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Human-in-the-Loop Simulation Analysis of Integrated RPAS Operations in Trajectory Based Operations Environment

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Abstract

In this paper, Human-in-the-Loop (HiTL) simulations of Remotely Piloted Aircraft System (RPAS) operations in two different Air Traffic Management (ATM) concepts, conventional radar vectoring and Trajectory Based Operations (TBO), were performed to assess the impacts of RPAS integration in the future ATM environment. TBO concept maximizes the throughput by planning and sharing 4-D trajectories between pilots and controllers, and it is considered one of the key concepts to enable RPASs to operate with manned aircraft in congested airspaces. RPASs are characterized by having communication delay or temporary loss of communication. TBO capability was added to the integrated air traffic simulation system for this study, which was developed in the Inha University. HiTL simulations were performed by a trainee air traffic controller with three scenarios, and the data were analyzed using safety, efficiency, and controller workload metrics. The results suggest that TBO were effective in reducing delays and controller workload while maintaining the level of safety.

Key words: Remotely Piloted Aircraft Systems (RPAS), Human-in-the-Loop (HiTL) Simulation, Trajectory Based Operation (TBO), Communication Delay

1. Introduction

The demands for Remotely Piloted Aircraft Systems (RPASs) are rapidly growing with the advancement of new technologies. Many countries are in the process of establishing 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.[1]

Trajectory Based Operation (TBO) is an operational method where a 4-D trajectory is scheduled and shared between air traffic personnel such as pilots, air traffic controllers, and airline dispatchers. TBO enables more accurate control of airborne aircraft by estimating the trajectories. International Civil Aviation Organization (ICAO) is establishing the trajectory management procedures and data link infrastructures for constructing the TBO environment.[2] In the United States, Federal Aviation Administration (FAA) is making a framework for trajectory management and separation standard related to TBO through the NextGen program.[3] European agencies have already performed flight tests and fulfilled an initial 4-D trajectory management concept evaluation study.[4]

For the integrated operations between manned aircraft and RPAS, it is important to understand how the unique characteristics of RPAS such as performances, communications, separations assurance methods, and human factors affect the Air Traffic Management (ATM) system. Because the pilot is not onboard the aircraft, an additional wireless link that is reliable and secure is required to fly the Remotedly Piloted Aircraft (RPA) in addition to the conventional means of communication between the remote

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pilot and the Air Traffic Control (ATC) system.

In previous research, Human-in-the-Loop (HiTL) simulations were performed with conventional radar vectoring approach for the integrated operations between manned aircraft and RPAS at the Incheon International Airport (RKSI). To model RPAS, artificial communication delays or temporary loss of communication were used in the simulation system. The result showed that he total flight time was increased and the workload was significantly increased. [5]

In this research, HiTL simulations were performed in the TBO environment with the same scenario as in [5]. And, simulation results with conventional radar vectoring approach and TBO are compared using three metrics, which are safety, efficiency, and controller workload. To perform these simulations, an existing ATC simulation system was enhanced to include TBO functionalities such as trajectory prediction and data communication. [5]

Following the introduction, Section 2 discusses about operational concepts and Section 3 describes the simulation system. Section 4 describes performance metrics such as Well Clear (WC), arrival delay, and controller workload. Section 5 explains the scenario where RPASs are integrated into the existing airspace system. Section 6 presents the analysis results. Finally, section 7 concludes this study.

2. Operational Concept

2.1 Command and Control (C2) Link in the integration of RPAS

The C2 link is one of the critical issues in RPA operation. [6][7] C2 link connects RPA and Remote Pilot Station (RPS) via wireless uplink and downlink data communication. C2 link latency or failure directly affects the aircraft controllability, ATC communication, and in some cases, Detect and Avoid (DAA) systems. Quantitative and verifiable requirements for the C2 link are still under investigation. [8]

As shown in Fig. 1, the RPA communicates with ATC using conventional VHF channel. The ATC communication signal is relayed to RPS using C2 link directly or indirectly over satellite. So, as the length of the communication path from ATC and RPS gets longer and the number of relay increases, the communication delay increases. The risk of C2 link delay has been recognized in several works for RPA which requires direct manual control. Thus, it is recommended that on-board flight control automation is required in certain level to ensure stability. [9] Another concern in C2 link is signal loss. When the C2 link is lost, the RPS cannot maintain control of RPA, which leads to serious hazard to nearby aircraft. To mitigate the risk, contingency procedure for C2 link loss is required. [6]

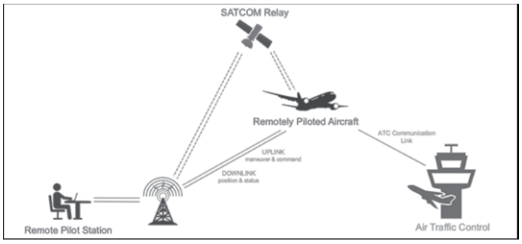


Fig. 1. Example of a C2 link structure

2.2 Trajectory Based Operations

TBO was introduced to accommodate increasing air traffic demand by transforming current ATM system. With development of Flight Management System (FMS), Controller Pilot Data Link Communication (CPDLC), Automatic Dependent Surveillance – Broadcast (ADS-B), and System Wide Information Management (SWIM), TBO means shifting clearance-based ATC to trajectory-based ATC. The 4-D trajectory includes latitude, longitude, altitude, and time of arrival at corresponding waypoints. By negotiations between airspace users and Air Navigation Service Providers (ANSPs), TBO enables users to fly preferred trajectories with constraints issued for ATM purposes. [10]

TBO can be performed by the following procedures. First, ATC issues

Controlled Time of Arrival (CTA) or Required Time of Arrival (RTA) in specific waypoints, so that the aircraft crosses the waypoints within a given time slot. Then the airspace user and the ANSPs agree on a trajectory that the aircraft will fly. Trajectory prediction and monitoring are constantly provided. The full 4-D implementation is expected to enhance the predictability and increase Terminal Maneuvering Area (TMA) capacities as a result of fewer tactical interventions. [11] TBO concept is summarized in Fig. 2.

TBO is a very broad operational concept and is still under development, which will eventually include trajectory optimization. In this research, only the fundamental ideas of

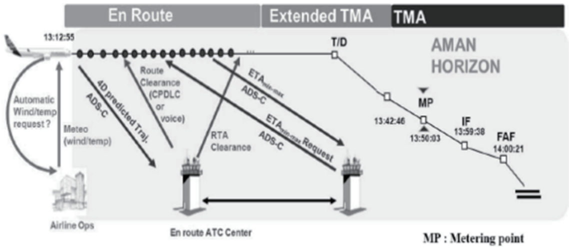


Fig. 2. Summary of TBO procedure. [16]

TBO are used as follows.

- Reference trajectory for each flight is defined prior to the beginning of the simulation.
- The controller and pilot negotiate the trajectory before entering TMA.
- Based on the reference trajectory, the controller assigns RTA constraints first. If necessary controller can modify route or speed.
- Flight start times can be adjusted if necessary.

3. Air Traffic Control Simulation System

The purpose of the ATC simulator is to evaluate and analyze new technologies and concepts as well as to train controllers and pilots. Fig. 3 shows the structure of the Inha University ATC simulator. It is composed of a server, multiple pilot stations, and multiple controller stations. To perform the TBO simulations, the system was enhanced to include trajectory prediction and data communication functionalities.

3.1 Server

The server manages the simulation scenarios and handles the data flow between the clients. Before a simulation starts, 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 the position of aircraft to ranges and bearings. These values are sent to the surveillance data processing system that handles calibration errors and filtering. Processed positions and flight paths are sent to the controller station. For this TBO simulation, CPDLC was added so that text messages can be exchanged between pilots and controllers as well as 4-D trajectory information.

3.2 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 and validated by comparing the simulation results with recorded flight trajectories.[19] Fig. 4 shows the pilot station display. Pseudo-pilots can input speed, altitude, heading, and waypoint commands through a typical flight management system interface. The pilot station

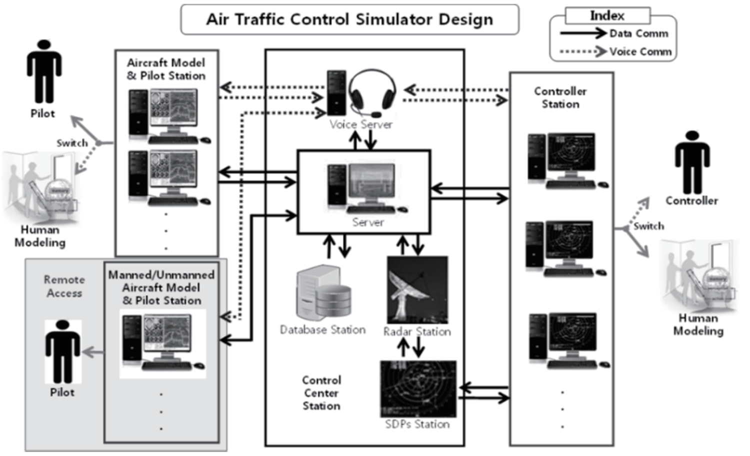


Fig. 3. Air Traffic Control Simulator Structure.

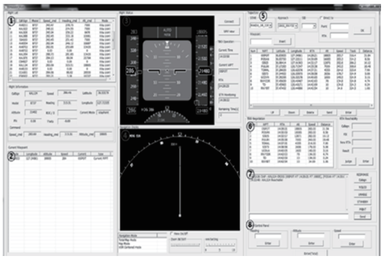


Fig. 4. Pilot Station UI

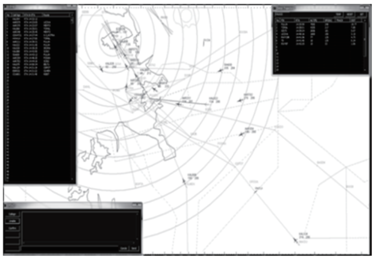


Fig. 5. Controller Station UI

display also includes primary flight display and navigation display. In order to properly simulate the scenarios on TBO environment, the flight dynamic model can control aircraft speed to satisfy the RTA at each waypoint. For climb or descent, the model tries to maintain constant climb or descent rate during altitude change.

3.3 Controller Station

Controller station display shows the current position of aircraft on the map with essential flight information including call sign, altitude, and speed. The map also shows airspace boundaries and flight routes. Displays and functionalities related to CPDLC communication of TBO parameters were added to the controller station. It shows the RTA and ETA at each designated waypoint for each aircraft. Depending on the traffic flow and separation between aircraft, the controller can issue new RTA in addition to altitude, speed, or heading commands. Fig. 5 shows the screenshot of the controller station's user interface.

4. Performance Metrics

4.1 Safety Metric

To determine safety levels, two metrics were evaluated. The first metric is Conflict Intrusion Parameter (CIP) that has been used to evaluate conflicts between aircraft. The second metric is Well Clear (WC) that uses the ideas from the traffic collision avoidance system and is being developed for RPA. One of the purposes of this research is to find a better metric assess the safety of integrated RPAS operations.

- Conflict Intrusion Parameter

CIP defined in Eq.1, is based only on the horizontal and vertical separate distances. [12] 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.

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

$$(0 \le CIP \le 1,\ t_{soc} \le t \le t_{eoc})$$

- Well Clear (WC)

The concept of well clear is proposed as an airborne separation standard for DAA systems. Correctly performing self-separation (SS) 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 parameters given in Eqs.(2), (3) and (4). τ_{mod} is calculated using distance modification(DMOD) and horizontal range and range rate. HMD is horizontal missed distance at the closest point of approach. HMD^* is the horizontal missed distance threshold. d_h is the vertical separation and h^* is the vertical separation threshold. As shown in Table 1, five safety levels are proposed with different threshold values. These values are constantly being updated. The values shown in Table 1 are values at the time of this research. Loss of Well Clear (LOWC) is the most dangerous situation that must be avoided.

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

$$\text{HMD} \le HMD^* \tag{3}$$

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

Table 1. Well Clear self separation alert level [17]

Well Clear Score (WCS)		**1**	**2**	**3**	**4**	**5**
Alert Level		Advisory	Caution	Caution	Warning	Danger
Must Alert Thre-shold	**Within Time**	60sec	55sec	55sec	40sec	35sec
	τ_{mod}	35sec	35sec	35sec	35sec	-
	DMOD, HMD	2.0nmi	0.66nmi	0.66nmi	0.66nmi	0.66nmi
	h*	1,200ft	700ft	450ft	450ft	450ft
Must Not Alert Thre-shold	**More than Time**	85sec	75sec	75sec	55sec	-
	HMDp	>5.0nmi	>2.0nmi	>1.5nmi	>1.0nmi	-
	Dh_p	>1,300ft	>800ft	>450ft	>450ft	-

Where,

$$\tau_{mod} = \begin{Bmatrix} -\dfrac{DMOD^2 - r^2}{r\dot{r}} & (r > DMOD) \\ 0 & (r \le DMOD) \end{Bmatrix}$$

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

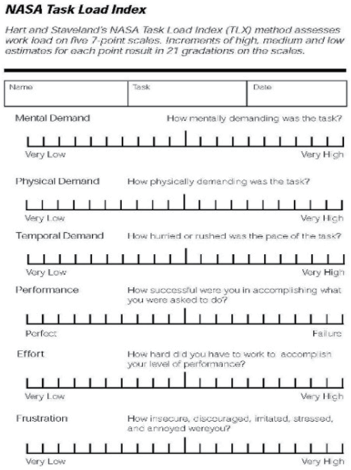
$$d_h = h_2 - h_1$$

4.2 Arrival Delay

Generally, any unplanned maneuver causes delay, which results in increased time and fuel cost. As the current study mostly involves arriving aircraft, arrival delay is chose to be the efficiency metric. Larger arrival delays will represent the adverse effect of introducing RPAS.

4.3 Controller Workload

NASA-TLX and ISA are efficient and reliable method for measuring human workload. Generally, these methods are used together for comprehensive measurement.



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

Fig. 6. TLX Worksheet

- NASA Task Load Index

The 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 TLX measures six items to assess the workload: mental demand, physical demand, temporal demand, performance, effort, and frustration as shown in Fig. 6. [14] Controllers grade weights and values of each workload item. Weight means the relative importance of each factor. The sum of six weights should be one. Value means the intensity of each workload item. The overall TLX score is the product of values and weights of all factors as in Eq. (5).

$$Score_{TLX} = \sum_{i=1}^{6}(Weight_i \times Value_i) \tag{5}$$

- Instantaneous Self-Assessment

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]

5. Simulation

5.1 Scenario

The scenario is based on recorded trajectories and actual flight plans from 08:00 to 08:30 (UTC) October 10th, 2015. It is during the peak operating hours of RKSI. Flights are ordered by the given inbound time and location (fix), and flight strips are given to the air traffic controller. Thirteen departures and 26 arrivals were scheduled for the 30 minute duration. Case1 represents normal operation with no RPA inbound. As shown in Table 3, Cases 2 and 3 have three RPAs inbound with communication delays of one, two, and ten seconds respectively to simulate the communication delay and Loss of Control (LOC) related to RPAS. The amounts of delay are not brief to the controller to prevent learning effect.

Table 2. ISA score description

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 stimulating 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.

5.2 Task

During the HiTL simulation, air traffic controller's task in the scenario was to perform approach control to manage the traffic in Seoul TMA. The air traffic controller vectored inbound aircraft to runways 34 and 33R of RKSI.

5.3 Participant

The participants consist of 1 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 May 2015. The controller was briefed about the experimental procedure except for the schedule of inbound RPAs to ensure realistic progress of the simulation.

5.4 Simulation Setting

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. On 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.

5.5 Measurements

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.

6. Simulation Results

6.1 Safety Metric

- CIP

Figure 7 shows the total CIP for radar vectoring and TBO respectively. Fig. 8 shows the CIP of approaching aircraft. The CIP measured in Case 2 and Case 3 (RPA with C2 link delay and LOC) were slightly higher than those in Case 1. The total CIP measured in TBO was higher than that in radar vectoring. Higher total CIP values in TBO is likely to be due to the tighter time interval between departure aircraft. For the arriving aircraft, TBO operation has smaller number of flights with CIP exceeding zero as shown in Fig. 8.

Table 3. Scenario Delay

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

- WC

In this study, a concept of Well Clear Score (WCS) is proposed to evaluate the level of safety. WCS is assigned to each level ranging from one for proximate traffic to five for LOWC. Fig. 9 is the result of maximum and average WCS from all the conflict pairs with respect to time on two different ATM environments. Most of the time during the simulations, maximum WCS remained at its maximum value due to the LOWC between manned aircraft. This indicates that LOWC might not be a suitable safety metric between manned aircraft. Fig. 10 presents total WCS, and Table 4 summarizes total, average, and maximum WCSs for all the aircraft, RPAs only, and manned aircraft only respectively. Fig. 11, 12 and 13 presents WCS of each RPA. Generally, TBO shows smaller WCS for most of the cases. Especially, TBO shows significantly less WCS when only the individual WCSs over the value of ten are summed.

6.2 Arrival Delay

Figure 14 show the number of arrived aircraft with respect

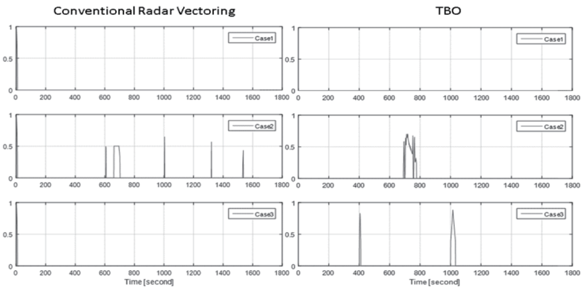


Fig. 7. Total loss of separation with CIP

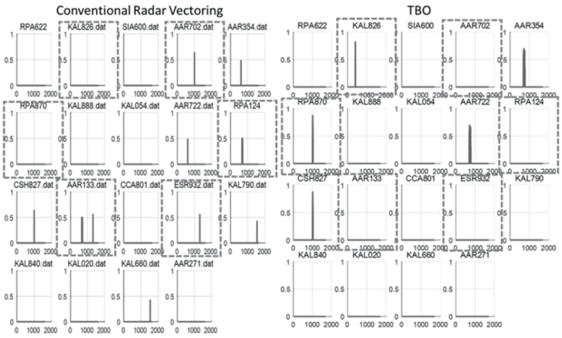


Fig. 8. Approach aircraft's loss of separation with CIP

to time comparing radar vectoring and TBO environments. Table 5 presents the total flight time. Fig. 15 and 16 indicate the individual arrival times of all the aircraft. With TBO, an efficient air traffic flow is observed in all cases and the adverse impact of the communication delays and LOC situation is not significant.

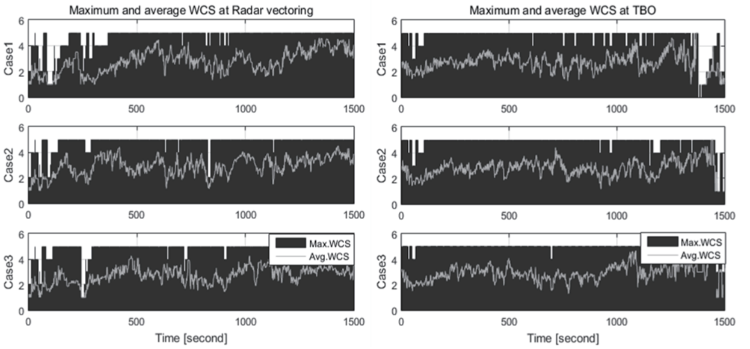


Fig. 9. Maximum and average WCS

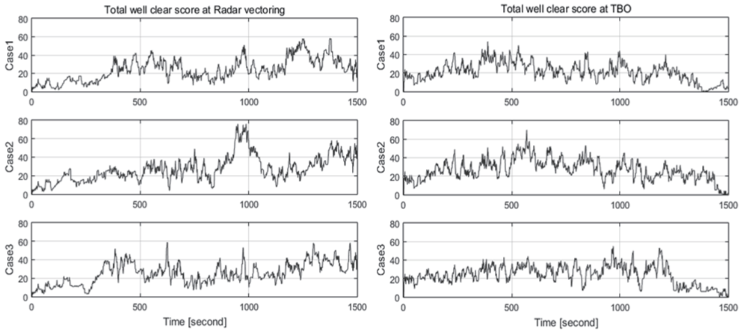


Fig. 10. Total WCS

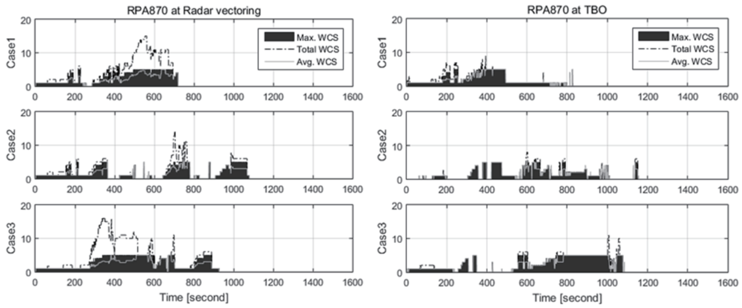


Fig. 11. WCS of RPA870

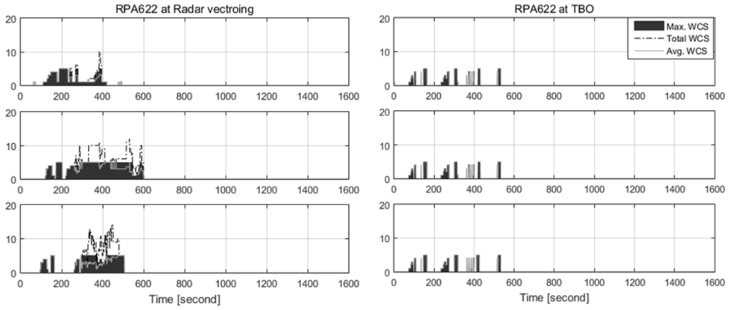


Fig. 12. WCS of RPA622

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6.3 Controller Workload

- NASA Task Load Index

As presented in Table 6, the NASA TLX scores show that overall ATC workload in TBO was lower than radar vectoring. And the results indicate that overall workload clearly increases when communication delays are present.

- Instantaneous self-assessment

Figure 17 shows the result of ISA score. 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, the ISA score decreases and maintains low to moderate levels as the traffic flow stabilizes in case 1. In radar vectoring, ISA score of cases 2 and 3 remained in higher levels. But the ISA scores of TBO decreases and maintain lower levels. Overall ISA scores in TBO are smaller than those in the radar vectoring.

7. Conclusion

To evaluate the effect of communication delays of RPAs in TBO environment, HiTL simulations were performed using a scenario based on the recorded trajectory data around the RKSI. Experienced trainee controller from Korean Aerospace University acted as the approach controller. CIP and WCS

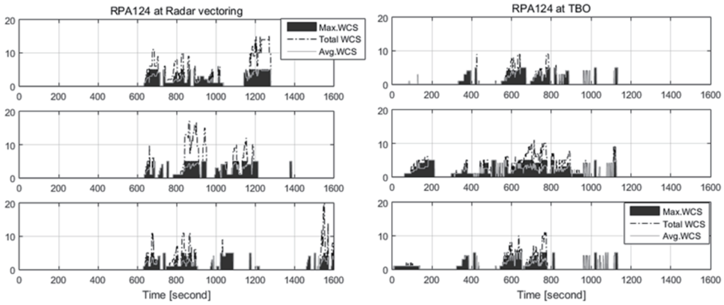

Fig. 13. WCS of RPA124

Table 4. Result of Total WCS

		All of aircraft			RPAs			Manned Aircraft		
		Case1	Case2	Case3	Case1	Case2	Case3	Case1	Case2	Case3
Radar Vectoring	Total	37,888	41,552	42,846	7,255	7,949	8,683	30,633	33,603	34,266
	Mean	23	25	26	1	2	2	1	1	1
	Max	58	76	68	15	17	21	12	4	13
	Over 10	1,443	4,446	1,716	274	198	309	1,252	1,503	1,400
TBO	Total	32,489	40,859	36,164	3,976	5,554	5,101	28,491	35,806	31,227
	Mean	19	24	21	1	1	1	1	1	1
	Max	54	70	55	9	11	11	4	0	4
	Over 10	78	1,638	429	0	19	30	739	1,194	812

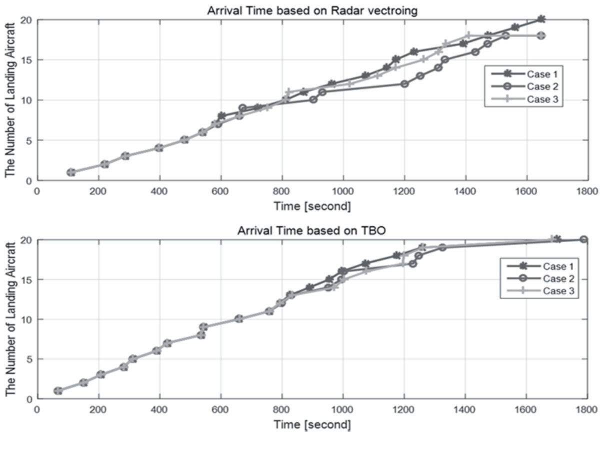

Fig. 14. The number of arrival aircraft

were computed as safety metrics. Arrival delays are used for efficiency metrics. For workload metrics, NASA-TLX and ISA were computed.

HiTL simulation results show that the overall performance has improved in TBO. And the adverse impact of communication delay and LOC was reduced compared to conventional radar vectoring. Moreover, with TBO was especially effective in reducing the controller workload and

Table 5. Total flight time

	Case 1	Case 2	Case 3
Radar Vectoring	17,250	19,780	19,865
TBO	13,972	14,477	14,327

Table 6. NASA-TLX Result

	Radar vectoring	TBO	Variation [%]
Case1	47.00	31.33	-33.34
Case2	66.00	53.65	-18.71
Case3	78.67	52.99	-32.64

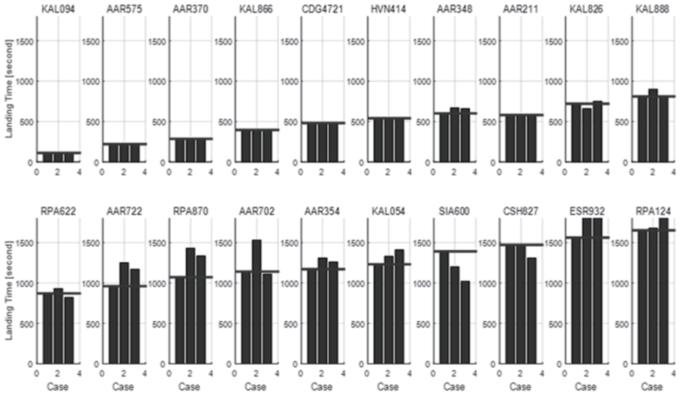

Fig. 15. Arrival Time based on Radar vectoring

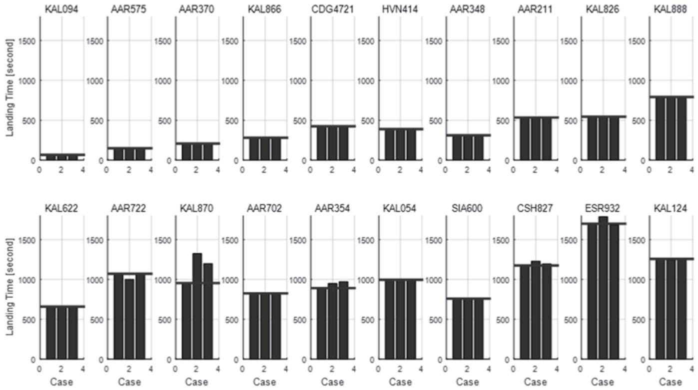

Fig. 16. Arrival Time based on TBO

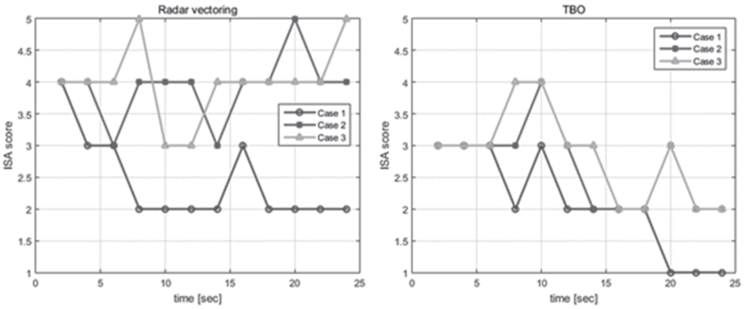

Fig. 17. ISA Result

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arrival delay when RPAs were present.

TBO generally showed slight better safety according to the metrics used. However, further investigation with larger amount of data is necessary to better quantify the safety.

Future research plan includes the investigation of the flight performance, DAA system, and human factors of RPAS in addition to the communication aspect.

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