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A LIDAR-based crop height measurement system for *Miscanthus giganteus*

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ABSTRACT

The objective of this research was to develop a stem height measurement system for *Miscanthus giganteus* (MxG), to be used as a component in a future Look Ahead Yield Monitor (LAYM). For this purpose, a SICK® LMS 291 LIght Detection And Ranging (LIDAR) unit was evaluated in static and dynamic mode. To eliminate the error caused by inclination angles from undulations in the ground surface and installation, an inclination correction algorithm was developed that improved the measurement accuracy in both static and dynamic mode.

In static mode, the sensor was kept stationary and evaluated among various MxG stem densities. The results showed an average error of 5.08% with a maximum error of 8% and a minimum error of 1.8%. The static height measurement approach was also employed to measure the crop height in a 5 × 10 m field, and, compared to manual measurements, an error of 4.2% was achieved.

In dynamic mode, the sensor was driven past a field edge to provide a three-dimensional structure of the crop. An Ordinary Least Squares based surface fitting algorithm was applied to generate both the top and ground surfaces of the covered area, resulting in an average crop height. The results showed that the dynamic height measurement achieved an average error of 3.8% with a maximum error of 6.5% and a minimum error of 1.5%.

1. Introduction

Yield monitoring is a key component in the evaluation of bioenergy crop performance. Field crops such as corn and soybean are harvested for their seeds, and various technologies have been developed to measure their yield in real time using (often indirect) geo-referenced mass flow measurements. However, in the case of bioenergy crops, the complete above ground plant is harvested, and grain mass flow measurement principles do not readily translate to energy crops. One of the crops that holds considerable promise owing to its high yield and low input requirements, is *Miscanthus giganteus* (MxG) (Jezowski, 2008; Lewandowski et al., 2003; Heaton et al., 2004). Depending on climatic conditions, MxG can achieve yields ranging from 15 to 25 Mg/ha (Clifton-Brown et al., 2004; Zub and Brancourt-Hulmel, 2010). The harvest of MxG takes place in wintertime, when the leaves have fallen off and nutrients have been recycled to the root system. At this point, the standing crop consists of groupings of tall, dry, stiff, quasi-cylindrical stems with diameters in the range of approximately 5.5–12 mm, that are cut and transported into a baler or a feeding mechanism akin to that found in forage harvesters. The shape and size of the stem parts entering the machine is not conducive to (even indirect) mass flow measurement, and therefore, an alternative termed the ''Look-Ahead Yield Monitor'' (LAYM) is proposed. This mechanism could also be used to optimize the field capacity of harvesters by adjusting the travel speed, allowing the machine to operate at maximum throughput capacity. The principle of the LAYM is founded on the assumption that the combined volume of *Miscanthus* stems standing directly in front of the harvester can be determined, and the instantaneous material input as well as the related localized yield inferred. A successful development of the LAYM requires that, in addition to an off-line determination of the material density, the following measurements take place in a predetermined field coverage area being (1) the average diameter of the stems, (2) an estimate of the number of stems, (3) a GPS coordinate to the geo-reference measurements and (4) the average height of the crop. Zub et al. (2011) showed that the crop height is indeed related to biomass yield and, as an added benefit, Clifton-Brown and Lewandowski (2002) showed that the plant height can be used to identify the genotype. In this research, part 4 of the mentioned requirements being the measurement of the average crop height is addressed whereas components 1 and 2 will be reported on in future publications.

Height measurement techniques are a broad research topic in forestry. Ulander et al. (1995), Dammert and Askne (1998) and Shimada et al. (2001) applied Synthetic Aperture Radar (SAR) to measure the height of trees using interferometric models. However, these methods were environment dependent and the instrumentation was relatively expensive. Alternatively, machine

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vision based methods were employed: Cai and Walker (2010) reported on the development of a monocular machine vision-based tree height measurement method that used a camera mounted on an unmanned aerial vehicle to capture top view images of trees. The depth information was reconstructed by dynamic programming with an occlusion-modeling algorithm and the reported error ranged from 1.1 to 1.8 m. In addition, research was conducted on tree height estimation using commercially available LIght Detection And Ranging (LIDAR) systems. For instance, Magnussen et al. (1999) and Nilsson (1996) measured tree heights using an airborne LIDAR. Persson et al. (2002) described a tree height measurement method based on an airborne LIDAR as well. Here, the height of trees was measured by creating a digital terrain map and canopy model, where the reported error was 0.63 m. Kwak et al. (2007) also used an airborne LIDAR, where a morphological image analysis method was applied to a digital canopy model to detect tree tops. Subsequently, a watershed segmentation method was applied to delineate individual trees, resulting in an error ranging from 1.13 to 1.32 m. Yamamoto et al. (2010) used a small footprint airborne LIDAR to measure the mean tree height in a forest and achieved an error of less than 1 m. To measure tree height, St-Onge et al. (2004, 2007) presented methods comprising a combination of a LIDAR and a machine vision system. Finally, in vineyards, Llorens et al. (2010) compared the use of ultrasonic sensors and LIDAR to characterize crop canopies. They concluded that the LIDAR unit yielded superior data compared to ultrasonic sensors, but that post-processing of the data required the development of dedicated algorithms.

The measurement of the average MxG crop height, in this research defined as the average of the combined LIDAR visible above-ground stem lengths, was also conducted using a LIDAR, but compared to research in forestry, several complications exist. For instance, MxG stems are much smaller and thinner than trees, and therefore require more accuracy. In addition, since the field sizes are much smaller than a forest scale, aerial vehicles are not feasible in this setting. Therefore, a ground-based LIDAR was applied to measure the height of the MxG crop. The method is similar to that used by Jaakkola et al. (2010), who applied a LIDAR to develop a mapping system for tree measurement as well as the method used by Van der Zande et al. (2006), who reconstructed the tree structure using a LIDAR as well.

The objective of this research was to develop a real-time, low-cost, high-accuracy height measurement system as part of ''Look-Ahead Yield Monitor'' (LAYM) for *Miscanthus giganteus*.

2. Materials and methods

To measure the height of MxG stems, a SICK® LMS 291 LIDAR was used. This unit consists of a 905 nm pulsed infrared laser that is rotated by a plane mirror whilst using the time-of-flight principle to determine distances to objects as a function of the instantaneous mirror angle. The LIDAR can be configured for a 100° or 180° view angle, up to 80 m operating range, and an angular resolution of 0.25° (for 100° view only), 0.5° (for both 100° and 180° views) and 1° (for both 100° and 180° views).

To obtain the highest probability that an entire MxG stem is captured by the LIDAR, the unit was configured for a 180° viewing angle, combined with an angular resolution of 0.5°. According to the manufacturer's performance specifications (SICK, 2006), the laser spot diameter increases linearly with the scan distance, and, since the laser beam is pulsed, so is the spacing among the spots being emitted. The scan distances in this research ranged from approximately 2 m, where the spot spacing was 2 cm and the spot size 5 cm, to 5 m where the spot spacing was 5 cm, and the spot size 8 cm. The fact that, for both scan distances, the spot size is larger than the spot spacing implies that the scanner yields a quasi-continuous signal in the vertical direction. This is however not essential in this case, since the objective was to find the tallest points in the datasets that represent the overall height of the crop, and potential gaps were ignored. An in-depth analysis of the technical intricacies of using a SICK LIDAR for measuring natural objects such as flowers, leaves, fruits, branches, and trunks is given in Sanz-Cortiella et al. (2011).

Fig. 1 shows the experiment field located at the University of Illinois SoyFACE location in Champaign county, IL (lat, lon: 40.042684, −88.237864). This plot was planted with MxG in 2002 using rhizomes, whereas the experiments took place during the spring of 2010.

The field experiments were conducted during calm sunny days, with no discernible wind disturbing the measurements. From Fig. 1, it is clear that the MxG crop consists of tall stiff stems, some of which had leftover tassels, and that the base of the stems is littered with debris from the previous season. The soil surface, on which the sensor arrangement was riding, was covered with grass that was close to emergence. When measuring the stem height of the plants manually for comparison, the distance was measured from the point where the stem protruded above the debris/soil, to the top of the tassels. This was the distance assumed visible to the LIDAR system.

2.1. Static height measurement

For static height measurements, the LIDAR was mounted sideways on a frame at a height of 50 cm above the ground surface to scan the MxG crop in a vertical direction. The mounting height of the sensor was later verified in the measurement data. The data consisted of sampling points in polar coordinates with the LIDAR as the origin that were translated into Cartesian coordinates for analysis.

The tangential resolution of the measurements is a function of the LIDAR angular resolution setting (here 0.5°) as well as the measurement angle. Fig. 2 shows a geometric model of the MxG height measurement where the tangential resolution is obtained as a function of the angular resolution, the elevation angle with respect to the ground, and the measured distance from the LIDAR to an MxG stem.

Eq. (1) shows the functional form of this relationship.

Fig. 1. *Miscanthus giganteus* field in Urbana, IL where experiments took place in the spring of 2010.