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An Autonomous Robot for Harvesting Cucumbers in Greenhouses

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Abstract. This paper describes the concept of an autonomous robot for harvesting cucumbers in greenhouses. A description is given of the working environment of the robot and the logistics of harvesting. It is stated that for a 2 ha Dutch nursery, 4 harvesting robots and one docking station are needed during the peak season. Based on these preliminaries, the design specifications of the harvest robot are defined. The main requirement is that a single harvest operation may take at most 10 s. Then, the paper focuses on the individual hardware and software components of the robot. These include, the autonomous vehicle, the manipulator, the end-effector, the two computer vision systems for detection and 3D imaging of the fruit and the environment and, finally, a control scheme that generates collision-free motions for the manipulator during harvesting. The manipulator has seven degrees-of-freedom (DOF). This is sufficient for the harvesting task. The end-effector is designed such that it handles the soft fruit without loss of quality. The thermal cutting device included in the end-effector prevents the spreading of viruses through the greenhouse. The computer vision system is able to detect more than 95% of the cucumbers in a greenhouse. Using geometric models the ripeness of the cucumbers is determined. A motion planner based on the A*-search algorithm assures collision-free eye-hand co-ordination. In autumn 2001 system integration took place and the harvesting robot was tested in a greenhouse. With a success rate of 80%, field tests confirmed the ability of the robot to pick cucumbers without human interference. On average the robot needed 45 s to pick one cucumber. Future research focuses on hardware and software solutions to improve the picking speed and accuracy of the eye-hand co-ordination of the robot.

Keywords: autonomous robot, robotics, manipulator, end-effector, computer vision, stereo-vision, collision avoidance, motion planning, greenhouse, cucumber, harvesting

1. Introduction

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

Today, 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. 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 even reducing the amount of human labour is a key issue today. Manual labour in a greenhouse is demanding, especially under poor climatic conditions. The jobs available are not very prestigious and the earnings are low. Therefore, it is becoming more and more difficult to obtain adequate staff. These are reasons why already many years ago, research was focused on the automation of the most tedious and repetitive tasks in horticultural crop production, both inside and outside greenhouses

(Tillet, 1993). Research has been conducted towards the application of robotics for harvesting e.g. citrus, apples, melons, tomatoes and cucumbers. See e.g. Tillet (1993) and Edan (1995) for an overview. Sévila et al. (1992), Kondo et al. (1996), Hayashi and Sakaue (1996) and Arima and Kondo (1999) reported research prototypes of harvesting robots for tomatoes and cucumbers. But autonomous harvesting robots have not yet been commercially applied in horticultural practice.

Because the robots reported in the literature were not suited for the high productivity growing systems used in Dutch horticultural practice, in 1996, IMAG began research on the development of an autonomous cucumber harvesting robot supported by the Dutch Ministry of Agriculture, Food and Fishery (Gieling et al., 1996; Van Kollenburg-Crisan et al., 1997). The task of designing robots for agricultural applications raises issues not encountered in other industries. The robot has to operate in a highly unstructured environment in which no two scenes are the same. Both crop and fruit are prone to mechanical damage and should be handled with care. The robot has to operate under adverse climatic conditions, such as high relative humidity and temperature as well as changing light conditions. Finally, to be cost effective, the robot needs to meet high performance characteristics in terms of speed and success rate of the picking operation.

In this paper, the concept of the modular cucumber harvesting robot is presented. We start with a description of the working environment of the harvesting robot in Section 2. During the peak season, several robots must operate simultaneously to replace human labour. Moreover, harvesting not only includes picking but also transportation of large quantities of fruit to the main storage area. Section 3, is devoted to the logistics of cucumber harvesting. The analysis of the logistics served as a basis for defining the design specifications of each individual harvesting machine. These specifications will be presented in Section 4. In view of these preliminaries, in Section 5, the individual components of the cucumber harvesting robot will be described, including the vehicle, the manipulator, the end-effector, the vision system and the motion control architecture. Section 6 reports on a field-test with the harvest robot in a greenhouse. And finally, in Section 7, the performance of the harvest robot will be discussed in view of the overall design objectives and directions for future research will be given.

2. The Working Environment of the Robot

Some exceptions excluded, in the Netherlands, cucumbers are grown in greenhouses having a rather uniform layout. A top view of the layout of such a greenhouse is shown in Fig. 1. The greenhouse contains two major parts: the growing area and the storage area, connected by a main path. In a standard 2 ha nursery, there is a main path along the centre of the nursery with long aisles of approximately 60 m perpendicular to the main path. On each side of the main path there are 100 rows with cucumber plants. An aisle is available between rows of plants, called a path. The distance between the two rows on each side of the aisle is 0.9 m. The distance between the cucumber stems in the row is 0.35 m. In total there will be about 180 stems in a row. Then the density amounts to 3.6 stems/m^2. In the aisles, heating pipes on the ground are used as rails for transportation during crop maintenance and harvest. During manual harvesting fruit are collected in crates on a trolley. Full crates are exchanged with empty crates in the main path. The harvested cucumbers are then transported to the storage area, where they are sorted, packed and stored awaiting transportation to the customer.

The traditional cultivation system used for growing cucumbers in the Netherlands was found to be unsuitable for automated harvesting. This cultivation system results in a very dense canopy, with a lot of leaves and stems obstructing the view and direct access to the fruit. In such cases even the growers sometimes overlook fruit that could have been harvested, rendering this task unfeasible for an automaton. Therefore, a new cultivation system was adopted, the so called high-wire cultivation system (see Fig. 2). In the high-wire cultivation system, every plant is attached to a wire. This single-plant wire is rolled on a spool and attached to a metal crop wire approximately 4 m above the ground. The crop wire is connected to the greenhouse construction. The growing plant is re-attached to the plant wire once or twice a week. Once the top of the plant reaches the crop wire, the plant is lowered approximately 0.50 m by unrolling the plant wire and moving the spool along the crop wire parallel to the aisle. Before lowering the plant, all leaves near the ground are removed. Growth of the cucumbers is manually restricted to one fruit per two axils. In this cultivation method, mature cucumbers can be found at heights between 0.8 m and 1.5 m above the ground. At these heights, the fruit is uniform in length and fresh weight. Research has revealed that leaves around ripe fruit can be removed without loss

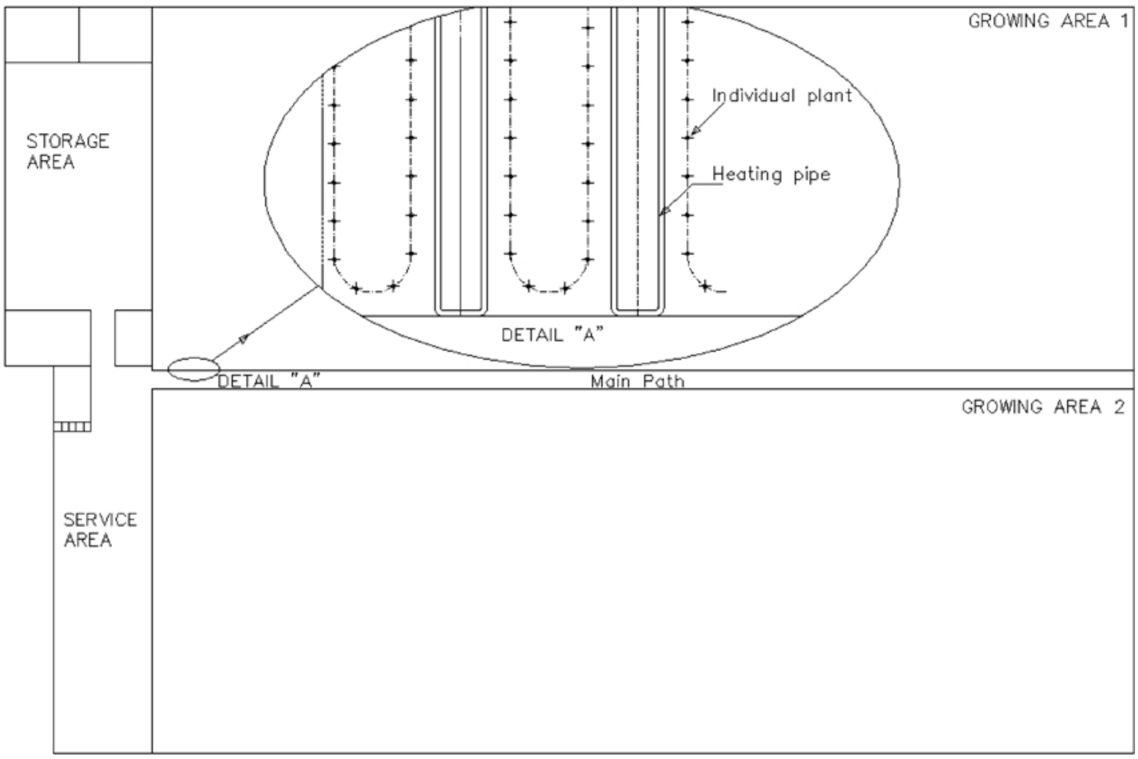

Figure 1. Top view of a standard 2 ha greenhouse.

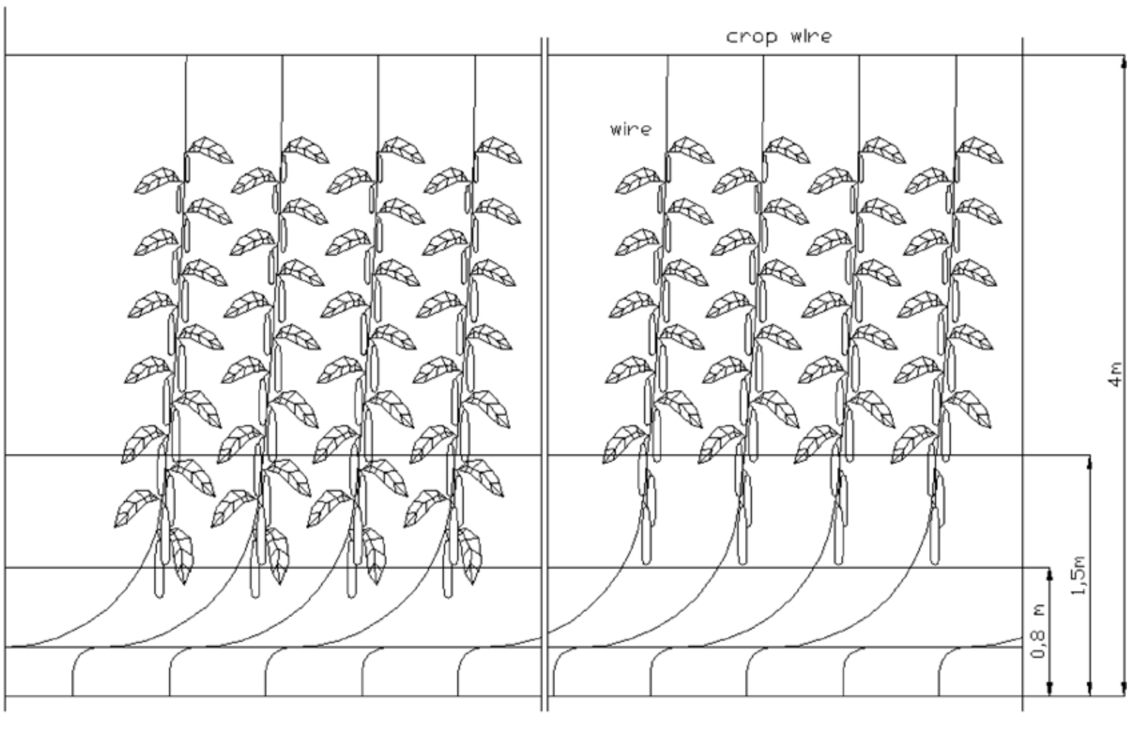

Figure 2. The high-wire cultivation system before (left) and after (right) removing the leaves around the ripe cucumbers.

of product quality and quantity, making automatic harvesting even more easily. Compared to the traditional cucumber cultivation, the main advantages of the high-wire cultivation system for automated harvesting are the open structure of the canopy and the distinct area in which ripe fruit can be found. In the high-wire training system it is easier to detect, locate and approach the fruit as illustrated in Fig. 3. Still the robot has to operate in a highly unstructured environment in which no two scenes are the same.

3. Logistics of Harvesting

During peak season in the summer, 12 skilled workers are needed to harvest cucumbers in a 2 ha greenhouse facility. Clearly, a single robot will not be able to replace 12 skilled people. Several robots must operate simultaneously to do the job. Moreover, harvesting not only includes picking but also transportation of large quantities of fruit to the main storage area. To attain insight into the logistics of harvesting, simulations were performed with the ARENA software package.

Cucumbers for fresh consumption are harvested two to three times a week, from February to November. According to task-time studies, a trained worker harvests the fruit with a speed of less than 6 s per cucumber (Hendrix, 1993). In practice the grower harvests no longer than 6 hours per day. Table 1 shows the amount of harvesting robots needed throughout the year for a standard 2 ha Dutch nursery. In the table a period represents 4 weeks. The second column refers to the amount

Figure 3. A close-up of the high-wire cultivation system.

Table 1. The harvested number of cucumbers throughout the year, the number of skilled workers and the number of robots needed per period of 4 weeks, for a 2 ha Dutch greenhouse.

Period	Harvested cucumbers (pieces)	Number of workers 6 h/pers/day	Number of robots
1	0	0	0
2	13400	3	1
3	20400	4	2
4	36200	8	3
5	50400	11	4
6	55000	12	4
7	47200	10	4
8	47200	10	4
9	34600	7	3
10	34600	7	3
11	20400	4	2
12	0	0	0
13	0	0	0

of cucumbers that have to be picked in the greenhouse considered. The table shows that 4 robots are required to do the same job as twelve workers, in a 2 ha Dutch nursery, during 4 consecutive periods in the summer. During 6 periods in spring and autumn, at least 1 and at most 3 robots are needed for harvesting. The simulations also revealed that one docking station suffices to support all four robots. This docking station is used to move the individual harvest machine from one path to another. Also, the docking station is used for collection and transportation of harvested fruit to the central storage room. A top view of a greenhouse with robots and a docking station is shown in Fig. 4.

These results were based on the following assumptions:

1. It was assumed that a single robot needs 10 s for a full harvest cycle. A harvest cycle includes fruit detection, fruit removal and fruit placement in the container as well as the motion of the vehicle to the next plant. The choice of 10 s for the cycle time of the harvest process was based on a trade-off between engineering and economics. A shorter cycle time will result in a smaller number of harvest machines. But, it also requires more advanced electromechanical and computing technology, at the expense of higher costs. A longer cycle will result in a higher amount of harvest machines needed for picking the fruit. The construction may be less expensive, but to be cost effective, the room for investment in each machine will be smaller as well. It was decided that

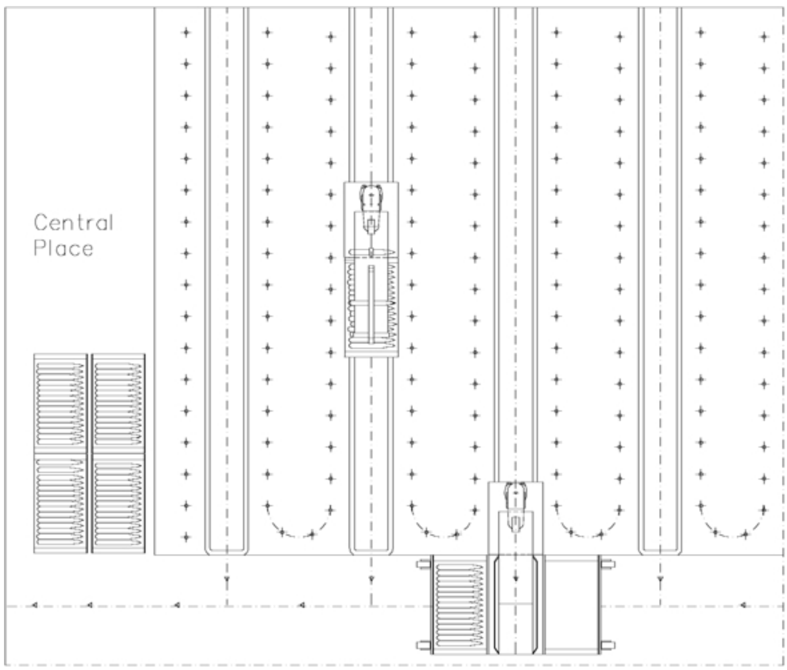

Figure 4. Top view of a greenhouse with harvesting robots and docking station.

at the moment a cycle time of 10 s is attainable and justified both from an engineering and economics point of view.
2. The harvest robot was considered to operate for 18 hours/day. The remaining 6 hours encompass brake down and reparation of the machine, regular maintenance, recharging batteries, etc.
3. The velocity of the robot vehicle was set at 0.8 m/s on one path.
4. The robot stops every 0.33 m and picks cucumbers from the plants within its working boundary and stores the harvested fruit into a crate or a container.
5. The crates/containers are mounted on a transport platform. Transport of the harvested fruit from the picking place to the main path is done with this platform. The platform is designed to carry 300 fruits and it can move together with the harvesting robot between the plant rows, as master and slave, making use of the heating pipes for guidance and support.

4. Robot Design Specifications

Based on the previous analysis, the following design specifications were defined. The harvest robot should have a cycle time of at most 10 s for a full harvest cycle including the motion of the vehicle along the aisle. The robot should be able to operate under adverse climatic conditions, such as high relative humidity and temperature as well as changing light conditions. The harvest robot should be able to move autonomously through the greenhouse. The robot should be able to detect cucumbers in the harvest region from 0.8 m to 1.5 m above the ground, to determine the ripeness of the detected cucumber and to locate the ripe cucumber in the 3 dimensional workspace. The manipulator should have a kinematic design such that it allows for picking all cucumbers in the harvest area of the crop. The manipulator should position the tool centre point with an accuracy of 1 mm. Motion planning should prevent collisions of the manipulator, end-effector and harvested fruit with the crop, the greenhouse construction and the robot itself (such as the vehicle and vision system) during the harvesting operation. To assure the quality of the harvested fruit, constraints have to be imposed on the travelling speed and accelerations of the manipulator during various portions of the motion path. The end-effector should gently handle the fruit to prevent damage and loss of quality. Finally, the cutting device should be designed such that transportation of viruses from one plant to the other during the harvest operation is prevented.

5. The Modular Harvest Robot

In Fig. 5 a functional model of the harvesting robot is shown. It consists of an autonomous vehicle, a 7 DOF manipulator, an end-effector, 2 camera vision systems and miscellaneous electronic and pneumatic hardware. Each module will be described hereafter in some detail.

5.1. The Autonomous Vehicle

The autonomous vehicle moves the harvesting machine along the aisles of the greenhouse. The vehicle uses the heating pipes mounted on the ground as a rail for guidance and support. It serves as a mobile platform for carrying power supplies, a pneumatic pump, electronic hardware for data-acquisition and control, the camera vision systems and the 7 DOF manipulator with the end-effector for cutting the fruit. During a harvest operation the mobile platform gains stability by putting 4 linearly actuated struts on the ground. Currently, due to the considerable energy consumption of various components used, the robot is not completely self-supporting in terms of electric power supply. Operation of this machine depends on a life-line mounted on a reel, which carries 220 V from a central main supply to the robot. The vehicle is driven by a 24 V DC motor and a servo controller combined with an incremental encoder. The position accuracy is better than 1×10^{-4} m. The acceleration is limited to approximately 0.3 m/s^2.

5.2. The Manipulator

The robot contains a 7 DOF manipulator for positioning of the end-effector during the harvest operation. The manipulator consists of a linear slide on top of which a Mitsubishi RV-E2 manipulator with an anthropomorphic arm and a spherical wrist is mounted. The particular choice of the manipulator geometry was based on a combined analysis of the robot task and the working environment as shown in Fig. 6. In the high-wire cultivation system, the ripe cucumbers all hang in a limited band between 0.8 m and 1.5 m above the ground. Then, using the vehicle for transportation along the aisles of the greenhouse, an empirical analysis revealed that 6 DOF consisting of 6 rotational joints would be

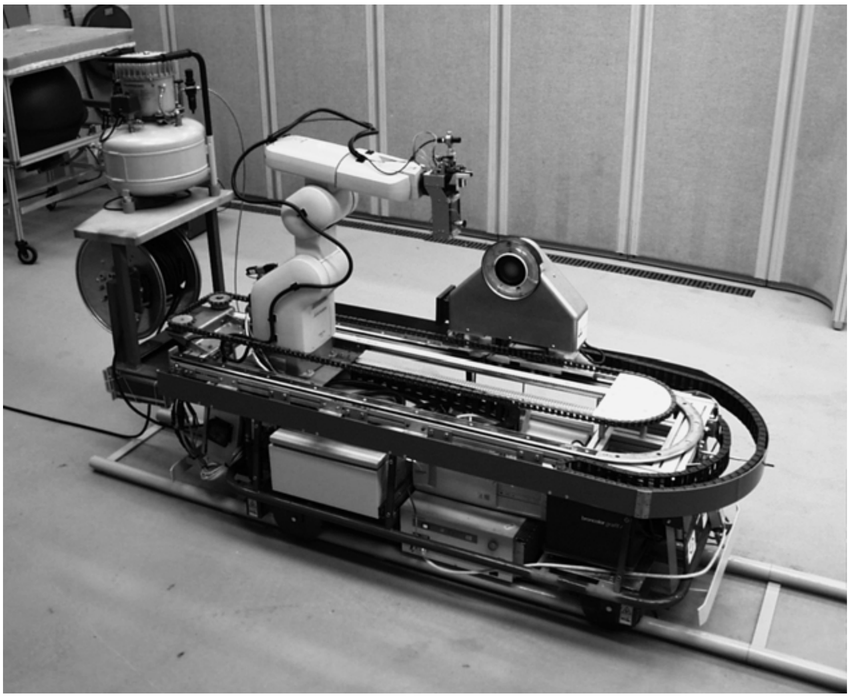

Figure 5. A functional model of the harvesting robot.

sufficient to perform the harvest operation. Limitations had to be put on the geometrical and physical properties of the manipulator because it has to deal with dense and rather fragile canopies. Also the amount of space between the rows of the crop is limited. For illustration of the concept of autonomous harvesting an industrial manipulator, the Mitsubishi RV-E2, satisfied these requirements best. The RV-E2 manipulator is driven by 24 DC motors and servo controllers combined with absolute encoders. Additional performance in terms of speed and collision avoidance in difficult task environments, was added to the manipulator by mounting the RV-E2 robotic arm on a linear slide. A 24 DC motor, a servo controller and an incremental decoder, drive the linear slide. The overall steady-state accuracy of the manipulator is $\pm 0.2 \times 10^{-3}$ m. The manipulator meets general requirements with respect to hygiene and the operation under adverse greenhouse climate conditions (high relative humidity and high temperature).

5.3. The End-Effector

The end-effector contains the following parts: a gripper and suction cup to grasp the fruit and a thermal cutting device to separate the fruit from the plant. Figure 7 shows a close-up of the end-effector, including the gripper and the cutting device. The light weight camera mounted on top of the end-effector is not shown in this figure.

Essentially, the gripper used in the cucumber harvester is a modified version of the Mitsubishi motor gripper 1E-HM01. Design requirements for the modified gripper were that it should have sufficient grip on the fruit during cutting and transportation of the fruit to the storage crate. However, since we are dealing with a delicate product, mechanical stress that reduces the quality of the fruit had to be prevented. The required and permitted forces were determined empirically. During the harvest process the two fingers of the motor gripper, grip the stalk of the fruit. Once the fruit has been cut, the suction cup mounted below the gripper fingers immobilises the fruit during the transportation phase. Upon arrival at the storage crate, the fruit is put in a horizontal orientation and gently lowered into the storage crate. Then the gripper releases the fruit.

The design of the cutting device required additional attention. In horticultural practice, the grower uses a knife to cut the stalk of the cucumber fruit. By using the same knife over and over again, there is a risk of transportation of viruses from one plant to the other.

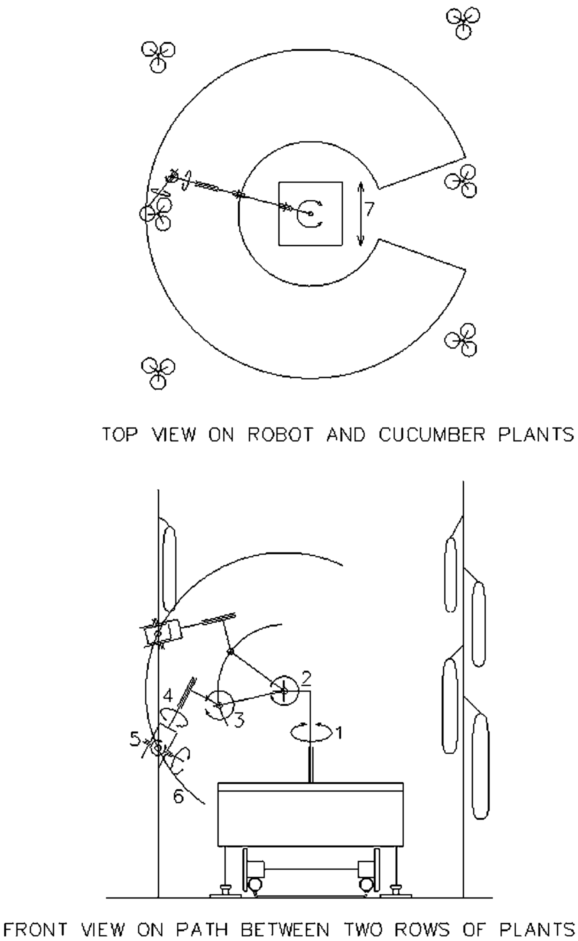

Figure 6. Manipulator geometry in relation to the working environment.

In horticultural practice this is prevented by immersing the knife in skimmed milk before each plant contact. For a robotics application this approach was not considered to be practical. For automated cutting of the cucumbers stalks a thermal cutting technique from medicine was adopted. It employs two electrodes carrying a high-frequency electrical potential. Once a stalk contacts the electrodes, it is cut by the HF current between the electrodes. Clearly, the high water content of the tissue material alleviates this process. This approach has two distinct advantages. First of all, during the cutting process viruses are killed due to the distinct temperature increase at the cutting surface. Secondly, the wounds of both the fruit and the plant are closed during the cutting process. This results in less water loss from the fruit and consequently a longer shelf life. Also, by closing the wounds, the plant is considered to become less vulnerable to fungal diseases. The method and cutting device have been patented (Van Kollenburg et al., 1999).

5.4. The Vision Systems

The harvest robot carries two camera systems. One camera is mounted on the vehicle on a rail that extends on both sides of the manipulator with a bend at the head-end of the vehicle. This construction offers the opportunity to use the camera for inspection of the crop on both the left-hand and the right hand side of the vehicle. Also, this camera is able to move independent from the manipulator. The other camera is a lightweight system mounted on top of the end-effector. Each camera system has a different task. The camera mounted on the vehicle is used for the detection of the fruit, determination of the ripeness and quality of the fruit and 3D localisation of the fruit for robot motion planning. The camera mounted on top of the end-effector is used for stereo imaging in the neighbourhood of the cucumber during the final approach of the cucumber with the gripper.

5.4.1. Detection of Fruit. Fruit detection is an intricate problem because the green cucumber fruit have to be found in a green plant environment. From the two main approaches, (a) recognition based on shape and (b) recognition based on spectral properties, the last seems to be the most promising. The camera system on the vehicle uses two synchronised charge coupled device (CCD)-cameras mounted onto one wide angle optical system. At a distance of 0.8 m, the average distance between the camera and the cucumbers, the field of view of the camera has a width of 1.0 m and a height of 0.7 m. Around the lens of the camera a circular xenon flash tube is mounted. The light intensity of the flash tube can be controlled and is far above the intensity of sunlight. Using a short exposure time of the CCD-cameras synchronised with a high intensity flash, the influence of natural sunlight on the image acquisition is minimised. The detection of the fruit is achieved by using different filters on each of the two cameras. One camera is equipped with a 850 nm filter, the other with a filter in the 970 nm band. Whereas leaves show approximately the same reflectance at 850 nm and 970 nm, the reflectance of cucumber fruit is at 850 nm significantly higher than at 970 nm (see Fig. 8). The filters

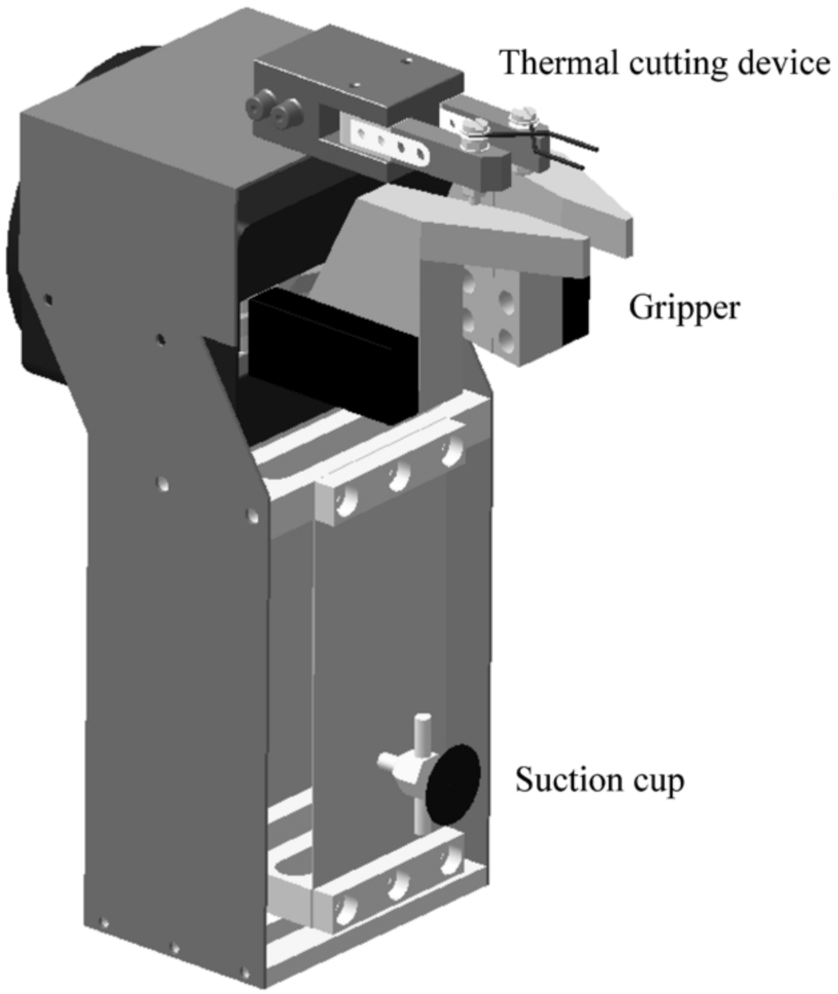

Figure 7. A close-up of the end-effector.

were selected according to the sensitivity of the cameras, the commercial availability and the bandwidth. As shown in Fig. 9 it is possible to detect the cucumber fruit in the green environment by combining the images of both cameras (Meuleman et al., 2000). The method has been patented (Kornet and Meuleman, 1999).

An experiment in a greenhouse was carried out in autumn 2000 to determine the accuracy of the vision system (Hemming and Van Der Meij, 2000). For this experiment 126 stereo-images of a plant stand of cucumbers were acquired. The crop was grown in the high-wire cultivation system. At the time of the experiment there were 106 ripe cucumbers in the analysed harvesting zone. Images were taken every 0.33 m using the camera mounted on the vehicle while moving the vehicle along the plant row. The relatively small motion of 0.33 m between two successive images ensured, that every part of the plant stand was three times in the camera's field of view but from different perspectives. By doing so, the effect of leaves or other plant-parts hiding the cucumbers from certain points of view was minimised. If a cucumber was detected in at least one of the three images it was counted as detected.

More than 95% of the cucumbers were correctly detected in this way. During the experiment 11 times leaves or parts of leaves were detected as fruit and 8 times stems were detected as fruit. The reasons for not detecting the fruit were mainly caused by illumination problems (reflection, flash intensity too high or too low), problems with separating two cucumbers, problems with separating fruit and stem, and by cucumbers completely hidden behind leaves. For the current stage

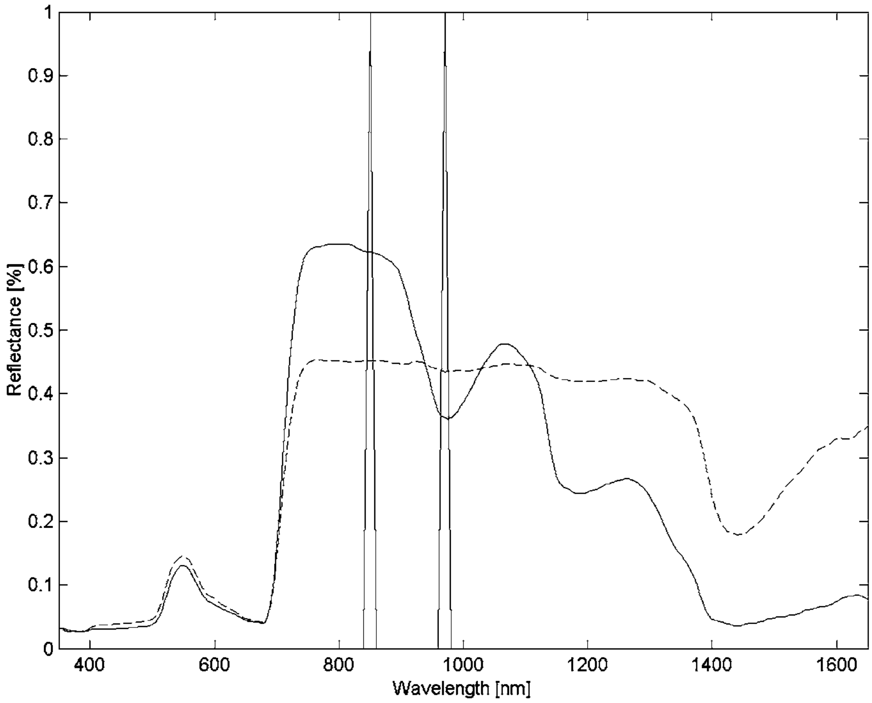

Figure 8. Reflectance of cucumber fruit (——) and leaves (---). Also indicated are the two band-pass filters at 850 nm and 970 nm.

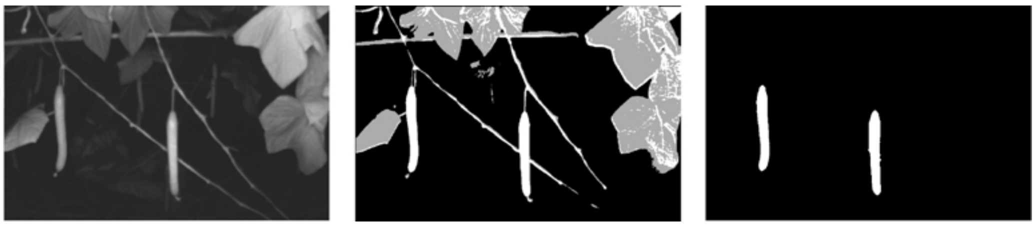

Figure 9. Detection of cucumber fruit using computer vision. Original image taken by the camera mounted on the vehicle (left), segmented image (middle) and detected fruit (right).

of the project these results were considered to be sufficient. Actually these results can stand a comparison with the performance of a skilled worker during manual harvest in a conventional cultivation system.

5.4.2. Determination of Ripeness and Quality. Cucumbers, as many other fruit, do not ripen at the same time and, consequently, every cucumber has to be evaluated for ripeness (classified) prior to harvesting. In practice, the main criterion for ripeness is the fresh weight of the cucumber, which should lie in the range of 300–600 g. So, to determine the maturity of cucumbers, an accurate non-destructive method for estimating the fresh weight was developed. The fresh weight of the cucumber is linearly related to the volume of the fruit. Research revealed that using a geometric model of the cucumber volume, the weight of cucumbers could be estimated with a correlation of 97%. A volume reconstruction using the distance transform yielded less accurate results (Langers, 1998a, 1998b). Figure 10 illustrates the approach.

5.4.3. 3D Localisation of Fruit. Both the camera on the vehicle and the camera on the end-effector are able to move on a rail. By taking two images from a slightly different perspective it is possible to perform a 3D-scene reconstruction using standard triangulation techniques (Meuleman et al., 2000). The accuracy of

Figure 10. Geometrical parameter determination and volume reconstruction using computer vision (left image: original image of cucumber, centre image: geometric model based on measurement of length, width and area, right image: volume reconstruction based on the distance transform of the silhouette).

the 3D reconstruction depends on the accuracy and repeatability of the camera shift and calibration of the camera model. The former was achieved by using low tolerance slides for shifting the cameras. For the calibration of the camera a procedure was used based on the work of Zhang (1999) and Heikkilä and Silven (1997). For objects at a distance of 0.6 m from the camera, the camera mounted on the vehicle produces a maximum error of 1.5×10^{-3} m in the x-plane and y-plane and about 7.5×10^{-3} m in the z-plane, perpendicular to the CCD-chip. Figure 11 shows a result of the 3D imaging with the camera mounted on top of the end-effector. It shows a close-up of the top of the cucumber fruit, the fruit stem, as well as the stem of the plant and a leaf stem. This image contains 3D information. The light-grey parts lie close to the camera, whereas the black objects lie further away from the camera.

5.5. *The High-Level Control System*

To use a human metaphor, high level control is all about a proper eye-hand co-ordination of the harvesting machine. The high-level control system includes

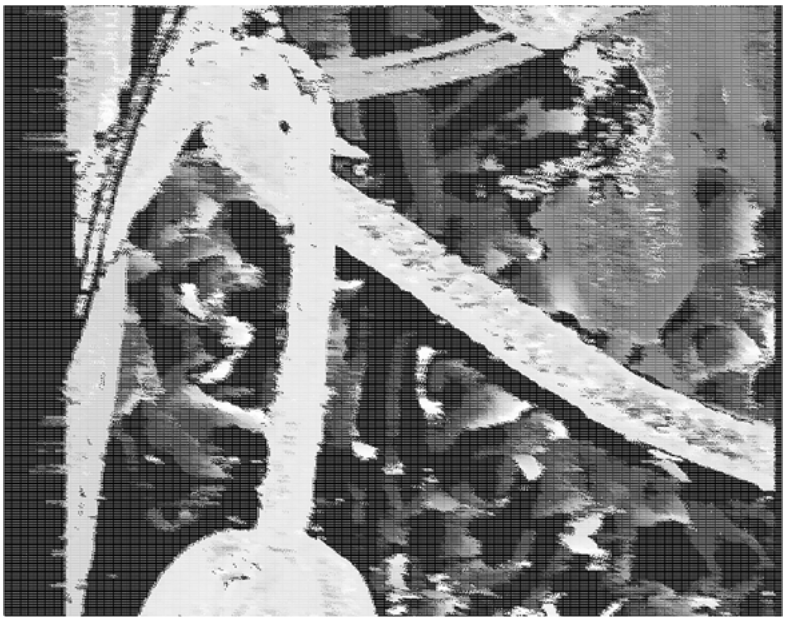

Figure 11. A 3D close-up of the top of a cucumber fruit (light grey: close to the camera, black: further away from the camera).

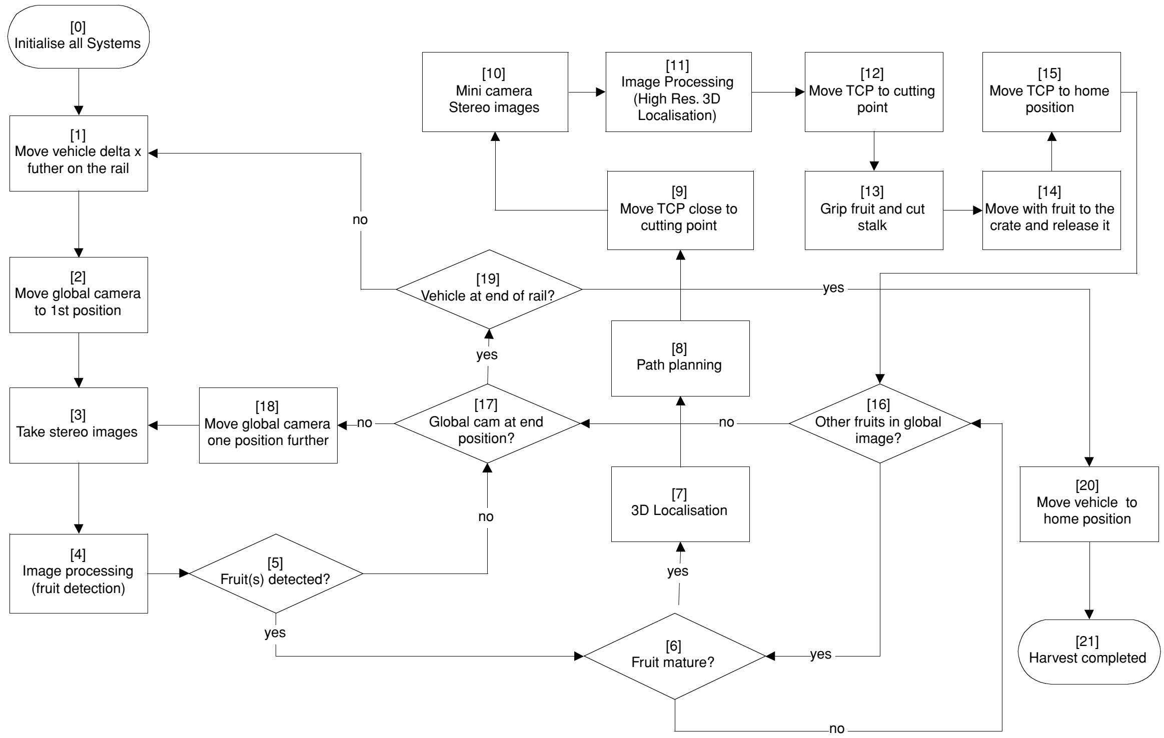

Figure 12. Task sequence of the harvest operation.

scheduling and execution of tasks such as data-acquisition, image analysis, motion planning and failure diagnosis and recovery.

A task sequence of the harvest operation is presented in Fig. 12. Approaching the cucumber during the picking operation is considered to be a two stage process. First, with the camera system mounted on the vehicle, the cucumbers are detected, their ripeness is assessed and their location is determined. In case it is decided to pick the cucumber, the images of the vehicle mounted camera are used for positioning the end-effector in the neighbourhood of the cucumber. Once the end-effector has arrived in the neighbourhood of the cucumber, then, using the camera system mounted on top of the end-effector, information of the local environment of the cucumber is obtained for the final accurate approach of the cucumber. The end-effector grips and cuts the stalk of the fruit. The detached fruit is fixed by the gripper and finally, the harvested fruit is moved to the storage crate. Obstacle avoidance motion planning is used both for the initial approach of the cucumber as well as the return journey of the harvested cucumber to the crate, to assure that other objects in the work space such as the robot vehicle itself but also stems and, if present, leaves and parts of the greenhouse construction are not hit. Clearly, the harvested cucumber increases the size of the end-effector, which should be considered during the return motion of the manipulator to the storage. A cucumber has on average a length of 0.3 m.

Eye-hand co-ordination heavily leans on the vision system and algorithms for collision-free motion planning of the robot arm. Figure 13 illustrates the components of a program that automatically generates collision-free motions for the manipulator of the cucumber picking robot adapted from Herman (1986).

5.5.1. World Description Acquisition. Collision-free motion planning relies on 3D information about the workspace in which the robot has to operate and about the structure of the robot. So, the first step in collision-free robot motion planning is the 3D *world description acquisition*. This 3D description is based on sensory information such as machine vision as described in Section 5.4. Also apriori knowledge about for instance the 3D kinematic structure of the robot is needed for collision-free motion planning. These data, originating from detailed CAD models, are stored, in a database for use during the *inverse kinematics* phase and the

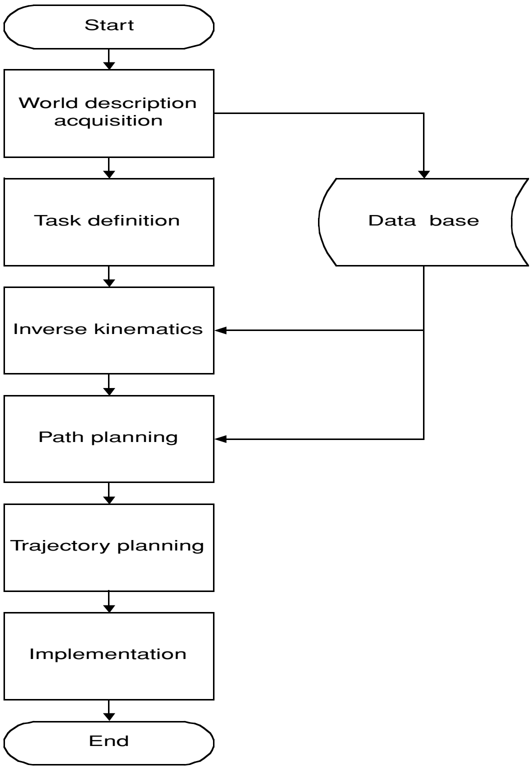

Figure 13. A program for automatic generation of collision-free motion paths.

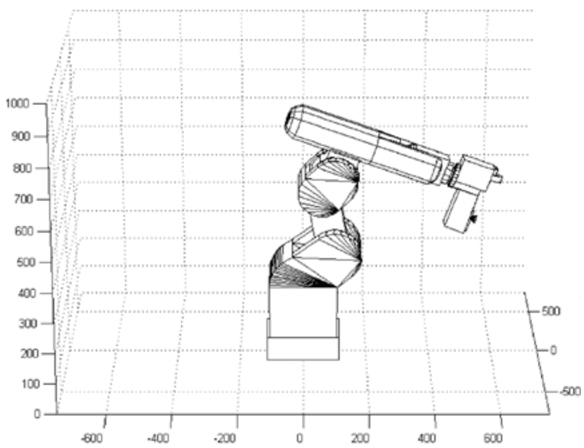

Figure 14. A 3D CAD model of the Mitsubishi RV-E2 manipulator.

path planning phase. Figure 14 shows a 3D model of the Mitsubishi RV-E2 manipulator used for that purpose.

5.5.2. Task Definition. With this information, during the *task definition* phase, the motion task of the robot is planned. It is decided which final position and orientation of the end-effector result in the best approach of the cucumber. Also specific position and orientation constraints are defined during this phase.

5.5.3. Inverse Kinematics. In the *inverse kinematics* phase the goal position and orientation of the end-effector, defined during *task definition*, are translated into a collision-free goal configuration of the manipulator in terms of a translation on the linear slide and 6 rotations of the joints (see e.g. Craig, 1989). This information will be used by the *path planner*. Additionally, the inverse kinematics algorithm is used to determine whether or not a detected ripe cucumber lies within the work space of the manipulator and can be harvested or not.

In case of the 6 DOF Mitsubishi RV-E2 manipulator an analytic solution of the inverse manipulator kinematics was obtained by Van Dijk (1999). For the 7 DOF manipulator, i.e. the Mitsubishi RV-E2 manipulator mounted on a linear slide, a straightforward analytic solution of the inverse kinematics does not exist due to the inherent redundancy in the kinematic chain. Schenk (2000) obtained a mixed analytic-numerical solution of the collision-free inverse kinematics of this redundant manipulator. Given the position of the ripe cucumber and obstacles in the workspace, the algorithm produces a collision-free harvest configuration of the manipulator. Also, it assures that the joints have sufficient freedom for fine-motion control in the neighbourhood of the cucumber. Figure 15 shows a top view of the manipulator in such a harvest configuration. The stars denote artificially generated obstacles.

5.5.4. Path Planner. The *path planner* uses a search technique to find a collision-free path from the start configuration of the manipulator to its goal configuration. The search for collision-free paths takes place in a search space that is different from the 3D-world space. In the motion planning system of the cucumber picking robot the search space is the so called configuration space. In case of the 7 DOF manipulator it is a 7 dimensional space spanned by the combination of 1 translation and 6 rotations.

Algorithms for performing fully automatic motion planning have been the object of much research. See e.g. Latombe (1991) and Hwang and Ahuja (1992) for an overview. A collision-free motion planner essentially consists of two important components: a

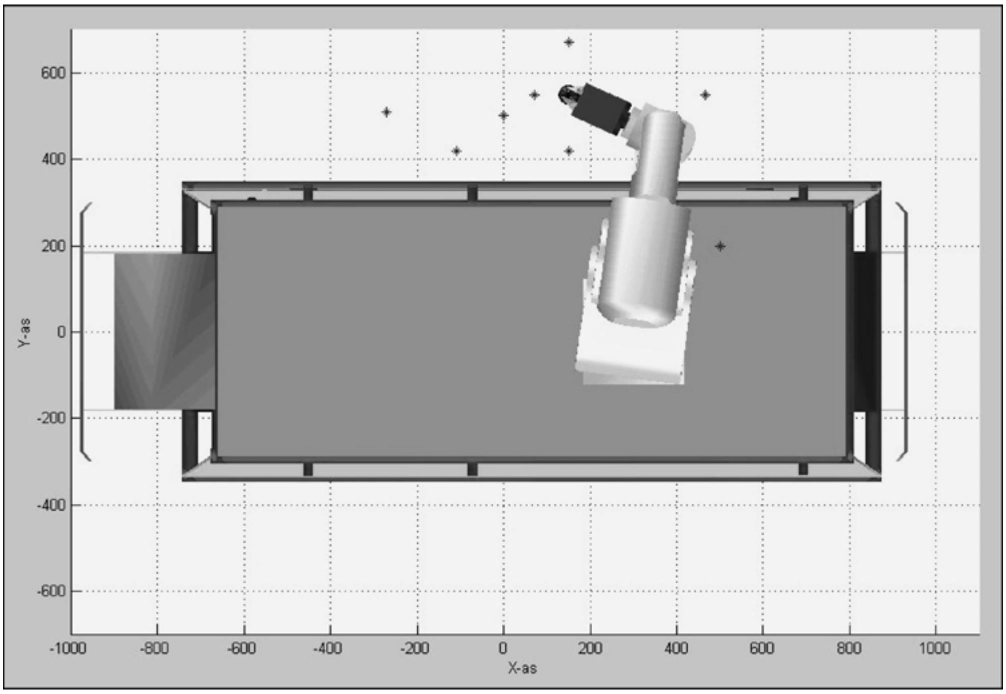

Figure 15. A collision-free harvest configuration of the 7 DOF redundant manipulator calculated with the inverse, kinematics algorithm with $*$ indicating artificially generated obstacles.

search algorithm and a collision detection algorithm. The search algorithm explores the search space, i.e. configuration space, for a feasible trajectory from the initial configuration to the goal configuration of the manipulator. The feasibility of each step in the search space is checked by a collision detection algorithm. This algorithm checks for collisions of the manipulator with other structural components such as the fruit, stems, but also the vehicle.

If a motion along a straight line in the configuration space from the start configuration to the goal configuration was found to be unfeasible, an A*-algorithm was used to find a feasible collision-free motion. For the A*-search the 7 dimensional configuration space of the 7 DOF manipulator was discretised by means of a fixed grid structure. The A*-algorithm is a best-first-search algorithm that searches a path from start to goal while minimising a cost function (Pearl, 1984; Kondo, 1991; Russell and Norvig, 1995). This cost function includes the cost of the path so far and an optimistic estimate of the cost from the current position to the goal. In this way, the A*-search strongly resembles dynamic programming. The A*-algorithm is both complete and optimal. Completeness of the algorithm assures that the algorithm finds a solution if one exists (Russell and Norvig, 1995). Optimality assures that the path obtained minimises the cost function used.

For collision detection an algorithm was implemented based on the ideas reported by Boyse (1979). This algorithm evaluates the intersection of surfaces of the robot model with the surfaces of other structural components in the workspace. Calculating the intersection of two surfaces essentially boils down to determining the intersection of all the edges of one surface with the other surface. All in all, collision detection is a computationally intensive task. Therefore, collision detection in a real-time application such as the cucumber robot, requires a trade-off between the desired accuracy of the collision detection and the available calculation time. The accurate CAD-model of Fig. 14 contains 600 triangular and rectangular surfaces. Collision checking with this model did not yield a feasible solution in terms of calculation time within a MATLAB environment. A factor 15 reduction in calculation time could be achieved by replacing the accurate manipulator model by a less accurate model built from so called oriented bounding boxes (OBB). This 3D OBB-model of the manipulator consisting of only 36 surfaces is shown in Fig. 16. Clearly, with the OBB-model some accuracy has been offered for the sake of calculation

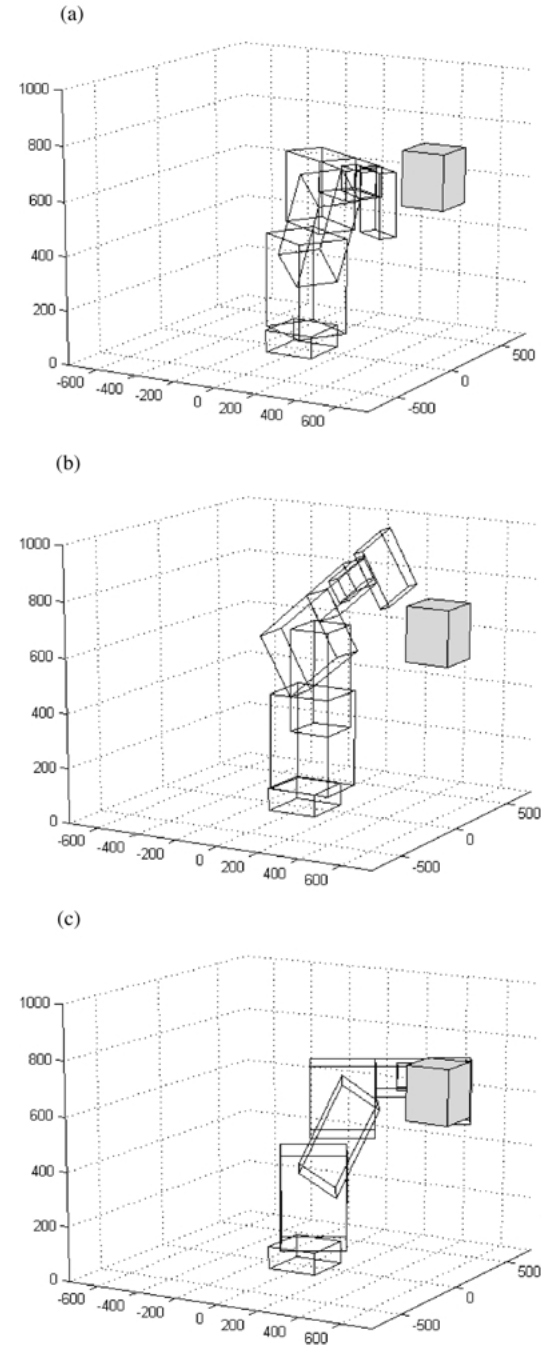

Figure 16. Three snap-shots of the collision-free motion of the RV-E2 manipulator: (a) and (c) are the initial and final configuration respectively.

speed. For the current investigations it was considered justifiable.

Figure 16 shows a collision-free motion of the RV-E2 manipulator in an artificial test environment, calculated with this path planner. The objective was to steer the manipulator to the opposite side of the box without hitting the box. To show the actual motion of the manipulator in the 3D-workspace is a bit difficult on paper. Essentially, the motion consists of an anti-clockwise rotation of the lowest joint while tilting the second and third joint backwards until the box has been circumvented. Then, the second and third joint tilt forward again to reach the goal configuration. Figure 16(a)–(c) try to visualise this motion.

5.5.5. Trajectory Planner. Once the collision-free path planning has been completed successfully, the trajectory planner converts the collision-free path into a trajectory that can be executed by the manipulator. Typically, the path planning process is concerned only with collision-free configurations in space, but not with velocity, acceleration and smoothness of motion. These factors are handled by the *trajectory planner* (Herman, 1986).

5.5.6. Implementation. The output of the *trajectory planner* includes the motion commands for the servomechanisms of the robot and actual *implementation* of the motion can take place. The motion is implemented in an open-loop fashion.

6. System Integration and Field Test

In autumn 2001 system integration took place and the robot was tested in an experimental greenhouse. With a success rate of 80%, i.e. 180 out of 225 cucumbers, field tests confirmed the ability of the robot to pick cucumbers without human interference. On average the robot needed 45 s to pick one cucumber. Both the detection of the cucumbers and the ripeness assessment performed as expected. The main part of the 20% failures were due to inaccuracies in the 3D position estimation. The origin of these inaccuracies is not yet known. In a small number of cases picking failed due to leaves hindering the motion of the manipulator and errors in the synchronisation of all joints during the motion of the manipulator. The thermal cutting device worked flawlessly.

7. Conclusions and Future Research

This paper reports on a modular concept of an autonomous robot for harvesting vegetable fruit suited for Dutch horticultural practice. Building such a robot is not just a matter of choosing a suitable mechatronic structure. We have shown that automation of the harvesting requires the adoption of a new high productivity cultivation system, the high-wire cultivation system. The high-wire cultivation system results in an open structure of the canopy, which makes it easier to detect and approach the fruit. We have also motivated that harvesting is more than just picking fruit. It also includes the transportation of considerable amounts of fruit to the central storage area. Based on simulations of the logistics and a trade-off between engineering and economics we were able to derive design specifications for the individual harvesting machines.

Then, we described the individual components of the modular harvest machine including the autonomous vehicle, the manipulator, the end-effector, the vision system and the high-level control system. In various experiments in the laboratory and the greenhouse the performance of the individual components have been assessed. The vehicle satisfied mechanical stability and motion accuracy. Both the accuracy and dexterity of the 7 DOF manipulator was found to be sufficient for picking cucumbers within the prescribed harvest region. The end-effector was able to handle the delicate produce without loss of quality. Moreover, the thermal cutting mechanism successfully prevented transportation of viruses from one plant to the other. The vision system detected more than 95% of the cucumbers in the greenhouse. Also the system was able to determine the weight and ripeness of the cucumbers. With the 3D vision systems it was possible to locate the cucumber in the 3D working environment. Algorithms for collision-free motion planning were implemented and tested with success. An algorithm was developed to calculate the collision-free inverse kinematics of the redundant manipulator. This algorithm is also used to determine whether or not the cucumber lies within the workspace of the robot.

The robot was tested in a greenhouse. With an average speed of 45 s per cucumber the robot was able to pick more than 80% of the cucumbers without human interference.

For autonomous operation with a cycle time of the 10 s or less, a fast and accurate eye-hand co-ordination is a point of major concern. Future research will therefore focus on improved hardware and software for 3D image processing and identification of various objects in the workspace of the robot. Also, fast motion planning will receive considerable attention. Emphasis will lie on efficient search algorithms and fast algorithms for collision detection. Results of research on computational geometry obtained throughout the last decade offer opportunities for reducing the calculation time of the collision detection task (see e.g. Lin and Gottschalk, 1998).

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