RESEARCH AND DEVELOPMENT FOR FAULT TOLERANT FLIGHT CONTROL SYSTEM – PART 1. INTELLIGENT FLIGHT CONTROL SYSTEM

Shinji Suzuki* and Akira Yanagida**
***The University of Tokyo, **The Society of Japanese Aerospace Companies**

Keywords: *Flight Control, Flight Dynamics, Intelligent Control, Optimal Control, and Aircraft*

Abstract

This paper presents a research project on a fault tolerant flight control system. The objective of this project is the development of an intelligent control system that can adaptively control and guide an aircraft during emergency situations. The background of the project and mathematical formulations are reported as Part 1 of the paper. Flight experiments will be presented in Part 2. A research group comprising members from academia, industry and research organization has been formed by the Society of Japanese Aerospace Companies (SJAC) for carrying out the project, Flight demonstrations of the developed system have been successfully performed from fiscal year 2005 to 2007.

1 Introduction

Aviation safety is highly guaranteed throughout the process of design, manufacturing, and operation of an aircraft. Since aviation continues to grow, there is a concern that, the increased number of flights will lead to more accidents unless steps are taken to drastically reduce accident rates.

While the safety of every aspect of aviation has been improved, the research project presented in this study focused on guidance and control technologies. Flight management system (FMS) comprising the autopilot and auto-throttle system has been increasingly providing reliable and accurate flight operations. However, since conventional FMS is not able to deal with the emergency situations, flight operations generally depend on the decisions and flight skill of the pilot.

When some air accidents occur, following are the necessary steps that are taken, (1) accurate detection of the cause of the failure and accident, (2) isolation and cancellation of those effects, (3) regeneration of possible flight trajectories to the nearest airport, and (4) control of the aircraft for an emergency landing using the available devices. Since these operations require high levels of human intelligence, autonomous control systems with fault tolerant capacities have been investigated by many researchers in order to provide intelligent features to conventional control system. Using the fund provided by the Ministry of Economy, Trade and Industry (METI), the Society of Japanese Aerospace Companies (SJAC) has been promoting research on autonomous flight control systems in collaboration with industrial, academic and national research groups[1,2]. The main purpose of this research program is to demonstrate the total system capability including the capability of autonomous flight control and guidance systems for civil aircraft through flight tasting.

The results of flight experiments will be presented in Part 2, and Part 1 provides an outline of the following control systems used in the project; (1) adaptive flight control system using neural networks (NNs), (2) engine power flight control system, (3) online trajectory optimization and 4-dimensional automatic guidance and control system for emergency landing, and (4) optimal air-collision avoidance system. In addition, it reports the flight experiments conducted using a small UAV for the validation of the adaptive flight control system using NN.

2 Basic Concept

This paper reports the details of a fault tolerant flight control system that can be used in the emergency situations, i.e., when some air accident occurs. As illustrated in Fig. 1, the entire system is divided into two parts, i.e., a fault tolerant control system and a fault tolerant guidance system.

In the former part, an adaptive flight control system will stabilize an aircraft with failures. If there is a single control surface failure, a configurable control method that identifies a mathematical model of a damaged surface and reconstructs it using control power distribution is employed. This system was developed in our previous project[1]. This project developed adaptive control methods using neural network (NN) technologies for complicated failures and also investigated the use of engine power for flight controllers. In the latter part, a fault tolerant guidance system will be used to guide and control aircrafts involved in accidents for emergency landing. The online trajectory optimization system was developed to obtain trajectories for an emergency landing. Additionally, the optimal air collision avoidance system was developed.

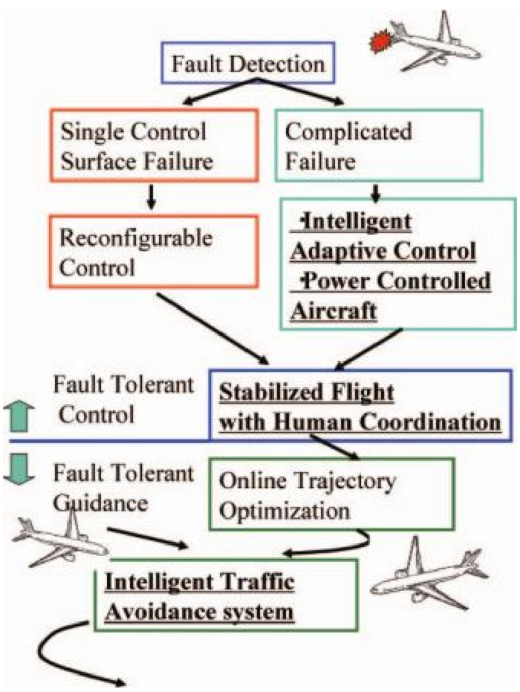

Fig. 1 Block diagram of intelligent fault tolerant flight control system

3 Fault Tolerant Control System

3.1 Neural Network Controller

This project explored the use of neural network (NN) technologies for the adaptive flight control system. A neural network (NN) is a mathematical model that is based on biological neural networks. It is recognized that NNs have a high capability to model a complex nonlinear system and they are used in a nonlinear adaptive controller[4].

Two types of NN controller designs were investigated in this project. One is the online modeling of an error function in a nonlinear dynamic inversion (NDI) controller[5,6], and the other is the online learning in a feedback error learning controller[7].

Nonlinear dynamic inversion (NDI) is a control law methodology that performs linearlization and provides desired command responses for a closed system by using inverted model equations in the feedback loop[8]. Since the inverted model is a simplified model, it is possible to specify controller gains without using a complicated gain scheduling. The dynamic model is represented as follows,

$$\dot{x} = A(x) + B(x)u \quad (1)$$

$$y = Cx$$

where u and y are the system input and output. By differentiating y, the following is obtained.

$$y^{(d)} = A^*(x) + B^*(x)u \quad (2)$$

When the left hand side of Eq.(2) is considered as a virtual input v, the system input can be written as,

$$u = [B^*(x)]^{-1}(v - A^*(x)) \quad (3)$$

where v can be generated by a conventional feedback controller as shown in Fig. 2.

During accidents, the mathematical model deviates from the original model. This change is undesirable for the NDI controller since an accurate inverted model cannot be obtained. A NN is used to an additional controller in which NN parameters are obtained to minimize the error between the model outputs and the sensor outputs. The block diagram of a NDI controller with a NN is illustrated in Fig. 3.

Another approach is the use of the feedback error learning controller, which has been developed as an analogy of a biological control mechanism. Biological feedback loops are extremely slow and have small gains. Consequently, the fast and coordinated motions of creatures require internal models in the cerebellum that is trained by practice. In feedback error learning, a neural network is used in the feedforward controller in a feedback loop as shown in Fig. 4. The parameters used in a neural network are optimized in order to minimize the power of the feedback signal. As a result, the neural network will acquire an inverted dynamic model of a system. In Fig. 4, the feedback error learning system can be used for a conventional output feedback control system even without dynamic Inversion.

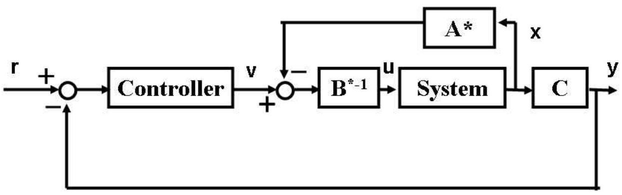

Fig. 2 Nonlinear dynamic inversion control

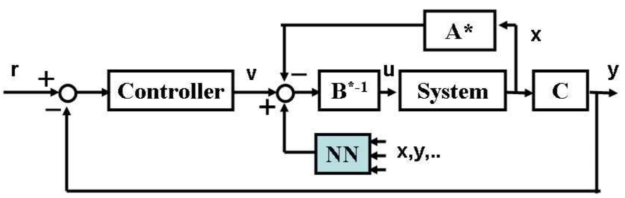

Fig. 3 Basic concept of NDI+NN controller

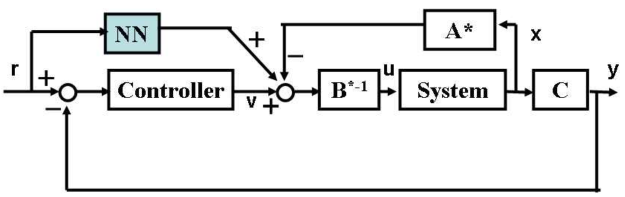

Fig. 4 Basic concept of NDI+feedback error learning controller

3.2 Engine Power Flight Control

When all of the hydraulic powers in control surface actuators is lost, the engine power control system has the potential to act as a flight control system[9]. In our project, engine power flight control system was developed for the experimental aircraft multipurpose aviation laboratory MuPAL-α as shown in Fig.5. This aircraft is a modified aircraft Do228-202 and is equipped with a fly-by-wire system. A H-infinity robust control method is applied, and the aerodynamic coefficients of each engine thrust were newly measured for this project[10]. It can be summarized that in-phase control generates a pitch moment and out-of-phase control produces a yaw moment. Since these moments are not sufficient for total flight control, the controller and flight paths should be set in order to avoid a catastrophic attitude change.

Fig. 5 Multi-Purpose Aviation Laboratory (MuPAL)-α developed by Japan Aerospace Exploration Agency (JAXA)

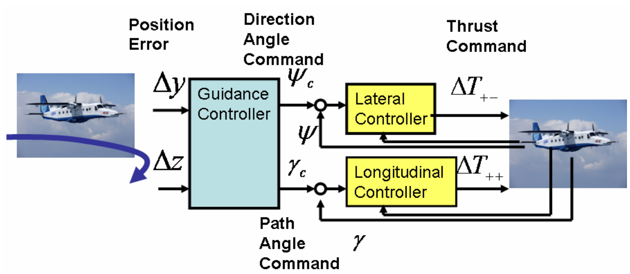

Fig. 6 Engine power flight control system

4 Fault Tolerant Guidance System

4.1 Online Trajectory Optimization

It is considered that automatic navigation to a safety landing area can improve the safety in emergency situations. The application of online trajectory optimization methods has been investigated by many researchers.

Trajectory optimization problems are formulated as follows,

$$\begin{aligned} &\text{Minimize}: J = \int_{t_0}^{t_f} g(x,u)dt + h(t_f) \\ &\text{Subject to}: \dot{x} = f(x,u) \\ &\qquad x(t_0) = x_0,\ x(t_f) = x_f \\ &\qquad a(x,u) \le 0 \end{aligned} \tag{4}$$

where J is an index function to be minimized while satisfying state equations, initial and terminal constraints, and equalit/inequality constraints.

In our previous project, a flight trajectory was generated by optimizing 4D waypoint parameters. In order to obtain more smooth flight trajectories, the use of a direct collocation method was attempted[11]. While a direct collocation method is a powerful optimization algorithm, it requires an appropriate initial solution and computer time, which cannot be provided for online optimization algorithms.

To cope with these difficulties, a multistage approach was developed and heuristic estimation was provided for initial solutions. The direct collocation method provides the time histories of control inputs and state variables as a set of nodal points at each time step. The multistage approach divides a flight trajectory into multiple segments in which the density of nodal points is adjusted according to the distance from the present position as shown in Fig. 7. The initial flight trajectories are automatically generated in a heuristic manner and they can be used to obtain the initial solutions for the numerical optimization process.

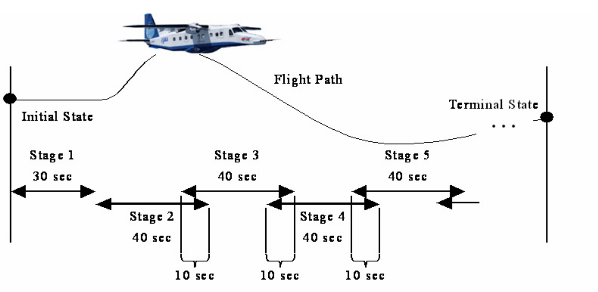

Fig.7 Multistage division for online flight trajectory optimization

4.2 4-D Guidance and Navigation System

Automatic guidance for following the obtained optimal trajectory is also required in emergency situations. It is difficult to employ the conventional autopilot and autothrottle design using the linear control theory since the generated flight trajectories for emergency situations are not conventional flight paths. Additionally, since the flight characteristics of a vehicle may change due to some accidents, adaptive capability should be provided. A combination of an extended Kalman filter and a nonlinear dynamic inversion controller with a singular perturbation method (NDI-SPM) was used for online fault estimating and nonlinear restructuable controlling in Ref. 12. In the present study, we use the NDI-SPM controller in a 4-D guidance control system[11].

Since NDI can realize a simple closed system by using inverted model equations, it can be performed without complicated gain scheduling. It is considered that NDI is suitable for restructurable controllers.

When a 4-D guidance control system is designed by using the NDI method, it is not practical to obtain the inverted model from the complete set of dynamic equations. If the system can be partitioned into several timescale systems, it can also be divided according to its time scale. Time-scale separation is a natural consequence of the underlying physics. In this study, we assume that the aircraft angular velocity increases to a greater rate than the attitude and velocity. Then, the SPM can be applied to simplify the NDI controller and increase the controller robustness. Fig. 8 illustrates the block diagram of the NDI-SPM flight controller.

4.3 Automatic Air Collision Avoidance System

An automatic air collision avoidance system should be developed for emergency landing situations in order to reduce the workload of the pilot. In this project, the collision avoidance system is considered in a horizontal plane because there are cases in which altitude change is difficult during the approach and landing phases.

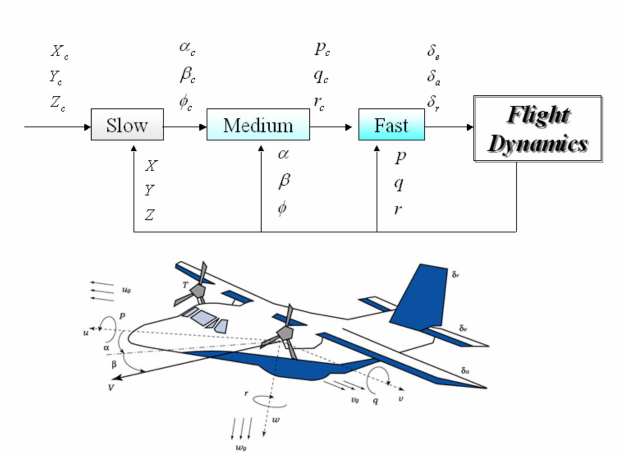

Fig. 8 Nonlinear dynamic inversion with singular perturbation method

The scenario assumed in this project is that another aircraft comes close to our aircraft when the latter is in the approach and landing phases as shown in Fig. 9. The automatic air collision avoidance system can generate an appropriate trajectory that enables the aircraft to avoid the incoming aircraft in the horizontal plane and to revert to the original flight path after the danger has passed[13].

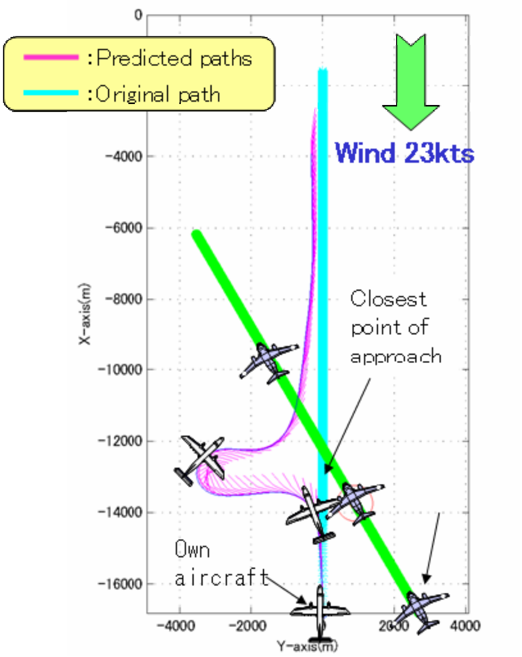

Fig. 9 Optimal air collision avoidance system

Assuming that the states of incoming aircraft can be accurately obtained, the corresponding roll command for controlling the aircraft can be obtained by nonlinear receding horizon control. In the receding horizon control, an open-loop optimal control problem that leads to a two-point boundary-value problem is solved in real time[14]. The receding horizon technique defines a performance index by using a receding horizon, ($t \le t' \le t + T$). Although it is difficult to solve a two-point boundary-value problem in real time, a continuous method can numerically and efficiently solve the problem very efficiently by gradually shifting the horizon.

5 Evaluation of Each Control System

The final objective of this project is the flight demonstration of the proposed fault tolerant flight control system. The following steps should be considered before the flight experiments.

1) Numerical Simulations
Simulation models and control algorithms were evaluated by numerical simulations where parameters in each algorithm were tuned for mathematical models.

2) Flight Simulator Experiments
When a pilot interface was to be evaluated, flight simulator was used to improve a man-machine interface. In particular, the control parameters were further tuned on the basis of the pilot comments and the necessary information was added on its flight display.

3) Hardware in the Loop Simulations
Software installed on the onboard computer should be tested using hardware-in-the-loop simulations. When the flight dynamics are simulated by the computers, the interface between the flight control computer and hardware system can be evaluated.

4) Flight Experiments
JAXA's MuPAL-α (Fig.5) [15] was used in the series of flight experiments in order to evaluate the proposed fault tolerant flight control system. The aircraft was developed by JAXA as a flying laboratory by modifying a Dornier Do228-202, which has a fly-by-wire flight control system. Further details will be presented in Part 2.

Additionally, flight experiments using a small unmanned aerial vehicle (UAV), which was owned by the University of Tokyo were carried out.

6 Flight Experiments using UAV

A flight experiment using UAV is suitable for studying of some failures that occur in the airframe structure. During the preparation of these demonstrations, flight tests of NN controller were carried out.

A small electric UAV (Fig. 10) with a take-off weight, wing area and wing span of approximately 2.0 kg, approximately 4.0 m^2. and 1.75 m, respectively was used in the experiments[16]. During a waypoint tracking control, the feedback gains in a bank angle controller were abruptly changed to 20% of the actual gains in order to simulate a failure. Fig. 11 illustrates a waypoint tracking control in which a bank angle command was generated based on the basis of the angle of the line of sight. A NN was incorporated in the bank angle controller for reducing the feedback signal in the feedback controller[17].

Fig. 12 shows a comparison of different flight trajectories. When the NN was inactive, the UAV easily meandered, while the NN was active, the UAV successfully identified the waypoints. Fig. 13 shows the time history of the measured bank angle and its command. When the NN was active, the roll angle followed the command more closely than when the NN was inactive. On the other hand, the trim angle of an aileron was suddenly changed during a flight. It was confirmed that the NN controller could compensate the change in the trim angle.

Fig.10 Small electric UAV

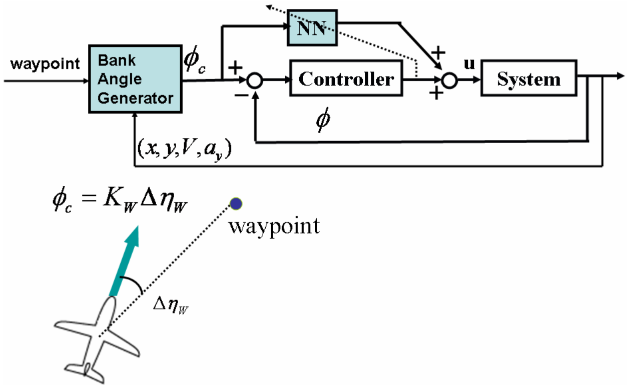

Fig. 11 Waypoint Tracking Controller with Neural Network

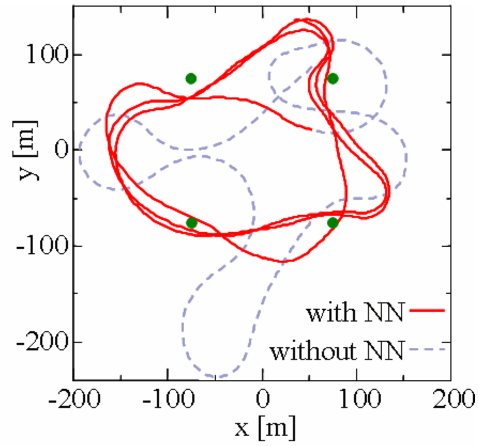

Fig. 12 Flight trajectories of UAV with and without NN

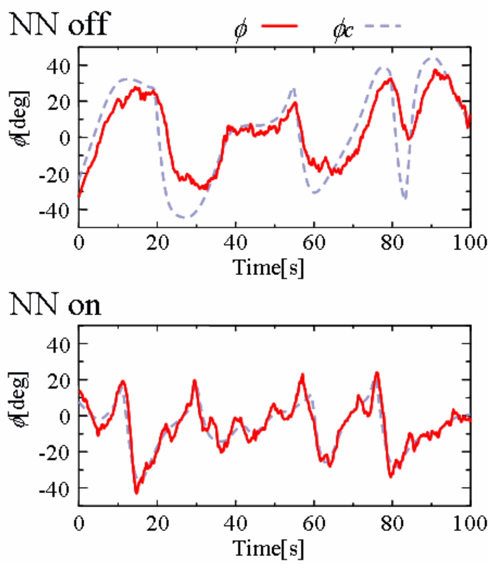

Fig. 13 Command bank angle and output data with and without NN

7 Conclusion

Research on the fault tolerant flight control and guidance systems for accident aircraft has been conducted in Japan by a group comprising members from the University of Tokyo, Mitsubishi Heavy Industries Ltd., Kawasaki Heavy Industries Ltd., Fuji Heavy Industries Ltd., and JAXA. The total system is basically divided into the following five subsystems; (1) an intelligent adaptive controller using a NN, (2) an engine power flight control system, (3) an online optimal flight trajectory computation, (4) an automatic guidance and control system using NDI+SPM, and (5) an optimal air collision avoidance system.

The main objective of this project is to perform the flight demonstration of the intelligent flight control systems. This paper described the background of this research and theoretical formulations, further, it reported the flight experiments conducted using a small UAV. The flight experiments performed using experimental artifact MuPAL-α are summarized in Part2[3]. While the fault tolerant flight control and guidance systems have been investigated to civil aircrafts, these technologies should be applied for UAVs for increasing their safety; this is because UAVs should possess autonomous capabilities to those systems for emergency situations.

Finally, it should be mentioned that this research program was funded by Ministry of Economy, Trade and Industry (METI), and was organized by The Society of Japanese Aerospace Companies (SJAC).

References

[1] Suzuki S., Kawamura F., and Masui K., “Autonomous flight control and guidance system of accident aircraft,” *Proc. ICAS2004,* Yokohama, 2004.

[2] Masui K., Tomita H., and Komatsu Y., “Flight experiment on a flight path optimization algorithm for aircraft in trouble,” *Proc. ICAS2004,* Yokohama, 2004.

[3] Masui K., Tomita H., and Yanagida A., “Research and development for fault tolerant flight control system –Part 2 flight experiments,” *Proc. ICAS2008,* Anchorage, 2008.

[4] Ham F.M., and Kostanic I., *Principles of Neurocomputing for Science and Engineering*, McGraw–Hill, New York, 2001.

[5] Burken J.J., Williams-Hayes P., Kaneshige J.T., and Stachowiak S.J., “Reconfigurable Control with Neural Network Augmentation for a Modified F-15 Aircraft,” NASA/TM-2006-213678, Apr. 2006.

[6] Akamine N., Matsutake K., Kouno M., and Sakaguchi A., “Intelligent Adaptive Flight Control System for General Aviation Aircraft (in Japanese),” *2006 JSAE Annual Congress, 20065327,* May. 2006

[7] Haga R., Matsuura A., Suzuki S., Kono M., and Sakaguchi A., “Neural network based adaptive flight control using feedback error learning,” *AIAA-2006-6341 Guidance, Navigation, and Control Conference and Exhibit*, 2006.

[8] Lane S.H., and Stengel R.F., “Flight Control Design Using Non-linear Inverse Dynamics,” Automatica, Vol. 24, No. 4, 1988, pp. 471–483.

[9] Burken J.J., and Burcham Jr. E.W., “Flight Test Results of Propulsion-Only Emergency Control System on MD 11 Airplane,” AIAA Journal of Guidance, Control, and Dynamics, Vol. 20, 1997, pp. 980–987.

[10] Shibuya H., and Onuma H., “Feasibility Study of Flight Trajectory Control by Thrust Control (in Japanese),” *2006 JSAE Annual Congress, 20065326,* May. 2006

[11] Sakai Y., Suzuki S., Miwa M., Tsuchiya T., and Maui K., and Tomit H., “Flight test evaluation of non-linear dynamic inversion controller,” *46th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV, USA, 2008/01/08.

[12] Tanaka N., Suzuki S., Masui K., and Tomita T., “Restructurable Guidance and Control for Aircraft with Failures Considering Gust Effects”, Journal of Guidance, Control, and Dynamics, Vol. 29, No. 3, 2006, pp. 671–679.

[13] Nagatsuka M., Shishido N., Masui K., and Tomita H., “Autonomous Area Avoidance Algorithm using Receding Horizon Control (in Japanese),” *2006 JSAE Annual Congress, 20065329,* May. 2006

[14] Ohtsuka T., and Fujii H., “Real-Time Optimization Algorithm for Nonlinear Receding-Horizon Control”, Automatica, Vol. 33, No. 6, pp.1147–1154, 1997.

[15] Masui K and Tsukano Y., “Development of a new inflight simulator MuPAL-α,”. *Proc AIAA Modeling and Simulation Technologies Conference and Exhibit,* Denver, AIAA-2000-4574, 2000

[16] Hirokawa R., Kubo D., Suzuki S., Meguro J., and Suzuki T., “A small UAV for immediate hazard map generation,” *AIAA Infotech@Aerospace 2007 Conference and Exhibit,* Rohnert Park, California, USA, 2007/05/07, AIAA-2007-2725.

[17] Yoshimatsu Y., Taniguchi H., Suzuki S., Hirokawa R., and Sanematsu Y., “Flight test evaluation of fault tolerant control system using neural network for UAV (in Japanese),” *Proc. of 39th JSASS Annual Meeting,* 2008, 166–169.

Copyright Statement