Performance Evaluation of Multiple UAV Systems for Remote Sensing in Agriculture

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Abstract—The introduction of multiple unmanned aerial vehicle (UAV) systems into agriculture causes an increase in work efficiency and a decrease in operator fatigue. However, systems that are commonly used in agriculture perform tasks using a single UAV with a centralized controller. In this study, we develop a multi-UAV system for agriculture using the distributed swarm control algorithm and evaluate the performance of the system. The performance of the proposed agricultural multi-UAV system is quantitatively evaluated and analyzed through four experimental cases: single UAV with autonomous control, multiple UAVs with autonomous control, single UAV with remote control, and multiple UAVs with remote control. The performance of each system was analyzed through six performance metrics: total time, setup time, flight time, battery consumption, inaccuracy of land, and coverage ratio.

I. INTRODUCTION

Owing to the development of unmanned aerial vehicle (UAV) technology, there have been diverse studies on their applications to the agriculture field, which has the greatest potential for UAVs. According to Association for Unmanned Vehicle Systems International (AUVSI), 80\% of the commercial market for UAVs will be occupied by agricultural UAVs in the future [1]. The reason why agricultural UAVs are popular is because they are expected to play an important role in overcoming some of the challenges of modern agriculture. In particular, an innovative agricultural UAV system is inevitable to ensuring the sustainability of agricultural productivity, which has become difficult to maintain because of climate change, and to meet the growing demand for agricultural products as the world's population increases. Currently, agricultural UAVs are operated only for pest control and monitoring numerous crops such as soybean, corn, vegetables, and rice. However, agricultural UAVs are expected to be used for soil and field survey, sowing, spraying, monitoring, irrigation, growth evaluation, mapping, remote sensing, reconnaissance and transportation [2].

By introducing a UAV into traditional agriculture, working hours and labor requirements have been significantly reduced, and the efficiency of agricultural works has improved significantly [3]. However, because a UAV uses a limited battery as its main power source, it is more efficient to use a multi-UAV system, than the current system of a single UAV, to perform agricultural works [4], [5]. For example, a single UAV is used for agricultural works such as spraying or monitoring a large farmland; however, it is very inefficient because it requires considerable time and energy. In contrast, when using a multi-UAV, it is possible to carry out cooperative works at the same time (collaboration) or individual agricultural tasks on the assigned farmland (division of labor). As a result, it is possible to complete the agricultural tasks quickly on a large farmland. In others, when using multiple UAVs to find diseased crops, the accuracy of the agricultural tasks is also increased because there are overlapping areas between the mission areas of each UAV. Therefore, the multi-UAV system is more efficient in many ways than the single-UAV system currently in use.

However, when analyzing the existing application of UAV system for agriculture (e.g., remote sensing [6], [7]; mapping [6]–[8]; monitoring [9], [10]; sowing and irrigation [11]), most studies execute agricultural tasks using a single UAV with an autonomous control. There are few studies on the use of the multi-UAV system in performing agricultural works; thus, it is only at the advanced stage of research [12], [13]. In [12], an autonomous system for use in inspections for precision agriculture based on the use of single and multiple UAVs was developed. In addition, in [13], precision agricultural technology based on the deployment of a team of UAVs that are able to take georeferenced pictures in order to create a full map by applying mosaicking procedures for post-processing was studied. Although [12] and [13] used the multi-UAV system for agricultural tasks, they used the centralized controllers through commercial software or a number of computers and did not perform a quantitative evaluation as the number of UAVs increased; thus, they overlooked the ease of the swarm controllers used.

Even if a multi-UAV system is used in agriculture, the most important factor is that the ease of control must be met such that a single operator can easily control multiple UAVs similar to controlling a single-UAV system. In [14], Ju et al. introduced a distributed swarm control algorithm and implemented a multi-UAV system into the simulator such that a single operator can easily control the multiple agricultural UAVs. Additionally, they argued that the agricultural task with a swarm control algorithm that efficiently and safely controls the multiple UAVs allows the operator to control the multiple UAVs more easily and intuitively and maximize the efficiency of agricultural works. As a extension of [14], this paper proposed a control algorithm for multi-UAV systems based on [14] and evaluated the performance of multi-UAV systems in agricultural scenarios.

This research was supported by the Ministry of Agriculture, Food and Rural Affairs, Korea(316048-3) and partially by the Technology Innovation Program (10076868) funded by the Ministry of Trade, Industry & Energy.

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For the agricultural scenarios, the remote sensing represents the task of the agricultural UAV because the remote sensing task is the most widely used task of research for agricultural UAVs and is a basic task achieved by attaching additional hardware or controllers at any time. As a result, in this study, the remote sensing task was set as a benchmark test because it is the basis for all agricultural tasks. In the evaluation, we focused on the ease with which the operator can control the multiple UAVs and improve the efficiency of agricultural works when performing remote sensing tasks using the developed agricultural multi-UAV system. Therefore, the experimental cases are divided into the use of a single-UAV system and the use of a multi-UAV system from the viewpoint of the number of UAVs. Furthermore, we compare the experimental cases by applying an automatic control method and remote-control method from the viewpoint of control. In other words, we perform a total of four experimental cases (single-UAV system using automatic control, hereafter, referred to as Auto-Single-UAV; multi-UAV system using automatic control, hereafter, referred to as Auto-Multi-UAV; single-UAV system using remote control, hereafter, referred to as Tele-Single-UAV; and multi-UAV system using remote control, hereafter, referred to as Tele-Multi-UAV) for remote sensing tasks. Finally, a total of six performance metrics (total time, setup time, flight time, battery consumption, inaccuracy of land, and coverage ratio) were defined to describe and predict the performance of an agricultural UAV system.

II. THE CONTROL OF MULTIPLE UAV SYSTEM

In here, we omit the distributed swarm control architecture and refer the reader to [14], [15] for further details.

III. EXPERIMENTAL DESIGN

A. Remote sensing task

In this experiment, we set the remote sensing for the agricultural task as shown in Figure 1. The experiment is the operation of sensing using UAV with mounted sensors for a predetermined area of the field, and the experimental procedure includes the whole process from setup time before takeoff to landing after a flight time of mission. The starting point of the remote sensing task is the position where the UAV was originally located at the base station, and this point is also set as the ending point.

Experimental progress is required for the operator to control the agricultural UAV system based on the distributed swarm control algorithm while performing the remote sensing through the sensor attached to the UAV. In addition, the operator was required to look at the camera screen mounted on the UAV. At this time, there is no reference path for the remote sensing tasks, and the UAV is remotely controlled by the intuitive judgment of the operator or is automatically controlled by setting a suitable waypoint. The time at which the UAV was landing properly was set as the criterion for the end of the experiment and the success of the experiment. Here, the operator decided to terminate the experiment by judging the moment when the UAV landed successfully.

Experiments consisted of four cases consisting of Auto-Single-UAV, Auto-Multi-UAV, Tele-Single-UAV and Tele-Multi-UAV. In the case of multi-UAV cases, a total of three quadcopters was used for remote sensing. When automatic control is used, the UAV is automatically controlled by specifying the GPS-based waypoint using ground control station (GCS). However, in the case of teleoperation, the operator controls the UAV by controlling the haptic device. In the case of Tele-Multi-UAV, it is a multi-UAV system applying our proposed distributed swarm control algorithm. A total of three trials were performed for each case and a total of 12 trials were performed in agricultural experiments.

B. Performance metric

We used a total of six performance metrics to evaluate the performance of agricultural UAV systems. The performance metrics are mainly focused on the control effort of the operator and the performance of the system for the agricultural task, and total time, setup time, flight time, battery consumption, inaccuracy of land, and coverage ratio were used as the metrics.

Total time is the completion time during the agricultural task as defined by

$$P_{TT} := \int_{t=0}^{t_c} dt$$

where \( t_c \) is the completion time of the agricultural task.

Setup time is defined as the time that the operator prepares before the UAV executes the agricultural task,

$$P_{ST} := \int_{t=0}^{t_s} dt$$

where \( t_s \) is the time that UAV takes off to perform the agricultural task.
The metric for the \textit{Flight time} is
\[ P_{FT} := \int_{t_c}^{t_s} dt = P_{TT} - P_{ST} \] (3)

Battery consumption is defined as
\[ P_{BC} := \frac{\int_{t_c}^{t_s} B_{\text{consumed}}(t) dt}{B_{\text{total}}} \times 100 \] (4)

where \( B_{\text{total}} \) is the total amount of battery and \( B_{\text{consumed}} \) is the consumption of the battery.

The metric for the \textit{Inaccuracy of land} is
\[ P_{IL} := \| p_i(0) - p_i(t_c) \| \] (5)

\textit{Coverage ratio} is defined as
\[ P_{CR} := \frac{1}{A_{\text{unit}}} \times \frac{A_{\text{covered}}(t)}{t} \times 100 \] (6)

where \( A_{\text{covered}} \) is the area covered by the sensor mounted on UAV, and \( A_{\text{unit}} \) is the area covered by sensor per time.

\( P_{TT}, P_{ST}, \) and \( P_{FT} \) are basically the most important time factors for the UAV to perform agricultural tasks. As the value of these metrics increases, it implies that energy and costs for agricultural task increase. Therefore, the smaller the value of \( P_{TT}, P_{ST}, \) and \( P_{FT}, \) the better the performance of the system. Similarly, the lower the value of \( P_{BC} \) and \( P_{IL}, \) the lower the energy consumption of the UAV and the lower the error of the landing. However, the values of \( P_{CR} \) indicate the performance of the remote sensing tasks; therefore, the higher the value, the better the performance.

\textbf{C. Experimental setup}

The experimental environment was built to allow the UAV to control and communicate with ROS on the notebook of the 16.04 LTS version Ubuntu. In the experiment, a remote sensing task is performed while recording a real-time image by attaching an RGB camera to the UAV. The experimental environment is shown in Figure 2 and the experiment was carried out on a clear day with low geomagnetic coefficient. The UAV used in the developed system was a quadcopter type UAV (3DR SOLO), which is suitable for remote sensing because of low vibrations. As shown in Figure 3, the UAV is basically composed of a frame and battery, a GPS receiver and a flight controller (FC), a camera, an IMU consisting of an accelerometer, a gyroscope, and a magnetic field, supplementary battery that supplies power to the onboard computer, onboard computer for controller, and a printed circuit board (PCB) for connection between the UAV and onboard computer. The payload of this UAV is 450g, and it flies without problems when all the components are connected; in this state, it can fly up to 20 min.

For the distributed system, we constructed a multi-UAV system using the above UAV, and the developed system consists of a number of UAVs and a base station. As shown in Figure 4, the base station consists of a PC with a ROS-based controller and a haptic device, which is used as the master device for teleoperation, a wireless adapter, and a router for the user datagram protocol (UDP) communication. Here, each PC and the onboard computer mounted on the UAV communicate with each other through a router and exchange data, thereby constructing a distributed system. It is also possible to construct a centralized system easily using this system configuration.
TABLE I
EXPERIMENTAL RESULTS FOR EACH CASE AND PERFORMANCE METRIC

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<tr>
<td>$P_{TT}$ [s]</td>
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<td>65.13</td>
<td>32.58</td>
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<tr>
<td>$P_{ST}$ [s]</td>
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<td>19.32</td>
<td>8.29</td>
<td>13.83</td>
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<tr>
<td>$P_{CR}$ [%]</td>
<td>100</td>
<td>300</td>
<td>100</td>
<td>300</td>
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IV. EXPERIMENTAL RESULTS

A. Total time

$P_{TT}$ is the highest for Auto-Single-UA and lowest for Tele-Multi-UA in experiment results. Additionally, $P_{TT}$ is less in the teleoperation method than in the automatic control method, and the multi-UAV system is less $P_{TT}$ than the single-UAV system. In detail, $P_{TT}$ decreased by 31.07 s from 96.20 s (Auto-Single-UA) to 65.13 s (Tele-Single-UA) and decreased by 46.24 s from 78.82 s (Auto-Multi-UA) to 32.58 s (Tele-Multi-UA).

When using the multi-UAV system, the decrease was 17.38 s from 96.20 s (Auto-Single-UA) to 78.82 s (Auto-Multi-UA) and 32.55 s from 65.13 s (Tele-Single-UA) to 32.58 s (Tele-Multi-UA). Moreover, when comparing the proposed Tele-Multi-UA and Auto-Single-UA, experimental results show that $T_{c}$ for Tele-Multi-UA is approximately 66.1% (from 96.20 s to 32.58 s) lower than Auto-Single-UA.

B. Setup time

In experiments, $P_{ST}$ is the highest at 64.48 s (Auto-Multi-UA) and $P_{ST}$ is the lowest at 13.52 s (Tele-Single-UA). The tendency is that $P_{ST}$ is less when using teleoperation method compared to automatic control method; however, when the multi-UAV system is used, $P_{ST}$ increases more than the single-UAV system. Quantitatively, $P_{ST}$ decreased by 35.17 s from 48.69 s (Auto-Single-UA) to 13.52 s (Tele-Single-UA) and decreased by 45.57 s from 64.48 s (Auto-Multi-UA) to 18.91 s (Tele-Multi-UA). However, $P_{ST}$ increased from 48.69 s (Auto-Single-UA) to 64.48 s (Auto-Multi-UA) in 15.79 s and from 13.52 s (Tele-Single-UA) to 18.91 s (Tele-Multi-UA) in 5.39 s.

Most importantly, $P_{ST}$ of Tele-Multi-UA compared to Auto-Single-UA was reduced by 61.2% (from 48.69 s to 18.91 s). Additionally, $P_{ST}$ of Tele-Multi-UA compared to Tele-Single-UA was increased by 39.9% (from 13.52 s to 18.91 s). $P_{ST}$ for Auto-Multi-UA increased by 32.4% (from 48.69 s to 64.48 s) compared to Auto-Single-UA. This result means that the use of multiple UAVs unconditionally increases the work efficiency; however, the operator’s control effort and fatigue increased even more. However, this result is heavily influenced by the user interface (UI), controller and feedback [16].

C. Flight time

The experimental results show that $P_{FT}$ is the lowest for Tele-Multi-UAV (13.67 s) and the highest for Auto-Single-UAV (51.61 s). However, there is no significant difference between Tele-Multi-UAV (13.67 s) and Auto-Multi-UAV (14.34 s). Considering Auto-Single-UAV (47.51 s) and Tele-Single-UAV (51.61 s), $P_{FT}$ increase when the teleoperation is used rather than automatic control.

It is seen that $P_{FT}$ is significantly reduced when using multiple UAVs than a single-UAV system. In the case of Auto-Single-UAV and Auto-Multi-UAV, the decrease was 33.17 s (from 47.51 s to 14.34 s). Additionally, in the case of Tele-Single-UAV and Tele-Multi-UAV, the decrease was 37.94 s (from 51.61 s to 13.67 s). Obviously, the case of Tele-Multi-UAV had a 71.2% (from 47.51 s to 13.67 s) decrease in $P_{FT}$ compared to Auto-Single-UAV in the experiment. These results indicate that using a multi-UAV system can save the battery by reducing $P_{FT}$ over a single-UAV system.

D. Battery consumption

In experiments, $P_{BC}$ is the smallest at 1.24% for Tele-Multi-UAV and the largest at 4.21% for Tele-Single-UAV. The difference between Tele-Multi-UAV and Tele-Single-UAV is 2.97%; however, if $P_{FT}$ is longer, the difference in $P_{BC}$ increases even more. Additionally, $P_{BC}$ decreased by 2.29% from 3.86% (Auto-Single-UAV) to 1.57% (Auto-Multi-UAV) when using the multi-UAV system. Furthermore, in the case of Tele-Multi-UAV, the results show that $P_{BC}$ is 2.62% (from 1.24% to 3.86%) less than Auto-Single-UAV.

As a result, it is more efficient to use multiple UAVs than to use a single UAV, because when $n$th UAV performs the agricultural task, the agricultural area is divided by $n$, and each UAV performs an agricultural task only on $1/n$ areas. However, if we proceed to the same accuracy of agricultural task for a given farmland, the teleoperation method consumes much more $P_{BC}$ than the automatic control method. This is because the control is limited when the operator performs teleoperation on the remote site.

E. Inaccuracy of land

$P_{IL}$ is the highest for Auto-Multi-UAV (19.32 cm) and lowest for Tele-Single-UAV (8.29 cm) in experiment results. The reason for this is that the disturbance can’t be ignored when performing the experiment in an outdoor environment, and error is particularly affected by GPS, which is considered to be inaccurate because of the performance of the device or the weather and wind.

Generally, $P_{IL}$ tends to increase when using multiple UAVs. In detail, $P_{IL}$ increased 1.28 cm from 18.04 cm (Auto-Single-UAV) to 19.32 cm (Auto-Multi-UAV) and increased 5.54 cm from 8.29 cm (Tele-Single-UAV) to 13.83 cm (Tele-Multi-UAV). The reason why $P_{IL}$ increases when using multi-UAV is because signal disturbance occurs. Additionally, $P_{IL}$ decreased by 23.3% (4.21 cm) from 18.04 cm (Auto-Single-UAV) to 13.83 cm (Tele-Multi-UAV). However, this result is reversed when using a more accurate and expensive GPS receiver.
F. Coverage ratio

$P_{CR}$ yields the performance of the agricultural task by calculating the covered area at the same time. This metric should be considered when developing a system as a very important indicator along with $P_{TT}$ in performing agricultural works. No matter how fast $P_{TT}$ is, if $P_{CR}$ is low, the efficiency of the agricultural task will be low.

Therefore, $P_{CR}$ represents the simultaneous covered area of the agricultural UAV system. In the experiment, the recording was done for the agricultural area through the RGB-camera mounted on UAV. As a result, $P_{CR}$ of a single-UAV system is only one-third of the performance compared to a multi-UAV system. In particular, when multi-UAV system is used, $P_{CR}$ is increased by as many as the number of UAVs; thus, it offers a much better performance.

V. DISCUSSION

Table II summarize the experimental results on the comparison between single and multiple systems and the comparison between automatic control and teleoperation. The results show the increase and decrease in teleoperation based on the single-UAV system when Single $\rightarrow$ Multi and automatic control when Auto $\rightarrow$ Tele.

A. Single vs multiple

Currently, a method for solving the problems of battery and payload shortage in an agricultural UAV system is to use a multi-UAV system. Using multiple UAVs requires more time to set up and extra initial cost; however, it brings about results such as improved accuracy of agricultural task, reduced working time, and reduced operator’s control efforts. As a result, agricultural multi-UAV systems are regarded as better systems than single-UAV systems. However, it is necessary to thoroughly confirm that it has acceptable performance before introducing the agricultural multi-UAV system. Therefore, in this subsection we will quantitatively evaluate and analyze the single-UAV system and multi-UAV system.

First, if Multi-UAV is used, $P_{TT}$ is reduced by 18.1% at Auto-UAV and reduced by 50.0% at Tele-UAV. These results show a clear reduction in $P_{TT}$ for Multi-UAV, which improves the efficiency of agricultural works. Although three UAVs were used in this study, the agricultural multi-UAV system based on distributed swarm control showed better performance as the number of UAVs increased and the farmland became larger.

However, experimental results show that $P_{ST}$ increases with Multi-UAV. An 32.4% and a 39.9% increase in Auto-UAV and Tele-UAV were confirmed, respectively. These values are disadvantages of the multi-UAV system; however, it is a more efficient system because multiple UAVs are controlled with a few $P_{ST}$. Generally, to control three UAVs, a $P_{ST}$ of three times is required. However, if the operator controls the multi-UAV with additional $P_{ST}$ of only 30% $\sim$ 40%, the agricultural works are economically beneficial. First, $P_{ST}$ is greatly influenced by UI; thus, $P_{ST}$ is significantly reduced if human-centered GUI and PUI are developed.

Even though $P_{ST}$ increases, multiple UAVs reduce $P_{FT}$ of each UAV through collaboration. This is the main reason why $P_{TT}$ decreases even if $P_{FT}$ increases. In the experimental results, Auto-UAV and Tele-UAV decreased by 69.8% and 73.5%, respectively. Because three UAVs are used for Multi-UAV, theoretically it should be reduced by approximately 66%. However, in the experiment, it is confirmed that it is lower than the reference value (66%), which means that the energy of the UAV is further reduced.

Furthermore, because $P_{FT}$ decreases, $P_{BC}$ is reduced, and the experimental results show that $P_{BC}$ is reduced by 59.3% (Auto-UAV) $\sim$ 70.5% (Tele-UAV) when three UAVs are used. As a result, it is considered that the multi-UAV system overcomes the battery shortage problem of current agricultural UAV systems. Therefore, no matter how vast the area of farmland is, multiple UAVs collaborate to perform agricultural tasks without encountering battery shortage.

Even though $P_{IL}$ tends to increase when using Multi-UAV, this metric is subject to a change by other factors. For example, in the case of Auto-UAV, $P_{IL}$ is greatly influenced by GPS. However, GPS varies with device resolution, wind, weather, and geomagnetic factors. In the case of Tele-UAV, $P_{IL}$ can be greatly influenced by UI because the operator directly watches the UAV or the camera mounted on the UAV for takeoff and landing.

Finally, $P_{CR}$ is significantly improved. When multiple UAVs are used, $P_{CR}$ increases (200%); thus, accuracy of remote sensing also increases, which lead to an increase in the efficiency of the farming. $P_{CR}$ clearly shows that the accuracy of the agricultural works when using Multi-UAV is improved.

As a result, when using the multi UAV system, a little $P_{ST}$ is required because it offers improved results in almost metrics ($P_{TT}, P_{FT}, P_{BC}, and P_{CR}$). In other words, Multi-UAV reduces the time, cost and operator’s environment, including the control effort in agricultural works. In addition, the battery shortage problem and low payload are easily solved, which are the current challenges of agricultural UAVs.

B. Autonomous vs teleoperation

The use of automatic control when controlling an agricultural UAV saves much control effort on the operator.
side. However, there are many limitations to applying the automatic control to actual farming, and there are moments when the teleoperation command of the operator is needed. Additionally, when teleoperation is used, it offers a better performance in working duration than automatic control. Each control method has advantages and disadvantages, and it is necessary to quantitatively evaluate the performance of the system.

\[ P_{FT} \] decreased by 32.3\% (Single-UAV) and 58.7\% (Multi-UAV) when Tele-UAV was used. Additionally, experimental results show that Tele-UAV has excellent performance in terms of \( P_{ST} \). In particular, \( P_{ST} \) is reduced by 72.2\% (Single-UAV) to 70.7\% (Multi-UAV) compared to Auto-UAV, and the simulation is also reduced by 81.3\% (Single-UAV) to 82.1\% (Multi-UAV). These results mean that there is nothing to set in the case of Tele-UAV; however, in the case of Auto-UAV, a long \( P_{ST} \) is required because it is necessary to specify the path to each UAV.

Unusually, \( P_{ST} \) increased for Single-UAV but decreased for Multi-UAV in the experiment results. However, the teleoperation method basically requires more \( P_{FT} \). The reason for this result in the experiment was that when using Tele-Multi-UAV, the operator did not control the UAV carefully and this carelessness caused the low accuracy of the agricultural task by flying fast. However, Auto-UAV running on GPS based waypoints is accurate and faster.

For other metrics, \( P_{BC} \) is similar to \( P_{FT} \) as mentioned above. In \( P_{TL} \), the results shows excellent performance when using Tele-UAV than using Auto-UAV. These results are due to the fact that GPS is interfered with the outdoor environment and is very variable. It means that performance is worse, and the UAV is dangerous when using Auto-UAV where GPS is not accurate. Additionally, there is no difference between Auto-UAV and Tele-UAV, because \( P_{CR} \) represents the simultaneous covered area.

Determining which control method is the better one depends on which performance metric is the priority; however, if time \( (P_{TT}, P_{ST}) \) is important, Tele-UAV is better than Auto-UAV. However, Auto-UAV is a good method, given the working time \( (P_{FT}) \), and energy consumption \( (P_{BC}) \).

### VI. CONCLUSION

In this study, we developed an agricultural multi-UAV system using quadcopters based on the distributed swarm control algorithm. To evaluate the proposed control and developed system, in this experiment, the remote sensing was set as the benchmark test. Thereafter, using the agricultural multi-UAV system, the performance evaluation was performed through four experiment cases consisting of Auto-Single-UAV, Auto-Multi-UAV, Tele-Single-UAV, and Tele-Multi-UAV. A total of six metrics were used to evaluate the performance, and the experimental results show that the multi-UAV system improved the performance obtained with a single-UAV system. As a result, the developed agricultural multi-UAV system with the distributed swarm control solves the problem of battery shortage and reduces working time and control effort. Most importantly, using the agricultural multi-UAV system improves the efficiency of agricultural works.

### REFERENCES


