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End-Effectors for Harvesting Manipulators - State Of The Art Review

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***Abstract*—There has been an increase in the variety of harvesting manipulators. However, sometimes the lack of efficiency of these manipulators makes it difficult to compete with harvesting tasks performed by humans. One of the key components of these manipulators is the end-effector, responsible for picking the fruits from the plant. This paper studies different types of end-effectors used by some harvesting manipulators and compares them. The objective is to analyse their advantages and limitations to better understand the requirements to design an end-effector to improve the performance of a custom Selective Compliance Assembly Robot Arm (SCARA) on the harvest of different types of fruits.**

***Index Terms*—End-effector, Harvesting, Manipulator, Agricultural Robotics**

I. Introduction

Agricultural robotics aims to simplify arduous agricultural tasks which were solely performed by human labour. The increasing world population has risen the necessity of an increment in the food production, namely in agricultural goods [1]. However, there is less human labour available to complete the necessary tasks, mainly due to the physical difficulties associated with this type of work. Furthermore, the cost of hiring labour has seen an increase, since the urbanization of the rural areas leads to more job opportunities, other than farming. As a result, the youth on those areas can achieve better qualifications compared to the same section of the population in the past [2].

The previously mentioned tasks, such as harvesting, require high precision to guarantee the fruit picked is not damaged in the process, nor the surrounding fruits and even the plant itself. The success of a task is not just dependent on the type of manipulator itself. The robot requires a complex set of interconnected modules [3] to guarantee the well function of the system, this including an end-effector. The end-effector consists in an external tool which is coupled to a manipulator and assists to fulfil the desired tasks of the robot, such as cutting, grasping, drilling, etc [4]. In harvesting manipulators the end-effector needs - besides other functionalities in some cases - to be capable of grasping the fruits to take them out of the plant without damaging them while having the necessary strength to not let them fall.

Having the above in consideration, this paper performs a short review of already existing end-effectors for harvesting manipulators. This will have as objective the study of different solutions to design the most fitting end-effector for a robot based on a custom Selective Compliance Assembly Robot Arm (SCARA) manipulator to be capable of harvesting different types of fruits in an efficient procedure, which combines both speed of actuation and safety of the crops.

It is fundamental to analyse the different manipulators as a whole, without focusing exclusively on the end-effector. This step was addressed in the research done by Tinoco *et al.* [5] [6] and consists on achieving an understanding on the role of the different parts of the manipulators in a given context, relating them to the success of the tasks. Tinoco *et al.* [5] [6] concluded there is a link between the type of end-effector used and the number of degrees of freedom (DoF) required by the manipulator to perform the tasks successfully. The degrees of freedom are consequently related to the number of joints in the manipulator, which can be prismatic or revolute. The prismatic joint movement is linear along an axis, while the revolute joint confers rotational movement [7].

The authors also noticed most of the harvesting manipulators were developed for a type of harvest. They were designed to be capable of harvesting fruits with specific characteristics and could eventually not be successful trying to harvest fruits with different shapes, sizes, etc. Other aspect noticed was that, even in the intended tasks, sometimes the manipulators would still have difficulties to perform and one of the reasons was related to the inefficiency of gripping the fruits.

Combining the above, it is possible to understand that the design of the end-effector will have influence on the efficiency of the manipulator on the desired tasks. However, it is crucial to understand that a good solution for a type of manipulator and harvest can be a bad one on a different scenario. This means that while analysing the different solutions developed it is important to compare them with the environment the end-effector is intended to be used. The same technology applied to different fruits or types of manipulators can result in a different efficiency when compared to the studied cases.

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II. Methodology

The information gathered for this document is the result of research in the following platforms: Scopus database, ResearchGate, Google Scholar and IEEE Xplore about end-effectors for harvesting manipulators. The following keywords were used: End-effectors, Harvesting End-effectors, Harvesting Manipulator.

As result of a simple research done on the Scopus database for harvesting manipulators (search: harvesting AND manipulator) and harvesting end-effectors (search: harvesting AND end-effector) it is possible to analyse that from 2017 to 2021 the number of documents published in overall as seen an increase, as shown in Figure 1 and Figure 2, meaning this has been a topic with an interest increase in the last years.

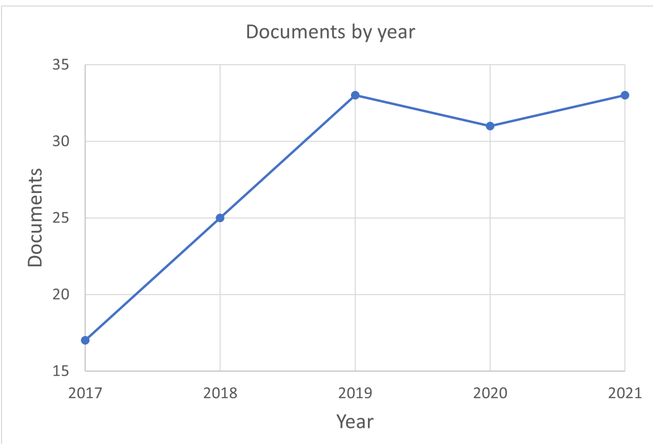

Fig. 1. Number of harvesting manipulators documents published between 2017-2021 - Scopus

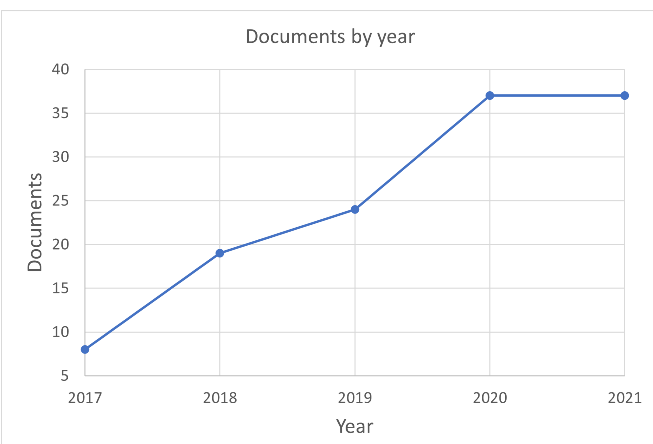

Fig. 2. Number of harvesting end-effectors documents published between 2017-2021 - Scopus

This document is organized in the following sections: Section III - Results, in this section it is made the review of already developed end-effectors used on harvesting manipulators; Section IV - Discussion, where the characteristics of the different end-effectors are compared; Section V - Conclusion.

III. Results

This section reviews different types of developed end-effectors. The objective, as mentioned before, is to find a fitting solution for a SCARA manipulator to be capable of harvesting different types of fruits. However, it is possible, by analysing other types of solutions for different fruits and manipulators, to find techniques and components that can be useful on the desired end-effector.

A. Tomato Cluster Harvesting Robot

In 2010, Kondo *et al.* [8] published an article about the development of an end-effector for a tomato cluster harvesting robot. The authors realized that focusing on harvesting clusters, instead of a single fruit at a time, would be more efficient as the robot could pick multiple fruits at once. The disadvantage of using this method is the increased probability of harvesting unripe fruit.

Harvesting clusters implies cutting the plant's peduncle, which can vary in diameter and consequently compromise the efficiency of the process. This fact was also a part of the study in the research from Kondo *et al.* [8], where it was stated that the maximum cutting resistance on the peduncles was near 60 N for the largest ones. This makes it a relevant aspect while designing the end-effector, since the cutting tool needs to apply this force to be able to cut the largest peduncles.

Kondo *et al.* [8] developed the robot based on a SCARA manipulator (Mitsubishi Electric Corporation, RH-6SH5520) resulting on a manipulator with four degrees of freedom. The authors concluded this was a capable choice, since the plants are mostly the same height. As a consequence, the prominent movements are horizontal and easily reachable with the SCARA robot arm. Analysing the manipulator used by Kondo *et al.* [8] it is possible to reflect on some aspects of the development of the end-effector. The authors developed a complex mechanism consisting mainly of two upper fingers, where the cutter is placed, and two lower fingers, all assembled on a structure capable of rotating on itself with the actuation of a servomotor. These fingers wouldn't grasp the peduncle of the cluster but surround the main stem of the plant. After that, the end-effector would move along the main stem until the "peduncle detection" sensor on the lower fingers detected a peduncle and then the cutter would cut it.

Kondo *et al.* [8] stated that the end-effector worked correctly as it was capable of harvesting the tomato clusters with an execution time of about 15 s for each cluster. The test, performed on 20 tomato clusters, resulted on a success rate of 50 %. The authors concluded that in seven of the tomato clusters not harvested the explanation for the failed procedure was due to the end-effector not being able to surround the main stem in high-density plants, ending up hitting the clusters near the actuation zone of the end-effector. One possible solution mentioned in the article is the reduction of the actuator height, making it more compact to reach the main stem in high-density plants, increasing then its efficiency.

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B. Sweet Pepper Harvesting

In 2017, Lehnert *et al.* [9] developed a robotic harvester with the purpose of harvesting sweet peppers, which was equipped with a novel end-effector also developed by the authors.

The end-effector consisted mainly of two fundamental parts, a suction cup to grip the pepper and an oscillating blade to separate the pepper from the plant. While designing the robot, the authors analysed different types of grippers and besides considering contact-based grippers, for example with mechanical fingers, effective on gripping the fruits, didn't opt to use them since this type of gripper can suffer interference from the surroundings, such as branches. Lehnert *et al.* [9] decided to use a suction cup for its simplicity and also because it only requires to reach a face of the pepper. The suction cup is coupled to the end-effector with a flexible strip and magnetically attached to the cutting mechanism of the end effector, an oscillating blade. The perception algorithm combines different frames obtained from a 'Red Green Blue-Depth' (RGB-D) camera to obtain a 3D model. Subsequently, the system segments the peppers to distinguish them from the background. This configuration allows the end-effector to detect and reach the pepper, and grip it with the suction cup. After it is successfully secured, the cup separates from the blade, allowing the arm to move and get the blade closer to the pepper stem and cut it (Figure 3). After dropping the pepper, the robot only has to point the end-effector down and using gravity to its advantage it is possible to re-connect again the suction cup to the cutting mechanism.

(a) Grip the pepper

(b) Cut the stem

Fig. 3. Sweet Pepper Harvester - Figure adapted from the video by Lehnert *et al.* [9]

Lehnert *et al.* [9] conducted two different field trials, testing on a total of 75 peppers. From these, 24 peppers were harvested in the first trial and 26 in the second, being the remaining 25 an additional test, however not under strict conditions. For the second trial, the team performed some modifications on the manipulator to improve the system behaviour. These modifications included changes to the end-effector, which was provided with a vacuum sensor to detect the attachment to the suction cup and a micro-switch to detect the decoupling of the suction cup and the cutting blade.

Overall, in the whole process (attachment and detachment) the robot achieved a success rate of 58 % and 48 % in the first and second trial, respectively. However, this means the robot could harvest the fruit, but doesn't guarantee it wasn't damaged in the process. Analysing the individual harvesting results in the article by Lehnert *et al.* [9] it is possible to understand that some successful harvested peppers were in fact damaged. This damage was mostly caused by the blade actuation. Large irregularities on the pepper would cause a poor estimation of the pose and the blade cutting the peduncle would also cut part of the pepper.

The authors then concluded that in future work it would be better if the robot could detect also the peduncle and not only the pepper, since at this stage the cutting point was determined assuming the peduncles were always vertical to the centre of the pepper, which wasn't always the case.

C. Autonomous Tomato Harvesting Robot With Rotational Plucking Gripper

In 2016, Yaguchi *et al.* [10] developed an autonomous tomato harvesting robot. In previous work, the authors developed a humanoid robot with a scissor hand that achieved 60 % success rate but needed teleoperation support of a human [11]. The authors realized that one of the tasks that could compromise the harvest was related to cutting the stem of the fruit, which requires recognition of the stem. This may be more difficult than just fruit recognition because the fruit has size and colour features, making it simpler to distinguish from the surroundings [10]. Having that in consideration, the authors opted for a rotational plucking mechanism instead of blades to cut the stem.

The perception module on the work developed by Yaguchi *et al.* [10] was achieved using a stereo camera. The algorithm uses colour extraction to find the possible candidates, find the nearest cluster, and uses the sphere fitting method to identify the tomatoes. The use of a stereo camera allowed to measure the distance from the end-effector to the tomatoes.

The end-effector designed by Yaguchi *et al.* [10] consisted of a hand with two degrees of freedom, one being the fingers (three rigid fingers) whose movement allowed them to open and close and the other being the infinite rotation of the wrist. The process of harvesting consists in grasping a single tomato by closing the fingers around it and then actuate the rotation of the whole hand. This allows for the pedicel to brake and separate from the rest of the stem, picking the fruit from the plant. The authors concluded this method could harvest

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a single tomato in 23 s and, after experimental testing, the success rate was 62.2 %. However, the authors believe this success rate is inaccurate because more harvesting trials need to be done.

Yaguchi *et al.* [10] detected some common cases of failure during the harvesting tests. In some attempts the position of the fruit was miscalculated or the manipulator would move part of the plant, causing the tomato not to be grasped by the hand. Another type of failed attempts consisted in the hand, while trying to reach the tomato in a cluster, grasping multiple fruits together - this situation occurred in cases of dense tomato clusters.

D. Integrated End-Effector For Picking Kiwifruit

In 2020, Mu *et al.* [12] proposed an automated method to pick kiwifruits, separating the fruit from the stem. The authors recognized there were already several studies on the harvest of this fruit, however the methods previously developed wouldn't completely combine the task of grab, separate from the plant and safely unload the fruit. For this purpose the authors conducted a study to design and test an end-effector capable of complete these three tasks without damaging the kiwis, whose peel can be easily damaged during the process.

The end-effector developed consisted mainly of a structure with two rigid fingers designed according to the dimensions of the fruits, a fibre sensor, a position sensor, a pressure sensor and a stepper motor. This configuration allows the end-effector to reach for an individual kiwifruit and embrace it from below with the two fingers, knowing it successfully enveloped it with the readings from the fibre sensor. Then the motor initiates the movement of the fingers' structure, pulling the fruit from the plant. The fingers then drop the fruit on a designated place and the motor resets to the original position to be ready to actuate again.

Mu *et al.* [12] conducted a field test where 240 fruits were harvested. The authors concluded the harvesting success rate was affected by the surroundings, such as presence of branches, length of the stem, as well as the fruit maturity. Failed tries might be caused by the separation of nearby fruits, failure to grab the fruit and the fingers slipping. The average success rate of this field test was 94.2 % and only 4.9 % of the fruits picked had damaged peels, which the authors concluded is lower than with humans harvesting because the manipulator drops fewer fruits. The average picking time calculated was around 4 to 5 s for each kiwi.

E. Integrated Gripper And Cutter For Harvesting Greenhouse Products

In 2009, Jia *et al.* [13] developed a tool capable of gripping and cutting to be integrated on harvesting manipulators.

This tool was intended to be light-weight, simple and low-cost, while being versatile so it could be used on different manipulators to harvest different fruits, such as tomatoes or grapes. For this purpose, the authors designed an end-effector consisting mainly of pliers (for the gripper) and a scissor for the cutter. This simple system was conceived with the objective of avoiding force sensors, since it would grab the peduncle instead of the fruit, making it possible for the manipulator to place the fruit/cluster on a desired place since it wouldn't fall after the cutting. This end-effector does not have a perception module, since it was designed focusing only on the harvesting tool, assuming the detection of the fruit is previously done on a different module of the manipulator.

Jia *et al.* [13] conducted tests in two different scenarios. The first test was to pick tomatoes by the peduncle from shelves. The authors observed the time it took to pick each tomato was 37 s and it was successful on all the tries. The second test had the objective to measure the strength necessary to cut tomatoes' peduncles. The authors verified values ranging from 31 N to 71 N with the average of 39.22±12.36 N.

The authors concluded this tool design is capable of performing harvest tasks of several different fruits, on the condition that the peduncles are long enough for the size of the designed end-effector.

F. A Field-Tested Harvesting Robot for Oyster Mushroom in Greenhouse

In 2021, Rong *et al.* [14] proposed an oyster mushroom harvesting robot to be used on a greenhouse. The authors considered that two of the main components of the robot would be the perception module and the end-effector. The perception module consisted of an RGB-D camera, capable of providing colour images and depth, and a light source to be able to operate in low light conditions. The authors opted to use soft grippers for the end-effector and mounted these grippers on a structure capable of rotating. The objective was to simulate manual picking, due to the fact the mushrooms could be easily damaged while harvesting. The soft-gripper, with four fingers, is capable of wrapping around the mushroom surface, which would not be possible with rigid fingers. Subsequently, the structure rotates 180 º to take the mushroom out of the cultivation bag.

The field experiments were conducted in daylight, with clear weather and good light conditions. Rong *et al.* [14] performed several system tests to evaluate the performance of the robot. After three experiments, the robot achieved a harvesting success rate of 86.8 %, taking an average of 8.85 s to pick each mushroom. The authors concluded the failed tries were mainly related to the perception module, such as plastic from the cultivation bags interfering with the detections or the existence of areas with poor illumination where the mushroom could not be identified. However, in some cases, the problem was also due to the gripper, where the mushrooms would slip from the fingers or some, having large dimensions, would cause the gripper to damage them while grasping. These situations were due to the inconsistent size and shape of the mushrooms, and also they tend to adhere together, causing the perception module to detect several mushrooms as one.

IV. Discussion

Reflecting on the previous end-effectors, whose main characteristics are presented in Table I, and comparing them, it is possible to better understand the working capability of a manipulator's end-effector and what aspects are needed when building one.

TABLE I
HARVESTING END-EFFECTORS

Source	Gripper	Application Field
Kondo et al. [8]	4 Fingers & Cutter	Tomatoes
Lehnert et al. [9]	Suction Cup & Cutter	Sweet Pepper
Yaguchi et al. [10]	3 Fingers	Tomatoes
Mu et al. [12]	2 Fingers	Kiwifruit
Jia et al. [13]	Pliers & Cutter	Tomatoes
Rong et al. [14]	4 Soft Fingers	Mushroom

For instance, Kondo *et al.* [8], developed a complex and functional end-effector, with relevant features that are a good "first step" to develop a tool for a similar outcome. The idea of adding a servomotor to allow the end-effector to rotate appears to be an efficient method to add another DoF to the manipulator in a way that becomes possible to approach stems/peduncles that are not vertically aligned with the manipulator. Yet, there were also some particularities that compromised the harvesting efficiency. One of these, mentioned before, was related to the size of the tool in plants with high-density. While it is crucial to have parts that guarantee the end-effector is on the correct stem/peduncle, it is also important to have all of them on a compact tool that can approach the plant safely without damaging fruits or branches nearby. The method of harvest chosen, holding the stem and finding the peduncle by moving the tool along that stem, guarantees the peduncles belonging to that stem are found and cut. However, in non-ideal cases, where the main stem is below a high quantity of leaves or other branches, even a more compact version of this end-effector could have problems to reach it.

The solution presented by Jia *et al.* [13] does not appear as robust as the previous one. Furthermore, it doesn't add any extra movement to the manipulator, since it is just the tool without additional joints, neither has a perception module to detect the fruits. However, considering the dimensions, which would be advantageous on high-density plants by having lower risk of compromising the harvesting while moving between clusters/branches, the design becomes an interesting alternative. Combined with an effective perception module and using additional joints to minimize the movement limitations, it could possibly be adapted to be used as a complete end-effector capable of completing harvesting tasks successfully. The technique used by Jia *et al.* [13] is also different from the one from Kondo *et al.* [8]: the end-effector, instead of embracing the main stem and "search" for the peduncles, is designed for a direct approach. Thereby, the tool actuates directly on the peduncle (the part that is intended to be grasp and cut). This can be useful in circumstances the main stem is unreachable, when the high-density of clusters or branches covers all the possible path.

The work done by Lehnert *et al.* [9] follows a completely different strategy. Instead of grasping the peduncle in a try for harvesting clusters, this work, developed for pepper harvesting, is focused on picking a single pepper at a time, grasping this one instead of its stem. The use of a detachable suction cup to grasp directly the pepper and a blade to cut the peduncle seems a more direct approach to a successful harvest, since it tries to avoid the problem of cruising between leaves and branches to reach for the peduncle. However, it can lead to high failure rates. This might occur because, to work properly, the system expects that some irregularities, both on the shape of the pepper and the orientation of the peduncle don't exist. That is to say, the system tends to work but it is limited to peppers with a surface the suction cup can grip and a vertically aligned stem that the cutting blade can reach. These assumptions, not being always the case on the field, led to the failed tries and damaged peppers mentioned by the author.

Mu *et al.* [12] managed to find an efficient solution for the kiwifruit harvest. The method developed and the end-effector designed showed to be one with a good success rate in harvesting. However, while focusing only on develop the end-effector to harvest kiwifruits in the described environment increases the efficiency of the tool for that task, it is simple to understand this efficiency will be difficult to acquire in different scenarios. That is to say, this end-effector is more specific than the other solutions analysed. Since the tool contains two fingers that embrace the kiwifruit from below, this configuration would be difficult to implement with different fruits. Even with kiwifruits with a more irregular shape or size the end-effector could face operational problems, as even the authors stated that fruits that were too small would slip from the fingers. The fact that the approach is only done from below can be affected by branches and leaves, since the end-effector can't find another path to the same fruit and it also limits to plants like vines, where the fruit can be accessible from below.

The rotational plucking mechanism developed by Yaguchi *et al.* [10] also doesn't use a blade similar to the one by Mu *et al.* [12]. The main difference is, while the previous one pulled the fruit downwards, the end-effector designed by Yaguchi *et al.* [10] rotates the hand while grasping the fruit. This method, as demonstrated by the authors, can safely pick the tomatoes most of the time without the danger of cutting the fruit, as seen in examples with a cutting mechanism associated with the end-effector. However, apart from the difficulties already mentioned by the authors, there is the fact that the hand is designed for picking a single tomato at a time. The end-effector can harvest this fruit because the rotational movement can brake the pedicel, but the same technique might not work on fruits with a stronger or thicker pedicel/stem, where it could compromise the harvest by damaging the fruit or the rest of the plant.

The end-effector developed by Rong *et al.* [14], similar to the previously two analysed, did not contain a cutting tool, opting for a rotational plucking mechanism as Yaguchi *et al.* [10]. However, the authors used soft grippers instead of rigid fingers. This technology allows to grip more sensitive materials that can be easily damaged, since the gripper tends to match the shape of the picked object without applying excessive force. However, the authors noticed, due to the fragility of the mushrooms, the uncontrolled force applied by the fingers sometimes could still cause damage to the mushrooms. Rong *et al.* [14] concluded that in future work the end-effector should be equipped with force feedback sensors to control the force applied and provide information if the mushroom was successfully picked.

V. Conclusion

This article consisted on a review of already existing end-effectors for harvesting manipulators. These end-effectors can successfully complete the tasks they were designed to fulfil; However, they are only guaranteed to have success in ideal conditions and assumption based situations. The authors of those end-effectors concluded the difficulties faced on the completion of the tasks can be minimized by improving the already existing designs to adapt to irregularities of the work environment, such as different shapes of fruits, density of branches and leaves and obstruction in the path to the fruit. Some of these improvements could be achieved, for example, using soft grippers capable of deforming or even match the shape of the fruit, such as in the work developed by Rong *et al.* [14] or even Fin Ray® Effect based fingers [15] [16]. The use of soft fingers would allow increasing the versatility of some end-effectors analysed, since it would minimize the problems caused by the gripper not being able to grasp fruits of different sizes, as in the technology by Mu *et al.* [12]. Also, it would lower the risk of damaging the fruits when compared to the use of rigid fingers [15].

The problems associated with the obstruction in the path to the fruit might be difficult to minimize without altering the environment. However, by implementing an end-effector with increased movement freedom, as seen in the coupling of the tool by Kondo *et al.* [8], it would be possible to consider different alternatives to the path initially stipulated. Also, it is crucial to understand that for each type of harvest there are different solutions with different efficiencies. For example, the single fruit harvesting solutions analysed might achieve good results on harvesting fruits such as tomatoes. However, they are non-practical for harvesting smaller fruits, such as grapes, where it is more efficient to harvest the entire cluster together. A general end-effector capable of working in both environments, or even being easily modified to suit different situations could be beneficial, since it would not require producing a different tool for each type of harvest. These are the type of considerations to have in mind while designing a tool for harvesting, understanding also that these already existing end-effectors can be improved to serve as a starting point to develop a more general tool that can harvest more than one type of fruit successfully.

In the future, the problems analysed in this article are expected to be solved in the development of the hardware and software necessary to implement an effective end-effector to be coupled to the mentioned SCARA manipulator. Tests will be performed to verify its efficiency on harvesting different types of fruits, as well as comparisons to the same tasks performed by human labour. Subsequently, it will be possible to evaluate its viability as a working tool for agricultural robotics.

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