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Determination of stem position and height of reconstructed maize plants using a time-of-flight camera

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A B S T R A C T

Three dimensional (3-D) reconstruction of maize plant morphology by proximal sensing in agriculture brings high definition data that can be used for a number of applications related with precision agriculture and agricultural robotics. However, 3-D reconstruction without methodologies for extracting useful information is a senseless strategy. In this research, a methodology for stem position estimation is presented relying on the merging of four point clouds, using the Iterative Closes Point algorithm, that were generated from different 3-D perspective views. The proposed methodology is based on bivariate point density histograms for detecting the regional maxima and a radius filter based on the closest Euclidean distance. Then, single plant segmentation was performed by projecting a spatial cylindrical boundary around the estimated stem positions on a merged plant and soil point cloud. After performing a local Random Sample Consensus, the segmented plant point cloud was clustered using the Density-based spatial clustering of applications with noise algorithm. Additionally, a height profile was generated by rasterizing the plant and soil point clouds, separately, with different cell widths. The rasterized soil point cloud was meshed, and the rasterized plant points to soil mesh distance was calculated. The resulting plant stem positions were estimated with an average mean error and standard deviation of 24 mm and 14 mm, respectively. Equivalently, the average mean error and standard deviation of the individual plant height estimation was 30 mm and 35 mm, respectively. Finally, the overall plant height profile mean error average was 8.7 mm. Thus it is possible to determine the stem position and plant height of reconstructed maize plants using a low-cost time-of-flight camera.

1. Introduction

One of the most appealing aspects of reconstructing the geometry of an agricultural environment is to obtain information about the crop status without the troublesome manual measurement. Doing so with an efficient investment in resources, such as fuel and working time (Steckel, 2017), would trigger the interest of farmers in this technology. The information provided by the scanned and digitized data would be very useful for decision-making throughout the cropping cycle; considering that it involves precision agriculture practices (Gebbers and Adamchuk, 2010). Tasks such as sensing and mapping: soil, crop, weed and yield are suitable for 3-D imaging systems. Other applications such as agricultural robotics and plant phenotyping for breeding purposes are among the most appealing (Blackmore et al., 2006). However, since research using 3-D imaging systems in agriculture was previously limited, particularly with the once expensive time-of-flight (ToF) cameras, there is still the need of new methodologies for extracting useful information out of the 3-D data for agricultural applications. Information such as stem diameter, plant height, leaf angle, leaf area index (LAI), number of leaves, biomass, etc. are of particular interest. If the cost of obtaining such information becomes economically accessible, new applications and solutions will come as a result (Vázquez-Arellano et al., 2016a). An off-the-shelf ToF camera such as the Kinect v2 (Microsoft, Redmond, WA, USA) offers a good cost/performance ratio solution for the development of ground-based 3-D imaging system for proximal sensing (Vázquez-Arellano et al., 2016b). In 3-D imaging a point cloud is a set of data points in space, where each point $\boldsymbol{P}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$ is a function of the spatial position (x, y, z) in a Cartesian coordinate system (Rusu and Cousins, 2011).

Until now, among the most commonly measured plant parameters

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using this ToF camera in agricultural research are plant height and biomass estimation. Recently, Hämmerle and Höfle (2016) developed a mobile system for maize plant height measurement using a Kinect v2 where they used a terrestrial laser scanner (3-D LIDAR) to digitize maize plants (as the reference) from different perspectives, using real time kinematic-global navigation satellite system (RTK-GNSS) for geo-referentiation, and artificial markers to facilitate the point cloud registration and alignment. With the Kinect v2 they obtained depth information, and through raster crop height model with a rough cell resolution (1 m × 1 m), they approximated the maize height with an R^2 determination coefficient of 0.89 with one of the approaches. However, they acknowledged that the accuracy was slightly below the results of other studies due to the rough terrain and the complex maize architecture, among others. Andújar et al. (2016) used the same ToF camera for weed volume estimation with R^2 determination coefficient for weed biomass of 0.7 but 0.58 for maize biomass. The lower value for maize could be explained by its complex architecture since one single perspective cannot describe it entirely, compared to the low-lying weed. Ribeiro et al. (2017) reconstructed vineyards using a small electric car and the Kinect v2 ToF camera with an RTK-GNSS for geo-referentiation. They relied on a variant of the ICP algorithm for the point cloud registration and stitching to reduce the problem of drifting. Then, they developed a four-step methodology for segmenting the canopy points from the entire point cloud. Finally, they used alpha shapes to envelop the canopy point clouds in order to create a volume map of the vineyard rows.

Individual maize plant phenotyping was also investigated by Lu et al. (2017) where they developed a robotic arm 3-D imaging acquisition system based on a SR-4000 ToF camera (MESA Imaging, Rueschlikon, Switzerland). They obtained measurements of different phenotypic traits such as stem height, leaf length and angle, and number of leaves of individual plants on pots. A similar research was done by Chaivivatrakul et al. (2014) using the same SR-4000 ToF camera but with the plant pot placed on a turntable driven by a stepper motor. They also achieved stem and leaves segmentation and phenotypic data extraction such as stem diameter; and leaf length, area and angle. They mentioned that the most challenging parameter, and with the highest error (21.89%), was the leaf area due to partial occlusions and rolling of some leaves. Aside from that, they also used the non-uniform rational basis spline algorithm for surface reconstruction for a 3-D holographic visualization. Nakarmi and Tang (2012) used a ToF camera to measure the maize inter-plant spacing by mosaicking depth images using encoder readings and a feature matching algorithm. They achieved an overall root mean square error (RMSE) of 0.017 m and a misidentification ration of 2.2%, concluding that the camera position of their research (side-view) achieved superior accuracies compared with previous researches (top-view) for inter-plant spacing sensing.

The aim of this research was to estimate the stem position of maize plant point clouds, calculate the height of the individual plants and generate a plant height profile of the rows using a low-cost ToF camera. In order to validate the stem position estimations with the real world, the seedling positions were used as ground truth data (on- site measurement using a total station after plant emergence), and for the plant height validation, manual measurements were used. The main contribution of this research is the estimation of single plant position and height to evaluate the potential and limits of the ToF camera used in the research.

2. Materials and methods

2.1. Hardware and sensors

The 3-D data used in this research was obtained using a robotic platform, developed at the University of Hohenheim, controlled by a joystick that navigated between maize plants in a greenhouse. The ToF camera was mounted at the front of the vehicle at a height of 0.94 m with a downwards angle of 45 degrees. The SPS930 robotic total station (Trimble Navigation Limited, Sunnyvale, USA) tracked the position of the robot by aiming at the Trimble MT900 Machine Target Prism. An Inertial Measurement Unit (IMU) (VectorNav, Dallas, USA) VN-100 was embedded inside the robotic platform and used to measure its orientation while driving. The 3-D imaging acquisition system is depicted in Fig. 1 and the technical characteristics of the robotic platform are described in detail by Reiser et al. (2015).

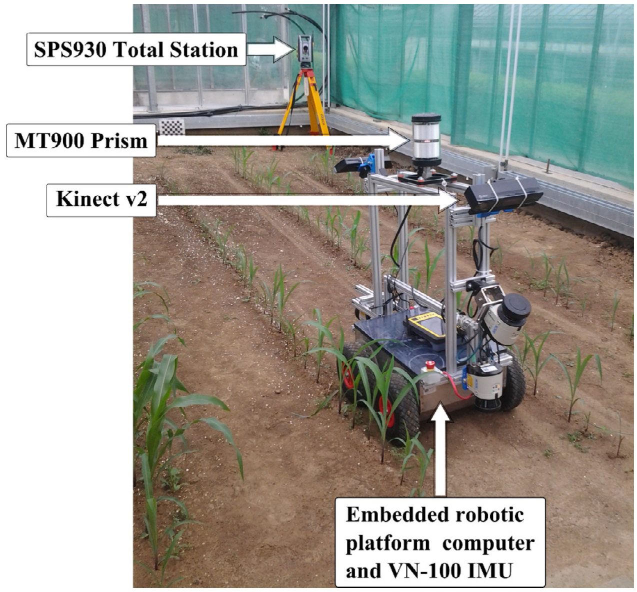

Fig. 1. 3-D imaging acquisition system with the TALOS robotic platform. The different components for 3-D image, orientation and position data acquisition are marked with arrows and annotations.

2.2. Experimental setup

The experiment was done in a greenhouse (3.75 m × 5.6 m) at the University of Hohenheim. The maize was planted in 5 rows with different standard deviations from the theoretical spacing: the inter-row spacing was 750 mm and the intra-row spacing was 130 mm. This deviation during seeding was done in order to emulate different seeding scenarios. From row 1 to 5 the standard deviations were 19, 17, 6, 48 and 47 mm, respectively. Every row had 41 plants in a length of 5.2 m, and the plant growth stage was between V1 and V4 (Ritchie et al., 1992). However, most of the plants (94%) were between V1 and V3. The ground truth was measured with a robotic total station tracking the target prism, mounted on a tripod, and pointing directly over each seedling with the help of a plummet. The robot platform was driven, using a joystick, in every path in the go and return direction. At every headland, the robot was turning 180 degrees, therefore, the 3-D perspective view was different in the go and return direction of every row. A viewpoint was stablished (camera plot in Fig. 2), to avoid confusion between the left and right side of the crop row. Since there were 3-D reconstructions while going and returning, the left and right side would be different (if a viewpoint was not established) depending on the driving direction. Additionally, the experimental setup is represented and depicted in Fig. 2.

2.3. Data processing

The raw data for this research was based on the maize plant registration and stitching from a previous research (Vázquez-Arellano et al., 2018). These point clouds were processed mainly using the Computer Vision System Toolbox™ of MATLAB R2016b (MathWorks, Natick, MA, USA). Also, some functionalities of CloudCompare (EDF R&D, 2011)