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Stem localization of sweet-pepper plants using the support wire as a visual cue

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ABSTRACT

A robot arm should avoid collisions with the plant stem when it approaches a candidate sweet-pepper for harvesting. This study therefore aims at stem localization, a topic so far only studied under controlled lighting conditions. Objectives were to develop an algorithm capable of stem localization, using detection of the support wire that is twisted around the stem; to quantitatively evaluate performance of wire detection and stem localization under varying lighting conditions; to determine depth accuracy of stereo-vision under lab and greenhouse conditions. A single colour camera was mounted on a pneumatic slide to record image pairs with a small baseline of 1 cm. Artificial lighting was developed to mitigate disturbances caused by natural lighting conditions. An algorithm consisting of five steps was developed and includes novel components such as adaptive thresholding, use of support wires as a visual cue, use of object-based and 3D features and use of minimum expected stem distance. Wire detection rates (true-positive/scaled false-positive) were more favourable under moderate irradiance (94/5%) than under strong irradiance (74/26%). Error of stem localization was measured, in the horizontal plane, by Euclidean distance. Error was smaller for interpolated segments (0.8 cm), where a support wire was detected, than for extrapolated segments (1.5 cm), where a support wire was not detected. Error increased under strong irradiance. Accuracy of the stereo-vision system (±0.4 cm) met the requirements (±1 cm) in the lab, but not in the greenhouse (±4.5 cm) due to plant movement during recording. The algorithm is probably capable to construct a useful collision map for robotic harvesting, if the issue of inaccurate stereo-vision can be resolved by directions proposed for future work. This is the first study regarding stem localization under varying lighting conditions, and can be useful for future applications in crops that grow along a support wire.

1. Introduction

This research is part of a project in which a robot is developed to harvest sweet-pepper in a greenhouse (Hemming et al., 2011). The manipulator and end-effector of this harvesting robot should avoid obstacles during motion towards a target (fruit or peduncle). The motion planner requires locations of these obstacles. In our prior research, plant stems were obstacles more difficult to detect than fruit, leaves or petioles (Bac et al., 2013a, 2013b). This work therefore focuses on stem localization.

A low-cost sensor, a Red, Green, Blue (RGB) camera, was selected to fit economic feasibility requirements for the harvesting robot (Pekkeriet, 2011). Alternative sensors, such as LIDAR for detection of canopy structure in apple trees (Fleck et al., 2004) were considered to be too expensive. X-ray scanners were used for rose stem detection (Noordam et al., 2005), but are rather expensive and require the object to be placed between a source and receiver, which is a complicated configuration in a greenhouse environment. In our previous work, multi-spectral imaging was used (Bac et al., 2013b). But, we selected an RGB camera because the algorithm, described in this work, relies little on spectral features and uses mostly object-based features (size and shape). Such features can be extracted from RGB images as good as from multi-spectral images.

Stem detection and localization was studied under controlled lighting conditions (Paproki et al., 2012). Yet, we reviewed studies pertaining to our work that include experiments conducted under varying lighting conditions, and employ either multi-spectral imaging or colour imaging. Two studies describe classification of

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cucumber plant parts into leaves, stems and fruit: a study regarding a cucumber leaf picking robot (Van Henten et al., 2006) and a multi-spectral imaging study (Noble and Li, 2012). Lu et al. (2011) detected branches of citrus using multi-spectral imaging. Stems of lychee were detected using colour imaging (Deng et al., 2011). Branches and trunk of apple trees were detected using colour imaging (Jidong et al., 2012). Two articles describe classification of grape foliage into several plants parts: a study using RGB (Dey et al., 2012), and a study using multi-spectral imaging (Fernández et al., 2013). Our previous work also dealt with detection of several plants parts (Bac et al., 2013b). Although work exists regarding stem detection or fruit localization (Bac et al., 2014), to the best of our knowledge, only one article exists in which stem localization was briefly described as part of a leaf picking robot (Van Henten et al., 2006).

To localize the stem, we used stereo-vision. Accuracy of stereo matching has been thoroughly investigated (Scharstein and Szeliski, 2002), but depth accuracy of stereo-vision seems mostly qualitatively described for applications in a crop (Song et al., 2011; Van Der Heijden et al., 2012). To fill this gap, this study quantified depth accuracy and validated if the required accuracy (±1 cm) can be achieved, to localize obstacles for robotic harvesting (Hemming et al., 2011).

The approach included novel elements in terms of the baseline and algorithm. A small baseline of 1 cm was taken to improve matching score of stereo-vision and to decrease occlusion of the stem. Delon and Rougé (2007) note that few studies applied a small baseline so far and describe the advantages. Yet, a disadvantage is the difficulty to record images simultaneously. Regarding the algorithm, 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. Support wires therefore approximate the location of the stem. Furthermore, the algorithm developed employed adaptive thresholding, object-based and 3D features, and filtering by minimum expected stem distance, to better handle varying lighting conditions.

Objectives were to (1) develop an algorithm capable of stem localization using detection of the support wire; (2) quantitatively evaluate performance of wire detection and stem localization under varying lighting conditions; (3) determine depth accuracy of stereo-vision under lab and greenhouse conditions.

This is the first study regarding stem localization and can be useful for future applications, to localize plant stems under varying lighting conditions. The algorithm and experimental set-up may not only be useful to localize obstacles for collision-free harvesting in sweet-pepper, but also in other crops that grow along a support wire, such as tomato, cucumber or egg-plant. The algorithm may furthermore fit for tasks other than harvesting, such as leaf picking, side shoot removal or plant phenotyping.

2. Image acquisition

Images of plants were recorded using an experimental set-up shown in Fig. 1. Plants were of the red sweet-pepper cultivar 'Waltz' and were cultivated in the V-system (Jovicich et al., 2004). A total of 151 stems were recorded in 38 scenes. Solar irradiance was measured and ranged from 140 to 880 W/m^2 for these recordings.

2.1. Camera and pneumatic slide

For stereo-vision, a camera was mounted on a pneumatic slide (Mini slide SLT; Festo AG & Co. KG, Germany). After recording the left image, the pneumatic slide was shifted to record the right image. Shifting took 0.4 s. The camera used was a 5 megapixel camera with a 2/3″ CCD (Prossilica GC2450C; Allied Vision Technologies GmbH, Germany). A low-distortion lens with 5 mm focal length (LM5JC10M; Kowa GmbH, Germany) was mounted on the camera. A digital laser rangefinder was used (PLR 50; Bosch GmbH, Germany) to validate calculated depth values of the stereo-vision system.

2.2. Artificial lighting

For illumination of the scene, 30 halogen lamps (230VAC, 50 W) were used. Six rows of lamps illuminated the vertical range of the image (2448 pixels). Distance between the rows was 15 cm. Each row consisted of five lamps to cover the horizontal range of the image (2050 pixels). Distance between lamps in a row was 14 cm. Similar to previous research (Bac et al., 2013b), each row was horizontally shifted (7 cm) with respect to the previous row to improve equal light distribution.

Lamps were equipped with a dichroic reflector (∅ 51 mm), to reduce strong reflections in the centre of the image. Two types of reflectors were used: a reflector causing a beam angle of 25° (GU10/50/Clear Prolite; Ritelite Ltd., UK) and a reflector causing a beam angle of 50° (HI-Spot ES50; Sylvania Europe Ltd., UK). Lamps (N = 18) emitting a beam angle of 25° were positioned at the edge of the lighting set-up, whereas lamps (N = 12) emitting a beam angle of 50° were positioned in the centre of the lighting set-up. As a result, light was more diffuse in the centre of the image than at the edge.

Fig. 1. Experimental set-up comprising a cart with a height-adjustable imaging set-up on top (left). Detailed view of the imaging set-up during recording in a row (right).