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Sources of angle-dependent errors in terrestrial laser scanner-based crop stand measurement

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ABSTRACT

In past years, research was conducted to investigate the potential of laser rangefinders and scanners for vehicle-based measuring of crop stand physical parameters. High coefficients of determination ($R^2 > 0.90$) were found between the crop biomass and the laser rangefinder and scanner readings in the form of the mean height of reflection points of the laser beam. It was observed that the height of the reflection point increased depending on the detecting angle of the laser beam in a considerable manner. This phenomenon indicates that farther crop plants generate higher reflection points, resulting in an overestimation of crop height respectively of crop biomass. In the face of these unsolved problems, the object of the paper was to investigate the measuring properties of a chosen laser scanner depending on the inclination angle and the scanning angle and to analyze the error sources for vehicle-based laser scanner measurements in crop stands. Therefore, the scanner was investigated in two test series (May 30, 2008 in winter wheat, and June 10, 2009 in winter rye) along a transect (tramline) with a length of approximately 700 m. The performed comparisons demonstrated that one part of the observed overestimation of the reflection point height can be explained theoretically by the geometry of the laser beam. The main part of overestimation was explained by the recognizability of the gap fraction in crop stands. Because no sufficient theoretical compensation algorithm for overestimation resulting from gaps exists, it must be concluded that for each specific laser rangefinder type and crop species, the overestimation depending on detection angles has to be investigated individually in field tests.

1. Introduction

Agriculture is required to produce foods and raw materials for an increasing world population with less environmental impacts over the next decades. New improved production processes are needed to fulfill this challenge. Agricultural engineering research has to take a key position in performing the technological implementation for these new and improved production processes. For sustainable agriculture in the last decades, the approach of "**P**recision **A**griculture" (PA) became a primary focus of research and was put into practical use. The center and starting point of PA was site-specific farming, which can be described more precisely by site-specific soil and crop management.

In site-specific crop management, the crop height and biomass are important parameters for the local assessment of crop stands (Ehlert et al., 2010, Zhang and Grift, 2012). Based on these parameters, the expected crop yields can be appraised, and the amount of fertilizers and pesticides for variable rate application can be optimized. Moreover, during harvesting, the combine parameters, such as ground speed or the rotation speed of functional units (rasp-bar cylinder, cutter head), can be adapted to the crop conditions. Furthermore, the autonomous guidance of agricultural machinery along tramlines and crop edges is of great interest to increase the machinery performance and to reduce the workload for the driver. Suitable sensors are needed to be robust and at a low cost to acquire these parameters.

2. Objectives

As expressed in the introduction, the crop biomass density and crop height are important plant parameters in Precision Agriculture, whereas the crop height and the crop biomass density are correlated (Zub et al., 2011). For the crop management (fertilizing, crop protection, harvest, yield mapping) the site-specific crop biomass density is more relevant than the crop height. Therefore, sensors should measure the crop biomass density with high reliability and efficiency. Under practical field conditions on farms, the laser rangefinders and scanners are used mainly for relative crop measurements because the information regarding absolute values, e.g., for biomass in kg m^{-2} or respectively t ha^{-1}, requires expensive calibration. For measuring of grown crop biomass, the sensor must be sensitive for gaps in crop stands reducing the biomass

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density. The best sensitivity for detecting both plants and gaps is given by laser rangefinders and scanners arranged direct above the crop stand with vertical beam direction. With this arrangement the sensor can detect only a small line or area immediately in front of the agricultural machinery. To increase the detected area and the needed delay time for control operations on machinery, the sensor must ‘look ahead and sideways’. This can be achieved only by inclined laser scanners.

In the past years, research was conducted to investigate the potential of laser rangefinders and 2-D scanners for vehicle-based measuring of the physical parameters of trees in forestry, trees in orchards and crop stands in agriculture. Resulting from the forward movement of the basic vehicle, 3-D models can be derived. As a result of the height of trees in forests and in orchards, the mounting height of scanners were less than the height of the trees and therefore, the laser scanners were used in a vertical position (Van der Zande et al., 2006; Palleja et al., 2010). For measurements in crop stands, the scanners were arranged mostly above the canopy and in a horizontal position (Saeys et al., 2009; Kaizu and Noguchi, 2009; Hosoi and Omasa, 2009; Ehlert et al., 2010; Dworak et al., 2011). Zhang and Grift (2012) measured the crop height of Miscanthus giganteus by a laser scanner placed below the top of the canopy in the vertical orientation.

In previous investigations, it was shown that crop stands can be detected with high reliability by vehicle-based laser rangefinders and scanners. High coefficients of determination ($R^2 > 0.90$) were found between the crop biomass and laser rangefinder and scanner readings in the form of the mean height of reflection points (Ehlert et al., 2009, 2010). For agricultural purposes, the laser scanner is mounted on the agricultural machinery at a defined height, whereas the main scanning direction is oriented towards the area in front of the vehicle according to the driving direction. Based on own field experiences, the authors evaluate that the sensor inclination angles in the range $45° < \varphi < 65°$ are appropriate for sufficient dimensions of detected areas in front of the agricultural machinery.

Fig. 1 demonstrates the spatial geometry of a laser beam for vehicle-based measurements in crop stands, where the *X*-axis is the direction of agricultural machinery movement and the *Y*-axis is the scanning direction respectively the working width. The height of the reflection point of the laser beam can be calculated according to Eq. (1).

(*X*, *Y*, Z axes of Cartesian coordinates; SA rotation axis of the mirror inside the scanner; Z_S height of the scanner *S* above ground; 0 virtual intersection of laser beam and ground; *R* reflection point; Z_R reflection height above ground; l_R measured range; l_{XR} projection of the laser beam on the *X*–*Z* plane; φ inclination angle of the sensor; γ scanning angle; α resulting angle from φ and γ).

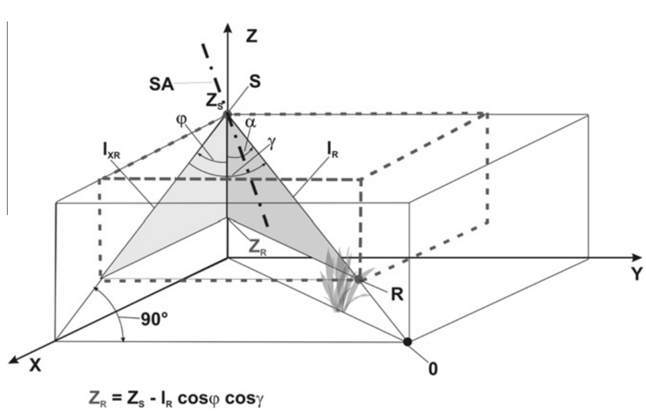

Fig. 1. Spatial geometry of laser measurements in crop stands.

$$Z_R = Z_S - l_R \cdot \cos\varphi \cdot \cos\gamma \quad (1)$$

Using the auxiliary variable resulting angle α, Eq. (1) can be simplified to:

$$Z_R = Z_S - l_R \cdot \cos\alpha \quad (2)$$

The laser beams of rangefinders and scanners can be arranged on the agricultural machinery as follows:

- fixed (φ and γ = constant; only for rangefinders with fixed beam)
- scanning in a cone shape (scanning axis [SA] identically with *Z*-axis; φ = constant; γ = variable; swiveled rangefinders with a specific mechanical cinematic)
- scanning in a plane shape (SA inclined in the *X*–*Z*-plane; φ = constant; γ = variable; 2-D laser scanners)
- scanning in a volume shape (φ = variable; γ = variable; 3-D laser scanners).

In investigations performed under field conditions, it was recognized that the height of the reflection point for crop stand assessment depends on the beam parameters, reflection distance, and detecting angle of the sensor. It was observed that increased resulting angles α cause an increased mean height of the reflection points (Ehlert et al., 2010). This phenomenon indicates that farther crop plants generate higher reflection points, thereby resulting in an overestimation of the crop biomass. For crop sensing on agricultural machinery, this measuring behavior would be a relevant problem, e.g., in the variable rate application of agro-chemicals and process-optimized forage harvesters and combine harvesters.

In face of these unsolved problems, the objectives of the paper were as follows:

- To investigate the measuring properties of a chosen laser scanner depending on the inclination angle φ and scanning angle γ in crop stands.
- To analyze the error sources for vehicle-based laser scanner measurements in these crop stands.

3. Materials and methods

Based on our own experiences and an analysis of commercially available laser rangefinders, a laser scanner that was developed for automobile driver assistance (ibeo ALASCA XT, Automobile Sensor

Fig. 2. Laser scanner ibeo ALASCA XT.