Development of a Low-Power Wireless Communication System Using LoRa for Structural Monitoring in Greenhouse Foundations

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ABSTRACT

Plastic greenhouses dominate protected cultivation in South Korea but are vulnerable to extreme weather and foundation instability. To address this issue, a low-power, low-cost monitoring system was developed to estimate foundation attitude and detect anomalies such as uplift. The system integrates an IMU (Inertial Measurement Unit)-based sensor node, LoRa (Long Range) communication, and a gateway in a star topology. Field tests, including pipe uplift and natural conditions, confirmed comparable accuracy to a commercial IMU despite a 30-fold cost difference. Attitude angle analysis showed that both instantaneous and gradual changes clearly distinguished abnormal uplift from normal conditions. The measured power consumption of about 55.1 mW enables long-term operation and potential energy harvesting. These results demonstrate the feasibility of applying low-cost IMUs to monitor lightweight structures such as plastic greenhouses.

Keywords: Greenhouse monitoring, Inertial sensing, Anomaly detection, Low-power embedded system, LoRa wireless communication

INTRODUCTION

Protected cultivation accounts for 11% of South Korea's agricultural output, with plastic greenhouses comprising over 99% of the total 52,723 ha of greenhouse area (MAFRA, 2024). In South Korea, between 2020 and 2023, about 73% of plastic greenhouse damage was caused by extreme weather, representing 25% of total private facility losses (KOSTAT, 2025). While the Rural Development Administration (RDA) has set standards for disaster-resistant greenhouses, no regulations address foundations, highlighting the need for a monitoring system to observe long-term foundation behavior and detect anomalies early.

MATERIALS AND METHODS

For attitude estimation, the BMI160 IMU (Inertial Measurement Unit) module (Bosch Sensortec, Germany) with a three-axis accelerometer and gyroscope was used. The ODR (Output Data

Rate) was set to reflect greenhouse foundation dynamics. Acceleration and angular velocity were obtained from the sensor output, elapsed time from the internal counter, and pitch and yaw were derived. The sensor node generated time, acceleration, angular velocity, pitch, and yaw data at 12.5 Hz.

For long-range communication, a LoRa (Long Range) module (E220-900T22D, Ebyte, China) was used. The transmitter operated in Normal mode only during data transmission and in Sleep mode otherwise to save power, while the receiver remained in Normal mode. To avoid collisions, the Listen Before Talk (LBT) technique was applied.

The system used a star topology with sensor nodes and a gateway. Each node detected attitude changes via the IMU and sent packets to the gateway when thresholds were exceeded, while other data were stored on a microSD card. The gateway, connected to an IP network, received node data and delivered them to the user.

Four field tests evaluated the accuracy, anomaly detection, and stability of the sensor nodes. Cases 1 and 2 involved pipe uplift (48 mm and 25 mm) with a commercial IMU for validation. Case 3 extracted segments from about 50 hours of natural-condition data, selecting periods with little wind and temperatures similar to Cases 1 and 2, while Case 4 assessed operating time using three Li-FeS$_2$ AAA batteries for about 98 hours.

RESULTS & DISCUSSION

Data were processed with complementary and Kalman filters and compared to a commercial IMU. In Cases 1 and 2, both filters showed similar trends, but RMSE analysis indicated the Kalman filter ($Q = 0.001, R = 0.1$) was more accurate and suitable for the system.

Instantaneous changes were evaluated by RMS of differentiated attitude angles, while gradual changes were assessed by applying the Reumann–Witkam algorithm for linear simplification and calculating RMS of slope variations by central differencing. Results showed uplift cases had pitch and yaw more than seven times larger than natural conditions, and gradual changes up to 24 times larger, confirming clear anomaly detection capability.

Datasheet power consumption was 26.81 mW, while Case 4 measurements showed 55.1 mW due to regulator losses and battery characteristics, about 13.8% of a commercial IMU (400 mW). Case 4 also showed stable operation with no missing data, consistent 80 ms intervals, and outlier ratios below 1.1%.

CONCLUSIONS

The sensor node achieved attitude estimation comparable to a commercial IMU at about 1/30 of the cost. Instantaneous and gradual attitude changes enabled reliable detection of uplift anomalies, and measured power consumption of 55.1 mW supports long-term operation and indicates the feasibility of energy harvesting. This study confirms the potential of low-cost IMUs for monitoring lightweight structures such as plastic greenhouses, with future work focusing on large-scale tests and edge-computing–based anomaly detection.

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