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A 3D CAMERA-BASED FERTILIZER RESIDUE MONITORING SYSTEM WITH ISOBUS FOR PRECISION AGRICULTURE

Changho Yun[1*], Gookhwan Kim[1], Changju Yang[1], Kyung-do Kwon[1], Choung-keun Lee[1]

[1] Department of Agricultural Engineering, National Institute of Agricultural Sciences, Republic of Korea.

*Corresponding Author: changho288@korea.kr

ABSTRACT

Accurate monitoring of fertilizer usage is critical for effective variable-rate fertilization (VRF), contributing to optimized nutrient management and environmental sustainability. VRF systems typically use open-loop control based on prescription maps and calibration data. However, this approach can introduce discrepancies between targeted and actual fertilizer application rates due to variations in fertilizer characteristics and environmental conditions. This study proposes a fertilizer hopper residue monitoring system utilizing a Time-of-Flight (ToF) camera integrated with ISOBUS communication protocols. The system continuously measures fertilizer residue inside a sealed hopper using real-time ToF camera data. An embedded microcontroller processes these data into residue percentages, communicating them via standardized ISOBUS messages (PGNs/DDIs) to the tractor's Virtual Terminal (VT). Field tests under realistic agricultural conditions demonstrated stable performance despite environmental disturbances such as vibration and dust. By combining real-time residue measurements, GNSS positioning, and open-loop fertilizer control data, the system enhances accurate spatial mapping and analysis of actual fertilizer application across specific field locations. Compatibility with ISOBUS ensures seamless integration with existing agricultural machinery. The developed system thus provides precise, geo-referenced fertilizer usage data, significantly contributing to improved agronomic decision-making, optimized fertilizer application, and enhanced environmental sustainability in precision agriculture.

Keywords: Fertilizer hopper residue monitoring, Time-of-Flight camera, Variable-rate fertilization, ISOBUS, Precision agriculture

INTRODUCTION

Reliable, real-time knowledge of fertilizer remaining in a hopper improves application accuracy, documentation, and refilling logistics. Threshold level sensors are binary; load-cell systems add cost and are sensitive to vibration. We propose a compact, non-contact 3D Time-of-Flight (ToF) camera method that estimates hopper residue in real time and converts volume to mass for practical on-board use. We (i) implement a residue-sensing pipeline, (ii) quantify laboratory accuracy, (iii) verify single-model reusability across runs, and (iv) prepare an ISOBUS-ready VT/TC interface concept for display and task-data logging.

MATERIALS AND METHODS

A SYNEXENS CS20 ToF camera was mounted above the hopper (central, downward view). A digital balance beneath the hopper provided ground-truth mass in laboratory trials. For baseline setup, with the hopper emptied, the system captures a stabilized point cloud, applies filtering, and converts it to grid heightmap.

$$\Delta h = H_0 - H_t,\ V_{residue} = \sum \Delta h \cdot \Delta A \quad (1)$$

and consumed mass is estimated by a compact linear model

$$M_{used} = aV_{residue} + b,\ \mathrm{M_{rem}} = \rho_{bulk} V_{residue},\ M_{used} = M_{init} - M_{rem} \quad (2)$$

This is consistent with the physics-informed relation in Eq.(2) and bulk density of the applied fertilizer was 0.8 kg/L. For user-side convenience, a five-point step-fill is provided; add 5 kg increments (5, 10, 15, 20, 30 kg), capture the corresponding residue values and fit (a,b) in the regression model. Using the ISOBUS interface, VT pages align with the algorithm states (Baseline Setup, Monitoring). On-bus, usage is exposed through yield DDIs (e.g., DDI 182 Dry Mass Per Time, mg/s; DDI 83 Volume Per Area, ml/m²) and recorded as ISOXML by TC with GNSS. Low-level is handled via a DTC event with a VT-configurable threshold, while remaining (%) is shown to the operator on VT.

RESULTS & DISCUSSION

Using five samples (5, 10, 15, 20, 30 kg) matched to camera-measured (a=-0.68, b=33.082). The fixed model was applied to two datasets acquired under different discharge regimes.

Table 1 Error summary by operating regime (RMSE/MAE, kg)

Regime	Overall	0–2 kg(coverage-limited)	≥ 2 kg(normal range)
Discharge, 2.72 kg/L	0.30 / 0.22	0.52 / 0.46	0.19 / 0.15
Discharge, 0.54 kg/L	0.34 / 0.26	0.84 / 0.80	0.23 / 0.20

The coverage-limited early-use band (0–2 kg used; hopper near-full) dominates the error. When the hopper is still highly filled, the camera's view into the bin is partially occluded and effective coverage is low; small apparent thickness changes at the top of the fill amplify quantization effects. Once > 2 kg has been used (coverage improves), the errors drop markedly (Table 1). Practically, quantitative readouts may be suppressed below ~2 kg and replaced by a VT low-level alert, while usage continues to be logged via VT/TC.

CONCLUSIONS

A 3D ToF-based residue system estimates consumed mass in real time with high accuracy. A single five-point step-fill calibration achieved low overall errors across two regimes, with higher errors confined to the near-empty band and substantially lower errors above 2 kg. A two-state workflow (Baseline Setup, Monitoring) and an ISOBUS-ready VT/TC mapping—using standard yield DDIs for usage and DTC for low-level alerts—prepare the algorithm for on-tractor deployment and as-applied documentation.

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