Adaptive Ground Control System of Multiple-UAV Operators in a Simulated Environment

Hyung-Jin Lim; Seong-Hwan Choi; Jangjin Oh; Byoung Soo Kim; Seungkeun Kim; Ji Hyun Yang

INTRODUCTION: In the present study, an Adaptive Ground Control System for Multiple-UAV Operator Workload Decrement (AGCS) has been developed and the effectiveness of the system has been analyzed using eye-tracking and task performance data. The AGCS contained four more functions than the conventional GCS (CGCS) functions. The functions were based on real-time operator gaze information, multiple UAV operational state, and mission state information to help safe and efficient multiple UAV operation.

METHODS: A total of 30 volunteers participated in the human-in-the-loop experiment to compare the performances of the newly developed AGCS and CGCS while executing reconnaissance and strike missions by operating multiple UAVs.

RESULTS: According to the results, the AGCS demonstrates a statistically significant increase in mission performance, such as the mission completion rate (M = 97.3 vs. M = 95.4; SD = 3.1 vs. SD = 4.9) and mission success rate (M = 90.4 vs. M = 88.4; SD = 5.7 vs. SD = 5.6). In addition, the subjects' pupil diameter and gaze indicator show significant differences in the direction of workload reduction ($\alpha = 0.05$). The subjects expressed positive opinions about using the AGCS.

DISCUSSION: The originally developed AGCS showed a promising future extension based on the experimental data. After completion of the experiment, domain experts were interviewed and the next version will reflect their opinion.

KEYWORDS: mental workload, eye movement, target detection, surveillance, military.

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With the advancement of unmanned aerial vehicle (UAV) automation technology, recent studies have focused on how a single operator can take supervisory control of multiple UAVs simultaneously.[1,3,21] In this regard, it is worth mentioning that if the number of UAVs assigned to a single operator increases, the amount of information to process may exceed the maximum work capacity of that operator.[7,15,16] For this reason, an adaptive ground control system needs to be developed which can check the workload status of a multiple-UAV operator and help reduce it.[4,19,22] Unfortunately, such studies are insufficient in Korea. Against this backdrop, the present study aimed to develop an adaptive ground control system capable of decreasing the workload of multiple-UAV operators and experimentally compare the proposed Adaptive Ground Control System for Multiple-UAV Operator Workload Decrement (AGCS) with the conventional GCS (CGCS). The effectiveness of the proposed AGCS was evaluated based on the results of the human-in-the-loop experiment conducted herein.

There are several UAV ground control systems (GCS) for UAV operation in the world. Among them, we will introduce some examples to help the readers understand the present status of UAV GCS. Supervision of Unmanned Vehicles Mission Management by Interactive Teams (SUMMIT) and Multirobot Operator Control Unit (MOCU) are introduced to show examples of configurable GCSs. Research Environment for Supervisory Control of Heterogeneous Unmanned Vehicles (RESCHU) and Multi-Autonomous Vehicle Insertion Extraction System (MAVIES) are mentioned to introduce research examples of estimating operator workload.

SUMMIT was developed by Lockheed Martin jointly with the U.S. Navy and was designed to move beyond the present model where systems are assigned to each operator to control,

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and to allow operators to flexibly share the control of the overall systems. It is a ground control system prototype in a new command and control mission-based display management paradigm. SUMMIT implements the functions to help U.S. Navy UAV operators complete mission analysis swiftly, improve their situational awareness, and share information, missions, and workload.[10]

The U.S. Space and Naval Warfare Systems Center developed MOCU, a prototype of a ground control system for sensor operator and unmanned vehicle control. The expandability, flexibility, and modularity of MOCU allow acceptance of a wide range of vehicles and sensors in diverse mission scenarios. As of 2006, MOCU is capable of controlling terrestrial, marine, and aerial vehicles and sensors of the Space and Naval Warfare Systems Center for development, such as the Spartan Advanced Concept Technology Demonstration Unmanned Surface Vehicle, and the iRobot PackBot Family of Integrated Rapid Response Equipment.[20]

The RESCHU, developed by the U.S. MIT Humans and Automation Laboratory, is an online experimental research testbed through which an operator can control complex terrestrial, marine, and aerial unmanned systems. Every unmanned system implements a surveillance mission and each unmanned system has mutually different functions, e.g., high-level sensor coverage, low-level target surveillance, and image collection.[5,14]

MIT and the United Technologies Research Center, located in Connecticut, USA, jointly developed MAVIES. Using MAVIES, an operator can surveil the state's unmanned cargo plane and multiple unmanned reconnaissance planes. They also implemented a study to identify the design requirements using Hybrid Cognitive Task Analysis.[11] The Modeling and Virtual Environment and Simulation Institute (MOVES) research center at the U.S. Naval Postgraduate School developed the Semi-Autonomous Wingman Supervisory Interface, a ground control system prototype of unmanned reconnaissance plane surveillance control operable on a tablet PC (Samsung's Galaxy Tablet GT-P7510MA), based on RESCHU source code developed by MIT. The Semi-Autonomous Wingman Supervisory Interface was once employed in F-18 simulators in the U.S. Navy training center for fighter pilots to investigate its effect on flight performance.[13]

Such a GCS has the limitation of being unable to recognize an operator's dynamics and different statuses. Therefore, the concept of adaptive GCSs has been actively studied in the current work. Very limited examples of adaptive GCSs can be mentioned below. The MOVES research center at the U.S. Naval Postgraduate School developed a manned/unmanned ground control system prototype in swarming flight to study Manned-Unmanned Teaming operation mode selection based on RESCHU source code developed by MIT. The MOVES RESCHU provides three different modes: 1) in the full automation mode, operators can only monitor and cannot interfere with mission assignments; 2) in the interactive mode, operators can rearrange the mission assignment based on the auction algorithm; and 3) in the manual mode, operators must manually assign mission arrangements.

Moreover, the corresponding ground control system prototype is also linked with Zephyr's Bioharness to monitor the operator's bio signals, such as heart rate and posture, simultaneously with mission execution.[24] Many attempts have been made to use biosignals as a measurement of an operator's workload. For example, Breslow et al.[2] and Yang et al.[25] suggested using eye movement information to investigate the cognitive processes of operators. Fixation, one of the eye-movement parameters, can be used as a factor to assess an operator's attention. Peterson et al.[18] showed an increase in saccades when mental workload increased. Matthews et al.[12] studied electroencephalography and heart rate to assess operator workload and showed significant heart rate differences according to task difficulty.

The Canadian national defense R&D research institute designed an intelligent adaptive interface that can change its display layout according to the status of an operator and mission. The intelligent adaptive interface provides the layout to execute missions such as UAV pilot, UAV sensor operator, and tactical navigation. It was produced as a part of the work station of marine reconnaissance planes. A comparison experiment was implemented with a nonadaptive ground control system prototype.[8]

In a study implemented by IIT of Germany in support of ARTEMIS-JU of Europe, Intelligent SA-Adaptive Interface, an adaptive ground control system prototype for formation flight unmanned vehicle operation was developed. It can process an operator's gaze motion in real time to assess the operator's situational awareness.[6]

Commercialized multiple-UAV ground control systems include the Universal Ground Control Station developed by Textron Systems of the USA and the Common Ground Control Station (CGCS) developed by Raytheon of the USA. Advanced cockpit GCS (ground control station) by General Atomics of the USA has the function to classify the degree of an operator's workability and establish it into data. The Magnet Systems' Nemesis GCS was set up by combining with a tablet PC. Lockheed Martin developed Expeditionary GCS for storage of flight data. Later, multiple-UAV operation function was added as ground control equipment.

In 2012, Brigham Young University of the USA initiated a study to help improve multiple-UAV operator's mission capability and reduce workload. In an indoor environment, they combined haptic and audio feedback and used ground control equipment with an additional information provision function to operate multiple quadrotors. The operators' workload was measured using the NASA Task Load Index method. The NASA Task Load Index measurement method recognized 6 dimensions of Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration Level in 21 stages. According to the test results, the physical haptic feedback improved mission capability and reduced workload markedly. By contrast, audio feedback had a very weak effect on the operators.[17,19]

In 2013, Boeing Research & Technology Europe of Spain performed a business-academic cooperation project to measure multiple-UAV operators' workload and developed ground control equipment which is capable of involving only few operators to efficiently control multiple UAVs. To operate multiple UAVs, a system architecture and block diagram were designed, and multiple communication channels were employed to control multiple UAVs in the ground control system. In order to avoid overwork of an operator controlling multiple UAVs, the system displays information selectively on the ground control system while visually warning about the problems that may occur during UAV operation through the screen of the ground control system. Furthermore, a system that can control multiple quadrotors was constructed and tested. The test results proved its ability to reduce overwork.[17]

In 2014, the Naval Research Laboratory in Washington, DC, USA, implemented a multiple-UAV operation experiment using the ground control program of RESCHU. The experiment was designed to let an operator operate five UAVs to deliver cargos to a destination while avoiding the danger areas. In the study, experiment difficulty was adjusted to analyze UAV damage during mission implementation and fan-out (based on mission time limit and operator response time, the number of UAVs operable simultaneously by an operator). Higher operability was found at lower experimental difficulty. The study was particularly based on operators' gaze data to understand their recognition state in real time.[2,23] The study acted as the foundation for the present research experimental design.

Diverse AGCSs are studied all over the world. However, the Republic of Korea has few studies on GCS development specialized in decreasing multiple-UAV mission workload. This research team compared conventional GCS,[9] developed AGCS based on operators' gaze information and mission information in real time, and implemented an experiment to test its performance.

METHODS

Subjects

To recruit experimental subjects, a recruitment notice was announced at Kookmin University. A total of 30 subjects (15 men and 15 women) joined the experiment. Their average age was 23.27 (SD: 3.05 yr). Of the 15 men, 9 had completed the national military service. Among the participating operators, five had experience with the preceding experiment (conventional GCS multiple-UAV operation experiment). The experiment was approved by the Institutional Review Board (KMU-201611-HR-126) and complied with the IRB regulations.

Equipment

The purpose of the experiment was to verify whether AGCS is useful for an operator's UAV operation; in other words, to evaluate the effectiveness of the new adaptive ground control system. Therefore, the independent variable of the experiment is the type of ground control system (conventional GCS and AGCS, shown in **Table I**). Both types of the GCSs employed the ground control software MissionPlanner opensource. Visual Studio C# was applied to this study after appropriate modification.

To form each ground control system, four monitors (one for a map, three for UAV control) were used, and each monitor for UAV control included a UAV control window for two UAVs. The conventional GCS' map panel and UAV control panel are shown in **Fig. 1A**. The map panel showed mission map, UAV status (latitude, longitude, altitude), and UAV mission remaining time bar. The UAV control panel consisted of a control space for UAV mission (image, text, and button to be explained again in the scenario section) and UAV status (current location, Euler angle) to help reduce multiple-UAV operators' workload and enhance operability. The AGCS' map panel and UAV control panel are exhibited in **Fig. 1B**. In comparison with the conventional GCS, the following four features were added to the AGCS.

Feature #1. The conventional GCS displayed a time bar showing the mission remaining time of the UAV within a mission area. However, the sky blue color did not change in the conventional GCS remaining time bar. So the operators could not easily see which UAV had little remaining time and thus required urgent involvement of the operators. The adaptive GCS' mission remaining time bar changes the color into red for UAVs with 5 s or shorter remaining time to help the operators assess better.

Feature #2. If multiple UAVs are required to execute a mission, the operator should first select the best UAVs for the task, and this selection has a direct effect on operability. For instance, if an operator requires 3 s on average to complete a mission and the operator is required to select a UAV to complete one

Table I. Comparison of Conventional GCS and Adaptive GCS Information.

TYPES	CGCS (CONVENTIONAL GCS)	AGCS (ADAPTIVE GCS)
Different features		
Map panel	N/A	- Mission remaining time bar color change - Function to display top-control-priority UAV based on algorithm
UAV control panel	N/A	- Function to change screen colors according to mission remaining time - Function to display mission remaining time
Common features		
Map panel	- Mission map	
	- UAV status (latitude, longitude, altitude, etc.)	
	- UAV mission remaining time bar	
	- UAV simulation time	
	- Data logging information	
UAV control panel	- Control space for UAV mission	
	- UAV status (current location, Euler angle, etc.)	

GCS: ground control system; UAV: unmanned aerial vehicle.

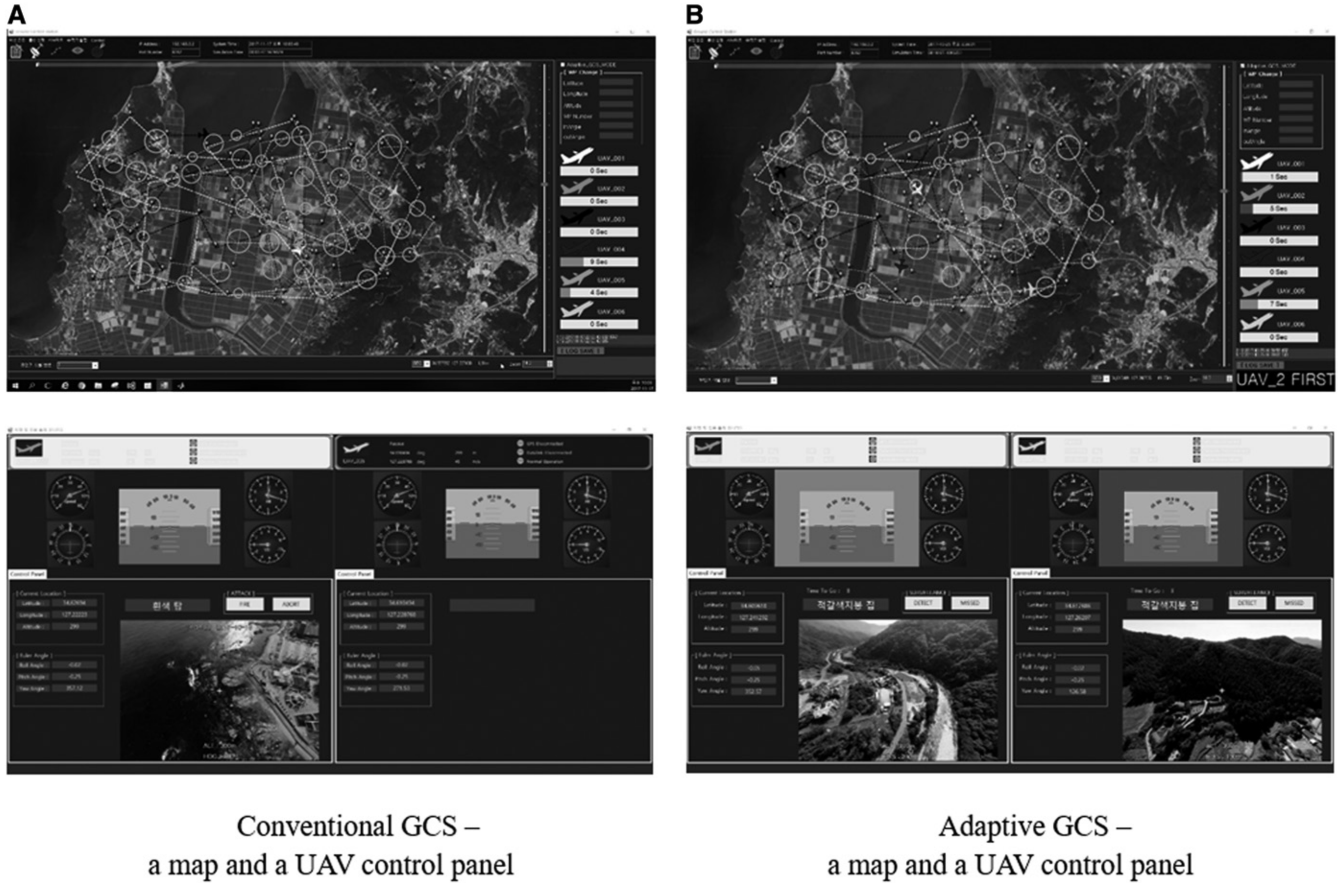

Fig. 1. Comparison of conventional and adaptive GCSs.

mission that spares 2 s of mission time and another that spares 4 s of mission time, the operator may not be able to complete both missions if they select the former UAV first. In addition, if the operator has the choice between a UAV that spares 4 s of mission time and another that spares 7 s of mission time, one or two missions could be completed depending on which UAV is selected first. Therefore, we have incorporated into the AGCS a feature to help operators choose the optimal UAV selection. This feature is based on an operator workload assessment algorithm that considers both the UAV mission status and the operator's gaze. **Fig. 2** shows a conceptual map of this algorithm. In this algorithm, m_time indicates the mean mission completion time for an operator and it is computed from the data accumulated before the experiment.

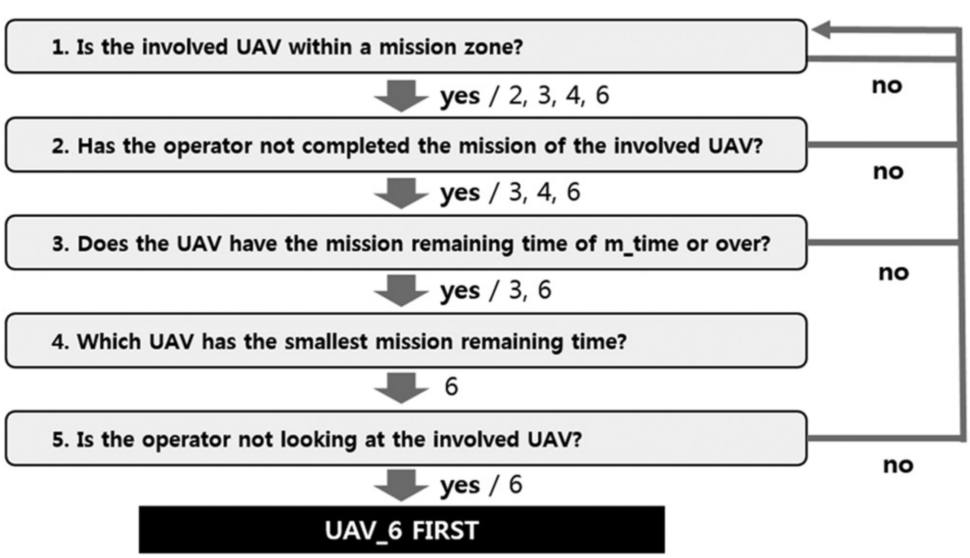

Fig. 2. Operator workload assessment algorithm resulting in the top priority UAV.

Features #3 and #4. The AGCS' UAV control panel changed its colors identically to the time bar color within the AGCS map panel. Therefore, even if an operator is not completing a mission, he can intuitively see the other UAVs' remaining times on the UAV control panel. In this way, AGCS' UAV control panel displayed the mission remaining time. So, together with the function in feature #3, feature #4 helped the operators understand the UAVs' mission remaining times.

The selected dependent variables (**Table II**) for this study were mission indicator (mean mission

Table II. The Experimental Variables.

CLASSIFICATION & VARIABLE	DESCRIPTION
Task performance indicator	
Mission completion time (seconds)	$\frac{\text{Total mission completion time}}{\text{Total number of missions given } (=170)}$
Mission completion rate (%)	$\frac{\text{Number of completed missions}}{\text{Total number of missions given } (=170)}$
Mission success rate (%)	$\frac{\text{Number of successful missions}}{\text{Total number of missions given } (=170)}$
Quantitative indicator (gaze indicator)	
Blink rate (%)	$\frac{\text{Summation of blink time during experiment time}}{\text{Total experiment time}}$
Fixation rate (%)	$\frac{\text{Summation of fixation time during experiment time}}{\text{Total experiment time}}$
Pupil diameter (mm)	Mean pupil diameter in total experiment time
Eye movement speed ($m \cdot s^{-1}$)	Mean eye movement speed in total experiment time
Meta indicator	
Fan-Out (FO)*	$\frac{\text{Summation of available time for mission performance}}{\text{Summation of actual time required for mission performance}}$
Subjective indicators	
Feature total	Answers to "How much did features interfere/help your mission performance?" (score: −2, −1, 0, 1, 2)
Feature #1	Answers to "How much did feature #1 interfere/help your mission performance?" (score: −2, −1, 0, 1, 2)
Feature #2	Answers to "How much did feature #2 interfere/help your mission performance?" (score: −2, −1, 0, 1, 2)
Feature #3	Answers to "How much did feature #3 interfere/help your mission performance?" (score: −2, −1, 0, 1, 2)
Feature #4	Answers to "How much did feature #4 interfere/help your mission performance?" (score: −2, −1, 0, 1, 2)

completion time, mission completion rate, mission success rate), gaze indicator (blink rate, fixation rate, mean pupil diameter, gaze movement speed), meta indicator (fan-out), and subjective indicator (the response to the question: whether the additional functions of the adaptive ground control system was helpful compared to the nonadaptive ground control system).

The basic set up for our experiment comprised the UAVs operation console and four monitors. A gaze tracker was attached at the top of the console to track the operators' gaze. To obtain the operators gaze data, gaze tracking devices, such as Kostech's Smart Eye Pro 3-camera system, and three Camera Basler GigE units were employed. The gaze tracker saved data at 60 Hz. Only one mouse was used as a UAV operation tool.

MissionPlanner opensource was used as the ground control software for this study. It was appropriately modified for this study using Visual Studio C#. A reconnaissance-type unmanned straight-wing aircraft was selected as the study model [wing span 4 m, cruise speed 144 km/h (40 $m \cdot s^{-1}$), cruise altitude 500 m]. A nonlinear 6 degrees of freedom unmanned aircraft model including an engine, landing gear, and standby model was created with Matlab/Simulink. Furthermore, guidance and navigation law was designed which can create and follow unmanned aircraft routes based on the mission information files. To implement automatic flight, PID-based control law was designed.

The experimental setup, as shown in **Fig. 3**, consisted of a total of four screens including one upper-side map panel and three UAV control panels (UAV 1–UAV 6) at the bottom. The operators executed a mission to operate six UAVs simultaneously to reconnoiter and strike a mission zone. The UAVs in this experiment were highly automated to move along a given route on their own. If a UAV enters a blue-colored circle on the mission map, i.e., the mission zone, the color in the upper left side of the UAV control panel changes to alert mission instruction. A yellow-colored alert means reconnaissance mission and orange indicated a strike. Since the six UAVs sporadically moved in and out of the mission zone, the operators were expected to complete the mission as soon as possible before each UAV moved out of the area. When the UAVs moved into the mission zone, the human operators followed the steps below to execute a mission.

Find a target represented as a text box on the mission zone photograph displayed on the UAV control panel.
If there is a target in the mission zone photograph, click the button at the upper left side (reconnaissance mission: Detect, strike mission: Fire).
If there is no target in the mission zone photograph, click the button at the upper right side (reconnaissance mission: Missed, strike mission: Abort).

The ultimate goal of an operator was to execute as many missions as possible with the highest possible accuracy. An operator in our experiment encountered a total of 170 missions (6 UAVs, reconnaissance mission + strike mission).

Procedure

Training for subjects and pre-experimental questionnaire completion (10 min). The experimental subjects were first informed about the experimental details, such as scenario and methodology, additional functions of the AGCS, and even terminologies (say, rotary, dome) so that they did not find any term unfamiliar. Next, the subjects were requested to complete a simple questionnaire asking their personal information, UAV operation experience, etc.

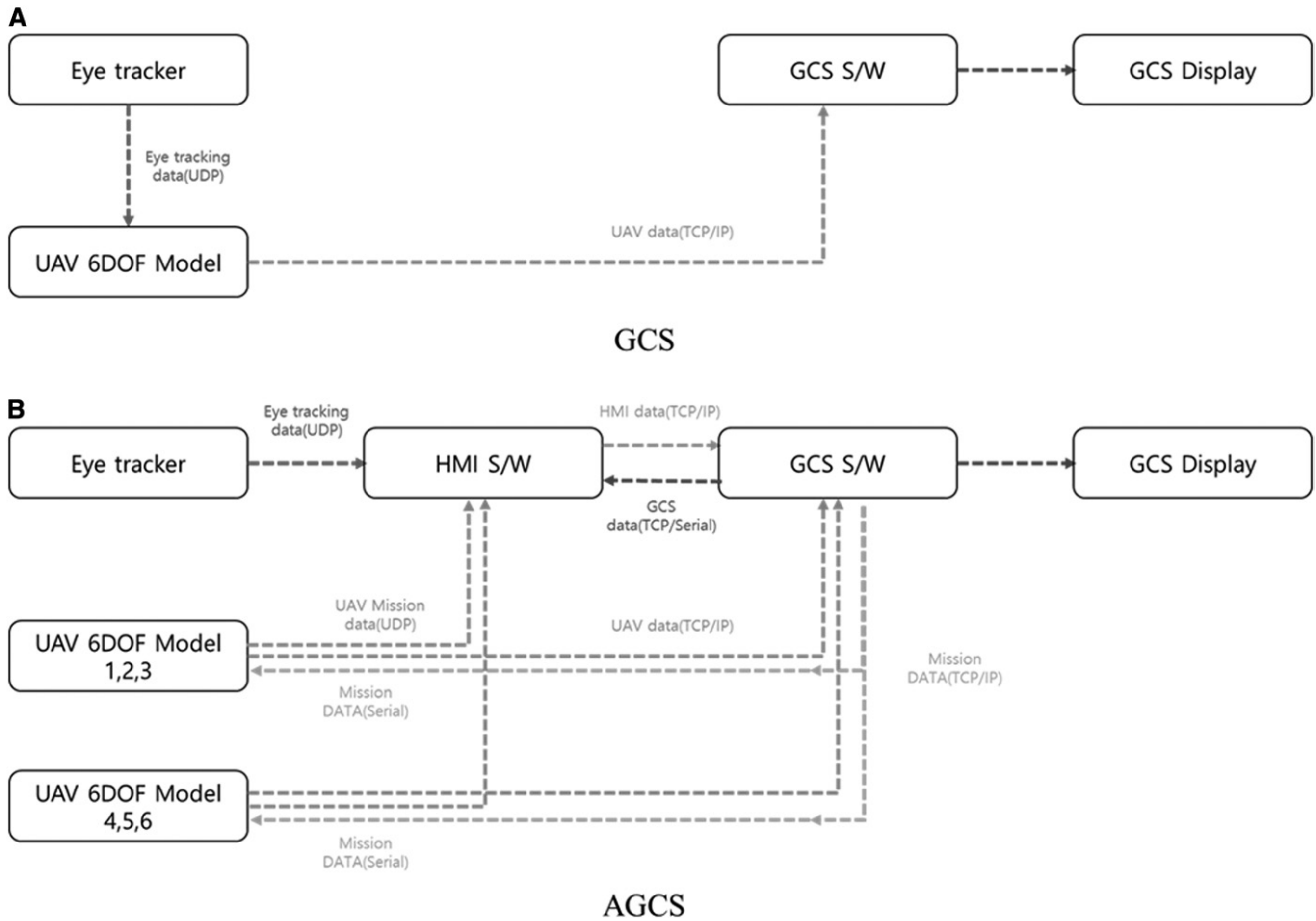

Fig. 3. The experimental environment.

Tutorial for adaptation to the experimental method and average mission completion time measurement (10 min). A practice experiment was conducted to familiarize the participants with the proposed system. The experimental method of the practice one was identical to that of the main experiment. The UAV control screen displayed different kinds of photographs and targets from those of the main experiment to prevent them from getting familiar with specific photographs and target objectives and avoid potential influence over the main experiment. In addition, the m_time included in the algorithm of feature #2 of the adaptive ground control system was measured during the process for application in the main experiment later.

Gaze tracker setting to obtain operators' gaze data (10 min). A gaze tracking program was optimized for the experimental subjects. The gaze tracking camera was adjusted in the up, down, left, and right directions according to an operator's height and posture. Gaze calibration was also done in the program (similar to the calibration in gun shooting).

Break (5 min). The experiment subjects were given a 5-min break before the main experiment.

Main experiment with conventional GCS (10 min). The subjects followed the experiment in the conventional GCS environment. During the experiment, they could not be questioned and were expected to focus on the experiment only.

Main experiment with AGCS (10 min). The subjects followed the experiment in the AGCS environment.

Post-experimental questionnaire fill-in (5 min). The post-experimental questionnaire contained questions on the subjects' own subjective views on their mission capability; how much the additional functions of AGCS interfered/helped their multiple UAV operation (highly interferential: −3 points; interferential: −2 points; a little interferential: −1 point; irrelevant: 0 points; a little helpful: +1 point; helpful: +2 points; highly helpful: +3 points). The effectiveness of the AGCS was assessed from the subjective views of the operators given in the post-experimental survey questionnaire .

Statistical Analysis

The study was designed as a within-subject comparison. The eight dependent variables summarized in Table II were measured for both the GCS ($N = 30$) and the AGCS ($N = 30$)

scenarios. No missing data were found in the 60×8 data matrix and no data were rejected for out-of-range factor values. Descriptive information about the aforementioned eight dependent variables is given in **Table III**. A repeated-measures multivariate analysis of variance (MANOVA) design was used to assess the effects of the adaptive characteristics of the ground control station on the eight objective measures, including three task performance indicators, four gaze indicators, and one meta indicator. Significance was defined as $P < 0.05$. The data were analyzed using SPSS Version 25.

RESULTS

Included in this study were 30 subjects and each subject was tested twice, once with AGCS and once with GCS in a random order. Descriptive statistics of the task performance indicators, gaze indicators, and meta indicator are summarized in Table III. The effects of the AGCS on the eight workload measures were assessed by conducting tests with a repeated-measures MANOVA. Mauchly's test of sphericity was satisfied. An inspection of the MANOVA with Wilk's lambda showed that the ground control stations had a significant main effect on the combined dependent measures [Wilk's $\lambda = 0.124$, $F(8, 22) = 19.47$, $P < 0.001$, partial $\eta^2 = 0.876$]. The results of the follow-up univariate tests showed that the ground control stations had a significant effect on the mission completion time [$F(1, 29) = 27.16$, $P < 0.001$, partial $\eta^2 = 0.484$], mission completion rate [$F(1, 29) = 15.23$, $P = 0.001$, $\eta^2 = 0.344$], mission success rate [$F(1, 29) = 11.85$, $P = 0.002$, partial $\eta^2 = 0.290$], pupil diameter [$F(1, 29) = 39.66$, $P < 0.001$, partial $\eta^2 = 0.578$], eye movement speed [$F(1, 29) = 6.53$, $P = 0.016$, partial $\eta^2 = 0.184$], and fan-out [$F(1, 29) = 27.71$, $P < 0.001$, partial $\eta^2 = 0.428$]. By contrast, the univariate tests revealed no significant effect of the ground control stations on the blink rate [$F(1, 29) = 3.70$, $P = 0.064$, partial $\eta^2 = 0.113$] and fixation rate [$F(1, 29) = 0.08$, $P = 0.777$, partial $\eta^2 = 0.003$].

Hypothesis Testing on Mission Performance Enhancement

H01: If an adaptive ground control system is used, mission completion time is shorter than when the conventional ground control system is used. The mission completion time was significantly lower for the AGCS (M = 2.933, SD = 0.682) than for the conventional GCS (M = 3.202, SD = 0.785) [$F(1, 29) = 27.16$, $P < 0.001$, partial $\eta^2 = 0.484$]. The mission completion time was about 8% lower for the AGCS compared to that of the conventional GCS as shown in **Fig. 4A**.

H02: If an adaptive ground control system is used, mission completion rate is higher than when the conventional ground control system is used. The mission completion rate was 2% higher for the AGCS (M = 97.333, SD = 3.054) than that for the conventional GCS (M = 95.373, SD = 4.933) [$F(1, 29) = 15.23$, $P = 0.001$, partial $\eta^2 = 0.344$].

H03: If an adaptive ground control system is used, mission success rate is higher than when the conventional ground control system is used. The mission success rate was 2% higher with the AGCS (M = 90.362, SD = 5.721) than the conventional GCS (M = 88.436, SD = 5.622) [$F(1, 29) = 3.70$, $P = 0.064$, partial $\eta^2 = 0.113$], as shown in **Fig. 4B**.

Hypothesis Testing on Gaze Indicator Changes

H04: If an adaptive ground control system is used, blink rate is higher than when the conventional ground control system is used. The blink rate was 11% lower for the AGCS (M = 6.819, SD = 3.969) than for the conventional GCS (M = 7.635, SD = 4.033); however, since $P = 0.064$ [$F(1, 29) = 39.66$, $P < 0.001$, partial $\eta^2 = 0.578$], it was impossible to reject the null hypothesis.

H05: If an adaptive ground control system is used, fixation rate is shorter than when the conventional ground control system is used. The fixation rate, compared to the conventional GCS (M = 69.424, SD = 6.810), was lower for the AGCS (M = 69.218, SD = 6.487). However, $P = 0.777$ [$F(1, 29) = 0.08$, $P = 0.777$, partial $\eta^2 = 0.003$] makes rejection of the null hypothesis impossible.

H06: If an adaptive ground control system is used, pupil diameter is smaller than when the conventional ground control system is used. The pupil diameter was about 3% lower for the AGCS (M = 4.182, SD = 0.472) compared to the conventional GCS (M = 4.315, SD = 0.477) [$F(1, 29) = 39.66$, $P < 0.001$, partial $\eta^2 = 0.578$], as shown in **Fig. 4C**.

H07: If an adaptive ground control system is used, eye movement speed is slower than when the conventional ground control system is used. Eye movement speed was about 9% higher for the AGCS (M = 1.562, SD = 0.462) than that for the conventional GCS (M = 1.438, SD = 0.331) [$F(1, 29) = 6.53$, $P = 0.016$, partial $\eta^2 = 0.184$], as shown in **Fig. 4D**.

Table III. Experimental Results.

DEPENDENT VARIABLE	CONVENTIONAL GCS M (SD)	ADAPTIVE GCS M (SD)	*P*-VALUE*
H01: Mission completion time (seconds)	3.202 (0.785)	2.933 (0.682)	<0.001
H02: Mission completion rate (%)	95.373 (4.933)	97.333 (3.054)	0.001
H03: Mission success rate (%)	88.436 (5.622)	90.362 (5.721)	0.002
H04: Blink rate (%)	7.635 (4.033)	6.819 (3.969)	0.064
H05: Fixation rate (%)	69.424 (6.810)	69.218 (6.487)	0.777
H06: Pupil diameter (mm)	4.315 (0.477)	4.182 (0.472)	<0.001
H07: Eye movement speed ($m \cdot s^{-1}$)	1.438 (0.331)	1.562 (0.462)	0.016
H08: Fan-Out (FO)	3.013 (0.645)	3.257 (0.676)	<0.001

N = 30.
GCS: ground control system.
* *P*-values for follow-up univariate comparison.

Hypothesis Testing on Changes in the Number of Operable UAVs

H08: If an adaptive ground control system is used, fan-out is higher than when the conventional ground control system is used. Fan-out was 8% higher for the AGCS (M = 3.257, SD = 0.676) than that for the conventional GCS (M = 3.013, SD = 0.645) [$F(1, 29) = 27.71$, $P < 0.001$, partial $\eta^2 = 0.428$], as shown in **Fig. 4E**. The gaze rate showed no significant difference in the directions of interground control system map panel, UAV control panel, and other areas.

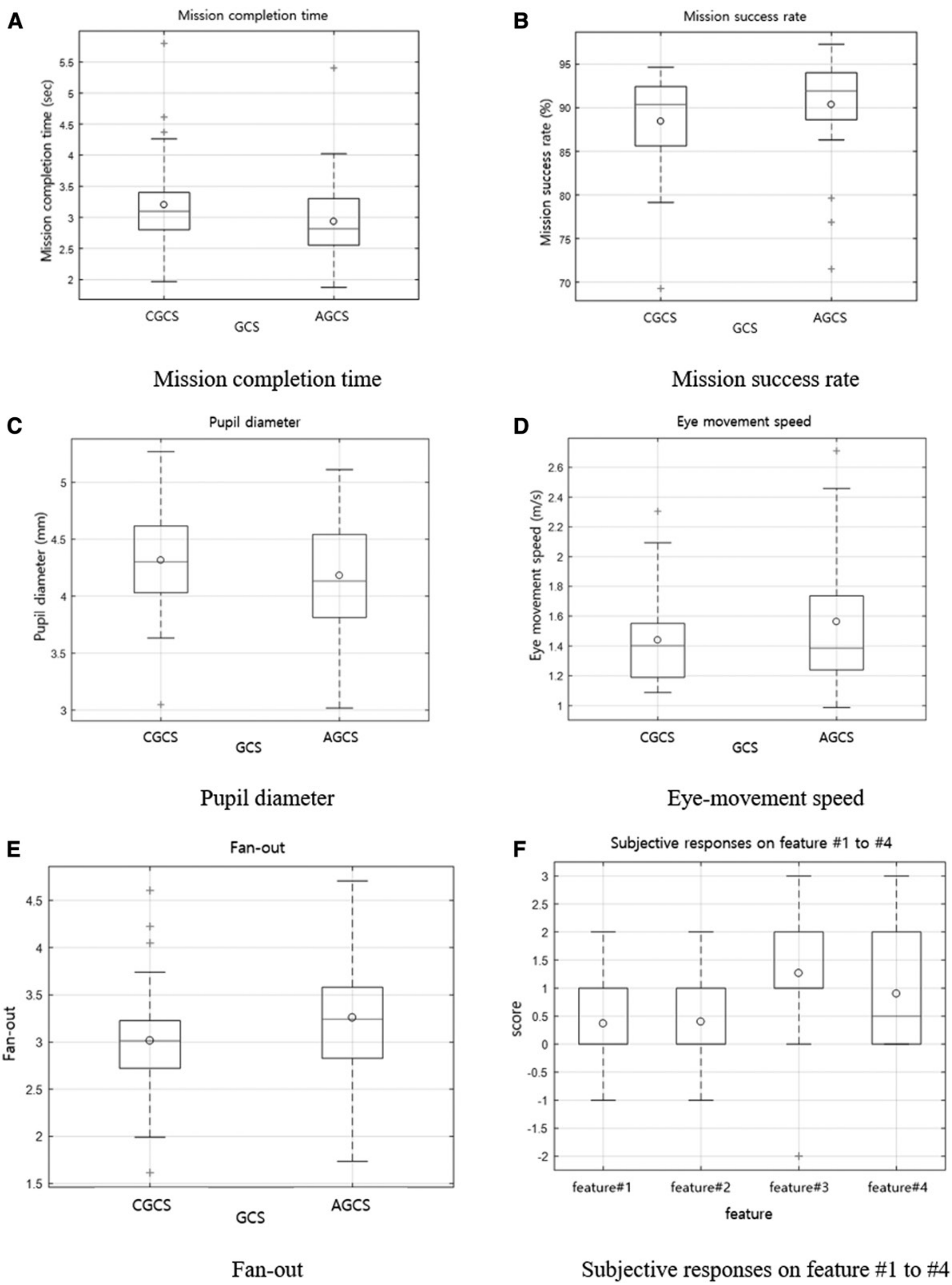

Fig. 4. Mission completion time, mission success rate, pupil diameter, eye-movement speed, fan out, and subjective responses on features #1 to #4.

Subjective Responses on Operation Performance Enhancement

The total subjective assessment of AGCS features was M = 0.730 (SD = 1.112). The subjective assessment score for each feature was found to be the highest in feature #3 (M = 1.270, SD = 1.285), followed by feature #4 (M = 0.900, SD = 1.062), feature #2 (M = 0.400, SD = 0.814), and feature #1 (M = 0.370, SD = 0.615) in order as shown in **Fig. 4F**. The operators' detailed feedback on each feature are listed in **Table IV**.

DISCUSSION

The purpose of this experiment was to see if an AGCS was helpful for operators' UAV operation; in other words, to verify the effectiveness of AGCS. Past research recognized two different circumstances in the single environment of conventional GCS, i.e., when UAVs were outside the mission area (low workload of the operators) and when UAVs were within the mission area (high workload of the operators).[10] Compared to the low-workload scenario, the high-workload case was found to have a higher fixation rate [0.682 (0.116) $<$ 0.807 (0.064), $P < 0.001$] and a lower blink rate [0.106 (0.056) $>$ 0.050 (0.044), $P < 0.001$]. The results showed that heavy workload meant a longer gaze time at a certain area and less blinking to implement a mission. The involved indicators were employed as the mission overload indicators in the present study. Moreover, in comparison to the low-workload case, the heavy-workload case had a higher pupil diameter value [3.798 (0.365) $<$ 4.046 (0.390), $P < 0.001$] and the involved indicators were also taken as the overload indicators.

In the preceding study introduced above, the mission completion time and mission success rate were chosen as the mission indicators. The current study added mission completion rate to the mission indicators. As a result, all of the mission indicators indicated that the AGCS was effective. The mission completion time was about 8% lower in the AGCS (mission completion was faster), and mission completion rate and mission success rate were about 2% higher in the AGCS, respectively. However, following the experiment, it was necessary to adjust the difficulty level so that the mission completion rate and mission success rate were as high as around 90%.

In the gaze indicators mentioned above, pupil diameter was significantly lower for the AGCS. Furthermore, eye movement speed was significantly higher for the AGCS. Considering this finding and the enhanced mission indicator results for the AGCS at the same time, it can be concluded that the operators moved their eyes swiftly and checked the additional features of the AGCS, thereby enhancing their mission performance. Fan-out, a meta indicator with the idea of the number of UAVs operable simultaneously by one operator, was also significantly higher for the AGCS.

The questionnaire on the effectiveness of the additional AGCS features gained answers that all four additional features were useful. Feature #3 (screen color change according to the mission remaining time), in particular, was found to be the most helpful in the subjective results. However, there was no significant difference when the gaze rates toward the UAV control panel were compared between the conventional GCS and AGCS. The opinions on the additional AGCS features included two subjects' views that it would be more effective to have more color steps in feature #3. Based on the opinions, further study is required to diversify the color steps of the feature and inspect the updated AGCS effectiveness in an additional experiment.

Table IV. Evaluation of the AGCS Features.

CLASSIFICATION	DETAILED FEEDBACK
Feature total	sub.6: During the pilot experiment after being told about the experiment, thought the AGCS would be helpful for mission execution. But the mission time limit in the experiment was too short so had to focus solely on the mission.
Feature #1	--
Feature #2	--
Feature #3	sub20: The feature was helpful for mission execution, but it would be good if the color representation area is a bit smaller. More color steps would be good. sub22: The higher the adaptability to the color change feature, the more it would be helpful. sub30: The effect of attention would be stronger if there are more color steps.
Feature #4	sub27: The time display was helpful. sub30: Hardly saw it.

AGCS: adaptive ground control system.

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