HARMONIZING AUTOMATION, PILOT, AND AIR TRAFFIC CONTROLLER IN THE FUTURE AIR TRAFFIC MANAGEMENT

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Abstract

Recently, research and development of automatic flight control systems has been promoted to achieve better capacity in air traffic control. One of the topics we should discuss is how to harmonize human beings (pilot and air traffic controller) and automation system working together in the same control loop.

This research proposes a new concept for automation design termed "Human As a Control Module architecture (HACM architecture)". In the architecture, human beings who engage in aircraft control are treated as modules of controlling aircraft. By adaptively adjusting control authority between human and the automation system, it avoids adverse effects to aircraft movement caused by interferences of their control inputs.

In this paper, we review our past work on the harmonization between human and automation in aircraft control. Two application results are summarized: the first applies it for PIO (Pilot-Induced Oscillation) situations to resolve conflicts between a pilot and an autopilot. The second mimics a situation under the next generation ATM concept. The proposed architecture is applied for harmonizing a new ground automation system, a pilot, and an air traffic controller.

1 Introduction

It is said that research and development of automatic flight control are classified into four generations: the first generation is improvement of maneuverability. The second is automation of guidance and control such as autopilot and auto throttle. The third is automation of navigation. In the fourth generation, automation of communication to manage air traffic has been promoted. The roles and tasks of pilot and air traffic controller are going to change, but it is expected that they will coexist in future automation system in the same control loop. One of the topics to discuss is how to harmonize human beings and automation system working together.

Both human and automation system have advantages and disadvantages in aircraft control. From the viewpoint of avoiding human-error, automation systems should be designed to eliminate human beings and protect automatic control. From the other perspective of system reliability, human-centered automation is required: automation system should allow human to override. Since these antithetical concepts sometimes reach to a limit, we proposed a new concept for automation design termed "Human As a Control Module architecture (HACM architecture) [1]-[6]".

The HACM architecture employs a modular structure [7]-[9]. In the proposed architecture, human beings, pilot and air traffic controller, are treated as modules of controlling aircraft. In the architecture, one of the modules termed "ARBITER module" calculates the weights given to both inputs of human and automation system. It adaptively adjusts control authority between human and automation system when they simultaneously give control inputs to the aircraft. The ARBITER module takes over the control from the human if he/she gives control inputs which cause instability of aircraft movement, and gives the control to the automation inputs in order to stabilize the aircraft movement. Adversely, in the case that the human side controls the aircraft safely, the module gives full control authority and prevents interference of the automation system. By automatically adjusting the control inputs simultaneously given by the human and the automation system, it realizes a system which compensates for both control abilities in the aircraft control. When either the human or the automation system provides irrelevant inputs, the module ignores the input and provides another suitable one.

In this paper, we review our work conducted in the past. Firstly, the concept of the HACM architecture is explained. Secondly, two application examples are summarized: the first applies it for PIO (Pilot-Induced Oscillation) [10]-[12] situations to harmonize a pilot and an autopilot. The second mimics a situation when the next generation Air Traffic Management (ATM) concept is introduced. The HACM architecture is applied for harmonizing a new automation system, a pilot, and an air traffic controller.

2 The HACM Architecture

2.1 Concepts

In Ref. [1]-[4], the concept of the HACM architecture is described. We shortly summarize in this section.

Figure 1 shows the block diagram of the HACM architecture. A human is treated as one of the control elements in the HACM architecture. The architecture consists of 3 control elements, the HUMAN module, CONTROLLER module and ARBITER module. The HUMAN module corresponds to a pilot and/or an air traffic controller, the CONTROLLER module corresponds to an automation system, and the ARBITER module works to harmonize the CONTROLLER module with the HUMAN module. As shown in Fig. 1, the HUMAN module and the CONTROLLER module are arranged in parallel. Both of the modules use flight information to generate control commands at the same time. These control commands are the inputs to the ARBITER module. It adjusts the control commands to harmonize the two different commands.

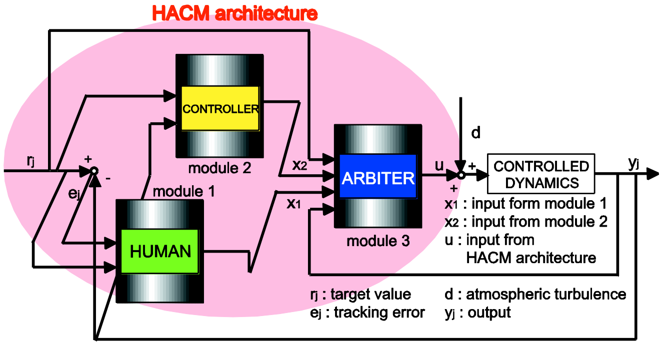


Figure 1 The HACM architecture

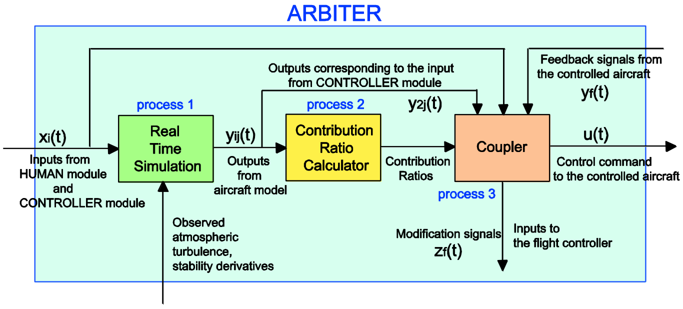


Figure 2 The ARBITER module

2.2 Mechanism

The ARBITER module simulates aircraft movements when each of the HUMAN and the CONTROLLER module controls the aircraft, then generates control commands given to the aircraft based on the simulated results. Through the ARBITER module, the HACM architecture avoids the overlapping of the control commands of a human and an automatic system by adaptively adjusting the contribution ratios.

Figure 2 shows the mechanism of the ARBITER module. The control commands, the elevator commands in this paper, from the HUMAN module and CONTROLLER module , $x_1(t)$ and $x_2(t)$, are input to the

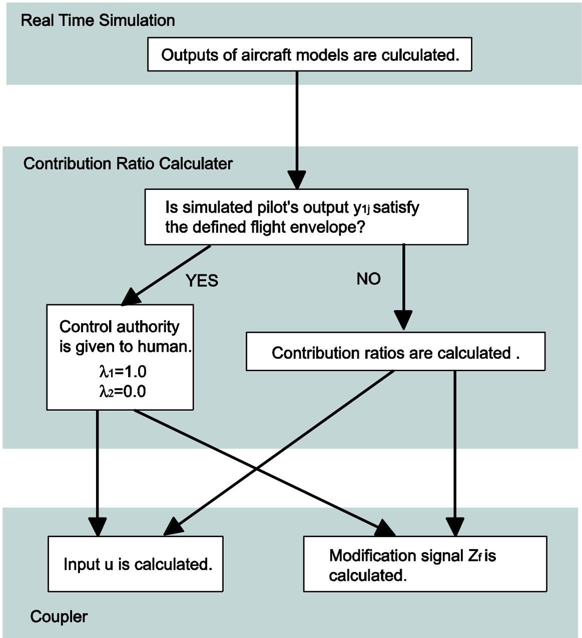


Figure 3 Flow chart in the ARBITER module

ARBITER module. The general mechanism in the ARBITER module comprises the following three processes— real time simulation, contribution ratio calculator, and coupler. Details of the algorithms are shown in Ref. [1]-[4].

- Real time simulation: In the first step, the ARBITER module simulates the outputs of the aircraft corresponding to the control commands of both the HUMAN and CONTROLLER modules at real time by using the dynamics model of the aircraft.
- Contribution ratio calculator: In the second step, contribution ratios $\lambda_i(t)$ $(i=1,2)$ are calculated by using the outputs simulated in the previous process. The contribution ratios are normalized between 0 and 1. The sum of the contributions of each module is 1. The contribution ratio means how much control authority each module has.
- Coupler: In the final step, the control commands from the HUMAN module and CONTROLLER module are adjusted. The control command to the controlled aircraft $u(t)$ to the aircraft is given as follows:

$$u(t)=\sum_{i=1}^{2}\lambda_i(t)x_i(t) \quad (1)$$

This implies that control inputs of the HUMAN module and the CONTROLLER module are added depending on their contribution ratio.

Figure 3 shows the flow chart in the ARBITER module. In order to calculate the contribution ratios, flight envelope protection is applied. In this paper, the flight envelope protection implies that the ARBITER module adjusts the control authority when the HUMAN module does not satisfy the defined flight envelope; this envelope defines that the range aircraft safely continues its flight. In this paper, the HACM architecture is applied for longitudinal control of the aircraft. Reference [4] shows details about the defined flight envelope.

3 On the Pilot-Autopilot Interaction

3.1 Conflicts between Pilot and Automated Aircraft

Aircraft accidents/incidents were induced after shifting autopilot control to pilot maneuver. In 1994, an A300 crashed at Nagoya airport in Japan [13]. Since the pilot attempted to land without knowing that the autopilot was set to TOGA (Take Off Go Around) mode, the interference between control inputs of pilot and autopilot caused the disaster. After this, the flight control system was improved to allow pilots to override autopilot's control. However, overriding the autopilot should be still refrained and is commonly prohibited in pilots training manuals. Pilots have to disconnect the autopilot with their own decision when they shift into manual control. In 1997, a MD11 flying with autopilot met an atmospheric turbulence [14]. Since the autopilot could not control the aircraft movement, the pilot shifted into manual control. Then, an oscillation of the aircraft movement (Pilot-Induced Oscillation: PIO) occurred. After the accidents, maneuverability of MD11 was improved by equipping pitch rate damper. However, different types of aircraft, a B747-400, caused the same types of PIO in 2002[15]. It is necessary to analyze the factors which induce accidents/incidents in pilot-autopilot interaction during flight for the future improvement.

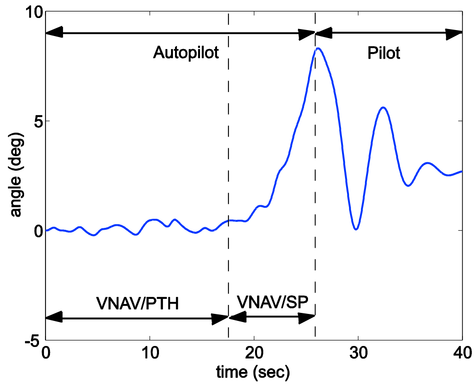


Figure 4 Simulation results of the aircraft incident: pitch angle

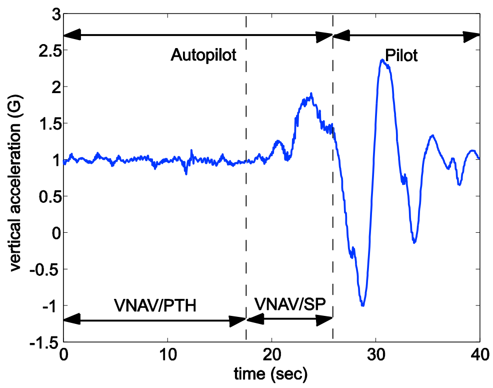


Figure 5 Simulation results of the aircraft incident: vertical acceleration

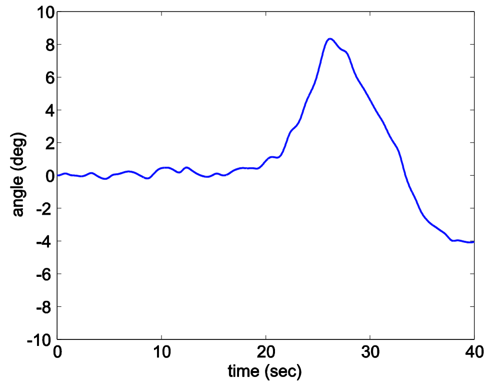


Figure 6 Simulation results in the case the autopilot keeps flight: pitch angle

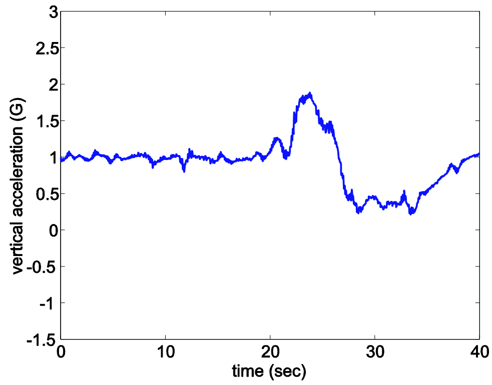


Fig. 7 Simulation results in the case the autopilot keeps flight: vertical acceleration

3.2 Analysis of a Past Aircraft Incident

We picked up an incident of a B747-400 in 2002 and simulated the situation [4]. Figure 4 and 5 show the pitch angle and vertical acceleration of the simulated results. A B747-400 flying at around 40,000 ft with autopilot in the Japanese airspace met with an atmospheric turbulence [15]. The airspeed suddenly increased. The mode of the autopilot changed to the speed control mode that controls airspeed with the pitch angle when the time axis of the graphs corresponds to 18 seconds. However, the autopilot could not reduce airspeed by using the pitch angle change. It is reported in the accident analysis report that the pitch angle increased to around 8.5 degree and the stick shaker moved. In the simulation, the autopilot was disconnected and manual control started when the time axis corresponds to 26 seconds. Because of the quick and high amplitude pilot control at a high altitude, a pitch angle oscillation occurred as shown in Fig. 4. As a result, the vertical acceleration drastically changed as shown in Fig. 5.

After the incident, the training manual was changed to extend the coverage of the autopilot in the case that the airspeed was increased to around the maximum limitation value V_{mo} . This means it was concluded that the incident was prevented if the pilot hadn't controled the aircraft manually and kept flight with the autopilot. In order to confirm the validity of the conclusion, we simulated the case that the autopilot kept controlling the aircraft after running into the turbulence. Figures 6 and 7 show the simulation results of the pitch angle and the vertical acceleration respectively. As shown in Fig. 6, the pitch angle gently decreased after taking the maximum values around 8.5 degrees after around 26 seconds. Figure 7 shows that the maximum value of the change of the vertical

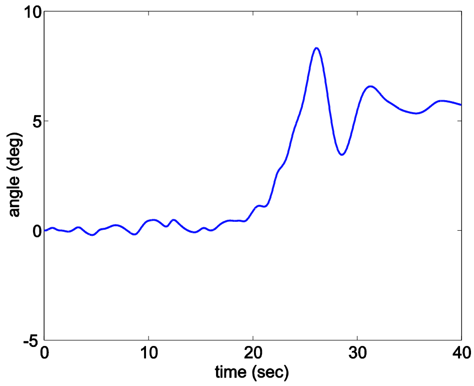


Figure 8 Simulation results in the case the pilot doesn’t control the aircraft: pitch angle

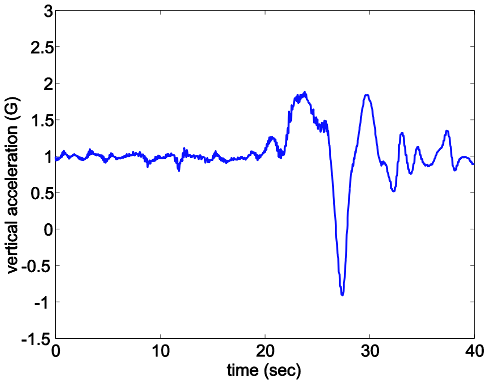


Figure 9 Simulation Results in the case the pilot doesn’t control the aircraft: vertical acceleration

acceleration is around 1.2G. Compared to Fig. 5, the change of the vertical acceleration was reduced in the case the autopilot kept controlling the aircraft.

The revision of the training manual might be a solution under the incident situation. However, the authors consider other factors which have possibilities to act on the incident situation. We discuss the incident factors in human-machine interaction with simulation results as follows.

1) It is unclear whether or not the pilot disconnected the autopilot. In the case that the autopilot was automatically disconnected, it is impossible to keep autopilot control after meeting with the turbulence. Figures 8 and 9 show the simulation results of the pitch angle and the vertical acceleration in the case that the pilot didn’t control the aircraft manually after the autopilot was disconnected at 26 seconds. As shown in Fig. 8, the oscillation of the pitch angle is caused. Fig. 9 shows that the maximum

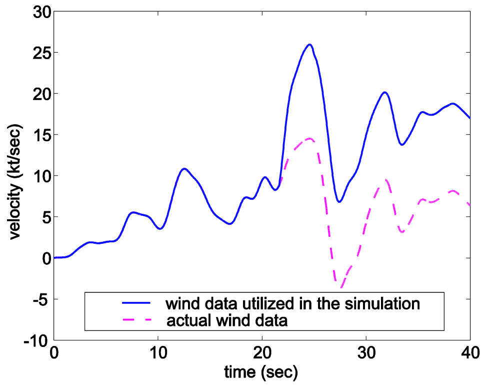


Figure 10 Simulated wind following the *x* direction of the earth axis

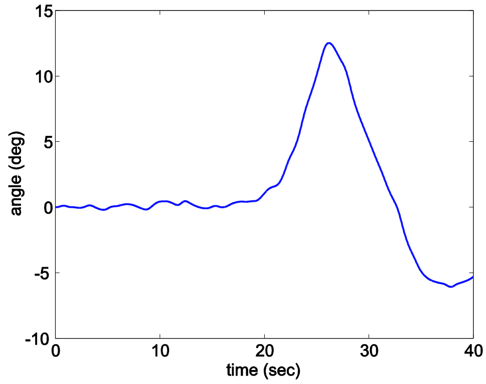


Figure 11 Simulation results in the case that the aircraft meets with the simulated wind while keeping autopilot control: pitch angle

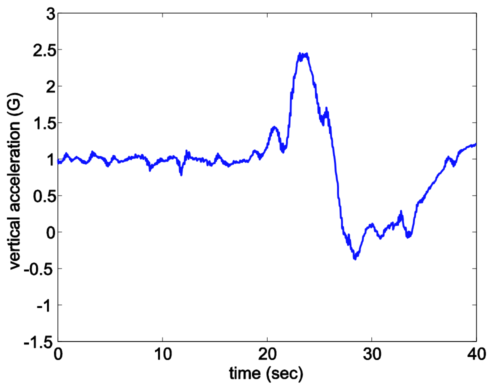


Figure 12 Simulation results in the case that the aircraft meets with the simulated wind while keeping autopilot control: vertical acceleration

value of the change of the vertical acceleration is around 2.6 G. In order to reduce the vertical acceleration change, appropriate pilot maneuver is necessary to keep the flight safely.

2) It is difficult to predict how the atmospheric turbulence influences the future aircraft movement. We changed the *x* axis element of the wind as shown in Fig. 10 to simulate the

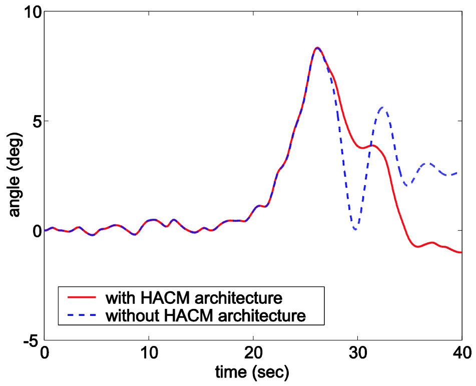


Figure 13 Application results: pitch angle

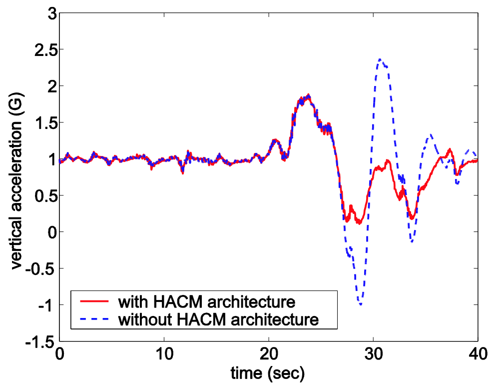


Figure 14 Application results: vertical acceleration

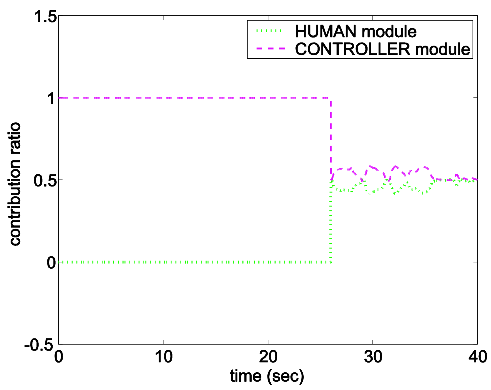


Figure 15 Application results: contribution ratios

aircraft movement in the case that the autopilot kept controlling the aircraft. The value of the change of the wind in this simulation was bigger than the real one. The exceedance probability to enter the simulated turbulence is around 10^{-6} according to Ref. 18. Figures 11 and 12 respectively show the simulation results of the pitch angle and the vertical acceleration. As shown in Fig. 11, the pitch angle increased after around 26 seconds and reached around 12 degrees. It shows the difficulty to keep safe flight. The change of the vertical acceleration was around 2.0 G as shown in Fig. 12. The simulation results do not show that keeping the autopilot control prevents the incident.

3.3 Application for the Past Aircraft Incident

It has still been difficult to decide whether or not the pilot should take over the control authority from the autopilot to interfere in the aircraft control because it depends on situations as shown in the simulation results in the previous section. Since automation systems based on the current design concept have not solved the problems in the human-machine interaction, we applied the HACM architecture to the accident situation to confirm its effectiveness [4].

Figures 13 and 14 show the effectiveness of the HACM architecture in the case it is applied to the situation of the aircraft incident. The results of the aircraft incident show that the maximum value of the change in the vertical acceleration is around 3.4 G as shown in Fig. 5. On the other hand, it is reduced to around 1.1 G in the case that the HACM architecture is applied. This means that the HACM architecture achieves 68 % of the PIO reduction. The contribution ratio is shown in Fig. 15.

4 On Harmonizing a Ground Automation, a Pilot, and an Air Traffic Controller

4.1 Ground Automation in a Next Generation ATM Concept

Automation has been considered as a mean to achieve higher capacity in air traffic control [16][17]. Several investigations on different levels of automation, from automated decision aids to full automation, have been undertaken since the 80's.

One of the recent innovative ideas is named "subliminal control [18][19] ", where an automated system assesses the future traffic to remove conflicts by automatical requests for changes of speeds or climb rate without intervention of human Air Traffic

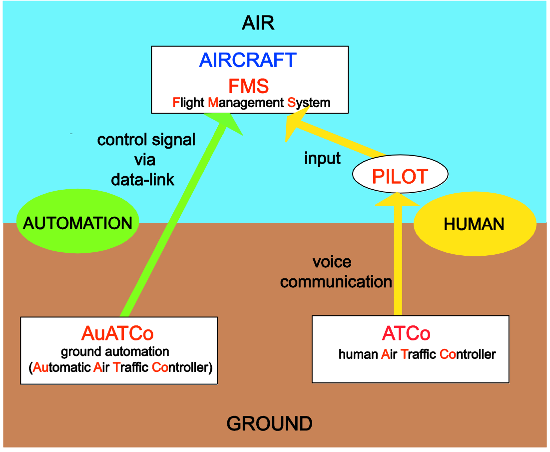


Figure 16 Future ATM system in subliminal control concept

Controller (ATCo). This future ground automation system creates control signals on the ground and sends them directory to the Flight Management System (FMS) via data-link. Since the ground automation has the potential not to address the emergent situation in an early phase of development, ATCo needs to get back the authority to manage air traffic and interfere in the automation control. The ground automation has been investigating and aiming at its practical use in the next generation ATM system, however, the impacts caused to ATCos and/or pilots who will be working with the future automation have not been analyzed and discussed yet. With this background, the impact of the subliminal control was analyzed [5].

4.2 Impact Analysis

Figure 16 shows the future ATM system in which human beings (ATCos and pilots) and the ground automation (Automatic Air Traffic Controller: AuATCo) are working together in the same control loop. In current ATM, information such as turning direction and speed etc., flows between ATCo and pilot through voice communication. Pilot operates autopilot and other automation settings in order to keep aircraft following ATCo instructions safely.

In the future ATM automation concept, additional information flows between AuATCo and FMS. Information, for example, flight plans, real time flight data and the target value of speed control etc, is shared between them. The problem comes from the fact that there is no information flow between ATCo and AuATCo. Because ATCo and AuATCo do not share the same information with each other, it is considered that there are interferences between human beings and automation when the control authorities are not determined according to traffic situations.

The authors consider the situation where AuATCo and ATCo simultaneously give control commands to aircraft with different strategies to manage air traffic. For example, AuATCo gives speed commands to the aircraft to resolve conflicts in the air, while ATCo gives climb/descent commands to decongest the airspace. In the concept of subliminal control, ATCo does not sense how the AuATCo is working, so there are possibilities that ATCo gives an altitude command to the same aircraft via the pilot. The ATCo command is given to the air through voice communication, so AuATCo does not sense the intent of ATCo. In this case, how do the commands interfere in each other and influence aircraft navigation? We conducted numerical simulations to mimic situations which cause interferences among ATCo (via pilot), AuATCo, and aircraft.

In Refs. [5] and [6], we conducted simulations which mimic situations of interferences between ATCo (via pilot) and AuATCo. This paper picks up one of the scenarios and analyzes its impact. This scenario simulates a situation where ATCo and AuATCo give different control commands to autopilot. AuATCo gives speed command to change small amount of airspeed of which en-route ATCo do not sense how AuATCo works on a display screen.

The scenario consists of the following 3 processes.

1) ATCo gives a command to descend altitude by 1,000ft, 2,000ft, 3,000ft, and 4,000ft while keeping the airspeed.
2) The pilot inputs the ATCo’s instruction to FMS. FMS selects an autopilot to control altitude.
3) AuATCo gives a command to decrease airspeed by 5 ft/s.

In this scenario, we mimic the situation that the AuATCo overwrites pilot input of the speed command. Autopilot was designed by

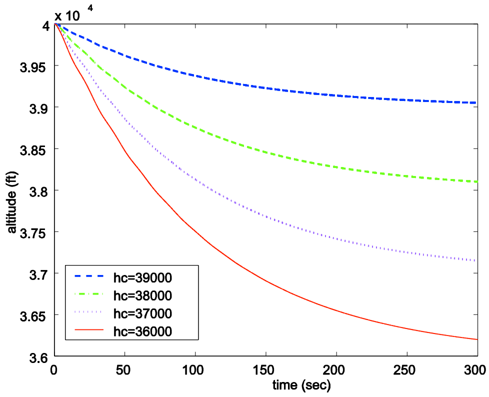


Figure 17 Performance of an autopilot controlling altitude: altitude

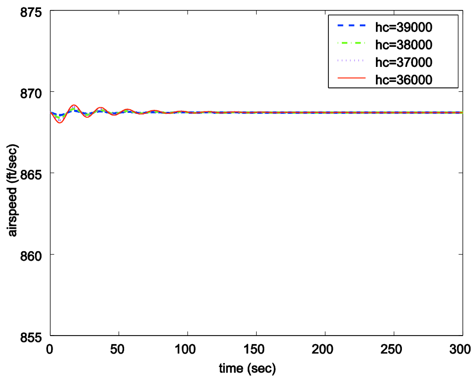


Figure 18 Performance of an autopilot controlling altitude: airspeed

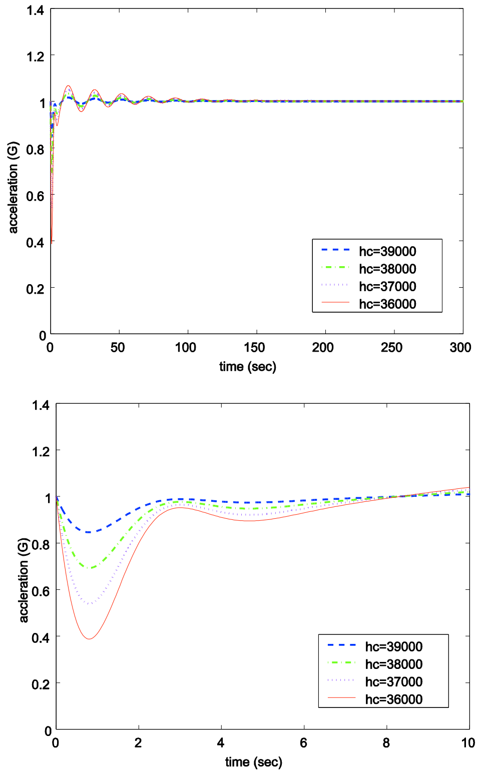


Figure 19 Performance of an autopilot controlling altitude: vertical acceleration

(Top: 300 seconds, Bottom: 10 seconds)

using the Total Energy Control System (TECS) [20]. Based on Ref. [21], nonlinear dynamics of a B747-100 flying at 40,000 ft are used in this simulation.

Performance of the altitude controller where the target altitude h_c is 39,000 ft, 38,000 ft, 37,000 ft, and 36,000 ft while keeping the current airspeed 867.8 ft/s is shown in Figs. 17 and 18. As shown in Figs. 17 and 18, the designed altitude controller works to achieve the target altitude while keeping the airspeed. Figure 19 shows vertical acceleration of the altitude controller. In this simulation, we used the same parameter set in the designed autopilot even though the target values of the altitude were different. In reality, it is considered that the values of the vertical acceleration change were reduced less than the values shown in Fig. 19 because the autopilot adjusts the value of the parameters depending on the target altitude.

Next, we simulate an interferences after the AuATCo gives an airspeed command V_c which reduces airspeed by 5 ft/s. Figures 20 to 22 show the results of the interferences between ATCo and AuATCo when the AuATCo command overrides the target airspeed during the flight. Compared to Fig. 19 and Fig. 22, the change of the vertical acceleration is increased by around 50 % when ATCo and AuATCo are acting together than the case that AuATCo is acting alone.

4.3 Application for the Future Ground Automation

The HACM architecture is applied for this scenario to confirm its effectiveness. Figure 23 shows the structure of the HACM architecture. In this case, the HACM architecture has two HUMAN modules corresponding to a pilot and

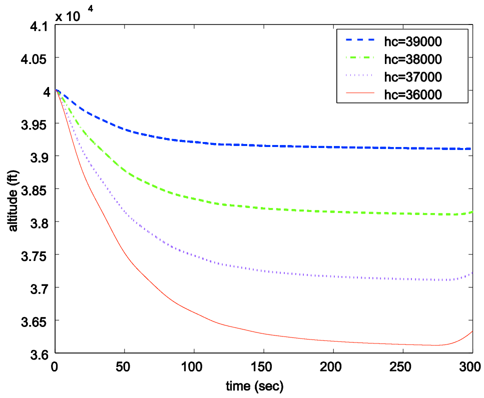


Figure 20 Interference simulated in scenario 1: altitude

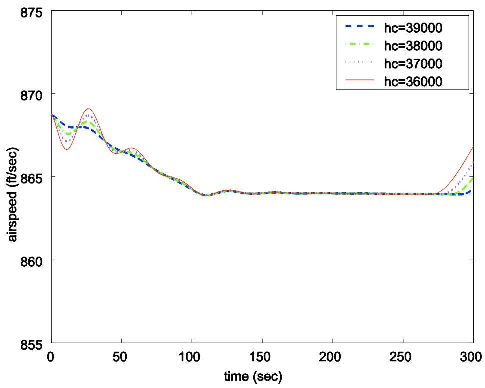
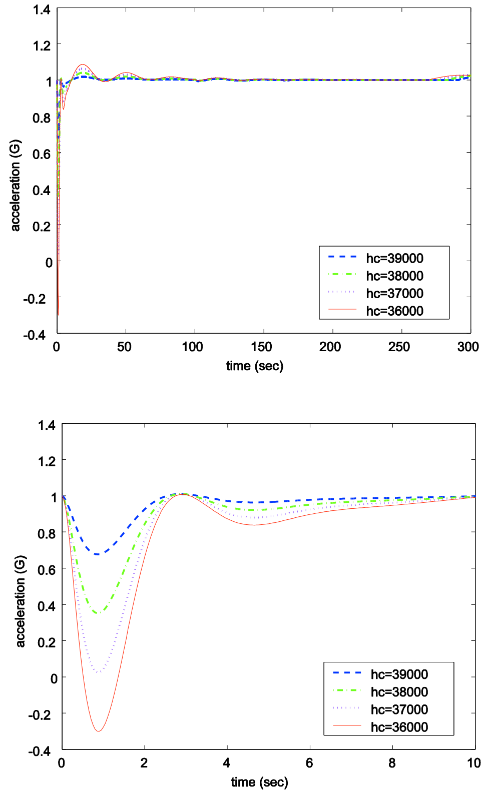


Figure 21 Interference simulated in scenario 1: airspeed

an ATCo which are connected in series. The details of the setting in the ARBITER module are shown in Refs. [5] and [6].

Figures 24 to 27 show the effectiveness of the HACM architecture. As shown in Figs. 24 and 25, the HACM architecture works to navigate the aircraft following the ATCo instruction which controls the altitude while keeping the airspeed. As shown in Fig. 26, the HACM architecture works to reduce the change of the vertical acceleration comparing with Fig. 26. As shown in Fig. 27, the ARBITER module reduces the control authority of the ATCo and mixes the inputs of the ATCo and AuATCo in early stage of the aircraft response in order to reduce the change of the vertical acceleration.



B. 10 seconds simulation

Figure 22 Interference simulated in scenario 1: vertical acceleration
(Top: 300 seconds, Bottom: 10 seconds)

5 Conclusion

This paper reviewed our research on harmonizing automation systems and human beings in flight control. A new concept of automation design was proposed as HACM architecture.

The HACM architecture allows situations in which both, automatic controller and human, give commands to aircraft simultaneously. By adaptively adjusting the control, it arbitrates conflicts between human and automation during flight. We picked up two application examples: Firstly, the HACM architecture was applied to resolve conflicts between pilot and autopilot. A past aircraft incident was picked up to analyze incident factors in pilot-autopilot interaction. Secondly, the HACM architecture was applied for the "subliminal control" concept proposed in the next generation ATM concept. The results showed that the HACM architecture stabilized

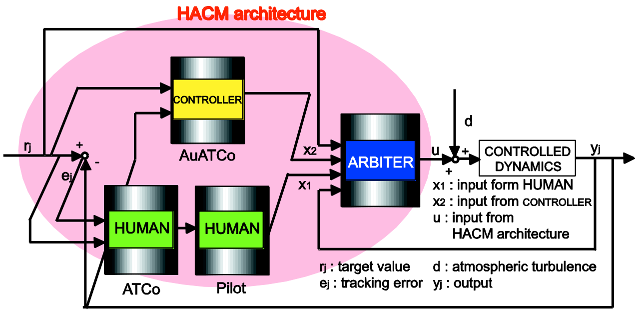


Figure 23 The HACM architecture applied for the future ATM concept

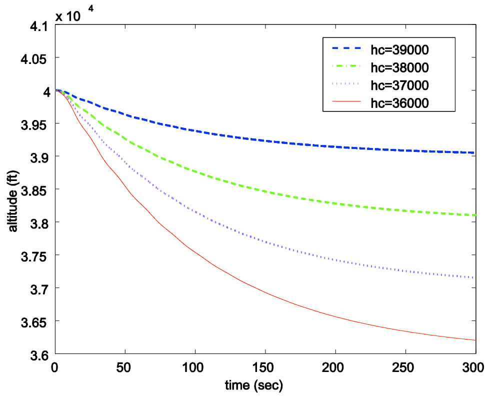


Figure 24 Application for scenario 1: altitude

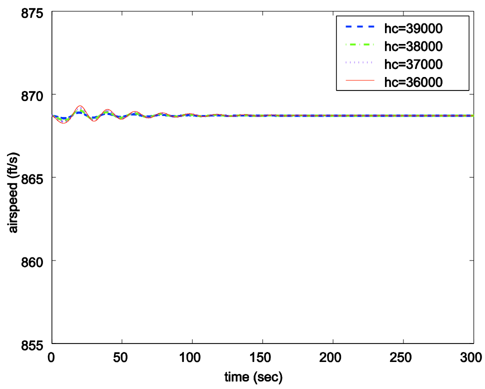


Figure 25 Application for scenario 1: airspeed

the aircraft movement following instructions of human air traffic controller.

The HACM architecture is a new concept of automation design, but not matured yet. One of the points is that it adjusts control based on the simulation results by using the model of the controlled dynamics in the ARBITER module. So the performance depends on the accuracy of the dynamics model.

One idea that recently attracted most interest is how to design automation which

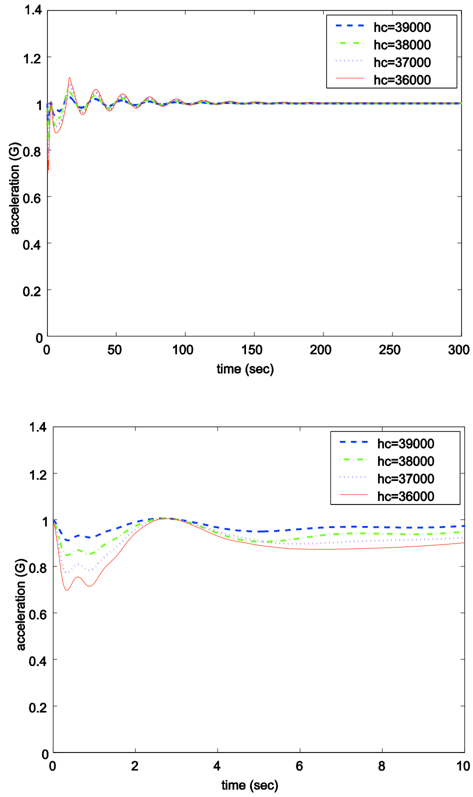


Figure 26 Application for scenario 1: vertical acceleration
(Top: 300 seconds, Bottom: 10 seconds)

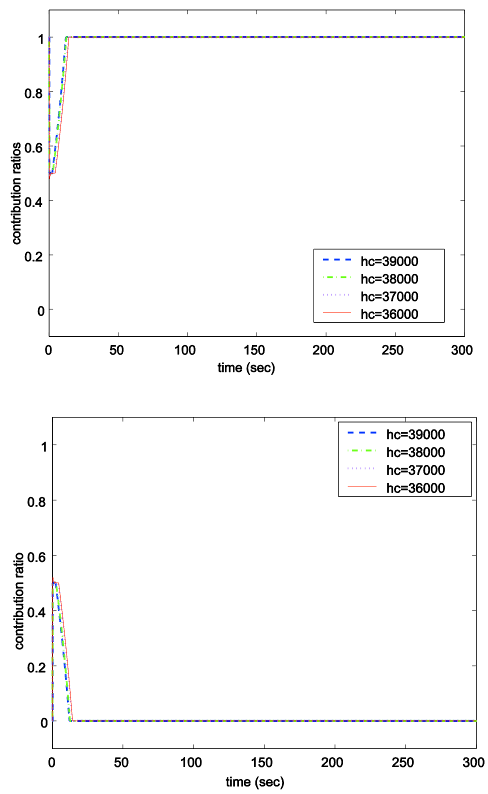


Figure 27 Application for scenario 1: contribution ratios
(Top: ATCo, Bottom: AuATCo)

supports pilots and air traffic controllers without confusion in the situation where multiple aircraft are flying in the airspace. In the future, we would like to extend this concept.

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Copyright Statement

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