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Test of a 3D Time of Flight Camera for Shape Measurements of Plants

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ABSTRACT

Agricultural plant experiments strongly depend on reliable methods for measuring or at least assessing the plant growth and the plant's phenological and morphological parameters. We tested a commercially available 3D time of flight camera, the PMD[vision]® S3, manufactured by the German PMDTechnologies GmbH. The test results showed that distance measurements of big plant leaves (eg. maize, maple) were possible, but the measured distances depended on the background colour behind the leaf, varying by about 50 mm at a 1.5 m distance. Sunlight did not show a significant effect on the measured distances. The calculation of a 3D model of the plant canopy was possible but the model resolution was poor due to the poor camera resolution.

Keywords: 3D, time of flight, PMD, plant height measurement, plant shape model.

INTRODUCTION

Quantified information about crop size and shape is needed for several purposes: Most of agricultural plant experiments, including breeding, depend on quantified data about plant growth. Even for several tasks in precision farming such information may be helpful. Spectral optical sensors may assess the amount of total green biomass on the field as well as its health and photosynthetic activity, but they are not able to deliver reliable information about the crop size and shape. A mechanical pendulum sensor was proposed for precision farming applications by Ehlert et al. (2003). This sensor estimates the plant mass and it may be assumed that the size and shape of the crop affects the deviation of the pendulum.

Various types of optical sensors are able to measure distances and 3D shapes of objects and surfaces. Ehlert et al. (2009) compared a laser scanner system based on the triangulation method and another laser system based on time of flight measurement for the measurement of crop biomass. Both physical principles are suited to deliver spatially resolved 3D height images. Recently, 3D cameras based on the time of flight principle (TOF) became available at a reasonable price. These cameras are simple in their handling, they deliver a distance image without the need of triangulation processing and they are supposed not to be sensitive to the environmental illumination. Klose et al. (2009) presented some test results encouraging the use of TOF cameras for measuring maize morphology from a moving platform. This paper describes some more tests of plant leaves measurement with a TOF camera.

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The 3D camera PMD[vision]® S3

The German manufacturer PMDTechnologies GmbH, Siegen, Germany, has developed an own technology for time of flight cameras. The sensors are able to capture a complete 3D scene in real time without any moving parts, as e.g. used in scanners. The semiconductor components directly allow to "perceive" distance in addition to the common greyscale information. A modulated optical signal sent out by a 850 nm transmitter illuminates the scene to be measured. The reflected light is detected by the photonic mixer device (PMD) sensor, which is able to determine the time-of-flight per every single pixel. Thus the complete 3D information is captured in parallel - without needing excessive calculation power. The sensors have first-class suppression of background illumination properties, built in to every single pixel. More detailed information about the PMD can be found in Möller et al. (2005) and in Ringbeck and Hadebeuker (2007).

The camera PMD[vision]® S3 has a resolution of 64 x 48 pixels and communicates via IP (RJ45 plug). The camera was delivered together with the control software CamVis Pro (Version 2.2.1 A2). The software contains a live viewer and it allows to store single images in an xml file format. According to the data sheet, the field of view is 40°/30°; these angles were confirmed by own tests.

Experiment 1: Distance measurement of plant leaves

The sensor's active illumination has an infrared wavelength of 850 nm. We supposed that this infrared wavelength might result in measurement errors due to the optical characteristics of plant leaves. At this wavelength, plant leaves have the property to reflect only a part of the light (in the order of 50%). Part of the infrared light is absorbed (~ 25%) and part is transmitted (~ 25%) through the leaf (Kumar and Silva, 1973; Gates et al., 1965; Woolley, 1971). The transmitted light may be reflected by some object behind the leaf, and this reflected light again is subject to partial transmittance through the leaf, thus returning a signal to the camera with a time of flight that is different from the light directly reflected by the leaf. In addition to this potential error source from transmitted light, there is also a potential error source in the directly reflected light: Only part of the light is reflected immediately by the surface; another part is only reflected after entering into the leaf and after passing multiple reflexions within the leaf (Kumar and Silva, 1973; Gates et al., 1965).

We wanted to test whether the measured distances to green leaves are influenced by the background behind/under the leaf. A maple leaf and a maize leaf were used for the test. From each of the leaves a rectangular piece (100 mm x 110 mm) was cut out. When cutting out the pieces, the maple leaf petiole and a part of the maize midrib were not cut off, so the leaves could be clamped to a tripod at the petiole resp. the midrib. For each test, one of the leaves was clamped to the tripod in front of the 3D camera. Additionally there where 3 polystyrene blocks located in the scene at three different distances from the camera. Each scene was measured twice, once with a white painted background and once with a black painted background. The precise infrared reflectance of the two painted surfaces was unknown.

The measured distances of the leaves and the equal-distant polystyrene surface differed, where the difference depended strongly from the background colour (Tab. 1). The real leaf distance to the camera was 1.5 m. With a black background, the average measured distance of the leaves was 33 mm shorter than the reference distance of the equidistant polystyrene surface. With a white background, the averaged measured distance was 19 mm longer than the reference. The leaf species did not affect the measured distances, and also did the measured distance not depend on the orientation of the leaf (upper vs. lower side towards the camera).

The experiment showed that the camera may measure inaccurate distances when dealing with plant leaves. The distance deviations that were found in this test are regarded to be relevant when measuring the 3D profile of plants, but they do not basically exclude the use of this camera for that purpose.

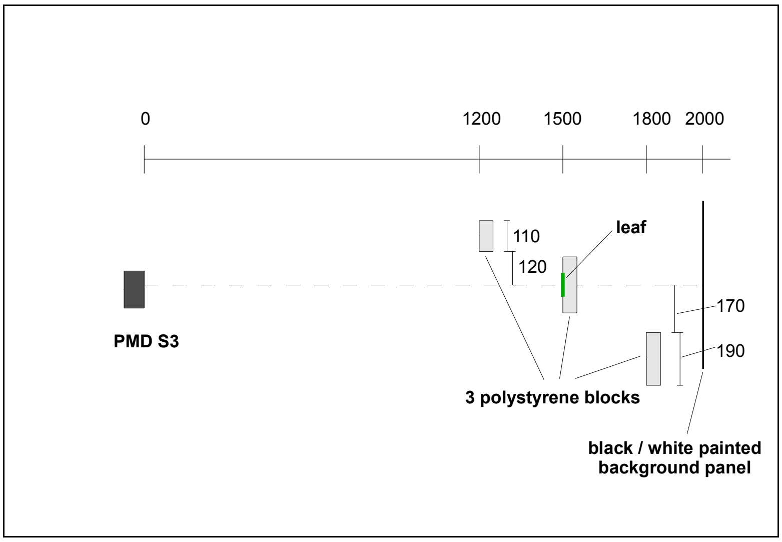

Figure 1. Experimental set-up (vertical projection) for the measurement of the distance of a green leaf with a mutually black and white background. All sizes in mm.

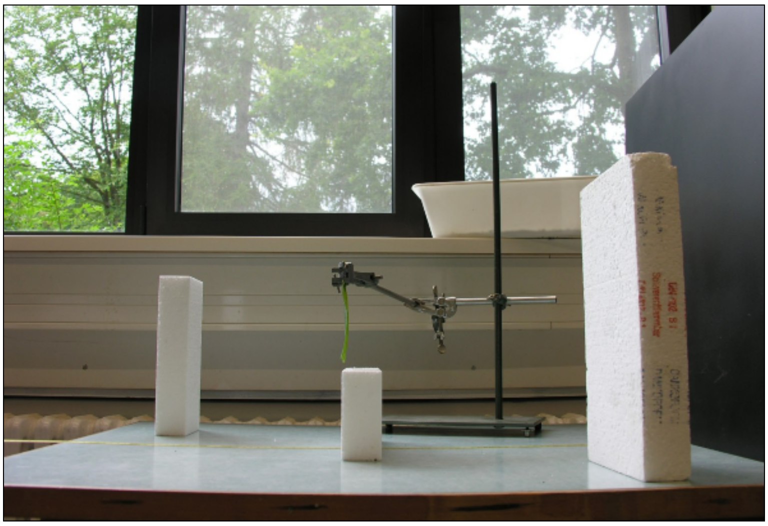

Figure 2. Lateral view of the experimental set-up for the leaf distance measurement with the maple leaf, 3 polystyrene blocks and the black background panel. The camera was positioned on the left side of the scene.

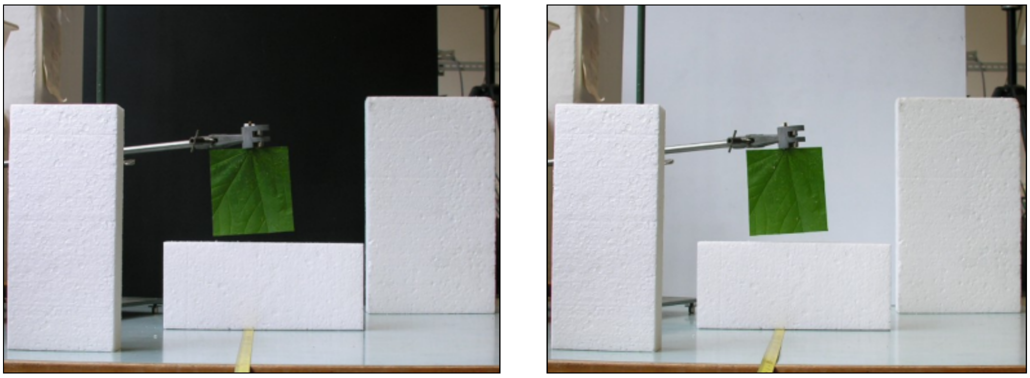

Figure 3. Experimental set-up for the leaf distance measurement from the view of the 3D camera with maple leaf and with black (left) resp. white (right) background.

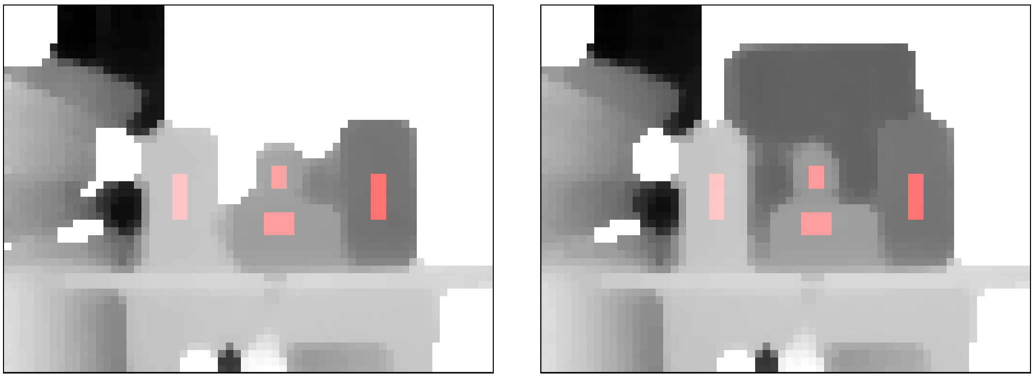

Figure 4. 3D images of the scenes in Fig. 3 with black (left) resp. white (right) background. Lighter grey values represent shorter distances. In the white areas, no distance signal could be measured. The distances were calculated from the marked rectangular areas as the median of the distance values in each of the four areas.

The exact cause of the measurement errors can not be determined without a profound knowledge of the measuring signal and the signal evaluation procedure. It may be assumed that the before-mentioned optical leaf properties at the wavelength of 850 nm play an important role. A longer time of flight may be provoked by multiple refractions within the leaf tissue as well as by light that was reflected by the white background and thereafter transmitted through the leaf. No explanation could be found for a shorter time of flight as it was measured with the black background.

Experiment 2: Height profile of maize plants

A plant pot with 12 maize plants was used for this experiment. The pot was put onto a trolley for practical purposes; the frame of the trolley is visible in the 3D images. The distance was measured vertically from above the pot. Documentation photographs were taken vertically and from two lateral sides of the maize. For the purpose of the acquisition of the photographs, polystyrene panels were positioned vertically at one side border of the frame; these panels are also visible in the 3D images.

Table 1. Measured distances of green leaves and polystyrene surfaces. All numbers are the original values as delivered by the camera, standing for millimeters. The leaf and the polystyrene area 2 had equal distances from the camera (about 1,500 mm). The areas 1 and 3 were positioned at distances of about 1,200 mm and 1,800 mm respectively.

Leaf species	Leaf side	Back-ground	Distance leaf	Distance polystyr. area 2	Distance deviation	Distance polystyr. area 1	Distance polystyr. area 3
Maize	Upper	Black	1476	1509	-33	1227	1799
Maize	Upper	White	1524	1511	13	1228	1809
Maize	Lower	Black	1468	1508	-40	1227	1797
Maize	Lower	White	1525	1508	17	1227	1800
Maple	Upper	Black	1475	1507	-32	1229	1808
Maple	Upper	White	1538	1517	21	1233	1815
Maple	Lower	Black	1480	1508	-28	1229	1807
Maple	Lower	White	1539	1513	26	1231	1812

Figure 5. Vertical view on the maize pot from the camera position.

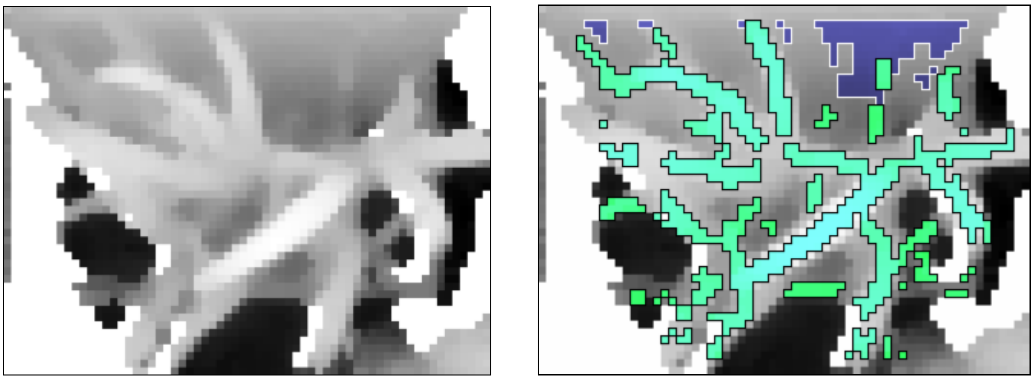

Figure 6. 3D image of the maize canopy in Fig. 5. In the white areas, no distance signal could be measured. The upper side of the image contains the polystyrene panel behind the plants. In the right image, all points are coloured that were selected by the automatic image analysis. The points marked in green and turqoise (black border) represent the leaves (and parts of the trolley). The deep blue pixels (white border) are part of the polystyrene panel.

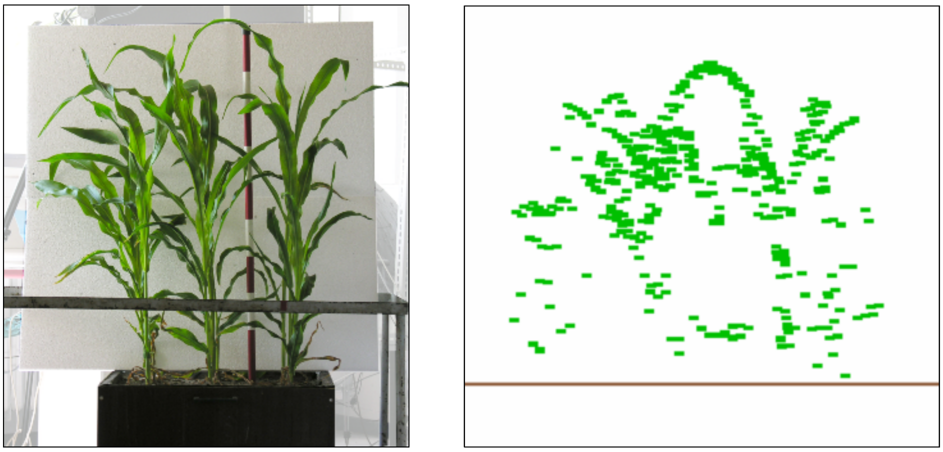

Figure 7. Front view of the maize (left) and frontal projection (right) of the 3D plant model which was calculated from the 3D image in Fig. 6. The horizontal line on the right image marks the manually detected vertical position of the soil surface in the pot.

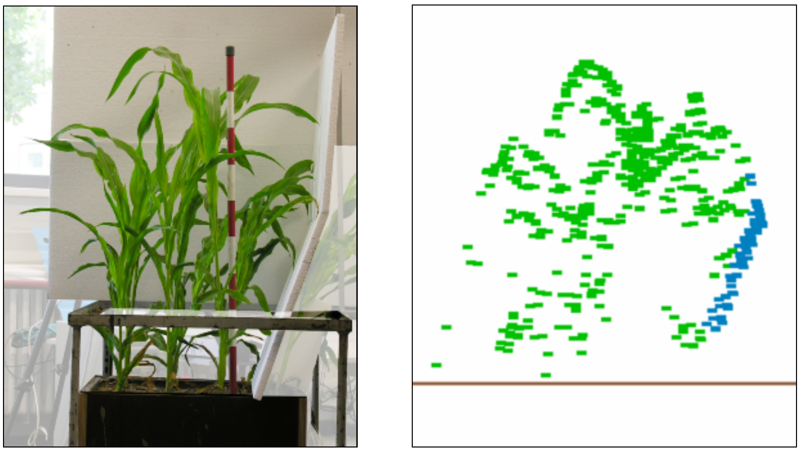

Figure 8. Lateral view of the maize (left) and lateral projection (right) of the 3D plant model which was calculated from the 3D image in Fig. 6. The blue points at the right side of the right image mark the polystyrene panel; the horizontal line marks the manually detected vertical position of the soil surface in the pot.

From the 3D image, a 3D model of the maize plants was derived: An automatic image analysis procedure was applied for the detection and localization of image points that were local maxima (= shortest distance from the camera) in at least one horizontal direction. This image analysis procedure was implemented as a rapid prototype and needs to be defined more precisely before further use. It is the purpose of the selection procedure to find the image points of the clearly visible and separable leaves. (Frame parts of the trolley were also selected.)

The selected points were transformed from polar coordinates into cartesian coordinates. They form the 3D model of the maize. In the Figures 7 and 8, the frontal and the lateral projection of the maize model is drawn. The large leaves at the top may be recognized and identified in the projection images. In contrast, almost no associated leaf points can be recognized in the lower leaf levels. This poor model quality is assumed to be due to the very simple image point selection procedure as well as to the low camera resolution. It is assumed, that some kind of image point selection is inevitable due to a big number of "mixed pixels", i.e. 3D image pixels measured at the border between two objects with different distances (e.g. leaf border and soil).

Experiment 3: Distance measurement under different natural illumination conditions

The PMD sensor is supposed not to be sensitive to environmental light in most cases due to its built-in background light suppression. In order to test the influence of the natural illumination, the camera was mounted on a tripod in 1.78 m height and thereafter in 1.63 m height above a turf area and oriented vertically downwards. The turf was not recently mown, thus the grass leaves had a height of up to 10 cm while the majority of the leaves were estimated to have a height of about 3 cm to 6 cm above ground. The images were taken on a sunny day at end July at about 3 pm MESZ.
All image points were transformed from polar to cartesian coordinates. In every image a central sub-area of 11 x 11 pixels was used for the evaluation. The measured distance was calculated as the average z coordinate of these pixels, the z coordinate representing the vertical distance between camera and turf area.

At both distances, one image was taken under full sunlight. Then the turf was shadowed by a large parasol and a second image was taken without any other change of the set-up.

Table 1. Measured distances of turf under natural sunlight and in the shadow of a parasol. The PAR value was measured at the turf level by a LiCor Li-189. The real distances could only be determined approximately. Measured distance and standard deviation refer to a central 11 x 11 pixel sub-area.

Illumination situation	**PAR** $\left(\frac{\mu mol}{s \cdot m^2}\right)$	**Real distance approx.**	**Measured distance**	**Standard deviation**
Sunlight	1,371	1,775 mm	1,816.9 mm	16.3 mm
Shadow	211		1,809.3 mm	8.6 mm
Sunlight	1,399	1,630 mm	1,600.4 mm	15.6 mm
Shadow	208		1,602.6 mm	8.0 mm

The different illumination conditions only led to small changes of the measured distances. At the first camera position, the measured distances were 1,817 mm under sunlight and 1,809 mm under the parasol. At the lower camera position, the distances were 1,600 mm resp. 1,603 mm. The differences between the sunlight and the shadow measurements were +7.6 mm and -2.2 mm. These small differences are insignificant regarding i) the measurement accuracy, ii) the standard deviation of the individual z coordinate values, and iii) the fact, that the deviation was not systematically dependent on the illumination situation. Klose et al. (2009) found, that another PMD camera (CamCube) was not able to detect height differences less than 3 cm.

However, the test showed that the standard deviation of the z coordinates was influenced by the illumination. With sunlight, the standard deviation was twice as large than with shadow. In this experiment, all occurred standard deviations must be accepted since the estimated standard deviation of the leaves' height was at least 15 mm. But Klose et al. (2009) also found an increased noise level when measuring a white board's distance under sunlight compared to under a halogen lamp.

Conclusion

The 3D camera PMD[vision]® S3 is suitable for the measurement of 3D profiles of plants and plant canopies with certain limitations. The handling is simple and robust.

The distance measurement of green plant leaves was affected by the basic optical properties of typical leaves at the employed wavelength of 850 nm. The measured distances are affected by the underground or background under resp. behind the leaf. The magnitude of the measurement deviation may be tolerable or not, depending on the measurement task. Further test experiments that are not documented in this paper showed the effect, that leaf borders were represented in the images with a bigger blurring than e.g. a white painted metal panel, as long as the border lay across the axis from the camera illumination source to the camera PMD chip.

No interferences between sunlight and the measured distances were detected.

All test experiments were carried out with measurement distances not above 2 m and with plants with very large leaves. It is evident that an image resolution of only 64 x 48 pixels does not allow the resolution of individual leaves in canopies of small leaf plants such as cereals. But the turf experiment showed that certain canopy height information may be acquired even without the resolution of individual leaves. The newer (and more expensive) camera model PMD[vision]® CamCube 2.0 offers a higher resolution of 204 x 204 pixels. The CamCube 2.0 further allows the measurement of distances up to 7 m, thus presumably allowing almost every imaginable vertical measuring position from a tractor or agricultural machinery.

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