An overview of pruning and harvesting manipulators

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Abstract

Purpose – The motivation for robotics research in the agricultural field has sparked in consequence of the increasing world population and decreasing agricultural labor availability. This paper aims to analyze the state of the art of pruning and harvesting manipulators used in agriculture.

Design/methodology/approach – A research was performed on papers that corresponded to specific keywords. Ten papers were selected based on a set of attributes that made them adequate for review.

Findings – The pruning manipulators were used in two different scenarios: grapevines and 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 three types of fruits: strawberries, tomatoes and apples. These manipulators revealed that different kinematic configurations are required for different kinds of end-effectors, as some of these tools only require movement in the horizontal axis and others are required to reach the target with a broad range of orientations.

Originality/value – This work serves to reduce the gap in the literature regarding agricultural manipulators and will support new developments of novel solutions related to agricultural robotic grasping and manipulation.

Keywords Harvesting, Agricultural manipulator, Agricultural robot, Pruning

Paper type Literature review

1. Introduction

The increasing world population, and the simultaneous decreasing agricultural labor availability, has sparked the motivation for research of robotics in the agricultural field (Jensen *et al.*, 2012; Wang *et al.*, 2018).

Many agricultural tasks require long working hours during harvesting periods and can become physically intense (Jensen *et al.*, 2012; Wang *et al.*, 2018; Zahid *et al.*, 2020; Hayashi *et al.*, 2010), and manual operations, such as in greenhouses, can account for up to 50% of total production costs (Ferreira, 2017; Cámara-Zapata *et al.*, 2019). Furthermore, a large part of these costs come from manual tomato harvesting, which requires 700 to 1400 h yr^{-1} ha^{-1} (Ferreira, 2017; Cámara-Zapata *et al.*, 2019).

Introducing robots into agricultural environments has many challenges (Oliveira *et al.*, 2021). Unlike an industrial

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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 color (Zahid *et al.*, 2020).

A robot capable of performing agricultural tasks, such as pruning or harvesting, requires various distinct elements to perform its task efficiently (Shamshiri *et al.*, 2018). Different modules are responsible for navigation and localization, perception, actuator control, mechanical structure and others (Shamshiri *et al.*, 2018).

This paper reviews robotic manipulators currently used in the agricultural field, namely, in pruning and harvesting. This document aims to reduce the gap in the literature about manipulators used in the agricultural field, in contrast to the literature about the end-effectors and computational systems used in this field.

Robotic manipulators are exposed to several agricultural context challenges. A pruning manipulator requires a complete perception system to understand the plant's structure and must know, which branches to cut and which branches to leave behind while avoiding them (Botterill *et al.*, 2016). A harvesting manipulator requires visual identification of the fruit, to determine if it is mature enough to be harvested (E Alam Siddiquee *et al.*, 2020); furthermore, these manipulators require a precise amount of grip strength so that the product is not damaged and, simultaneously, does not slip (Silwal *et al.*, 2017). To overcome these challenges, robotic manipulators perform their tasks slowly, making their overall performance insufficient to compete with manual labor (Zhao *et al.*, 2016).

For this literature review, platforms such as Research Gate, Google Scholar, IEEE Xplore and Science Direct were considered. The terminologies considered on search engines were agricultural robot, pruning manipulator, harvesting manipulator and precision agriculture. The information collected was the type of manipulator, if the manipulator is used in pruning or harvesting, the reach, the payload, what sensors are incorporated on the manipulator, the manipulator control method and the test environment. The choice of manipulators took into account how relevant and promising they were for pruning, fruit trimming and harvesting.

The manipulators in this article are divided into two sections: for pruning and for harvesting, and are presented chronologically, according to the date of their development, and by task type (type of plant to prune or fruit to harvest).

2. Pruning manipulators

Pruning consists in trimming plants by cutting away overgrown branches to maintain their structure, increase yield and growth or reduce the risk of diseases (Gilman, 2011). Similar to pruning, fruit trimming, or fruit pruning, is the act of removing selected fruits from a growing batch, to concentrate more nutrients on the ones that were left on the plant (Gilman, 2011; Bertin *et al.*, 2001). A manipulator to be used in pruning must have enough Degrees of Freedom (DoF) to be able to reach the branch with a suitable orientation, determine which branches, and fruits, to cut off and have a suitable end-effector for a suitable cut (Zahid *et al.*, 2020). Although fruit trimming is an act of pruning, its execution is the same as harvesting with a different fruit evaluation. Given this, the presented manipulators will focus solely on pruning.

2.1 Robotic system to prune grape vines

In 2016, Botterill *et al.* (2016) developed a robotic platform for pruning grapevines. The robotic platform was created to reduce visual errors induced by the sunlight. The manipulator, 6 DoF commercially available UR5 robot arm robots.com (2021a), was placed 1.6 m behind the cameras to perform a full 3 D reconstruction of the grapevine plant before pruning. For pruning the branches an end-effector consisting of a router mill-end attached to a highspeed motor was used. While tested on a row of *Sauvignon Blanc* vine, this system was able to successfully cut the intended branches and to move aside the ones not meant to be cut. Nonetheless, trials were canceled on some plants as there were problems with entangled cables and connection failures. The robotic system and manipulator are show in Figures 1 and 2, respectively.

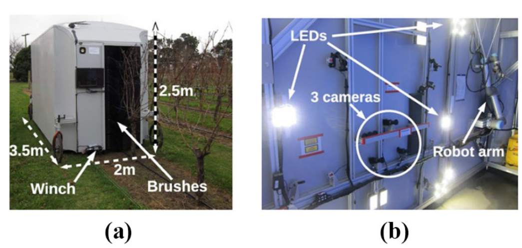
2.2 Simulation of grapevine pruning manipulator

Magalhães *et al.* (2019) benchmarked different path planning algorithms on a simulated pruning manipulator with a mobile base, based on an existent manipulator, shown in Figure 3, for pruning grapevines in steep slope vineyards. The manipulator is a 6 DoF Robotis Manipulator-H. The simulation used different path planning algorithms from the Open Manipulation Planning Library (OMPL) Kavraki Lab. For success rates near 100%, the path planning algorithms require at least 5 s of maximum planning time and the best one (considering the classification order of importance of the highest success rate, the lowest planning time, the lowest path length and the highest path clearance) is the BiTRRT path planning algorithm. To improve planning times and to run different systems simultaneously with the path planning, they suggest the parallelisation of algorithms. Furthermore, they suggest using a non-probabilistic path planning algorithm, such as A*.

2.3 Integrated 3R end-effector with a cartesian manipulator for pruning apple trees

Zahid *et al.* (2020) developed a manipulator with 6 DoF for pruning apple trees branches, and used a shear cutter as the end-effector. This manipulator is divided into a 3 DoF prismatic segment, shown in Figure 4, and a 3 DoF rotational segment, shown in Figure 5, and presents a square base (with a 3 DoF PPP configuration) selected to: lower the vibration and improve the stability. As stated, the manipulator has a 3 DoF RRR segment, at the end of the prismatic segment, for moving the end-effector to the intended orientation. To provide

Figure 1 Grape vine pruning platform from the exterior (left) and from the interior (right) (Botterill *et al.*, 2016)



Notes: (a) Outside; (b) inside

smooth and splint-free pruning, a cutting shear was integrated with the end-effector. During field tests performed on the manipulator to verify if it could prune tree branches, it successfully reached and aligned itself with the correct orientation relatively to branches. Moreover, the end-effector was capable to cut the branches in varying diameters up to a maximum of 25 mm. As ideas for further improvements, Zahid *et al.* suggested the development of a collision-free path planning algorithm for the manipulator and a 3 D reconstruction of the tree canopy to locate pruning points accurately.

2.4 Non-holonomic mobile manipulator for grapevine winter pruning

Teng *et al.* (2021) proposed a motion controller that can regulate a non-holonomic mobile manipulator for grapevine winter pruning. This system consists of a non-holomonic mobile base, using differential drive and a 7 DoF RRRRRRR manipulator. The proposed controller is based on hierarchical tasks and divides several tasks into different priorities, with the end-effector trajectory task as the top priority. The used manipulator is a commercially available Panda Arm Manipulator, shown in Figure 6, by Franka Emika Robots (a). The mobile base serves as an additional prismatic 2 DoF, serving two purposes: mobility and manipulation. The mobile manipulator was tested in a lab environment and dealt with grapevine pruning tasks smoothly, while satisfying singularity avoidance and joint limitation avoidance. For future work, the authors propose an extension of their framework for whole-body motion and perception coupling.

2.5 Tree pruning manipulator

A pruning manipulator designed to prune fruit trees was presented in 2020 by You *et al.* (2020). This manipulator is a 6 DoF commercially available UR5e manipulator Robots (b), similar to the one shown previously in Figure 2. It is considered a Fast Reliable and Efficient Database Search Motion Planner (FREDS-MP) framework for motion planning and an eye-in-hand Red Green Blue Depth (RGB-D) camera for perception. The end-effector has a cutter with a pneumatic actuator to cut the branches. Experimental tests were performed with a lab setup similar to a sweet cherry tree with an upright fruiting offshoot. The manipulator was meant to cut the horizontal branches that came out of the vertical leads. During the tests,

Figure 2 UR5 manipulator with router mill-end end-effector (Botterill *et al.*, 2016; robots.com, 2021a)

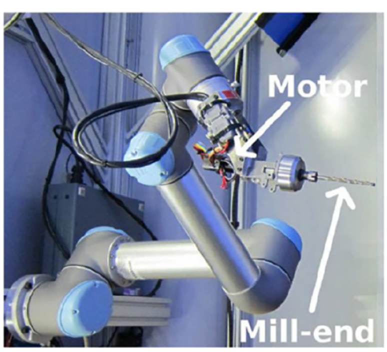


Figure 3 Pruning manipulator on a mobile base

Figure 4 Apple tree pruning manipulator prismatic segment (Zahid *et al.*, 2020)

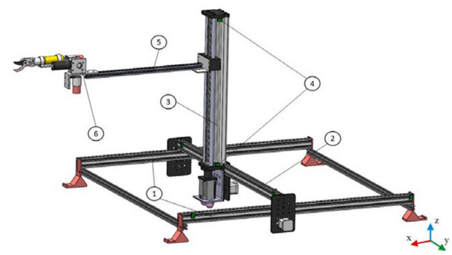


Figure 5 Apple tree pruning manipulator rotary segment (Zahid *et al.*, 2020)

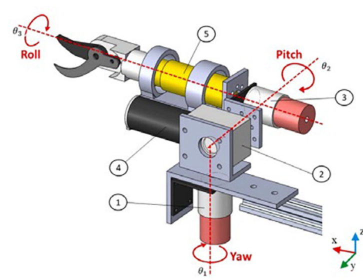
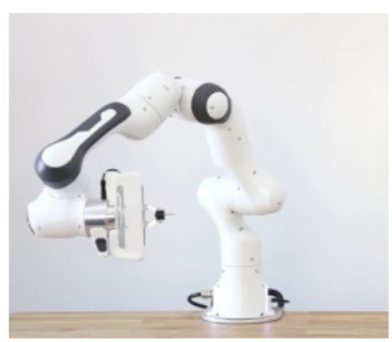


Figure 6 Panda robotic arm robots (a)



the manipulator had an average success rate of 92% with planning times of hundreds of milliseconds. However, the trajectory and cutting time was slow, with an average time of 5.12 s. This happens due to the safety limitations in the UR5e manipulator. To improve travel times, the authors suggest using a 7 DoF manipulator instead of a 6 Dof manipulator, and the installation of the manipulator on a mobile base; furthermore, they suggest the addition of a high-resolution stereo camera to scan the entire tree.

3. Harvesting manipulators

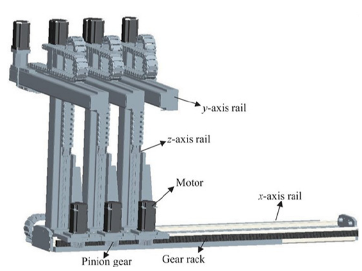
Like the previously presented pruning manipulators, harvesting manipulators need enough reach and DoF to reach the target with the correct orientation; furthermore, the end-effector must be capable of successfully picking and depositing the fruit without damaging it (Zhang *et al.*, 2020).

3.1 Strawberry-harvesting robot

Xiong *et al.* (2020) developed a multi-arm strawberry picking manipulator (Figure 7). The authors focused on developing a manipulator that is cheaper than an industrial manipulator as these are too expensive to be used in a farming scenario where several manipulators are required to achieve human performance. The manipulator consists of two or more 3 DoF cartesian arms placed on a common rail. Being on the same rail, the arms share the same x-axis and have independent y and z-axis. Each of the manipulator's arms has a three-finger gripper as the end-effector. The manipulator uses RGB cameras to obtain point clouds of its surroundings and to detect the strawberries.

Field experiments were performed on a table-top strawberry growing system in a greenhouse. The manipulator was presented with different types of strawberry distributions, ranging from 1 or 2 ripe strawberries with no other strawberries surrounding them, to 1 or 2 ripe strawberries with several unripe strawberries surrounding it. The manipulator had a picking success rate of 97% on the first attempt and 100% with two attempts on a single isolated ripe strawberry. These success rates decreased as the number of unripe strawberries surrounding the ripe strawberry increases. When the strawberry was partially surrounded by unripe strawberries the picking success rates were of 50 and 75% for the first attempt and for two attempts, respectively. Finally, when the strawberry was completely surrounded by unripe strawberries, the picking success rates dropped to 5 and 20%, respectively. The common reasons for unsuccessful pickings were due to localization errors, strawberries not being detected, strawberry diameter too big for the end-effector and due to the target being out of reach. For future work, the authors propose resolving the common reasons for unsuccessful pickings, presented previously.

Figure 7 Strawberry-harvesting manipulator (Xiong *et al.*, 2020)



3.2 Tomatoharvesting robots

Kondo *et al.* (2010) developed a robotic platform for harvesting tomatoes in clusters. Tomato clusters are considered to be identical in both high-wire and high-density systems. As it was observed that horizontal movements are sufficient for harvesting tomato clusters, a Mitsubishi RH6SH5520 SCARA manipulator was used. Given that the end-effector needs multidirectional access to grasp and cut the tomato peduncle from any direction, the designed tool is mainly composed of two upper and two lower fingers and a cutter, with the addition of a photosensor (for detecting the tomato cluster main stem) attached to it. Experiments were performed on 20 tomato clusters, taking around 15 s to harvest a single tomato cluster. In some cases, the end-effector could not reach the stems as their dimensions were sometimes greater than the tomato stem length. The manipulator had a success rate of 50%, being most of the unsuccessful tries due to the end-effector dimensions. The authors concluded that their proposed manipulator and end-effector were suitable for tomato cluster harvesting in high-wire system; however, it is required a smaller and more compact end-effector for harvesting tomato clusters in high-density systems.

Later, Yaguchi *et al.* (2016) developed a robot capable of harvesting tomatoes. The manipulator used was a 6 DoF commercially available UR5 robot arm robots.com (2021a), presented previously in Section 2.1. The authors chose this manipulator since the end-effector must reach the tomato with a specific angle to grasp the object and pluck it without desecrating it. The end-effector consists of a three-finger gripper that grabs the tomato, rotates and plucks it. Rotating the tomato reduces the probability of damaging the fruit while plucking it.

As the end-effector has a smaller dimension, this manipulator solves the problem of harvesting tomatoes in high-density systems. Furthermore, the end-effector can reach the target with more orientations than the previous manipulator as it is more than just horizontal rotations. However, the previous manipulator harvests clusters of tomatoes and not a single tomato at a time. Therefore, both of these manipulators have their applications. If the goal is to pluck a cluster of tomatoes in a lower density system, then the manipulator by Kondo *et al.* (2010) is better. If, on the contrary, 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.* (2016) is advantageous.

The manipulator presented by Yaguchi *et al.* (2016) 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%. This failure rate is mainly due to the robot not recognizing if the tomato is grasped or in grasping range, given the small size of some of the fruits, and the end-effector could not grasp the small tomatoes to pluck them. A possible solution suggested by the authors is the use of multiple view direction measurements. Moreover, 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. Therefore, the authors suggest that grasp state estimation is necessary for future work.

3.3 Robotic apple harvesters

De-An *et al.* (2011) developed an apple harvesting robot. As it is suggested that using a joint manipulator with multiple degrees of freedom can avoid obstacles by operating the corresponding joints when the end-effector reaches the object position, they proposed a 5 DoF PRRRP manipulator. The first joint lifts the whole manipulator upwards, while the first rotational joint turns the manipulator around the waist. The second and third joints turn the end-effector up and down, and the last one is used for elongation, allowing the end-effector to reach the target location. The end-effector was designed considering the target object's biological characteristics (e.g. spherical fruits such as apples): it is a spoon-shaped two-finger gripper with pressure, position, collision and vision sensors. The manipulator is also equipped with several collision detection sensors, as the collision probability is high and hall sensors on each joint, and its control method is based on image-based visual serving (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, being three apples dropped as they were too small for the end-effector. The authors concluded that there is needed further research on real-time obstacle avoidance, improving the picking success rate and harvesting efficiency.

Silwal *et al.* (2017) also developed a robotic manipulator for apples harvesting. They faced challenges while designing the manipulator, concerning the tree systems and fruit distributions within the same orchard. Moreover, information was needed regarding the infrastructure that holds the trees, to define the optimal DoF that the manipulator requires. Once this information was obtained, were performed Monte Carlo simulations on several permissible end-effector orientations to determine link lengths for a 6 DoF model. It was 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. This manipulator has an extra DoF when compared to the manipulator developed by De-An *et al.* (2011), which increases control complexity, but allows the end-effector to reach the target with more available orientations. This manipulator does not have sensors incorporated and uses a feedforward open-loop control algorithm. A three-finger gripper is used as end-effector. According to Silwal *et al.* (2017), an advantage of this end-effector type 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. This 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, due to issues mainly related to position and calibration errors and the presence of apples on long thin branches, on which case the end-effector was not able to pluck the fruits. Silwal *et al.* (2017) concluded that enhanced robustness, especially in the obstacle detection, is required to improve harvest efficiency; additionally, is also required force sensing on the end-effector for feedback on grasp status.

Both these manipulators use grasp end-effectors. Although they are of different types (spoon-shaped and three fingered), they function in the same way, as their shape allows the fruits to be grasped with no-slip and with a small force applied. 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.

4. Analysis and comparison

The manipulators presented previously focused solely on pruning and were created for specific pruning tasks (apple trees, grapevines, sweet cherry trees). These manipulators were designed with kinematics that allowed them to reach their destination successfully with a correct angle to precisely cut a branch. Furthermore, only the manipulators developed by Zahid *et al.* (2020) and by Botterill *et al.* (2016) were tested in a real environment. The rest were tested through simulations and in a lab environment.

4.1 Pruning manipulators

The manipulator developed by Zahid *et al.* (2020) was able to successfully cut small branches out of apple trees, while the one introduced by Botterill *et al.* (2016) was not as successful. Although these two manipulators were intended for cutting branches of different tree types, the grapevine pruner presented issues concerning cable tangling and connection failures. Furthermore, to overcame lighting problems the grapevine pruner platform blocked the sun and artificial light was used. On the other hand, the apple tree pruner, with its prismatic joints, presents a greater reach than the latter. As previously stated, these two systems were designed for different sorts of plants; however, results allow to conclude that using artificial light can reduce visual errors induced by sunlight, and prismatic joints can be used in scenarios where is needed an increased reach.

Reaching a branch with the ideal orientation to cut it without compromising the plant's health requires a high number (6 – 7) of DoF, which all of the analyzed manipulators had. Additionally, it was verified that these manipulators present challenges concerning path planning. Although Magalhães *et al.* (2019) successfully planned the path for a manipulator using different algorithms, it took much longer than a human would take to determine a path. You *et al.* (2020) managed to obtain lower planning times, but their manipulator took a high amount of time to execute the path, making it also inefficient when compared to a human.

4.2 Harvesting manipulators

As for the reviewed harvesting manipulators, for some products (such as tomatoes), a horizontal rotation was proven to be successful Kondo *et al.* (2010). 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 axes, to grab the product with the correct orientation. The manipulator presented by Xiong *et al.* (2020) introduced a different methodology to improve efficiency by increasing the number of arms, contrary to the single arm manipulators presented in this article. This allowed the manipulator to pick several fruits at a time with a simpler control system.

A comparison between the presented manipulators is shown in Table 1.

Table 1 Manipulators used for pruning and harvesting

Source	Kinematic configuration	No. links	Prune	Reach	Payload	Sensors	Control	Test environment
Botterill *et al.* (2016)	RRRRRR	7	Grapevine	0.85 m	5 kg	–	–	Real
Magalhães *et al.* (2019)	RRRRRR	7	Grapevine	0.633 m	3 kg	Photosensor	–	Sim
Zahid *et al.* (2020)	PPPRRR	7	Apple Tree	0.24	–	Hall Sensor	–	Real
Teng *et al.* (2021)	RRRRRRR	8	Grapevine	0.86 m	3 kg	–	–	Lab
You *et al.* (2020)	RRRRRR	7	Fruit Trees	0.85 m	5 kg	Eye-in-hand Camera	FREDS-MP	Lab
			Harvest					
Xiong *et al.* (2020)	RRR	4	Strawberries	0.5 m	–	Photosensor -	–	Real
Kondo *et al.* (2010)	RRPR	5	Tomatoes	0.55 m	6.0 kg	Photosensor	–	Real
Yaguchi *et al.* (2016)	RRRRRR	7	Tomatoes	0.85 m	5 kg	–	–	Lab
De-An *et al.* (2011)	PRRRP	6	Apples-	–		Pressure, Colli- IBVS sion, Vision, Position		Real
Silwal *et al.* (2017)	PRRRRRR	8	Apples	0.67 m	2.5 kg	-	Open Loop	Real

5. Future directions and trends

For future directions, most of the problems presented in this article are to be resolved with the goal of creating effective pruning manipulators with performance similar to a human. These problems consist in determining, which is the best path planning algorithms and also find ways to autonomously determine, which branches are to be cut for an efficient and healthy pruning, or which fruits are ripe enough to be harvested. These future directions are stepping stones to develop a generic manipulator, capable of pruning different kinds of plants and harvesting different kinds of products.

6. Conclusion

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

The majority of these manipulators were designed and developed specifically for a certain type of application as 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 primarily caused by path planning, collision avoidance, gripping and due to the dimensions of some manipulators. Exceeding these challenges could pave the way into developing more generic manipulators with application in the agricultural field and not a product-specific manipulator.

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