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Human-in-the-Loop Simulation Analysis of Conflict Resolution Maneuvers Using an Air Traffic Control Simulation

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As the technologies and demands of Remotely Piloted Aircraft Systems (RPASs) growing rapidly, integration of RPAS into the existing airspace system is becoming an issue in many countries. To establish rules and regulations for RPAS integration, it is important to understand the impacts of RPAS, which have different flight performances, communication characteristics, separation assurance mechanisms, and human machine interfaces from manned aircraft, on the airspace system. A simulation system that integrates manned aircraft, air traffic control, and RPASs is developed in Inha University to investigate these impacts through Human-in-The-Loop (HiTL) simulations. For the initial test, a scenario with communication delays between the controller and the pilot of the RPAS was constructed. HiTL simulations were performed with several trainee controllers in Korean Aerospace University. Metrics such as Loss of Well Clear (LOWC), delay, and NASA Task Load Index were investigated to analyze the relation between safety, efficiency, and workload respectively. The results show that the introduction of RPASs with communication delay generally causes other manned aircraft to maneuver, which leads to increased delay and workload. Meanwhile, safety is not significantly impacted.

I. Introduction

The demands for RPASs are rapidly growing as new technologies expand the performance envelopes and capabilities of RPASs while reduce the cost. Many countries are preparing the institutional frameworks such as the aviation law, aircraft certification standards, and operational specifications as well as mid-term and far-term roadmaps for RPAS integration in their airspaces. In 2007, the International Civil Aviation Organization (ICAO) established the Unmanned Aircraft System Study Group (UASSG) where eleven institutions in eighteen countries participated in. ICAO is planning to establish standards for airspace integration of RPAS in 2023-2028 timeframe. European Union published the final version of the roadmap about the integrated operation of a RPAS according to the ICAO's schedule.[1] The United States published a draft roadmap for airspace integration of civil RPAS in 2013.[2]

For the integrated operations between manned aircraft and Remotely Piloted Aircraft (RPAs), it is important to understand how the unique characteristics of RPAS such as dynamic performances, command and control communications, separations assurance mechanism, and human factors affects the current air traffic management system. There exist a large variations in the flight performances among different RPAs due to differences in configurations, sizes, or missions. Because the pilot is not onboard the aircraft, an additional wireless link that is reliable and secure is required to fly the RPA in addition to the conventional means of communication between the remote pilot and the air traffic control system. In terms of separation

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assurance, a system that can replace the see and avoid requirement is necessary. Developing Detect And Avoid (DAA) system is one of the biggest technical challenges in the RPAS integration. Finally, RPAS has to be compatible with the current air traffic management system that includes operating personnel such as pilots and controllers.

For the development and verification of the RPAS operational standards and requirements, it is necessary to repeatedly perform HiTL simulations involving pilots and controllers and to analyze the results. For the past several years, Inha University has been developing a flexible and expandable air traffic control simulation system. In this study, a scenario that involves three RPAs with communication delays around the Incheon International Airport was developed based on the opinions gathered from experience air traffic controllers in Republic of Korea. HiTL simulations were performed with trainee controllers in Korean Aerospace University acting as air traffic controllers and students in Inha University acting as pseudo pilots of manned aircraft and RPAs. The simulation system was set up to artificially add prescribed communication delay. All simulation data were recorded, and the participants filled out questionnaires for the workload survey.

Following the introduction, Section II describes the simulation system, and Section III describes performance metrics such as LOWC, arrival delay, and controller workload. Section IV explains the scenario where RPASs are integrated into the existing airspace system. Section V presents the analysis results. Finally, section VI concludes this study.

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II. Air Traffic Control Simulation System

The purpose of the Air Traffic Control (ATC) simulator is to evaluate and analyze new technologies and concepts as well as to train controllers and pilots. Figure 1 shows the structure of the Inha University ATC simulator. It is composed of a server, multiple pilot stations, and multiple controller stations.

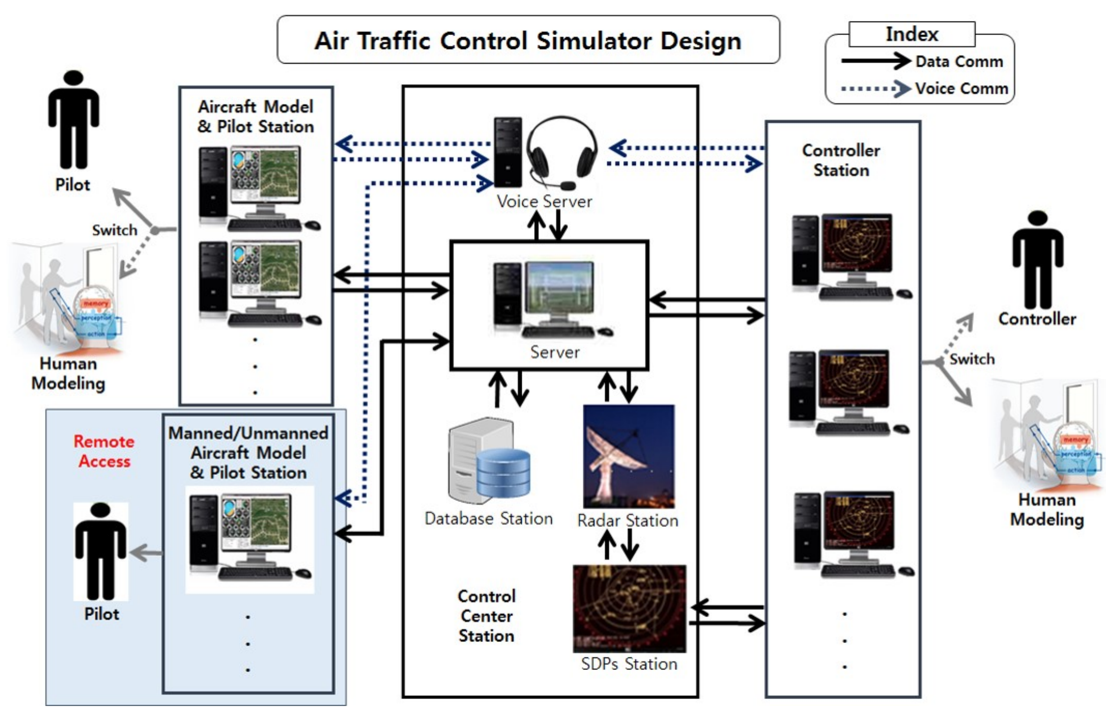

Figure 1: Air traffic control simulator structure.

A. Server

The server manages the simulation scenarios and handles the data flow between the clients. Before a simulation start, a scenario is created. Information such as initial states of aircraft and radars are distributed to the clients. Once the simulation is started, the flight states received from pilot stations are sent to the radar model that resides inside the server. The radar model converts position of aircraft to distance and bearing. These values are sent to the surveillance data processing system model that handles calibration errors and filtering. Processed positions and flight paths are sent to the controller station.[7]

B. Pilot Station

Each pilot station can control multiple aircraft, and multiple pilot stations can be connected to the server. The pilot station has a five degree-of-freedom simplified flight dynamics model to generate trajectories according to pilot inputs. Five dynamic models were developed to represent different aircraft classes. Figure 2 shows the pilot station display. It can receive speed, altitude, heading, and waypoint commands through a typical flight management system interface. The pilot station display also includes primary flight display and navigation display.

Figure 2: Pilot station UI.

C. Controller Station

Controller station display shows the map and aircraft with essential flight information including call sign, position, altitude, and speed. Figure 3 shows the screen shot of the controller station's user interface. It also shows airspace boundaries and flight routes.

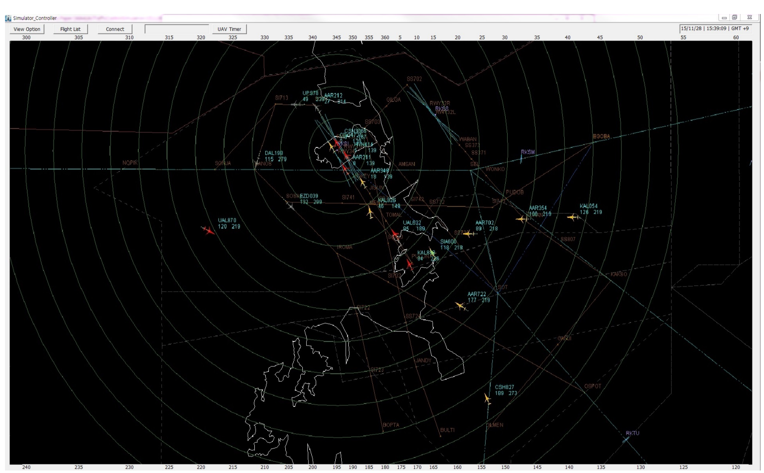

Figure 3: Controller station UI.

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III. Performance Metrics

A. Safety Metric

1. *Conflict Intrusion Parameter(CIP)*

To determine safety levels, several metrics were evaluated. The first metric, Conflict Intrusion Parameter (CIP) defined in Eq. (1), is based only on the horizontal and vertical separate distances. [8] Horizontal and vertical separations standards, S_{std} and h_{std}, are set to 5 nmi and 1,000 ft respectively. The maximum value of CIP is one, which means collision has occurred. As the original purpose of this metric was to quantitatively describe separation between aircraft mostly in class A airspace, it is used only for reference in this study.

$$CIP = 1 - 0.5 \times \left\{ min\left(\frac{\Delta s(t)}{S_{std}} + \frac{\Delta h(t)}{h_{std}} \right) \right\},\ (t_{soc} \leq t \leq t_{eoc}) \tag{1}$$

2. *Well Clear (WC)*

The concept of well clear is proposed as an airborne separation standard to which any DAA systems must satisfy, and performing self-separation (SS) correctly means remaining well clear of other aircraft. This definition is proposed by the UAS Executive Committee Science and Research Panel (SaRP) and the Radio Technical Commission for Aeronautics (RTCA).[13] Well clear definition consists of three parameter given in Eqs. (2), (3) and (4). As shown in the table 1, five levels of safety levels are proposed with different threshold values. LOWC is the most dangerous situation that must be avoided.

$$0 \leq \tau_{mod} \leq \tau^*_{mod} \tag{2}$$

$$HMD \leq HMD^* \tag{3}$$

$$-h^* \leq d_h \leq h^* \tag{4}$$

where,

$$\tau_{mod} = \begin{cases} -\frac{DMOD^2 - r^2}{r\dot{r}}\ (r > DMOD) \\ 0\ (r \leq DMOD) \end{cases}$$

$$HMD = \begin{cases} \sqrt{(d_x + v_{rx}t_{cpa})^2 + (d_y + v_{ry}t_{cpa})^2}\ (t_{cpa} \geq 0) \\ -\inf\ (t_{cpa} < 0) \end{cases}$$

$$d_h = h_2 - h_1$$

Table 1: Well clear self separation alert level.

Self Separation		Proximate Traffic	Preventative Alert	Corrective Alert	Warning Alert	LOWC
Alert Level		Advisory	Caution	Caution	Warning	Danger
MustAlert Threshold	Within Time	60 second	55 second	55 second	40 second	35 second
	τ^*_{mod}	60 second	55 second	55 second	40 second	-
	DMOD, HMD	2.0 nmi	0.66 nmi	0.66 nmi	0.66 nmi	0.66 nmi
	h^*	1,200ft	700ft	450ft	450ft	450ft
MustNotAlert Threshold	More than Time	85 second	75 second	75 second	55 second	-
	HMD_p	5.0 nmi	2.0 nmi	1.5 nmi	1.0 nmi	-
	D_{h_p}	1,300ft	800ft	450ft	450ft	-

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B. Arrival Delay

Generally, any unplanned maneuver causes delay, that translates into increased time and fuel cost. As the current study mostly involves arriving aircraft, arrival delay is chose to be the efficiency metric. In this study, total arrival delay all aircraft is measured during the HiTL simulations. Larger arrival delays will represent the adverse effect of introducing PRAS with communication delays.

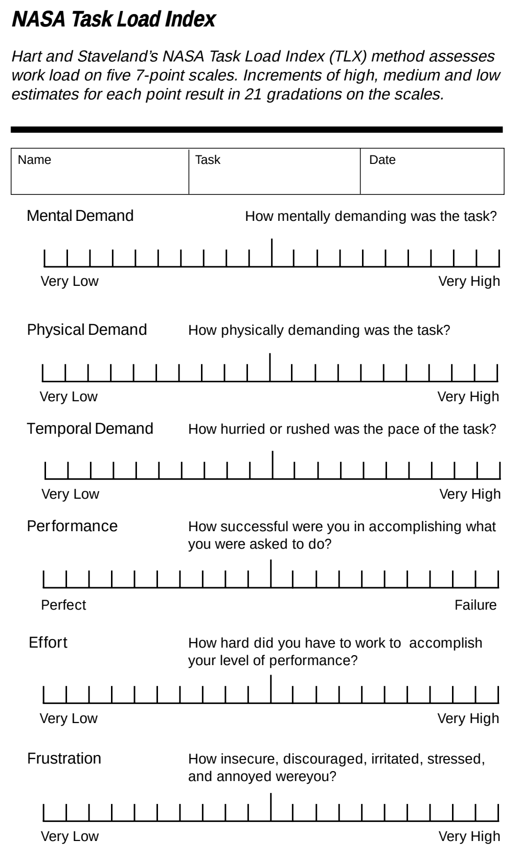
C. Controller Workload

1. *NASA Task Load Index (TLX)*

The NASA-TLX is a multi-dimensional scale designed to obtain workload estimates from one or more operators while they are performing a task or immediately afterwards. The NASA-TLX measures six items to assess workload: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. [14] With weight derived from individual participant, the overall NASA-TLX score is the product of value and weight of each factors.

2. *Instantaneous self-assessment (ISA)*

ISA is a technique that has been developed as a measure of workload to provide immediate subjective ratings of work demands while performing the primary work tasks. Participants self-rate their workloads during a task every two minutes on a scale of 1 (low) to 5(high). [15]



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?
Very Low — Very High

Physical Demand — How physically demanding was the task?
Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?
Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?
Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?
Very Low — Very High

Figure 4: TLX Scale.

Level	Workload	Capacity	Description
5	Excessive	None	Behind on tasks; losing track of the full picture
4	High	Very Little	Non-essential tasks suffering. Could not work at this level very long.
3	Comfortable	Some	All tasks well in hand. Busy but stim ulating pace. Could keep going continuously at this level.
2	Relaxed	Ample	More than enough time for all tasks. Active on ATC task less than 50% of the time.
1	Under-Utilised	Very Much	Nothing to do. Rather boring.

Table 2: ISA score description.

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IV. Simulation

A. Scenario

The scenario is based on recorded trajectory and actual flight plan from 08:00 to 08:30 (UTC) October 10th, 2015. It is during the peak operating hour of Incheon International Airport. Thirteen departures and 26 arrivals were scheduled for the 30 minute duration. Flights are generated ordered by the given inbound time and location (fix), and flight strips are given to the air traffic controller. Case1 represents normal operation with no RPA inbound. As shown in table 3, Cases 2 and 3 have three RPAs inbound with communication delay of one, two, and ten seconds respectively. Communication delay of ten seconds means Loss of Control (LOC).

	RPA870	RPA622	RPA124
Case1	0 second	0 second	0 second
Case2	1 second	2 second	10 second
Case3	2 second	10 second	1 second

Table 3: Scenario (Delay).

B. Task

During the HiTL simulation, air traffic controllers task in each of the scenarios was to perform approach control to manage the traffic in Seoul Terminal Maneuvering Area (TMA). The air traffic controller vectored inbound aircraft to runways 34 and 33R of Incheon International Airport (RKSI).

C. Participant

The participants consist of one air traffic controller and two pseudo pilots. The air traffic controller was a graduate student in air traffic control training program, and obtained the ATC license in 2015. The controller was briefed about the experimental procedure except for the schedule of inbound RPAs to ensure realistic progress of the simulation.

D. Simulation Settings

Three cases of about 26 minute in duration were simulated. In the experiment, several Instrument Flight Rule (IFR) flights were selected to act as RPAs with specific amount of communication delay. The delay or LOC was not informed to the controller during the simulation to observe the impact of RPAS on overall traffic flow. One the radar screen, RPAs were distinguished from other manned aircraft by having a different color, special squawk code, and callsign starting with the letter U.

E. Measurements

Experiments were conducted with three different approaches: risk standard approach, elapsed time of aircraft, and workload questionnaire. Data log files collect trajectory history to analyze CIP, LOWC, and arrival delay. The air traffic controller rates ISA every two minutes during the simulation to assess current level of workload, and the NASA-TLX survey was completed after the end of each case.

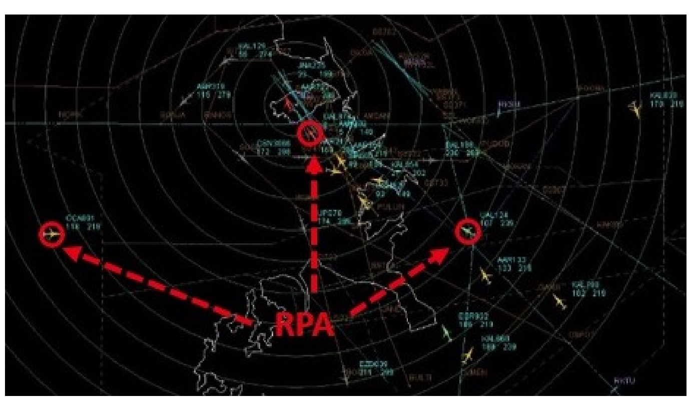

Figure 5: Scenario.

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V. Simulation Results

A. Safety Analysis

1. CIP

Figure 6 is the total number of loss of separation with CIP. Figure 7 is the values CIP around the three RPAs. Only RPA124 experienced loss of separation, which have the ten seconds communication delay.

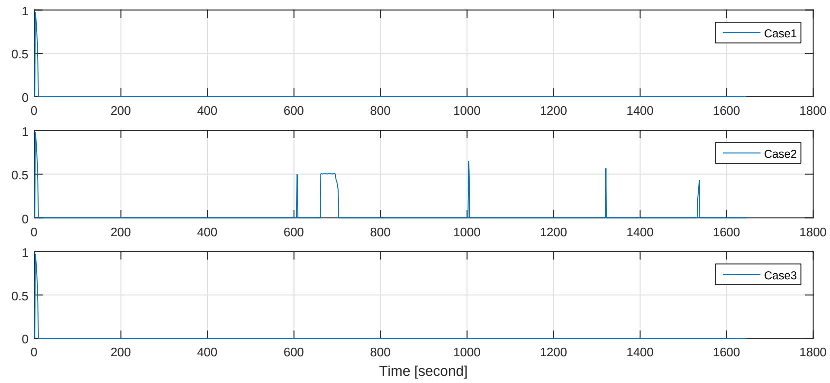

Figure 6: Total loss of separation with CIP.

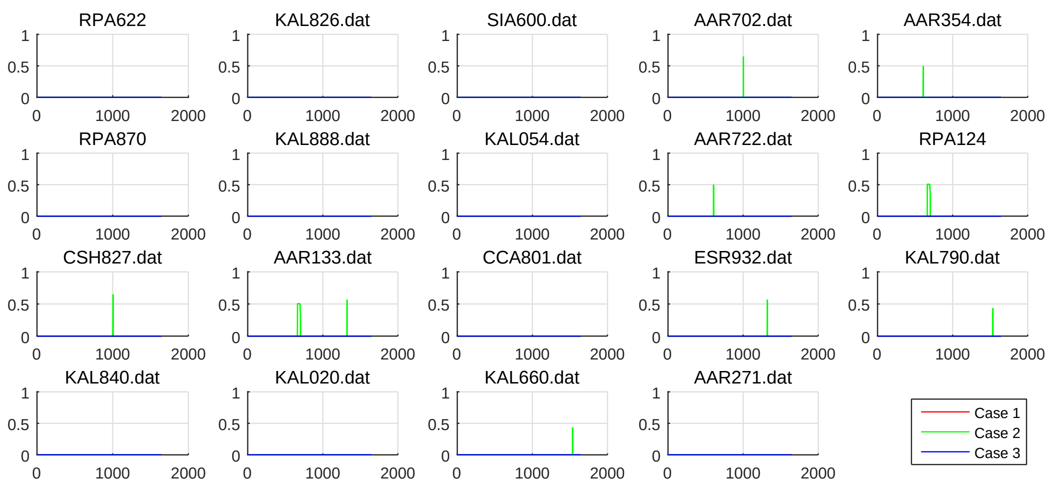

Figure 7: Loss of separation with CIP.

2. Well Clear (WC)

For this study, an index called Well Clear Score (WCS) is defined. The proximate traffic is one, preventative alert is two, corrective alert is three, warning alert is four, and LOWC is five as in table 1. Figure 8 shows the maximum and average WCSs computed from all the conflict pairs with resptect to time. It can be observed that for all three cases, maximum WCS remained at five most of the time, which means at least one conflict pair with LOWC existed throughout the simulation. As will be discussed later, most of these conflict pairs with LOWC are conflicts between manned aircraft. The results suggest that LOWC might not be a good safety metric between manned aircraft.

Figure 9 shows the total WCS with respect to time. Although it is not clearly visible, cases 2 and 3 shows higher WCS towards the end of the simulation. This is partly caused by maneuvering manned aircraft that leads to delayed arrival and increased congestion.

Table 4 summirizes total, average, and maximum WCSs for all the aircraft, RPAs only, and manned aircraft only. All the values indicated that the aggregate that case 1 is the safest and case 3 is least safe. For case 2, the RPA124 with LOC was introduced to the simulation towards the end, so that the simulation was ended before the full impact of this aircraft can be exhibited. For case 3, RPA662 that was introduced in the middle of the simulation with LOC generally caused more safety concerns.

Figures 10 through 12 shows the WCS for conflict pairs that involves the given RPAs. It should be noted that even without communication delays, there exits regions of LOWC involving RPAs. When communication delays are introduced, the pattern of WCS significantly changes. Generally it is difficult to conclude a definite trend about safety from the given data.

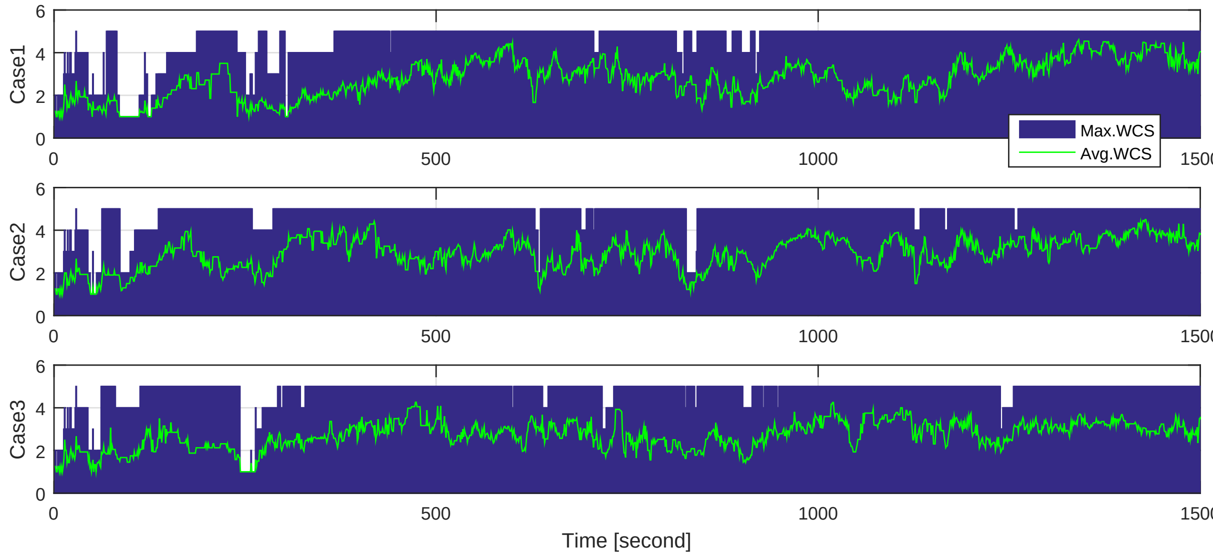

Figure 8: Maximum and average WCS.

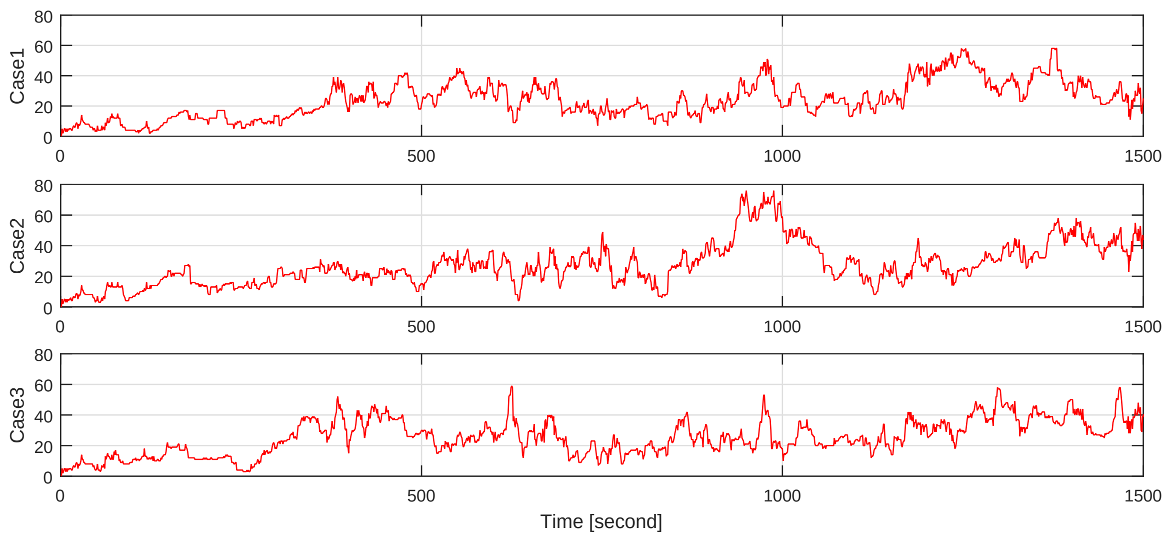

Figure 9: Total well clear score (WCS).

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	All of aircraft			RPAs			Manned Aircraft		
	Case1	Case2	Case3	Case1	Case2	Case3	Case1	Case2	Case3
Total	37,888	41,552	42,846	7,255	7,949	8,683	30,633	33,603	34,266
Mean	22.01	25.24	26.03	1.44	1.58	1.72	0.94	1.03	1.05
Max	58	76	68	15	17	21	12	4	13
Over 10	55,692	55,692	58,812	274	198	309	1,252	1,503	1,400
Over 50	1,443	4,446	1,716	-	-	-	-	-	-

Table 4: Total WCS.

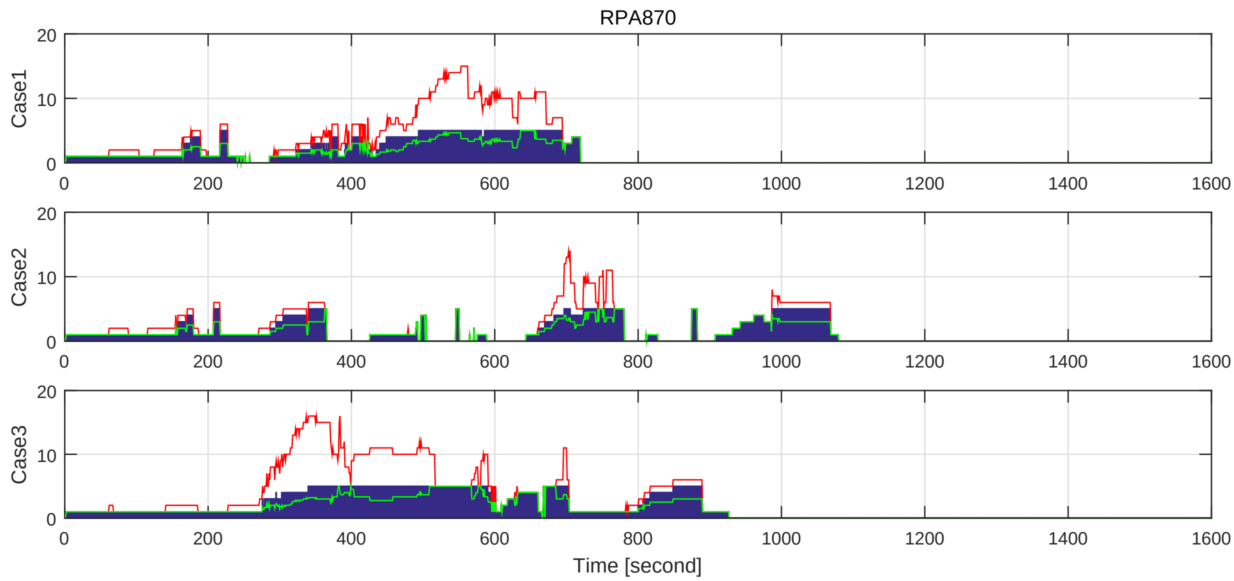

Figure 10: WCS of RPA870.

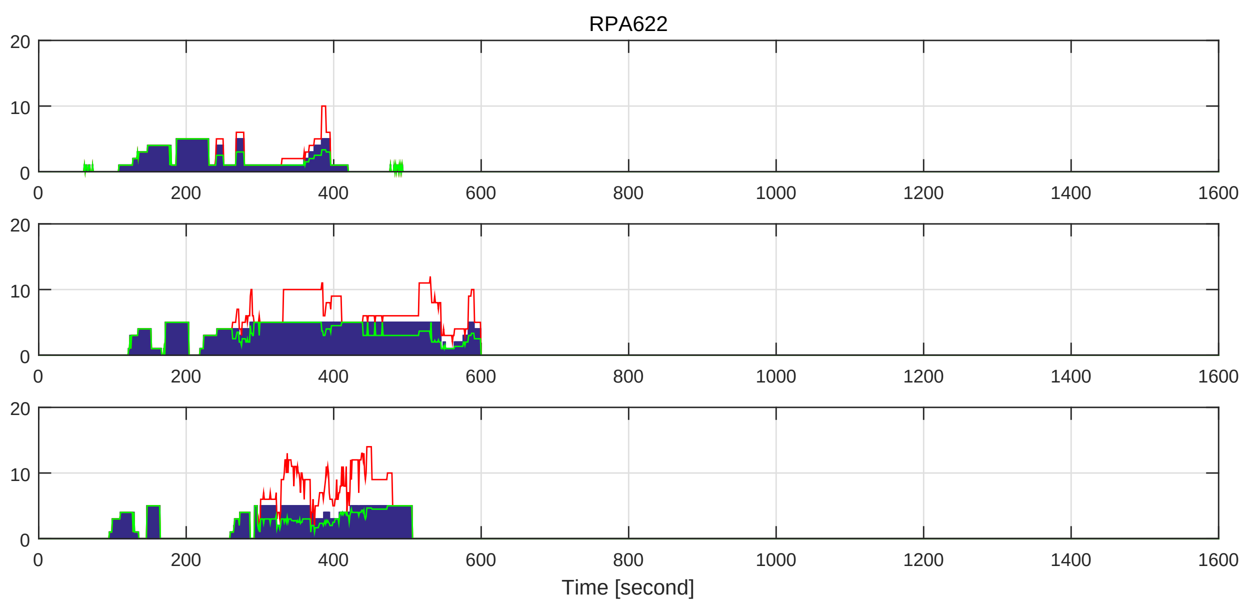

Figure 11: WCS of RPA622.

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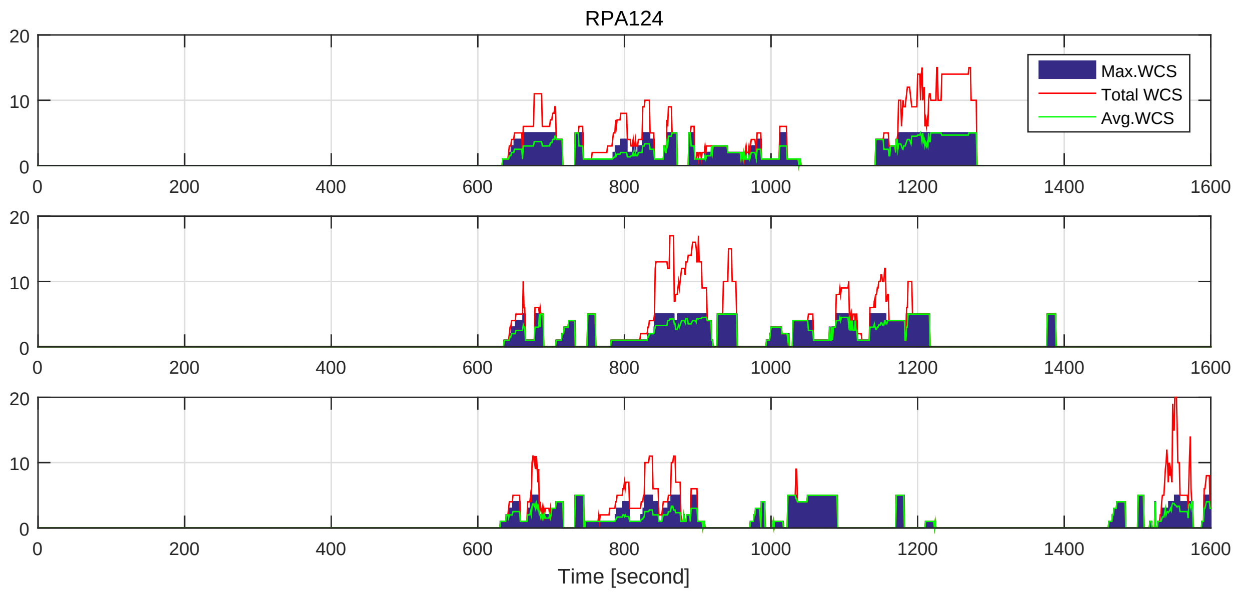

Figure 12: WCS of RPA124.

B. Arrival Delay

Figure 13 shows the number of aircraft that have landed with respect to time. AS can be seen from the figure, compared to case 1, it can be observed that the communication delay causes delay in landings. This is also indicated in table 5 that compares total flight time. Figure 14 shows the individual arrival times of all the aircraft. It clearly shows the arrival delay increases towards the end of the simulation. For case 3, RPA662 was in LOC condition. The controller gave priority to this aircraft while delaying other aircraft.

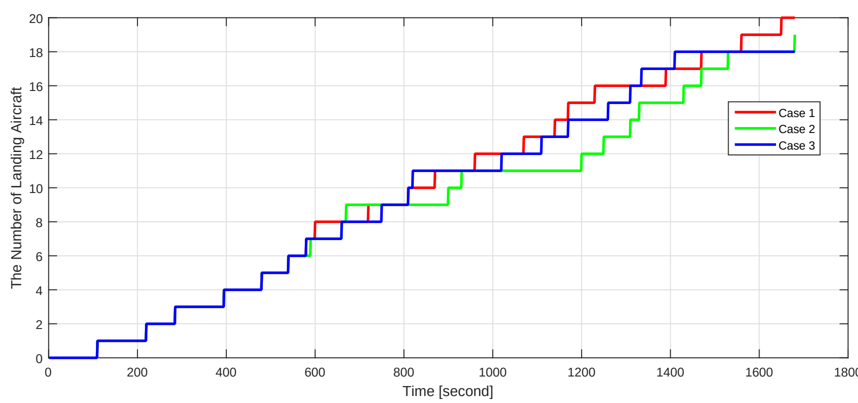

Figure 13: The number of arrival aircraft.

	Case1	Case2	Case3
Total flight time	17,250 second	19,780 second	19,865 second

Table 5: Total flight time.

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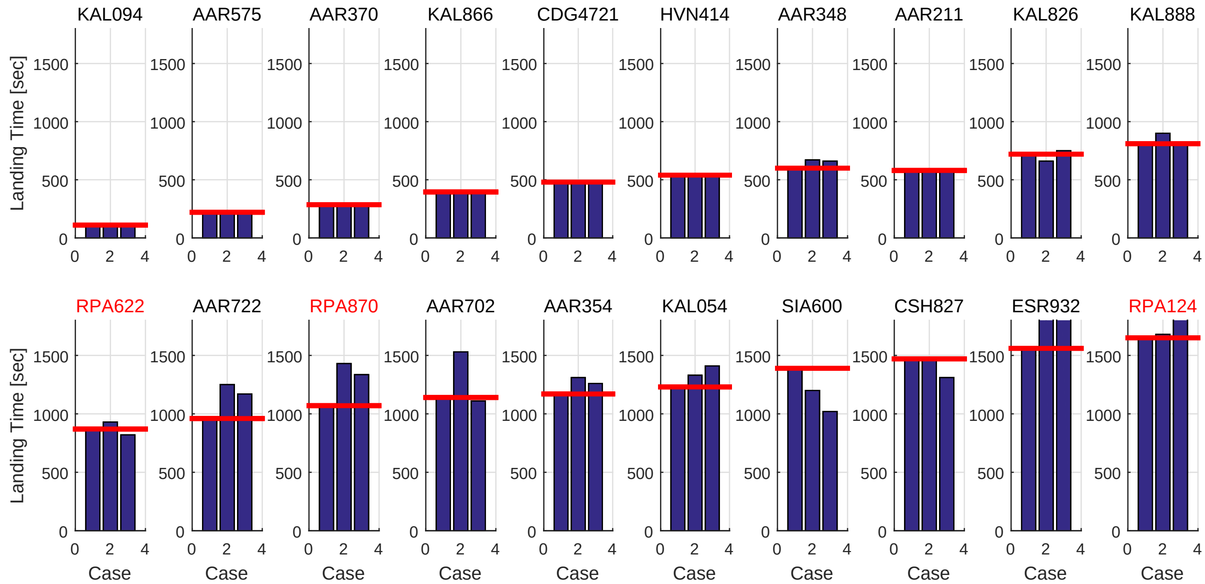

Figure 14: Arrival time.

C. Controller Workload

1. NASA Task Load Index (TLX)

The results indicate that overall workload clearly increases when communication delays are present. case2 with NASA-TLX of 66 and ISA of 3.917 and case3 with NASA-TLX of 78.67 and ISA of 4.0 shows distinctively higher workload indices compared to the normal operation of case1 with NASA-TLX of 47 and ISA of 2.417.

Comparing NASA-TLX scores between cases 1 and 2, the Temporal Demand shows the highest score and steepest increase. This indicates that RPAS integration with communication delay brings ATC task pace busier and ATC tend to rush during the operation. Participants stated that, because of the delays from RPAs, the entire traffic flow was disturbed compared to the normal operation.

Comparing the NASA-TLX scores between cases 2 and 3, Mental Demand and Frustration show the biggest gain while Frustration being the highest score among all of the factors. This means that, with Control LOC, ATC feels intense stress and even shows emotional turbulence during the task. Participants stated that the RPA124 that was in LOC near the end of simulation felt as if it was an emergency situation.

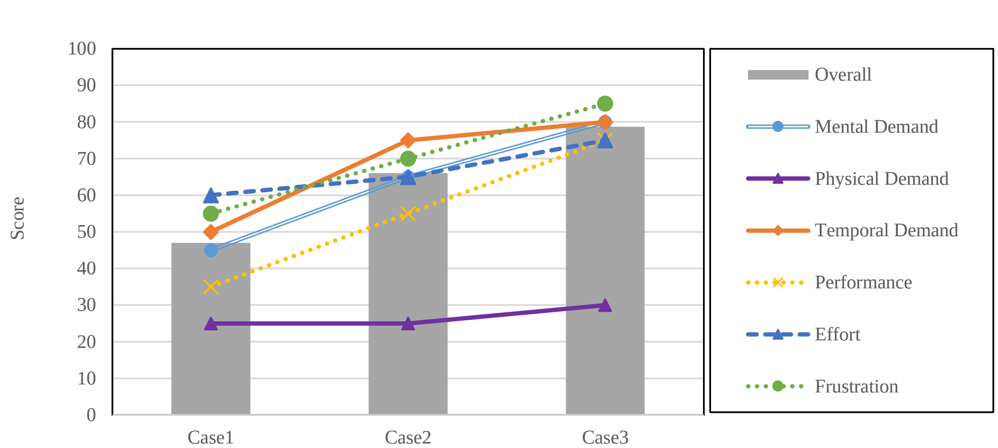

Figure 15: NASA TLX total score.

	Case1	Case2	Case3
Mental Demand	45	65	80
Physical Demand	25	25	30
Temporal Demand	50	75	80
Performance	35	55	75
Effort	60	65	75
Frustration	55	70	85
Overall	47	60	78.67

Table 6: NASA TLX total score.

2. Instantaneous self-assessment (ISA)

There is a distinctive difference in ISA scores between the case 1 and the others. In every case, there is a peak right after the ATC shift time (0 min 6 min). However in case 1, the ISA score decreases and maintains low to moderate levels as the traffic flow stabilizes. In contrast, ISA score of cases 2 and 3 maintained in high levels. This could be a consequences of RPA operations that caused delay in traffic flow and triggered accumulation of traffic in airspace.

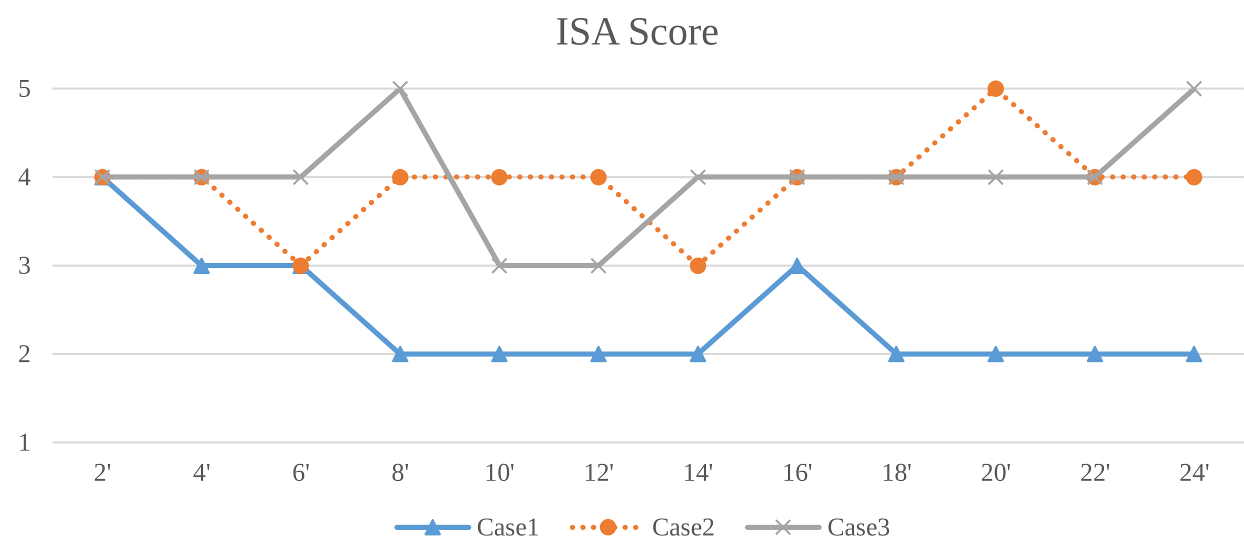

Figure 16: ISA score.

VI. Conclusion

To assess the impact of communication delay of RPASs, HiTL simulations were performed using a scenario based on the recorded trajectory data near the Incheon International Airport. An experienced trainee controller from Korean Aerospace University acted as the approach controller. CIP and WCS were computed as safety metrics. Arrival delays are used for efficiency metrics. For workload metrics, NASA-TLX and ISA were computed. HiTL simulation results do not show definite trend in the safety metrics. However, the arrival delays were increased and, especially, the workload indices showed significant jump from the case with no communication delay. Better analyses of safety metrics are left for future work.

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