# Field test of different end-effectors for robotic harvesting of sweet-pepper

J. Hemming[1,a], B.A.J. van Tuijl[1], W. Gauchel[2] and E. Wais[3]

[1]Wageningen UR Greenhouse Horticulture, Droevendaalsesteeg 1, 6708 PB, Wageningen, The Netherlands; [2]Festo AG & Co. KG, Ruiter Str. 82, 73734 Esslingen, Germany; [3]Wageningen University, Droevendaalsesteeg 1, 6708 PB, Wageningen, The Netherlands.

***Abstract***

**This paper focusses on field experiments with two different types of end-effectors for robotic harvesting of sweet-pepper fruits. One of the major issues is to reach, grasp and detach the fruit efficiently, without damaging it, while avoiding obstacles in the environment. End-effectors for harvesting fruit must be able to adapt to different fruit sizes and geometries. Two types of end-effectors were designed and realized. The first one had four fingers which utilized the "Fin Ray" effect to grip the fruit. A scissor-like cut mechanism on top of the fingers was used to cut through the fruit peduncle. The second, a lip-type end-effector first stabilized the fruit using a suction cup after which two rings enclosed and cut the peduncle with a circular blade integrated in the upper lip. Both end-effectors had integrated miniature cameras with a LED illumination system: one Time of Flight camera and the other a colour camera. To study the performance of the end-effectors a number of harvesting experiments were performed in commercial sweet-pepper greenhouses. Special attention was paid to the following aspects: positioning at the target fruit, separation of the fruit from the plant, fruit damage, leaf damage and plant stem damage. Both end-effector designs had their strengths and weaknesses. The Fin ray type end-effector harvested a maximum of 80% of the fruits on the plant, the lip-type end-effector a maximum of 76% of the fruits. In none of the experiments more than 64% of the fruit could be harvested without fruit damage.**

**Keywords:** greenhouse, adaptive jaws, Fin Ray effect, lip-type, grasping, gripper

## INTRODUCTION

Developing robotic systems for selective harvesting of horticultural products is a major research challenge due to the harsh working conditions, dynamic environments and the complicated tasks. The European-funded project Clever RObots for croPS (Bontsema et al., 2014; CROPS-project, 2014) has conducted research on a modular robotic system for several different agricultural and horticultural tasks (harvesting apples, grapes, sweet-peppers and site-specific spraying). For harvesting *Capsicum annuum* (sweet-pepper) different types of end-effectors have been explored during the project.

Research on agricultural robots to automate the harvesting process has been actively pursued over the last 30 years with various results (Bac et al., 2014). Many end-effectors have been developed for different types of fruit. The concept of the lip-type gripper presented in this paper has parallels with an end-effector for robotic harvesting of citrus from the tree as described by Harrell et al. (1990) and Pool and Harrell (1991). More specifically, Bachche and Oka (2013a) recently worked on a thermal cutting system for harvesting sweet pepper and also designed an end-effector with a gripper and scissor on a circular disc to cut the fruit peduncle (Bachche and Oka, 2013b). The cultivars of peppers used in their studies were much smaller than the pepper cultivars used in this study and also the cropping system was different. For the end-effectors presented in this paper a structured design process described by van Tuijl et al. (2013) was applied to cope with the unknown variables which cannot be controlled in a horticultural environment as opposed to an

[a]E-mail: jochen.hemming@wur.nl



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industrial environment.

The objectives of this paper were (i) to describe the requirements of an end-effector to harvest sweet-pepper fruit, (ii) to design and describe the working principles, and (iii) to assess the end-effector performances by quantifying its fruit gripping success rate, fruit removal success rate, and damage inflicted to fruit and plant during greenhouse experiments.

## END-EFFECTOR DESIGN OBJECTIVES AND REQUIREMENTS

The end-effector should be able to reach, grasp and detach a ripe sweet-pepper fruit from the plant and transport it to a storage container. The concept must work in the current common practice cropping system for growing sweet-peppers e.g., in greenhouses in the Netherlands. A typical crop has a crop row distance of 1.33 m and an average plant distance in the row of about 0.2 m. Temperature in the greenhouse can reach up to 35°C and relative humidity (RH) is normally above 70% and can exceed 90% (Hemming et al., 2014b). The end-effector should not damage the fruit or the plant and should allow a short cycle time. Moreover, the end-effector should hold cameras which are used for fruit localization. Another requirement is the possibility to harvest fruits hanging close together, both horizontally and vertically. The fruit size and also fruit geometry are different for every single fruit. The minimum and maximum diameters of sweet-pepper fruits the end-effector must be able to harvest were based on measurements (Hemming et al., 2011) and the requirement was set to a minimum fruit diameter of 45 mm and a maximum fruit diameter of 100 mm. The length of the peduncle of a fruit differs by cultivar and changes that occur during the growing season. The peduncle can be as short as 20 mm or also as long as 100 mm. An end-effector should be able to operate within these changing conditions.

## MATERIALS AND METHODS

### The modular robot system

The experiments included in this paper were performed without the integrated robot system. The end-effector will finally be used in the modular robot system shown in Figure 1. The robot consists of two carrier modules – (i) a manipulator module, and (ii) a sensor module. On the first module, the manipulator with end-effector, the air compressor for the pneumatics, the control electronics and the computers are mounted. On the second module, cameras for fruit and obstacle detection and illumination are placed. The coupled modules can move in between the crop rows on the greenhouse rail system. A detailed description of the robot system is reported in Hemming et al. (2014b).

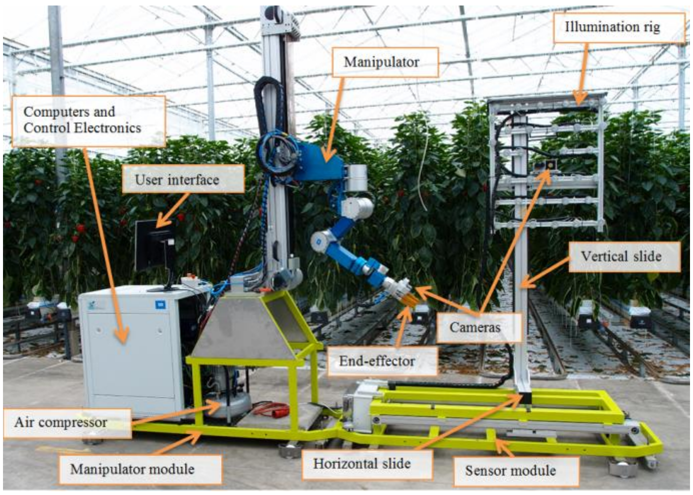


Figure 1. Robot for harvesting sweet-pepper fruit.

**End-effectors**

There are three relevant possibilities for detaching a sweet-pepper (i) grasp the fruit peduncle and cut it, (ii) grasp the fruit body and cut the fruit peduncle, and (iii) cut the fruit peduncle without grasping the fruit and catch/collect the detached fruit. The first possibility has the advantage of not touching and thus not damaging the fruit body. Moreover, such a gripper could be much smaller than a gripper to grasp the fruit. However, because of occlusion by leaves and fruits (Hemming et al., 2014a) it was very demanding to automatically localize the gripping point and often difficult to get access to the peduncle. Therefore this study focused on two end-effector concepts that targeted the fruit body. One concept where the end-effector gripped the fruit body (Fin Ray) and the other concept where the device did not grip but encircled the fruit (lip-type). Both types of end-effectors had in common an integrated light emitting diodes (LED) illumination ring as well as two cameras for fruit localization: a miniature remote head RGB colour camera (VRMagic, Mannheim, Germany) and a small-size 3D Time of Flight camera (CamBoard nano, Pmdtechnologies Gmbh, Siegen, Germany). As the end-effectors had to work in a rough and changing environment pneumatic operations seemed to be most suitable and were used in both devices.

**1. Fin Ray gripper.**

This device features a double acting pneumatic long-stroke gripper as main drive and two single acting pneumatic drives for cutting as shown in Figure 2. This end-effector first grips the fruit with four fingers, after that the peduncle is cut. The working principle of the slim fingers is based on the Fin Ray Effect as described in Gauchel and Saller (2012). This effect allows the passive adaption of the fingers to the workpiece geometry. The two lower fingers can rotate around their longitudinal axis for better adaption to different geometries of peppers. The fingers are produced by water jet cutting of a thermoplastic elastomer (TPE) plate. Figure 3 illustrates the operation of the gripper during a harvest sequence.

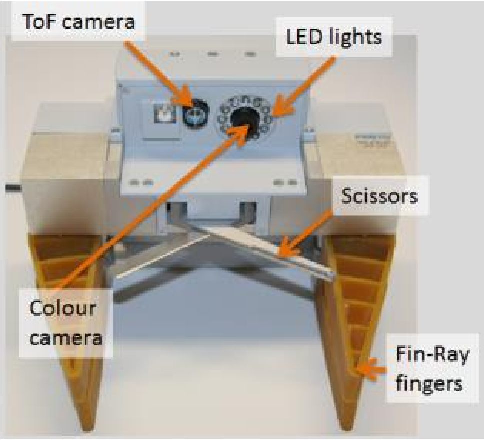


Figure 2. Fin Ray type end-effector.

Figure 3. Fin Ray type end-effector fruit detachment sequence.

**2. Lip-type end-effector.**

Figure 4 shows a photo of the patent pending lip-type end-effector. The first step in its operation cycle is to connect the sweet-pepper to the suction cup. In case of a successful fruit fixation the lips are moved forward. This motion is powered by a telescopic air piston (RT 120-025-0100, Univer, Milano, Italy). Next, the rotating lips are operated by a radial gripper (DHRS-40-A, Festo, Esslingen, Germany). The lips encircle the sweet-pepper; the lower lip acts as a base and stops at the backside of the peduncle. The upper lip contains a shielded knife and meets the lower jaw at the top of the peduncle. Without stopping, the lower lip and upper lip pinch the peduncle and cut through it. The lips are hinged and therefore they stop regardless of the position of the peduncle in relation to the sweet-pepper. The lower lip is enclosed by a flexible collection sock such that the detached fruit will be guided into a flexible tube attached to it. This tube guides the fruit to a storage container (Figures 4 and 5).

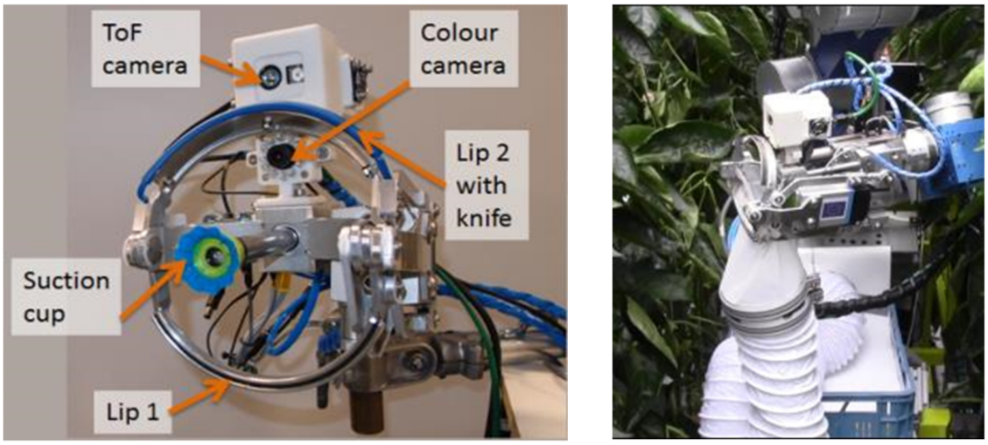


Figure 4. Lip-type end-effector front view (left) and the flexible tube attached to the end-effector for guiding the fruit to the storage container (right).

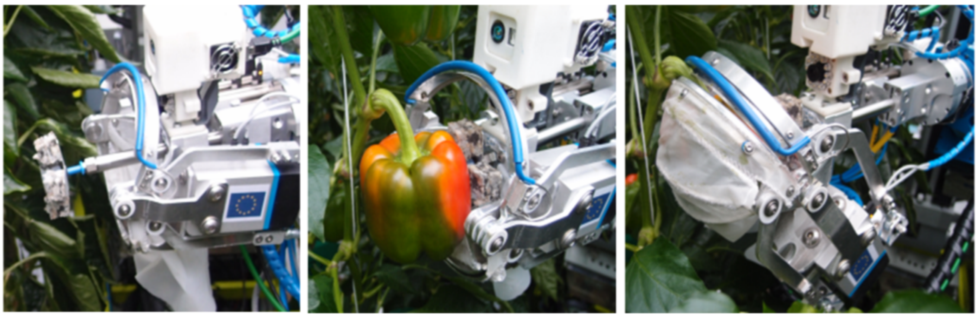

Figure 5. Lip-type end-effector fruit detachment sequence.

**Experimental setup**

To determine the performance of the two end-effectors a number of greenhouse experiments were carried out. Two experiments in a greenhouse of a Dutch sweet-pepper grower and two at a sweet-pepper grower in Israel. Table 1 gives an overview of the experimental data. For the experiments carried out in The Netherlands the crop was grown in the common practice V-shape cropping system. For the experiments carried out in Israel the crop was grown in the Spanish type cropping system. In that cropping system the main plant stems get entangled with each other in a full grown crop. To be able to compare the results of both locations the plant stems with the fruits used for the experiments in Israel were prepared by singularizing them manually before the harvest attempts were performed. Fifty to 70 full grown fruits were harvested with the end-effectors in each of the experiments. For each harvest attempt the following procedure was undertaken:

- Both end-effectors were manually positioned to be able to grip or suck the fruit as good as possible. To do so the end-effector was mounted onto an aluminium tube system mimicking a robotic arm with all degrees of freedom to manually move it around. For harvesting the plane of the scissor of the Fin Ray end-effector was positioned in such way that the peduncle was within reach. The suction cup of the lip-type end-effector was pushed against the fruit surface. By design the lip-type end-effector does not require to be tilted for different fruit poses and was always kept horizontal with respect to the greenhouse floor.
- Preferably, the end-effector should be positioned in front of the fruit, so that the stem to which the sweet-pepper is connected to is positioned behind the fruit. We aimed to orient the end-effector in such way that there was a minimum interference with the plant canopy. The maximum allowed pose of the end-effector was parallel with the crop row. Consequently, fruits that were hanging at the back side of the plant stem were gripped/sucked with a not ideal end-effector pose.
- After positioning the end-effector, the cut operation was manually controlled by digital I/O and with pressurized air using a developed test application from a connected laptop.
- Success or failure of fruit grip or suction and detachment was recorded.
- Damage to fruit, leaves, plant (stem) and crop wire while harvesting was recorded.

Table 1. Overview greenhouse experiments.

| Experiment number | Date | Location | Plant condition | End-effector type | Number of fruits |
|---|---|---|---|---|---|
| 1 | May 2013 | Netherlands | Early season | Lip-type | 50 |
| 2 | Oct. 2013 | Netherlands | Full grown | Fin Ray | 50 |
| 3 | Feb. 2014 | Israel | Full grown | Lip-type | 70 |
| 4 | Feb. 2014 | Israel | Full grown | Fin Ray | 50 |

The air pressure available to operate the end-effector was 6.5 bar for experiment number 1. It was found that this pressure was insufficient to successfully cut the fruit peduncle in many cases and therefore pressure was increased to 10 bar for the remaining experiments.

**RESULTS AND DISCUSSION**

The fruit harvest success rate per experiment is summarized in Figure 6. The lip type gripper was able to harvest 14% of the fruits in experiment 1 and 76% of the fruits in experiment 3 with none of the fruits damaged in experiment 1 and 14% of the fruits damaged in experiment 3. The Fin Ray end-effector harvested 80% of the fruits (with 18% damaged fruit) in experiment 2 and 70% of the fruits (with 14% damaged) in experiment 4. Table 2 gives detailed descriptions of different types of problems that occurred. Fruit damage rate and leaf damage rate were higher with the Fin Ray end-effector than with the lip-type end-effector. The plant stem damage rate was not very different between the two types of end-effectors. However, the Fin Ray gripper completely destroyed the main plant stem and/or the supporting crop wire in 18% of the cases whereas this did not happen for the lip-type gripper (experiment 1). In 7% of the cases (experiment 3) the main stem of the plant was broken with the lip-type gripper while the gripper was closing its lips. The full grown crop in that experiment was at the end of the season and it was observed that these plant stems broke off easily.

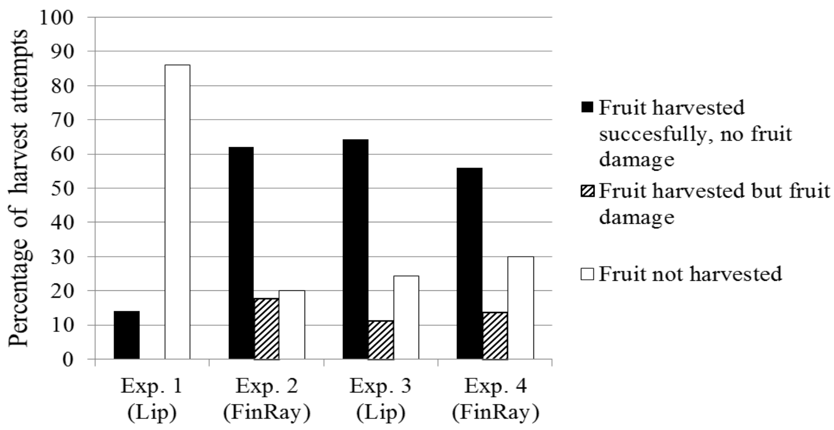


Figure 6. Fruit harvest success rate per experiment.

Table 2. Occurrences of harvest problems for the different experiments. Multiple problems per harvest attempt possible.

| Type of problem | Exp. 1 (Lip) | Exp. 2 (Fin Ray) | Exp. 3 (Lip) | Exp. 4 (Fin Ray) |
|---|---|---|---|---|
| | % | | | |
| Fruit damage | 4 | 22 | 14 | 12 |
| Leaf damage | 2 | 24 | 4 | 16 |
| Plant stem damage | 30 | 34 | 23 | 22 |
| Main stem cut or broken or crop wire cut | 0 | 18 | 7 | 18 |
| Can't approach fruit, leaf/stem/other fruit is obstructing | 12 | 6 | 6 | 22 |
| Did not cut successfully (knife too long/short, force too low or path obstructed) | 80 | 16 | 17 | 12 |
| Fruit does not fit in end-effector (too big) | 2 | 0 | 0 | 0 |
| Not successful grip or suction/fruit get lost | 6 | 0 | 13 | 0 |

**Fin Ray gripper specific**

With no limits in degrees of freedom the end-effector could be positioned well for most of the fruits. The size of the end-effector is not a problem for positioning it, at least not if neighbouring plants are pushed gently away, if needed. The end-effector body width is too big to move it between two neighbouring plants to the back side of the plant. The end-effector needs to be positioned in an accurate slant and tilt angle to prevent the knife from cutting in the fruit or neighbouring fruits or, even worse, the main stem or supporting wire of the plant. This positioning task is very difficult to realize. The camera system will need to deliver a very accurate fruit pose to assure a successful and not damaging harvest action. Moreover, sweet-pepper fruits are often too close together or clamped between stems so that there is no cutting plane available and consequently cutting is not possible in such cases without damaging the fruit or plant. The Fin Ray fingers gripped the fruit stably without damaging it. The knife cut quickly and smoothly through the fruit peduncle leaving a clean cutting surface. The knife blades sometimes collided with a stem or a neighbouring fruit. When that happened, kinetic energy was lost or they got stuck and were unable to cut the peduncle. In almost every harvest action a number of nearby leaves were also damaged or removed. However, this happens also during manual harvesting and it is not expected to have a significant effect on future plant growth. Sometimes leaves were gripped together with the fruit and that made it more difficult to return the end-effector to the main path. Sometimes a plant stem and wire got gripped together with the fruit. If the gripped stem is at the side of the fruit, it is not a problem because it slips out easily by going backwards. If, however, the main plant stem is in front of the fruit it will get cut. This is a major problem since the plant will not recover and will be lost for further fruit production for the remainder of that season.

**Lip-type end-effector specific**

The tool centre point (TCP) of the lip-type end-effector, the suction cup, could be positioned very accurately at the target connection point, the centre of the front surface of the fruit. Even if a leaf or stem obstructed the sweet-pepper the end-effector was still able to connect to the fruit. As the suction cup is attached to a small diameter shaft which extends from the end-effector, it is possible to manoeuvre it while avoiding surrounding obstacles. Only in cases of a very dense plant canopy with many leaves or many side shoots or many fruit clusters, the still open lips can cause the plant/fruit to be pushed away before the TCP can contact the target. In 6% of the cases (experiment 1) and 13% of the cases (experiment 3) the fixation of the fruit with the suction cup failed or was not strong enough to hold the fruit in place during the cut operation. Depending on the individual fruit, the surface might not be smooth or have strong indentations that made it difficult to suck the fruit. Moreover, because of the flexible plant stem, fruits provided very little counterforce and were possibly pushed away when approached by the end-effector. In experiment 1 in 80% of the cases the knife failed to cut the peduncle. As described above, in many of these occurrences the air pressure was insufficient to successfully cut the fruit peduncle. Therefore in experiment 3 a higher pressure was applied. Here, in 17% of the cases the cutting operation was not successful. Failures in cutting were mainly caused by obstructions of the closing lip mechanism by side shoots, leaves or fruits in clusters below the target fruit. If the cut was successful it resulted in a clean cutting surface. In some cases the stem of the plant suffered a small bruise caused by the lower lip which scratched the stem while closing. A cut of the main stem or the crop wire by the knife did not occur. Fruit damages occurred due to the fact that – (i) the fruit slipped out of the suction cup during the cutting operation, (ii) the fruit changed position with respect to the knife during the cutting operation, and (iii) the shield of the upper knife was not preventing damages caused by the inner side of the blade. Damages to leaves occurred in not more than 4% and it is expected that this does not have an effect on plant health. In only one single case the fruit was too big to fit in the end-effector (experiment 1).

## CONCLUSIONS

Both end-effector approaches had their strengths and weaknesses. In none of the experiments more than 64% of the fruit could be harvested without fruit damage. The fingers of the Fin Ray gripper which adapted themselves to the surface of the fruit resulted in a very robust grip without damaging the fruit. The slim fingers could successfully reach the fruit in many cases. However, the Fin Ray gripper required very accurate positioning with respect to the fruit and peduncle orientation and with respect to the fruit position on the stem to assure a non-damaging harvest action. Occlusion of fruit and peduncle prevent current state-of-the-art sensors from providing the information needed to grasp the fruit and cut the peduncle. In 18% of the harvest operations performed with this gripper the main stem or crop wire of the plant was damaged. This is a very critical issue as such plants will be lost for further production. Future work on that gripper should focus on solutions for this issue. The lip-type end-effector had the advantage that by design it required less accurate positioning and also less degrees of freedom to position it as it could approach and fixate the fruit without changing the tilt angle. The enclosing rings would always find and cut the peduncle and would not cut the main stem or crop wire. However, technical problems with the cutting mechanism, either caused by too little air pressure or caused by obstructing leaves or side shoots, needed further attention. Problems in attaching the fruit to the suction cup or losing the fruit from the suction cup while operating the cutting mechanism needs for further analysis. To increase the harvest success of both types of end-effectors, it would help to harvest from the front and back side of the plant. The lip-type gripper was less dependent on the fruit pose with respect to the gripper pose but even in this case harvesting from both sides would increase the success rate. As a result, the cropping system should be adopted in such a way that this is possible. The density and complexity of a sweet-pepper crop with many occluded and clustered fruits make the task of selective harvesting of sweet-pepper with a robotic end-effector in a greenhouse a very demanding task. There is still a lot of work that needs to be done.

**ACKNOWLEDGEMENTS**

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