# RESEARCH AND DEVELOPMENT FOR FAULT TOLERANT FLIGHT CONTROL SYSTEM – PART 2 FLIGHT EXPERIMENTS

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## Abstract

*This paper describes flight experiments of a fault tolerant flight control system to guide and land an airplane suffering from reduced controllability or other restrictions caused by unexpected failures safely to a suitable airport. The system aims at a further reduction of the fatal accident rate and preventing the number of fatal accidents from increasing in proportion to the number of operations. An online flight trajectory optimization system, an intelligent collision avoidance system, an adaptive control system with neural network, and flight control by engine thrust are proposed as essential technical elements of the fault tolerant control system needed to accomplish emergency landings safely.*

*This paper outlines the aircraft used for flight evaluation of the technical elements and introduces typical flight experiment results that demonstrate the applicability of each element to the proposed fault tolerant flight control system.*

## 1 Introduction

The introduction of flight management systems and highly automated flight control has greatly contributed to reducing the fatal accident rate of transport airplanes. However, these systems cannot adapt themselves to maintain their proper functions in the case of unexpected failures such as flight control system damage. The fatal accident rate has remained almost constant for the past twenty years, while the amount of air transportation continues to increase steadily. Further reduction of the fatal accident rate is therefore essential to prevent the number of fatal accidents from increasing in proportion to the number of operations.

Since fiscal year 2002, the Society of Japanese Aerospace Companies (SJAC) has been promoting a project to research and demonstrate a fault tolerant flight control system that can guide and land an airplane suffering from control difficulties or other restrictions caused by unexpected failures to a suitable airport safely under a contract from the Ministry of Economy, Trade and Industry. The fault tolerant flight control system identifies the failures and reconfigures the flight control system to compensate for them. It then searches for an optimal flight trajectory to a suitable airport under the constraints caused by the failures and guides the airplane to the airport, either by autonomous control or by supporting the pilot to reach the airport under manual control.

The first phase of the project, from fiscal year 2002 to 2003, was carried out by the Japan Aerospace Exploration Agency (JAXA), the University of Tokyo and Mitsubishi Heavy Industries Ltd. (MHI) cooperating under the coordination of the SJAC. This phase involved research on failure detection, online parameter identification and reconfiguration of the flight control system, and an online four-dimensional flight trajectory optimization algorithm [1]. For the latter, flight experiments demonstrated that the newly proposed algorithm could generate an optimal flight trajectory under restrictions caused by failures and that a pilot could track the optimal path manually [2].

During the second phase, from fiscal year 2005 to 2007, JAXA, the University of Tokyo, MHI, Kawasaki Heavy Industries Ltd. (KHI) and Fuji Heavy Industries Ltd. (FHI) cooperated under the coordination of the SJAC to research and develop of an online flight trajectory optimization system, intelligent collision avoidance system, adaptive control system with neural network, and flight control by engine thrust [3], and to demonstrate the applicability of these elements by flight experiments.

This paper outlines the research aircraft and ground systems used to support the flight experiments, and introduces typical flight experiment results obtained in the second phase.

## 2 Flight Experiment System

### 2.1 Research Aircraft

JAXA's Multi-Purpose Aviation Laboratory (MuPAL)-α (Fig. 1) [4] was used in the series of flight experiments to evaluate the applicability of each technical element of the fault tolerant flight control system. MuPAL-α was developed by JAXA as a flying laboratory based on a Dornier Do228-202, and has carried out flight experiments in support of research and development of various advanced guidance and control technologies. MuPAL-α is equipped with a unique experimental fly-by-wire (FBW) flight control system, a flexible pilot display system, and a high accuracy data acquisition system (Fig. 2).

Fig.1. MuPAL-α

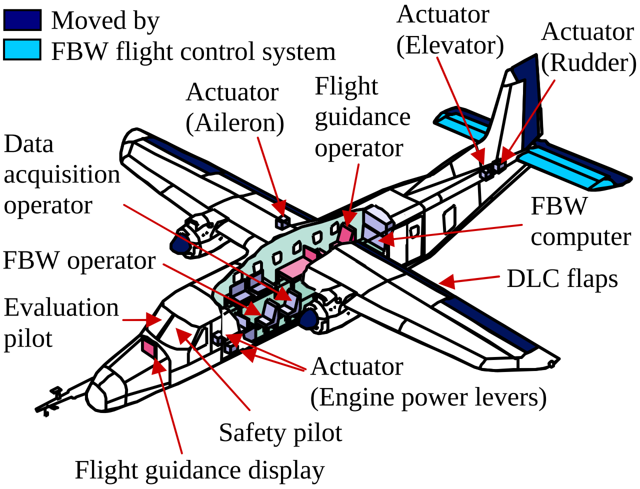


Fig.2. Outline of MuPAL-α

MuPAL-α is operated by two pilots: during an experiment an evaluation pilot flies the aircraft through the FBW flight control system, while a safety pilot monitors the flight and can if necessary manually disengage the FBW system and take over control at any time using the aircraft's original mechanical flight controls. The FBW flight control system also disengages automatically when its operational limits are exceeded. Researchers are thus free to design FBW flight control computer guidance and control programs and flight guidance displays for the evaluation pilot without any impact on the aircraft's airworthiness, and can change the program parameters in flight. Up to three independent programs can be installed. The FBW computer can communicate with other personal computers executing flight trajectory optimization programs, image generation programs for the pilot display and so on. These flexible qualities are useful for conducting experiments efficiently.

Fig. 3 shows a schematic diagram of the experiment system used in this research. For technical subjects to be evaluated by manual control, a flight trajectory optimization program installed in the Guidance PC generated optimal trajectories or control references for the pilot, the Display PC generated the instrument images indicating flight parameters and pilot guidance cues, and the FBW computer generated the commands for the electric actuators to move the control surfaces and power levers based on the

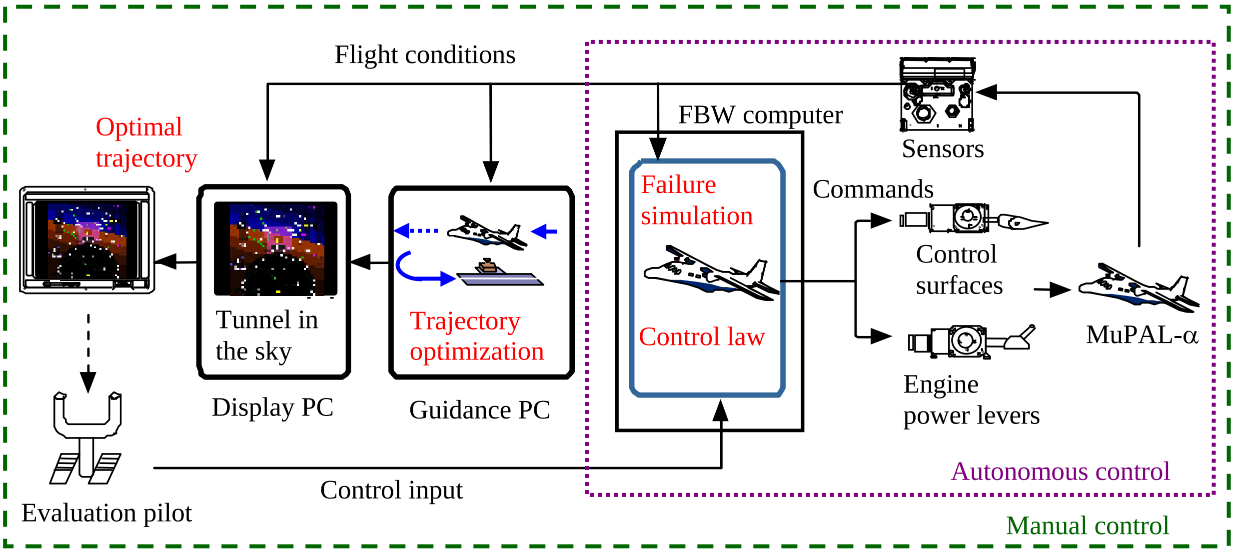


Fig.3. On-Board Experiment System of MuPAL-α

evaluation pilot’s control inputs. The FBW computer also simulated failures such as jammed control surfaces as required. For technical subjects to be evaluated by autonomous control, guidance and control programs installed in the FBW computer generated commands for the electric actuators based on sensor data, and simultaneously simulated failures as necessarily. The evaluation pilot monitored the behavior of the aircraft and control devices.

In addition to MuPAL-α, the FABOT (Fuji Aerial roBOT) developed by FHI (Fig. 4) [5] and an Unmanned Aerial Vehicle (UAV) developed by the University of Tokyo and Mitsubishi Electric Corp. (Fig. 5) [6] were also used for control algorithm evaluation. FABOT was developed by modifying a Super Dimona motor glider of Diamond Aircraft Industries. It is equipped with an experimental FBW control system. The UAV has a take-off weight of 1,985 kg and is driven by an electric motor. It is equipped with a programmable autonomous flight control system and uses hybrid GPS-INS navigation.

## 2.2 Ground Support Systems

In order to execute the MuPAL-α flight experiments more efficiently, preliminary evaluation and validation was carried out using ground support systems.

Fig.4. FABOT (photo by FHI)

Fig.5. UAV (photo by the Univ. of Tokyo)

### *2.2.1 Flight Simulator*

Pilot-in-the-loop simulations were carried out using JAXA’s ‘Flight Simulator Complex for Advanced Technology’ (FSCAT) to verify and refine the guidance display formats, pilot

Fig.6. Flight Simulator

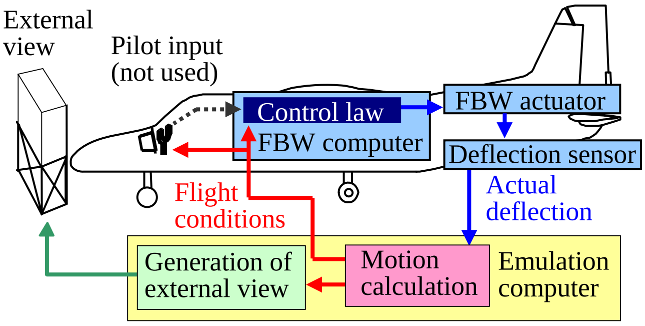


Fig.7. Emulation system

control techniques and experiment procedures prior to manual control flight experiments. A generic fixed-wing aircraft cockpit (Fig. 6) was used with its hydraulic cockpit motion system disabled. The MuPAL-α Guidance PC to be used in the flight experiment was connected to the FSCAT flight dynamics computer and generated the optimal trajectories or control references in real time. These were shown in the simulator cockpit with the same display format as in the flight experiment.

### *2.2.2 Emulation System*

Hardware-in-the-loop simulations were carried out using a MuPAL-α emulator (Fig. 7) prior to autonomous control flight experiments. The guidance and control programs in the FBW computer activate the aircraft's actuators in the same way as in actual flight. An emulation computer receives the control surface and power lever movements, calculates the aircraft's response in real time and transmits it to the FBW computer to close the control loop. The emulation computer also simultaneously generates external view images based on the simulated aircraft motion and presents them on a display in front of the cockpit to help the understanding of flight conditions. The emulation system is useful for the pre-flight evaluation of effects due to the dynamic characteristics of actuators, mechanical play in the control system and so on, which are difficult to model accurately.

## 3 Outline of Flight Experiment

For the MuPAL-α flight experiments, guidance and control programs developed by the project partners (University of Tokyo, MHI, KHI and FHI) [3] were installed into MuPAL-α and the function and performance of each program was evaluated by JAXA on the ground in cooperation with its designer. After confirming the feasibility of the flight experiments, JAXA drew up and carried out a flight experiment plan. A total of 26 flight experiments each of 1–2 hours duration were carried out over the three-year span of Phase 2 of the project from fiscal years 2005 to 2007. All experiments were executed between 3,000 ft (914 m) and 9,000 ft (2,743 m) altitude and were accompanied by the guidance and control program designer.

## 4 Flight Experiment Results

### 4.1 Online Flight Trajectory Optimization

When an emergency landing is required due to some failure, prompt guidance to reach a suitable airport safely will be helpful to the crew,

Fig.8. Tunnel-in-the-Sky Display

whose workload will be high with coping with the situation.

### *4.1.1 Flight Trajectory Optimization for Jammed Elevator*

For an aircraft with an elevator stuck in a fixed position, the University of Tokyo developed an online four-dimensional flight trajectory optimization algorithm. The proposed algorithm divides the flight from the present location to an airport into multiple sections and optimizes the flight path and airspeed in each section sequentially. In each section, it searches for an optimal trajectory to the airport, which minimizes a penalty function, and determines the flight path and airspeed for the subsequent section before the end of the current section is reached. The penalty function reflects the failure situation. Considering the reduced maneuverability caused by an elevator failure, each section is assumed to consist of straight and level flight, level turns and straight descent at constant airspeed.

During the flight experiments, MuPAL-$\alpha$'s FBW flight control system held the elevator at a fixed angle. The evaluation pilot tracked the optimal flight trajectory and target airspeed presented on a tunnel-in-the-sky display (Fig. 8) [7] using the stabilizer and engine thrust control. The stabilizer angle and engine output torque values for each trim condition were presented to the pilot as additional control targets.

Fig. 9 shows a typical flight trajectory in a simulated approach to a “virtual” runway in the air. The origin of the inertial reference frame is located at the touchdown point on the virtual runway with the *x*-axis along the runway centerline. Fig. 9 also shows the time histories of representative variables, including indicated airspeed (*IAS*), horizontal deviation (*CRSerr*),

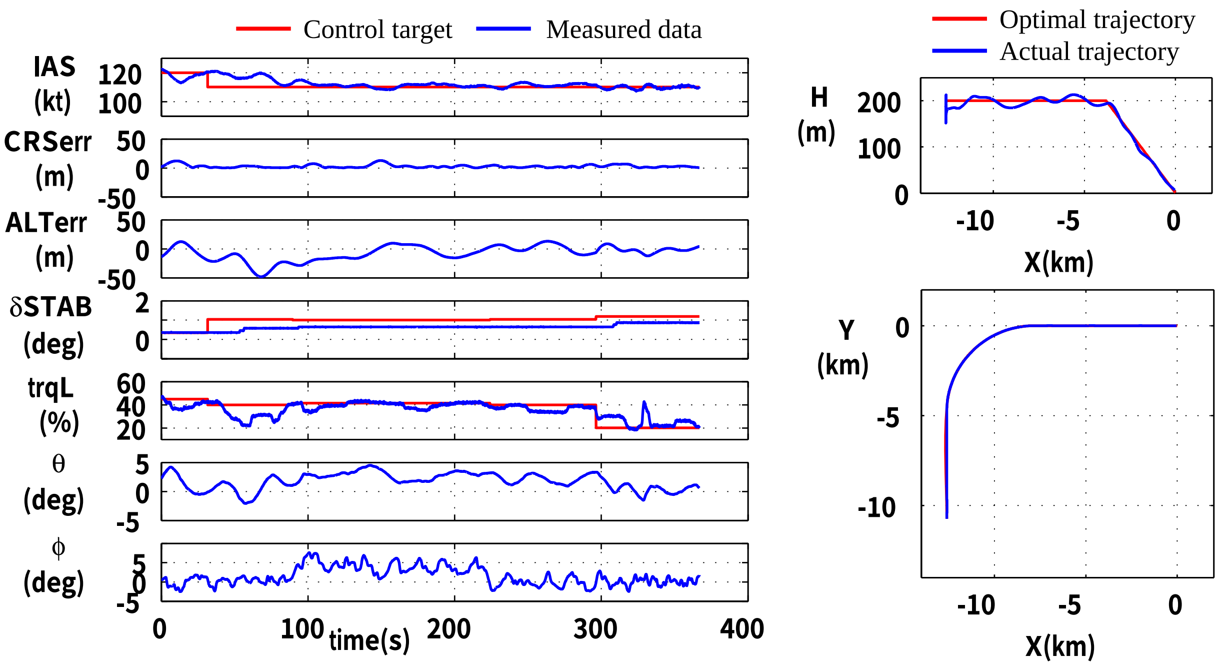
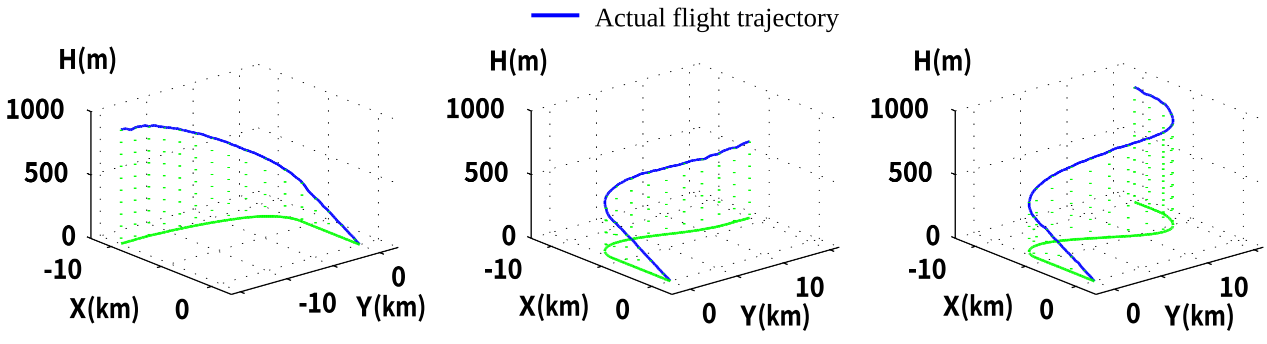


Fig.9. Flight Trajectory Optimization for Jammed Elevator



Case 1 Case 2 Case 3

Fig.10. Flight Trajectory Optimization Considering a Steady Wind

and altitude deviation (*ALTerr*) from the optimal flight path, stabilizer angle (*δSTAB*), output torque of the engine on the left wing (*trqL*), pitch angle (*θ*) and bank angle (*ϕ*). During the flight tests, two different pilots were able to successfully track the optimized flight trajectories by manual control with a jammed elevator. The pilots commented that the workload to fly along the tunnel was acceptable if a small deviation from the target airspeed was allowed and that the workload did not depend on the direction of the steady wind. During final approach, the root mean squares of airspeed deviation were within 1.5m/s (3kt) and those of altitude deviation were within 15m. The flight tests also demonstrated that the stabilizer angle and engine output torque values for each trim condition were effective as additional control targets.

### 4.1.2 Flight Trajectory Optimization Considering a Steady Wind

For aircraft suffering from one or more failures, the University of Tokyo developed a new online four-dimensional flight trajectory optimization algorithm using the direct collocation method and the stage-dividing method which can cope more flexibly with various constraint conditions. It can also estimate the steady wind in real time and consider its effect in order to keep the bank angle and sink rate to track the optimized trajectory within suitable limits.

MuPAL-α demonstrated that the proposed algorithm can generate an optimal trajectory to reach three different virtual runways in the air for two or more wind directions (Fig. 10). The evaluation pilot was able to manually track each trajectory indicated by the tunnel-in-the-sky display. During final approach, the root mean squares of airspeed deviation were within 1m/s (2kt) and those of horizontal deviation and altitude deviation were within 5m. The pilot commented as follows:

- Workload to track the optimal trajectories was not high, although some indications differed from normal procedure, such as acceleration during approach.
- For different directions of steady wind, the bank angle and the sink rate could be kept in the prescribed limits during the flight along the indicated trajectories.

### 4.1.3 Autonomous Tracking of Optimal Flight Trajectory

To enable the aircraft's automatic flight control system to track an optimal flight trajectory, an algorithm using the singular perturbation method and the dynamics inversion method was developed by the University of Tokyo and installed into MuPAL-α's FBW computer.

Fig. 11 shows a typical achieved trajectory and time histories of tracking errors and representative variables, including ground speed (*VG*), sideslip angle (*β*), angle of attack (*α*) and flight path angle (*γ*). Although momentary overshoot of the reference trajectory occurred during some turns, all optimal trajectories were tracked successfully. The sideslip angle during turns was less than 1 degree. During the last 20 seconds of the approach, the horizontal tracking error (*CRSerr*) was within 10m, while ground speed deviation was within 1m/s (2kt). The

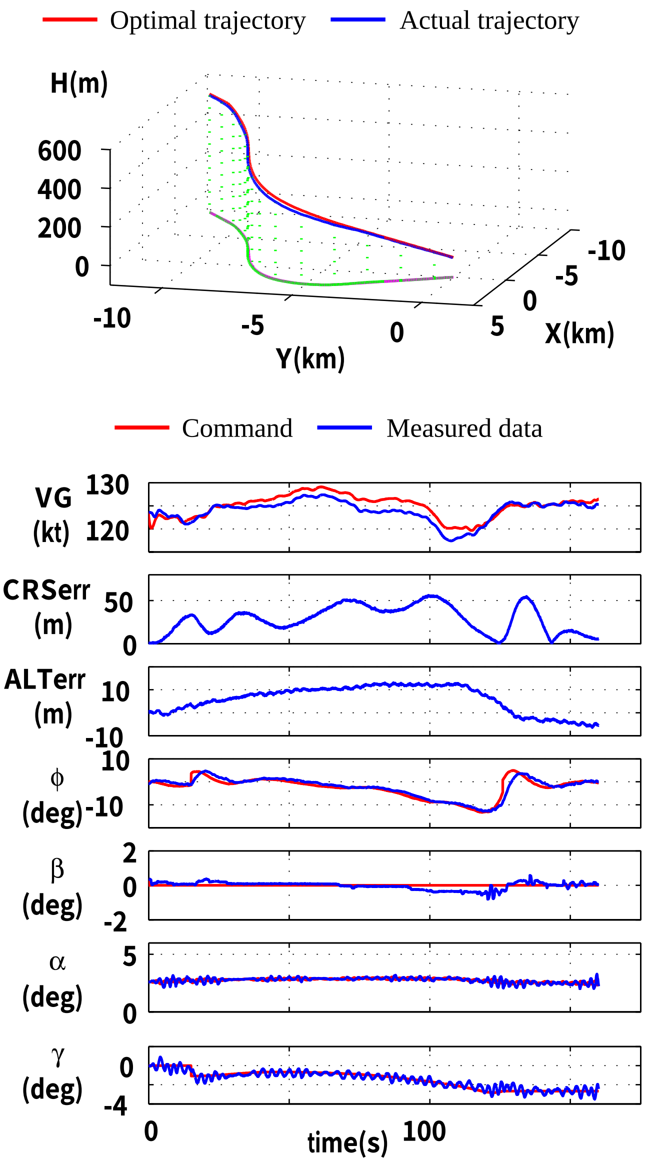
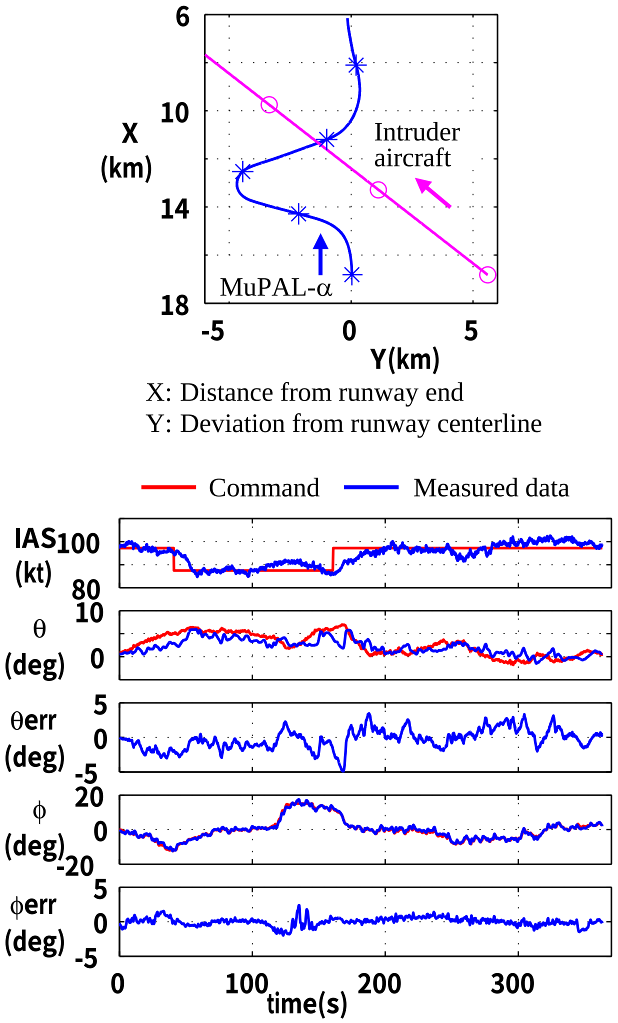


Fig.11. Autonomous Tracking of Optimal Flight Trajectory



X: Distance from runway end
Y: Deviation from runway centerline

Fig.12. Collision Avoidance by Manual Control

altitude error from the reference trajectory (*ALTerr*) was within 10m except for one case. The flight path angle during approach was maintained at the reference value in all cases. Control input stroke and frequency were within appropriate limits. The algorithm could track the optimal trajectory stably under simulated gusts excited by manual pilot inputs. Moreover, robustness against moderate turbulence was demonstrated during the flight experiments.

### 4.2 Intelligent Collision Avoidance System

During an emergency landing, it may be necessary to maneuver horizontally to avoid another aircraft and then return to the original flight path after evasion. KHI developed an algorithm to search for an appropriate trajectory using receding horizon state feedback control and generate corresponding bank angle commands. The algorithm also generated airspeed commands to reduce the time for evasion and pitch commands to maintain altitude.

The proposed algorithm was evaluated by autonomous control and manual control. In the case of manual control, the evaluation pilot tracked the bank and pitch commands indicated on a conventional flight director display. The target speed was displayed near the airspeed indicator tape and the change of target speed was announced verbally by an experimenter.

MuPAL-α demonstrated that the proposed algorithm could avoid an intruder aircraft crossing from various directions while keeping a prescribed minimum separation in both autonomous and manual control cases. Fig. 12 shows a typical flight trajectory and time histories of commands and measured data of indicated airspeed (*IAS*), pitch angle ($\theta$) and bank angle ($\phi$). Fig. 12 also includes the tracking errors for pitch angle ($\theta err$) and bank angle ($\phi err$). The smaller the relative angle between the flight path of the ownship and intruder becomes, the more effective acceleration and deceleration are in reducing the time to regain the original flight path.

## 4.3 Adaptive Control System with Neural Network

If an aircraft's control characteristics are altered due to a failure, it will be difficult for pilots to recognize the new characteristics and adapt their control technique immediately.

In fiscal year 2005, FHI evaluated a non-linear Dynamic Inversion (DI) controller compensated by the Neural Network (NN) proposed by FHI and an adaptive controller using the Feedback-Error-Learning (FEL) method proposed by the University of Tokyo using its FABOT (Fig. 4). Both controllers successfully compensated for reduced control effectiveness or bias error of the elevator and ailerons. The University of Tokyo continued the flight experiments using its UAV (Fig. 5) and showed that the FEL method is also effective in compensating for the effects of wind on bank angle control. In fiscal year 2007, both controllers were installed into MuPAL-α to demonstrate their applicability.

### *4.3.1 Non-Linear DI Controller Compensated by NN*

Halfway through each flight experiment case, MuPAL-α's FBW flight control system simulated a failure of either the elevator, aileron or rudder, such as reducing its effectiveness or biasing its position. The FHI-developed adaptive controller attempted to continue following the prescribed motion by adapting to the failure.

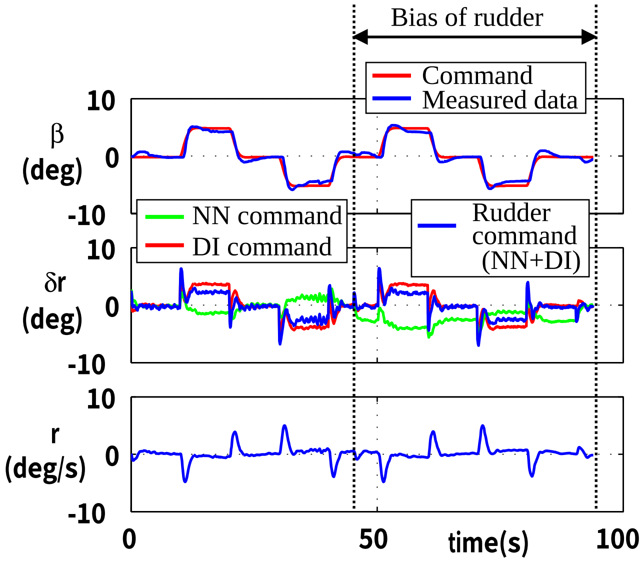
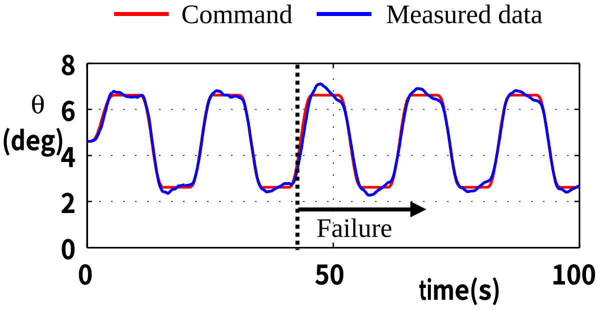
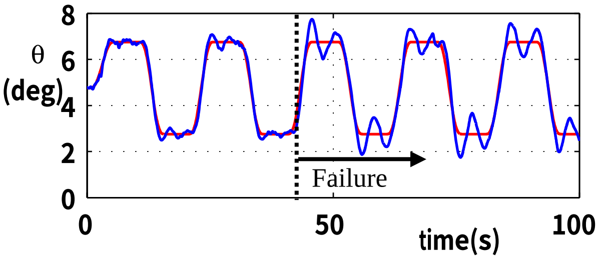


Fig.13. Non-Linear DI Controller Compensated by NN



Adaptive controller using FEL



PID controller

Fig.14. Adaptive Controller using FEL Method

Fig. 13 shows the result of a flight experiment in which the rudder was biased during a periodic change of sideslip angle, including the time histories of sideslip angle ($\beta$), rudder commands ($\delta r$) and yaw rate ($r$). The controller immediately recognized a rudder failure and the NN command compensated its effects. No remarkable change was found in the time history of sideslip angle after the failure occurred. For all other cases, the controller recognized each failure appropriately and continued the prescribed motion by compensating its effects.

### *4.3.2 Adaptive Controller using FEL method*

MuPAL-α's FBW flight control system reduced the elevator's effectiveness 40 seconds after commencing a periodic pitch angle change. The adaptive controller developed by the University of Tokyo attempted to continue to follow the pitch command.

Fig. 14 shows the flight experiment results for the adaptive controller using the FEL method and a typical PID controller. The adaptive controller learned the change of control characteristics and was able to continue pitch angle control to follow the prescribed motion even if the elevator effectiveness was reduced to 40% of normal. An overshoot that occurred just after the failure was quickly suppressed. On the other hand, the PID controller leads to a large overshoot and a continuous oscillation.

## 4.4 Flight Control by Engine Thrust

In some accidents where a total hydraulic failure has disabled all control surfaces, pilots have attempted to control the aircraft using engine thrust. However, a safe landing in such situations is extremely difficult even for pilots who have been trained in appropriate control techniques.

MHI developed a PCA (Propulsion Controlled Aircraft) control law to control pitching and yawing moments using only engine thrust assuming all aerodynamic control surfaces inoperative. The law was designed using a PID technique. In a simulated landing on a virtual runway in the air, the PCA control law guided MuPAL-α to make a turn to align with the runway and then to start descent at the point where the flight path angle became -2 degrees. Flare control was applied just before touchdown.

The wind direction was varied, and two or more virtual landings were carried out for each wind direction. In all cases MuPAL-α was able to approach the runway almost along the prescribed path and to flare successfully. Fig. 15 shows a sample flight experiment result. Differential thrust (*ΔTq*) was used for lateral and directional control such as level turns. The amount and frequency of thrust control were within acceptable limits. The proposed PCA control law was able to maintain the aircraft's attitude and flight path stably not only during turbulence encountered during the flight experiments, but also against disturbances excited by pilot manual inputs.

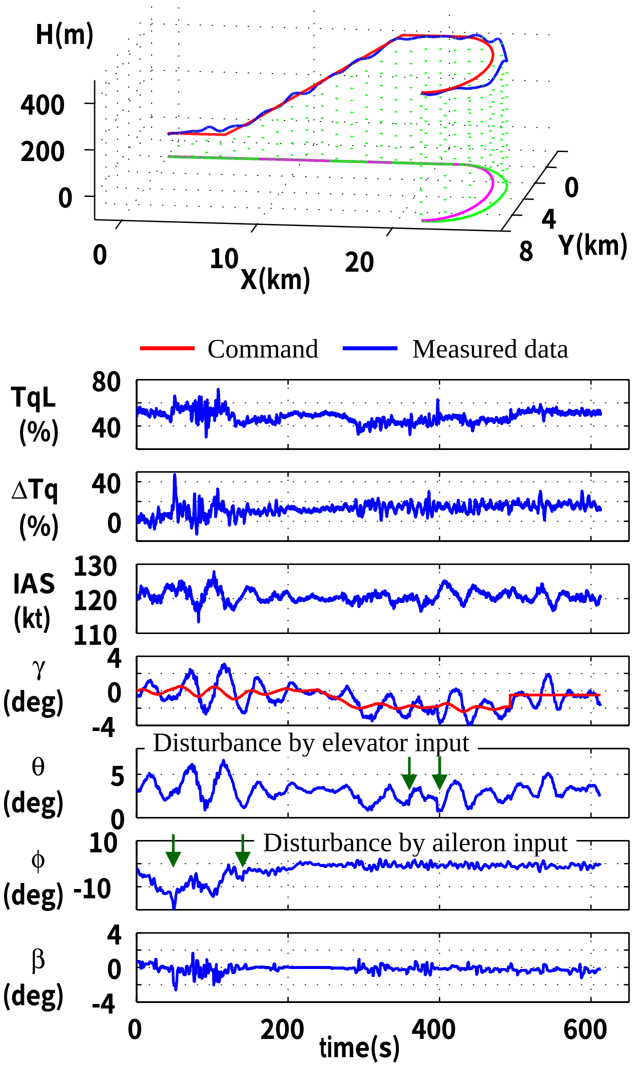


Fig.15. Flight Control by Engine Thrust

## 5 Conclusions

Through a series of flight experiments using the MuPAL-α flying laboratory, the applicability of several technical elements of fault tolerant flight control system were demonstrated in a real flight environment. Further improvements of the performance and reliability of each technical element and their demonstration through flight experiments will be continued aiming for a further reduction in the fatal accident rate.

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