JOURNAL OF AEROSPACE INFORMATION SYSTEMS
Vol. 16, No. 4, April 2019

Safety and Workload Assessment of Lost C2 Link on Seoul–Jeju Route

Jisoo Kang,* Hyeonwoong Lee,† Hyeju Oh,* Keeyoung Choi,‡ and Hak-Tae Lee§
Inha University, Incheon 22212, Republic of Korea
and
Hyejung Hong¶ and Sang Hyun Kim**
Korea Transport Institute, Sejong 30147, Republic of Korea

DOI: 10.2514/1.I010670

One of the most distinctive characteristics of the remotely piloted aircraft systems (RPASs) is the absence of an onboard pilot. Because the aircraft is remotely controlled by the command and control (C2) link, it is important to establish procedures for a lost C2 link and understand their impacts. In this paper, three lost C2 link procedures (two return-to-base scenarios and one continue-to-destination scenario) are developed on a route between Seoul and Jeju: one of the busiest air routes in the world. Then, human-in-the-loop simulations of an RPAS in a lost C2 link situation are performed with a student controller and two experienced controllers. The simulation results are analyzed in terms of safety and controller workload metrics. The two return-to-base scenarios showed better scores than the continue-to-destination scenario in all the metrics. The well clear alert, which is a safety metric devised for RPAS operations, happened only in the continue-to-destination scenario. Although the subjective surveys did not show notable workload differences among the three scenarios, the participating controllers issued more heading change commands to surrounding traffic in the continue-to-destination scenario than in the two return-to-base scenarios, which suggests that controller workload is higher.

Nomenclature

d_h	=	vertical separation
d_x	=	horizontal separation in the x dimension
d_y	=	horizontal separation in the y dimension
h_{std}	=	vertical separation standard for the conflict intrusion parameter
HMD*	=	horizontal miss distance threshold for well clear
h^*	=	vertical separation threshold for well clear
r_{xy}	=	horizontal separation
$\dot{r}_{xy}$	=	horizontal range rate
S_{std}	=	horizontal separation standard for conflict intrusion parameter
t_{CPA}	=	time to the closest point of approach
v_{rx}	=	relative horizontal velocity in the x dimension
v_{ry}	=	relative horizontal velocity in the y dimension
τ_{mod}	=	modified tau
τ^*_{mod}	=	modified tau threshold for well clear

I. Introduction

CONVENTIONAL aircraft are controlled by a pilot on board. Ever since the introduction of unmanned aircraft, it has been a challenge to accommodate and integrate the operations of unmanned aircraft in an airspace that has been used by manned aircraft [1,2]. With the increasing demand for international operations of unmanned aircraft, the lack of standards has become an issue. In accordance with member states' needs, the International Civil Aviation Organization (ICAO) formed a panel for remotely piloted aircraft systems (RPASs) and published a manual [3].

The RPAS manual defines a remotely piloted aircraft (RPA), its associated remote pilot station (RPS), and a command and control (C2) link, all of which constitute an RPAS as a system. Figure 1 shows an example of an RPAS. The C2 link connects the RPA with the RPS and enables the remote pilot on the ground to control the RPA. The RPAS panel defines the functionalities of the C2 link as 1) aviate, 2) navigate, 3) communicate, 4) integrate (surveillance), and 5) manage [4]. The remote pilot in the RPS controls the maneuvers of the RPA by the aviation function and manages the flight plan and trajectory by the navigation function. The communication function relays the voice or data communication between an RPA and air traffic control (ATC) to the RPS. Surveillance data obtained by equipment such as Automatic dependent surveillance-broadcast (ADS-B) are transmitted to the RPS via the C2 link. The management function is to monitor and manage the C2 link itself. Figure 2 shows system interfaces related to the RPAS [5].

Presented as Paper 2018-3034 at the 2018 Aviation Technology, Integration, and Operations Conference, Atlanta, GA, 25–29 June 2018; received 11 June 2018; revision received 30 December 2018; accepted for publication 12 January 2019; published online 5 February 2019.

*Ph.D. Student, Department of Aerospace Engineering, 100 Inha-Ro, Michuhol-Gu. Student Member AIAA.
†M.S. Student, Department of Aerospace Engineering, 100 Inha-Ro, Michuhol-Gu. Student Member AIAA.
‡Professor, Department of Aerospace Engineering, 100 Inha-Ro, Michuhol-Gu. Senior Member AIAA.
‡Associate Professor, Department of Aerospace Engineering, 100 Inha-Ro, Michuhol-Gu. Member AIAA.
§Researcher, Department of Aviation, 370 Sicheong-Daero.
**Associate Research Fellow, Department of Aviation; currently, Senior Researcher, Korea Aerospace Research Institute, Daejeon 34133, Republic of Korea (Corresponding Author).

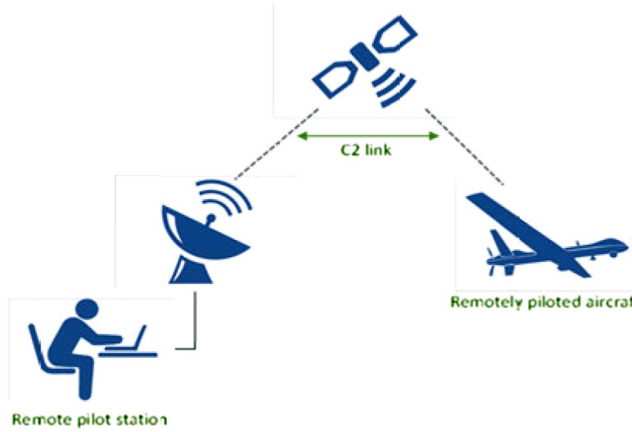


Fig. 1 Illustrative example of an RPAS (for beyond radio line of sight) [3].

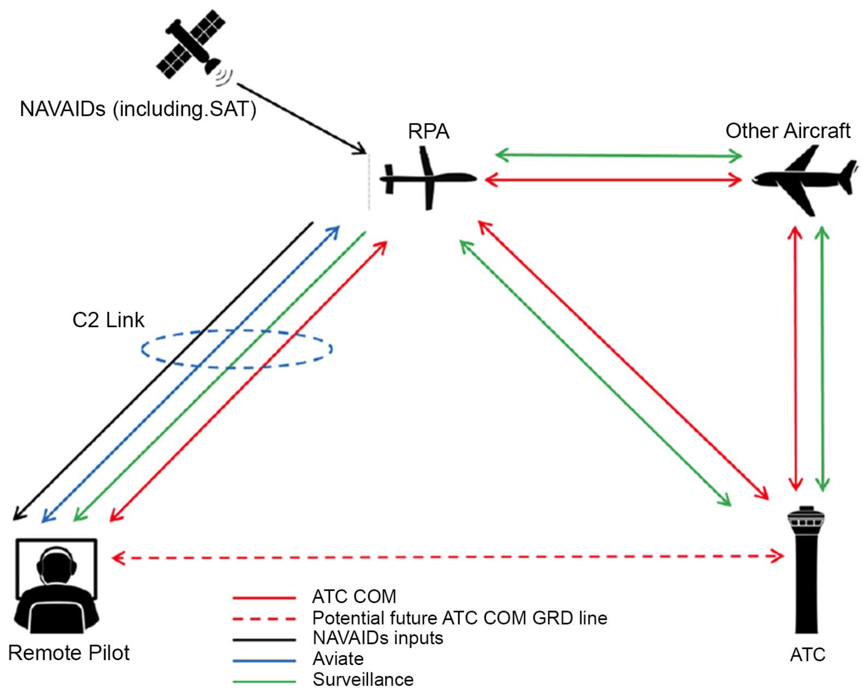


Fig. 2 System interfaces related to the RPAS [5] (SAT, standard instrument departure; COM, standard terminal arrival route; SDP, surveillance data processing; UAV, unmanned aerial vehicle; GRD, ground).

Because the C2 link connects the RPA and the RPS, when the C2 link is lost, the RPA should follow a predefined procedure without external input, which will threaten the safety of other traffic in nonsegregated airspaces.

Because a reliable C2 link is crucial for the integrated operations of the RPAS, contingency procedures for a lost C2 link attracted international attention, including the RPAS panel of the ICAO. The panel has been trying to establish an international standard for the contingency procedures. The current working version of the contingency procedures is described in the next section. However, each member state needs to establish its own detailed procedures based on the ICAO's general guidelines using qualitative and quantitative analyses of safety and controller workload. In this respect, there exist several studies on the analysis of the contingency procedures. Kamienski et al. designed lost C2 link contingency procedures and analyzed them with human-in-the-loop (HITL) simulations focusing on the response time of the controllers [6]. Hu and Jella proposed a synthesized voice message that was broadcast from an RPA to ATC and surrounding traffic when the C2 link was lost. The message included flight and communication status, as well as intended operational procedures [7]. This proposed voice system enables twoway voice communication between the RPA and ATC. Fern et al. implemented four contingency procedures (two return to base with different lag times, continue to destination, and emergency landing) in HITL simulations with a current-day traffic situation at the Southern California Terminal Radar Approach Control [8]. The safety, workload, and efficiency were measured by the numbers of losses of separation, handoff accept time, and time (or distance) flown by each aircraft, respectively. In addition, the workloads were rated by the NASA Task Load Index (TLX) and other questionnaires. They concluded that the presence of an RPA with a lost C2 link does not significantly impact safety, workload, or efficiency. However, the continue-to-destination procedure was preferred by the controllers who participated in the simulation.

This paper presents lost C2 link contingency procedures for the Korean national airspace and assesses them in terms of safety and controller workload through HITL simulations. Because the Seoul–Jeju route used in this paper is the busiest route in the world in terms of the number of passengers, the lost C2 link situation in this route can be considered one of the worst-case scenarios for en route operation. Therefore, if a contingency procedure is acceptable in terms of safety and workload in this route, it should be applicable to other routes with similar or lower levels of traffic. Hence, the results of this paper will contribute to the establishment of international standards for the lost C2 link contingency procedures. This paper focuses on the en route phase, partially due to time and resource limitations but also due to the reasoning that, unlike the

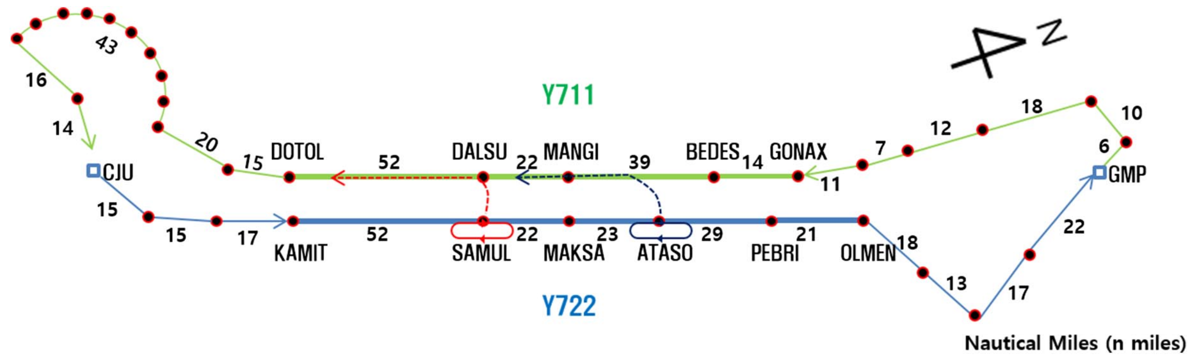


Fig. 3 Seoul (GMP)–Jeju (CJU) route and distances in nautical miles.

terminal operations that are highly dependent on each airport's specific characteristics as well as arrival and departure routes, the en route contingency procedures can be relatively universal. This paper is one of the first attempts to analyze en route contingency procedures in a busy class A airspace in which the RPA operates with other manned aircraft. The findings of this paper might be different from those of Fern et al. [8], which assessed contingency procedures for a terminal area. In this paper, it is assumed that the lost C2 link will not be recovered for a sustained period while other flight functions such as the engine or navigation work properly.

The rest of the paper is organized as follows. Section II explains the lost C2 link contingency procedures, and Sec. III describes the HITL simulations that are used to evaluate the contingency procedures. Section IV explains the simulation methodology. Section V presents the analysis results by comparing evaluation metrics. Finally, Sec. VI concludes the paper.

II. Lost C2 Link Contingency Procedures

A. Lost C2 Link Contingency Procedures Proposed by RPAS Panel

Working group 6 (air traffic management (ATM)) of the RPAS panel proposed lost C2 link contingency procedures at the sixth meeting of the panel in 2016 [9] and an amendment to ICAO document 4444 (procedures for air navigation services (PANS)-ATM) at the ninth meeting in accordance with the previously proposed contingency procedures [10]. The contingency procedures are separated into two parts: for the terminal area, and for en route. All the procedures start with a dedicated squawk code (e.g., 7400) and ADS-B emergency/urgency modes. An RPA that loses its C2 link while departing from an airport follows the standard instrument departure procedures and the planned route for 7 min. Then, the RPA returns to the base. An RPA that loses its C2 link while approaching a destination airport proceeds to the preprogrammed Navigational Aid, and then it descends to a holding pattern and approaches the destination airport. According to the amendment, the en route contingency procedures can be either continue to destination (continue), return to base (return), or divert to alternate (divert).

B. Lost C2 Link Contingency Procedures for the Seoul–Jeju Route

The Seoul–Jeju air route is the busiest route in the world in terms of the number of passengers according to the International Air Transport Association [11]. The air route consists of two unidirectional routes (Y711 and Y722) and one bidirectional route (B576). B576 was the main air route between Seoul and Jeju until 2012 but is now reserved. Y711 is southbound (Seoul to Jeju), whereas Y722 is northbound (Jeju to Seoul). Among the three options in the amendment to PANS-ATM, the divert option is excluded for the Seoul–Jeju route because all candidate airports for diversion are military airports that require coordination between ATC and the military.

There are two published holding patterns on Y722: one at ATASO fix and the other at SAMUL fix, as shown in Fig. 3; however, no holding pattern is specified on Y711. Hence, two return scenarios are available on Y722, but a new holding pattern needs to be created on Y711 for the return option. Hong et al. designed possible en route contingency procedures for Y711 and Y722 for the RPAS [12]. In this paper, contingency procedures for Y722 are assessed because it is possible to compare the effects of the locations of the return point. Because the safety and workload may be influenced by the ratio of the remaining distance to the flown distance, three scenarios are generated for the HITL simulation, as shown in Table 1.

For scenarios 2 and 3, the RPA circles around the holding pattern once and changes its heading toward Y711. Air routes, fixes, and corresponding distances are given in Fig. 3. Bold and thin lines indicate air routes and standard instrument departure/standard terminal arrival route procedures, respectively.

As shown in Fig. 3, the section of Y722 for the Seoul–Jeju route is KAMIT–SAMUL–MAKSA–ATASO–PEBRI–OLMEN, and the total distance is 147 n miles. In the second scenario, the RPA proceeds to the ATASO fix that is about two-thirds along Y722. In the third scenario, the RPA proceeds to the SAMUL fix that is about one-third along Y722. Therefore, the travel distance on class A routes (Y711 and Y722) of the

Table 1 List of the three contingency procedures [12]

Scenario	List of the fixes	Flown/remaining distance to the destination, n miles	Ratio of flown to total distance
Scenario 1: continue	Jeju → KAMIT → SAMUL → MAKSA → ATASO → PEBRI → OLMEN → Seoul	264/0	1
Scenario 2: return at ATASO	Jeju → KAMIT → SAMUL → MAKSA → ATASO → Holding → MANGI → DALSU → DOTOL → Jeju	144/120	0.545
Scenario 3: return at SAMUL	Jeju → KAMIT → SAMUL → Holding → DALSU → DOTOL → Jeju	99/165	0.375

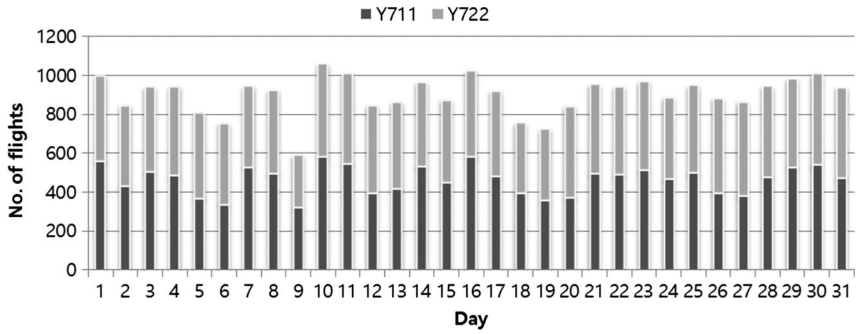


Fig. 4 Number of flights on Y711 and Y722 in July 2014.

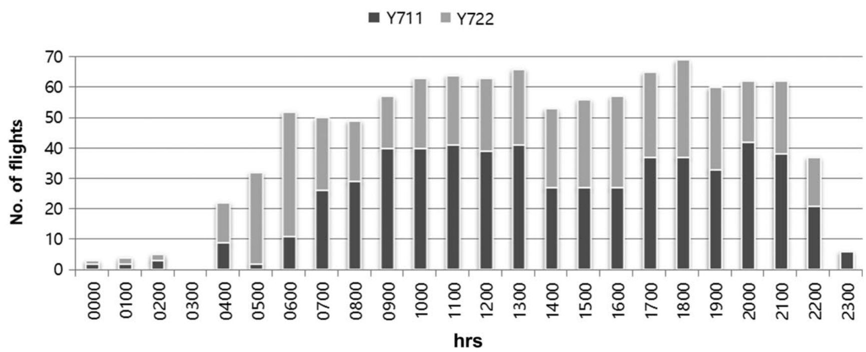


Fig. 5 Number of flights on Y711 and Y722 on 10 July 2014.

second scenario is roughly 30% longer than that of the first scenario, and the travel distance of the third scenario is roughly 30% shorter than that of the first scenario.

III. Human-in-the-Loop Simulation

A. Simulation Dataset

Flight schedules on Y711 and Y722 in July 2014 are used to generate background traffic for the HITL simulation. Figure 4 shows the number of flights for each day. The day with the highest total traffic volume (10 July 2014) is selected for the simulation because both Y711 and Y722 are involved in two of the three scenarios.

The travel time between Seoul and Jeju is about 1 h from gate to gate. Figure 5 shows the hourly traffic on Y711 and Y722. The total traffic level is the highest from 1800 to 1900 hrs, and the traffic volumes on both the routes are well balanced, with Y722 experiencing a second peak during this time period. Based on this traffic level analysis, 2 h of traffic data from 1730 to 1930 hrs on 10 July 2014 are chosen for the HITL simulation. The aircraft count in the 15 min bin is given in Table 2. Aircraft with flight times less than 180 s within the selected time window are filtered out.

B. Simulation Environment

1. Simulation System

To assess the lost C2 link contingency procedures, the ATC simulator developed by Inha University was used. Figures 6 and 7 show the structure of the ATC simulator and the system layout, respectively. The ATC simulator mainly consists of three components: a server, multiple pilot stations, and multiple controller stations [13].

RPAs and manned aircraft are controlled by a pseudopilot at the pilot station. The pseudopilot communicates with the controller using headsets. The voice communication is implemented using voice-over-internet protocol data communication inside the simulation system. Once the air traffic controller gives maneuver commands to the pseudopilot, the pseudopilot reads back and then maneuvers the aircraft using the pseudopilot interface.

The server manages the simulation scenarios and controls the data flow between the clients. Especially, the state information such as position and velocity of each aircraft that are generated by the flight dynamics model in the pilot station is collected and processed at the server.

Table 2 Number of flights on Y711 and Y722 during the simulation time window

15 min bin, hrs	Y711	Y722
1730–1744	9	18
1745–1759	13	15
1800–1814	19	10
1815–1829	15	14
1830–1844	10	14
1845–1859	19	13
1900–1914	17	13
1915–1929	12	11

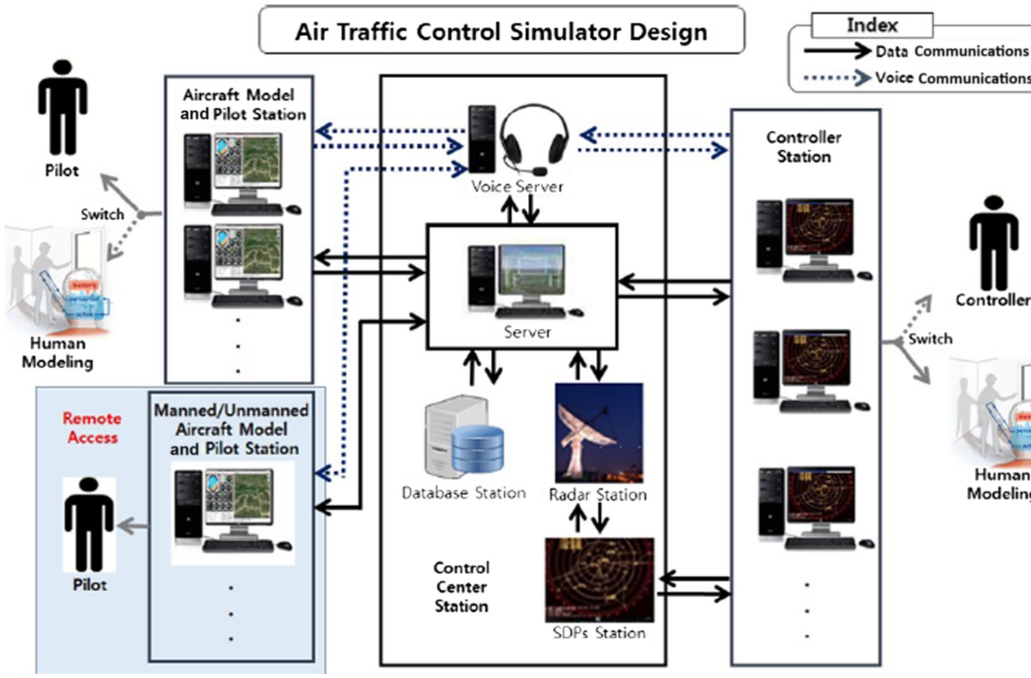


Fig. 6 ATC simulator structure.

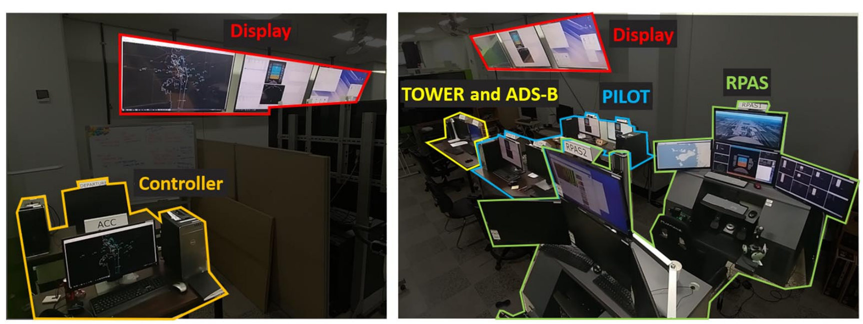
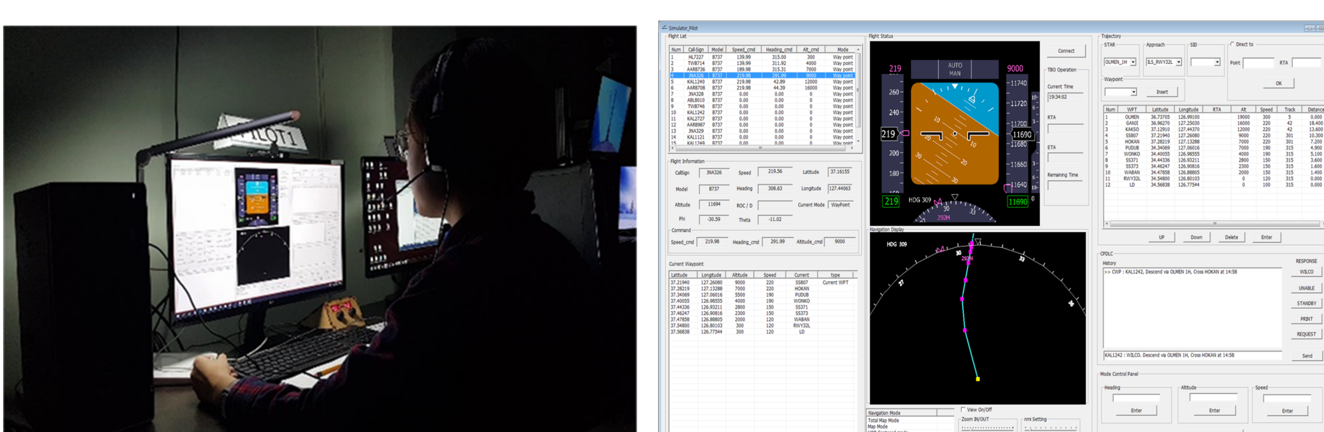


Fig. 7 ATC simulator layout.

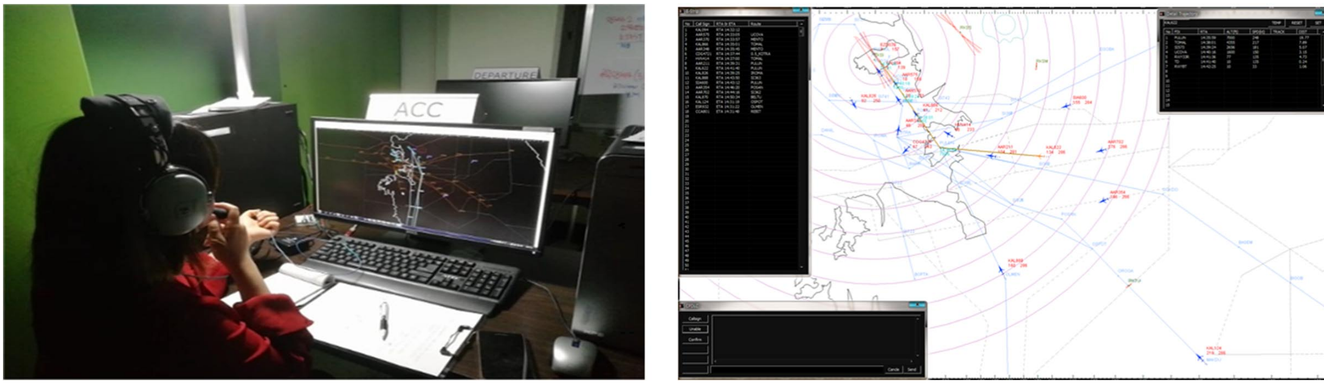
Multiple pilot stations are connected to the server, and each pilot station can control multiple aircraft. For this simulation, one pseudopilot controlled all the aircraft. A five-degree-of-freedom point mass model is used for the aircraft dynamics combined with control and guidance routines created using the performance and operational specifications from the Base of Aircraft Data [14]. Figure 8 shows the pilot station.

The controller station shows the current position of aircraft with the data block on the map as well as airspace boundaries, fixes, and air routes. In the controller station display, RPAs are displayed in green, and manned aircraft are displayed in yellow. When an RPA loses its C2 link, it automatically transmits a 7400 squawk code, and the color is changed to red. Figure 9 shows the controller station.



a) Pilot station view **b) Pseudopilot user interface**

Fig. 8 Pilot station.



a) Controller station view

b) Controller user interface

Fig. 9 Controller station.

2. Participants and Simulation Settings

HITL simulations were performed with one pseudopilot and three controllers, one licensed student controller, and two active controllers with both area control procedural ratings and area control surveillance ratings. The student controller had participated in other HITL simulations using the same system. So, the student controller was familiar with the simulation environment. On the other hand, the two active controllers were well experienced with the task of managing the traffic on busy air routes, but they were not familiar with the simulator. They were given 10 min of training time before the actual HITL simulation started. The pseudopilot was not licensed but had participated in numerous HITL simulations as a pseudopilot.

Each controller performed the three scenarios given in Table 1, and the corresponding contingency procedures (e.g., hold at ATASO fix, merge at MANGI fix, and then return to Jeju) were given in the flight plan of the RPAs. The experimental procedures were briefed to the controllers before the simulation. While one controller conducted the simulation, the other controllers waited in a separate space in order to avoid getting familiar with the traffic situation. Also, the controller and the pilot were partitioned so that they could not see each other's screen. They communicated through aviation headsets that blocked outside sound.

3. Scenarios

Each scenario contains three RPAs that are arbitrarily selected among the manned aircraft flying on Y722. The controllers are aware of the expected behavior of a lost C2 link RPA, but they do not know which of the three RPAs will lose its C2 link. This prevents the controllers from anticipating the lost C2 link behavior of the RPA and accumulating learning effects. The controllers are able to notice the occurrence of a lost C2 link by the squawk code and the color change. The reference scenario is the one without the loss of the C2 link, and no controller intervention is necessary. This reference scenario is used as a baseline for the comparison of safety and controller workloads. The fleet mix on the Seoul–Jeju route is semihomogeneous. Most aircraft are narrow-body types, such as variants of the Boeing 737 or Airbus 320. So, the flight performance of RPAs is assumed to be similar to that of a Boeing 737-800.

IV. Metrics

The results of the HITL simulations are analyzed for two different aspects: safety and controller workload. For the safety, two metrics are introduced: the conflict intrusion parameter (CIP) and the well clear score (WCS). For the evaluation of controller workload, three metrics are used: NASA TLX, instantaneous self-assessment (ISA), and the number of maneuver commands by the controllers. NASA TLX and ISA are widely used for measuring an operator's workload. The number of maneuver commands is introduced in this paper as an additional metric for controller workload. The ISA measures the current workload level every 2 min according to the established measurement procedure, whereas the NASA TLX is surveyed after each simulation run is completed. The controllers give maneuver commands to avoid a conflict, which include altitude change, speed change, heading change, or possibly any combination of the three.

A. Safety Metrics

1. Conflict Intrusion Parameter

The CIP is defined in Eq. (1), which is dependent only on the horizontal and vertical separation distances [14,15]. Horizontal and vertical separation standards, S_{std} and h_{std}, are set to 5 n miles and 1000 ft, respectively. The CIP value ranges from minimum zero, meaning the instant separation exceeds the standard separation criteria, to maximum one, meaning collision:

$$\mathrm{CIP}(t) = \max\left\{1\text{–}0.5 \times \left\{\left(\frac{r_{xy}(t)}{S_{std}} + \frac{d_h(t)}{h_{std}}\right)\right\}, 0\right\} \tag{1}$$

2. Well Clear Score

Well clear has been proposed by the Unmanned Aircraft System Executive Committee Science and Research Panel and Radio Technical Commission for Aeronautics Special Committee 228 Detect and Avoid (DAA) working group as the separation requirements for the DAA system of the RPAS [16]. Well clear is defined with three key parameters. First, τ_{mod}, defined in Eq. (2), is a temporal separation metric that estimates the time to the closest point of approach (CPA) between two aircraft. Second, the horizontal miss distance (HMD), given in Eq. (3), is the projected separation in the horizontal dimension at the predicted CPA using linear extrapolation. Lastly, d_h is the vertical separation between two aircraft. A risk level is determined by comparing the three parameters of τ_{mod}, HMD, and d_h against their corresponding parameter values listed in Table 3 using Eqs. (4)–(6) along with the alert times (where DMOD denotes the distance modifier):

Table 3 Parameters for DAA well clear alert

Alert type	Preventive alert	Corrective alert	Warning alert	LOWC
WCS	1	2	3	4
Alert times, s	55	55	25	0
τ^*_{mod}, s	35	35	35	35
DMOD and HMD*, ft	4000	4000	4000	4000
h^*, ft	700	450	450	450

$$\tau_{\mathrm{mod}} = \begin{cases} 0 & (r_{xy} \le \mathrm{DMOD}) \\ \dfrac{\mathrm{DMOD}^2 - r_{xy}^2}{r_{xy}\dot{r}_{xy}} & (r_{xy} > \mathrm{DMOD} \text{ and } \dot{r}_{xy} < 0) \\ \infty & (r_{xy} > \mathrm{DMOD} \text{ and } \dot{r}_{xy} \ge 0) \end{cases} \tag{2}$$

where

$$\dot{r}_{xy} = \frac{d_x v_{rx} + d_y v_{ry}}{r_{xy}}$$

$$\mathrm{HMD} = \begin{cases} \sqrt{(d_x + v_{rx} t_{\mathrm{CPA}})^2 + (d_y + v_{ry} t_{\mathrm{CPA}})^2} & (t_{\mathrm{CPA}} > 0) \\ r_{xy} & (t_{\mathrm{CPA}} \le 0) \end{cases} \tag{3}$$

where

$$t_{\mathrm{CPA}} = \frac{d_x v_{rx} + d_y v_{ry}}{v_{rx}^2 + v_{ry}^2}$$

$$0 \le \tau_{\mathrm{mod}} \le \tau^*_{\mathrm{mod}} \tag{4}$$

$$\mathrm{HMD} \le \mathrm{HMD}^* \tag{5}$$

$$-h^* \le d_h \le h^* \tag{6}$$

Alert times indicate the range of prediction from the current time. For example, two aircraft are in corrective alert if Eqs. (4)–(6) are predicted to be satisfied in 55 s using the parameter values for the corrective alert. Because the parameter values are identical to the loss of well clear (LOWC), it means, if the two aircraft continue without any mitigation or maneuver, they will be in LOWC in 55 s. Similarly, warning alert means 25 s before LOWC. Finally, if Eqs. (4)–(6) are satisfied at the current time, the two aircraft are at a LOWC situation. The DAA system should guide the aircraft to avoid LOWC. At each risk level, three different sets of alert times are specified [16]: minimum average time of the alerts, late threshold, and early threshold. For this study, the minimum average time of alerts is used for all the levels. To quantify the level of safety, a metric called the WCS was proposed [14]. A score from one (preventive alert) to four (LOWC) is assigned to the risk levels.

B. Controller Workload

1. NASA TLX

The NASA TLX is a multidimensional rating procedure that allows users to measure the subjective workload of operators working with various human–machine interface systems [17]. The NASA TLX derives an overall workload score based on a weighted average of ratings on six evaluation areas: mental demand, physical demand, temporal demand, performance, effort, and frustration.

2. Instantaneous Self-Assessment

The ISA was developed by the Air Traffic Management Development Center to measure the mental workload of an operator at five levels [18]. Participants assess the level of the workload from one (underused) to five (excessively busy) every 2 min while on duty.

3. Number of Maneuver Commands by Controller

Air traffic controllers give various maneuver commands to pilots to assure proper separation. The instructions consist of three commands: altitude change, speed change, or heading change (or any combination of the three). In this paper, to quantify the workload that cannot be clearly distinguished by the NASA TLX or ISA, the number of maneuver commands is counted by their types. The heading change is assumed to be the most demanding because it requires the controllers to issue subsequent instructions to return the aircraft to its original course. On the other hand, altitude or speed changes do not involve any detour from the original route.

V. Results

HITL simulations were conducted with the three scenarios described in Sec. III. The results in the form of recorded flight trajectories and voice instructions as well as questionnaires were analyzed by the safety and controller workload metrics presented in Sec. IV. In the following series of figures, the student controller is referred to as controller 1, and the two active controllers are referred to as controllers 2 and 3.

A. Safety Analysis

For the safety analysis, the maximum values of the safety metrics (i.e., CIP or WCS) and the numbers of conflict pairs are given. The maximum value shows the most dangerous situation at each time step. When there exists a potentially dangerous situation, the number of conflict pairs is usually one, which means the situation involves only two aircraft. When the number of conflict pairs is larger than one, there are multiple dangerous situations at the same time.

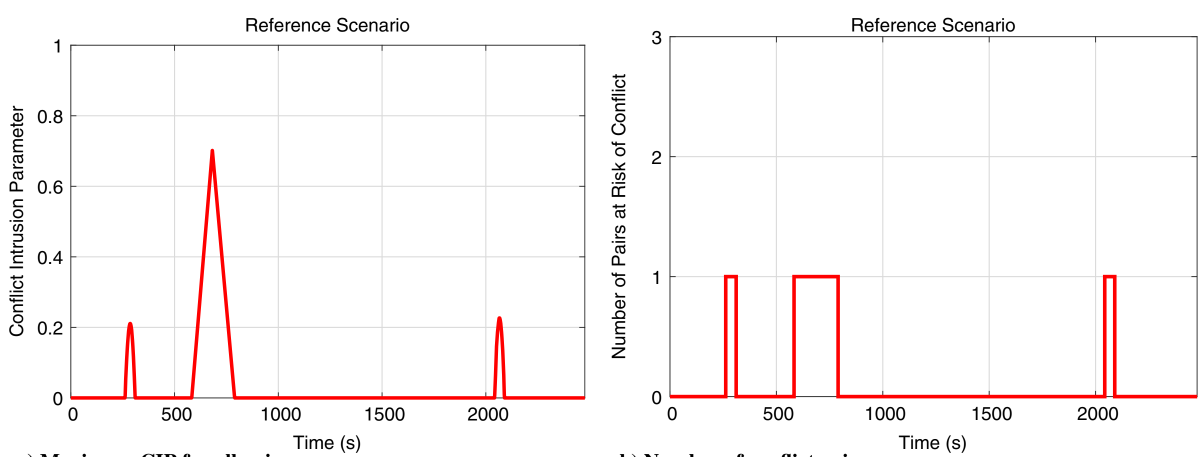
1. CIP

Figure 10a shows the maximum value of the CIP among all aircraft pairs at each time step in the reference scenario. Figure 10b shows the number of aircraft pairs that causes the CIP values to become greater than zero. One instance of a high CIP value around 0.7 is between two aircraft on the final approach paths at around 2500 ft, which is not considered a risk situation. Figures 11–13 show the maximum value of the CIP and the number of conflict pairs for scenarios 1, 2, and 3, respectively. The solid colored areas under the curves in Figs. 11–13 indicate a conflict between a manned aircraft and an RPA with a lost C2 link. The operation times of the RPAs are marked by shaded areas. A lightly shaded time interval means the C2 link of the RPA worked properly, and time interval with a darker shade indicates the time interval during which the C2 link was lost.

The maximum CIP value is greater than 0.5 at around 1000 s for controller 2 and at around 1400 s for controller 3 in scenario 1, which occurs between manned aircraft. In scenario 3, the maximum CIP value is greater than 0.5 at around 500 s for controller 1, and it is between manned aircraft. Table 4 summarizes the CIP analysis showing the number of occurrences of the nonzero CIP and the maximum CIP during the simulation. Because the orders of the scenarios in terms of the CIP results do not display any noticeable trends, it is difficult to reach an overall conclusion from Table 4. However, scenario 1 is the worst in terms of the maximum CIP value and the number of conflict pairs if the results for all three controllers are aggregated.

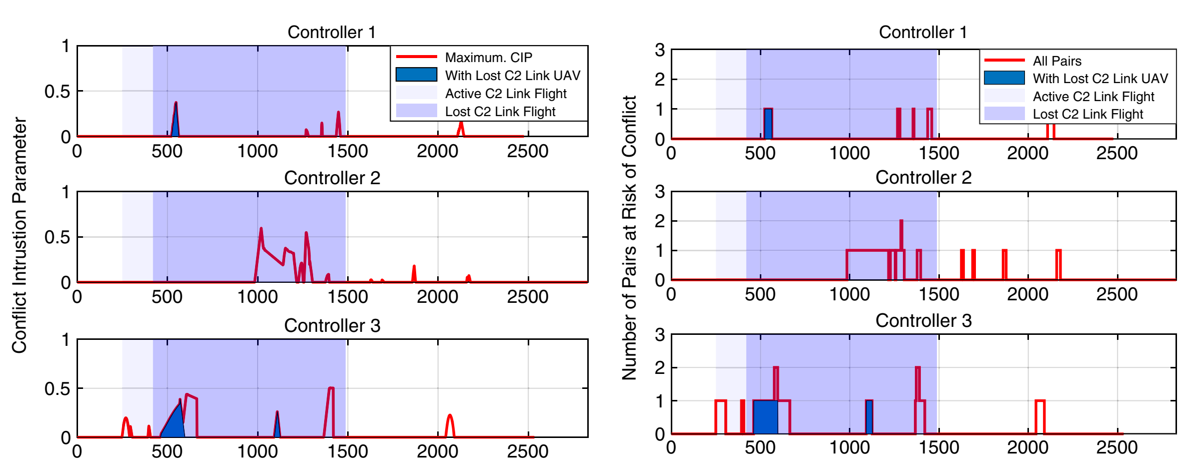
2. WCS

Similar to the CIP analysis, the maximum value of the WCS and the number of well clear alerts are compared. A well clear alert indicates any WCS of one or higher. In the reference scenario, no well clear alert is detected, which agrees with the fact that the reference scenario is based on the track data already managed by the controllers. Figure 14 shows the maximum value of the WCS and the number of well clear alerts in scenario 1. Note that well clear alerts are observed only in scenario 1. Unlike the CIP metric, which is based only on the distances between two aircraft, the WCS uses time. Also, the WCS is used to predict a potential conflict risk level through extrapolation within a certain alert time. So, even when the CIP value is large, its WCS metric could be zero. The first well clear alert for controller 2 occurs between a manned aircraft and an RPA with a lost C2 link at around 1100 s, and the conflict resolution maneuver causes the second well clear alert at around 1200 s. The second alert happens



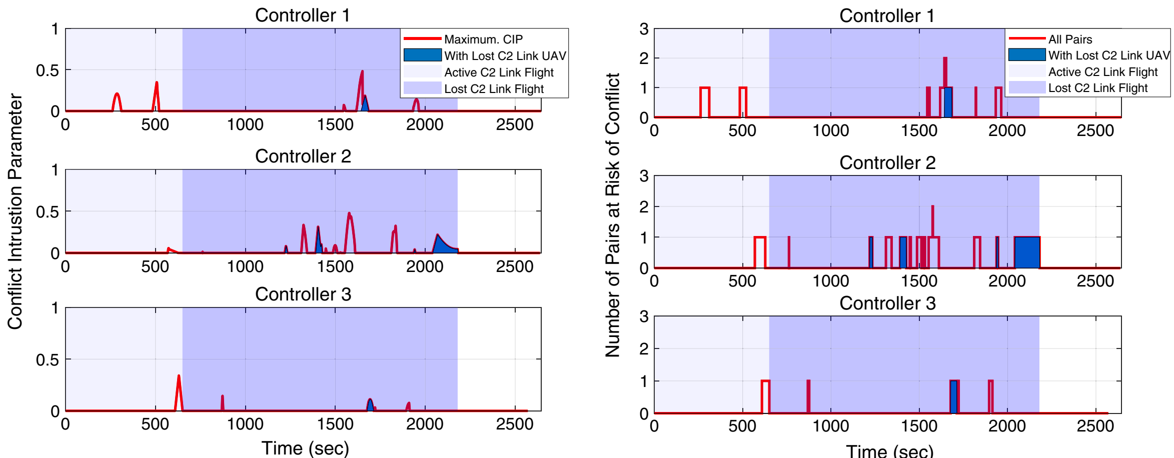
a) Maximum CIP for all pairs **b) Number of conflict pairs**

Fig. 10 CIP results for the reference scenario.



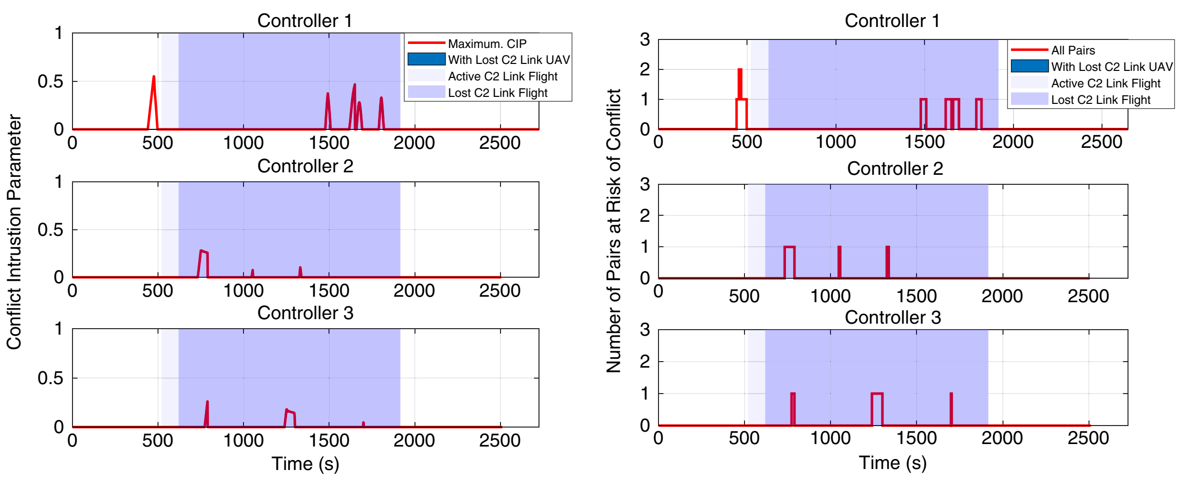
a) Maximum CIP for all pairs **b) Number of conflict pairs**

Fig. 11 CIP results for scenario 1.



a) Maximum CIP for all pairs b) Number of conflict pairs

Fig. 12 CIP results for scenario 2.



a) Maximum CIP for all pairs b) Number of conflict pairs

Fig. 13 CIP results for scenario 3.

between two manned aircraft. In this exceptional case, an actual LOWC situation happens, as shown in Fig. 14a. Figure 15 shows a snapshot of the controller display at this moment. It is considered to be an outlier due to the controller not being familiar with the RPA operation and the simulation environment that is not identical to their working environment. This indicates that the initial training time given to the active controllers may not be sufficient. Controller 2 seemed to fail to notice the collision risk between ABL8015 and AAR724 when giving the heading change command, which is the resolution maneuver to avoid the RPA with the lost C2 link at around 1160 s. The unfamiliarity with the simulation environment and the RPAS operations may have distracted the controller from understanding the overall air traffic situation. Table 5 summarizes the WCS analysis. Note that the average WCS is the sum of all WCSs divided by the total number of well clear alerts. Similar to the CIP analysis, scenario 1 is the worst in terms of safety.

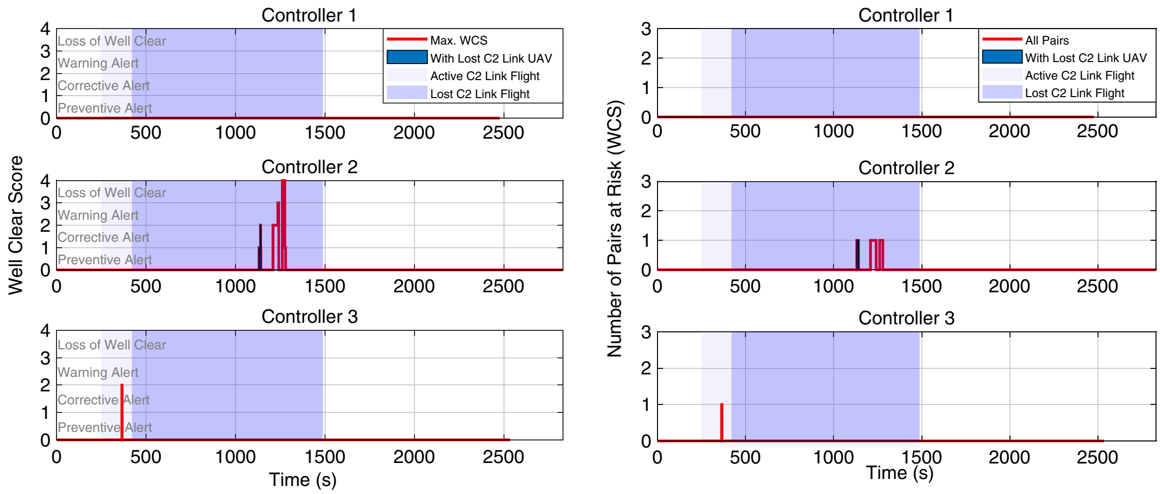
B. Controller Workload

1. NASA TLX

The NASA TLX results are given in Table 6. The workload of the student controller (controller 1) is higher than those of the active controllers in every scenario, whereas the two active controllers show similar workloads in all three scenarios. Due to the lack of field experience, controller 1 directed aircraft more conservatively than other controllers, as indicated by the WCS results in Table 5, which increased the workload. The sum of the NASA TLX is not significantly different among the scenarios, but scenario 2 shows the highest sum because the flight distance of the RPAS with the lost C2 link is longer in this scenario than others, as given in Table 1.

Table 4 Summary of the CIP results

	Controller 1		Controller 2		Controller 3		Average	
	Number	Maximum	Number	Maximum	Number	Maximum	Number	Maximum
Scenario 1	119	0.374	394	0.595	442	0.504	318.3	0.491
Scenario 2	206	0.482	422	0.477	110	0.341	246.0	0.434
Scenario 3	196	0.551	78	0.280	82	0.261	118.7	0.364



a) Maximum value of WCS for all pairs b) Number of pairs of WCS

Fig. 14 WCS results for scenario 1.

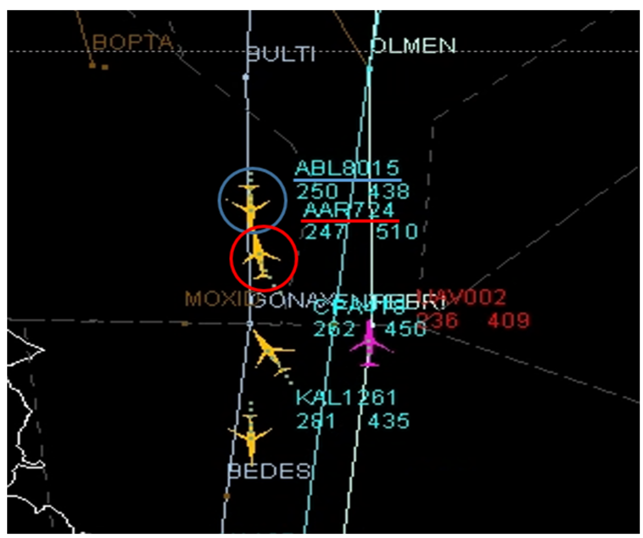


Fig. 15 LOWC situation between ABL8015 and AAR724 in scenario 1 for controller 2.

2. *ISA*

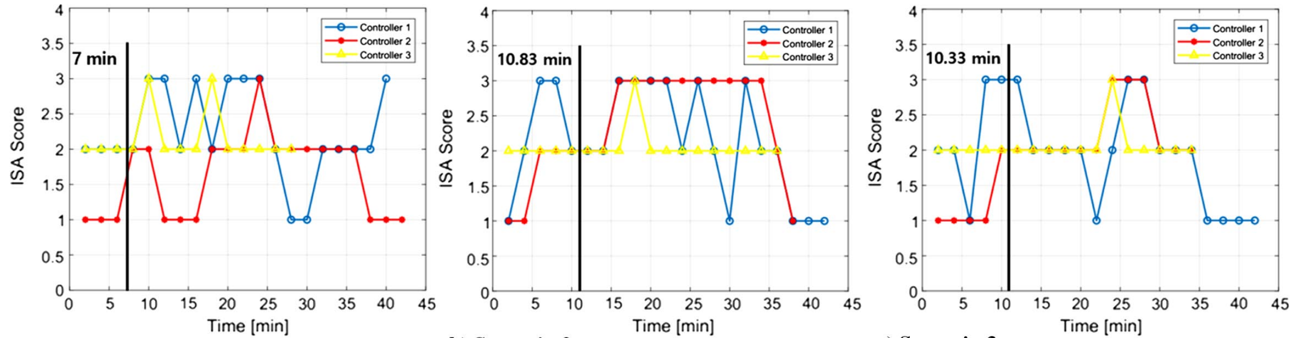
The ISA results are given in Fig. 16. The workload of the controller increases slightly when the controller notices a lost C2 link, which is marked by the solid vertical lines with time stamps in Fig. 16. However, the ISA results show a large variation between the controllers and do not show noticeable correlation with the CIP or WCS results.

Table 5 Number of well clear alerts and average WCS

Scenario	Controller	Preventive alert	Corrective alert	Warning alert	LOWC	Average WCS
3*1	1	0	0	0	0	3*2.328
	2	12	28	5	14	
	3	1	1	0	0	
3*2	1	0	0	0	0	3*0
	2	0	0	0	0	
	3	0	0	0	0	
3*3	1	0	0	0	0	3*0
	2	0	0	0	0	
	3	0	0	0	0	

Table 6 NASA-TLX results

	Controller 1	Controller 2	Controller 3	Sum
Scenario 1	49.2	20.0	26.7	95.9
Scenario 2	55.8	20.8	27.5	104.1
Scenario 3	41.7	18.3	27.5	87.5
Sum	146.7	59.1	81.7	— —



a) Scenario 1 b) Scenario 2 c) Scenario 3

Fig. 16 ISA results.

Table 7 Summary of the number of maneuver commands issued by the controllers

	Controller 1			Controller 2			Controller 3			Average		
Maneuver command type	Speed	Altitude	Heading	Speed	Altitude	Heading	Speed	Altitude	Heading	Speed	Altitude	Heading
Scenario 1	16	25	5	7	50	5	7	26	3	10.00	33.67	4.33
Scenario 2	11	27	1	8	45	1	18	37	1	12.33	36.33	1.00
Scenario 3	12	26	2	12	37	1	16	48	1	13.33	37.00	1.33

3. *Number of Maneuver Commands*

Table 7 summarizes the number of maneuver commands issued by the controllers in each scenario. The number of speed and altitude commands do not vary greatly between the three scenarios. However, scenario 1 shows the most frequent heading changes, which indicates the two return scenarios (scenarios 2 and 3) are better in terms of the controller workload than the continue scenario (scenario 1).

4. *General Comments by the Participating Controllers*

The three participating controllers were interviewed about the overall experiences after the HITL simulations. They made the following comments on the design of the contingency procedures. According to the comments, the controllers seem to prefer scenario 1, but the safety and workload metrics showed the worst results for scenario 1. The following comments show the controllers' personal thoughts about the lost C2 link situation, and that they preferred scenario 1 due to its simplicity. However, the seemingly contradictory metrics indicate that the preference of controllers does not necessarily agree with their workload.

"It seems inappropriate to return to base at the ATASO fix, which is close to the destination airport. I suggest proceeding to the destination airport after holding at the ATASO fix rather than returning."

"The RPA with a lost C2 link reduces speed for holding and increases it back to rejoin the air route. However, I found it unsafe."

"The holding time must be enough to prepare for the separations with other traffic when returning to the air route."

"I have a concern in the two return scenarios that separation between aircraft could be violated while joining the opposite air route."

Also, one controller rated the scenarios as follows.

"Trajectory deviation itself is so stressful. If keeping the original flight plan, it is easier to maintain the separation. So, I prefer the continue scenario."

In addition, they commented on the simulation environment.

"I am aware of the contingency procedure briefly, but I like to know more details on what actions the RPA will take. Because there is no information on the distance between aircraft in the scenarios, I need to make some assumptions on the separation."

"There are so many differences between the planned and the actual altitudes. That is weird because the difference is usually less than 50 ft in the real environment."

"It requires me to keep monitoring the heading due to its disagreement with the route. It barely happens, indeed."

VI. Conclusions

In this paper, lost C2 link procedures were developed on a route between Seoul and Jeju. Three scenarios were generated based on a hypothesis that safety and workload would be affected by the ratio of the remaining distance to the flown distance. Using an air traffic simulation system, human-in-the-loop simulations were performed with one student controller and two active controllers. The results were evaluated using safety and controller workload metrics. The two return-to-base scenarios demonstrated advantages in both safety and controller workload as compared to the continue-to-destination scenario. The results of this paper can contribute to the establishment of international standards for the en route contingency procedures in case of a lost C2 link and work as a reference for the operational procedures that each member state will make once the international standards are established. However, this paper does not consider a scenario in which the remotely piloted aircraft system with a lost C2 link diverts to a third airport due to the constraints in the Korean national airspace. Also, future work needs to consider a contingency procedure for a terminal area and/or the addition of more objective measures of controller workload, such as an electrocardiogram or eye tracking.

Acknowledgments

This work was supported by the Flight Safety Regulation Development and Integrated Operation Demonstration for Civil Unmanned Aircraft Systems (No. 18ATRP-C108186-04) project under the Aviation Safety Technology Development Program funded by the Ministry of Land, Infrastructure and Transport in the Republic of Korea.

References

[1] Dalamagkidis, K., Valavanis, K. P., and Piegl, L. A., "On Unmanned Aircraft Systems Issues, Challenges and Operational Restrictions Preventing Integration into the National Airspace System," *Progress in Aerospace Sciences*, Vol. 44, No. 7, 2008, pp. 503–519. doi:10.1016/j.paerosci.2008.08.001

[2] Watts, A. C., Ambrosia, V. G., and Hinkley, E. A., "Unmanned Aircraft Systems in Remote Sensing and Scientific Research: Classification and Considerations of Use," *Remote Sensing*, Vol. 4, No. 6, 2012, pp. 1671–1692. doi:10.3390/rs4061671

[3] *Manual on Remotely Piloted Aircraft Systems (RPAS)*, 1st ed., International Civil Aviation Organization Doc. 10019, Montreal, 2015.

[4] "Candidate SARPS for RPAS Functions Supported by the C2 Link and the Corresponding Required C2 Link Performance," International Civil Aviation Organization TR RPASP/8-WP/7, RPAS Panel Working Group 2 (C2), Montreal, 2017.

[5] "Remotely Piloted Aircraft System (RPAS) Concept of Operations for International IFR Operations," International Civil Aviation Organization TR, Montreal, 2017.

[6] Kamienski, J., Simons, E., Bell, S., and Estes, S., "Study of Unmanned Aircraft Systems Procedures: Impact on Air Traffic Control," *Digital Avionics Systems Conference (DASC)*, IEEE Publ., Piscataway, NJ, 2010, pp. 5.D.2-1–5.D.2-10. doi:10.1109/DASC.2010.5655467

[7] Hu, Q., and Jella, C., "Intelligent UAS Situation Awareness and Information Delivery," *Digital Avionics Systems Conference (DASC)*, IEEE Publ., Piscataway, NJ, 2010, pp. 5.C.3-1–5.C.3-6. doi:10.1109/ICNSURV.2011.5935391

[8] Fern, L., Rorie, R. C., and Shively, R. J., "UAS Contingency Management: The Effect of Different Procedures on ATC in Civil Airspace Operations," *14th Annual AIAA Aviation, Technology, Integration and Operations Conference*, AIAA Paper 2014-2414, 2014. doi:10.2514/6.2014-2414

[9] "Contingency Procedures for C2 Link Loss," International Civil Aviation Organization TR RPASP/6-WP/6, RPAS Panel Working Group 6 (ATM), Montreal, 2016.

[10] "Proposal for Amendments to Annex 2 and Doc PANS-ATM 4444 Related to C2 Failure Link ATC Procedures," International Civil Aviation Organization TR RPASP/9-WP/4, RPAS Panel Working Group 6, Montreal, 2017.

[11] "60th Edition of IATA World Air Transport Statistics Released," International Air Transport Association, July 2016, http://www.iata.org/pressroom/pr/Pages/2016-07-05-01.aspx [retrieved 7 Oct. 2017].

[12] Hong, H.-J., Joo, T.-H., and Kim, S.-H., "Lost C2 Link Contingency Procedures for RPAS on Seoul–Jeju Route," *Transport Research*, Vol. 24, No. 4, 2017, pp. 11–23.

[13] Oh, H., Jeong, S., Choi, K., and Lee, H.-T., "Human-in-the-Loop Simulation Analysis of Conflict Resolution Maneuvers Using an Air Traffic Control Simulation," *AIAA Modeling and Simulation Technologies Conference*, AIAA Paper 2016-0169, 2016. doi:10.2514/6.2016-0169

[14] Kang, J., Oh, H., Choi, K., and Lee, H.-T., "Development and Validation of an Improved 5-DOF Aircraft Dynamic Model for Air Traffic Control Simulation," *Advanced Navigation Technology*, Vol. 20, No. 5, 2016, pp. 387–393. doi:10.12673/jant.2016.20.5.387

[15] Bilimoria, K. D., and Lee, H. Q., "Properties of Air Traffic Conflicts for Free and Structured Routing," *AIAA Guidance, Navigation, and Control Conference*, AIAA Paper 2001-4051, 2001. doi:10.2514/6.2001-4051

[16] "Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems," RTCA TR, SC-228, 2017.

[17] Hart, S. G., "NASA-Task Load Index (NASA-TLX); 20 Years Later," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, SAGE, Thousand Oaks, CA, 2006, pp. 904–908. doi:10.1177/154193120605000909

[18] Tattersall, A. J., and Foord, P. S., "An Experimental Evaluation of Instantaneous Self-Assessment as a Measure of Workload," *Ergonomics*, Vol. 39, No. 5, 1996, pp. 740–748. doi:10.1080/00140139608964495

H. L. Choi
Associate Editor