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Machine vision for a selective broccoli harvesting robot

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Abstract: The selective hand-harvest of fresh market broccoli is labor-intensive and comprises about 35% of the total production costs. This research was conducted to determine whether machine vision can be used to detect broccoli heads, as a first step in the development of a fully autonomous selective harvester. A texture and color based image segmentation was used to separate the broccoli head from the background. Segmentation results were compared to a ground truth dataset of 200 images. In these images, 228 broccoli heads of varying sizes were classified by two human experts with the GrabCut algorithm. Image segmentation was evaluated by two different metrics. The first was a pixel-based spatial overlap between the ground truth classification and image segmentation, which resulted an average overlap of 93.8%. The second metric was the individual broccoli head detection and the corresponding confusion matrix. These showed a precision score of 99.5%, indicating only one false positive. The specificity was 97.9%, negative predictive value was 69.7% and overall accuracy 92.4%. In total, 208 broccoli heads were detected by the machine vision software, indicating a sensitivity score of 91.2%. The average pixel size of the non-detected heads was smaller than the pixel size of the detected heads.

Keywords: Agriculture, Cameras, Computer vision, Image processing, Intelligent machines

1. INTRODUCTION

Broccoli (*Brassica oleracea* convar. *botrytis* var. *italica*), which is grown for the fresh market, is considered as a high-value crop. It is estimated that 120.000 hectares of broccoli is annually grown in the world (Grubben and Denton, 2004). In the open field production of broccoli, there exists a lot of variation between individual crop sizes. Yet, retailers demand a uniform product in the fresh market based on the United Nations Economic Commission for Europe (UNECE) Standard FFV-48. This standard demands that the head diameter of fresh market broccoli is at least 6 cm with a corresponding size-ratio of at least 2:1 with the floral stem (UNECE Standard FFV-48, 2010). Furthermore, the fresh market broccoli must be free of any leaves and the buds must be fully closed.

Currently only hand-harvest is used to cut the fresh market broccoli. This is a selective harvest, because the farm workers must analyse each broccoli head and only harvest the ones which are estimated to be at least 6 cm and of acceptable maturity. In return, this requires skilled farm workers (Ramirez, 2006). Selective harvesting also requires farm workers to re-examine each row of broccoli over a period of days and weeks so that only the heads of marketable size and maturity are picked. This is a very labour intensive and physical demanding job. It is estimated that 100 to 150 hours are needed to hand-harvest one hectare of broccoli in the Netherlands. Corresponding labor costs are estimated between € 1900 - € 2500 per hectare for Dutch circumstances (Schreuder and Hendriks-Goossens, 2010). For US Californian circumstances harvest costs are about $ 2000 – $ 2500 per hectare, comprising 35% of the total production costs (Surendra et al., 2012).

There are single-pass machines that harvest field broccoli mechanically, but these machines do not yet differentiate in size and therefore harvest all heads simultaneously. For several farmers this harvest method is not preferable, as for most broccoli varieties less than 50% of the broccoli heads are marketable for the fresh market at any one time (Walton and Casada, 1988). As such, the mechanized single-pass harvest significantly reduces the yield of one hectare of broccoli, because the smaller broccoli cannot grow to their full potential. For these reasons, a new broccoli robot is being developed that adds selectivity to the harvest process. The aim of the overall work is to develop a selective and autonomous broccoli harvester that meets the end-user requirements regarding product quality while reducing manual labour. The robot should only cut broccoli from a pre-determined size, leaving behind smaller ones to grow further. This allows multiple harvest moments throughout the

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growing season and a uniform size for the fresh market.

The current robot prototype consists of an image acquisition and manipulator module built on a self-propelled carrier (Fig. 1). The image acquisition module is responsible for the image capture of the field grown broccoli crop. A pneumatic Cartesian manipulator with an attached end-effector and knife can autonomously cut and transport the broccoli. Input for this robotic harvest is the object recognition of the broccoli head, realized by machine vision software. Several attempts to automatically detect broccoli heads has been reported, e.g. with color reflectance (Soule and Sides, 1988), multi-spectral reflectance (Qui and Shearer, 1992) and pattern recognition of leaf veins (Ramirez, 2006). It was concluded that light reflection was unsuccessful due to the harsh lighting in open field conditions. The pattern of leaf veins was not distinctive as it was confused with the pattern of the broccoli florets.

Objective of the work reported in this paper was to research the machine vision hard- and software regarding its ability to detect broccoli heads in open field conditions. The focus of this paper is on the image acquisition and pixel-based segmentation of the broccoli head and will not go into further detail about the robotic cutting. The research reported here is focussed on the overall broccoli head segmentation as a first step towards selection by size.

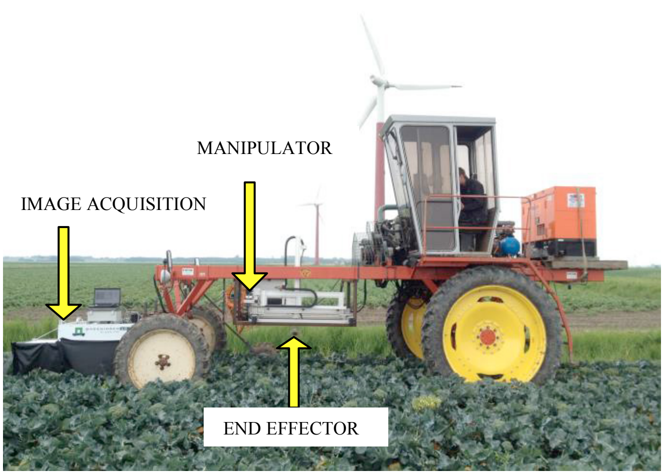

Fig. 1. The image acquisition module is built in front of the self-propelled carrier and the manipulator module in between the front and rear axle.

2. MATERIAL AND METHODS

2.1 Image acquisition module

The image acquisition module was an enclosed box of 1.1 m by 0.8 m by 1.0 m, equipped with a color-camera, artificial light installation and a computer. Natural light was blocked using a black curtain to limit the effect of variable outdoor light conditions on the image quality. Artificial light was provided by 50 white (6000K) light-emitting diode (LED) strips, which were equally divided over the interior ceiling of the box. Each LED strip had a beam angle of 120°, reaching a total luminous flux of 13.500 lm inside the box. As a result, the plants were illuminated with a bright and diffuse light source, which was not influenced by ambient light.

A 5 megapixels (2448 x 2050) red, green, blue (RGB) color camera (AVT Prosilica GC2460) with a 2/3 inch charge-coupled device (CCD) sensor was used. The camera was facing straight downwards at a distance of 50 cm to the broccoli head, to get a top view of the crop. The field of view was equal to 52.7 x 43.9 cm at the height of the broccoli head. The camera was connected via the Gigabit Ethernet interface to a laptop computer, which contained an Intel Core i7-2030QM processor with a 2GHz clock speed.

Images were acquired after a hardware trigger to the camera and stored for offline processing. The hardware trigger was generated by an electronic encoder wheel which was attached to the right frontal wheel of the self-propelled carrier. At each 150 mm of real world displacement (+/- 1.3 mm displacement error) a hardware trigger was generated resulting in an image sequence with an average image scene overlap of 46%.

2.2 Field trials and image acquisition

In total, 7008 images from field grown broccoli plants were captured with the image acquisition module. This was conducted during five separate field trials in 2014 and 2015 in Sexbierum, The Netherlands. Trials were conducted on five different fields containing two broccoli varieties; Ironman, which was a summer crop and Steel, which was an autumn crop (Seminis, St. Louis, U.S.A.). The row distance on all fields was 75 cm and the plant distance was 30 cm.

1655 images were captured during the first field trial which was called image set D1 (07-10-2014). And 2352, 1916, 742 and 343 images were captured on D2 (13-07-2015), D3 (14-07-2015), D4 (15-07-2015) and D5 (15-10-2015). Images taken on D1 and D5 comprised the Steel variety and D2, D3 and D4 the Ironman variety. The dataset consisted of images of various broccoli head sizes and heights, crop colors, different crop locations and images which contained no broccoli head, bare soil, yellowed leaf and weeds.

2.3 Ground truth labelling

200 images were randomly selected from the dataset; 39 (D1), 78 (D2), 59 (D3), 21 (D4) and 3 (D5) images respectively. All broccoli heads were labelled in the images regardless of their size, because no head size determination by field validation or additional sensors was conducted on the 7008 images. Ground truth labelling of the images was realized by the GrabCut algorithm (Rother et al., 2004) to extract the broccoli head region in each image. One human expert conducted an offline manual fine-tuning of the GrabCut segmentation by adding masks of the broccoli head and background to each image (Fig. 2-1). Another human expert independently validated and if necessary corrected the masks of the broccoli head and background afterwards. Obviously, this was a single offline manual processing which is not required under real field testing conditions. An image merge was conducted to combine multiple masks in one single image. The ground truth classification was stored for each image (Fig. 2-2).