Large-term sensing system for agriculture utilizing UAV and wireless power transfer

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***Abstract*—In recent years, in order to improve crop production and quality of agricultural operations, an "agricultural remote monitoring system" have been attracting a lot of attention. The existing studies have proposed an agricultural remote monitoring systems using Wireless Sensor Network (WSN). In the existing system, the environmental information is collected from a large number of sensor nodes installed in the farm using a low-power wireless communications (e.g., ZigBee, LPWA). However, in these systems, even when the low-power wireless technology is utilized, it is difficult to run permanently on batteries because the battery capacity is not infinity. In addition, in the case of a large-scale field, a large number of intermediate nodes should be installed in the field, hence the installation and operation costs are high.**

On the other hand, a wireless power transfer technology is evolving and equipment which is capable of supplying power to places dozens of centimeters away has been available. In addition, Unmanned Aerial Vehicles (UAV) that can fly stably for a long time and has a large loading capacity has appeared.

Therefore, in this study, we propose and develop a wide-area sensing system for large-scale farms using a UAV, a wireless power transfer technology, and an energy-saving short-range wireless communication system (i.e., Bluetooth Low Energy (BLE)). The UAV flies autonomously to the location of sensor nodes that are widely installed in the large farm for collecting the sensor data. Here, the UAV is designed to supply the power to the sensor node to measure and send the environmental information using the wireless power transfer technology. It eliminates the need for periodic battery replacement of the sensor node, which reduces the cost of operating the system.

Through the experimental evaluation using the developed system, it has been confirmed that the UAV can accurately be controlled by the proposed feedback control to land near the sensor nodes, and that the sensor nodes can be operated by the wireless power transfer from the embedded system of the UAV.

***Index Terms*—UAV, Wireless Power Transfer, BLE, Agriculture**

I. INTRODUCTION

In recent years, in order to improve crop production and quality of agricultural operations and to reduce labor's cost, an "agricultural remote monitoring system" for remotely observing the environmental condition of the farm and a "precision agriculture" that is a farming management concept based on observing, measuring and responding to inter and intra-field variability in crops have been attracting a lot of attention.

So far, the existing studies have proposed an agricultural remote monitoring systems using Wireless Sensor Network (WSN) and remote sensing using Unmanned Aerial Vehicles (UAV). In the existing WSN-based system, the environmental information (e.g., temperature, humidity, illuminance) is collected from a large number of sensor nodes installed in the farm using a low-power wireless communications (e.g., ZigBee, LPWA). However, in these systems, even when the low-power wireless technology is utilized, it is difficult to run permanently on batteries because the battery capacity is not infinity. In addition, in the case of a large-scale field, a large number of intermediate nodes should be installed in the field, hence the installation and operation costs are high.

On the other hand, a wireless power transfer technology is evolving and equipment which is capable of supplying power to places dozens of centimeters away has been available. In addition, UAVs that can fly stably for a long time and has a large loading capacity has appeared.

Therefore, in this study, we propose and develop a wide-area sensing system for large-scale farms using UAV, a wireless power transfer technology, and an energy-saving short-range wireless communication system (i.e., Bluetooth Low Energy (BLE)). In the proposed system, the UAV flies autonomously to the location of sensor nodes that are widely installed in the large farm for collecting the sensor data. Here, the UAV is designed to supply the power to the sensor node to measure and send the environmental information using the wireless power transfer technology. The combination of the UAV and the wireless power transfer technology not only cover a wide area of several kilometers to dozens of kilometers but also eliminates the need for periodic battery replacement of the sensor node and reduces the cost of operating the system.

II. RELATED WORKS AND OBJECTIVES OF OUR STUDY

A. *WSN-based Remote Monitoring System for Agriculture*

Kassim and Patil have proposed and implemented a WSN system to remotely monitor temperature and humidity on the farm in real time [1] [2]. In addition, Fitriawan has evaluated performance (e.g., packet loss rate, throughput) of ZigBee-based WSNs in various communication types (e.g., one-to-one, many-to-one, multi-hop) and environments (e.g., indoor, outdoor) [3] [4]. In these existing studies, a large number of intermediate nodes should be installed for constructing a wide area WSN system, which results in high installation and operation costs. Especially, it is difficult to construct a wide-area agricultural remote monitoring system that covers a range of a few kilometers to dozens of kilometers because the throughput decreases as the number of hops in the communication path increases. Furthermore, even if the low-power wireless technology such as ZigBee and LPWA is utilized, the battery of the sensor node should sometimes be replaced because the battery capacity is not infinity.

B. UAV-based Remote Sensing System

In the existing studies, the UAV has been used for supporting agriculture [5] [6] [7]. Katsigiannis have used multispectral and thermal cameras to take aerial photographs to observe the vegetation and the water stress [8]. In addition, Rokhmana have used a high-resolution camera to take and analyze photos of the field to understand farmland area and growth variability [9]. However, these studies focus on analyzing images using high-priced cameras, and there is no consideration for utilizing UAV to efficiently collect environmental information.

C. Objectives of This Study

Based on the problems described in the previous sections, this study develops a new sensor network system utilizing the UAV equipped with not only a camera but also an embedded system with a short-range wireless communication (BLE) and a wireless power transfer module. The BLE module is used to collect the environmental information related to crop growth from sensor nodes installed at multiple locations of a large farm. In addition, by using wireless power transfer technology, the sensor nodes installed on the farm can be run without a battery, which eliminates a cost for periodic battery replacement.

III. PROPOSED SYSTEM

Overview of our proposed system is shown in Fig.1. A main component of the system is an embedded system which controls flight of a UAV and supports a BLE communication and a wireless power transfer, a stationary sensor node which collects environmental information (e.g., temperature, humidity, illumination) on the farm, and a server that manages and analyzes the data collected by the UAV.

When the embedded system receives a flight command from a terminal owned by the administrator, it sends a control command including the location information of the stationary sensor nodes to the UAV. Then, the UAV flies to the location of the stationary sensor node, takes a picture of the growth condition of the crop on the farm, and lands on the ground near the stationary sensor node. After the stationary sensor node is activated by being supplied power from a power transmission substrate of the wireless power transfer module mounted on the embedded system, It transmits the measured sensor data to the UAV using BLE communication. After the UAV finishes acquiring sensor data from all sensor nodes, it returns to the start point of the flight and sends the collected sensor data and the image pictures to the server via HTTP communication through wireless LAN. The server manages and analyzes the data received from the UAV, and provides the visualized data to the browser of the smartphone, tablet, and PC browsers.

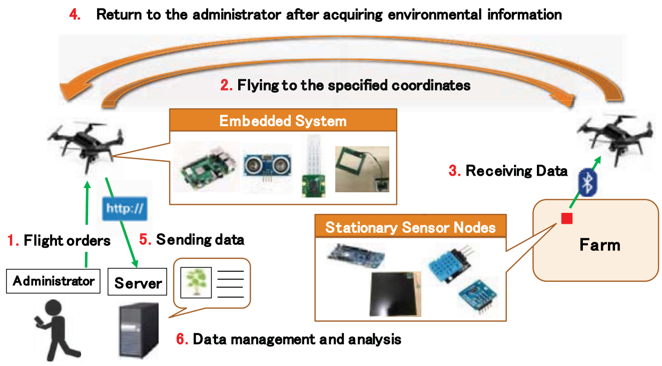

Fig. 1. Overview of Proposed System

TABLE I
UAV SPECIFICATIONS

Estimated Flight Time	20 to 25 minutes.
Maximum height	48 meters
Communication Distance	800m
Payload	800g

A. Device/Functional Structure of the Proposed System

In the following sections, we explain device and functional structure of the main components of the proposed system: a UAV with an embedded system, a stationary sensor node and a server.

1) UAV with Embedded System: Device configuration of the embedded system is shown in Fig.2 and the appearance of the UAV is shown in Fig.3. The proposed system uses 3D Robotics's 3DR SoLo as a UAV, which is capable of stable flight based on GPS coordinate and can be controlled by receiving the commands from the embedded system through the wireless LAN. The main specifications of the UAV are shown in Teb.I. In addition, the embedded system on the UAV is based on a Raspberry Pi 4 Model B, which is a single-board computer supporting Wi-Fi and Bluetooth. The UAV operates as an access point for a wireless LAN, and the embedded system connects to the UAV through the wireless LAN and controls the flight function of the UAV. This structure allows the embedded system to control the UAV even when the UAV flies away from the administrator beyond the limit of the communication distance of the wireless LAN. The embedded system is equipped with a Raspberry Pi Camera V2, an inexpensive camera module for capturing images of the lower part of the UAV, a HC-SR04 that is a ultrasonic sensor for accurately measuring the altitude of the UAV, and a MQS-1PXD-R1, power transmission substrate for supplying power to the stationary sensor nodes using wireless power transfer technology.

2) Stationary Sensor Node: Device configuration of the stationary sensor node is shown in Fig.4 and the appearance

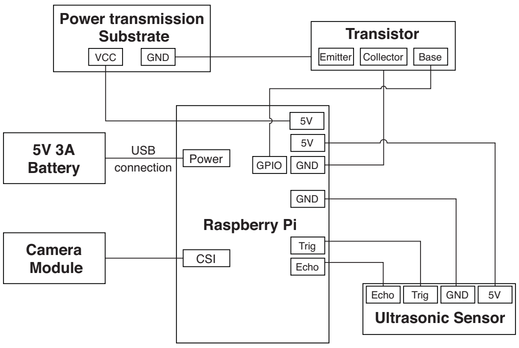

Fig. 2. Device Configuration of Embedded System

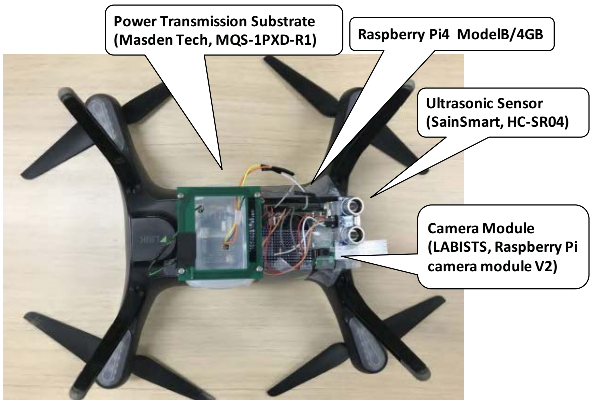

Fig. 3. Appearance of UAV

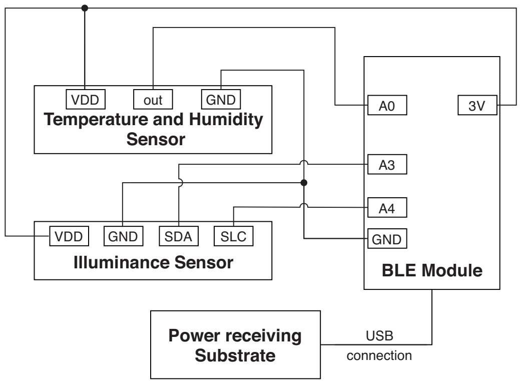

Fig. 4. Device Configuration of Stationary Sensor Node

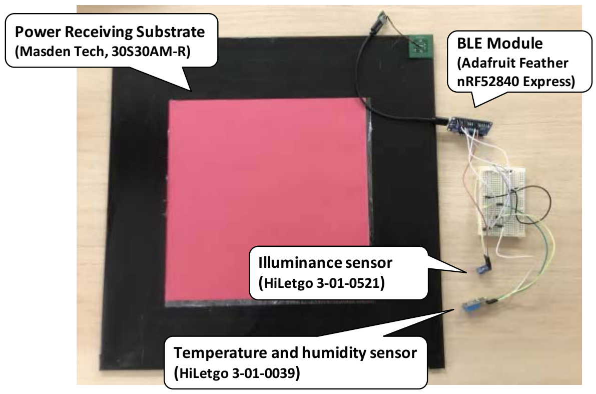

Fig. 5. Appearance of Stationary Sensor Node

is shown in Fig.5. The stationary sensor node installed on the farm is composed of a microcontroller supporting a BLE communication, Adafruit Feather nRF52840 Express. The microcontroller is equipped with a temperature and humidity sensor, and an illuminance sensor. In addition, the stationary sensor node is connected with a power receiving substrate of the wireless power transfer module, and is activated by a power supply from the UAV. After activated by the UAV, it measures the sensor data, and sends the measured sensor data to the UAV using BLE communication. The packet format of the sensor data is shown in Teb.II.

3) Server: In the proposed system, we use a standard PC server as the server. The server centrally manages data of the environmental information on the farm and the images of crops using MySQL, and analyzes the data and images received from the embedded system to estimate the crop growth and weather conditions. Furthermore, it executes the HTTP server to provide the visualized data to the browser of the smartphone, tablet device, and PC so that the administrator can easily understand the condition of the farm.

B. Algorithm for Autonomous Flight

1) Sensor Data Collection Using Wireless Power Transfer: In this proposed system, the UAV is controlled based on the GPS coordinate and the result of the analysis of the image captured by the camera connected to the UAV so that it can land correctly on the stationary sensor node. After that, by supplying electric power from the UAV to the stationary sensor node using the wireless power transfer technology, the stationary sensor node can be configured without a battery.

The flight and data acquisition procedure of the UAV is shown in Fig.6. First of all, when the UAV with the embedded system receives a flight control command that includes coordinate of the stationary sensor nodes from the administrator, it flies and moves to the position just above the stationary sensor node based on the GPS coordinate. The accuracy of coordinate measured by the GPS of the UAV is about 2 meters, hence the distance between the UAV and the sensor node is within the range of the BLE communication if the UAV is landed simply based on the coordinate of the GPS. However, if the UAV is apart such a distance from the stationary sensor node, it cannot supply enough power to the stationary sensor node to activate the measurement and BLE communication functions. Therefore, the embedded system analyzes the images taken by the camera mounted on the lower part of the UAV and controls the UAV using the landing algorithm of feedback control (see Section III.B.2) so that the UAV can land just above the stationary sensor node. At this time, if the distance between the power transmission substrate in the UAV and the power receiving substrate connected to the stationary sensor

TABLE II
PACKET FORMAT OF ENVIRONMENTAL INFORMATION

ID	1Byte	2
Temperature	1Byte	24°
Humidity	1Byte	30%
Illuminance	2Byte	12000lx

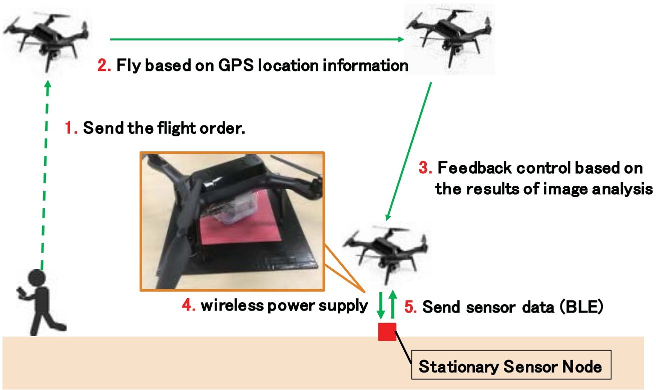

Fig. 6. Procedure for Acquiring Sensor Data

node is sufficiently short, power is supplied from the UAV to the stationary sensor node.

2) Feedback Control of UAV Using Image Analysis: After arriving in the sky above the sensor node based on the GPS coordinate, if the embedded system detects the shape of the power receiving substrate in the image taken by the camera, the UAV horizontally moves so that the power receiving substrate appears at the central point of the image. This process is repeated while lowering the altitude of the UAV until the wireless power transfer can be started. If the embedded system cannot detect the power receiving substrate in the captured image, the UAV increases the altitude and takes the image again.

The detection procedure of the power receiving substrate is described below. In this study, in order to make the detection easier, a $25\text{cm} \times 25\text{cm}$ piece of red drawing paper is pasted on the surface of the power receiving substrate of the sensor node, and the power receiving substrate is detected by applying color extraction and rectangular extraction process to the original images. First, the embedded system uses the color extraction based on the HSV model to extract only pixels of a specific color from the image. Next, the embedded system executes the rectangular extraction process for the pixels that are extracted by the color extraction process and calculates the center coordinate of the power receiving substrate. An example of the extraction process is shown in Fig.7.

Next, the embedded system calculates the horizontal movement distance between the UAV and the central point of the sensor node, and moves to the position just above the sensor node. The actual distance per pixel in the image varies with the altitude of the UAV as shown in Fig.8. Therefore, the embedded system calculates the actual distance per pixel

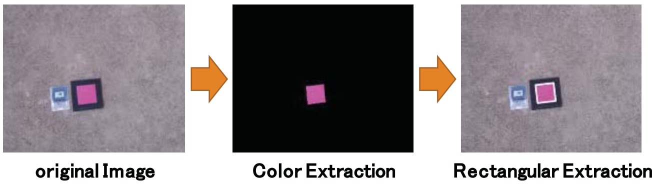

Fig. 7. Example of Extraction Process

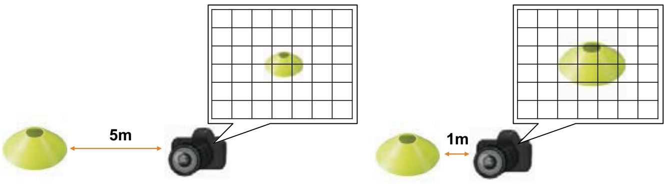

Fig. 8. Relationship Between Distance and Number of Pixels

from the angle of view of the camera and the altitude of the UAV, and then calculates the horizontal distance to the center coordinate of the power receiving substrate. Here, the current altitude can be measured using a barometric pressure sensor which is standardly installed on the UAV, but the sensor cannot accurately measure the altitude. Therefore, the ultrasonic sensor is used to measure the altitude after the altitude of the UAV reaches the measurement range of the ultrasonic sensor (i.e., 3 meters). After that, the UAV lowers the altitude and is moved to the direction of the stationary sensor node for the calculated distance. This process is repeated until the distance is close enough to supply power to the sensor node using the wireless power transfer.

IV. PERFORMANCE EVALULATION OF WIRELESS POWER TRANSFER

In this section, we conduct preliminary experiments to evaluate the power supply performance of the wireless power transfer module used in this proposed system.

A. Magnitude of Current Supplied by Wireless Power Transfer

First, the magnitude of current supplied from the power transmission substrate to the power receiving substrate during wireless power transfer is investigated. In the proposed system, the power is supplied by the power transmission substrate with 1W/5V output when approaching the power receiving substrate of 40cm square. At this time, the amount of current supplied to the power receiving substrate is expected to vary depending on the distance between the substrates and the positional relationship. Therefore, the magnitude of current supplied in various positional relationships is measured.

The experiment is conducted in a flat area in a room at Ritsumeikan University, where there is no metal around. In the experiment, the height of the power transmission substrate is fixed at 0, 2 and 4cm from the floor. The power transmission substrate is moved from the center of the power receiving substrate by every 1 cm in the lateral and diagonal directions

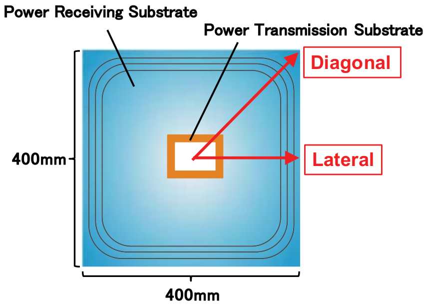

Fig. 9. Evaluation of Wireless Power Transfer Module

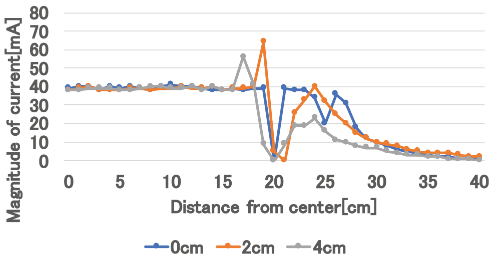

Fig. 10. Evaluation of Wireless Power Transfer Module(lateral)

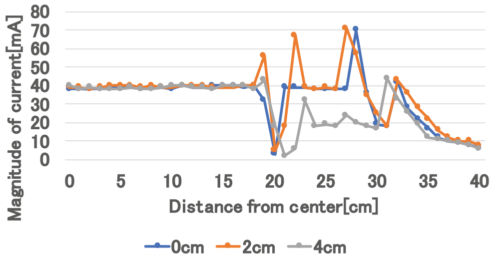

Fig. 11. Evaluation of Wireless Power Transfer Module(diagonal)

as shown in Fig.9, and the magnitude of current supplied is measured at each point.

The results of the experiments when moving the power transmission substrate in the lateral and diagonal directions are shown in Figs.10 and 11, respectively. These figures show the relationship between the distance between the power transmission and receiving substrates and the magnitude of current. As shown in these figures, after the distance between the substrates increases beyond a certain distance, the magnitude of current supplied tends to decrease. In addition, the magnitude of current significantly decreases when the power transmission substrate passes near the edge of the receiving substrate (around 20cm in x-axis) because the coils are crowded around the periphery of the power receiving substrate and it is not possible to generate a stable induction current due to the positional relationship.

By confirming the actual operation of the BLE module used in the proposed system, it is clarified that the module works fine within 31cm from the center of the power receiving substrate, except for the 20cm area mentioned above, when the height of the power transmission substrate is 2cm. Therefore, we can conclude that the UAV can provide sufficient power to the BLE module using the wireless power transfer by landing within an area of 62cm square.

B. Packet Loss Rate during Wireless Power Transaction

In this study, we prototype a stationary sensor node using the BLE module and evaluate the communication performance during wireless power transfer. This experiment is conducted in the ground at Ritsumeikan University.

In this experiment, the stationary sensor node repeatedly transmits the packet of 20 bytes (maximum packet size of BLE) to the embedded system on the UAV 100 times during a wireless power transfer. This measurement is performed when the power transmission substrate is placed at various points within an area (i.e., 62cm square) where the wireless power transfer is successful.

In the experiment, the embedded system can correctly receive all data packets with no data corruption or missing. Thus, it can be clarified that the wireless power transfer is useful to operate the stationary sensor node for collecting the environmental information.

V. PERFORMANCE EVALULATION OF LANDING CONTROL ALGORITHM

In this section, we develop an embedded system installed on the UAV, and conduct a demonstration experiment to evaluate the effectiveness of the proposed landing control algorithm.

A. Detection Accuracy of the Stationary Sensor Node by Image Analysis

In this experiment, We firstly evaluate detection accuracy of the power receiving substrate of the stationary sensor node by image analysis. This experiment is conducted in the ground at Ritsumeikan University, and the altitude of the UAV is raised at 5m intervals and 20 images are taken at each altitude. Then, the images are analyzed for detecting the shape of the power receiving substrate, and the detection accuracy is evaluated at each altitude.

Figure 12 shows the relationship between the altitude of the UAV and the detection rate of the stationary sensor node. From this figure, the detection rate tends to decrease as the altitude of the UAV increases. In addition, the detection rate of sensor nodes is stable when the altitude of the UAV is lower or equal to 20 meters. However, when the altitude exceeds 25 meters, the accuracy markedly decreases because the different objects can be detected as the sensor nodes. Here, when the altitude of the UAV is 20 meters, the image taken by the camera module can capture an area of about 20 meters square. Therefore, even if the measurement error of the GPS coordinate is about 5 meters, it is possible to keep the stationary sensor node within the angle of view of the camera module by navigating the UAV based on the GPS coordinate.

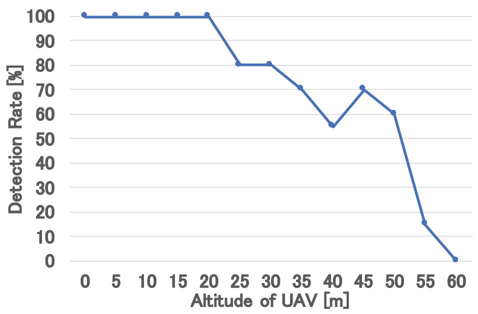

Fig. 12. Detection Accuracy of the Sensor Nodes Using Image Analysis

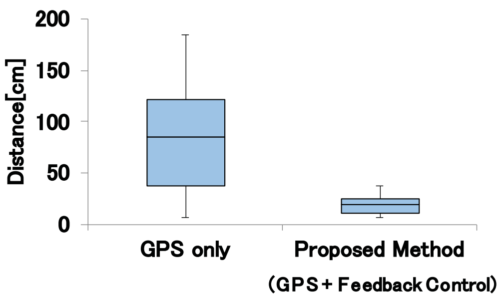

Fig. 13. Effectiveness of Feedback Control using Image Analysis

B. Landing Accuracy of Feedback Control Algorithm

In order to evaluate the effectiveness of the proposed feedback control algorithm, we compare the performance between the proposed algorithm and the simple GPS-based navigation in terms of the distance between the landing point and the center point of the sensor node. In addition, we confirm whether the wireless power transfer succeeds a landing point in each algorithm.

This experiment is conducted on the same ground as the previous sections. The sensor node is installed at a position 30 meters away from the takeoff point of the UAV, and the UAV is controlled by the embedded system to land near the sensor node. In this evaluation, ten trials are performed for each method and the distance between the power transmission substrate and the power receiving substrate at the landing point is measured.

Figure 13 shows the box plot of the measured distance in each method. As shown in this figure, the proposed method achieves an accurate navigation of the UAV, and the UAV can land on the position where the wireless power transfer is succeeded (i.e., the distance is shorter than 31 cm) with high probability. As a result, the proposed method landed in a position where wireless power transfer could be successful 6 times out of 10 trials. In the future, the feedback algorithm will be enhanced so that the landing procedure is repeated until the UAV can receive sensor data after landing.

VI. CONCLUSION

In this study, we have proposed a new sensor network system that autonomously collects data related to crop growth from sensor nodes installed in multiple points scattered over a vast farm. For eliminating the need for periodic battery replacement of the sensor node and reduces the cost of operating the system, the UAV flies over a vast farm and the stationary sensor nodes are operated using wireless power transfer from the UAV.

Through the experimental evaluation using the developed system, it has been confirmed that the UAV can accurately be controlled by the proposed feedback control to land near the sensor nodes, and that the sensor nodes can be operated by the wireless power transfer from the embedded system of the UAV. In the future, we will consider enhancement of the feedback control algorithm so that the wireless power transfer is always succeeded and will propose a method to estimate the crop growth by collecting and analyzing sensor data during the actual crop growth stage.

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