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Segmentation of lettuce in coloured 3D point clouds for fresh weight estimation

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ABSTRACT

Monitoring the health and yield of crops during production is an important, but labour intensive component of commercial agriculture, especially in high value crop such as lettuce. This article proposes a novel method for segmenting lettuce in coloured 3D point clouds and estimating the fresh weight. The proposed segmentation method operates by clustering points into leaves and then evaluating their affiliation to a lettuce of interest. From the segmented lettuce point clouds, the volume, surface area, leaf cover area and height predictors are extracted and correlated to the fresh weight. The proposed segmentation and yield estimation methods are evaluated on Cos and Iceberg lettuce point clouds generated from images collected by an agricultural robot in an outdoor field experiment. The results demonstrate that the proposed segmentation method is able to successfully isolate lettuce (F_1-score = 0.88–0.91). Analysis of the segmented lettuce models show that the calculated surface areas correlate strongly with measured fresh weight (R^2 = 0.84–0.94). Not only does this validate the segmentation method, it allows an accurate estimate of the lettuce fresh weight (RMSE = 27–50 g) to be produced non-destructively.

1. Introduction

Continuous monitoring of crops is an important tool for determining the status of crops in both commercial farming and agricultural research. Deviations from the expected status will alert the farmer or researcher and action can be taken to mitigate the problems, e.g. irrigation, fertilization or pest, weed and disease control. This is especially important in high value crops such as lettuce, where the loss or damage to the crops is more costly than in most other agricultural crops. Monitoring may also be used for determining the optimal harvest time based on observed and expected yield. The monitoring may be performed by visual inspection and/or through measurements.

Direct measurements generally provide the most accurate measurements, if a proper sampling strategy is chosen, but they are labour intensive, tedious and time consuming. In addition to this, destructive direct measurements prevent repeated measurements as the crop is removed from the field (Tucker, 1980) and they affect the growth of neighbouring plants.

Remote sensing using aircraft (Shanahan et al., 2001) or satellites (Jeppesen et al., 2017) is a promising tool for performing non-destructive indirect measurements for broad-scale analysis of crops on a field level, but it generally has a low spatial resolution making it hard to identify and analyse individual plants. Hand-held devices such as the GreenSeeker (Raun et al., 2002), the Crop Circle (Solari et al., 2008) and the Multiplex (Ghozlen et al., 2010) and sensors mounted on ground-based vehicles (Underwood et al., 2017) allow non-destructive measurements in close proximity to the crop. Using hand-held devices can, however, be a tedious and time consuming process, which ground-based vehicles does not suffer from to the same extend as they allow for a greater level of automation. The development of unmanned aerial vehicles (UAVs) in recent years has closed the gap between remote and proximal sensing by enabling lightweight aircraft to capture high resolution images at a field level (Mortensen et al., 2015) and hover in close proximity to the plants (Madsen et al., 2017).

This paper focuses on proximal sensing using stereo colour cameras mounted on an agricultural robot for fresh weight estimation of lettuce. Sequences of stereo image pairs are used to generate high density 3D colour point clouds of the lettuce, which are then analysed and

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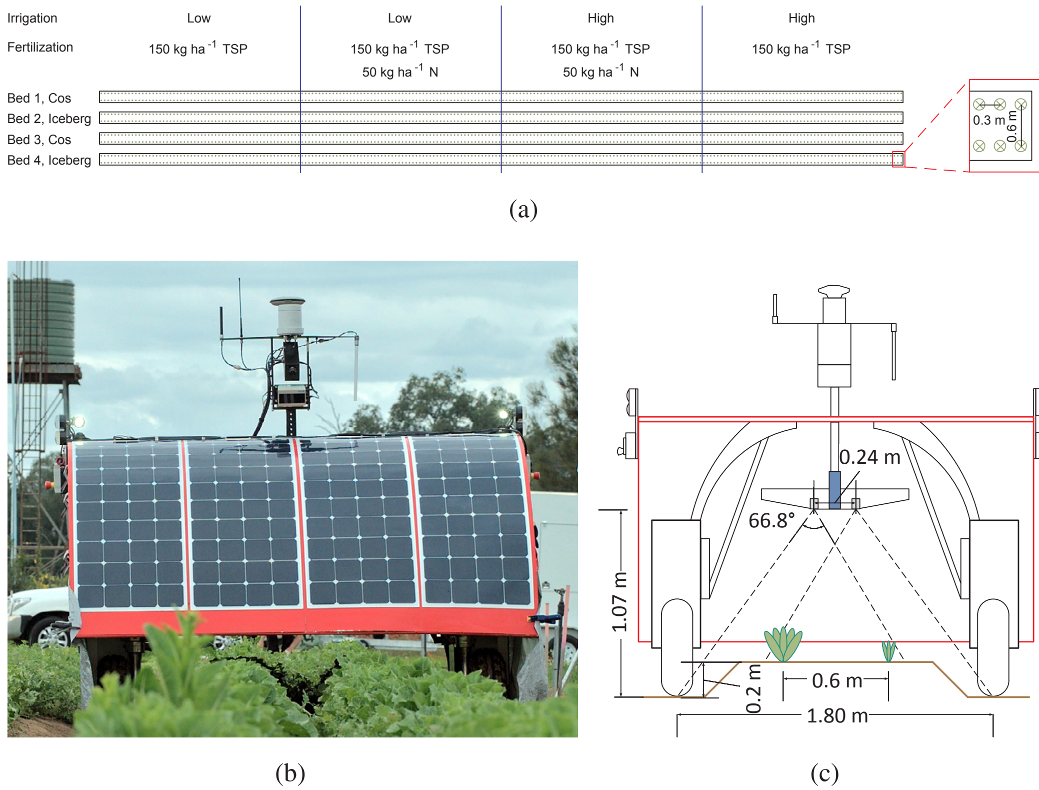

Fig. 1. (a) Layout of the field experiment. N = Nitrogen. TSP = Triple superphosphate. (b) Photo of Ladybird scanning a lettuce bed in week 8. (c) Illustration of camera (gray rectangles) and flash (blue rectangle) placement on Ladybird and their field of view with respect to the bed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

correlated to the lettuce fresh weight.

1.1. Related work

Lettuce has been analysed in a machine vision context using 2D colour images, 2D multispectral images (Slaughter et al., 2008; Lee et al., 2014; Mo et al., 2015; Ren et al., 2017) but less so in 3D point clouds (Gai et al., 2016). The analysis typically involves three main steps: (1) Segment lettuce from the background. (2) Extract features from the segmented lettuce. (3) Correlate extracted features to observed measurements.

The analyses have been explored in both controlled indoor environments and natural outdoor environments. In indoor environments the plants are imaged on a high contrast background with controlled illumination (Lin et al., 2011; Yeh et al., 2014; Jung et al., 2015). Often the plants are imaged individually, however, in a plant factory setting they may be imaged together (Yeh et al., 2014). Outdoor environments are generally more complex due to stands of multiple plants, a less uniform background and uncontrolled illumination. The background in an outdoor setting is mainly soil, but it can also include objects that complicate the segmentation task such as weeds and equipment. Outdoor scenes are often only illuminated by ambient light and are subject to changes in the weather, the time of day and high dynamic range conditions. During imaging, the scene may also be shaded from the sun and artificially illuminated (Jensen et al., 2013) or simply illuminated by a high powered flash (Overskeid et al., 2013; Laursen et al., 2017).

In 2D colour images, lettuce segmentation is performed using colour, intensity, textures and morphological operations. Depending on the method, the segmentation process may require human interaction (Bumgarner et al., 2012; Fernández-Pacheco et al., 2014). From the segmented image, an predictor for the observed measurement is extracted. The predictor may be the percentage ground cover (Bumgarner et al., 2012), leaf area index (Sandmann et al., 2013), pixel count (Jung et al., 2015) or a metric value (Yeh et al., 2014). Yeh et al. (2014) segment lettuce in stitched colour images. From the disparity image created in the stitching process, the average height and volume index can be extracted for each plant over time to create growth curves.

Lettuce have been studied to a lesser extent in 3D point clouds and to the best of the authors knowledge only by Gai et al. (2016). Gai et al. (2016) studied lettuce and broccoli localization and discrimination for weed control in an outdoor setting using the Kinect v2, which provides a colour image and time-of-flight derived depth image. A mixture of 2D features and height derived from the depth image were used to segment the plants from the background and neighbouring plants.

In a wider context of leafy vegetables, Lati et al. (2013) have studied black nightshade as well as non-leafy vegetables (sunflower, tomato, corn and cotton) in 3D point clouds using a stereo vision setup in an outdoor setting. Estimated convex volumes from the point clouds showed a high correlation to the actual biomass ($R^2 = 0.94$). Similarly, Jay et al. (2015) used structure from motion (Ullman, 1979) to generate 3D point clouds of Savoy cabbage, cauliflowers and Brussels sprouts in an outdoor environment. The plants were fairly well spaced and segmented from the background using a combination of colour and height. Height and leaf area estimated from the segmented point clouds showed a high correlation to the observed height ($R^2 = 0.99$) and leaf area ($R^2 = 0.94$).

This paper proposes a novel method for segmenting lettuce in coloured 3D point clouds and estimating their yield. The proposed method is applied to lettuce grown in an outdoor field experiment (Section 2.1). As a result the method must be robust to the influence of weeds and overlapping lettuce canopies. Structure from motion using multiple image pairs from stereo machine vision cameras is used to produce dense 3D point clouds of the lettuce and the surrounding area (Section 2.3). Soil and weeds are removed from the point clouds using dynamic height filtering (Section 3.3). The lettuce of interest (LOI) is segmented from adjacent lettuce by clustering the points into leaves and