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DEVELOPMENT OF A MEASUREMENT AND ANALYSIS SYSTEM FOR TILLAGE OPERATIONS IN PADDY FIELDS

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ABSTRACT

This study developed a foundational technology for real-time tillage depth measurement using Inertial Measurement Units (IMUs). The ultimate goal is to enable variable-rate tillage operations tailored to spatial variations in topsoil depth. The system consisted of an RTK-GNSS module and two IMUs to measure the respective pitch angles of the tractor and implement. Tillage depth was estimated using a model derived from the geometric relationship between the implement's pitch angle and its ground height. Field validation in a paddy field in Ishikawa Prefecture, Japan showed strong agreement with manually measured ground-truth depths (RMSE=0.5 cm). Subsequently, the collected data were used to generate a tillage depth map, successfully visualizing spatial variability of tillage depth. In conclusion, this study demonstrated that the developed IMU-based system can provide accurate tillage depth measurement and mapping, serving as an essential first step toward enabling future variable-rate tillage operations.

Keywords: tillage depth, IMU, GNSS, precision agriculture, mapping

INTRODUCTION

In Japanese agriculture, individual fields remain small and dispersed while the scale of farm management is expanding. This situation complicates site-specific management and highlights the need for precision agriculture technologies to manage fields uniformly (Shibusawa, 2022). In rice cultivation, maintaining a uniform topsoil depth above the hardpan is critical for stable yields (Matsunaga, 2018). However, conventional tillage methods, which typically maintain a constant depth relative to the soil surface, fail to account for variations in topsoil depth, resulting in uneven soil environments. To address this, our ultimate goal is to develop a system for dynamic tillage depth control using a topsoil depth map. However, the lack of a reliable method to measure tillage depth in real-time remains a major obstacle. Without such a system, it is impossible to verify whether the control is being conducted as intended.

Therefore, this study focuses on overcoming this fundamental challenge. We developed and validated a real-time tillage depth measurement system, which serves as the foundational technology for future tillage control systems.

MATERIALS AND METHODS

The system consisted of two IMUs (BWT901CL, Witmotion) mounted on the tractor cabin frame and three-point linkage respectively and an RTK-GNSS module (UM982, Unicore) mounted on the tractor roof. Data acquisition and synchronization were carried out in real-time using ROS2 Humble on a mini-PC (Intel N5095). A tillage depth estimation model was constructed based on the geometric relationship between the implement's pitch angle and its actual ground height. The ground-truth heights for model calibration were acquired by a LiDAR sensor (MID-70, Livox). The system was validated during an autumn tillage operation in November 2024 in a paddy field in Ishikawa Prefecture, Japan.

RESULTS & DISCUSSION

CALIBRATION MODEL

A tillage depth estimation model was developed based on the geometric relationship between the implement's pitch angle (*θ,* rad) and tillage depth (*H,* cm). This relationship was described by the following quadratic regression in Eq. (1):

$$H = 0.075\,\theta^2 - 3.81\,\theta + 21.4 \quad (1)$$

A comparison between the depths estimated by Eq. (1) and the LiDAR-measured reference values yielded an RMSE of 0.2 cm, indicating the calibration accuracy of the model.

VALIDATION TEST

The system's performance was validated in a field trial in Ishikawa Prefecture, Japan. The estimated depths showed strong agreement with ground-truth depths, with an RMSE of 0.5 cm (N=114). The increase in RMSE from the calibration result was likely due to field factors, such as errors in manual measurements caused by stones and soil mounds, as well as the tractor sinkage. Nevertheless, the error remained at the millimeter scale, indicating that the system achieves sufficient accuracy for practical applications. Additionally, the estimated tillage depths were used to generate a tillage depth map (Fig.1). This map successfully visualized the spatial variability of tillage depth across the field and provided detailed, objective operational records.

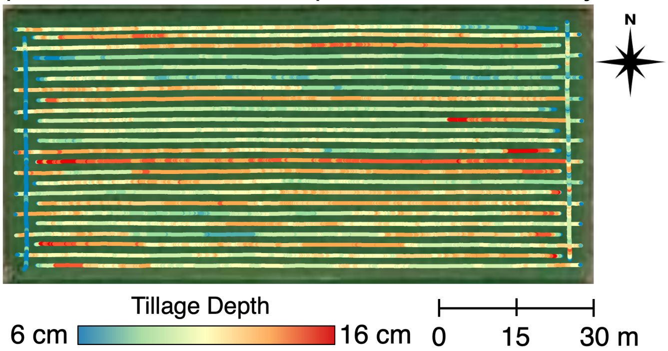

Fig. 1 Tillage depth map generated from the autumn tillage operation.

CONCLUSIONS

The developed system demonstrated accurate tillage depth measurement and effective mapping in paddy fields. This study successfully provides the foundational technology essential for future variable-rate tillage. By providing objective operational records in the form of a map, the system facilitates the transfer of expertise, enabling less experienced farmers to learn from the practices of skilled farmers and objectively review their own work.

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