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A robot for harvesting sweet-pepper in greenhouses

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Abstract

This paper describes the results of the development of a robot for harvesting sweet-peppers in greenhouses. A description is given of the working environment of the robot and its design objectives. The base of the robot consists out of two carrier modules. On the first, the manipulator, the control electronics and the computers are located. To assure maximum flexibility the realized manipulator prototype has nine degrees-of-freedom. On the second, the sensors and illumination are placed. The coupled modules can move in between the crop rows on the greenhouse rail system. The heights of the modules can be adjusted to match the height of the crop. On the sensor carrier module two 5 megapixel colour cameras and a Time of Flight camera are installed. The colour images and three dimensional (3D) data were calibrated and registered. Around the sensors, a lighting rig is placed to illuminate the scene. The sensor system is mounted on a linear motorized slide and can be horizontally moved in and out of the workspace of the manipulator. Machine vision software localises ripe fruits and obstacles in 3D. For fruit detection different approaches have been developed. One option is to initiate fruit detection by simple red colour blob detection. Another option is to perform fruit localization in two sequential steps. First Regions of Interest in the RGB image are selected which is suspected to contain target fruits. Next the fruit localization is performed in the corresponding 3D data, based on 3D point cloud template matching. Obstacle detection algorithms are used to localise plant stems and non-target fruits using the small baseline stereo images. In order to harvest the fruits, a motion planning module assures a collision free path for the manipulator to position the end-effector at the harvesting position. Two different types of end-effectors were designed and tested. The “Fin-Ray gripper” features a combined grip and cut mechanism. This end-effector first grips the fruit and after that the peduncle of the fruit is cut. The “Lip-type end-effector”, first stabilizes the fruit using a suction cup after which two rings enclose the fruit and cut the peduncle of the fruit. Both end effectors have a miniature RGB and a ToF camera for refining the fruit position and to determine the fruit pose. The main software platform of the robot was implemented for the Linux operating system and uses the open source middleware Robot Operating System (ROS). The coordinating control structure is based on a finite state machine and includes diagnostic tools and performance measures. The system was tested under simplified laboratory conditions in 2013. During these early tests 189 out of 194 fruit could be detected (97%), 167 fruits could be reached (86% of all fruits) and 154 picked (79% of all fruits). In spring 2014 final system integration took place. In a commercial greenhouse it was proven that the system is able to harvest pepper fruits fully autonomously.

Keywords: horticulture, automation, field-test, fruit-detection, obstacle-detection

1 Introduction

Currently there is a high demand to automate labour in modern greenhouses. The availability of skilled labour that accepts repetitive tasks is decreasing rapidly. Furthermore, the climate conditions of the working environment in greenhouses are harsh. A comprehensive review about the state-of-the-art in robotic fruit harvesting and challenges ahead is recently published by Bac et al. (2014) and shows that over the past three decades research has been carried out for about 50 systems the harvest e.g. apples, oranges, tomatoes, cucumbers strawberries and melons. The European FP7 project CROPS (CROPS-project, 2014) is developing a modular robotic system for several different tasks (harvesting apples, grapes, sweet peppers and spraying). The objective of this paper is to describe the major hardware and software components of the robot developed for harvesting sweet-peppers (*Capsicum annum*) in a greenhouse.

2 Working environment of the robot, design objectives and requirements

The system for robotic harvesting sweet-peppers is designed for the current common practice V-cropping system of sweet-peppers in the Netherlands. This practice uses a strategy where the plants are grown in heated glasshouses on gutters with stone wool substrate slabs with automatic water and nutrient supply. A typical set-up uses 8 m wide compartments which contain 6 plant rows with a row distance of 1.33 m and an average plant distance in the row of about 0.2 m. Heating pipes mounted on the ground are used as a rail for crop maintenance trollies and to transport harvested fruit. Each main stem of the plant is supported by a plastic wire which is wrapped in intervals around the stem to support the plant. 20 weeks after planting plant length is about 160 cm. This length is doubled at week 40, the end of the season. In summer, the minimum temperature in the greenhouse is about 18 degrees Celsius (°C) and can reach up to 35 °C. In autumn, the minimum temperature can be as low as 13 °C. Relative humidity (RH) is highest in the early morning hours where the level can exceed 90%. Most of the time RH is above 70%. First of all, the robot is required to be able to operate in the environment described. Detection and localization of the fruits to harvest is as well mandatory as the possibility to reach and detach the fruit. The most important variable requirement is that the robot must have a high success rate for fruit harvesting followed by the requirement that the robot “must avoid stem damage” and “must not damage fruits”. The requirements for a robotic system in this working environment have been comprehensively described in Hemming et al. (2011).

3 The modular robot system

3.1 Hardware modules

Figure 1 shows a the complete integrated robotic system inside a sweet-pepper greenhouse. The system is powered with a cable connected to the power grid. In the following sections the different hardware modules will be described.

3.1.1 Carrier platform

The base of the robot consists out of two carrier modules, a manipulator module and a sensor module (Figure 1). 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, sensors for fruit and obstacle detection and illumination are placed. The coupled modules can move in between the crop rows on the greenhouse rail system. The heights of the modules can be adjusted by inserting additional metal frame segments to match the height of the ripe fruits in the crop.

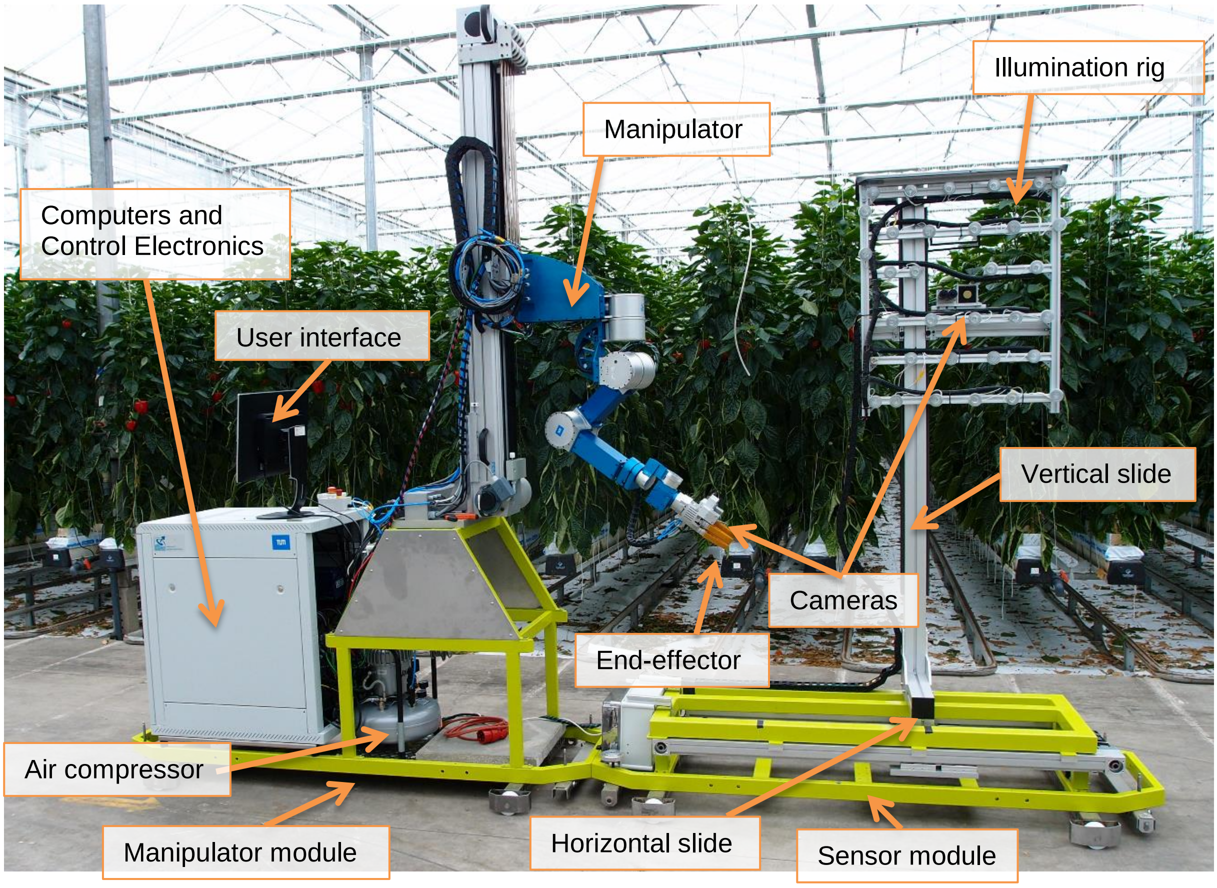

Figure 1: Integrated robotic system for harvesting sweet-pepper fruit.

3.1.2 Robotic manipulator

A 9 degree of freedom (DoF) redundant and modular manipulator turned out to be the most promising concept for this cluttered and space limited application and was realized (Bauer et al., 2013, 2014; Schuetz et al., 2014). Figure 2 shows a rendering of the 9 DoF robotic manipulator. As the other applications of the CROPS project (apple harvesting, precision spraying) have different requirements the 9 DoF version can easily be converted into a 7 DoF version with less complexity. The 7 DoF version is shown in Figure 1. To fulfil the requirements for the environmental conditions stated above the manipulator has sealed drive modules and is splash-waterproof.

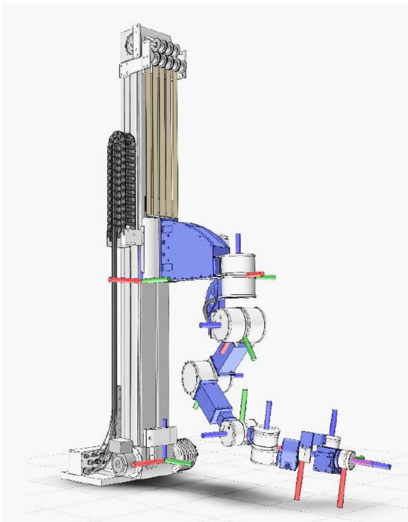

Figure 2: Rendering of the 9 DoF robotic manipulator

3.1.3 Overview cameras and illumination

On the sensor module (Figure 1) two 5 megapixel 2/3'' CCD RGB colour cameras (Prosilica GC2450C, Allied Vision Technologies GmbH, Germany) with a horizontal baseline of 0.033 m are installed. In addition a 3D Time of Flight (ToF) camera (Swiss Ranger SR400011, Mesa, Switzerland) is mounted close to the colour cameras (Figure 3). Around the sensors, a lighting rig was placed to illuminate the scene. This rig consists out of a 5x6 grid of 50 watt, 230 volt halogen lamps. The sensor system is mounted on a linear motorized slide and can be horizontally moved in and out of the workspace of the manipulator. In this way, the sensors and manipulator can share the same workspace without colliding during operation.

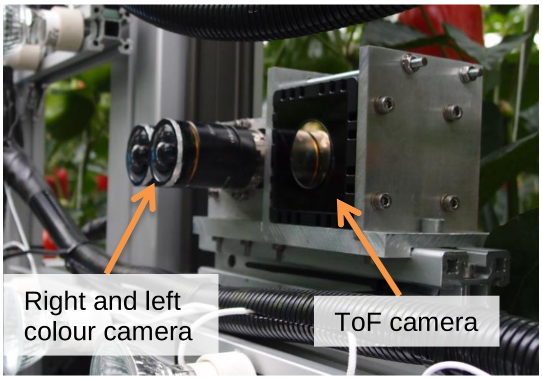

Figure 3: Colour camera stereo set-up and Time of Flight camera on the main sensor rig.

3.1.4 End-effector and mini cameras

Two different types of end-effectors for detaching sweet-pepper fruits from the plant were realized. The first one, the "Fin-Ray gripper", features a combined grip and cut mechanism. This end-effector first grips the fruit after the peduncle is cut. (Gauchel & Saller, 2012). The second end-effector, the "Lip-type end-effector", first stabilizes the fruit using a suction cup after which two rings with a lip each enclose the fruit and cut the fruit peduncle. Both types of end effectors have integrated LED illumination as well as two cameras; 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).

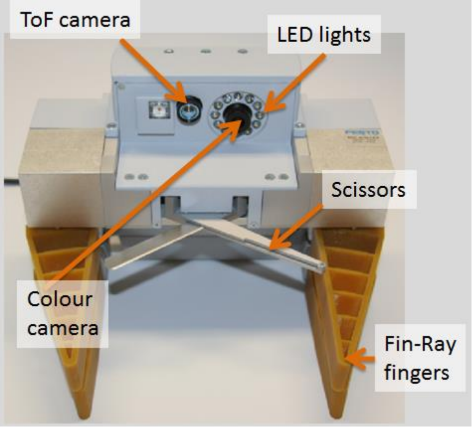

Figure 2: Fin-Ray type end-effector

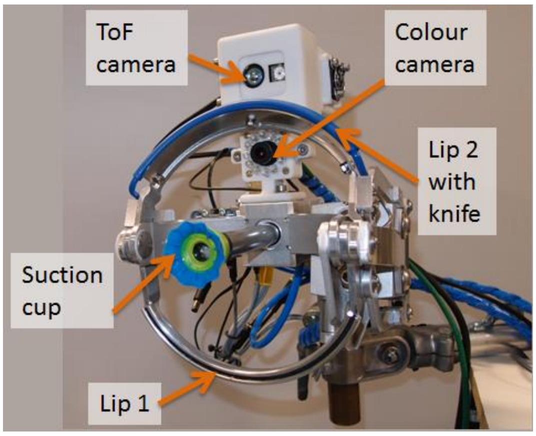

Figure 3: Lip-type end-effector

3.1.5 Computational hardware and communication interfaces

For the high level control and to interface the various sensors an off-the shelf industrial PC is used. The sensors are connected to the system by either gigabit Ethernet (GigE) interface or USB connection. The controller of the robot manipulator is realized by using the xPC target real-time software environment from MathWorks (Natick, USA) on a dedicated x86-based PC. The drive units and end-effectors of the manipulator are connected to the real-time PC using EtherCAT and CAN-bus interfaces. The real-time unit is connected to the ROS network (see section 3.2) by an Ethernet (UDP) link. Selected sub tasks like the computational intensive image processing can be executed on an additional laptop which is linked to the system by Ethernet using the master slave functionality of ROS. For the low level control of the end-effectors (open and close gripper, suction, open and close knife, status feedback) microcontrollers are used. These controllers communicate with the system by digital I/O and CAN interface.

3.2 Software modules

Most software development of the robot is done using the Robot Operating System (ROS, version Groovy, C++) an open source robot middleware running on Linux (Ubuntu 12.04). ROS encourages object-oriented development and manages parallel execution of software modules, denoted nodes, and administrates Ethernet based communication between nodes (message passing). Details on the software framework developed for this application are described by Barth et al. (2014).

3.2.1 Fruit detection, maturity determination and 3d localization

Fruit detection and localization take place at two different levels. First, a side-view image of the crop row is taken by the cameras on the sensor rig. The colour image of the camera mounted next to the ToF camera is pixel-wise registered to the ToF image. The method applied is based on the assumption that the objects in the scene belong to the same plane. As a result, the colour data match its corresponding 3D measurements from the ToF camera. Figure 4 shows the registered images of the colour camera (left) and the corresponding distance image of the Tof camera (right) of an example scene with artificial fruit and plants in the laboratory. Fruit ripeness is determined by analysing the level of red coloration of the sweet-pepper fruit. For fruit detection different approaches have been developed. One approach is by simple red colour blob detection. This blob detection is followed by morphological image processing operations to clean up noise. In the next step the corresponding x,y and z real world values from the ToF sensor is extracted for the centre of each detected fruit (Figure 4, middle). Another approach is to localize fruit with an algorithm that is using two sequential steps. This algorithm first selects regions of interest in the RGB image which are suspected to contain target fruits. Next the fruit localization is performed in the corresponding 3D data from the ToF camera, based on 3D point cloud template matching. Moreover an adaptive sensor fusion algorithm was developed and implemented (Vitzrabin & Edan, 2013). It provides one output based on multiple feature data inputs, such as the two different fruit detection algorithms described above.

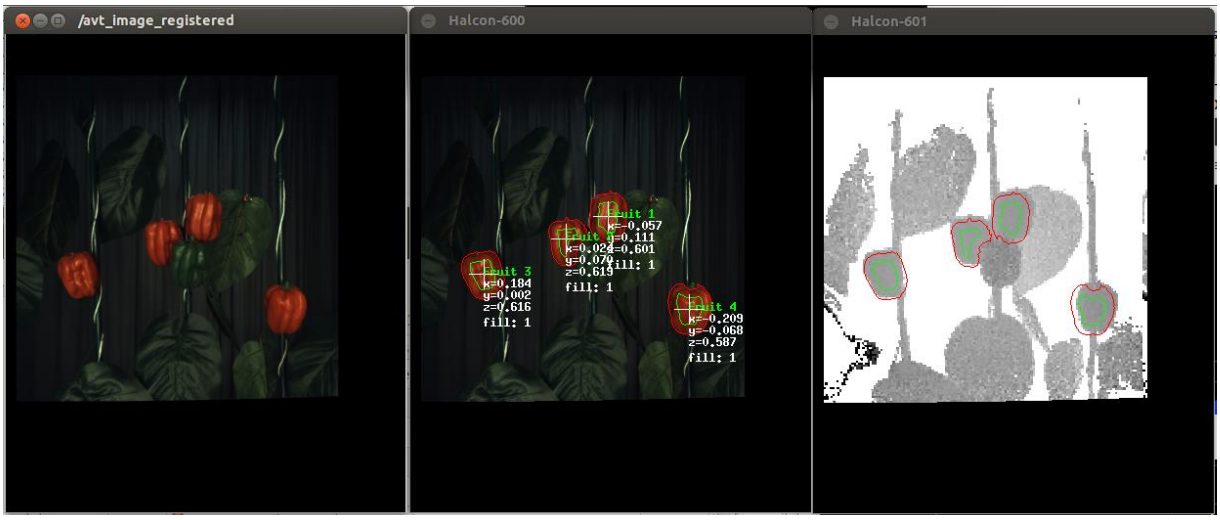

Figure 4: Registered images of the colour camera (left) and the corresponding distance image of the Tof camera (right) and the localized fruits (middle)

The position obtained from the first level localization can differ with the real fruit position due to noise in the ToF camera and/or calibration and registration inaccuracies. Therefore a second level for fruit detection and localization was added. On the second level the cameras on the end-effector are used to refine the found fruit position on the first level. For this purpose the end-effector is positioned 25 cm in front of the detected fruit position and a colour and ToF image from the cameras on the end-effector are acquired. As for the overview cameras fruit detection in these images is performed by red colour blob detection. In the next step the corresponding x,y and z real world coordinates from the ToF camera is extracted for the centre of each detected fruit (Figure 5). From the data of the cameras on the end-effector not only the position but also the fruit orientation is estimated. This information can be used to determine the best grasp pose for the end-effector (Eizicovits & Berman, 2014). The target robot position and orientation to grip and detach the fruit is updated with this information.

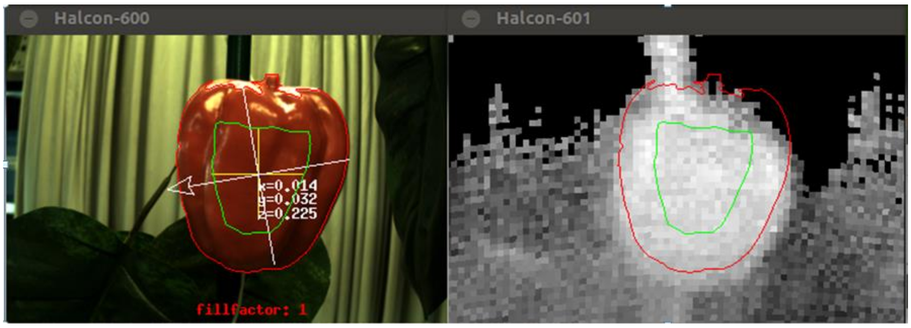

Figure 5: Images of the cameras on the end-effector. Registered colour image (left), registered ToF distance image (right)

3.2.2 Obstacle localization

Obstacles block access to the fruit and reduce visibility. Fruits can be occluded by other fruits and leaves causing difficulties for fruit localization (Kapach et al., 2012). The integrated obstacle detection is currently able to detect and map hard obstacles such as the plant stems and non-target fruits. The method makes use of a set of small baseline stereo images acquired by the two overview colour cameras on the main platform. The small baseline of 3.3 cm was taken to improve matching score of stereo-vision and to decrease occlusion of the stem. Support wires were used as a visual cue to localize the plant stem because wires are twisted around the stem and can be distinguished from the vegetation. More details on the obstacle localization are described in Bac et al. (2014) and Bac et al. (2013).

3.2.3 Motion planning

A motion planner that detects and prevents robot self-collisions and collisions with other parts of the platform is implemented in the real time xPC controller of the manipulator (Baur et al., 2014). After receiving a goal position, the controller checks the path execution and reports problems to the main control software. A software module which uses the Rapidly-exploring Random Tree (RRT) robotic path planning algorithm for motion planning is under development for this application within the ROS MoveIt framework.

3.2.4 Mission control and task planning

The coordinating control structure of the robot is based on a finite state machine and includes diagnostic tools and performance measures registration of the harvesting operation. The state machine based framework has proven to be useful for coordinating and sequencing of operations. It logically arranges the computations to be performed by all ROS nodes. The algorithmic sequence to be executed is defined with a flowchart, which can be directly translated into the state machine. It contains three main functionalities: initialization, sensing and harvesting. The detailed flowchart for the pepper harvesting application is given in Barth et al. (2014).

4 Experimental results

The system was tested under simplified laboratory conditions with unoccluded single fruits in 2013. During these early tests 189 out of 194 fruit could be detected (97%), 167 fruits could be reached (86% of all fruits) and 154 picked (79% of all fruits). For images acquired with the overview cameras in a commercial greenhouse a true positive rate for fruit detection of 0.87 could be achieved (see Table 1).

Table 1: Fruit detection summary. True positive rate TPR) and false positive rate (FPR)

Number of images	Number of fruits	TPR	FPR
221	479	0.87	0.05

In spring 2014 the final integrated system was tested in a commercial sweet-pepper greenhouse (Figure 6) and it was proven that the system is able to harvest pepper fruits fully autonomously. The final performance determination of the system is still ongoing.

Figure 6: Harvesting robot in the greenhouse

5 Conclusions and outlook

This paper reports on a modular concept of an autonomous robot for harvesting sweet-pepper in the real world environment. The objective to build a system which is able to fully autonomously harvest fruits was reached. Due to the complexity of the task and the limited visibility of the targets multiple sensors are used for fruit and obstacle localization. One of the major parts of the system is a redundant and modular manipulator with 9 DoF. Two types of end-effectors to detach fruit have been developed and tested. Concerning software, the ROS framework has worked to satisfaction and due to its modular nature has simplified integration of components developed by different project partners. Future work is to determine the performance of the robot in terms of harvest success rate, cycle times and causes of failures.

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