Robotic applications on agricultural industry. A review

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Abstract. In this paper we aim to present an evolution of the development of robotic end effectors with applications in fruit and vegetable harvesting but without exhaustively covering all technical solutions. This study is focused on robotic final effectors dedicated to harvesting fruits that have reached an advanced stage of development for apples, tomatoes, sweet peppers and cucumbers. The performances of these final effectors (harvesting speed, success rate, costs, etc.) are compared with the performances of human operators and we could say that so far the robots fail to reach the efficiency of human operators in the harvesting processes. The success rate is below 90% and the harvest times are longer than 10 seconds and this means a low efficiency. Although the level of commercial robots for fruit harvesting has not been reached, technological developments indicate an improvement in the performance of this category of robots, an increasing number of research projects are focused on tomato and apple harvesting technologies.

1. Introduction

The concerns related to the robotization of agricultural works, in addition to the research in other fields, as medical robotics [1]-[4], social robotics [3], [4], cooperative robotics [7]-[11], humanitarian demining [12]-[16], walking robots [17]-[21], have been around for decades, but commercial solutions have not yet been reached to carry out all operations with the help of robots [22], [23]. Several studies have been performed on the development stage of final effector with applications in agriculture [24]-[28], in this paper we will perform an update and a synthesis of these devices depending on the technology used.

The harvesting often involves individual acting on each fruit and the movements and forces that are developed by the human operator or the robot are complex. In the harvesting process, the specifics of each crop are taken into account and the optimal operations for detaching the fruit from the stem are analyzed in such a way as the robot will be “inspire” to perform movements similar to those of a human operator [29].

The diversity of the crops requires that each project be adapted according to the specifics of each crop. The sizes of the fruits are varied so that the sizing of the gripper type devices is done according to these sizes. There are concerns to design clamping devices that allow the handling of a wide variety of sizes [30].

An agricultural robot is structured on three major components: the locomotion equipment, the manipulating structure and the final effector. The role of locomotion equipment is to move the manipulator structure and the final effector in the work area so that through the manipulator structure,
which is often in the form of an arm, the final effector will have direct access to the area where they will perform specific functions. In the case of harvesting robots, the final effector will grasp the fruit, detach it from the stem and place it in a periodic storage box.

The most robotic platforms are on wheels (to be listed) and in terms of the manipulator structure the chosen solution is either a suspended mechanism or a manipulator arm (open kinematic chain). The differentiation of agricultural robots is made by the particularities of the gripper mechanisms that are dedicated for certain agricultural operations: for sowing, for weeding, for harvesting, etc.

2. Harvesting end effectors
The end effectors intended for fruit harvesting are mechatronic subsystems which have the main function of detaching the fruit individually from the stems and placing them in a temporary storage box. The robotic harvesting involves a complex process of recognizing ripe fruit by means of video cameras and recognition algorithms, grasping the fruit with a gripper, moving the fruit by means of a manipulator arm, and storing it in a container.

In agricultural robotics, grippers for harvesting can be classified into:
- end effectors with precision grip as models we can highlight end effectors for picking strawberries, apples, tomatoes, sweet peppers [31]-[35].
- grips with gripping power by compression [36] which are distinguished by larger areas of contact between the fingers and in principle little or no ability to transmit movements with the fingers. As a model we can mention grippers that act by grabbing and vibrating the trunks.

In this paper we will approach precision end effectors dedicated to harvesting apples, tomatoes and cucumbers and we will monitor their technological evolution for the last decade of research. The characteristics of interest are: the harvest success rate, defined as the number of successfully harvested fruits from the number of ripe fruits, the harvest time which is the period necessary for the recognition of a ripe fruit, for the detachment of the fruit from the stem and for its placement in a temporary storage box, the complexity of the manipulator arm (with single or double arm) and the complexity of the final effector (with clamping device + cutting device) or with clamping-pulling device.

2.1. Precision grippers for apples harvesting
Harvesting apples is done by acting individually on each fruit and the forces to be developed for detachment by the stem depend on the resistance forces of the peduncle (bending resistance and cutting resistance). The mechanical and kinematic structure of a gripper is conceived and designed starting from the natural movements performed by the hand of a human operator in the harvesting process [33], [39] the results being in some cases mechanisms with articulated fingers, similar to the fingers of a hand [37].

![Figure 1. The experimental model of the device for analyzing the forces necessary to harvest an apple [33].](image)

The structure of an experimental model for analyzing the detachment forces for an apple is presented in Figure 1 and consists of the following components: a) the cup-shaped gripper b) the clamping element c) the force sensor d) the linear motion module controlled by a stepper motor e) main shaft f) miniature torsional transducer g) sliding frame h) stepper motor for shaft drive.
The operations that must be performed by the gripper in the process of harvesting apples are: catching the fruit and fixing it, cutting the “tail” of the fruit in order to detach it from the stem and releasing the fruit in a storage device.

A technical solution for gripping the fruit by means of two spoon-shaped blades is shown in Figure 2. The two blades are pneumatically operated and the cutting device is electrically operated [38].

![Figure 2. End effector for apples harvesting: a) with spoon shape; b) implementation of a prototype [38].](image)

Fruit fragility involves the exercise of a controlled tightening force that is done through the force of compressed air and by using a pressure sensor. Hall sensors (for determining the position of the arm joints) and video sensors are also involved in the process of handling the fruit. The use of this technique with manipulator arm and gripper for harvesting apples has, in our opinion, a low efficiency requiring complex precision movements with the involvement of several actuators and more, it is known that pneumatic energy is costly.

Before designing a mechanism dedicated to harvesting apples, some parameters were analyzed, such as the resistance force of the peduncle and the optimal movement through which the apple can be detached most easily from the stem. The tensile strength of the peduncle is around 47N and the rotational force is about 0.05 Nm [39]. Starting from these hypotheses, a gripper was conceived and designed, which has as main elements a gripping part and a wrist (Figure 3). The peduncle is held by two fingers that are driven by a DC motor, the opening of the fingers is 15 mm and the force of 11 N is enough to support the fruit by the peduncle knowing that Fuji apples have an average weight of 400 g. The wrist is operated by a stepper motor and develops a twisting motion with a torque of 1.5 Nm that is large enough for the peduncle to detach from the stem [40].

![Figure 3. The gripper mechanism for harvesting Fuji apples (a) and manual harvesting phases for an apple (b) [40].](image)
Table 1. The evolution of the performance of the final effectors for the harvesting of apples.

| References | Harvesting success | Time Sec/fruit | Manipulator | End effector | detection | year | OBS |
|------------|--------------------|----------------|-------------|--------------|-----------|------|-----|
| 1 [57]     | 90%                | 16             | Single arm, UR3 (UNIVERSAL ROBOTS) | With four fingers | SSD algorithm | 2019 |
| 2 [58]     | 67%                | 7.3            | Single arm  | With three fingers, pneumatic | Haar-like features | 2019 |
| 3 [41]     | 95%                | 6.8            | Single arm  | Three fingers | Circular Hough Transformation | 2016 |
| 4 [38]     | 77%                | 15             | Single arm  | Two fingers with shear cutting | SVM algorithm | 2011 |

An experienced worker can harvest an apple every 2 seconds [41], this period also depends on the density and distribution of the fruits on the branches. The best performance, among the analyzed works, is approx. 7 seconds [41] (the time dedicated to harvest a fruit by the robot).

2.2. Precision grippers for tomatoes harvesting

The demand for tomatoes on the market is increasing and on the other hand the price of labor is increasing, these being only two of the reasons for which the efforts to make efforts to robotize the process of tomato growing are justified. A robot dedicated to harvesting tomatoes consists of a mobile platform, a manipulator arm, a gripping and cutting tool (the end effector) and a vegetable recognition sensor [35]. The design and implementation of tomato harvesting devices is done taking into account the physical properties of the fruit, these properties being: texture, rigidity, peel strength, color, shape and size [61].

Several technical solutions for harvesting tomatoes are known in the literature: by gripping / grasping, by suction and hybrid suction-gripping solutions [42]. The detachment of the fruit from the stem is done by two methods: by rotation-pulling and by cutting. The rotation-pulling method involves a simpler data processing but the detachment movements are more complex and are not homogeneous for all harvested fruits because the detachment forces by the stem are different from fruit to fruit. The method of detachment by cutting involves a more complex image processing to identify the peduncle, but detachment by the stem by cutting the peduncle is safer, shear force of the peduncle is little influenced by its strength.

![Figure 4. Example of gripper for harvesting tomatoes by suction: a) effector scheme; b) stages of the harvesting operation [43].](image-url)
Tomatoes are very fragile so the control of the tightening forces must be very fine. An adopted method is the aspiration of the tomato through a suction cup, its fixation by means of two fingers and the detachment by the stem. (Figure 5).

![Figure 5. The tomato gripper (a) and Greenhouse tomato robot (b) [44].](image1.png)

The mechanisms with continuous kinematics, of the “elephant horn” type, present a wide range of maneuverability and a large number of degrees of freedom. Unlike classical mechanisms, where the movement is performed in well-defined locations such as joints, in the case of a continuous kinematic chain the movement takes place along a certain section [45].

The use of a two-arm manipulator and binocular video sensor increases the accuracy of fruit identification and capture, which is found in a successful harvest rate of 87.5% [46]. The harvesting times obtained are less than 30 s. The two arms have attached a gripper, the one on the left has the role of sucking the fruit and positioning it so that its stalk is cut by the cutting gripper mounted on the arm in right (Figure 6).

![Figure 6. The prototype and the schema of dual arm harvesting robot [46](image2.png)

We see as a disadvantage of the technical solution with two harvesting arms the mechanical complexity and the large workload which makes this robot to have high energy consumption and to be difficult to handle in tight spaces. A specific feature of this robot is its ability to operate in unstructured environments where greater information processing capacity and better flexibility of the robot’s mobile structures (mobile platform, manipulator arms and grippers) are required.

A hybrid clamping solution is presented in [42]. The suction-gripping mechanism consists of a four-finger gripper, a vacuum suction cup, and a linear motion device that moves the suction cup (Figure 7). Crushing of the fruit is avoided by means of force sensors that are mounted on the fingertips.
Figure 7. Grasping absorption gripper mechanism [42].

The operation of grasping the fruit is done in three stages: in a first stage the fruit is absorbed by a suction cup (Figure 8a), during which time the fingers of the effector are positioned inside to avoid the collision with certain obstacles. In the second stage the fingers open by surrounding the fruit which is properly positioned by retracting the suction cup (Figure 8b). In the third stage the fruit is comprised between the fingers of the effector by performing a controlled clamping force to avoid crushing (Figure 8c) [42].

Figure 8. Gripper movements in the grip-absorption stages [42].

A special end effector has been designed for harvesting tomato clusters, which, by means of a two-fingered gripper, grabs the peduncle on which a certain number of fruits are located and cuts it by shearing with a cutting device. (Figure 9). The final effector is mounted on a SCARA manipulator, RH-6SH5520, produced by Mitsubishi Electric Corporation [45].

Figure 9. End effector with two fingers and cutting device for harvesting tomato clusters [47].
Table 2. The evolution of the performance of the final effectors for the tomato harvest.

| References | Harvesting success | Time Sec/fruit | Manipulator | End effector | detection | year | OBS |
|------------|--------------------|----------------|-------------|--------------|-----------|------|-----|
| 1 [46]     | 87.5%              | 30             | Dual arm    | vacuum cup + cutting gripper | AdaBoost classifier and color analysis | 2019 |
| 2 [63]     | 83%                | 8              | Single arm, DENSO VS-6556G | with two fingers + cutting device | CogPMAlignTool | 2018 cluster |
| 3 [48]     | 60%                | 80             | Single arm, UR5 | Rotational plucking | Z-sorting, RANSAC | 2016 |
| 4 [47]     | 50%                | 15             | Single arm, SCARA, RH-6SH5520 | with two fingers + cutting device | photosensor | 2010 cluster |
| 5 [62, 64] | 70%                | 3              | Single arm   | Pneumatic, suction | Dedicated algorithm | 1996 |

The complexity of the final effectors for harvesting tomatoes (double grip with vacuum and gripper, two arms, grip-cut) ensures a good precision of execution but leads to increased harvesting times. A robot that uses the detachment of the fruit by pulling [48] is found in a version declared to be very close to the stage of a commercial robot [49].

2.3. Precision grippers for cucumbers harvesting

Harvesting of vegetables and fruits is done taking into account at least three parameters: gripper positioning accuracy, tightening and detaching / cutting forces and execution speed. When harvesting cucumbers (Figure 10), the gripper must be positioned with an accuracy of +/- 2mm [50]. The time allocated for a complete harvesting cycle is about 10 sec., during this time the following operations are performed: fruit detection, detachment and placement in the container [51]. Decreasing the respective time and increasing the harvesting speed implies increasing the complexity of the electromechanical and video processing equipment of the harvesting system.

Figure 10. Structured crop of cucumbers (a) and harvesting gripper (b) [50].

The cucumber harvesting effector consists of two major components: the gripper (for gripping the fruit) and the cutting device [50], both components being attached to the same manipulator arm.
A gripper equipped with an absorption suction cup and a thermal cutting device is used for the automatic harvesting of cucumbers (Figure 11) [51].

![Figure 11](image1.png)

**Figure 11.** Hot wire cucumber harvesting gripper: scheme (a) and experimental model (b) [51].

A peculiarity of the cucumber harvesting robot presented in [52] is the manipulator mechanism dedicated to this application (Figure 12), while most of the harvesting robots found in the literature use, at least in the test part, general purpose manipulators.

![Figure 12](image2.png)

**Figure 12.** Cucumber harvesting robot: a) kinematics scheme; b) 3D model [52].

| References | Harvesting success | Time Sec/fruit | Manipulator | End effector | Detection | Year | OBS |
|------------|-------------------|---------------|-------------|--------------|-----------|------|-----|
| 1 [52]     | 93%               | -             | Single arm, dedicated | shear cutting device | -         | 2009 | ballscrew transmission |
| 2 [51]     | 80%               | 45            | Single arm, Mitsubishi RV-E2 | Suction cup with thermal cutting device | A*-algorithm | 2002 |
| 3 [50]     | -                 | 10            | Single arm | Cutting with high voltage | -         | 1998 |

**Table 3.** The evolution of the performance of the end effectors for harvesting cucumbers

The end effectors dedicated to cucumber harvesting have been of interest since the 2000s, but lately no progress has been made and the number of research projects on this topic is small. The harvesting
time specific to a human operator is about 6 seconds and the best performance found in the literature is 10 seconds [50].

2.4. Precision grippers for sweet pepper harvesting.
Cutting with high frequency currents has at least two advantages: heating at high temperatures leads to the destruction of potential pathogens found on the peduncle and secondly by cauterizing the cutting area both the harvested fruit and the stem will not have open channels through which could infest [51].

Detaching of the peppers by the stem is done, in most cases, by cutting. An interesting cutting method is by electric arc or wire heating [53]. The final harvesting effector consists of the gripper and the cutting electrodes, being supported and oriented by the manipulator arm of the harvesting robot (Figure 13).

Two of the latest versions of final effectors, presented in the literature in 2017, are those with Fin Ray and Lip-type mechanisms [54], Figure 14 and Figure 15. The Fin Ray technique is inspired by the movements of fish fins that have the ability to shape around an obstacle without exerting forces that could damage fragile surfaces [60].

The final “Lip Type” effector uses a valve to catch the fruit and a sensor to detect a successful catching operation, followed by the operation of cutting the peduncle by closing some “lips”.

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**Figure 13.** Sketch of the gripping and cutting device with electrodes [53].

**Figure 14.** End effector with “Fin Ray” mechanism [54].

**Figure 15.** End effector with “Lip type” mechanism [54].
The performances obtained by testing the two types of final effector shows us that this harvesting technology is still far from satisfactory for implementation in commercial harvesting operations. The harvesting success rate for the “Fin Ray” effector was 6% and for “Lip-type” 2%. The simplification of the harvesting area, by removing the bunches, has led to an increase in performance by improving the success to 26% for “Fin Ray” and 33% for “Lip Type”.

A harvesting end effector for sweet peppers, presented as an innovative technical solution in patent application PCT / NL2019 / 050396 [53], Figure 16, was implemented at prototype level through the SWEEPER research project within the Horizon 2020 program, grant no. 644313 [22]. Two particularities of this mechanism are identified: the detachment of the fruit is done through a vibration cutting device and then the fruit is caught in a device with fingers without being squeezed.

![Figure 16](image)

**Figure 16.** The components of the end effector described in patent application PCT / NL2019 / 050396 (a), a sketch (b) and the prototype of the end effector with the fruit gripping device (c) [22].

Compared to the end effectors presented in [54], the results obtained during the tests are superior, but a modification of the working field is necessary (removal of the leaves covering the fruits, removal of the bunches, etc.). In the case of unmodified areas, the success rate was 18% and after removing the disturbing elements (leaves, bunches) the success rate increased to 49%.

Another example of an end effector with suction cup and oscillating cutting device is presented in [56]. This type of effector lacks the gripping device, the gripping function is performed by the suction cup which, having a large contact surface with the fruit, positions it for the cutting phase of the peduncle and then releases it into the collecting box [56].

**Table 4.** The evolution of the performance of the end effectors for the sweet pepper harvest

| References | Harvesting success | Time Sec/fruit | Manipulator | End effector | Detection | Year | OBS |
|------------|--------------------|---------------|-------------|--------------|-----------|------|-----|
| 1 [56]     | 76.5%              | 40            | Suction cup with oscillating cutting blade | HSV colour segmentation algorithm, MiniInception algorithm | 2020 |
| 2 [22]     | 61%                | 24            | Single arm, Fanuc LR Mate 200iD | Catching device, cutting by vibrating knife | Canny edge detector, Hough transform | 2020 |
| 3 [59]     | 70%                | 51            | Customer design, dedicated | Two fingers, shear cutting | backpropagation algorithm | 2019 |
| 4 [54]     | 33%                | 94            | Custom made (dedicated) | Fin Ray, Lip-type | Direct Linear Transformation algorithm, Normalized Difference Index (NDI) | 2017 |
Harvesting sweet peppers is of relatively important interest, as evidenced by very recent studies in this field [56, 22]. The final effectors dedicated to these operations have a peculiarity due to the complexity of the detachment devices which are both mechanical (by shear or vibration) and electrical (with hot wire or with electric arc).

3. Classification of the end effectors dedicated to fruit harvesting

A classification of the end effectors dedicated to fruit harvesting, as a synthesis of this paper, is presented in Figure 17. The components of a harvesting device are the gripper, the detachment device and the video acquisition equipment. The video acquisition equipment, together with the detection algorithms, have the function to identify the ripe fruit after that the gripper will grasp the fruit and the detachment device will detach the fruit by the stem in order to be placed in a storage basket. The fruit can be caught mechanically, pneumatically or in a hybrid mechanical-pneumatic technique. Mechanical gripping is similar to the technique of gripping a hand, being provided with two or more fingers [57, 58, 41, 38, 59]. The mechanical grasping is especially suitable for harvesting apples because the apples have a higher rigidity and the risk of being crushed during tightening is lower.

![Figure 17. Classification of end effectors dedicated to fruits harvesting.](image)

4. Conclusion

Concerns about the robotization of vegetable and fruit harvesting operations have been known for over 30 years [45] but have not become widespread so far. We consider that the main causes of the involvement of human operators in agricultural activities are the following: a) higher execution speed of a human operator compared to a robot b) human labor costs are lower than robotization costs. We could define two trends that indicate a direction for the development and use of agricultural robots: i) the increase in the cost of labor and the cheapening of technology and ii) the increase in the speed of operation of robots.

It is difficult to say whether from a mechanical point of view a technological limit has been reached in terms of the development of mechanisms dedicated to robots for harvesting fruits and vegetables. The literature indicates a decreasing number of scientific papers on the mechanisms of end effectors
for harvesting. Research directions are defined to find effective solutions in terms of fruit video recognition technology and determination of target coordinates. We believe that technological challenges are aimed at finding efficient image acquisition solutions (such as cameras with ToF - Time of Flight technology).

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