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Research Paper

An adaptable tillage depth monitoring system for tillage machine

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Tillage depth plays an important role in crop growth and should be well managed during cultivation. Herein, an adaptable tillage depth monitoring system, which is provided with a surface-fitting swing arm and an optical encoder to measure the rotation of the swing arm, has been designed and developed. In the paper, the processes of uphill and downhill, which have been divided into 5 stages, are analysed respectively. Moreover, a LabVIEW program that can be employed to adjust the depth measurement according to the pitch angle between the implement and the ground, as well as the inclined angle of the ground, has been established to achieve adaptable measurement on different terrain morphologies. The system uses different models to allow for the variation of the angle and displacement in the process of tractor-implement combination going through the slope, and thus can achieve adaptable measurement of tillage depth. Besides, the tillage depth monitoring system can not only monitor tillage depth in real time, but also display a graphical trace of tillage history. Field experiments have been conducted to evaluate the system's performance, and have demonstrated good accuracy on both regular surface and sloped surface, showing maximal absolute errors of 11.3 mm and −12.8 mm, as well as maximum relative errors of 7.40% and 8.53% for the field experiments respectively. Hence, such a measuring system holds good potential for its application to the current tillage depth monitoring, particularly in the case of covered ground as in conservation farming.

1. Introduction

Tillage depth, as a key factor to evaluate the performance of the tillage machine, plays an important role in crop growth (Arvidsson, Westlin, & Sörensson, 2013; Condon, Ward, & Holden, 2001; Rasmussen, 1999). Traditionally, tillage depth is determined by manually measuring the soil layer with steel rulers, which is labour intensive and time consuming (GB/T 24675.2-2009). In addition, in this way, only sporadic data points can be generated with limited systematic depiction (Etana, Hakansson, Zagal, & Bucas, 1999).

Recent advances in tillage depth monitoring mainly focus on the technologies employed to achieve automatic real-time measurements of depth, and can be classified into two main

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categories, namely contact type and non-contact type. Moreover, ultrasonic and optical sensors, which are commonly used in non-contact measurements, have been widely studied in recent years (Rosell & Sanz, 2012; Saeys, Engelen, Ramon, & Anthonis, 2007; Søgaard, 1998; Van der Linden, Mouazen, Anthonis, Ramon, & Saeys, 2008). The distance can be sensed by an ultrasonic sensor installed on the implement (Kiani, 2012; Suomi & Oksanen, 2015), or an optical distance meter installed on the tractor (Lee, Yamazaki, Oida, Nakashima, & Shimizu, 2000). However, the accuracy of these non-contact sensors is strongly affected by the ground condition, especially when the surface is covered as is the case for conservation tillage (Lee, Yamazaki, Oida, Nakashima, & Shimizu, 1996; Qi, Zhang, Yu, Li, & Xu, 2010). Moreover, conservation tillage has gained substantial attention in agriculture over the past decades, thus achieving wide application, particularly in the northeast of China (Jia, Wang, Tan, & Ma, 2010; Jia et al., 2013). Nevertheless, it often requires surface coverage by stubbles and plant residues to return nutrients back to the soil, which impairs the accuracy of the non-contact tillage depth measuring system, e.g. Mouazen, Anthonis, Saeys, and Ramon (2004).

In contrast, contact tillage depth measurements, in which a physical element is utilised to make direct contact with actual surface, can still be applied to the covered ground. A tillage depth measuring system with implement wheel and a linear variable displacement transducer has been developed by Mouazen et al. (2004), and tests of this system have been performed on four surfaces. The system is suitable for the implement connected to the as a through hanging device. When it comes to an irregular surface, the applicability and accuracy of the model will be affected in the case of slope changes. Wu and Ma (2007) have designed an automatic ploughing depth control system, which unfortunately, cannot be mounted onto traction type machine. More recently, Xie, Li, Zhu, and Mao (2013), as well as Li et al. (2013) have developed a contact method based on the geometric relationship between tillage depth and lift arm angle of the tractor. However, this system can only measure the tillage depth on a horizontal surface due to the fact that the inclinometer measures the angle relative to horizontal plane. Hence, there is still a lack of a simple, surface-adaptable and tractor-mountable measuring system for real-time tillage depth monitoring.

In the present work, an adaptable tillage depth monitoring system has been developed by measuring the angle between the implement and a surface-fitting swing arm with an encoder. Moreover, a mathematical model, which is able to adjust the depth measurement on different terrain morphologies, has also been established to achieve adaptable measurement. Both in-house laboratory tests and field experiments have been conducted to validate the system and evaluate its performance.

2. Materials and method

2.1. Measuring mechanism

In order to measure tillage depth, a surface-fitting swing arm able to adapt to terrain curvature has been mounted onto the implement. The mechanical measuring arm consists of three main parts (Fig. 1): a ground wheel, a swing arm and a measuring module. The swing arm is connected to the beam of the implement by rotation axis (Joint in Fig. 5). Besides, the ground wheel of the device is pulled by the implement to roll on the untilled land. When the tillage depth increases by d, the distance between the Joint and the ground will be reduced by d, thereby resulting in a simultaneous change in the angle between the swing arm and the vertical plane (the plane perpendicular to the ground, Fig. 2(a)). As a consequence, the angle increases from θ_1 to θ_2, where θ_1 and θ_2 represent the starting and working angles between the swing arm and the vertical plane, respectively. The angle change can be detected by the encoder and converted into tillage depth through a formula, implemented in a LabVIEW program. The program has been designed to compute the tillage depth based on the relative positioning between the implement and the ground, as well as the parameters of the ground surface. The mathematical model for calculation includes four cases, shown as follows.

2.1.1. *Case 1: horizontal ground with parallel implement*

In this case, θ_1 refers to the initial angle between the swing arm and the vertical plane before tilling. When tilling begins and the tillage depth increases by d, the angle will change from θ_1 to θ_2 (Fig. 2(a)). The tillage depth can be calculated with the following equation:

$$d = L \times (\cos\theta_1 - \cos\theta_2) \tag{1}$$

where d represents the tillage depth in mm; L refers to the length of the swing arm in mm; θ_1 and θ_2 are the starting and working angles between the swing arm and the plane perpendicular to the ground, respectively.

2.1.2. *Case 2: horizontal ground with unparallel implement*

In this case, the ground is horizontal but the implement is not parallel to the ground with a tilted angle of θ_i (Fig. 2(b)). Thus, the actual tillage depth can be calculated with Equation (2) after the correction of θ_i:

$$d = L \times \cos(\theta_1 - \theta_i) - L \times \cos(\theta_2 - \theta_i) \tag{2}$$

θ_i refers to the angle between the ground and the implement, which is the same with the angle between the vertical plane (plane b–b in Fig. 2(b)) and the plane perpendicular to the implement (plane a–a in Fig. 2(b)).

2.1.3. *Case 3: inclined ground with parallel implement*

In this case, the ground is inclined at an angle (θ_g) relative to the horizontal plane, whereas the implement is parallel to the ground (Fig. 2(c)). In terms of the actual tillage depth, it is the tilled distance (d) in the plane a–a. Hence, the actual tillage depth d can be calculated by Equation (3).

$$d = L \times (\cos\theta_1 - \cos\theta_2) \tag{3}$$

2.1.4. *Case 4: inclined ground with non-parallel implement*

In this case, the inclined angle of the ground is θ_g relative to the horizontal plane, while the implement is not parallel to the inclined ground with a tilted angle of θ_i (Fig. 2(d)). The actual tillage depth refers to the distance (d) in the plane c–c.