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CROPS

Intelligent sensing and manipulation for sustainable production and harvesting of high value crops, clever robots for crops.

Final Report
Sweet-Pepper Harvesting Robot

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Nederlandse Samenvatting

Dit rapport beschrijft de resultaten van de verschillende laboratorium- en kasexperimenten uitgevoerd met de verschillende prototypes van de paprika oogstrobot ontwikkeld in het CROPS project.

In juni en juli 2013 zijn een aantal laboratoriumexperimenten uitgevoerd met het systeem zoals beschreven in deliverable D5.6. Dit systeem maakte gebruik van het eerste prototype van de manipulator. De belangrijkste doelstellingen van de laboratoriumexperimenten waren om gegevens over de prestatie en nauwkeurigheid van de verschillende subsystemen te krijgen. Voor de prestatie-analyse van alle basismodules van het systeem werden 194 vruchten in 45 scènes benaderd. Tijdens deze proeven konden 189 van de 194 vruchten worden gedetecteerd (97%), konden 167 vruchten worden benaderd (86% van alle vruchten) en 154 geplukt (79% van alle vruchten). De belangrijkste redenen voor mislukte plukhandelingen waren manipulatorproblemen (falende remmen) en onnauwkeurige vruchtpositiebepaling. Na het uitvoeren van de laboratoriumexperimenten is een lijst met suggesties voor verbeteringen met het consortium besproken.

Voor de kasexperimenten zijn een aantal modules vervangen door een nieuwere versie, zoals de definitieve manipulator, een nieuwe belichtingsunit voor de camera's en nieuwe prototypes van de twee end-effectors. De eerste resultaten na de integratie van geavanceerde motion planning modules, vruchtlokalisatiemodules en sensorfusiemodules, die ontwikkeld werden in de andere werkpakketten, bleken onvoldoende. Daarom werden met het oog op de uiteindelijke praktijkexperimenten eenvoudigere maar robuustere versies in het systeem geïntegreerd. Tussen mei en juli 2014 zijn kasexperimenten met de geïntegreerde paprika oogstrobot in een gewas met rode paprika's uitgevoerd bij een Nederlandse teler. Tijdens deze experimenten is de haalbaarheid van het autonoom oogsten van paprika's bewezen. De experimenten hebben een schat aan informatie opgeleverd. Er zijn een aantal problemen geconstateerd die de beperkte prestaties veroorzaakten. Het percentage van foutloos en zonder beschadiging geoogste vruchten in een niet aangepast praktijkgewas lag slechts tussen 2% en 6%. Na het vereenvoudigen van het gewas door het verwijderen van vruchtclusters en het verwijderen van bladeren, die de vrije zicht van de sensoren op de vruchten beperkten, werd het succespercentage verbeterd tot 33%. De gemiddelde doorlooptijd om een vrucht te plukken was 94 seconden. Het pluksucces en de doorlooptijd zijn in de praktijk nu nog onvoldoende, maar met de eerste werkende paprika-oogstrobot in een realistische omgeving is er in dit project een belangrijke mijlpaal bereikt. Ook zijn experimenten gedaan met een in dit project nieuw ontwikkelde methode, die bij het grijpen van de vrucht rekening houdt met de positie van de hoofdstengel van de plant. Door het gebruik van deze methode daalde de beschadiging van de stengel door de robot. Voor de Lip-type end-effector is door gebruik van deze methode ook het grijpsucces toegenomen. De verwachting is dat door de nieuwe inzichten opgedaan tijdens de kas experimenten en een succesvolle integratie van de nieuwste modules, voor het waarnemen, motion planning en kunstmatige intelligentie de prestaties van het systeem aanzienlijk kunnen verbeteren. Deze modules waren tijdens de kas experimenten nog in ontwikkeling en nog niet beschikbaar.

De paprika oogstrobot is meermaals tijdens de looptijd van het project gedemonstreerd, zowel in het laboratorium als in een kas. In juli 2013 is een eerste versie van het volledig geïntegreerde systeem met het eerste prototype van de manipulator in het laboratorium van Wageningen UR gedemonstreerd aan de leden van begeleidingscommissie (BCO). Daarnaast is de robot in verschillende stadia van de ontwikkeling aan bezoekersgroepen gedemonstreerd. De demonstratie van het systeem in de kas voor de BCO vond plaats op 3 juli 2014. De robot is ook getoond aan het wetenschappelijk publiek tijdens afsluitende CROPS workshop op 8 juli 2014 tijdens de Agricultural Engineering Conference (AgEng 2014) in Zürich, Zwitserland. De robot is ook live gedemonstreerd voor een breed publiek op een speciale georganiseerde informatie en demonstratie dag in Nederland op 4 september 2014. Verschillende videoclips van de paprika oogstrobot in de kas zijn geproduceerd en zijn te downloaden op de video sectie van de projectwebsite: http://www.crops-robots.eu/.

English summary

This report describes and compiles the results of the different laboratory and greenhouse experiments carried out with the different prototypes of the sweet-pepper harvesting robot developed in the CROPS project.

In June and July 2013 a number of laboratory experiments with the first fully integrated system have been carried out. The laboratory experiments were carried out with the robot prototype with all modules integrated as described in CROPS deliverable D5.6. This system made use of the first manipulator prototype. The major objectives of the laboratory experiments were to gain data on the performance and accuracy of the different subsystems with special focus on the manipulator. A total of 194 fruit in 45 scenes were approached for performance analysis of integration of all basic modules. During these 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). Main reasons for unsuccessful picks were manipulator arm collapses (unsufficient brakes) and inaccuracies in the fruit depth determination. After conducting the laboratory experiments a task list and suggestions for improvements was discussed with the consortium.

For the greenhouse experiments a number of modules were replaced by their final versions, such as the final manipulator prototype, a new light rig for the cameras on the sensor module and new prototypes of the two different end-effectors. First results after the integration of advanced motion planning modules, fruit localization modules and sensor fusion modules developed in the other workpackages turned out to be insufficient. Therefore simple but robust versions only were integrated in the system for the purpose of the final experiments. Between May and July 2014 greenhouse experiments with the integrated pepper harvester were carried out in a red colored sweet-pepper crop grown in a Dutch commercial greenhouse. During these experiments the robot successfully demonstrated its ability to localize ripe fruit and to harvest pepper fruits fully autonomously. However, there were several difficulties noted which caused limited performance. The experiments revealed that harvest success in an unmodified crop was only between 2% and 6%. After simplifying the crop by removing fruit clusters and occluding leaves harvest success improved up to 33%. The average cycle time to pick a fruit was 94 seconds. Additionally, a novel stem-dependent determination of the grasp pose method was evaluated. This indicated that by using this feature the plant stem damage decreased. For the Lip-type end-effector the grasp success increased using that feature. It is expected that using the new insights gained during the greenhouse experiments and a successful integration of the latest modules developed in the project for sensing, motion planning and artificial intelligence can significantly increase the performance of the system. These modules were finalized only in parallel with the greenhouse experiments. Thus, due to in parallel carried out work, time restrictions and resource limits and the availability of a sweet-pepper crop in the greenhouse, this advanced state of integration was not achieved completely.

The selective sweet-pepper harvester was demonstrated several times during the project in the laboratory as well as in the greenhouse and at couple of other events. In July 2013 an early stage demonstration event of the fully integrated system with the first manipulator prototype was held in the laboratory of Wageningen UR for the members of the growers advisory board. Moreover Wageningen UR presented different stages of the development of the pepper harvesting robot system in the laboratory to groups of visitors. The final demonstration of the system in a greenhouse for the growers advisory board took place on July 3, 2014. The sweet-pepper robot was demonstrated to the scientific community during the final Crops workshop on July 8, 2014 at the Agricultural Engineering conference (AgEng 2014) in Zürich, Switzerland. The robot was also live demonstrated to the broader public at a special organized information and demonstration day in The Netherlands on September 4, 2014.
Several video clips of the sweet-pepper robot operating in the greenhouse were produced and diss-eminated and are available for download in the video section of the Crops public website: http://www.crops-robots.eu/.

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1 Introduction

This report describes and compiles the results of the different laboratory and greenhouse experiments carried out with the different prototypes of the sweet-pepper harvesting robot developed in this project. In June and July 2013 a number of laboratory experiments with the first fully integrated system have been carried out. In February 2014 the final prototype of the manipulator was integrated in the sweet-pepper harvesting platform. Between May and July 2014 greenhouse experiments were carried out in a commercial Dutch greenhouse.

2 Material and Methods

2.1 Robot set-up

The laboratory experiments were carried out with the robot prototype with all modules integrated as described in CROPS deliverable D5.6 (Figure 2-1). This system made use of the first manipulator prototype. For the greenhouse experiments a number of modules were replaced by more advanced versions, such as the final manipulator prototype, a new light rig for the cameras on the sensor module and new prototypes of the two different end-effectors. First results after the integration of advanced motion planning modules, fruit localization modules and sensor fusion modules turned out to be unpredictable and unstable. Therefore simple but robust versions were integrated in the system for the purpose of the final experiments. The system is described in Hemming et al. (2014b) and Bac et al. (2015) in the following only a brief summary is given. The base of the robot consists out of two carrier modules. On the first carrier module 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 carrier module, 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 color cameras and a Time of Flight camera are installed. The color 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. Figure 2-2 shows an overview photo of the final robot. Figure 2-3 to Figure 2-7 show different modules of the robot.

Figure 2-1: Prototype of the sweet-pepper harvesting robot as used for the laboratory experiments.

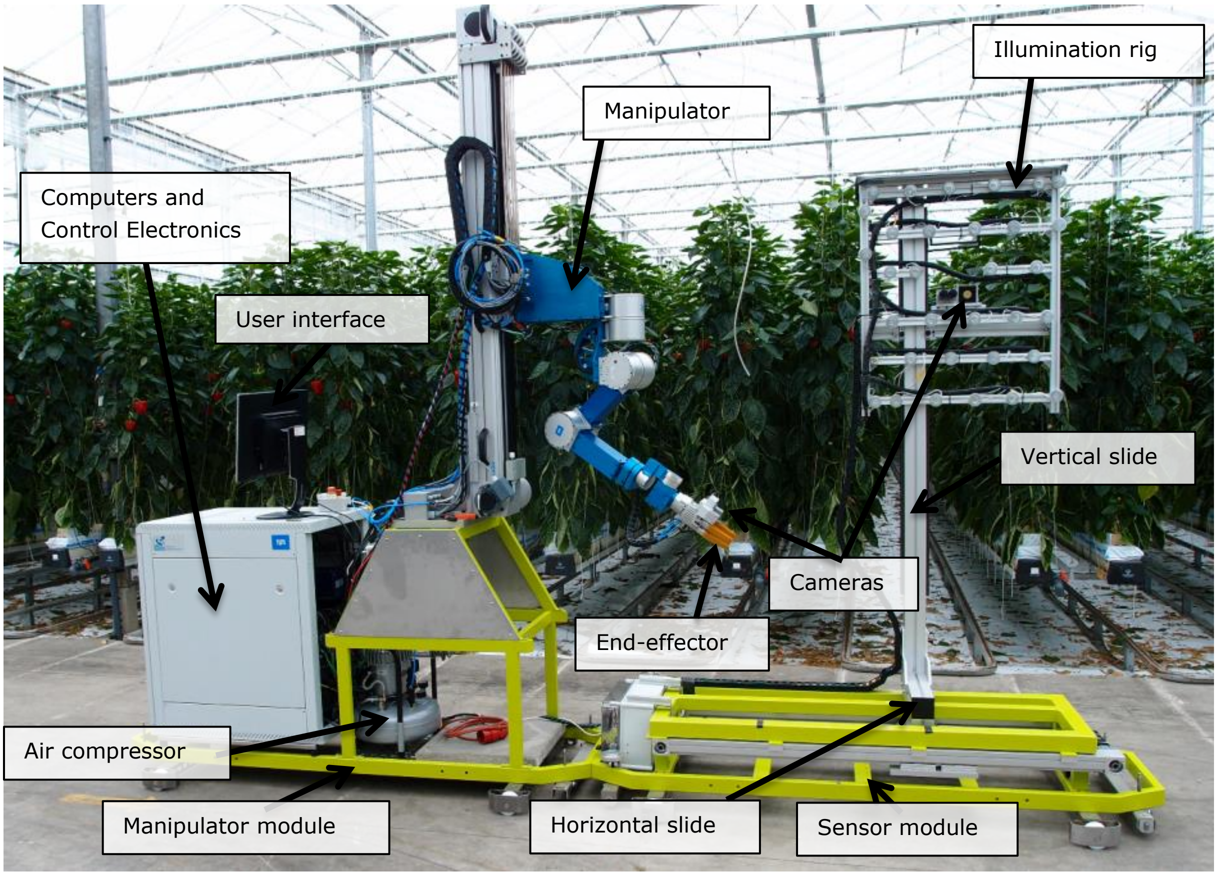

Figure 2-2: Final integrated robot for harvesting sweet-pepper fruit as used for the greenhouse experiments.

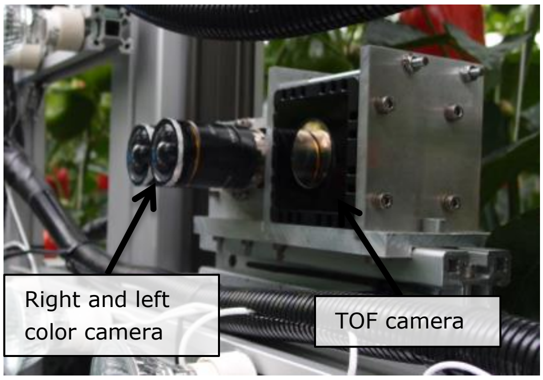

Figure 2-3: Color camera stereo set-up and Time of Flight camera on the main sensor rig.

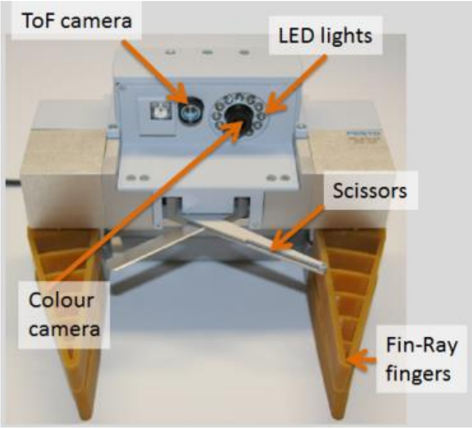

Figure 2-4: Fin-Ray type end-effector

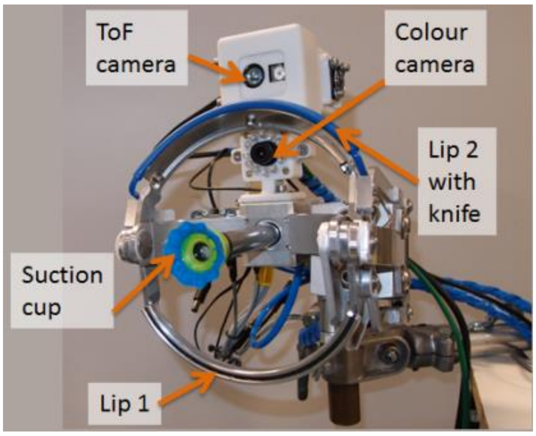

Figure 2-5: Lip-type end-effector

A dutch patent was requested for the "Lip-type end-effector". The patent request is registered under N2013066. Some of the drawings used in the patent can be found in Figure 2-7.

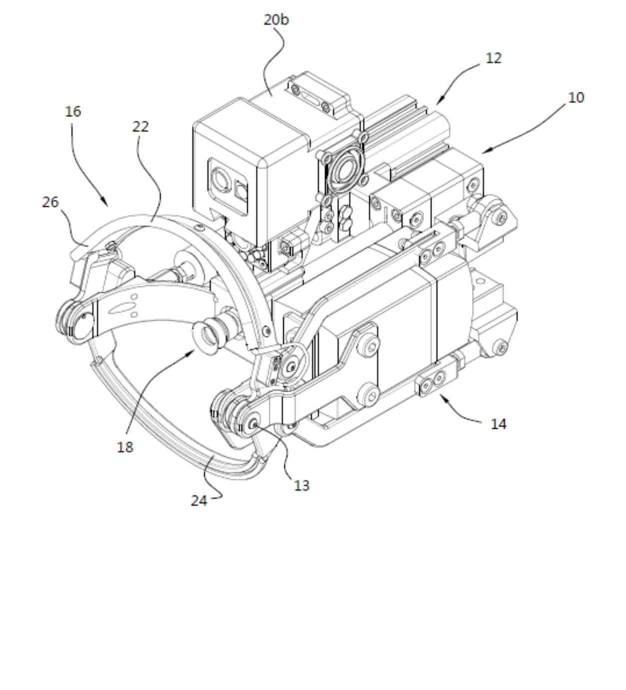	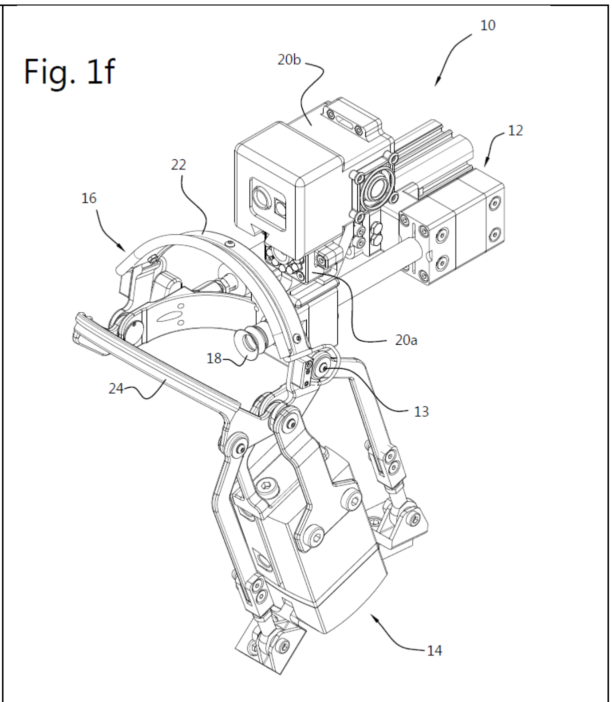
Harvest device approaching a fruit	Harvest device cutting the fruit blind

Figure 2-6: Drawings used in "Harvest device" Dutch patent N2013066

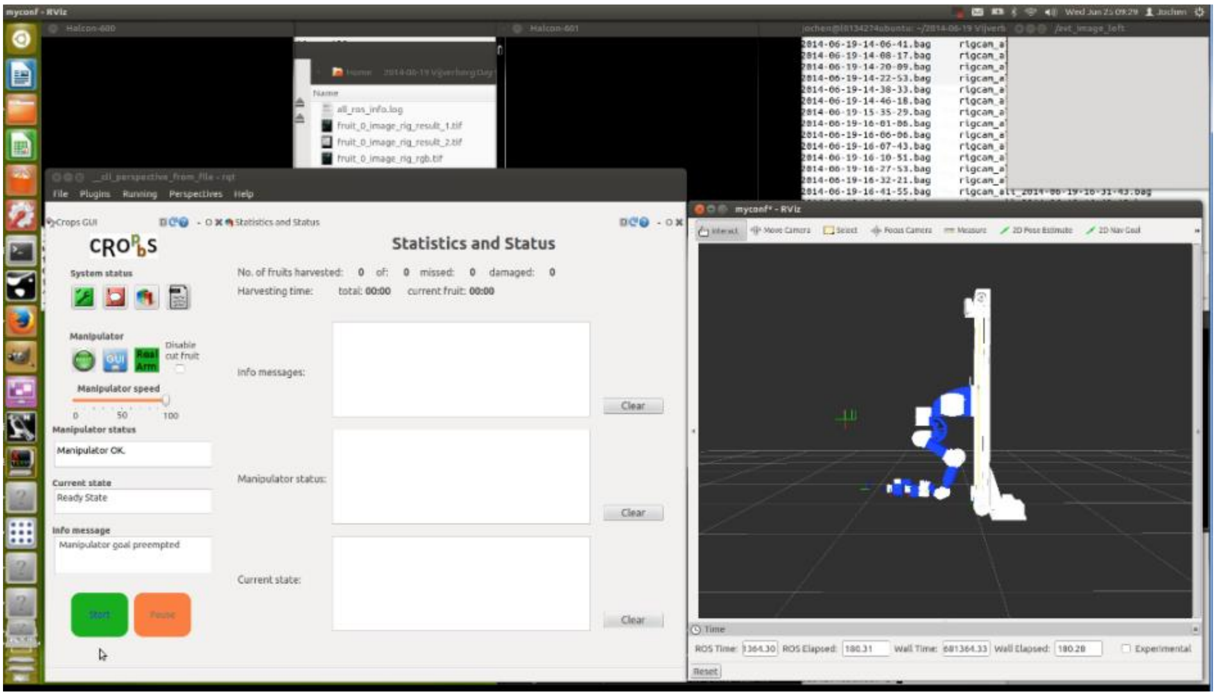

Figure 2-7: Screenshot of the GUI of the robot

2.2 Laboratory experiments

The major objectives of the laboratory experiments were to gain data on the performance and accuracy of the different subsystems with special focus on the manipulator.

Integration results reported are for following conditions:

- For localisation only the Swiss Ranger TOF camera on the main sensor module was used, no cameras on the gripper.
- No visual servoing, no use of cameras on the end-effector
- TOF camera with internal calibration which accounts for intrinsic parameters of the camera (lens distortion) when producing 3d point clouds.
- TOF camera basic detection only trained for outdoor peppers (WUR July 2012 dataset; trained on 4 peppers).
- Cameras rotated and not accounted for in software.
- Unregistered and un-calibrated imaging (TF manually measured).
- No hand-eye calibration.
- No path planning.
- No grasp planning.
- Festo Fin-Ray end effector (2012 model with 6 fingers) attached to old wrist with grasp, no cutting mechanism.
- Full cycle with rig and robot in&out of workspace (complete state diagram).
- Unpowered motors at measurement points and with stops at waypoints.

Figure 2-8: Harvesting robot in the laboratory, typical setup with 3 plastic peppers in the robot workspace, demonstration for the growers advisory board (BCO)

2.3 Greenhouse experiments

After lab testing the robot was transferred to a greenhouse. Between April and July 2014 experiments with the final integrated pepper harvester were carried out. The components and modules used during the greenhouse experiments were as follows (main partner who has contributed this module is listed in brackets):

Hardware

- Manipulator: final prototype (3rd manipulator) with 9DOF including XPC unit (TUM).
- End-effector:
  - Final prototype of Fin-Ray gripper as shown in Figure 2-4 (FESTO).
  - Final prototype of Lip type end-effector as shown in Figure 2-5 (WUR).
- Platform
  - Platform to move on greenhouse rails (heating pipes) consisting out of manipulator module and sensor module, as shown in Figure 2-2 (JENTJENS).
  - Motorized horizontal slide to move main sensors in and out of the manipulator workspace (WUR).
  - Illumination rig on sensor module (WUR).
  - Compressor for pressurized air to operate the pneumatics.
- Cameras
  - Camera unit on sensor module consisting out of Mesa TOF camera and Prosilica color camera according to the specifications of CSIC. In addition 2nd Prosilica color camera in small-base line stereo setup as shown in Figure 2-3 (WUR).
  - on both type of end-effectors VRM color camera and PMD TOF camera.
- Computers
  - Real time XPC as robot controller.
  - Tower PC with Quad core CPU and multiple GigEthernet ports and USB ports for interfacing the sensors and interfacing the horizontal sensor slide and the light control.

Software

- PC: Ubuntu 12.04 Linux operating system and ROS Groovy.
- GUI/Main control/state machine/data logging: based on C++ and Python code developed by UMU (UMU/WUR).
- Image acquisition: ROS modules developed by CSIC using camera drivers from the camera manufactures and OpenCV.
- Camera calibration/registration: ROS modules developed by CSIC for using intrinsic camera parameters from a set of images of a calibration pattern and a direct linear transformation (DLT)

algorithm to register the TOF image and the color image of the main sensor rig and also in the same way for the cameras on the gripper.

- Hand-eye calibration: manually measured and adjusted transformation matrices (using ROS TF package) between coordinate frames of cameras, manipulator and end-effectors until a satisfactory hand-eye "calibration" was realized (WUR).
- Fruit ripeness determination: based on color properties. Red blob in image with sufficient size and shape was considered as ripe fruit (WUR).
- Fruit detection and localization using main cameras: Simple color blob detection and position determination (WUR) using the calibrated and registered images of ToF and RGB (CSIC) as input. For an algorithm description see Bac et al. (2015).
- Refined fruit localization using mini cameras on gripper: Algorithm operational and succesfully tested but software and hardware unstable and therefore not used during the performance experiments in the greenhouse. Simple color blob detection and position determination (WUR) using the calibrated and registered images of mini TOF and mini RGB (CSIC). For an algorithm description see Bac et al. (2015).
- Stem detection: Small baseline stereo-vision using the crop-wire as visual cue (WUR). See for details Bac et al., 2014b.
- Grasp pose determination: Calculation of up to three grasp poses per fruit (WUR). If motion was not possible or not successful an alternative grasp pose was tried. For a part of the experiments the best grasp pose was calculated using the detected stem positions, see for details: Bac et al., 2015 (WUR).
- Sensor fusion: not used.
- Task planning (which fruit to pick first): Simple processing of the array of containing all the fruits detected by the main cameras (WUR).
- Motion planning: Point to point motion planning using XPC robot controller (TUM). As this planner is not performing collision avoidance intermediate hardcoded waypoints and stops were required and implemented (WUR).

Figure 2-10 shows some photo impressions from the greenhouse experiments. The experiments and the obtained results are described and discussed in detail a recently submitted manuscript for publication in Autonomous Robots: Bac C.W.; Hemming, J.; van Tuijl, B.A.J.; Barth R.; E. Wais, van Henten E.J.: Performance evaluation of a harvesting robot for sweet-pepper (Bac et al., 2015). In this deliverable only a brief summary is given.

The harvesting experiments were conducted in a red colored sweet-pepper crop grown in a commercial greenhouse of one of the members of the growers advisory board in Berkel en Rodenrijs in the Netherlands. The greenhouse layout consisted of common pairs of crop rows with aisles in-between pairs to move the robot along a crop row. On April and May 2014 pre-experiments were carried out and in June 2014 the final performance experiments. Table 2-1 gives an overview of the performance experiments conducted in the greenhouse. The test scenario included both types of end-effectors (Fin Ray, Figure 2-4; Lip-type, Figure 2-5) and two crop conditions (unmodified and simplified). In the simplified crop condition leaves occluding the fruit were removed and clustered fruit were removed (Figure 2-9).

Table 2-1. Overview of tests conducted in the greenhouse (adopted according to Bac et al., 2015)

End-effector	Crop conditions	Dates of testing	Fruit labelled	Stems labelled
Fin Ray	Unmodified	13 and 16 June	47	46
Fin Ray	Simplified	27 and 30 June	47	69
Lip-type	Unmodified	20 and 26 June	43	78
Lip-type	Simplified	24 and 25 June	39	69

Figure 2-9: Crop before (left) and after (right) removal of leaves and the fruit cluster present within the white circle (left). Green labels indicate the stem number. (Bac et al., 2015)

The robot was evaluated using these performance indicators which, as indicated in a parallel study as part of Crops (Bac et al., 2014a), should be included in an agriculture robot evaluation:

- Fruit localization success (%): The number of localized ripe fruit per total number of ripe fruit in the canopy.
- False-positive fruit detection (%): The number of objects falsely detected as fruit per total number of ripe fruit in the canopy.
- Grasp success (%): The number of ripe fruit successfully grasped per total number of localized ripe fruit. This indicator was added to assess the grasping mechanism of the end-effector.
- Cut success (%): The number of fruit successfully cut per total number of fruit successfully grasped. This indicator was added to assess the cutting mechanism of the end-effector.
- Detachment success (%): The number of successfully harvested ripe fruit per total number of localized ripe fruit. This rate corresponds with a multiplication of grasp success and cut success.
- Harvest success (%): The number of successfully harvested ripe fruit per total number of ripe fruit in the canopy.
- Cycle time (s): time of an average full harvest operation, including ripeness determination, localization, fruit detachment, transport of a detached fruit, but without manual displacement to the next robot position.
- Fruit damage rate (%): the number of damaged fruit per total number of localized ripe fruit. Stem damage rate (%): the number of damaged stems per total number of labelled stems.
- Leaf damage rate (-): the number of damaged leaves per total number of labelled stems.

In a second experiment a novel functionality of stem-dependent determination of the grasp pose (Bac et al., 2015 and Bac et al., 2014b) was evaluated. In the disabled mode, the algorithm computed three fixed grasp poses. In the enabled mode, the grasp pose was determined involving man stem location and fruit location. The algorithm selected three poses with the smallest deviation between the azimuth angle of the fruit and of the end-effector to ensure minimum chance of collision of the robot with the crop while approaching the fruit and with maximum expected performance of the end-effector.

Figure 2-10: Photo impressions from the harvesting robot in the greenhouse in June 2014.

3 Results

3.1 Laboratory experiments

3.1.1 Positioning accuracy of manipulator and camera rig

Table 3-1: Span of measurements for constant 1 positioned fruit in workspace (m) (std where applicable)

	X	Y	Z
Camera rig	NA	0.001*	NA
Detection	0.032 (0.0088)	0.036 (0.0087)	0.04 (0.0088)
Robot (with no faults)	0.007 (0.0196)	0.006	0.011
Robot (overall: Difference before and after fault and rehoming)	0.014 (0.0166)	0.015	0.022
Overall	0.035 (0.0091)	0.033	0.037

*or less, within range of measuring device.
NA not applicable

<u>Camera rig:</u> measured by laser (digital laser rangefinder, PLR 50, Bosch GmbH, Germany with a typical measurement accuracy of 2.0 mm) mounted on camera rig.
<u>Detection:</u> as reported by detection node for constant 1 plastic fruit located@center of work space and same fruit.
<u>Robot:</u> measured in fruit cycle for constant 1 fruit location entered manually (without detection to ensure identical return of robot to same position).
<u>Overall:</u> measured in fruit cycle with detection for constant 1 fruit location in center of workspace
For both Robot and Overall:
YZ-measured maximum difference between center of points marked manually on center of laser point at visual servoing point@ 0.35 from fruit in X direction; X measured by laser (accuracy=0.001) mounted on TCP.

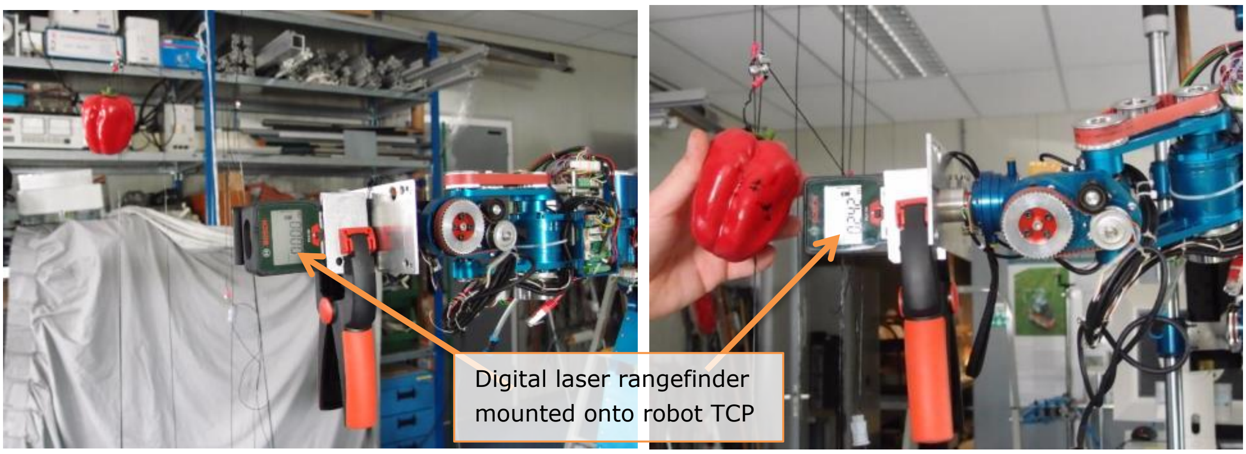

Figure 3-1: Photos of the manipulator with mounted digital lase rangefinder

Figure 3-2: Plastic pepper fruits with a collection of black dots (reached fruit centre positions) drawn with a marker based on a laser pointer mounted onto the robot TCP

3.1.2 Overall cycle

A total of 194 fruit in 45 scenes were approached for performance analysis of integration of all basic elements. Fruit setup in scenes included both plastic and real peppers setup randomly within workspace (not at extended positions).

Fruit dimensions:

Plastic: Height-0.08; Width-0.07;
Real: Height1-0.1; Width1-0.08;
Height2-0.11;Width2-0.09.

Figure 3-3: Typical setup with plastic peppers in the robot workspace and illumination rig turned on.

Table 3-2: Number detected, missed, reached and picked fruits

Number of Fruit	Detections	Missed	False Detect	Reached	Picked
194 (100%)	189 (97%)	19	14	167 (86%)	154 (79%)

3.1.3 Recorded problems

Table 3-3: Overview of recorded problems

Grip collapse	X	Y	Z too high >2cm	Z too high (+2cm)	Z too high (+1cm)	Z too low (-1cm)	Z too low (-2cm)	Z too low <-2cm
24	0	2	2	5	9	20	17	0

Z too high/too low would result in unsuccessful cut.
“”Too low”” was usually the cause for NON PICK; combination of too low and grip collapses always resulted in NON PICK.
In addition 4 times we recorded total gripper misplacement requiring manual correction and homing

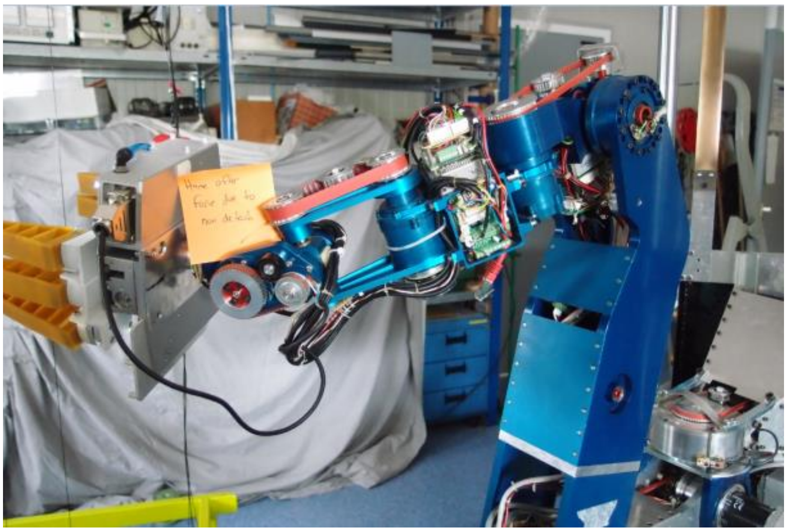

Figure 3-4: Manipulator which returned to wrong home-position after exposed to some force due to a non-successful fruit detachment

Reasons for unsuccessful pick with recommendations for improvements:

- Gripper collapse (unsufficient brakes, can be resolved via non stop of motor conditions at grasp position).
- Inaccuracy in Z detection is critical for successful grasp – for current pepper dimensions when distances were inaccurate by +/- 1-2 cm many cases resulted in NOT PICK (seems too low is more critical for success TBD; Please note this is without cut/knife which will require need for increased accuracy and depends also on penducle dimension and distance fruit top-knife).
- Joint 1 break not strong enough? Consider to add breaks/absolute encoders on wrist?
- Small forces applied on wrist cause distortion in wrist orientation – consider absolute encoders and feedback to determine overload (pull of stem, strings/wires).
- No correction of homing of gripper in case of misplacement (happened during “fruit” picking and camera rig calibration several times) – misalignments of joint 9 recorded: 2.412, 4.5, 9 degrees (corrected manually by levering followed by homing which is necessary for correct operation).
- In only 1 case incorrect Y detection caused unpick (there is flexibility within fingers to overcome the XY inaccuracies; to be confirmed in field experiments...).

Some additional notes:

- Path planning is essential –continuous path planning that considers also the via point before actual grasp must be included.
- In path planning must ensure continuous operation of motors (no stop); also when gripper close/open operation and also transfer between trajectory to visual servoing point and visual servoing and then grasping.
- Visual servoing will probably be necessary to correct for Z misplacement.

3.2 Greenhouse experiments

It must be noted that all results reported in the following are for the final integrated system. As described above (section 2.3) and discussed below (section 4.2) this system did not include all final modules developed in the other workpackages of the project. During the experiments it was proven that the robot is able to harvest pepper fruits fully autonomously. However, there were several difficulties noted which caused limited performance. Harvest success in the unmodified crops was only 6% (Fin Ray) and 2% (Lip-type). After simplifying the crop by removing fruit clusters and occluding leaves, harvest success improved to 26% (Fin Ray) and 33% (Lip-Type). Figure 3-5 shows details of the success rates and damage rates for the two different end-effectors. The average cycle time to pick a fruit was 94 s.

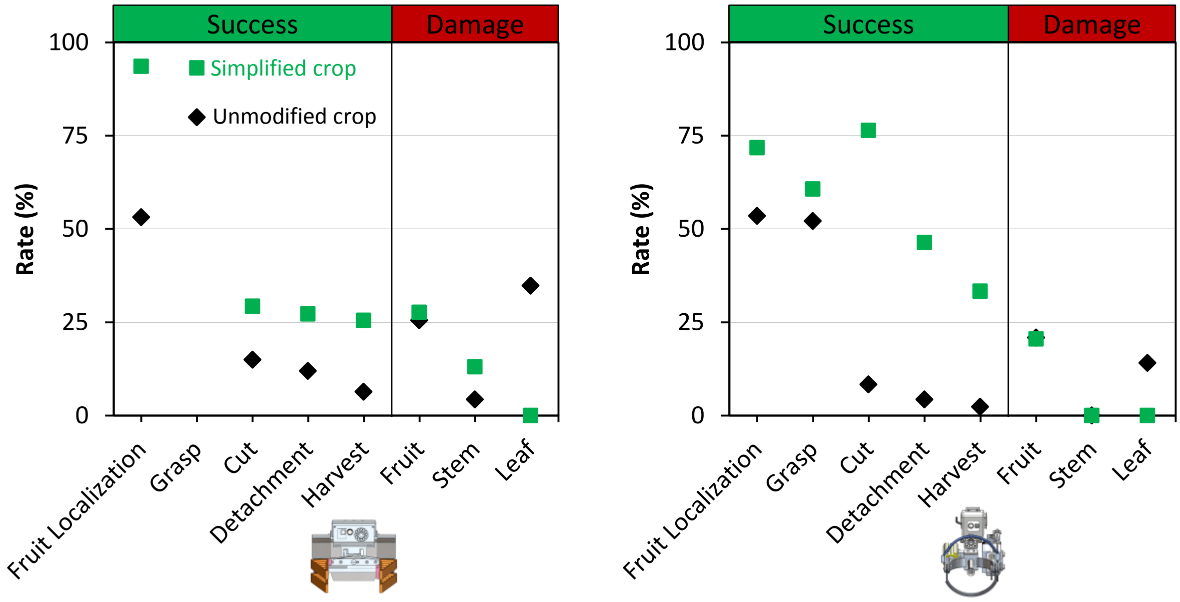

Figure 3-5: Success rates and damage rates of tests conducted using the Fin Ray end-effector (left) in the unmodified crop (◆) and simplified crop (■). Similarly, a test was conducted with the Lip-type end-effector (right) mounted on the robot. (Bac et al., 2015)

The second experiment investigated the novel functionality of stem-dependent determination of the grasp pose. For the Fin Ray end-effector, no notable change in grasp success was observed after enabling. However, stem damage decreased from 7% to 4% (out of 46 stems) in the unmodified crop and from 19% to 13% (69 stems) in the simplified crop. For the Lip-type end-effector, stem damages never occurred. Grasp success increased from 48% to 52% (22 fruit) in the unmodified crop and from 41% to 61% (28 fruit) in the simplified crop.

4 Discussion and suggestions for improvement

4.1 Laboratory experiments

After conducting the laboratory experiments the following task list and suggestions for improvements were communicated to the project partner in question.

4.1.1 Manipulator issues to be resolved

- Joint 5 tracking error frequently reported during motions and when holding in online control mode.
- Slip on joint 1 axis (Z motion) noted when in online control mode and also in extreme configurations.
- Gripper slip at different positions due to small forces uncorrected in homing
- Path planning:
  - Continuous motion without stopping motors at via points.
  - Must consider via point for approaching fruit in correct grasp orientation– gripper dependent.
- Optimize speed and waiting times for gripper open/close/cut.
- Actionlib required for continuous motion.
- Gripper I/O operations: currently too many “”sleeps”” integrated into software?? Cannot be solved via ActionLib but must ensure somehow execution of open/close before continue.
- Open/close gripper should be enable without stopping manipulator motors (continuous power to motors) to avoid slip and save time – motors should be continuously powered during all states of the state diagram.
- Bug in Power Electronics in GUI: after Home Sequence and Initial Position status is Task Finished (& does not move to Idle): this requires additional restart.
- In online control mode sometimes after several seconds ELMO FAULT (mostly due to Joint 5 tracking error but not always this is the cause) .

4.1.2 Camera issues to be resolved

- Camera images should be rotated at acquisition level before published to ROS topic.
- Confidence matrix of Mesa TOF camera should be used by detection/acquisition node – includes important information which can simplify (reduces noise) – registration should clean up the point cloud.
- TOF camera requires 2 resets at initialization (wrong calibration file loaded on 1st reset).
- TOF camera has some buffer so use only 2nd view of camera (seems to be only a problem with the WUR camera, was fixed via WUR HotFix).

4.1.3 Software/state machine issues to be resolved

Issues with different software modules related to the pepper harvesting application were noted

Task	**Issue was sovled before greenhouse experiments?**
For all the camera driver nodes (avt, sr, vrm, pmd) make a parameter to specify a rotation angle of the image in such a way that images and pointclouds acquired gets rotated before published on a topic. This will ease the use of a rotated mounted camera.	Yes
Implement pointcloud filter based on confidence image at camera driver level for **srmesa_camera_crops** (how about the PMD cam?)	Yes
Revise **pmd_camboard_nano** such that it is: Working with ROS Groovy	Yes

Possible to request images same way than for the other cameras (service/request) (Re)configure camera using a launchfile (including specification od calibration.dat file).	
icvl_unified_fruit_detector. Revise node so that classifier is initialized before a message is received (will speed up). Maybe make it using action lib so that progress can be monitored (now detection takes several seconds). Or somehow change **detected fruit service in task planner** so that no fixed sleeps are required.	No
Make **fruit detection** more robust. Make also use of point cloud filtering based on confidence image.	No
Motion planner must take into account that there will be at a certain distance to the target a switch to visual servoing mode – including adoption of path to target position. Now we stop 10 cm in front of fruit with already the orientation of gripper set and then move the last piece in a second movement. Switch to visual servo mode should be without intermediate stop of motion.	Partly
Implement **diagnostics** for a lot of nodes.	Yes
Agree on how to **acquire stereo images** without interfering with the fruit detection node. Suggestion: publish left and right image on different topics (**camera driver** must change to subscribe to state of the stereo-sledge in order to know on what topic to publish, set a default when no stereo sledge is available).	Yes
Statistics screen of harvested fruits not yet displaying the right information (harvest success or damage?, there is no info on that)	Yes
BUG: Visualization of TCP TF of robot is moving around in RVIZ even after harvest cycle is completed.	Yes
Make **init of USB port for pepper_motor controller** more convenient (now always an extra terminal asking sudo password)	No, not critical.
Adapt fruit detection node (or fusion or grasp affordance) such that when playing image data from rosbags the **timestamp of image messages** is set to the current time and not the time of the rosbag. Otherwise fruit message will be too old to be taken over. Use a **launch parameter** to do so.	Yes
Task & grasp planning should be setup based on specific gripper	Yes

4.2 Greenhouse experiments

The greenhouse experiments are discussed in detail Bac et al. (2015). In this deliverable report only a brief summary is given. Although the feasibility of sweet pepper harvesting has been proven, the harvest success rate of 6% (Fin Ray) and 2% (Lip-type) shows that the robot had great difficulty in successfully picking sweet-peppers. The cycle time achieved was a factor of 16 too long compared with the economically feasible time of 6 s calculated in WP12. The mechanics and electronics of manipulator itself can execute motions with a much higher speed. However, in the current development stage the integrated system was not capable to use an in that aspect optimized motion planning and execution. Using a stationary camera would eliminate the time required to move the platform into and out of the workspace. Possibly, the manipulator motion required to provide space for the horizontal slide could be eliminated or reduced as well. The long execution time of a grasp attempt (32.2 s) could be reduced by deploying a different motion planner and to avoiding waypoints. Moreover, the manipulator speed was also reduced during testing for security measures. It is expected that using the new insights gained during the experiments and a successful integration of the latest modules for sensing (WP2), motion planning (WP3) and artificial intelligence (WP4) developed in the project can significantly increase the performance of the system. Latest results from these workpackages show good detection (0.87 TPR) of the adaptive sensor fusion algorithm developed (D4.14) with low FPR (0.05) when checked on the large database of 221 images which included 428 red peppers (D4.14). Furthermore, these results have been further enhanced and applied for the latest pepper database. The adaptive sensor fusion algorithm with both the adaptive threshold and ICVL detection algorithm detected 1.00 TPR with low FPR (0.06). These modules were finalized by the project partners only in parallel with the greenhouse experiments. Thus, due to in parallel carried out work, time restrictions and resource limits and the availability of a productive sweet-pepper crop in the greenhouse this advanced state of integration was not achieved completely. It must also be noted that the fruit detection used in the robot is based on analyses from a single image taken from one viewpoint. Analysis by Hemming et a. (2014a) indicated that from a single viewpoint only 69% of the fruit are detectable. This publication also shows that in order to detect 97% of the fruits (where the fruit surface is occluded for not more than 30%) three camera viewpoints are needed. It is recommended, that future work should focus on systems using several camera viewpoints. The full use of the mini cameras integrated in the end-effectors could further improve results. However, is expected that this improves mostly accuracy needed for improved grasping and not the actual fruit detection. The pepper growers in the advisory board have indicated that a number less than 90% harvest success with a robot would also be acceptable if the price of the final system would be such that an additional manual harvest operation of the remaining fruits can be justified.

5 Dissemination and demonstration activities

Several video clips of the sweet-pepper robot operating in the greenhouse were produced and diss-eminated and available for download in the video section of the Crops public website: http://www.crops-robots.eu/. A significant number of peer-reviewed articles in a journals and conference proceedings as well as a PhD thesis (http://edepot.wur.nl/327202) have been published:

Bac, C.W. (2015): Improving obstacle awareness for robotic harvesting of sweet-pepper. PhD thesis, Wageningen University. http://edepot.wur.nl/327202

Bac, C.W. ; Henten, E. van; Hemming, J. ; Edan, Y. (2014): Harvesting Robots for High-value Crops: State-of-the-art Review and Challenges Ahead. Journal of Field Robotics .

Bac, C.W. ; Hemming, J. ; Henten, E. van (2014): Stem localization of sweet-pepper plants using the support wire as a visual cue. Computers and Electronics in Agriculture 105 . - p. 111 - 120.

Hemming, J. ; Ruizendaal, J. ; Hofstee, J.W. ; Henten, E. van (2014): Fruit Detectability Analysis for Different Camera Positions in Sweet-Pepper Sensors 14 (4). - p. 6032 - 6044.

Bac, C.W. ; Hemming, J. ; Henten, E. van (2013): Robust pixel-based classification of obstacles for robotic harvesting of sweet-pepper. Computers and Electronics in Agriculture 96 . - p. 148 - 162.

Hemming, J., Tuijl, B. A. J., Gauchel, W., & Wais, E. (2014): Field test of different end-effectors for robotic harvesting of sweet-pepper. In: Proceedings of the IHC conference, Brisbane, August 2014.

Hemming, J. ; Bac, C.W. ; Tuijl, B.A.J. van; Barth, R. ; Bontsema, J. ; Pekkeriet, E.J. ; Henten, E. van (2014): A robot for harvesting sweet-pepper in greenhouses. In: Proceedings of the International Conference of Agricultural Engineering, 6-10 July 2014, Zürich, Switzerland.

Tuijl, Bart van; Wais, Ehud; Edan, Yael (2013): Methodological design of an end-effector for a horticultural robot. 4th Israeli Conference on Robotics 19-20 November 2013.

The selective sweet-pepper harvester was demonstrated several times during the project in the laboratory as well as in the greenhouse and at couple of other events.

In July 2013 an early stage demonstration event of the fully integrated system with the first manipulator prototype was held in the laboratory of Wageningen UR for the members of the growers advisory board. The demonstration scenario consisted out of artificial plastic peppers that were hung up with a string. The system autonomously detected, localized and picked the fruits. During these laboratory tests 97% fruit could be detected, 86% of all fruits could be reached and 79% of all fruits could be harvested. Moreover Wageningen UR presented different stages of the development of the pepper harvesting robot system in the laboratory to groups of visitors.

The final demonstration of the system in the greenhouse took place on July 3, 2014 and was conducted in a red colored sweet-pepper crop grown in a Dutch commercial greenhouse (Figure 5-1). During this event the robot successfully demonstrated its ability to localize ripe fruit and to harvest pepper fruits fully autonomously.

The selective sweet-pepper harvester was demonstrated using a presentation and video clips to the scientific community during the final Crops workshop on July 8, 2014 at the Agricultural Engineering conference (AgEng 2014) in Zürich, Switzerland. The robot was also live demonstrated at an information and demonstration day organized by Wageningen UR at the Innovation and Demonstration center for robotics in horticulture at the Demokwekerij Westland in Honselersdijk, The Netherlands (http://www.demokwekerij.nl) at September 4, 2014. As there was no real pepper crop available at this location at this time of the year the demonstration was carried out with artificial plants and fruits. A group of about 40 people consisting out of journalists, TV teams, growers, representatives of companies (suppliers, machine builders), researchers from other universities and students attended this event.

Figure 5-1: Photo impressions from the final greenhouse demonstration to the growers advisory board (BCO) at July 3, 2014

References

Bac, C.W. ; Henten, E. van; Hemming, J. ; Edan, Y. (2014a): Harvesting Robots for High-value Crops: State-of-the-art Review and Challenges Ahead. Journal of Field Robotics.

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List of Crops public deliverables related to this report (see http://www.crops-robots.eu for details):

WP	NO	TITLE	DATE OF PUBLICATION
5	1	Report with design objectives and requirements (sweet pepper)	06/04/2011
5	2	Report with required functions and identified working principles (sweet pepper)	05/01/2012
5	3	Final report with conceptual design including design evaluation of prototype of harvester (sweet pepper)	07/05/2013
5	4	Report containing description and evaluation of generic concepts other than harvesting (sweet pepper)	18/07/2013
5	5	Test report of modules of harvester, including suggestions for revision and improvement (sweet pepper)	25/09/2014
5	7	Report of prototype test under laboratory and field conditions, including suggestions for improvements (sweet pepper)	07/10/2014
11	3	Selective sweet pepper harvester with 90-95% success rate	25/09/2014
12	1	A simulation of economic viability for each application	23/11/2011
12	2	Report on social aspects, standard requirements and other requirements for sustainability	23/11/2011
12	4	Report on validation	09/10/2014