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Original article

Impact of intensive modification of sweet pepper plants on performance of end effectors for autonomous harvesting

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Summary

This paper evaluates an intensive modification of the sweet pepper crop with respect to the usage of autonomous harvesting by a robot. Objectives were to assess the productivity of the plants after long-term intensive training of the plants compared with standard training and to use end-effectors instead of manually harvesting. The performance of two types of end-effectors was calculated by marketable yield, which includes accessible fruits without physiological disorders like blossom-end rot and sunscald. The experiment was executed in a greenhouse under commercial-like conditions. The marketable yield was significantly reduced by end-effector harvesting compared to manually harvesting. There was a tendency that end-effector A could pick more fruits from intensive trained plants than from standard trained plants. The second type of end-effector B was able to cut the fruit peduncle even at a smaller angle compared to end-effector A. The effect of intensive modification of sweet pepper plants on total and marketable yield and on occurrence of physiological disorders is discussed.

Keywords

blossom-end rot, *Capsicum annuum* L., harvesting robot, marketable yield, physiological disorders, plant training system

Significance of this study

What is already known on this subject?

- Sweet pepper fruits are harvested manually over several months resulting in a high labor input. An autonomous harvesting robot has a high potential for saving manual work and input-costs. For many tasks that a robot has to fulfill, only a partial success is achieved. Depending on the type of end-effector, an autonomous harvesting robot cannot reach all the fruits without damaging plant stem, leaves and neighboring fruits.

What are the new findings?

- The intensive training of plants increased the accessibility of fruits for the Fin-Ray end-effector. The prototype end-effector B was able to cut the fruit peduncle even at a smaller angle compared to the Fin-Ray end-effector. The intensive modification of sweet pepper plants reduced the marketable yield, partly caused by the increase of physiological disorders.

What is the expected impact on horticulture?

- To optimize the autonomous robot the type of end-effector has to be improved in multidisciplinary cooperation. The adaptation of sweet pepper plant architecture as a precondition for the best possible use of the autonomous robot results in the increase of physiological disorders of fruits and diminishes the marketable yield.

Introduction

Sweet pepper (*Capsicum annuum* L.) is a long-term crop commercially cultivated in greenhouses because of the demand for controlled environment including warm temperature throughout the year. It is a high-value crop within horticulture, which requires high labor input mainly because fruits do not ripe simultaneously and have to be harvested manually once a week over several months. Therefore, the use of autonomous harvesting robots offers high saving potential in manual work and input-costs (Lehnert et al., 2017).

Recent studies have shown partial success in many tasks an autonomous sweet pepper harvesting robot has to fulfil. These include detection of fruits by differentiating it from the surrounding plant mass (leaves and stems), the decision on ripeness and readiness for harvesting, gripping the fruit or the peduncle, cutting the peduncle, catching the fruit, and moving it to the fruit container without loss of quality (Arad et al., 2020; Bac et al., 2017; Lehnert et al., 2017; Hemming et al., 2014). Further challenges are the variability in plant growth and architecture, the changing environmental conditions within the greenhouse and within the season. Each step of the procedure inside the sweet pepper canopy should be executed carefully to avoid negative impact on plant growth and yield and to preserve fruit quality.

In commercial greenhouse sweet pepper cultivation, the branching pattern is restricted to two to four main stems per plant. The goal of controlling plant architecture is to facilitate light perception throughout the leaf canopy for more efficient light interception. A two stems plant had higher extra-large fruit yield per plant than a single stem plant (Jovicich et al., 1999). A higher success rate of the CROPS autonomous harvester was achieved when occluding leaves and crop clusters were removed for better detection and fruit picking (Hemming et al., 2014).

However, an open canopy can increase the occurrence of physiological disorders like blossom-end rot (BER), which will result in non-marketable fruit. The occurrence of BER is related to calcium deficiency in fruit tissue (Marcelis and

Ho, 1999). There is a complex relationship between environmental conditions such as air temperature and air humidity, radiation, supply with calcium, nitrogen concentration and composition of nutrient solution, transpiration rate of plants and the transport of calcium to leaves and fruits. For these reasons, intensity of removing occluding leaves affects the leaf area and therefore the occurrence of BER (Jovicich et al., 2004; Marcelis and Ho, 1999).

The end-effector, which grasps and cuts the fruit, is one of the key components of a harvesting robot (Lehnert et al., 2017). Gripping fingers (Fin-Rays) with a scissor-like cut mechanism has been used as well as suction cups and two rings cutting the peduncle of the fruit (Lip-type end-effector) (Hemming et al., 2014). To prevent the spreading of viruses through the greenhouse, a thermal cutting device was included in the end-effector of an autonomous harvester for greenhouse cucumbers (Van Henten et al., 2002). An oscillating multi-tool for cutting stems has been tested on the robotic harvester Harvey (Lehnert et al., 2017).

From the long list of challenges for the use of an autonomous sweet pepper harvester, two factors were chosen for investigation in a field experiment. Firstly, the impact of changes in plant architecture by different training systems on the yield and quality of sweet peppers was evaluated. Optimization of crop management was done to improve accessibility to ripe fruits. Secondly, the use of two types of end-effectors for picking sweet pepper fruits was compared with manual harvest. The performance of the end-effectors was evaluated based on total and marketable yield and in connection with fruit parameters like length and curvature of fruit peduncle.

Materials and methods

Cultivation of plants

In 2018, the sweet pepper plants were grown in the greenhouse of GHL Dürnast, Technical University of Munich, Germany, according to the common practice cropping system.

Capsicum annuum cv. 'Maranello' F_1 seedlings were transplanted on April 9, 2018 in grow bags filled with coconut fiber substrate. The distance between plants in the row was 100 cm. Two main stems of each plant grew in a V-shape system within the rows, which resulted in a distance of 50 cm between the main stems at a height of 3 m. One main stem represented one repetition for statistical analysis. The distance between plants rows was 190 cm. Cultivation was done according to good agricultural practice for optimized plant growth and yield and for avoiding physiological disorders of fruits. For the drip-irrigation, a complete nutrient solution was used. The watering time was from 8:00 am to 6:30 pm with a time gap of 2 hours between each supply. Each watering lasted 5 to 10 minutes depending on climatic parameters. The drainage was between 25 to 45%. The concentration of minerals of the nutrient solution was optimized according to plant growth stage. From May on, the potassium concentration was reduced to prevent possible cation competition with calcium. Calcium solution was applied on the leaves to prevent blossom-end rot. From May on, the shading set point of the greenhouse was 35 klx. The use of beneficial insects replaced the application of pesticides. Crown flowers were pulled out to promote plant growth before fruit set. Standard training of the plants included twisting the stems around the crop-supporting wire and removing lateral shoots and third node flowers at the axils every two weeks from planting date on and once a week from June 19, 2018.

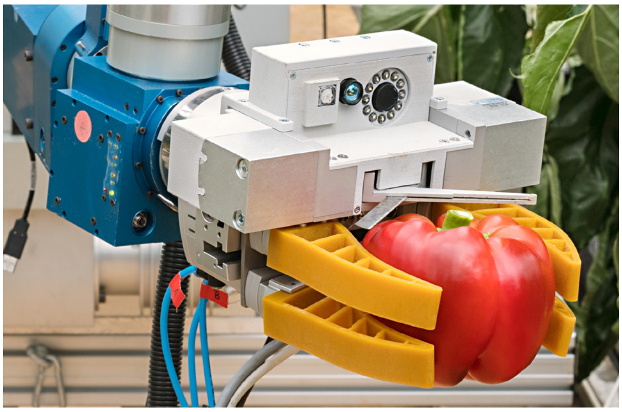

FIGURE 1. End-effector A. Fin-Ray type. Four fin-ray grippers catch the fruit. They can adjust themselves to the curvature of the fruit. Thereafter, the blade, which is mounted above the grippers, cuts off the peduncle.

Experimental design

To investigate the effect of plant architecture, standard training (S) of plants was compared with long-term intensive training (I) of plants. For the intensive training, in addition to the standard training, leaves and lateral shoots were removed, which would hinder the end-effector harvesting sweet pepper fruits. The intensive training was carried out every two weeks from May 3, 2018 in addition to the standard training along the plant stem to the upper developing fruits with a diameter of 3–6 cm.

Two different end-effectors were used for harvesting sweet pepper fruits and compared to harvesting by hand, where the fruit peduncle was cut off close to the main stem with a knife.

End-effector A, Fin-Ray type, Figure 1, was developed by Festo for the FP7 EU research project CROPS (Pfaff et al., 2014). It consists of four fin-ray grippers, which are actuated using a pneumatic slider. Thanks to their fin-ray like design, the grippers can adapt to the profile of the sweet pepper fruits without harming them. Above the gripper mechanism, a large blade is located to cut the stem of the fruit. The cutting mechanism is also actuated using a pneumatic valve. The first series of greenhouse trials in 2017 at GHL Dürnast revealed some flaws in the design:

- The large size of the fin-ray grippers makes it difficult to reach tightly clustered sweet pepper fruits.
- Since the blade is always oriented parallel to the fin-ray grippers, the fruits must be grasped in an orientation that allows the stem to be cut precisely. This turned out to be a rather difficult task, since already a slight misalignment caused the blade either to cut into the fruit itself or to hurt the plant in an undesirable way.
- The blade is operated with a pneumatic valve and always closes using the maximum pressure available once actuated. This sometimes caused the stem of the sweet pepper to be squashed. Often multiple cutting attempts were necessary to cut a thick stem.

Because of these disadvantages, the Chair of Applied Mechanics, TUM, developed a new prototype, the peduncle grasping type, Figure 2. The new end-effector B uses a smaller pneumatic slider with a small rubber gripper to grasp the peduncle of the sweet pepper fruit directly. The blade is still located directly above the gripping mechanism, but has now a pointy triangular shape. The blade is actuated using a Brushless DC motor with a large gear ratio and moves in a linear motion over the grasping mechanism to cut the pe-

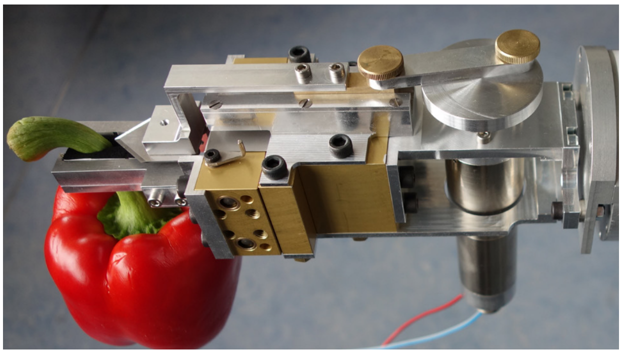

Figure 2. End-effector B. Peduncle grasping type. A pneumatic slider with a small rubber gripper directly grasps the peduncle. The blade is actuated using a BLDC motor to cut the peduncle.

duncle. Although it is now more difficult to grasp the fruit at the peduncle, it is guaranteed that the peduncle is correctly cut without damaging the plant or the fruit. The blade also moves with a slow and smooth motion, utilizing the high torque of the motor. This usually results in a clean cut on the peduncle on the first attempt.

The experiment was performed as follows with a main plant stem representing a repetition:

- Hand harvesting (H): 36 repetitions for standard training plants (SH), 41 repetitions for intensive training plants (IH);
- Harvesting with robotic end-effector A (RA): 22 repetitions for standard training plants (SRA), 22 repetitions for intensive training plants (IRA);
- Harvesting with robotic end-effector B (RB): 20 repetitions for standard training plants (SRB), 20 repetitions for intensive training plants (IRB).

Plant parameters

The harvest period for evaluation was once a week from June 12 to July 24, 2018. A fruit was considered ripe for picking when 80% of the skin surface has turned to a bright red color independent of occurrence of physiological disorders. This decision was done by experienced researchers. When harvested by hand, the fruit peduncle was cut off close to the stem. When harvesting by end-effectors, the fruit peduncle was cut off at a different length and the peduncle part remaining on the stem was cut off manually. Masses of the fruit and of the rest of the peduncle were combined as total fruit mass for comparison with hand harvesting.

The total yield (g) per repetition was evaluated to check the effect of different plant trainings. By using the marketable yield (g) per repetition, the practicability of two end-effectors were compared with hand-harvesting at two different intensities of plant training. To interpret the effects of training system and end-effectors harvesting, additional parameters were measured and recorded after the fruits were picked: the fruit peduncle length and angle, fruit's damages during picking and physiological disorders like sunscald and blossom-end rot.

SAS was performed for data analysis. A one-way analysis of variance and the multiple mean comparison by Scheffé-test at 95% probability were used.

The experiment included in this paper was performed without the integrated robot arm. The end-effector was positioned by hand.

Results

Long-term intensive training of plants was done seven times and resulted in a less dense canopy compared to standard training of plants (Figures 3A and 3B). The average loss of 32 g plant mass per stem by long-term intensive training led to a reduction of the total yield and a decline in productivity (Figure 4). By using end-effector A, there was a significantly smaller total yield for the intensive training system compared to standard training system.

Unmarketable fruits are fruits not reachable by end-effectors and fruits with physiological disorders. Therefore, the marketable yield per stem was significantly higher by hand harvesting compared to end-effector harvesting (Figure 5).

Fruit clustering hinders efficient operation of end-effectors. The phenomenon of fruit clustering was reduced by long-term intensive training system. This treatment resulted in considerably smaller fruit losses. The end-effectors A and B were unable to pick 25.53 and 25.32% of total marketable fruits, respectively (Table 1). The standard training system

Figure 3A. Panoramic view of standard trained sweet pepper plants (S). Standard training includes twisting the stem around the crop-supporting wire and removing lateral shoots and third node flowers at the axils. Fruits are hidden by leaves and secondary stems.

Figure 3B. Panoramic view of intensive trained sweet pepper plants (I). In addition to the standard training, intensive training includes removing of leaves and lateral shoots, which would hinder the end-effectors harvesting sweet pepper fruits. Compared to Figure 3A, fruits are more visible, leave mass is smaller.

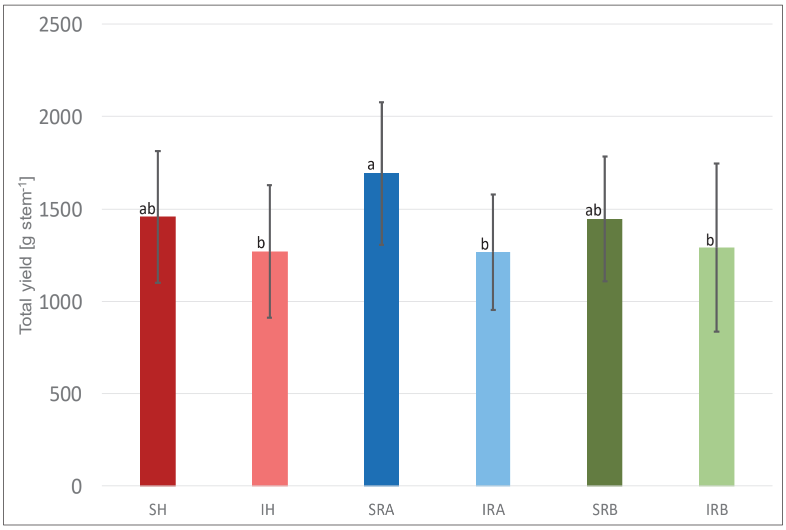

FIGURE 4. Total yield of sweet pepper fruits (g) per stem. Means ± standard error are reported. Different letters indicate statistically significant differences among treatments. SH: standard training and hand harvesting; IH: intensive training and hand harvesting; SRA: standard training and harvesting with end-effector A; IRA: intensive training and harvesting with end-effector A; SRB: standard training and harvesting with end-effector B; IRB: intensive training and harvesting with end-effector B.

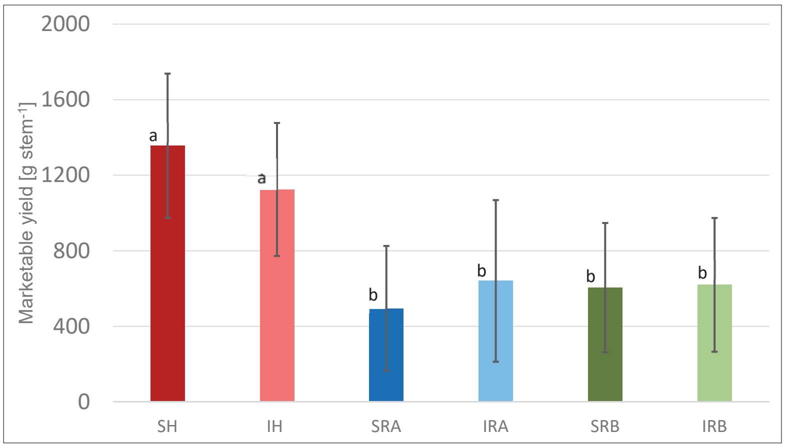

FIGURE 5. Marketable yield of sweet pepper fruits (g) per stem. Means ± standard error are reported. Different letters indicate statistically significant differences among treatments. SH: standard training and hand harvesting; IH: intensive training and hand harvesting; SRA: standard training and harvesting with end-effector A, IRA: intensive training and harvesting with end-effector A; SRB: standard training and harvesting with end-effector B; IRB: intensive training and harvesting with end-effector B.

resulted in higher fruit losses namely 40.16 and 38.38% for end-effector A and B, respectively (Table1).

Some sweet pepper fruits have peduncles that have not grown vertically. This can result in peduncle angle being too small and peduncle length too short making it too difficult for end-effectors to harvest the fruits. Too small angles of fruit peduncle led to losses (Table 2), but these were smaller compared to losses due to fruit clustering. A total of 22.31 and 23.41% of the fruits could not be picked due to small angle of the peduncle with end-effector A in the standard training system and in the intensive training system, respectively. In addition, the end-effector B showed a better ability to cut fruit peduncles having smaller angle as compared to end-effector A. Five percent more fruits with a peduncle angle ≥31° could be harvested with end-effector B from plants of the intensive training system than end-effector A. In the standard training system, 5 percent more fruits with a peduncle angle ≥46° could be picked by end-effector B than end-effector A (data not shown).

The intensity of plant training affected the occurrence of physiological disorders like blossom-end rot and sunscald (Table 3). The standard training led to considerably less fruit loss by hand harvesting (8.5%) and by end-effector harvesting (6.2%) compared to intensive training (14.0%, resp. 12.7%).

TABLE 1. Non-harvestable but marketable fruits due to fruit clustering (% by no. of total no. of fruits per stem).

Plant training	End-effector	Loss (%)
Standard training	End-effector A	40.16
Standard training	End-effector B	38.38
Intensive training	End-effector A	25.53
Intensive training	End-effector B	25.32

TABLE 2. Non-harvestable but marketable fruits due to too small angle of fruit peduncle (% by no. of total no. of fruits per stem).

Plant training	End-effector	Loss (%)
Standard training	End-effector A	22.31
Standard training	End-effector B	17.00
Intensive training	End-effector A	23.41
Intensive training	End-effector B	16.42

TABLE 3. Effect of the intensity of plant training on the occurrence of physiological disorders (blossom-end rot and sunscald) (% by no. of total no. of fruits per stem).

Plant training	Method of harvesting	Physiological disorders (%)
Standard training	Hand harvesting	8.5
Intensive training	Hand harvesting	14.0
Standard training	End-effector harvest	6.2
Intensive training	End-effector harvest	12.7

Discussion

The automation of tasks in horticultural crop production includes among others the very labor-intensive process of harvesting individual fruits. On the one hand, the necessary complex mechatronic system should be robust against the special climatic conditions in the greenhouse, such as very warm temperature and high air humidity. On the other hand, individual solutions are required for the different plant species and cultivars in order to harvest effectively and without damaging the fruits and the plants. The detection system has to localize the fruits despite differences in shape and color, despite partial occlusion by leaves and despite adverse lighting conditions in the greenhouse. The gripper system has to be brought quickly to the fruit without injuring the plant.

The standard training system of sweet pepper plants results in a very dense canopy. In general, this makes it difficult for an autonomous robot to detect and to localize a fruit. Leaves and stems can obstruct the direct access of end-effector to the fruit. In the present experiment, an average of 32 g plant mass per stem (leaves and lateral shoots) was removed every second week by modification of the training system called long-term intensive training. In consequence, the open structure of the canopy made it easier for the end-effectors to approach the fruits. However, the reduced plant masses, in particular the reduced leaf area and thus reduced photosynthetic activity, could be the main reason for the decline in total yield and in productivity of sweet pepper. The decrease was independent of the harvesting method. For cucumber, it could be shown that leaves around ripe fruits could be removed at beginning of harvesting without loss of product quality and quantity (Van Henten et al., 2002). For sweet pepper, improved harvest success of an autonomous robot was even achieved by removing fruit cluster and occluding leaves, which was done directly before harvesting (Bac et al., 2017). In contrast, in our experiment removing the plant mass started 40 days before the period of harvest with considerable impact on plant growth and yield.

The end-effectors could not approach each fruit because leaves, stems and fruits blocked the access. It was decided by researchers not to harvest every fruit with the end-effectors if there was a risk of damaging the fruit itself, the leaves, lateral shoots or neighboring fruits. In this way, there was rarely any mechanical fruit damage by end-effectors. However, this method contributed to a reduction in the marketable fruit yield picked by the end-effectors compared with manual harvesting of the fruits and the advantage of this procedure was that plant mass was preserved.

In each treatment, the experienced researchers decided if the fruit is ripe for picking. Therefore, compared to manual harvesting the decreased efficiency of end-effectors visible as marketable yield is based on less accessibility and losses by physiological disorders.

The occurrence of physiological disorders like blossom-end rot and sunscald can have many reasons resulting in a localized calcium deficiency in fruits. Among others, temperature, air humidity, radiation and the non-shading the fruits by the leaf canopy can cause blossom-end rot (Bosland and Votava, 2000; Marcelis and Ho, 1999). In our experiment, parameters of good agricultural practice were controlled and optimized to avoid BER, like temperature, air humidity, shading the greenhouse, concentration and composition of the nutrient solution, watering, application the leaves with calcium. In comparison to the standard training, the intensive training system reduced the leaf canopy and thus the shadowing effect. Consequently, this training system resulted in higher light intensity and in considerably higher fruit loss regardless of the harvesting method. Sweet pepper plants pruned to the "V" system with a lesser number of leaves had a greater proportion of BER fruits than plants with a higher number of leaves (Jovicich et al., 2004). Shading of sweet pepper plants led to a reduction of sunscald damage of the fruits (Rylski and Spigelman, 1986).

While the use of end-effectors in the autonomous harvest of sweet pepper fruits can considerably be facilitated by a long-term intensive training system of plants, the resulting reduction in leaf canopy will have a negative effect on the yield and quality of the fruits. Because of the sensitivity of sweet pepper plants to high light intensity, the types of shading screens in greenhouses and the control of shading should be optimized.

A yellow shading net was used for commercial cultivation of red sweet pepper in open fields to achieve higher yields compared with a green shading net. However, using a green or ChromaticNet red shading resulted in the highest total carotenoid content (Ambrozy et al., 2016).

The use of shade cloths for tomato greenhouse cultivation modified the nutritional needs of the plants and affected productivity and quality of the fruits (Hernandez et al., 2019). Furthermore, the development of lateral shoots on the main stem of the plant could be reduced by shading (Rylski and Spigelman, 1986). In general, physiological stress of plants have to be avoided.

Cultivars of sweet pepper differ in plant morphology. Past and current results confirm the great challenge for plant breeders to select cultivars that are better suited for automated harvesting (Lehnert et al., 2017), with fruit on special long, vertically growing, thin peduncles. The ideal configuration would consist in having one fruit on the canopy surface with minimal occlusion (Burks et al., 2005). The essential shading of the fruit should be provided by shading screens in the greenhouse.

Results and practical experience with the Fin-Ray end-effector (FP7 EU research project CROPS and in the experiment of the previous year) showed, among other things, the major difficulty of reaching clustered sweet pepper fruits. To solve this problem the Chair of Applied Mechanics, TUM, developed a new type of end-effector (B), the peduncle grasping type, which was used in the present experiment to compare its applicability with the Fin-Ray end-effector (A). End-effector B grasps the fruit peduncle and cut it. By this, the fruit body is not touched and the risk of damaging the fruit body is decreased.

To evaluate the performance of these two end-effectors the indicator 'non-harvestable but marketable fruits due to fruit clustering' was used (Table 1). In the standard training system, the loss of marketable fruit tended to be lower for end-effector B than for A despite the fruit clustering. The special treatment of plants by the long-term intensive training system reduced the occurrence of fruit clustering and there was no difference between the performances of the two end-effectors in the intensive training system but the marketable yield was reduced compared to manual harvesting. For melon plants, an air blower was used to move the occluding leaves and to improve the detection of melon fruits for robotic harvesting (Edan et al., 2000). However, when this technology is used on a greenhouse crop like sweet pepper, the risk of spreading plant diseases from one plant to another is very high.

In addition to fruit-clustering, a too small peduncle angle was a second attribute that hindered harvesting by end-effectors. It could be shown that the newly developed prototype (B) diminished this problem. The detection of the peduncle is a prerequisite for the successful use of end-effector B. Arad et al. (2020) used an end-effector with a vibrating knife to cut the fruit peduncle and thereafter six fingers hold the picked fruit. To prevent plant damage caused by the knife a plant stem fixation mechanism was developed as an innovation of the end-effector. However, a longer peduncle could not reduce the risk of cutting into fruit bodies by this end-effector. Moreover, there was an increased uncertainty about the exact location of the cutting point. In summary, the end-effector B will promise higher efficiency after its mechanics have been improved and optimized. A future improvement of end-effector B could be the described thermal cutting to prevent the transportation of viruses from one plant to the other (Van Henten et al., 2002).

Overall, the plant system must be designed for successful automation of sweet pepper harvest (Burks et al., 2005). In addition, it has been shown that maintaining the peduncle maximizes the shelf life and market value of each fruit (Sa et al., 2017).

A time evaluation of the difference between manual and automated harvesting should be done after the further development of the optimal end-effector and incorporating a sensor for fruit detection.

The results of this work show that the training system of sweet pepper and the gripper techniques have to be improved for autonomous robotic harvesting. In addition, the breeding of varieties and the cultivation techniques need to be adapted before an autonomous, intelligent robot can harvest in commercial sweet pepper production. This gap has to be closed by multidiscipline collaborative research.

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