A NEW ARCHITECTURE TO HARMONIZE AUTOMATION WITH PILOT MANEUVER

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Abstract

In a pilot/automation interface, it is said that automation is still the potential cause of new types of errors induced by the confusion between the pilot and the automatic flight control system; such confusions trigger disasters. A new approach is required for futuristic automation design for resolving conflicts between the pilot and automation.

With regard to this, this research proposes a new architecture termed "Human As a Control Module architecture" (HACM architecture) to promote harmonization between the automation and pilot maneuvers. In the HACM architecture, a pilot is treated as a single module for controlling the aircraft. The proposed architecture contributes to circumventing the effect of the conflicting action taken by the pilot and the automatic flight control system by breaking the chain of events that lead to aircraft accidents.

In this paper, the HACM architecture is applied to prevent pilot-induced oscillation (PIO) and its effectiveness is shown through numerical simulations and flight simulator experiments. An aircraft accident caused by PIO in the past is reconstructed, and the HACM architecture is applied in order to demonstrate how the architecture guarantees beneficial effects for improving aircraft safety.

1 Introduction

While automation can reduce the frequency of pilot errors, it is still a potential cause of new types of errors induced by the confusion in pilot/automation interfaces [1–3]. According to reference [2, 3], pilots tend to get confused about the unforeseeable behavior of automated airplanes when responding to an abnormal situation; such confusions trigger disasters. For example, an autopilot sometimes causes confusion in the cognitive and decision-making process of a pilot and interferes with the duties of basic airmanship. Feedback control with fly-by-wire technology is related to the pilot-induced oscillation (PIO) caused by actuator limiting. In order to resolve these conflicts between the pilots and automation, a new approach is required for futuristic automation design.

In automation design, "human-centered automation" is highly desired to improve air safety. With regard to the pilot, human-centered automation implies automation designed to work cooperatively with pilots in the pursuit of the stated objectives [2, 4]. There are two main types of approaches for achieving human-centered automation: 1) creation of better environments for pilots to prevent mistakes and 2) adaptive management and modification of inappropriate actions by pilots and/or automatic systems. The first approach is termed an error-resistant approach while the latter one is an error-tolerant approach. The error-resistant approach includes improvement in the cognitive and decision-making tasks, for example, flight deck and display design, design of flight management systems, etc. Although some of these designs are being used in practice, this approach is not the only solution for human-centered automation. During the design process,

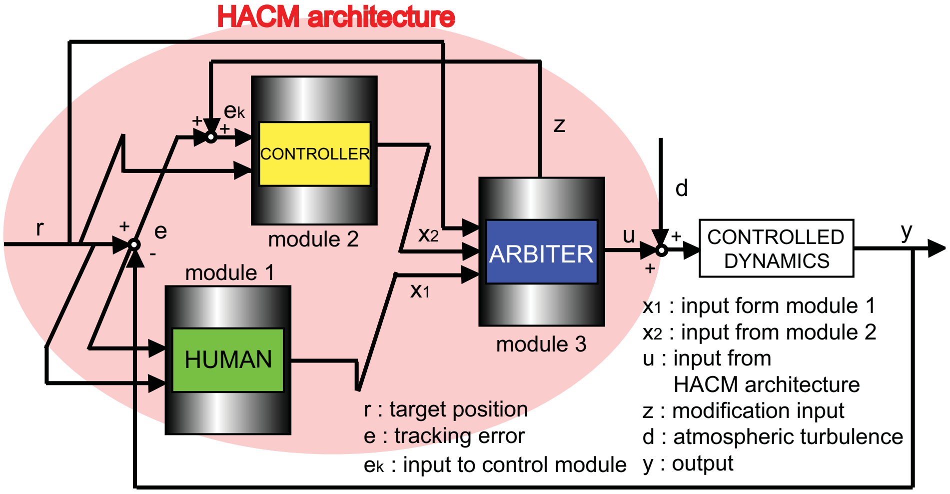

Fig. 1 Basic Structure of HACM architecture

the error-resistant approach is required to hypothesize how a design coordinates between a pilot and automation. However, it is difficult to define automation designs that support pilots because we might not foresee or understand autoflight systems and pilot behaviors under all circumstances including abnormal situations during flight. In addition, the error-resistant approach may not adaptively measure up to the conflicts related to the dynamics of both the pilot maneuver and automated aircraft as represented by the PIO problem. Because these conflicts are mainly attributed to the dynamics change of the pilots and automated flight systems during a flight, a context-sensitive support based on the adaptive approaches is required. Considering the above discussion, this research considers human-centered automation from new perspectives and introduces the error-tolerant approach by using the proposed architecture termed as the "Human As a Control Module architecture" (HACM architecture) [5, 6]. The HACM architecture adaptively contributes toward circumventing the effect of inappropriate actions by the pilot and the automatic flight control system by breaking the chain of events that lead to aircraft accidents.

This paper applies the HACM architecture for solving the PIO problem and demonstrates how the architecture guarantees beneficial effects for improving aircraft safety. First, this paper introduces the HACM architecture and explains its concept. Second, the HACM architecture is applied to prevent PIO. The effectiveness of this architecture is shown through numerical simulations and flight simulator experiments. Third, an aircraft accident caused by PIOs in the past is reconstructed, and the HACM architecture is applied for the case. The effectiveness of the architecture is confirmed in the practical situation through the reconstructed aircraft accident. Finally, we summarize the effectiveness of this research and conclude this paper.

2 Human As a Control Module architecture: HACM architecture

2.1 Concept of HACM architecture

The HACM architecture treats a pilot as a single module for controlling an aircraft. Figure 1 shows a block diagram that includes the fundamental structure of the HACM architecture and a controlled dynamics, which in this case is the dynamics of the aircraft. As shown in Fig. 1, the basic structure of the HACM architecture comprises three types of modules—the human module, controller module, and arbiter module. The characteristics and roles of each module are described below:

- *Human module*

This module corresponds to pilot. It is difficult to represent pilots using numerical models because pilots flexibly change their dynamics depending on the situation within the bounds of their physiological abilities. It is advantageous for a pilot to assess situations well and track their performance. On the other hand, their physiological ability is limited. In addition, they sometimes make mistakes during cognition and decision making. Humans also tend to take conflicting actions intentionally.

- *Controller module*

This module corresponds to an automatic controller that is appropriately designed with controlled dynamics. The automatic controllers can achieve good performance within the design conditions. The disadvantage is that a trade-off exists between the tracking performance and the robustness toward the disturbance input and modeling error. In addition, the controllers are subject to deteriorating control ability beyond the design conditions. Various design approaches can be applied to this module. This paper precedes discussions on a simple feedback controller because the purpose of this paper is to introduce HACM architecture and confirm its effectiveness.

- *Arbiter module*

This module manages inputs $x_i(t)$ $(i=1,2)$ from both the human and controller modules that simultaneously provide control commands to the aircraft. These commands are gated in the arbiter module by the contribution ratios, which are calculated using the softmax function. The contribution ratio represents the extent to which each module presently accounts for the behavior of the controlled dynamics. The role of the arbiter module is to eliminate inappropriate control commands from the other two modules to the controlled dynamics and generate appropriate control inputs that suit the present conditions. Through the arbiter module, the HACM architecture enables us to realize a control system that compensates for the limitations of the human module and controller module and utilizes their advantages in the aircraft control. As a result, the module realizes a backup system that comprises the pilot and the automated controller that have different characteristics as mentioned above. When either the human or controller modules provide irrelevant inputs, the arbiter module ignores the input and provides another suitable one. The mechanism to adjust the inputs in the arbiter module is explained in the next subsection.

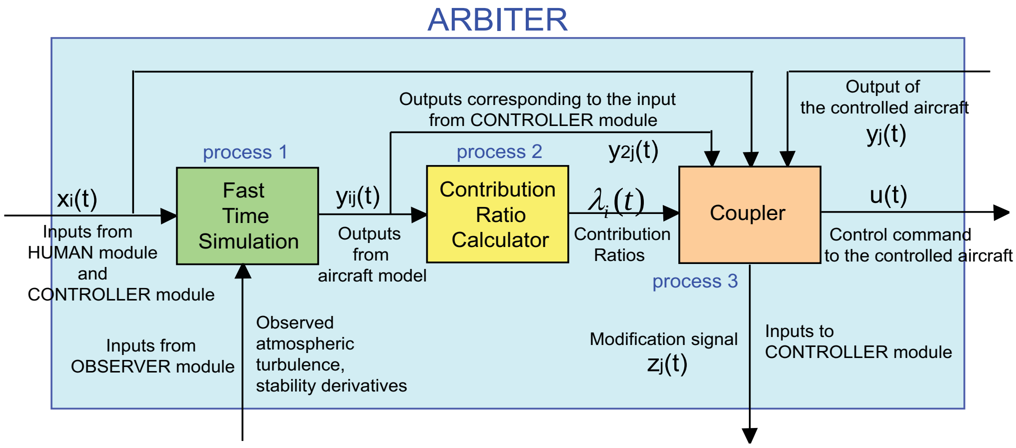

Fig. 2 Arbiter Mechanism

2.2 Arbiter mechanism

Figure 2 shows the mechanism of the arbiter module that arbitrates the control commands inputted by the pilot (human module) and automatic controller (controller module). As shown in Fig. 2, the control commands from the human module $x_1(t)$ and controller module $x_2(t)$ are inputted to the arbiter module. The general mechanism in the arbiter module comprises the following three processes—a fast-time simulation, contribution ratio calculator, and coupler.

1. Fast-time simulation

First, the arbiter module predicts the outputs of the aircraft corresponding to the control commands of both the human and controller modules. The arbiter module possesses the dynamic model of the controlled aircraft within its framework. By using the dynamic model, the outputs $y_{ij}(t)$ $(i=1,2 \quad j=1,2,\ldots l)$ for inputs $x_i(t)$ $(i=1,2)$ to the aircraft are numerically simulated. l corresponds to the number of outputs from the aircraft model that are used to calculate the contribution ratios in the next process. The values of $y_{1j}(t)$ correspond to the outputs when the control command $x_1(t)$ is inputted to the aircraft model. The values of $y_{2j}(t)$ correspond to the outputs when the control command $x_2(t)$ is inputted to the aircraft model.

Since the atmospheric disturbance needs to be taken into account in order to simulate aircraft movement, a new module named the observer module is included in the HACM architecture; this module observes wind dynamics. The details of the observer module are discussed in section 4.

2. Contribution ratio calculator

Second, contribution ratios $\lambda_i(t)$ $(i=1,2)$ are calculated by using the outputs of the aircraft model predicted in the previous process. The contribution ratio represents the extent to which each module presently accounts for the behavior of the aircraft dynamics.

In order to calculate the contribution ratio, first, the performance of the human and controller modules are individually quantified. We measure the performances of each module based on the following index $E_{ij}(t)$ $(i=1,2 \;\; j=1,2,\ldots l)$, which is given by

$$E_{ij}(t)=\frac{\sum_{k=n-m}^{n}\left|\varepsilon_{ij}(t_k)\right|^2 e^{k-n+m}}{\sum_{k=n-m}^{n} e^{k-n+m}} \qquad (1)$$

where $\varepsilon_{ij}(t)$ is the error between $y_{ij}(t)$ and target values, which are the desired outputs of the aircrafts at present time t and n is the number of time steps at present time t. In this case, t is equal to t_n. m is the number of time steps of the past tracking errors considered in the index. By using the index as shown in Eq. (1), the performances of each module are numerically evaluated. Eq. (1) measures the performances of each module by using the value of errors predicted in the past.

The contribution ratios of each module $\lambda_i(t)$ are calculated by using Eq. (1) and the softmax function. The contribution ratios are given as follows:

$$\lambda_i(t)=\frac{\sum_{j=1}^{l} e^{-(E_{ij}(t)/\sigma)}}{\sum_{i=1}^{2}\sum_{j=1}^{l} e^{-(E_{ij}(t)/\sigma)}} \qquad (2)$$

where σ is a scaling constant. The softmax function normalizes the tracking errors across the modules so that the contribution ratios lie between 0 and 1 and the sum of the contribution over the modules is 1.

3. Coupler

Third, the control commands from each module are adjusted and added in this process. The input from the HACM architecture $u(t)$ to the aircraft is given as follows:

$$u(t)=\sum_{i=1}^{2}\lambda_i(t)x_i(t) \qquad (3)$$

The module with a smaller error index than that of the others greatly contributes to input $u(t)$. Conversely, the other module has a low contribution to $u(t)$.

Another function of this process is to generate a modification signal $z_j(t)$ $(j=1,2\cdots l)$ that is inputted to the controller module. The details of modification signal are presented in section 4.

3 Resolving the PIO problem : Preliminary Results

3.1 Problem Establishment

Based on references [7, 8], the PIO problem is briefly explained as follows. PIO refers to an oscillation in which aircrafts respond adversely to the intentions of a pilot because of quick and high amplitude maneuvers. It is difficult to predict the occurrence of PIO because of the adaptive nature of the pilot maneuvers. The recent accidents of YF-22 and JAS-39 Grippen have been attributed to the PIO due to the performance limitation of actuators. These accidents increased the awareness of the problem in the industry. With regard to this, in this section, we consider the application of the HACM architecture for improving the PIO problem caused by the actuator limitation in order to confirm the effectiveness of the proposed architecture.

According to reference [8], we have established a situation in which Category II PIO is caused by actuator rate and/or position saturation. The pitch altitude control of a B747-100 [9] with feedback gain is selected as a controlled dynamics. In this section, we use the linear model of the aircraft model. In order to trigger pilot control that induces PIO, the gear ratio that represents the ratio of gain between the control stick angle and the elevator angle is maintained as 7.0. As a target signal that is the target value of the pitch angle aircraft should follow, a 0.5-second step input is provided. This paper employs a simple feedback controller (PID controller) in the controller module and confirms the effectiveness of the framework. The gain constants of the PID controller are selected as $K_P = -1.5$, $K_I = -0.8$, and $K_D = -1.0$. The parameter m in Eq. (1) and parameter σ in Eq. (2) are 50 and 0.14, respectively.

3.2 Simulation results

First, a numerical simulation was carried out using a pilot model. In this case, the human module implies the pilot model. The pilot model $Y_p(s)$ employed for the simulation is expressed as follows:

$$Y_p(s) = -0.8e^{-0.25s} \times \frac{5s+1}{s} \times \frac{15s+1}{0.001s+1} \quad (4)$$

The pilot model given in Eq. (4) satisfies the handling qualities criteria corresponding to the controlled dynamics in B747-100 with feedback gains, as are required in MIL-HDBK 1797 [10].

The simulation results are shown in Figs. 3, 4, and 5. As shown in Fig. 3, since the control command from the pilot model exceeds actuator

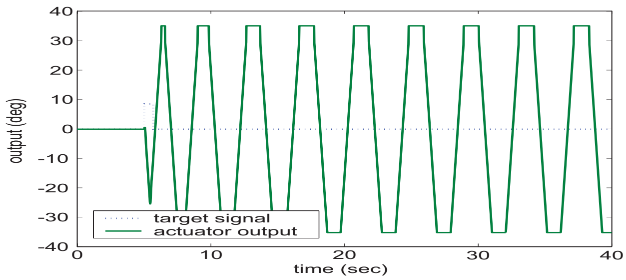

Fig. 3 Simulation results of output from actuator where the pilot model causes PIO

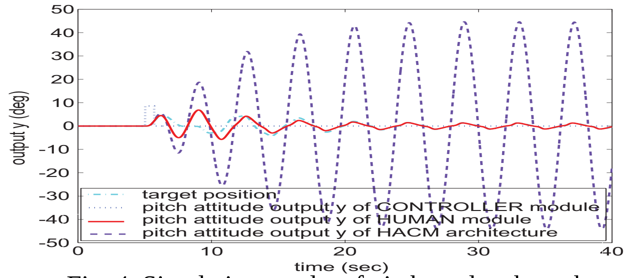

Fig. 4 Simulation results of pitch angle where the pilot model causes PIO

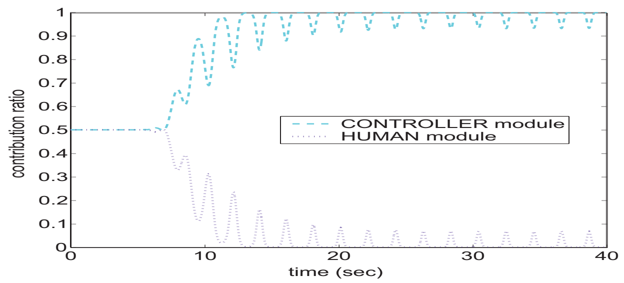

Fig. 5 Simulation results of contribution ratios where the pilot model causes PIO

limiting, the output from the actuator exhibits triangular and trapezoidal waveforms. As a result, Fig. 4 shows that a PIO of a large amplitude occurred when the human module alone was acting. The output from the human module is calculated in the arbiter module. We ignore the stalls in the flight of the controlled aircraft in the fast-time simulation. However, it is considered that large oscillations of pitch angle stall an aircraft. On the other hand, the HACM architecture achieves a reduction in the amplitude of the PIO as shown in Fig. 4. Figure 5 shows the time series data of the contribution ratios. As shown in Fig. 5, the arbiter module provides a larger contribution ratio for the controller module and usurps the control authority from the human module. The arbiter module predicts the outputs of the aircraft corresponding to the inputs from the human module and the controller module and adaptively arbitrates the performance of each module. Thus, the HACM architecture prevents the PIO problem.

3.3 Results of flight simulator experiments

Second, flight simulator experiments were carried out. Figure 6 depicts the primary flight display (PFD) used in the flight simulator experiments. A human pilot controls the joystick for 40 seconds.

The results of the flight simulator experiments are shown in Figs. 7, 8 and 9. As shown in Fig. 7, since the control command from the human pilot exceeds the actuator limit, the output from the actuator exhibits triangular and trapezoidal waveforms. As a result, Fig. 8 shows that a PIO of large amplitude occurred when the human module, in this case the human pilot, acted alone. On the other hand, the HACM architecture reduced the amplitude of the PIO as shown in Fig. 8. Figure 9 shows the transitions of the contribution ratios corresponding to each module. As shown in Fig. 9, the contribution ratios are calculated in order to provide a lower value to the human module. The arbiter adaptively usurps the authority of control from the human module when PIO occurs.

Since the HACM architecture gives pilots time to modify inappropriate control, it is effective in solving the PIO problem.

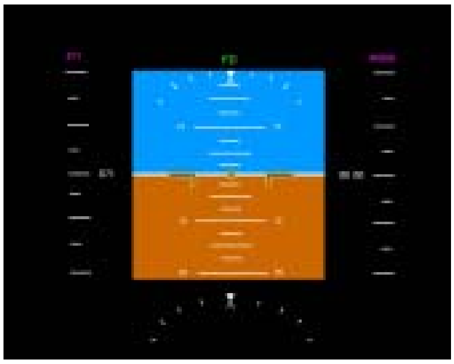

Fig. 6 Primary Flight Display (PFD)

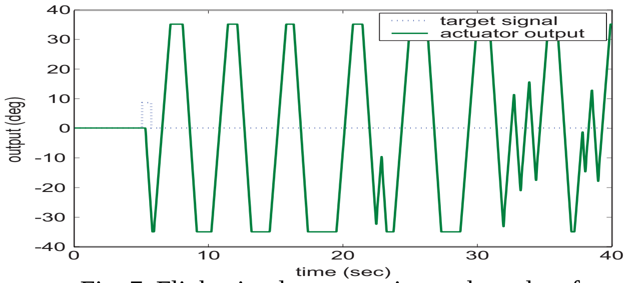

Fig. 7 Flight simulator experimental results of output from actuator where a pilot causes PIO

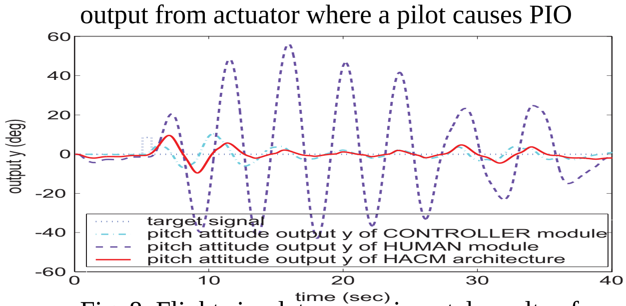

Fig. 8 Flight simulator experimental results of pitch angle where a pilot causes PIO

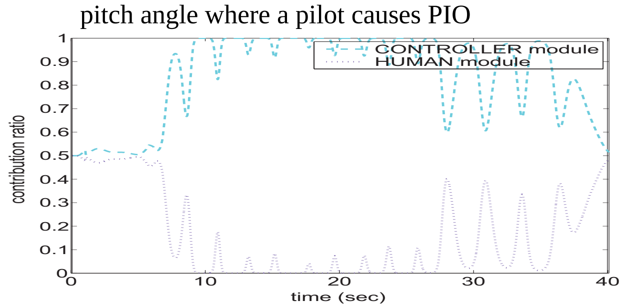

Fig. 9 Flight simulator experimental results of contribution ratios where a pilot causes PIO

4 Application for an aircraft accidents caused by PIO in the past

4.1 Reconstruction of an aircraft accident

In this section, we confirm the effectiveness of the HACM architecture by applying it to an aircraft accident in the real world. In 2002, a B747-400 flying at around 40000 ft in the Japanese airspace suffered PIO after running into turbulence [11]. The present study considers this accident and explains how the HACM architecture works in this situation.

According to the official data in the accident analysis report, the data of changes in wind, the elevator angle (pilot controlled), the yaw angle, and the roll angle are extracted and used to reconstruct the accident. Since the details of autopilot design are not disclosed, we design an autopilot that captures the characteristics of an equipped autopilot in a distressed aircraft based on the accident analysis report. The nonlinear dynamics of the B747-100 [12] is used in this simulation.

The simulation results for a duration of 40 seconds of the aircraft accidents are shown in Figs. 10, 11, and 12. Figure 10 shows the airspeed, Fig. 11 shows pitch angle, and Fig. 12 shows vertical acceleration. The aircraft flying with an autopilot ran into atmospheric turbulence, and the airspeed increased as shown in Fig. 10. The mode of the autopilot changed to a speed control mode that controls airspeed with a pitch angle when the time axis of the graph corresponds to 18 seconds. However, the autopilot could not reduce airspeed by using a pitch angle change because the autopilot controlled the pitch angle slowly under the rate limitation of vertical acceleration. The feedback of the airspeed to the autopilot filtered out the background noise; therefore, the time delay between the real and filtered airspeeds influenced the slow change in the pitch angle. The pitch angle increased and the stick shaker moved. Then, the pilot disconnected the autopilot and switched to manual control when the time axis corresponded to 26 seconds. Because of the quick and high amplitude pilot control at a high altitude, the pitch angle oscillation occurred as shown in Fig. 11. As a result, the vertical acceleration drastically changed as shown in Fig. 12.

The accident analysis report does not indicate the accurate time for which the autopilot is disconnected. It is also uncertain whether the pilot disconnected the autopilot. In this paper, the aircraft accident was reconstructed based on the assumption that the pilot disconnected the autopilot and switched manual control on when the time axis corresponded to 26 seconds.

4.2 Improvement in the HACM architecture

In order to apply the HACM architecture for the condition of the aircraft accident, it is enhanced as follows:

- Addition of the observer module

As shown in Fig. 13, a new module named observer is added to the HACM architecture. The function of the observer module is to observe wind dynamics and/or dynamics change

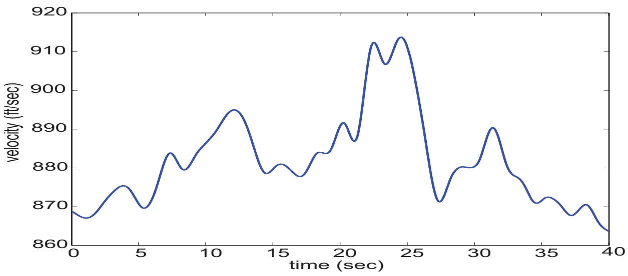

Fig. 10 Reconstruction of the aircraft accident : airspeed

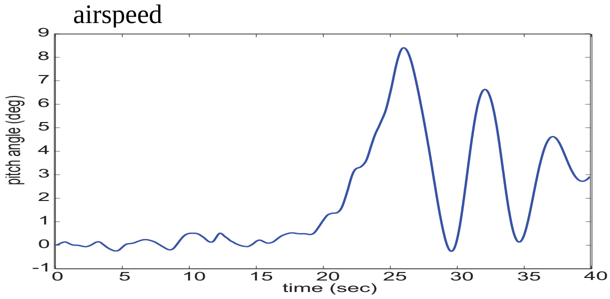

Fig. 11 Reconstruction of the aircraft accident : pitch angle

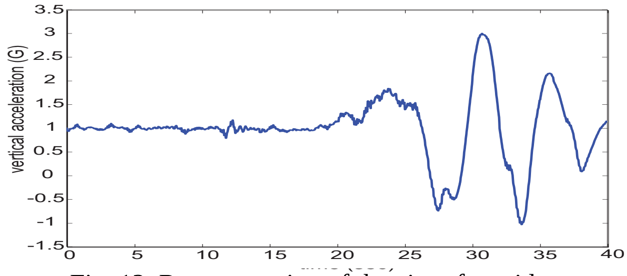

Fig. 12 Reconstruction of the aircraft accident : vertical acceleration

of the aircraft during the flight. In the observer module, the extended Kalman filter (EKF) [13] is added, and it adaptively transmits the observed data to the arbiter module in order to carry out fast-time simulation online. In this paper, the observer module observes wind dynamics and transmits the observed wind data

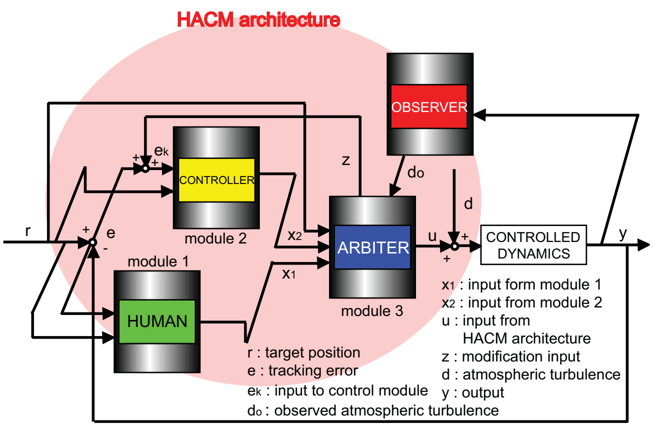

Fig. 13 HACM architecture with observer module

to the arbiter module.

The performances of the observer module are shown in Figs. 14 and 15. Both these figures compare the real wind and the observed wind that blow along the x axis and the z axis of the body axis. Since the performance of the EKF is limited, estimation errors exist between the real wind and the observed wind. In this paper, we confirm whether the HACM architecture works well when we utilize the existing observer method (EKF). Therefore, we use the observed wind data that includes the estimation error in the arbiter module and confirm the effectiveness of the HACM architecture under this condition.

- Application of flight envelope protection

In order to calculate $\varepsilon_{ij}(t)$ in Eq. (1), flight envelope protection is applied. In this paper, the flight envelope protection implies that the arbiter module adaptively 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. The flight envelope is defined as follows:

$$\begin{aligned} \theta_{\min} &\le \theta_1(t) \le \theta_{\max} \\ \dot{\omega}_{\min} &\le \dot{\omega}_1(t) \le \dot{\omega}_{\max} \\ \ddot{\omega}_{\min} &\le \ddot{\omega}_1(t) \le \ddot{\omega}_{\max} \end{aligned} \quad (5)$$

where $\theta_1(t)$, $\dot{\omega}_1(t)$, and $\ddot{\omega}_1(t)$ are the outputs of the aircraft model corresponding to the input from the human module calculated in the arbiter module. As shown in Eq. (5), the upper and lower limits are introduced for the pitch angle, vertical acceleration, and rate of vertical acceleration. This paper yields $\theta_{\min} = -11(\deg)$, $\theta_{\max} = 11(\deg)$, $\dot{\omega}_{\min} = -1.0(G)$, $\dot{\omega}_{\max} = 2.5(G)$, $\ddot{\omega}_{\min} = -0.15(G/\sec)$, and $\ddot{\omega}_{\max} = 0.15(G/\sec)$. The upper and lower value of $\dot{\omega}$ is the designated value at which B747-400 flies safely. The limitation of $\ddot{\omega}$ is the rate limitation of the vertical acceleration in the speed control mode of the autopilot in the distressed aircraft. $\varepsilon_{ij}(t)$ is defined as follows:

$$\text{if} \quad y_{ij}(t) < y_{j\min},$$

$$\text{then} \quad \varepsilon_{ij}(t) = \left| \frac{y_{ij}(t) - y_{j\min}}{y_{j\min}} \right|^2 . \quad (6\text{-}1)$$

$$\text{If} \quad y_{j\max} < y_{ij}(t),$$

$$\text{then} \quad \varepsilon_{ij}(t) = \left| \frac{y_{j\max} - y_{ij}(t)}{y_{j\max}} \right|^2 . \quad (6\text{-}2)$$

where

$$\begin{aligned} & y_i(t) \ \ (i = 1,2) \\ &= [y_{ij}(t)]^T \ (j = 1,2,3) \\ &= [y_{i1}(t), \quad y_{i2}(t), \quad y_{i3}(t)]^T \\ &= [\theta_i(t), \quad \dot{\omega}_i(t), \quad \ddot{\omega}_i(t)]^T . \end{aligned} \quad (6\text{-}3)$$

$y_1(t)$, the output of the aircraft model, corresponds to the input from the human module and $y_2(t)$, the output of aircraft model, corresponds to the input from the controller module.

- Fast-time simulation by using a nonlinear aircraft model

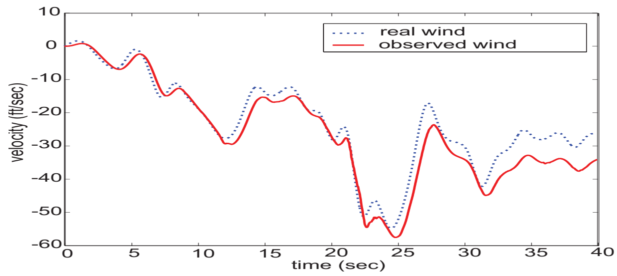

Fig. 14 Performance of observer module
: X axis wind (body axis)

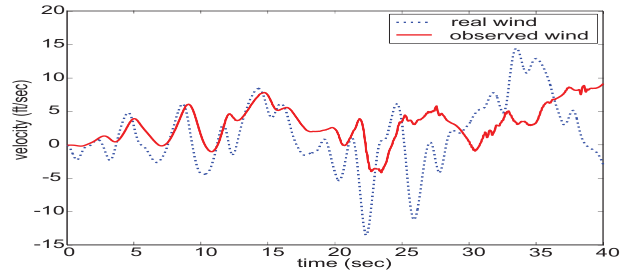

Fig. 15 Performance of observer module
: Z axis wind (body axis)

In the case that the aircraft runs into turbulence as shown in Fig. 14, the nonlinearity of aircraft behavior is strongly exhibited. Therefore, the nonlinear aircraft model [12] is utilized in the arbiter module, and the effectiveness of the HACM architecture is confirmed by using a nonlinear model.

- Modification signal

Modification signal $z_j(t)$ is defined as follows.

$$z_j(t) = y_{2j}(t) + \lambda_2(t)(y_j(t) - y_{2j}(t)) \quad (7)$$

$y_j(t)$ is the output of the real aircraft. Eq. (7) yields $y_{2j}(t)$ where $\lambda_2(t) = 0$ in order to prevent the autopilot from sensing the pilot control as disturbance. When $\lambda_2(t) \neq 0$, the modification signal (Eq. (7)) will make the autopilot to stabilize the aircraft movement caused by the adverse effects of the pilot maneuver.

4.3 Effectiveness of HACM architecture

Figures 16, 17 and 18 show the effectiveness of the HACM architecture that is applied to the reconstruction of the aircraft accident. Figure 16 shows that the HACM architecture works to reduce the amplitude of the pitch angle oscillation. Thus, the HACM architecture contributes toward reducing the change in the vertical acceleration (Fig. 17). As shown in Fig. 17, the results of the aircraft accident show that the maximum value of the change in the vertical acceleration is approximately 4 G. On the other hand, the maximum value of the change in the vertical acceleration is approximately 1.5 G in the case that the HACM architecture is applied for the same condition. This result shows that the HACM architecture curbs the influence of the aircraft damage and reduces the negative impact on the human body caused by the change in the vertical acceleration. Figure 18 shows that the arbiter module adaptively adjusts the contribution ratios. Since the arbiter module does not completely usurp the authority of pilot control, the pilot senses that his/her control

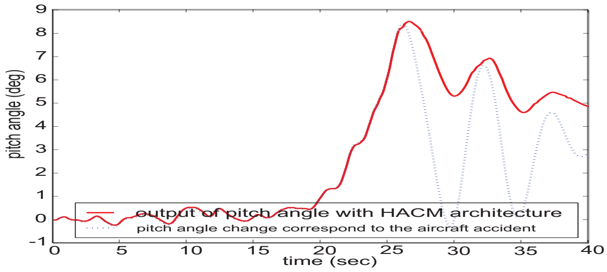

Fig. 16 Effectiveness of HACM architecture : pitch angle

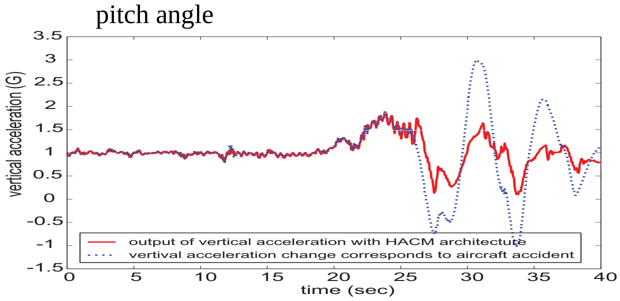

Fig. 17 Effectiveness of HACM architecture : vertical acceleration

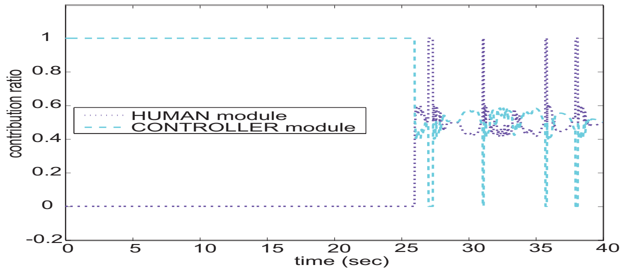

Fig. 18 Effectiveness of HACM architecture : contribution ratios

input is reflected in the aircraft behavior. The manner in which this effect eases manual control will be confirmed by the comments of the pilots via flight simulator experiments.

6 Conclusion

"I had no time to check the information displayed on the monitor." "I cannot remember whether or not I disconnected the autopilot." These were the comments by the pilot who controlled the aircraft, which met with an accident caused due to PIO, in the accident analysis report. Conventionally, in order to prevent human errors, a man-machine interface design that supports the cognitive and decision making tasks of the pilot such as the flight display design has been developed. However, these comments show that sometimes such tools cannot work well under strained conditions that require prompt action. In highly automated

aircrafts, in particular, since pilots find it difficult to predict how an autopilot works in an unforeseeable situation, it is difficult to appropriately operate the autopilot system. In this case, if a pilot makes mistakes that lead to aircraft accidents, it is effective to temporarily usurp the control authority of the pilot by using the automatic control system thereby harmonizing automation with pilot maneuver.

This research proposed Human As a Control Module architecture (HACM architecture) and introduced its concept to coordinate automation and pilot maneuver. There are two potential benefits in employing the HACM architecture. First, the use of HACM architecture allows us to realize a backup system comprising the pilots and the automated flight control systems. The arbiter module usurps control authority from the pilot or an automated flight controller, which takes inappropriate action, and generates an appropriate an input command to the controlled aircraft. Second, the HACM architecture has a simple framework and its algorithm comprises three types of modules—human, controller, and arbiter. Therefore, it is possible to utilize the architecture online. In addition, it is convenient to add modules with various functions to the architecture in order to develop a better automation system.

This paper applies the HACM architecture for PIO problem, and the effectiveness of the architecture is confirmed through simulation by using a pilot model and flight simulator experiments. An aircraft accident caused by PIO in the past is reconstructed, and the HACM architecture is applied to this case. Therefore, it is confirmed that the HACM architecture is effective for reducing the negative impact of the PIO phenomenon under a condition similar to that under which the aircraft accident occurred. The HACM architecture guarantees beneficial effects under the influence of an estimation error of atmospheric turbulence caused by the existing observer method (EKF).

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