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A Review of Pruning and Harvesting Manipulators

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***Abstract*—The increase of the world population and a decrease in agricultural labour availability have motivated research robotics in the agricultural field. This paper aims to analyze the state of the art related to manipulators used in the agricultural robotics field. Two pruning and seven harvesting manipulators were reviewed and are analyzed. The pruning manipulators were used in two different scenarios: (*i*) grapevines and (*ii*) apple trees. These manipulators showed that a light-controlled environment could reduce visual errors and that prismatic joints on the manipulator are advantageous to obtain a higher reach. The harvesting manipulators were used for 5 different products: (*i*) strawberries, (*ii*) tomatoes, (*iii*) apples, (*iv*) sweet-peppers and (*v*) iceberg lettuce. The harvesting manipulators showed that a different kinematic configuration is required for different end-effectors, as some end-effectors only require horizontal movements and others require more degrees of freedom to reach and grasp the target. This work will support new developments of novel solutions related to agricultural robotic grasping and manipulation.**

***Index Terms*—Agricultural Robot, Agricultural Manipulator, Pruning, Harvesting**

I. Introduction

Due to the increase of the world population and decrease in agricultural labour availability, the motivation for research of robotics in the agricultural field has increased [1], [2]. Many agricultural tasks require long working hours during harvesting periods and can become physically intense. [1]–[4]. Moreover, the transition into agricultural robots has many challenges [5]. Contrary to an industrial environment where objects are uniform, and the workspace constraints are controllable, an agricultural environment is dynamic since the fruits, vegetables, and plants vary in shape, sizes and colour [3].

A robot capable of performing agricultural tasks, such as pruning or harvesting, requires several different modules to perform its task efficiently [6]. The different modules are responsible for navigation and localization, motor control, sensing, mechanical structure, and others [6].

In this article, a review is done about robotic manipulators currently used in the agricultural field, namely in pruning and harvesting. The purpose of this review is to decrease the gap in the literature as there is little information specifically about manipulators used in the agricultural field, contrary to the literature about the end-effectors and computational systems used in this field.

Robotic manipulators face several challenges regarding the agricultural field. A pruning manipulator requires a complete and connected model of the plant's structure and must know which branches to cut and which branches to leave behind while avoiding them [7]. A harvesting manipulator requires a visual identification of the fruit in order to determine if it is mature enough to be harvested [8]; furthermore, these manipulators require a precise amount of grip strength so that the product is not damaged and, simultaneously, does not slip [9]. In order to overcome these challenges, robotic manipulators perform their tasks slowly, making their overall performance insufficient to compete with manual labour [10].

Robotic manipulators are typically composed of a serial chain of links that are connected through revolute (R) and/or prismatic (P) joints. The joints define the manipulator type (e.g., a manipulator with three revolute joints and one prismatic joint is denoted as an RRRP manipulator). The revolute joints rotate the links around an axis while the prismatic joints give the links relative linear movement [11]. A manipulator can replace a human in the agricultural field as it can mimic a human arm movement [1]–[4].

The research that was the basis of this document consisted of searching articles, in platforms such as: Research Gate, Google Scholar, IEEE Xplore and Science Direct, about agricultural robots that had relevant information about their manipulator, using the following keywords: Agricultural Robot, Pruning and/or Harvesting Manipulator and Precision Agriculture. This information consists of: (*i*) the type of manipulator, (*ii*) if the manipulator is used in harvesting or pruning, (*iii*) the reach, (*iv*) the payload, (*v*) what sensors are incorporated on the manipulator, (*vi*) the manipulator control method, and (*vii*) the test environment. The choice of manipulators took into account how relevant and promising they were for harvesting and pruning.

This document is organized in the following way: in Section II and Section III, a review of pruning and harvesting manipulators, respectively, is made; in Section IV, the reviewed manipulators are analyzed and compared; in Section V, future directions and trends are proposed; finally, in Section VI conclusions of the reviewed manipulators are drawn.

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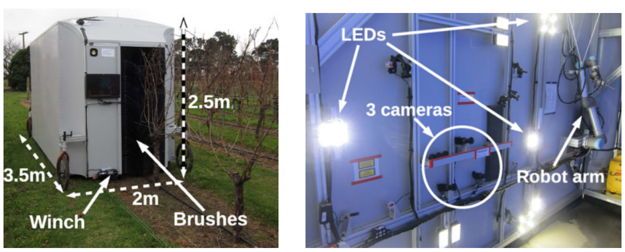
II. Pruning Manipulators

In this section, a review is addressed on pruning manipulators. The reviewed works are presented chronologically.

Pruning is the act of cutting small branches from trees or other plants to maintain their structure, increase yield or reduce the risk of diseases [12]. A robotic manipulator capable of pruning must have enough Degrees of Freedom (DoF) to be able to reach the branch with a suitable orientation; furthermore, the manipulator must have an end-effector capable of cutting branches [3].

A. A Robot System for Pruning Grape Vines

In 2015, Botterill *et al.* [7] developed a robotic platform with the purpose of pruning grapevines. To reduce visual errors induced by the sunlight, the authors developed a mobile platform that completely covers the grapevines. This platform, shown in Figure 1, serves to cover the workspace from the sunlight; this provides control over the lighting quality since the lighting conditions will always be the same. The manipulator is a 6 DoF commercially available UR5 robot arm [13], shown in Figure 2. This arm has a reach of 0.85 m and a payload of 5 kg. The manipulator was positioned 1.6 m behind the cameras to perform a full 3D reconstruction of the grapevine plant before pruning. The end-effector used for pruning the branches consists of a router mill-end attached to a high-speed motor. The manipulator was tested on a row



(a) Outside (b) Inside

Fig. 1. Grape Vine Pruning Platform From the Outside (Left) and From the Inside (Right) [7]

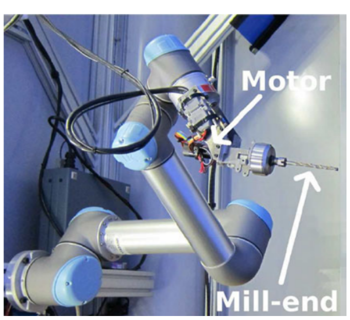


Fig. 2. UR5 Manipulator with Router Mill-End End-Effector [7], [13]

of *Sauvignon Blanc* vine, being able to successfully cut the desired branches and to move aside the branches that were not meant to be cut. However, trials were cancelled on some plants as there were problems with cable tangling and connection failures.

B. Integrated 3R End-Effector With a Cartesian Manipulator for Pruning Apple Trees

In 2020, Zahid *et al.* [3] developed a 6 DoF tree pruning manipulator that uses a shear cutter as an end-effector to prune apple trees. The manipulator consists of a 3 DoF prismatic segment, shown in Figure 3 and a 3 DoF rotational segment, shown in Figure 4 [3]. The manipulator has a square base and was selected to (*i*) dampen the vibration and (*ii*) improve the stability of the system. The mentioned base has a 3 DoF PPP configuration. At the end of this prismatic segment, the manipulator has a 3 RRR DoF segment that moves the end-effector to the desired orientation. This manipulator has a reach of 0.24 m. A cutting shear was integrated with the end-effector

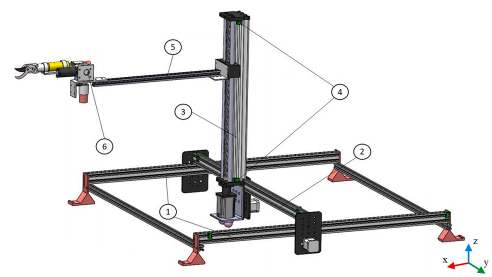


Fig. 3. Apple Tree Pruning Manipulator Prismatic Segment [3]

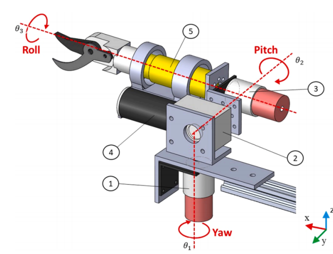


Fig. 4. Apple Tree Pruning Manipulator Rotary Segment [3]

in order to provide smooth and splint-free pruning. Field tests were performed on the manipulator to verify if it could prune tree branches. The tests were successful as the end-effector was able to reach and align perpendicularly to a branch. The cutter end was also able to cut the branches with diameters up to 25 mm. For future work, the authors suggest developing a collision-free path planning algorithm for the manipulator and a 3D reconstruction of the tree canopy to locate pruning points accurately.

III. Harvesting Manipulators

In this section, a review is made on harvesting manipulators. The manipulators in this section are presented chronologically, according to the date of their development, and by fruit type.

Like the pruning manipulators, the harvesting manipulators need enough reach and DoF to reach the target with the correct orientation; furthermore, the end-effector must be capable of successfully grabbing said target fruit without damaging it [14].

A. Strawberry-Harvesting Robot

In 2008, Hayashi *et al*. [4] developed a robot capable of harvesting strawberries in a greenhouse. The robot moved in a straight line in between 2 strawberry beds. For this reason, a manipulator able to rotate between the two beds was required. Thus, a cylindrical RPP manipulator was designed. A revolute joint in the base frame rotates the manipulator to reach the strawberries from both sides of the robot. The linear actuators allow the end-effector to move vertically and horizontally. During the harvesting, the fruits should remain untouched as much as possible to avoid damage. For this reason, the end-effector must harvest the strawberry by the peduncle. The authors developed an end-effector composed of a suction gripper to hold the fruit, and a cutter, to separate the fruit from the plant. Furthermore, the manipulator has a horizontal reach of 0.30 m and has a photoelectric sensor to detect the fruit's presence. The manipulator was able to pick up strawberries with an average time of 7.7 s per fruit. The manipulator had an overall success chance of 41.3 % to pick up a strawberry and to place it in a tray in a sample of 1130 strawberries. The authors concluded that using a suction gripper and a non-suction gripper presented similar results. Thus the miniaturization of the end-effector is possible by removing the suction unit. However, it would be necessary to develop a method to reduce the swinging of the strawberry during transfer to the basket and to check that the grasping was successful.

B. Tomato Harvesting Robots

In 2010, Kondo *et al.* [15] developed a robotic platform with the goal of harvesting tomato clusters. The authors argue that tomato clusters are similar in both high-wire and high-density systems. Given this, they concluded that there are more horizontal manipulator motions than vertical motions. For this reason, a Mitsubishi RH-6SH5520 SCARA manipulator was used. This manipulator has a reach of 0.55 m, a maximum payload of 6 kg, and uses the CR2B-574 controller. Due to issues detecting the tomato peduncle orientation, the authors considered that the end-effector needs multi-directional access to grasp and cut the tomato peduncle from any direction. The designed end-effector is mainly composed of 2 upper and two lower fingers and a cutter; furthermore, a photosensor is attached to the end-effector to detect the tomato cluster main stem. Experimental tests were performed on 20 tomato clusters, taking around 15 seconds to harvest a single tomato cluster. In some situations, the end-effector could not reach the cluster stems as its dimensions were sometimes larger than the tomato stem length. The manipulator had a success rate of 50 %, while most of the unsuccessful tries were due to the end-effector dimensions. The authors concluded that their proposed manipulator and end effector was suitable for tomato cluster harvesting in high-wire system; however, a smaller and more compact end-effector is required for harvesting tomato clusters in high-density systems.

Later, in 2016, Yaguchi *et al*. [16] developed a robot capable of harvesting tomatoes. The manipulator used was a 6 DoF commercially available UR5 robot arm [13], presented previously in Subsection II-A. This arm has a reach of 0.85 m, a payload of 5 kg and uses the ROS middleware for control purposes. The authors chose it since the end-effector must reach the tomato with a specific angle to grasp the object and pluck it without any damage. The end-effector consists of a three-finger gripper that grabs the tomato, rotates and plucks it. By rotating the fruit, the end-effector will have a reduced chance of damaging the tomato.

This manipulator solves the previous problem of harvesting tomatoes in high-density systems as the end-effector is smaller. Having more than just horizontal rotations, the end-effector can reach the target with more orientations than the previous manipulator. However, the previous manipulator harvests clusters of tomatoes and not a single tomato at a time. Both of these manipulators have their use cases. If the goal is to pluck a cluster of tomatoes in a lower density system, then the manipulator by Kondo *et al.* [15] is better. If the goal is to pluck a single tomato at a time in scenarios where the end-effector is too large, then the manipulator by Yaguchi *et al.* [16] is advantageous.

The manipulator was experimented on a tomato harvesting competition. It was able to pluck a tomato from the plant about every 23 s, with a success rate of 62.2 %. The failure rate is mainly due to the robot not recognizing if the tomato is grasped or in grasping range. This is mainly due to the small size of some of the fruits. A solution suggested by the authors is the use of multiple view direction measurements. Another reason for the failure rate was the size of some of the fruits being too small. The end-effector could not grasp the small tomatoes in order to pluck them. The experiments were done in a controlled environment, as this was a competition. In a real farm, there would be disturbances for each procedure of the harvesting. The authors suggest that grasp state estimation is necessary for future work.

C. Robotic Apple Harvesters

In 2011, De-An *et al*. [17] developed an apple harvesting robot. The authors suggested that a joint manipulator with multiple degrees of freedom can avoid obstacles by operating the corresponding joints when the end-effector reaches the object position. Therefore, they propose a 5 DoF PRRRP manipulator with six links. The first joint lifts the whole manipulator upwards. The first revolute joint turns the manipulator around the waist. The second and third joints turn the end-effector up and down. Finally, the last joint is used for elongation, making the end-effector reach the target location. The suggested end-effector was determined by the target object's biological characteristics (*e.g.*, spherical fruits such as apples). The end-effector is a spoon-shaped two-finger gripper with a pressure sensor, a position sensor, a collision sensor, and a vision sensor. Furthermore, the manipulator is composed of several collision detection sensors, as the collision probability is high, and hall sensors on each joint. The control method was based on Image-Based Visual Servoing (IBVS).

Field tests were performed on an orchard, where 30 apples were successfully picked up and transferred into a container. The process took 10 min, and three apples were dropped as they were too small for the end-effector. The authors concluded that there is a necessity for further research on real-time obstacle avoidance, improving the picking success rate and harvesting efficiency.

Following the previous manipulator, in 2015, Silwal *et al.*. [9] developed their robotic manipulator to harvest apples. The authors faced challenges while designing the manipulator regarding the tree systems and fruit distributions within the same orchard. Furthermore, information was needed about the infrastructure that holds the trees to define the optimal DoF that the manipulator requires. Once the previous information was obtained, Monte Carlo simulations were performed on several permissible end-effector orientations to determine link lengths for a 6 DoF model. The authors concluded that a seventh prismatic DoF was required to reach adjacent rows in the apple tree canopy. The designed manipulator is a 6 DoF RRRRRR manipulator with a 1 DoF prismatic base and 8 links. This manipulator has an extra DoF when compared to the manipulator developed by De-An *et al.* [17], which increases control complexity but allows the end-effector to reach the target with more available orientations. The manipulator's approximate payload is 2.5 kg and has a reach of 0.67 m (including end-effector), does not have any sensors incorporated and uses feedforward open-loop control. The end-effector is a three finger gripper. According to the authors, an advantage of this kind of end-effector is the control over its workspace dimensions. Unlike vacuum and funnel designs with a constrained opening span, it is possible to incorporate grasp planning for fruits in cluttered environments. The manipulator was able to identify 150 apples out of 193, successfully reaching and grabbing 127 without damaging or bruising them. Twenty-three apples were not successfully picked up mainly due to issues related to position and calibration errors and the presence of apples on long thin branches. The end-effector was not able to pluck the apple in the latter situation. Finally, the authors concluded that to improve harvest efficiency, enhanced robustness, especially in the obstacle detection, is required; furthermore, force sensing on the end-effector is also required for feedback on grasp status.

Both of the presented manipulators use grasp end-effectors. Although they are of different kinds (spoon-shaped and three fingered), they function in the same way as their shape allows the fruit to be grasped with no-slip and with little force applied. The manipulator by Silwal *et al.* [9] has an extra DoF when compared to the one presented in De-An *et al.* [17], allowing it to reach the target with more grasping orientations, but increasing control complexity. Having more grasping orientations allows the manipulator to pick fruits that would otherwise be impossible to pick up due to their position and/or orientation, and allows for better obstacle avoidance.

D. Multi Purpose Harvesting Agricultural Robot

In 2012, Baur *et al.* [18] developed a multipurpose harvesting agricultural robot and used the manipulator to harvest sweet-pepper. The manipulator was designed to fulfil tasks like harvesting, pruning or spraying in a greenhouse environment with a task-specific end-effector. The manipulator requires a workspace that can reach all of the objects, in this scenario, sweet-peppers. Given the greenhouse environment, the sweet-peppers are disposed of in rows with a walking path between each row. The manipulator must be able to reach the objects from both sides of the robot, reach and pull a stem while pushing aside the neighbouring stems. Given this, the authors suggest a manipulator with a 9 DoF P8R arrangement (one prismatic joint and eight revolute joints). This manipulator moves a mass of 16 kg and has an expanded arm length of 1.39 m. The manipulator has a decentralized control architecture implemented using a real-time control unit. No field experiments were performed for this manipulator; however, the kinematics and control were simulated. The authors were able to validate if the end-effector could reach a certain position. The authors suggest that further research dedicated to path planning, inverse kinematic algorithms and enhanced control algorithms is required.

E. Robotic Harvesting System for Iceberg Lettuce

In 2018, Birrell *et al.* [19] developed a robot capable of harvesting iceberg lettuce. Contrary to most fruits, lettuce is grown on the ground; therefore, a manipulator whose end-effector can reach the ground is required. The proposed manipulator is a commercially available 6 DoF 6R UR10e [20] robotic arm, shown in Figure **??**. This manipulator has a payload of 10 kg, a reach of 1.30 m and was controlled using the ROS middleware. The manipulator uses force-feedback sensors to record the force and torque applied to the end-effector; furthermore, a visual sensor is mounted on the end-effector. The end-effector must have enough cutting force to cut a lettuce stem, and a straight cut is required at the base of the lettuce. The authors developed an end-effector with two actuators: one for grasping and one for cutting. The iceberg lettuce harvester was tested on a farm and successfully harvested 31 out of 69 lettuces. The average time it took to harvest each lettuce was around 2 s. The authors propose future research to use this design in other applications apart from harvesting lettuce, suggesting that a more universal harvesting system would increase both commercial and research impact.

IV. Analysis and Discussion of the Presented Devices

The manipulators presented previously were created for specific purposes (grapevine pruning and apple harvesting). These manipulators were designed with kinematics that allowed them to reach their destination successfully with a correct angle, either to pick a piece of fruit without damaging it or precisely cut a branch.

In the case of the pruning manipulators, the manipulator presented in Zahit *et al.* [3] was able to successfully cut small branches out of apple trees; however, the one described by Botterill *et al.* [7] was not as successful. Although both of these manipulators were used to cut branches out of different kinds of trees, the grapevine pruner had issues regarding cable tangling and connection failures. Nevertheless, the grapevine pruner overcame lighting issues as the platform blocked the sun and used artificial light. On the other hand, the apple tree pruner, with its prismatic joints, has a greater reach than the latter. As mentioned previously, these were designed for different kinds of plants; however, the results show that using artificial light can reduce visual error induced by sunlight, and prismatic joints can be utilized in scenarios where a high reach is needed.

As for the reviewed harvesting manipulators, for some products (such as tomatoes), a horizontal rotation was proven to be successful in Kondo *et al.* [15]. However, the other reviewed manipulators did not have the same end-effector as this one and required more than just a horizontal rotation. The manipulators that use a fingered gripper require their links to rotate in all axis, in order to grab the product with the correct orientation.

A comparison between the presented manipulators and its end-effectors is presented in Table I and Table II, respectively.

V. Future Directions and Trends

For future directions, most of the problems presented in this article are to be resolved with the goal of creating an effective harvesting and pruning manipulator with performance similar to a human. These consist of finding the best number of DoF and manipulator configuration, in order to have more grasping orientations, and control algorithms/architectures for different kinds of fruits and branches, in order to achieve an agricultural manipulator capable of operating in more broad scenarios, and applications, as opposed to their current niche applications of only one type of product to harvest or plant to prune.

VI. Conclusion

In this article, several manipulators used in agricultural tasks were reviewed. These manipulators are capable of pruning and harvesting. Depending on the harvest and on the end-effector type, the manipulator requires a different number of DoF in order to perform its task successfully. Moreover, in some cases, these manipulators are equipped with embedded sensors (known as eye-in-hand sensors) - such as visual cameras, LiDAR, and pressure sensors - to detect if they reached the fruit or branch and if they successfully grabbed/cut them.

Most of these manipulators were designed and developed specifically for a certain type of harvest since fruits and vegetables have different shapes, textures and resistance comparatively to each other. Although the presented manipulators had successful results (partially), they would not be as effective at pruning or harvesting another type of plant or vegetable. Furthermore, the presented manipulators still face challenges regarding their tasks. These challenges are mainly due to path planning, collision avoidance, gripping and due to the dimensions of some manipulators. Surpassing these challenges could pave the way into developing more generic manipulators with application in the agricultural field and not a product-specific manipulator.

References

[1] Kjeld Jensen, Søren Hundevadt Nielsen, RN Joergensen, A Boegild, NJ Jacobsen, OJ Joergensen, and CL Jaeger-Hansen. A low cost, modular robotics tool carrier for precision agriculture research. In *Proc Int Conf on Precision Agriculture*, 2012.

[2] Heng Wang, Cameron J. Hohimer, Santosh Bhusal, Manoj Karkee, Changki Mo, and John H. Miller. Simulation as a tool in designing and evaluating a robotic apple harvesting system. *IFAC-PapersOnLine*, 51(17):135 – 140, 2018. 6th IFAC Conference on Bio-Robotics BIOROBOTICS 2018.

[3] Azlan Zahid, Md Sultan Mahmud, Long He, Daeun Choi, Paul Heinemann, and James Schupp. Development of an integrated 3r end-effector with a cartesian manipulator for pruning apple trees. *Computers and Electronics in Agriculture*, 179:105837, 2020.

[4] Shigehiko Hayashi, Kenta Shigematsu, Satoshi Yamamoto, Ken Kobayashi, Yasushi Kohno, Junzo Kamata, and Mitsutaka Kurita. Evaluation of a strawberry-harvesting robot in a field test. *Biosystems Engineering*, 105(2):160 – 171, 2010.

[5] Luiz F. P. Oliveira, António P. Moreira, and Manuel F. Silva. Advances in agriculture robotics: A state-of-the-art review and challenges ahead. *Robotics*, 10(2), 2021.

[6] Redmond Shamshiri, Cornelia Weltzien, Ibrahim Hameed, Ian Yule, Tony Grift, Siva Balasundram, Lenka Pitonakova, Desa Ahmad, and Girish Chowdhary. Research and development in agricultural robotics: A perspective of digital farming. *International Journal of Agricultural and Biological Engineering*, 11:1–14, 01 2018.

[7] Tom Botterill, Scott Paulin, Richard Green, Samuel Williams, Jessica Lin, Valerie Saxton, Steven Mills, Xiaoqi Chen, and Sam Corbett-Davies. A robot system for pruning grape vines. *Journal of Field Robotics*, 34, 09 2016.

[8] Kazy Noor E Alam Siddiquee, Md Shabiul Islam, Mohammad Yasin Ud Dowla, Karim Mohammed Rezaul, and Vic Grout. Detection, quantification and classification of ripened tomatoes: A comparative analysis of image processing and machine learning. *IET Image Processing*, 14(11):2442–2456, sep 2020.

[9] Abhisesh Silwal, Joseph Davidson, Manoj Karkee, Changki Mo, Qin Zhang, and Karen Lewis. Design, integration, and field evaluation of a robotic apple harvester. *Journal of Field Robotics*, 34, 03 2017.

[10] Yuanshen Zhao, Liang Gong, Yixiang Huang, and Chengliang Liu. A review of key techniques of vision-based control for harvesting robot. *Computers and Electronics in Agriculture*, 127:311 – 323, 2016.

[11] Serdar KuCuk and Zafer Bingul. The inverse kinematics solutions of industrial robot manipulators. In *Proceedings of the IEEE International Conference on Mechatronics, 2004. ICM'04.*, pages 274–279. IEEE, 2004.

[12] Edward F Gilman. *An illustrated guide to pruning*. Cengage Learning, 2011.

[13] Universal robots.com. 2021. Ur5 collaborative robot arm — flexible and lightweight robot arm.

[14] Baohua Zhang, Yuanxin Xie, Jun Zhou, Kai Wang, and Zhen Zhang. State-of-the-art robotic grippers, grasping and control strategies, as well as their applications in agricultural robots: A review. *Computers and Electronics in Agriculture*, 177:105694, 2020.

[15] Naoshi Kondo, Koki Yata, Michihisa Iida, Tomoo Shiigi, Mitsuji Monta, Mitsutaka Kurita, and Hiromi Omori. Development of an end-effector for a tomato cluster harvesting robot. *Engineering in Agriculture, Environment and Food*, 3(1):20 – 24, 2010.

[16] H. Yaguchi, K. Nagahama, T. Hasegawa, and M. Inaba. Development of an autonomous tomato harvesting robot with rotational plucking gripper. In *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 652–657, 2016.

[17] Zhao De-An, Lv Jidong, Ji Wei, Zhang Ying, and Chen Yu. Design and control of an apple harvesting robot. *Biosystems Engineering*, 110(2):112 – 122, 2011.

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TABLE I
MANIPULATORS USED FOR PRUNING AND HARVESTING

Source	**Kinematic Configuration**	**Nº Links**	**Prune**	**Reach**	**Payload**	**Sensors**	**Control**	**Test Environment**
Botterill et al. [7]	RRRRRR	7	Grape Vine	0.85 m	5 kg	-	-	Real
Zahid et al. [3]	PPPRRR	7	Apple Tree	0.24	-	Hall Sensor	-	Real
			Harvest					
Hayashi et al. [4]	RPP	4	Strawberries	0.30 m	-	Photoelectric	-	Real
Kondo et al. [15]	RRPR	5	Tomatoes	0.55 m	6.0 kg	Photosensor	-	Real
Yaguchi et al. [16]	RRRRRR	7	Tomatoes	0.85 m	5 kg	-	-	Lab
De-An et al. [17]	PRRRP	6	Apples	-	-	Pressure, Collision, Vision, Position	IBVS	Real
Silwal et al. [9]	PRRRRRR	8	Apples	0.67 m	2.5 kg	-	Open Loop w/ Feedforward	Real
Baur et al. [18]	PRRRRRRRR	9	Sweet-Pepper	1.39 m	16 kg	-	-	Real
Birrell et al. [19]	RRRRRR	7	Iceberg Lettuce	1.30 m	10 kg	-	Real	

TABLE II
END-EFFECTORS USED FOR PRUNING AND HARVESTING

Source	**Gripper**	**Application Field**
Botterill et al. [7]	Miller	Grape Vine
Zahid et al. [3]	Cutter	Apple Tree
Hayashi et al. [4]	Suction & Cutter	Strawberries
Kondo et al. [15]	4 Finger & Cutter	Tomatoes
Yaguchi et al. [16]	3 Finger	Tomatoes
De-An et al. [17]	2 Finger	Apples
Silwal et al. [9]	3 Finger	Apples
Baur et al. [18]	-	Sweet-Pepper
Birrell et al. [19]	-	Iceberg Lettuce

[18] J. Baur, J. Pfaff, H. Ulbrich, and T. Villgrattner. Design and development of a redundant modular multipurpose agricultural manipulator. In *2012 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, pages 823–830, 2012.
[19] Simon Birrell, Josie Hughes, Julia Y. Cai, and Fumiya Iida. A field-tested robotic harvesting system for iceberg lettuce. *Journal of Field Robotics*, 37(2):225–245, 2020.
[20] Universal robots.com. 2021. Ur10e collaborative industrial robotic arm - payload up to 10 kg.