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An Autonomous Robot for De-leafing Cucumber Plants grown in a High-wire Cultivation System

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The paper presents an autonomous robot for removing the leaves from cucumber plants grown in a high-wire cultivation system. Leaves at the lower end of the plants are removed because of their reduced vitality, their negligible contribution to canopy photosynthesis and their increased sensitivity to fungal diseases. Consuming 19% of the total labour input, leaf removal is considered by the growers and their staff as a tedious, repetitive and costly task. Automation alleviates their job and results in a significant cost reduction. The paper describes a functional model and preliminary results of a field test of a de-leafing robot. Despite the small number of repetitions during the field test, the favourable results confirmed the feasibility of the concept of the de-leafing robot. The vision system and manipulator control performed relatively well. However, particularly, the mechanics of the end-effector were failure prone and need re-engineering. With a cycle time of 140 s per two leaves on average, the execution time of the de-leafing robot is approximately 35 times slower than manual leaf picking. For economic feasibility this cycle time should be reduced.

1. Introduction

In the Netherlands, large quantities of tomatoes, cucumbers and sweet pepper are produced in greenhouses. The total production area for these vegetables is approximately 3000 ha. The average size of the nursery has increased throughout the last decade to more than 1 ha and large production facilities of more than 5 ha are quite common today (LEI/CBS, 2000).

Labour is the largest cost factor of a modern greenhouse holding. More than 30% of the total production costs are spent on wages for the grower and his employees and this percentage is still showing a rising trend. Obviously, to cope with saturating market demands and increasing competition, the grower is looking for ways to improve the over-all efficiency of the production process. Improving the efficiency of human labour or reducing the amount of human labour has become a key issue and automation is called for. Automation is also motivated by the declining availability of skilled labour. Manual labour in a greenhouse is demanding, the jobs are not prestigious and the earnings are low. Finally, the prevention of musceloskeletal disorders has motivated the replacement of human labour by automatons.

These were driving forces motivating the development of an autonomous cucumber picking robot at the former Institute of Agricultural and Environmental Engineering (IMAG Ltd) in The Netherlands. Various aspects of the development and field test of this agro-robotic system have been reported throughout the years (Van Henten *et al.*, 2002a, 2002b, 2003a, 2003b; Van Willigenburg *et al.*, 2004). Clearly, the development of this harvest machine fits into a trend starting in the early 80s of the 20th century, aiming at the automation of tedious, repetitive or labour-intensive tasks in horticultural crop production. See technical overviews by Sarig (1993), Tillet (1993), Edan (1995), and Kondo and Ting (1998).

After the successful field test of the harvest machine in late 2001 (Van Henten *et al.*, 2003b), the research effort was redirected in 2002 towards the development of a robot for removing the leaves from cucumber plants grown in a high-wire cultivation system. In a high-wire cultivation system for tomatoes and cucumbers, leaves at the lower end of the plants are removed about once a week, because of their reduced vitality, their negligible contribution to canopy photosynthesis and their increased sensitivity to fungal diseases. See *Fig. 1* for a schematic picture of the crop before and after leaf removal. Refer to Van Henten *et al.* (2002b) for more details of the high-wire growing system. Consuming 1345 hours per 1000 m^2, *i.e.* 19% of the total labour input, leaf removal is considered by the growers and their staff as a tedious, repetitive and costly task. Automation would alleviate their job and would result in a significant cost reduction. Additionally, removal of the leaves results in an open structure of the canopy in which the fruit are clearly visible and accessible. This was found to be an advantage for automatic harvesting (Van Henten *et al.*, 2003b) and can be done without loss of production capacity (Bruins & Van Gurp, 2000).

This paper describes a functional model and field test of an autonomous robot for de-leafing cucumber plants grown in a high-wire cultivation system. This functional model removes the leaves below the fruit harvesting zone ($>1{\cdot}2$ m) in the crop as shown in *Fig. 1*. To the best of our knowledge it is the first time that a machine that selectively removes leaves from individual cucumber plants is developed and tested.

2. Materials and methods

2.1. *A methodological approach to engineering design*

To reduce loss of project time and capital, a methodological approach to engineering design was used throughout the whole project, from project initiation until the field test. This design methodology is reported in a paper of Van Tuijl *et al.* (2004).

2.2. *A functional model of the de-leafing robot*

From the design procedure surprisingly followed that, to deal with the considerable biological variability in the working environment of the robot, an automated de-leafing procedure for cucumber grown in a high-wire cultivation system, should first find the main stem of the plant and then move upwards to find the leaves. This contradicts the human operation. A manual worker tends to grab the leaf and move one hand along the leaf stem before breaking the leaf from the plant. Furthermore, it was concluded that the de-leafing robot, to a

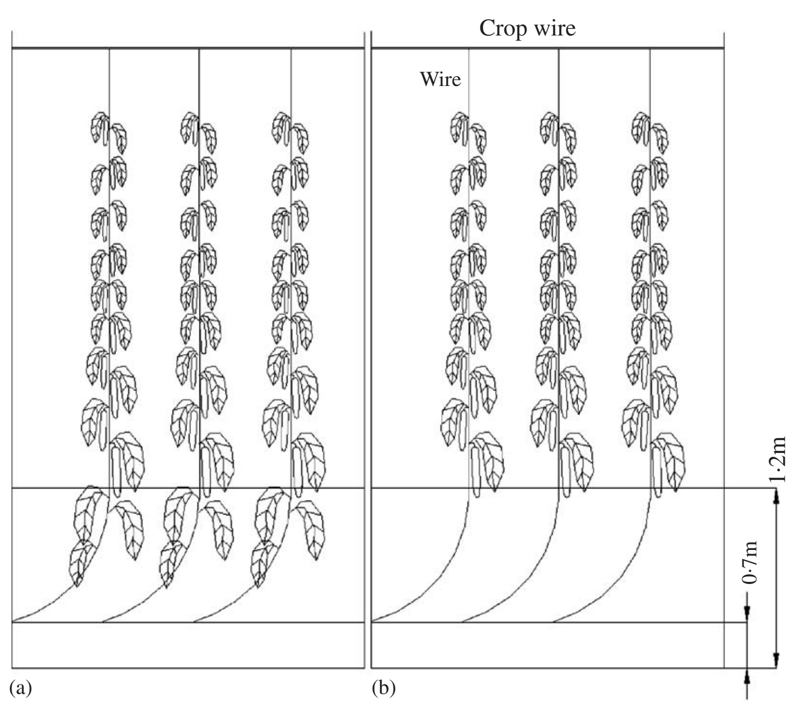

Fig. 1. Cucumbers grown in a high-wire cultivation system; (a) before and (b) after leaf removal

large extent, could be based on the mobile platform and constituents of the cucumber-harvesting robot. See the detailed description by Van Henten *et al*. (2002a, 2002b, 2003a, 2003b). The vehicle used the hot water heating pipes on the ground for guidance and support. It carried electronic and pneumatic hardware for data acquisition and control of the robotic system. On the vehicle, a seven link manipulator was mounted. The manipulator carried an end-effector specially developed for removing the leaves from the cucumber plants. Main differences with the harvest robot were the end-effector and software components to use the available vision system, manipulator and end-effector for the task of detecting, locating and removing leaves from the plants.

2.3. *Procedure of leaf removing*

Figure 2 shows a task sequence of the leaf removing procedure. Essentially, the robot positioned an end-effector at the stem at the lower end of the plants where leaves had been removed during an earlier de-leafing cycle as can be seen in *Fig. 1*. This part of the stem was easy to detect and to approach. Then, the end-effector was moved upwards along a pre-defined stem segment while removing the leaves, present.

A near-infrared-based computer vision system was used to detect the stem. The vision system took two images of this scene. If stems were detected, the three-dimensional (3D) position was calculated using stereo-vision. For objects at a distance of 0·6 m from the camera, the camera produced an error of $1{\cdot}5 \times 10^{-3}$ m in the X plane and Y plane and about $7{\cdot}5 \times 10^{-3}$ m in the Z plane, perpendicular to the CCD chip. A collision-free motion of the manipulator was calculated to bring the end-effector to the stem. The end-effector was attached to the stem and moved in discrete steps upwards along the stem. After each motion, it was checked if a leaf stem had been detected by the sensor system mounted on the end-effector. If so, the leaf stem was cut using a thermal cutting device. Then, the end-effector was moved upwards another step, repeating the above sequence until the end of a pre-defined stem segment was reached. At the end of the stem segment, approximately 1·2 m above the ground, the end-effector was released from the stem and the manipulator was moved to its home position. In case more than one stem was detected within the field of view of the camera, stems were treated sequentially. After all stems in the field of view of the robot had been treated, the vehicle moved a fixed distance along the path until the end of the path was reached.

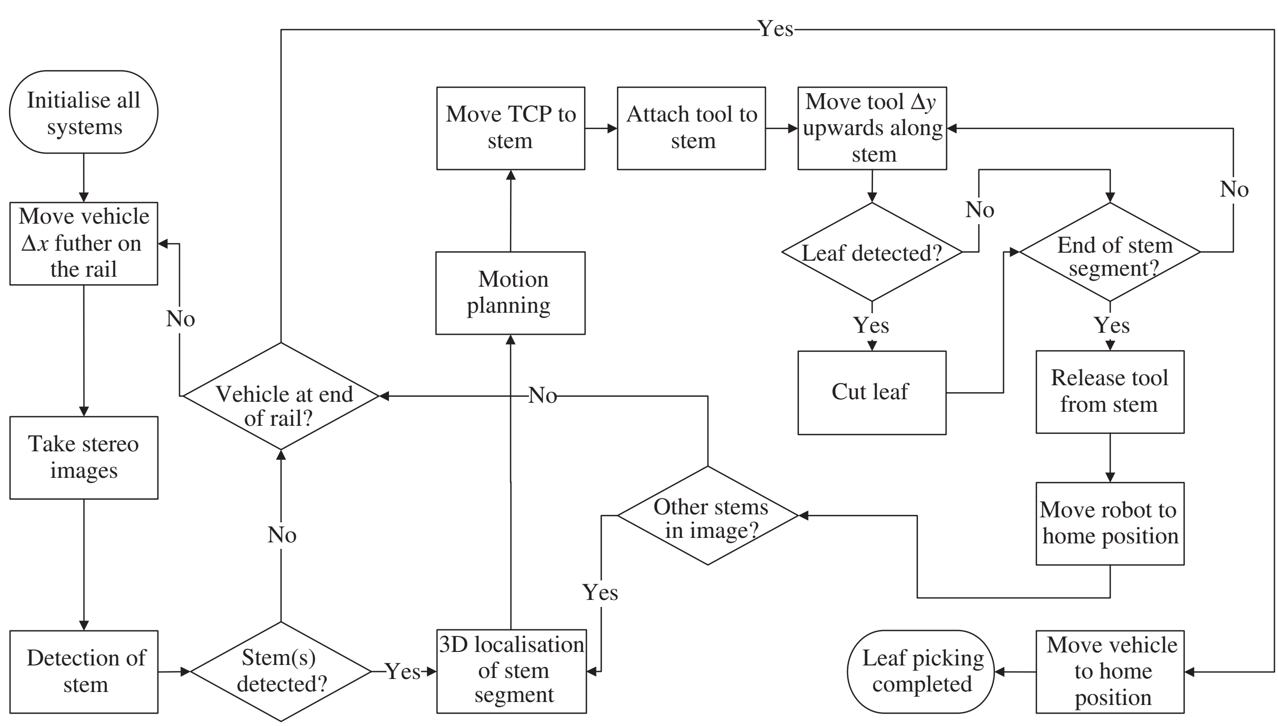

Fig. 2. Task sequence during leaf picking in a whole path: Δx and Δy, translation along x and y coordinates; 3D, three dimensional; TCP, tool centre point

2.4. *Vision system for detecting and locating stems*

In the same way, cucumber fruit can be localised on the plant based on spectral properties in the NIR and visible radiation images, stems can also be identified. The reflectance of dense objects with high water content such as fruit and plant stems is at 850 nm significantly higher than at 970 nm. On the other hand the leaves show approximately the same reflectance at 850 and 970 nm (Van Henten *et al.*, 2002b). Stems can be distinguished from fruit objects by segmenting thin and longish structures using the morphological image processing operators erosion and dilation. By shifting the camera along a straight line over say 5 cm and taking two images, 3D information can be reconstructed from the images.

Figure 3 shows the results of the stem detection algorithm. The figure shows the original image and the process of detecting stems as well as the extrapolation of the visible stem used to generate a motion of the end-effector along that portion of the stem that is occluded by leaves that still have to be removed.

2.5. *Manipulator control*

In the same way, as with the cucumber harvester, a collision-free motion was calculated to move the end-effector to the stem without hitting the crop and the construction of the robot. The direction of the occluded stem, as extrapolated from the vision data was used to generate a path along a pre-defined portion of the (partially occluded) cucumber stem.

2.6. *End-effector for removing leaves*

The end-effector used for removing the leaves is shown in *Fig. 4*. In the open configuration, the end-effector could be mounted around the stem. In the closed configuration, the end-effector fully enclosed the stem. The shape of the end-effector was adapted to the 120° angle between leaf stems of cucumber. The 'teeth' of the end-effector are needed to capture the leaf stems. Between these teeth, a contact sensor was mounted to detect the presence of leaf stems. The contact sensor consisted of two electrodes with a low voltage potential between them. A stem was detected by measuring the current flow between the two electrodes. If a leaf stem was detected during an upward motion, a thermal cutting device, also mounted between the teeth of the end-effector, was activated to cut the leaf stem. The thermal knife consisted of two electrodes of which one was statically mounted on the end-effector between the teeth and the other was mounted on a pneumatically driven rotary actuator yielding a cutting motion upon activation. Cut leaves were not collected but fell on the ground.

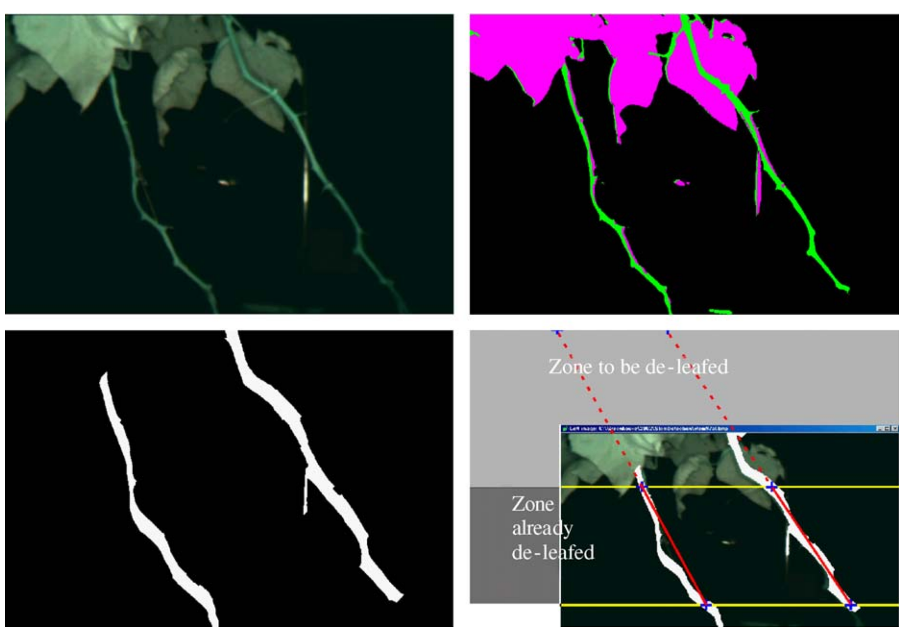

Fig. 3. Sample of stem detection for use with a de-leafing robot, input image showing zone already de-leafed (top left), stems separated from leaves (top right), stems detected by image analysis software using orientation-dependant morphological operations (bottom left), estimation of direction of occluded stem (bottom right)

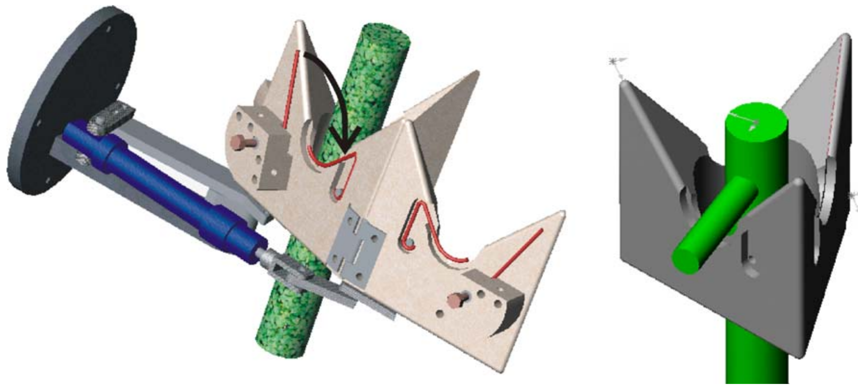

Fig. 4. The end-effector of de-leafing robot in opened configuration (left) and closed configuration (right): arrow indicates motion of rotary actuator of thermal cutting device

2.7. *Greenhouse experiment*

In August 2002, cucumbers (*Cucumis sativus* cv. RZ24-110) were planted on rockwool slabs in a 240 m^2 research greenhouse. The crop was grown in a high-wire cultivation system with an average in the row distance of 0·50 m. Refer to Van Henten *et al.* (2002b) for details of this growing system. In this experiment, leaves were removed by the robot between 0·7 and 1·2 m above the ground as shown in *Fig. 1*. In this area, one or two leaves were present and had to be removed. Because leaves were removed below the fruit-harvesting area ($>1{\cdot}2$ m), the robot did not have to distinguish between leaves and fruits. Crucial steps in the de-leafing procedure such as image processing, robot motion control and end-effector operation, were qualitatively evaluated. Sources of error and execution times were not recorded in detail.

3. Results of a field test and discussion

The experiments in the research greenhouse clearly demonstrated the feasibility of this concept. While moving upwards along the stem segment, in a number of cases, one leaf was successfully removed, sometimes two leaves.

Execution time of the de-leafing operation was measured at 140 s for two leaves on average. This is approximately 35 times slower than manual leaf picking. But there is plenty of room in the hardware and software design to increase the speed. Furthermore, a robot does not have to work at the same speed as a manual worker to be economically feasible, because robots can work more hours during the day.

Figure 5 shows the de-leafing robot in action in the greenhouse. *Figure 5*(*a*) shows a successful approach of the main cucumber stem with an open end-effector. *Figure 5*(*b*) shows the end-effector enclosing the stem and demonstrates that the orientation of the end-effector is adapted to the orientation of the main stem of the cucumber plant before moving upwards along the stem. Finally, *Fig. 5*(*c*) shows a close-up of the end-effector while cutting a leaf stem of the cucumber.

Analysis of the results of the experiments revealed the following strengths and weaknesses of this functional model of the de-leafing robot. The analysis is based on the flow-chart in *Fig. 2*. In all cases stems were successfully detected. The motion of the end-effector to the stem did not cause many problems, but in some cases the end-effector pushed the stem away instead of enclosing the stem. The origin of this failure was two-fold. First of all, the depth of the stem was not accurately enough determined. This was cured in a practical way by moving the end-effector further along the Z axis than the position determined by the imaging system. Secondly, due to its physical structure (shape of gripper, pneumatic tubes, actuators) the end-effector in some cases collided with the crop. The orientation of the main stem was accurately enough determined and positioning of the end-effector proceeded accordingly, as illustrated in *Fig. 5*(*b*). During the feasibility test, detection and cutting of the leaf stem sometimes failed. In some cases leaf stems were not detected, possibly because the sensing device mounted in the end-effector was not sensitive enough. Sometimes, once a leave stem was detected, the cutting device did not produce enough force to cut through the stem. Slight modifications of both the detection and the cutting device will cure these problems. Finally, in some cases, having cut one or two leaves, the end-effector was not successfully disconnected from the main stem. Then, the stem got stuck in the end-effector, but the pulling motion of the manipulator in most cases resolved this problem.

Fig. 5. (a) The de-leafing device approaching the stem; (b) the orientation of the end-effector of the de-leafing robot adapted to the orientation of the main cucumber stem; and (c) the end-effector of the de-leafing robot while cutting a leaf stem

4. Conclusions

The paper describes a functional model and preliminary results of a field test of the de-leafing robot. Despite the small number of repetitions during the field test, the favourable results confirmed the feasibility of the concept of a de-leafing robot for cucumber plants grown in a high-wire cultivation system. In a number of cases one leaf was successfully removed. Sometimes two leaves were removed. The experiments revealed some weaknesses but all of them can be cured by relatively small modifications of the hardware and software. Especially, the mechanics of the end-effector were failure prone and need re-engineering.

With 140 s for two leaves on average, the execution time of the de-leafing procedure per plant was approximately 35 times longer than manual leaf picking. For economic feasibility, the de-leafing robot has to operate at a higher speed, but there is plenty of room for improvement in hardware and software to increase the speed of the de-leafing robot. Furthermore, a robot does not have to work at the same speed as a manual worker to be economically feasible, because robots can work more hours during one day.

Finally, it is worth noting that with only two modifications, *i.e.* a different end-effector and modified computer vision software, the cucumber-harvesting robot was converted into a de-leafing robot for cucumber. Thus, a robotic platform was created which is able to perform two tasks on different objects, *i.e.* cucumber harvesting and removing of leaves, with just a limited amount of changes in hardware and software. This is a unique feature not yet shown before in horticultural engineering that is of great interest when application in horticultural practice is concerned.

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