A Method for Visualizing Trade-offs in En-route Air Traffic Control Tasks

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Abstract. In Air Traffic Control (ATC) tasks, controllers face paradoxical demands for dealing with increasing amounts of air traffic while keeping (or enhancing) safety and efficiency. Controllers are required to handle the demands in uncertain and variable traffic situations. This paper proposes a visualization method of trade-offs in en-route ATC tasks, and conducts a tentative analysis of trade-offs in a high fidelity human-in-the-loop simulation using this method. The obtained results strongly imply that controllers are required to maintain a balance between the optimality of control strategies for an existing situation and the tolerance for the variability of the situation. Through this analysis, the basic effectiveness of the proposed visualization method was demonstrated.

1   INTRODUCTION

In Air Traffic Control (ATC) tasks, controllers face paradoxical demands for dealing with increasing amounts of air traffic while keeping (or enhancing) safety and efficiency.

Controllers handle the demands in uncertain and variable traffic situations by making performance adjustments (Sperandio 1971, Fothergill 2008). In order to support appropriate management of trade-offs among contradicting demands, the detailed analysis for revealing the nature of the trade-offs is definitely required. However, how to visualize and describe the trade-offs for objective analysis is still an open issue in the ATC domain. The present research, therefore, proposes a visualization method of trade-offs in en-route ATC tasks with utilizing our process visualization tool of ATC tasks called COMPASi (COMPAS in interactive mode / COMPAS: COgnitive system Model for simulating Projection-based behavior of Air traffic controllers in dynamic Situations). The basic effectiveness of the proposed method is examined through a tentative analysis of trade-offs in a high fidelity Human-In-The-Loop Simulation (HITLS).

2 EN-ROUTE ATC TASKS AND TARGET SECTOR

En-route air traffic control is a part of ATC services provided for in-flight aircraft. The ATC tasks have two major purposes: they are to ensure safety and efficiency of air transportation. The primary goal is to achieve the maintaining of safety by assuring a minimum separation of 5 nautical miles (NM) horizontally or 1000ft vertically between aircraft. In the en-route control, a team of controllers takes charge of a divided airspace called a "sector". The present research has adopted an actual sector, that is, Kanto-North (T03) sector in Japan, as the target sector. Fig. 1 shows sector T03 that is the northern part of the Tokyo region. The size of sector T03 is approximately 120NM by 120NM. The small white circle and capital letters, that is, TLE, in Fig. 1 indicates one of the geometrical points and its name used for aiding in air navigation.
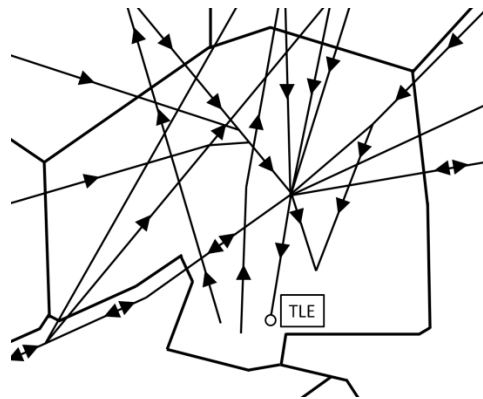

Fig. 1. Sector T03 and Traffic Flows

Two hub airports, Tokyo (Haneda) International Airport and Narita International Airport, are located southward of sector T03. In addition, multiple smaller airports and air force bases are located in the surrounding areas of this sector. Furthermore, overflight aircraft between North America and East Asia pass through this sector in an east-west direction. Thus, this sector provides ATC services to various kinds of

commercial and military flights. Regulations require the controller of sector T03 to achieve additional target altitude and separation of aircraft along with assuring minimum separation. For example, an aircraft arriving at Tokyo airport has to establish a 10NM in-trail separation from another aircraft arriving at the same airport and also has to reach 13,000ft by the TLE point (see Fig. 1). In order to achieve the target states of aircraft, the controller can issue speed, altitude, and heading/rerouting instructions to the aircraft.

3   METHOD

3.1   COMPASi

COMPASi is a PC-based ATC simulation/visualization tool equipped with a kind of cognitive model of a controller called Situation Recognition Unit (SRU) that is capable of detecting ATC tasks in a given traffic situation. SRU models controller's situation awareness including realistic future projection with a certain safety margin for inevitable errors caused by situational uncertainty and variablility (Karikawa et al. 2013).

Figure 2 shows the conceptual diagram of COMPASi. Given the initial states of traffic (e.g., aircraft's initial position, altitude, indicated air speed, etc.) and the log of ATC instructions, the Air Traffic Simulator (ATS) simulates air traffic flow with continuous performance calculation of aircraft and automatic issuing of ATC instructions. The SRU analyzes the simulated air traffic situation and automatically detects ATC tasks in the situation. The detected tasks are classified based on Task Demand Levels (TDLs) shown in Table 1, which is an ATC task index for identifying ATC tasks and their execution states. Aircraft coming from an upstream sector have various TDLs ranging from Lv.1 to Lv.3+. By completing necessary ATC tasks in the sector, the TDL of each aircraft is expected to be reduced to Lv. 1 before it enters a downstream sector.
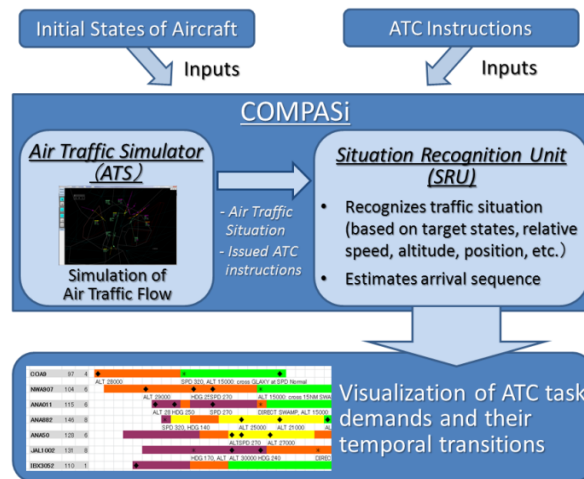
Fig. 2. Conceptual Diagram of COMPASi

Table 1. Task Demand Levels (TDLs) (adapted from Aoyama et al. 2010)

Lv.	Situation / Task Demand	Display Color on COMPASi
4	time-critical situation in terms of conflict resolution(s)	Red
3+	multiple separation assurances (conflict resolution(s) / in-trail spacing(s)) between the target aircraft and two or more related aircraft	Magenta
3	separation assurance (conflict resolution / in-trail spacing) between the target aircraft and one related aircraft	Orange
2	altitude change	Yellow
1	(ATC tasks are completed)	Green

As an output, COMPASi provides TDL of each aircraft in two forms: color codes of the flight number and of the lateral trajectory on a simulated radar display (see Fig. 3), and a time series graph called Chart of ATC task Processing State (CAPS) (see Figs. 4 - 7). CAPS illustrates situation changes resulting from the instructions along the timeline, which is a visualization of the ATC task process. COMPASi also outputs flight distance and the number of instructions of/for each aircraft. The details of COMPASi was described in Karikawa et al. (2013).

3.2   Visualization of Tradeoffs in ATC Tasks

Using TDLs and other output data, COMPASi can visualize performance of ATC tasks from multiple aspects. As described in Section 3.1, the TDL of each aircraft is expected to be reduced to Lv.1 by completing necessary ATC tasks. Thus, reductions of TDLs reflect efficiency in completing ATC tasks (This performance aspect is referred to as "efficiency" in this paper). In addition, since greater levels of TDL, i.e., Lv.3, Lv.3+, and Lv.4, illustrate complex tasks such as conflict resolution and in-trail spacing, durations and accumulations of them indicate a potential intensive workload situation for a controller, which might compromise safety (Thus, this performance aspect is referred to as "safety"). Moreover, COMPASi records flight distance of each aircraft, which is a major factor affecting fuel consumption of the aircraft (referred to as "fuel economy").

That is, by using TDLs and flight distances provided by COMPASi, trade-offs among safety, efficiency, and fuel economy can be visualized. Furthermore, through multiple simulation cases with varied simulation conditions, the performance tolerance of control strategies for situational variability can be examined.

4   ANALYSIS AND RESULTS

In the present research, performances of two types of control strategies for a traffic scenario have been analyzed using COMPASi. The strategies were observed in the HITLS

conducted in 2006 with 8 professional participants. This chapter describes a tentative analysis of the natures of tradeoffs in ATC tasks through visualization and comparison of performances of control strategies used by controllers.

4.1 Traffic Scenario and Control Strategies

Figure 3 and 4 depict a simulated sector, a traffic scenario, and control strategies analyzed in the present research. The target sector is sector T03 described in Chapter 2. Although there are several flights in those figures, the analysis in the present research focuses on arrival flights to Tokyo airport (that is, ANA882, ANA50, and JAL 1002). Based on regulations, the controller of sector T03 is required to achieve target states of those aircraft (that is, 10 NM in-trail separation and 13000ft at TLE), while continuously assuring the minimum separation from ADO11, a departure flight from Tokyo airport.

Two types of control strategies for this situation were observed in the HITLS. The first strategy (called Strategy A: ST-A) is depicted in Fig. 3(i). The sequence of Tokyo-inbound flights in ST-A was ANA882, ANA50, and JAL1002. To achieve this sequence, following an ATC instruction, ANA882 took a shortcut in the direction of the TLE point as the first aircraft. The second strategy (called Strategy B: ST-B) is shown in Fig. 3(ii). The arrival sequence in ST-B was ANA50, JAL1002, and ANA882. To achieve the sequence, ANA 882 was vectored to the east as the third aircraft to extend its flight distance.
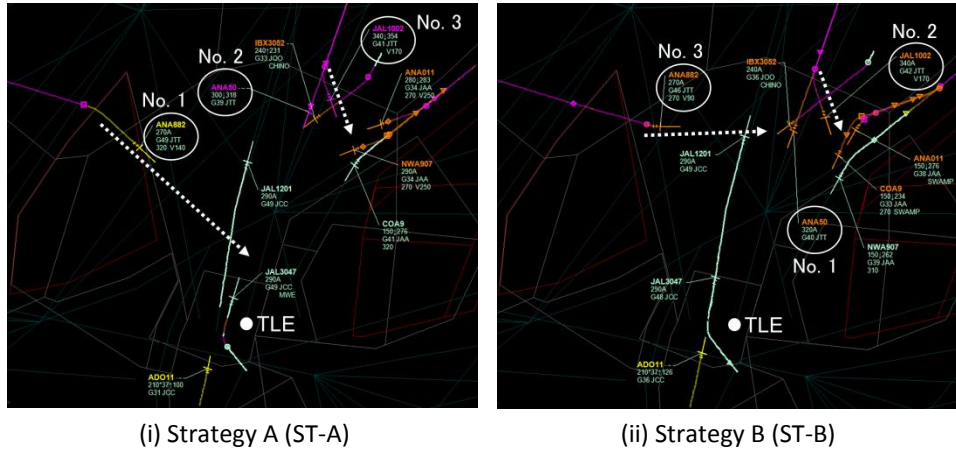

| (i) Strategy A (ST-A) | (ii) Strategy B (ST-B) |

Fig. 3. Control Strategies

4.2 Simulation Settings

For simulating the control strategies on COMPASi, two series of ATC instructions corresponding to ST-A and ST-B were extracted from recorded controller-pilot communication of the HITLS, and formatted as input files to COMPASi. Other necessary input data to COMPASi, that is, the initial state and performance data of each aircraft, were also prepared based on the recorded data of the HITLS. In addition, for evaluating

the tolerance of the strategies for situational variability, two sets of simulation conditions summarized in Table 2 were prepared.

Table 2. Simulation Conditions

Simulation Conditions	Wind Condition		Control Strategies & Simulation Cases
Cond. 1 **-Baseline Condition-**	240 deg.	at 80 knots at 40,000ft	ST-A: Case 1A
		at 60 knots at 20,000ft	ST-B: Case 1B
Cond. 2	240 deg.	at 80 knots at 40,000ft	ST-A: Case 2A
		at 30 knots at 20,000ft	ST-B: Case 2B

4.3 Results

Simulation Condition 1 (Baseline Condition) In Case 1A and 1B, simulation conditions and traffic situations of the HITLS were replicated on COMPASi. According to the simulation results, the completion time of required ATC tasks of the flights in question, which is indicated by the time when all TDLs of ANA882, ANA50, and JAL 1002 turn to Lv.1, are 14.5 minutes in ST-A versus 16.5 minutes in ST-B (see Fig. 4(a) and Fig. 5(a)). This result has demonstrated the higher efficiency of ST-A in completing ATC tasks. In addition, Lv.3 of TDL of ADO11, which indicates conflict between ANA882 and ADO11 in these cases, is not shown in each figure (see Fig. 4(b) and Fig. 5(b)). This fact points out that possible conflict between ANA882 and ADO11 was effectively prevented in both ST-A and ST-B. In terms of flight distances, the total flight distances of the target flights are 430 NM in ST-A versus 464 NM in ST-B. It indicates that ST-A has an advantage in fuel economy as compared to ST-B. From these results, it can be said that ST-A has better performance in efficiency in completing ATC tasks and fuel economy of aircraft than ST-B, although both strategies are effective in conflict prevention that can be a major factor in safety performance.
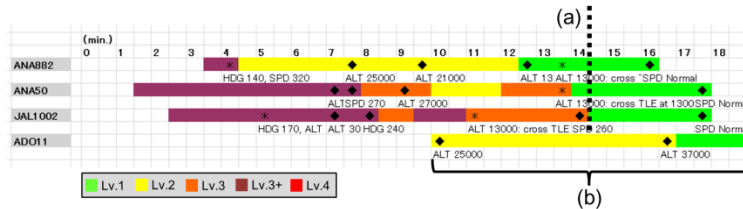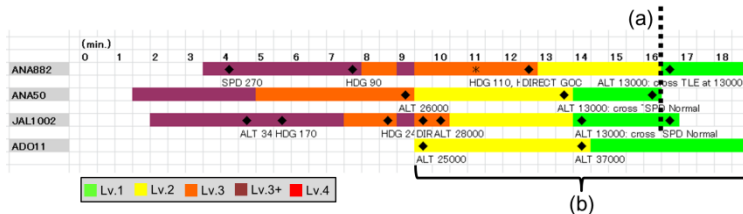

Fig. 4. CAPS of Strategy A (Case 1A)

Fig. 5. CAPS of Strategy B (Case 1B)

Simulation Condition 2 In Cond. 2, the wind condition was modified for simulating a situation where the wind velocity becomes weaker rapidly as aircraft descend, which is an example of situational variablity. Figure 6 and 7 show that, while any negative effects (that is, appearances of higher TDLs as compared to corresponding cases of Cond. 1) caused by change of wind condition are not shown in Case 2B, timeframes of Lv. 4 of TDLs of ANA882 and ADO11 are shown in Case 2A (see Fig. 6(a)). It means that a conflict between ANA882 and ADO11 occurred in Case 2A. The cause of the conflict is that the geometrical point and the timing of the crossing of ANA882 and ADO11 shifted from those in Case 1A because weaker wind at lower altitude affected ground speeds of ANA882 and ADO11 and also the flight track of ANA882.
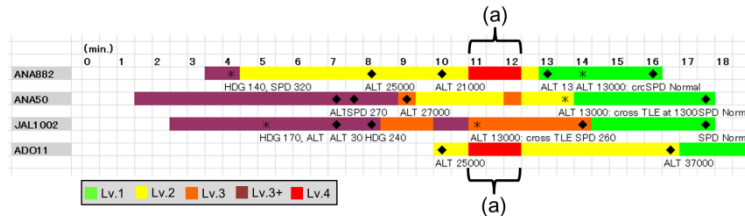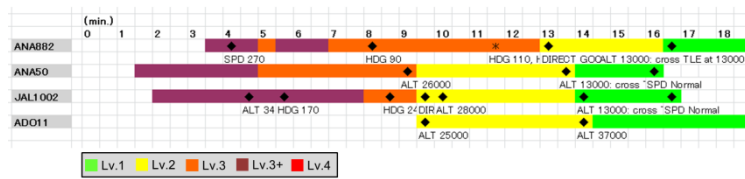

Fig. 6. CAPS of Strategy A (Case 2A)

Fig. 7. CAPS of Strategy B (Case 2B)

In the performance analysis described above, ST-A showed equivalent or higher performance both in safety and in efficiency as compared to ST-B under the baseline condition, whereas its safety performance was obviously decreased in the case that the simulation condition was modified for simulating the variability of the situation. On the contrary, ST-B showed the opposite performance: it was tolerant of the variability of a situation, while its efficiency was inferior to that of ST-A. Interestingly, despite good performance of ST-A in safety and efficiency under the baseline condition, ATC instructors have evaluated that ST-B can be more recommended even for less experienced controllers although both ST-A and ST-B are reasonable for dealing with the sample situation. This fact strongly implies that controllers are required to balance between the optimality of control strategies for an existing situation and their tolerance for the variability of the situation. The analysis described in this section has shown that COMPASi can be helpful for analyzing the natures of trade-offs in ATC tasks.

5   DISCUSSION

The present research proposed a visualization method of trade-offs in ATC tasks, which is essential for managing them. Since COMPASi can be used to visualize not only performances of control strategies in a certain situation but also their tolerance for the variability of the situation, we consider that it has potential applicability for estimating safety margins of controllers' activities. If simulations on COMPASi using realistic traffic situations and actual working processes reveal a potential tendency that controllers too often use working methods that are highly efficient in existing situations but less tolerant of the variability of the situations, the simulation results should be carefully fed back to controllers for sustaining their successful performance adjustments. In addition, for organizations, the results might be a sign that the controllers are exposed to high productivity pressures, and so the decision to sacrifice productivity might be required for ensuring safety. Now, we are developing an additional function of COMPASi called Variability-Tolerance Visualizer (VTV), which supports efficient analysis of tolerance of control strategies for situational variability. Further detailed analyses using VTV will be planned for revealing the nature of trade-offs in ATC tasks and controllers' management activities.

6   CONCLUDING REMARKS

The proposed visualization method using COMPASi has successfully visualized trade-offs in ATC tasks taking into account situational variability. It can contribute to accumulate objective data and knowledge concerning the trade-offs and controllers' management activities, which can be essential for supporting management of trade-offs. The visualization using COMPASi can also be useful for effective training of ATC trainees in order to enhance their ability to cope with trade-offs. Although the target domain of the present research is limited to ATC at this moment, we believe that the experience and findings of the present research might be useful for other industrial domains dealing with uncertain and variable situations.

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