematics solver.

**Keywords:** agricultural robotics, automated harvesting, robot manipulator, control algorithms

## 1 Introduction

Robotic automated harvesting of fruits and vegetables has been developed during the last decade due to the lack of farm workers and its costs' growth [Sh18]. Scaling up in agriculture and saving labor are essential in solving these problems. Robotic harvesting can enhance productivity by decreasing manual human resource and costs of production, increasing yield and quality, and providing superior control over environmental implications. However, adaptive (to high crop variability), robust systems are required for the complexity of agricultural environments along with the high production needs.

Fruit harvesting robots are mainly composed of a fruit detection system, a fruit picker, a manipulator, a control system, and a traveling device [Bu05]. Two major challenges need to be considered and solved during robotic applications development for harvesting horticultural products. The first one is the detection of a target fruit location. The second is the precise end-effector's movement towards the mentioned location so that the harvest

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action could be performed. There are multiple solutions for each of these challenges. The robot parts design should be adapted to a distinct type of fruit as different crops have different physical properties and characteristics, e.g. in contrast to tomato, sweet peppers' leaves are not picked and mostly cover the fruit, making the fruit hardly detectable and difficult to localize [BHV16]. Moreover, sweet pepper crops sometimes grow in clusters, rendering it complex to access, and pick each single fruit without damaging. Also for apple crops, the fruit is rotated (not pulled) until the detachment of fruit peduncle from the branch [Bu05]. Therefore, the manipulator, the end-effector and the control algorithms should be designed based on the harvesting procedure, guaranteeing suitable robot adaptation to the crop type. Control algorithms are designed by using both control theory and control engineering principles, and constitute the control system which drives the desired movement of the harvesting robot.

This paper provides an overview of control systems as one of the main parts of robotic harvesting for two different crops. The reviewed researches have been selected based on their precise indication of the implemented control systems. The designed control schemes in automated sweet pepper harvesting are described in Section 2. Section 3 reviews three different control strategies for robotic apple harvesting, followed by the conclusion remarks in Section 4.

## 2 Sweet pepper harvesting

A simulation approach in V-REP software, Robot Operating System (ROS) and MATLAB software has been carried out in [Sh18]. The research has been conducted in two phases: (i) the creation of the simulated workspace in the virtual robot experimentation platform (V-REP), and (ii) the development of communication and control architecture using ROS and MATLAB. An exact replica of the 6 DOF Fanuc LR Mate 200iD robot manipulator, models of sweet pepper fruit and plant system, and different vision sensors were created in V-REP to form the simulated workspace. Two control schemes were developed and evaluated; the first one was based on joint velocity control and the second one based on joint position control. A Proportional-Integral-Derivative (PID) control law was applied to both of the designs in order to minimize the offset error between the center of the camera frame and the image position of a detected fruit. Results demonstrated that the robot could self-adjust so that its tip RGB sensor displays maximum possible view of the largest detected fruit and fast stabilization. The stability was achieved in 2.5 seconds without overshoot and oscillations.

A flexible modular framework for eye-in-hand sensing and motion control in robotic sweet pepper harvesting was provided in [BHV16] as a standardized approach. In contrast to specialized software, the framework suggested goals to support various agricultural applications, hardware and extensions. A set of ROS nodes was created to guarantee modularity and separation of concerns, implementing functionalities for application and robot motion control, image acquisition, fruit detection, visual servo control and simultaneous localization and mapping (SLAM). Baxter robot was selected for its native

ROS support and the ability of publishing the pose of the end-effector and all joints and also running a ROS master core to which an internal controller publishes and executes target joint angles. The objective of the experiment was to demonstrate that the robot could find and access the fruit. The final pose of the end-effector was always centered with the fruit, except for cases where a solution of the joint positions could not be found due to the failure of robot's inverse kinematics (IK) solver. These instances were specified by the robot arm already being fully extended to its limits, but not yet horizontally or vertically aligned with the fruit.

In 2017, harvesting experiments were conducted in a sweet pepper crop located in a commercial greenhouse [Ba17]. Figure 1 provides an overview of the harvesting robot which was developed as part of the research project CROPS "Clever Robots for Crops". The manipulator module of the platform (Jentjens Machinetechniek BV, the Netherlands) included a 9 DOF custom-made manipulator, end-effector and air compressor for its pneumatics, and a cabinet containing computers and electronics. The motion planner of the robot calculated a straight path through the workspace, i.e. point-to-point planning. IK were then solved to realize the motion by using an algorithm developed in [Ba13], capable of exploiting the redundant DOF. The results of failure analysis for four different testing conditions showed that the contribution of manipulator error to total failures was of 3% for the Fin Ray and of 6% for the Lip-Type end-effectors. Furthermore, the number of DOF influenced the maneuverability around obstacles. In this application, planned motions were relatively simple and fewer DOFs had not a strong influence on the result. However, in other applications, DOFs could play an important role.

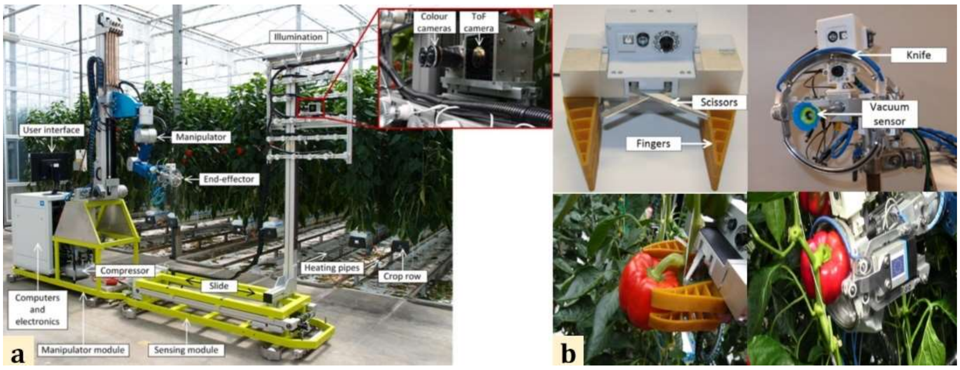


Fig. 1: (a) An overview of the CROPS project harvesting robot [Ba17] and (b) Fin Ray (left) and Lip-type end-effectors (right)

## 3 Apple harvesting

An apple harvesting robot was developed in [Bu05] by using a feedback controller and machine vision for the manipulator. As the detected fruit had to be in the image center in order to measure for its distance from the camera, the camera was mounted on the manipulator and had to be specifically positioned. Two feedback control strategies using machine vision have been implemented and simulated for this positioning procedure.

The first design was a three-position on-off controller for moving the camera at a constant step and have the machine vision monitor the position of the fruit until the fruit is at the image center. In order to avoid instability or oscillations, the constant step's value had to be set to a minimum. Consequently, the response time for the system to position the fruit in the image center is affected. The second scheme was a proportional (P-) controller with variable gain for moving the camera with a value proportional to the error. The controller was tuned in three steps. The camera is moved at a determined step distance at first. Then, the pixel change in the image is computed, and finally, the proportional gain is calculated using the defined step distance and the pixel change. Numerical results showed that both controllers were capable to move the manipulator to position the fruit in the image center, which proved the feasibility of applying machine vision as a feedback sensor and also, the faster response time of the P-controller compared to the three-position controller.

A reliable low-cost robot for automatic apple harvesting has been developed and evaluated in [De11]. The robotic setup included a manipulator, end-effector and image-based VSC system. In order to obtain a quasi-linear behavior and to simplify the control design, a geometrically optimized manipulator with a 5 DOF Prismatic Revolute-Revolute-Revolute-Prismatic (PRRRP) structure was implemented (Fig. 2. a). The control system was composed of an industrial computer and an AC servo driver. The image-based vision servo (IBVS) control algorithm was used in the robot control system in order to perform the localization and achieve the picking motion for the target fruit (Fig. 2. b).

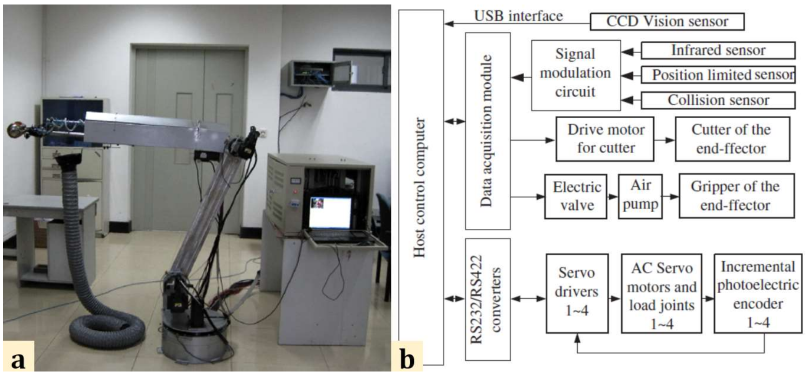


Fig. 2: (a) PRRRP 5 DOF manipulator [De11] and (b) Hardware structure of apple harvesting robot control system

The performance of the prototype robotic setup was demonstrated by laboratory tests and field experimental evaluations. 100 laboratory picking tests were performed in 10 different positions, resulting in 86 successful and 14 failed pickings (success rate 86%) and 14.3 seconds for average picking time of one apple. Continuously picking field experiments were carried out in an orchard with a complex environment. Overall, the mean recognition time was 15.4 seconds and the picking success rate was 77%, proving the performance of the prototype harvesting robot and the designed control system.

A fast and precise scheme with a Single Shot MultiBox Detector (SSD) was developed in [On19] to detect the position of fruit and achieve an automated harvesting using a 6 DOF UR3 robot arm made by UNIVERSAL ROBOTS. The joints angles and the route of the robot arm are calculated by IK at the detected position, followed by the robot arm movement towards the target fruit. The robotic harvesting is then performed by twisting the hand axis. Experimental results indicated the detection of more than 90% of the apples in 2 seconds and the harvesting of an apple in 16 seconds. Moreover, the suggested apple harvesting scheme is assumed to be applicable for near species of apple.

The reviewed harvesting robots and control strategies as well as their corresponding camera and/or sensor(s) are summarized in Table 1.

| **Crop** | **Manipulator** | **DOF** | **Controller** | **Camera/Sensor** | **Reference** |
|---|---|---|---|---|---|
| Sweet Pepper | Fanuc LR Mate 200iD | 6 | PID | Logitech C920 HD Pro USB/proximity Hokuyo URG04LXUG01 | [Sh18] |
| Sweet Pepper | Baxter | 7 | ROS *actionlib* service | USB CMOS color Autofocus Camera (DFK 72AUC02-F, TheImagingSource) | [BHV16] |
| Sweet Pepper | CROPS | 9 | IK-based | VRmMS-12; CamBoard nano/ SR4000; Prossilica GC2450C | [Ba17] |
| Apple | Multi-joint vertical manipulator | 4 | Machine Vision Feedback P-based | color CCD camera/ laser ranging sensor | [Bu05] |
| Apple | PRRRP Structure manipulator | 5 | IBVS | color CCD camera/ infrared double photoelectric cells | [De11] |
| Apple | UR3 | 6 | IK-based | ZED | [On19] |

Tab. 1: Summary of reviewed harvesting robots, control strategies and their camera/sensors

## 4 Conclusion

The design of a low-cost and efficient harvesting robot requires collaboration in areas of horticultural engineering, machine vision, sensing, robotics, control, intelligent systems, software architecture, system integration, and greenhouse crop management. In this study, we reviewed different harvesting robot manipulator components with an emphasize on control systems and considering carried out numerical and in-field experimental results in literature. As such, we could conclude that future researches should consider advanced and adaptive nonlinear control algorithms. These control strategies are robust to the unknown fruit motion caused by wind gusts and the dynamical robot modeling uncertainties. Consequently, they could overcome the undesirable fruit motion that might influence the automatic harvesting efficiency. Also, the reviewed VSC systems relied on high-gain feedback for disturbance compensation. However, it is well-known that the performance of high-gain feedback controllers could be significantly compromised in the presence of measurement noise. Therefore, future research activities should be focused on the design of optimized robust nonlinear control algorithms for disturbance compensation.

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