AUTONOMOUS FLIGHT CONTROL AND GUIDANCE SYSTEM OF ACCIDENT AIRCRAFT

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Abstract

The purpose of this paper is to present a research program for autonomous control flight system of an aircraft in accidents or in trouble. The system will be expected to reduce the total loss number of accident aircrafts. Research subjects to be developed are automatic fault detection and identification, restructure algorithm of control system, and automatic guidance for the accident aircraft. System evaluations in computer simulation and flight test using an in-flight simulator are conducted. Three research groups from university, industry and national research laboratory are working together to integrate those technologies. This paper describes the outline of this research program, and the detail of the newly developed online flight path optimization method.

1 Introduction

The safety of airliners is highly guaranteed throughout design, manufacturing, and operation processes. As aviation continues to grow, there is a concern that unless steps are taken to drastically reduce accident rates, increased flights will lead to more accidents. The National Civil Aviation Review Commission endorsed a goal to cut the fatal accident ratio by 80 percent by 2007[1].

While there are many reasons of fatal accidents of aircrafts, this paper considers the loss of control due to the failures of control surfaces. The failures include lock in place, hard over, and loss of effectiveness of control surfaces. These cases deteriorate the handling quality and increase the pilot workload, and then may lead to fatal crash. Autonomous flight control systems have been widely investigated to increase aircraft safety in civil and military aircrafts[2,3,4,5]. The autonomous flight control systems have the capability to detect and identify failures, to reconstruct control law, and to guide the damaged aircraft for safety flight or landing. The Society of Japanese Aerospace Companies has been promoting the research on autonomous flight control systems in corporation with industrial, academic and national research groups. The main feature of this research program is to demonstrate the total system capability including autonomous flight control and guidance systems for civil aircrafts throughout various simulation studies and flight tasting.

This paper will outline the research program and focus on the online optimal flight trajectory design method and its computer simulations. The flight testing of the proposing method has been carried out from 2003 to 2004 by using in-flight simulator MuPAL-α and its results will be presented in another paper in this conference.

2 System Concept

Present advanced aircrafts usually equip automatic flight control system that can greatly reduce pilot's workload and makes a significant contribution to air transportation safety. However, the automatic control system fundamentally assumes that every system is normal and has no trouble. Consequently, when aircrafts have some troubles or accidents, pilots have to manage to control their aircraft immediately. In order to control damaged or accident aircraft, firstly, pilots have to recognize or estimate damaged parts. If control systems such as engines or control surfaces have some troubles, pilots have to stabilize the aircraft by themselves. In some cases, this maneuver is very difficult since it is difficult to pinpoint damaged parts or the dynamic characteristics are greatly changed. Furthermore, if pilots have not experienced the troubles, the maneuver may be very difficult for them. Secondly, pilots have to guide the damaged aircraft to safety zones. If damaged aircrafts should be operated to lower altitude, or be landed to a nearest airport, pilots have to determine an adequate flight course in a short time.

This research was intended to develop a new system that can cope with the above problem autonomously or can assist pilots by providing necessary information. Figure 1 indicates the proposing system concept that is divided into the following items to be developed.

2.1 Fault Detection and Identification System(FDIS):

By comparing the normal states computed in the original system model with the real output data of an accident aircraft, the location and status are identified to minimize the difference between model output and flight data.

2.2 Restructurable Flight Control System(RFCS):

The flight control law is restructured by using the information of damaged parts that are estimated in FDIS. The purpose of RFCS is to stabilize an accident aircraft by increasing the robustness of the original control law and restructuring the distribution law of control power.

2.3 Online Flight Trajectory Optimization System(OFTOS):

Flight trajectories for emergency are computed by considering the system accidents estimated in FDIS. Real Time Algorithms are applied to optimize the flight path by onboard computers.

3 System Description

Mathematical background of three systems

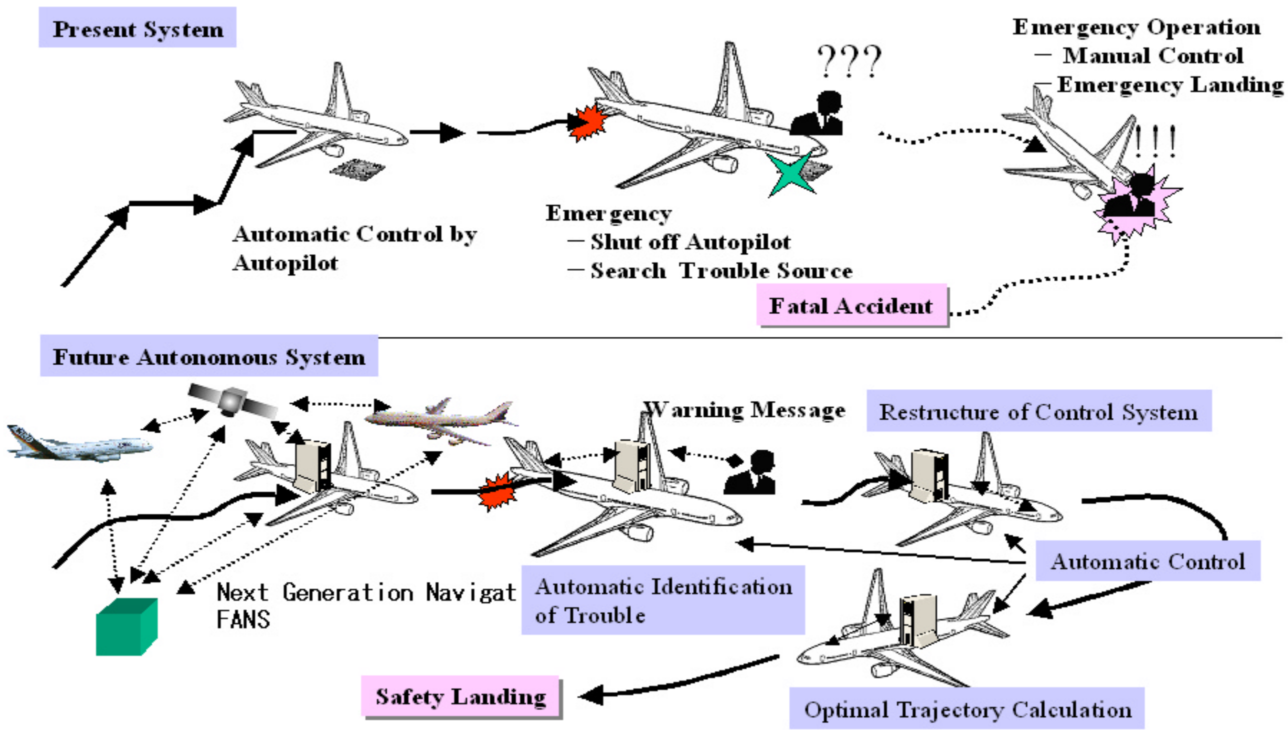

Fig. 1. Future Autonomous Flight Control System

FDIS(Fault Detection and Identification System), RFCS(Resutructured Flight Control System), and OFTOS(Online Flight Trajectory Optimization System) will be explained briefly.

3.1 FDIS(Fault Detection and Identification System)

FDIS is formulated as a system identification problem. The fundamental idea is to minimize the error between the real flight data measured from a set of sensors and the computed flight data from a mathematical flight model with system parameters to be estimated (as shown in Fig.2)[6]. While there is a wide range of faults or accidents, this study considers the damage of control surfaces. Therefore, the stability derivatives of each control surface must be identified by an online processing. The following three methods are developed for this purpose.

- MSLS(Modified Sequential Least Mean Square Method)

A Sequential Least Mean Square Method is widely applied for linear system identification problems. Three linear momentum equations are considered for this problem. All stability derivatives including those of control surfaces and constant disturbances are estimated by using sensor output data, e.g., the time derivatives of pitch rate, roll rate and yaw rate signals. The mean square error is minimized sequentially with consideration of the constraints for each stability derivative.

- NN(Neural Network)

The mean square error used in MSLS can be minimized by using the Backward Propagation method that is utilized in Neural Networks(NN). Although the linear model is used in this study, the NN has a potential for nonlinear estimation problems.

- EKF(Extended Kalman Filter)

For nonlinear estimation problems, the Extended Kalman Filter is widely applied. This method linerlizes nonlinear dynamic equations and applies the Kalman Filter to obtain the system parameters that consist of control stability derivatives and disturbances. The Kalman Filter is designed to minimize the estimation error by considering the system noise and sensor noise.

It is widely known that the adequate artificial inputs are necessary to obtain accurate estimations for any kind of estimation methods. It is noted that all of control surfaces are adequately moved during the Identification Process.

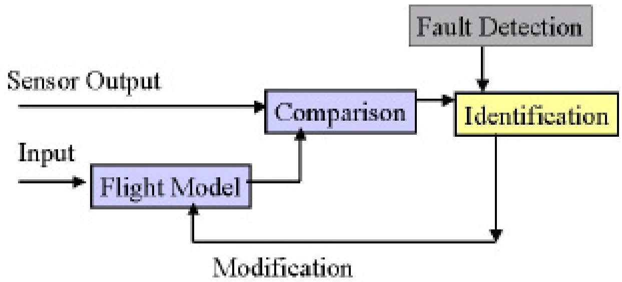

Fig. 2. FDIS(Fault Detection and Identification System)

3.2 Restructurable Flight Control System(RFCS):

The Flight Control System must be modified to compensate the deteriorated handling quality for damaged aircrafts. While a wide range of methods is proposed for this purpose, the robust control design[7] and the control mixing method are used in this research since the damage of control surface is considered[8].

RFCS is depicted in Fig.3 where FDIS sends information to the controller to restructure the control law. RFCS generates pseudo commands those are distributed to the deflection angle of each control surface. RFCS is divided into the longitudinal and lateral controllers as shown in Fig. 4. The pseudo inverse matrix is used to divide the pseudo commands into actual deflection angle of control surface. The information of estimated stability derivatives of each surface is utilized to construct the pseudo inverse matrix.

3.3 Online Flight Trajectory Optimization System(OFTOS)

The guidance and the navigation of damaged aircrafts increase the pilot workload unusually. Consequently, the automatic generation of flight paths for the emergency flight is strongly recommended.

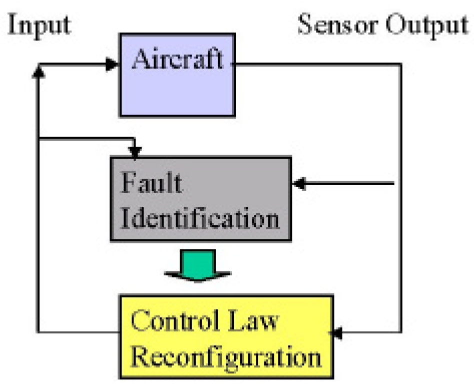

Fig. 3. Restructurable Flight Control System(RFCS):

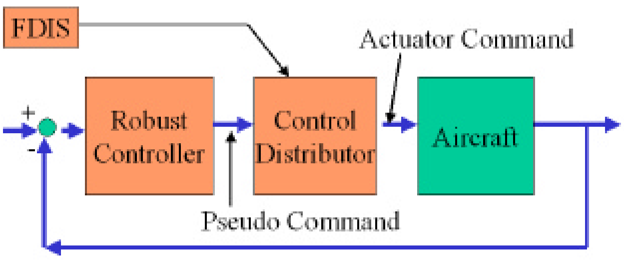

Fig. 4. Robust Controller and Control Distributor

The determination of flight trajectories satisfying several constraints is mathematically formulated by the optimal control theory that minimizes or maximizes a certain objective function with constraints. The optimal control theory is defined by the calculus of variations and some numerical computational methods have been developed[9]. Since these methods are time consuming and are not suitable for on-line computation, a new method is required for the on-line trajectory optimization.

Several on-line methods based on heuristic search such as A* algorithm have been developed for path search problems[10]. Since these methods assume simple path search, they are not suitable for emergency flight that may require unusual flight patterns. This paper proposes the new method that combines the RTA* algorithm and the R-TABU search method[11]. The RTA* algorithm sequentially applies A* algorithm for on-line path search and the R-TABU search method is a kind of random search that controls search regions to improve computational efficiency.

The new algorithm sequentially generates the new way point as shown in Fig 5 where the way point n and the flight path to the point n were determined in the previous step. The next way point n_i and the flight path from the way point n to the point n_i are computed before an airplane arrives at the way point n_i. The new way point and the new flight path are determined to minimize the following objective function;

$$J = g(n, n_i) + h'(n_i) \qquad (1)$$

where $g(n,n_i)$ is an objective function calculated along the flight path from the way point n to n_i, and $h'(n_i)$ is a heuristic function that estimates an objective function from the way point n_i to the terminal point by using simple or heuristic methods. It should be noted that a set of constrains such as terminal conditions, and path constraints is included into objective functions by using a penalty function method.

The R-TABU method is applied to minimize the objective function in Eq. (1). The outline of this method is illustrated in Fig. 6. This method uses sampling points selected at random around the initial solutions, and then the search range is shrunk gradually. The best solutions selected in this process are used for the next search. The parameters to be optimized are the coordinates at the way point n_i and coefficients that determine the flight path from the way point n to the point n_i. It is noted that the flight path is represented as a set of trigonometric functions. For example, the x coordinate is written as:

$$x(t) = A_0 + \sum_{n=1}^{N} (A_n \cos w\,t + B_n \sin w\,t) \qquad (2)$$

where the fundamental angular frequency is defined as $w = p/(t_{n_i} - t_n)$.

Since the flight path is represented as functions of time, the angle of attack, the bank angle, the load factor, and the thrust can be calculated by differentiating the flight path functions with considering a point mass model of an airplane. The upper and lower limits of these values must be specified along the flight path to obtain the optimal flight trajectory.

The way point is extended sequentially according the above process. When an airplane nears the terminal point within the distance R_{ref}, the final flight path to the terminal point is computed. In that case, the terminal conditions such as the coordinates, the velocity vector are specified.

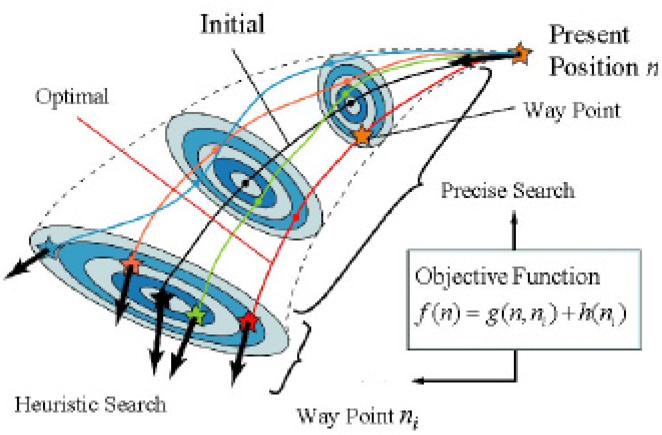

Fig. 5. RTA* combined R-TAB method

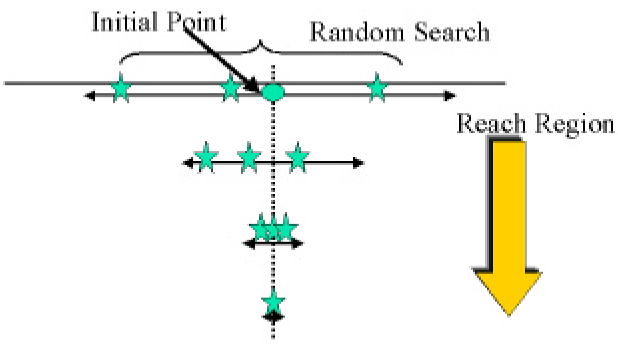

Fig. 6. R-TABU Search method

Fig. 7. Multipurpose Experimental Airplane, MuPAL-α [12]

3 Numerical Simulation of Online Flight Trajectory Optimization System(OFTOS)

The flight test using the experimental aircraft MuPAL-α [12] is conducted in this research program. Since the flight test results are reported in another paper[13], the numerical simulations carried out for the preparation of the flight test are summarized in this paper.

MuPAL-α (Fig. 7) is based on Do-228 and has various capability and equipments for experiments. The initial and the terminal conditions are specified as shown in Table 1, when the emergency landing is considered.

Table 1 Initial and Terminal conditions

	Initial	Terminal
Coordinate (x,y,z)(m)	(10000, -15000,1000)	(0,0,100)
Velocity (m/s)	61.7	61.7
Path angle (deg)	0	-1
Direction angle (deg)	170	90

Table 2 Constraints

	Minimum	Maximum
Velocity (m/s)	46.3	77.2
Angle of attack (deg)	-5	15
Bank angle (deg)	-20	20
Load factor	0.5	1.5
Thrust (N)	-560~1040	10800~14800
Height (m)	0	-

Table 2 shows the constraints specified in the trajectory optimization. It is noted that the maximum and minimum thrust values are assumed to be the linear functions of the flight velocity. The objective function to be minimized is the flight time from the initial to the terminal, since the emergency landing is considered in this simulation.

Table 3 summarizes the parameters used in the optimization computation. Two different types of constraints and their optimized flight path are considered so as to check our method. Case 1 is a normal case and Case 2 is an emergency case that has different constrains, i.e., the deep left bank is limited. Two cases are compared in Table 4.

Figure 8 illustrates the initial and terminal points and calculated flight paths. The normal aircraft (Case 1) firstly turn right and then turn left in order to minimize the flight time (337.3 sec). On the other hand, the emergency aircraft avoids a deep left turn, which leads a longer flight time (374.9 sec). Figure 9 that compares the flight velocity shows both aircraft try to maintain the maximum velocity to minimize the flight time, and reduce the velocity in the final stage in order to achieve the terminal velocity. Figures 10 and 11 illustrate the thrust and the angle of attack time histories. It is shown that the maximum thrust is not necessary since the paths are descent flights and the velocities reach the maximum values. However, the frequent thrust control is necessary in the final stage to accommodate the terminal conditions. Figure 11 shows the bank angle histories for two cases. It is confirmed that the strong constraint in the left bank angle is satisfied in the Case2.

Table 3 Parameters in Optimization

No. of samplings in one sub region	10
Shrink ratio of search sub region	3
Maximum no. of sampling in one search	100
Order of trigonometric function	5
Search time in RTA* (s)	40
Terminal search range in RTA*(m)	9000

Table 4 Two Cases

	Case1	Case2
Status	Normal	Accident
Min left bank (deg)	-20	-7
Max right bank (def)	20	20
Flight time (s)	337.3	374.9

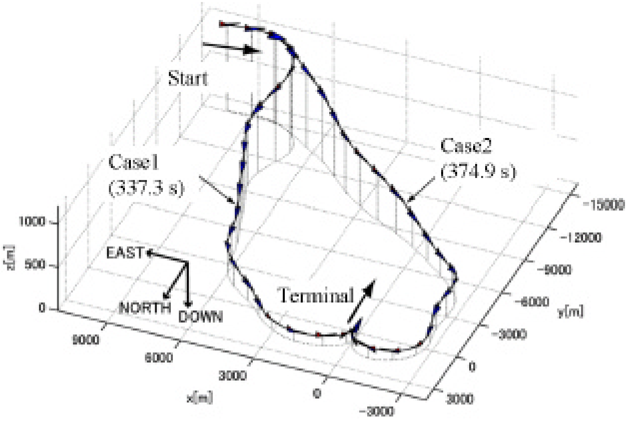

Fig. 8. Optimized Flight Paths (Case1: normal, Case 2: damaged aircraft)

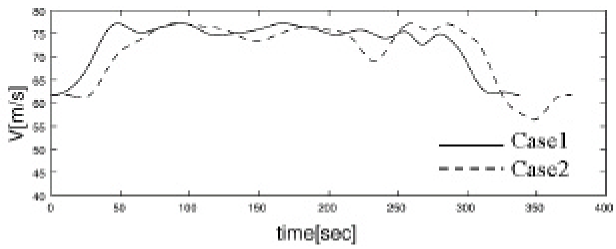

Fig. 9. Flight velocity (Case1:normal, Case2:Accident)

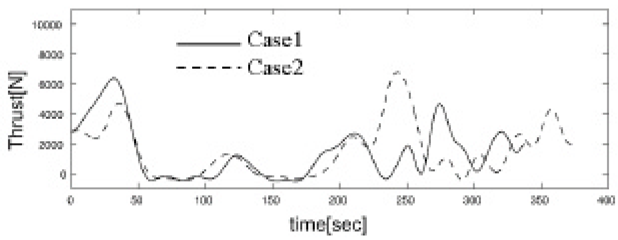

Fig. 10. Thrust (Case1:normal, Case2:Accident)

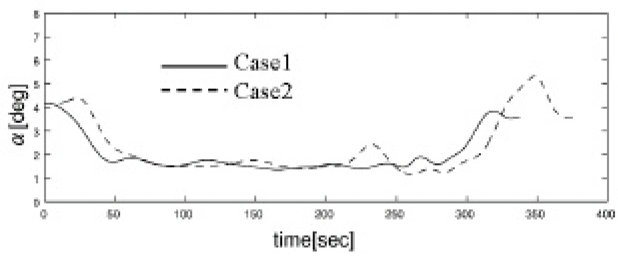

Fig. 11. Angle of Attack (Case1:normal, Case2:Accident)

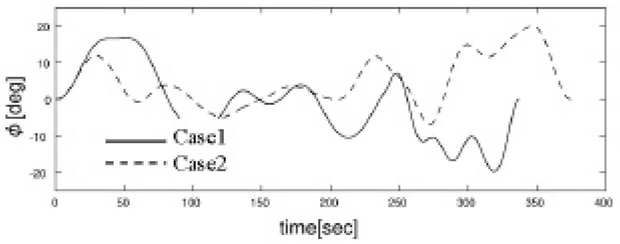

Fig. 12. Bank Angle (Case1:normal, Case2:Accident)

4 Conclusion

The research on the autonomous flight control and guidance systems of accident aircrafts have been conducted in Japan by the cooperative groups from industrial, academic, and governmental research institutes. The total system is basically divided into three subsystems, i.e., (1) Fault Detection and Identification System (FDIS), (2) Restructurable Flight Control System (RFCS), and (3) Online Flight Trajectory Optimization System (OFTOS). Wide range of simulation studies and the flight test using the experimental research airplane have been carried out. The present paper focuses on the simulation study on OFTOS (Online Flight Trajectory Optimization System), since FDIS and RFCS have been widely reported and the flight test will be presented in another paper[13].

On-line trajectory optimization techniques were applied to determine the emergency flight path with the consideration of aircraft accidents or failures. Since the unsteady flight dynamics should be considered in the emergency flight, the optimization problem should be solved in a strict manner by using onboard computers. The new method combining the RTA* algorithms with the R-TABU search makes it possible to provide the optimal flight path during the flight. The effectiveness of the presented method was confirmed from the simulation study. The flight test using an experimental airplane was conducted in our research, and the availability of the system was also confirmed, which will be presented in another paper[13]. The flight test of the total system including FDIS, RFCS, and OFTOS will be planned to develop the advanced autonomous flight control and guidance system.

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

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