FAULT IMMUNE FLIGHT CONTROL SYSTEM FOR CIVIL TRANSPORTS

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Abstract

The reconfiguration control for the aircraft, which is faced at the critical failure, is very important, and the many papers concerned the problem so far. The author presents the effects of the dual layers control for the situation. The reflection type of reconfiguration control is required for the case of the failure at near to a ground or with significant impacts in attitude or altitude change of the aircraft. This is done at the basic control layer with a simple feedback control law and with the flexible actuation system, under which the aircraft can keep the controls in many possibilities. The conventional type of the reconfiguration control with the intelligent control at the top layer is to be added to the above to complete the control, covering any kind of the failure situations and to generate the optimum flight path in the following flight. The concept comes from the fact that the reflex action in human body is very effective and useful to keep us safe in any case and is controlled by the autonomic nervous system, being aside from the brain control.

The author introduces the concept of the fault immune flight control system, which has no accidents level in reality at the operations with the ultra highly reliable systems concerned. The system necessitates the autonomous control for the missions to restrain from getting the human errors, and the autonomous reconfiguration control to keep the system in safe. The general discussion for the system leads to the proposal for the reliability design regulation to make more stringent to 10^{-12} per flight hour for a critical failure, and for the one-man pilot operation system for the transport.

1 Introduction

It is said that the statistics for the aircraft accidents worldwide have been slightly improving these days. However, the figure for the accidents per flight hour have stayed at about 10^{-7} per flight hour for worldwide, and at about 10^{-8} level for developed area for over 15 years at the same level, which means that the actual accidents have been increasing in number, reflecting the tremendous growth of the revenue miles per year for the aircraft transporting of these days. And the accident analyses result in the facts that almost 70% of the cases in the critical accidents are caused from human errors. [1)] We have to pay much more efforts in many areas and to find the ways to reduce the aircraft accidents for keeping it in safe much more.

This kind of saying became a sort of worn-out phrase recently. However, this is still our working big target. The author presents the general discussion on the matter especially from the point of the flight control, presenting the concept of fault immune flight control system, and develops the autonomous reconfiguration concept to keep the aircraft in the operation mode in safe through the dual layers control in the flight control system, introducing the autonomous control for other general flight phases, like in a traffic avoidance and in a landing approach, etc.

The safety operation of the aircraft requires the total system safety, where whole of the relevant systems are included, such as the aircraft system itself, the aircraft operating systems by the pilot, or the airlines, or the ground air traffic control system, and the aircraft maintenance system, and other relating systems concerned. The paper discusses mainly from the point of the flight control, including to the pilot, and the ATC (Air Traffic Control) interfaces.

The author is introducing the word of the Fault Immune Flight Control System in this paper. The ultra safety aircraft could be realized to structure the ultra high reliable systems, with which the aircraft would endure or be tolerant to a critical failure of the system by keeping the operational safety in any conditions, including operating human errors. The basic concept for the system is to give an alternative for the failure of any kind in full time. When it comes to the hardware system, including the computer system, the complete redundant structure for the system is to be the solution.

The control of the system plays a major role to make it active in full time for keeping aircraft in safe. Especially, the autonomous control would be important for the control in subconscious level to achieve the ultimate operational safety, in the region of, say the reconfiguration control, and the effective mission control, including to the see and avoid, even with the human faults.

If we could extend the concept to the man-machine interface area, where the smooth and errors-free interfaces are realized through the human instinctive interfaces, applying the intuitively recognizable displays or the intuitive operation pilot inputs method, we would be able to build a totally immune system to a critical failure or fault to the system.

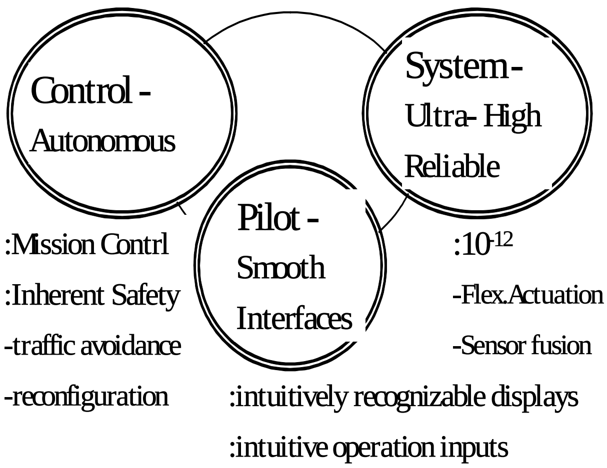

Fig. 1 General Concept for Fault Immune Flight Control System -1

The concept is shown in the figure 1 for general, and figure 2 for structure.

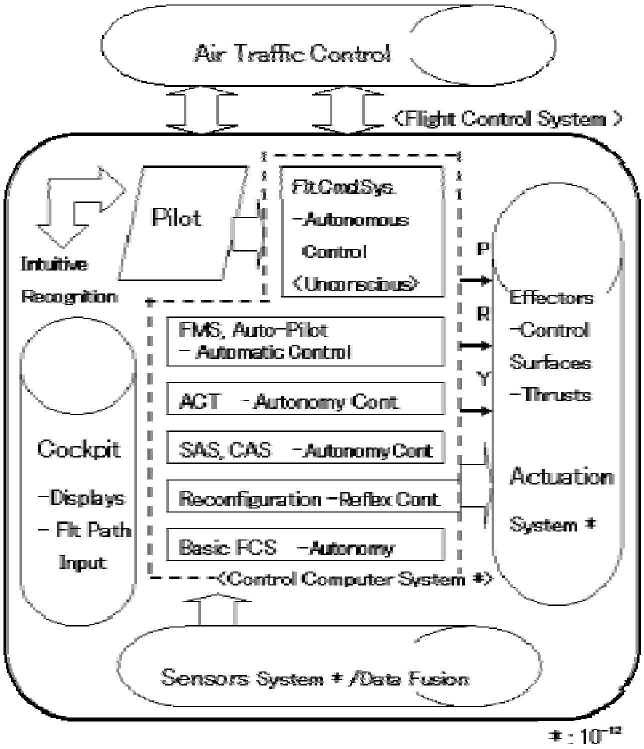

Fig. 2 Structure Concept for the System

The system immune to a critical failure should be prepared by the antibodies to the pathogenic, and by the reflex motions through the autonomic nervous against the dangers, and furthermore by the brain to be wise enough for the safe operation with the wider sensing nerves.

2 Autonomous Reconfiguration Control

The autonomous control has several facets in the mission control under the communication with the ATC Controllers, such as for the case of the see & avoid, or of the landing approach, and in the safety control, such as for the reconfiguration control.

2.1 Basic Layer Control for the Reflex Type of Reconfiguration

The basic concept is shown in the figure 3.

2.1.1 Reflex Action to an Impact of a Failure

For a big change in the aircraft attitude or altitude by a failure, or a failure happened near

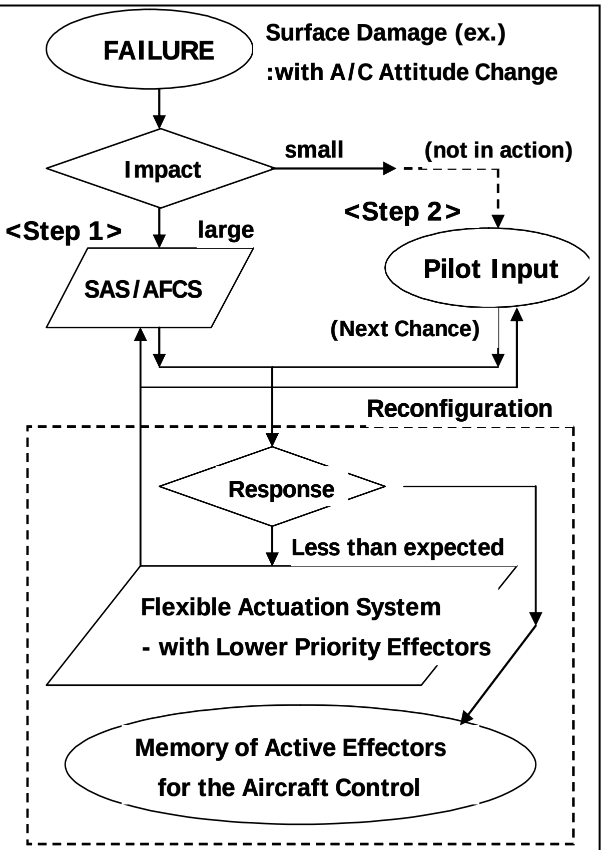

Fig. 3 Autonomous Reconfiguration Control in Basic Layer

to the ground, the control law must react immediately to correct the hazardous effects to keep the aircraft in safe state. All of the possible counter-reactions would be expected to generate the movement in a direct control route at the basic control layer only for keeping the aircraft in safe, just like the reflex actions in our human body. All of the possible effectors for the corrective actions are considered to be applicable, irrespective to the conventional concept for the effectors defined like the way of the elevators for the pitch, the ailerons for the roll, and the rudders for the yaw. For example, a differential elevator can contribute to control the attitude of the aircraft in the roll, and simultaneous ailerons are accepted for the pitch control. The flexible control surfaces in the current morphing aircraft, and the independent simplex actuation for effectors could have many ways and candidates to support the idea.

Once the aircraft get the failure impacts to change the attitude, all of the possible effectors are activated to correct the impact within the limit of their remaining capability. The successfully applied effectors or actuators are memorized, and applied thereafter with the priority, which is defined to each of the actuator.

The control theory to subdue the mal-effects to the aircraft is simply due to the feedback control of SAS, and the attitude hold in AFCS in the above case, aiming to reduce the reactions by the disturbances.

This is shown in the figure 3 as Step 1. Although SAS or AFCS in the conventional control layer are applied for the corrective actions as the logic circuitry, the flexible actuation system is applied for a driver as a basic control layer movement.

2.1.2 Action to a Small Impact of a Failure

There must also be a failure, which does not give a significant impact to the aircraft at the occurrence of the failure. In this case, the corrective actions are not necessarily required at the moment, the consequent pilot inputs to the column or pedals are to be reacted in line with the pilot intention, even with the failure condition for the control surfaces, for example.

This is shown at the figure 3 as the step 2. The pilot intention to control the aircraft is shown through the column or the pedal movement. If a pilot wants to control the aircraft in pitch direction, he would move the column in forward or backward and activate the effectors in the pitch control group, irrespective of the conventional definition for the effectors, in which they might be sometimes the simultaneous ailerons or a stabilator.

After the aircraft got the impacted failure mentioned in sec.2.1.1, the memorized active actuators corresponding to the proper control group would be applied correctly respond to the pilot column inputs. When it comes to the case in this section, firstly assigned effectors or actuators are activated being in line with the column inputs in a conventional ways, and secondly or thirdly prioritized other actuators defined for the control group are summoned to move the aircraft with the pilot intention for the case there is no or not enough response to the aircraft gotten by the first actions, observing the sensors information of the aircraft reaction.

Again the differential elevators, for another example, would be applied by the lateral movement of the column to the right or to the left.

If the actuation system would be categorized in the control group by the function for each surface or actuators, according to the way of the independent use or the simultaneous use, the alternatives for the correct actions would be easily found and picked up properly to achieve the role.

The author calls this concept of the actuation system as the flexible actuation, and shows in the figure 4.

2.2 Top Layer Control for the Intelligent Type of Reconfiguration

The aircraft requires another reconfiguration control by the upper layer of the flight control. Because there are many cases, in which do not require quick corrective actions, and the optimum flight path after the failure is necessary to be fixed in line with the aircraft situation.

The author asserts that the most powerful reconfiguration control of this sort for the aircraft in the case of critical failures is to reset and redesign the original control laws through the reallocation of the active effectors, after the failure detection and identification through a direct sensing method, such as by an intelligent material with fibers inside. The optimum control methodology by LQG-LTR, for example, would be appropriate for the control law, which is not necessarily by some intelligent way of control for the corrective motion for the reconfiguration. And the expected actions for the aircraft as a next step could be generated through another ordinal optimized control theories, including to some of the intelligent ways for the control logic. [2)]

However, we can find many papers [3)] [4)] to counter the situation in many ways, especially with some intelligent theories to fix the reconfiguration laws and set the consequent optimum flight path to lead the aircraft in safe way.

Although either concept of those would be accepted, the important thing is to put the sort of control in the uppermost layer for the flight control other than the basic layer control mentioned above for the reflex reconfiguration. Both of the basic layer control for the case of quick actions required and the upper layer control for the case of more wise action required are necessitated for the optimal reconfiguration control for the aircraft flight control at the same time. Because the expected reaction time and controlled results are different from situation to situation.

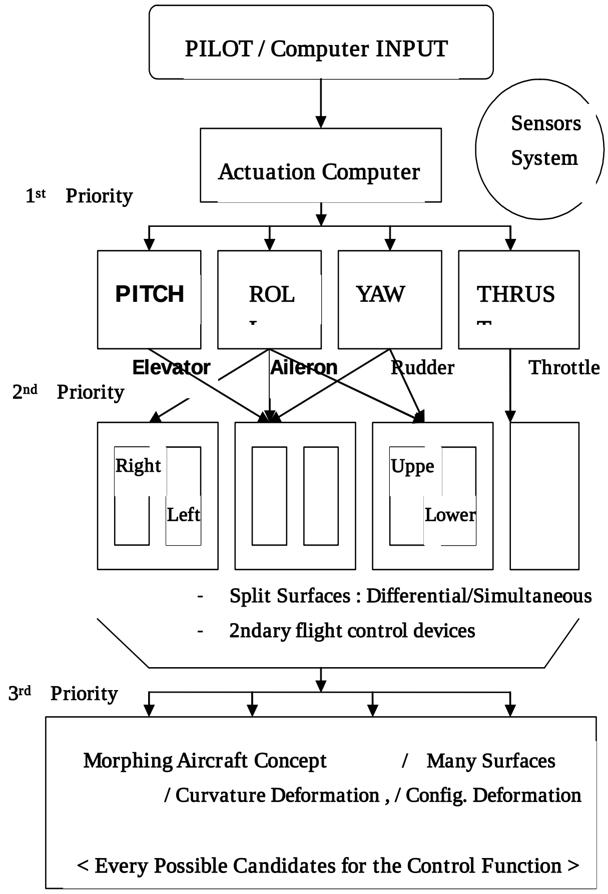

Fig. 4 Flexible Actuation System

3. Flexible Flight Control Actuation System

The concept is shown in the figure 4 for the next generation of the Flight Control Actuation System. This is also the actuation system, necessary for the reconfiguration control in the dual layers above mentioned.

3.1 General Concept for the Actuation System

The control surfaces or effectors should have the alternatives for the configuration to cope with the critical failure, which impacts with the aerodynamic effects to the aircraft and is hard to be detected, such as the case of a blow-off of a surface. The current studies require the split control surfaces, or the thrust control for the maneuver as alternatives, with the adequate artificial intelligent control laws. However, only one or two alternatives are not enough to conform with much more reliable system, and the application of the engine thrust for the aircraft maneuver is possible, but has a very difficult aspect for the control due to the large time lag for the response.

The way to increase the redundancies in the current aircraft configuration is to give the independent actuation for each of effectors. For example, the differential elevator can contribute to the roll control, as well as the simultaneous usage of both surfaces can contribute to the pitch control as in a conventional method. The simultaneous applications of the ailerons at the same time could be a control tool for the pitch attitude of the aircraft. Furthermore, the thrust is powerful candidate for the control the aircraft in the pitch or the roll as alternatives, as well as the secondary flight control devices would also be effective in case.

Moreover, the morphing concept for the future aircraft gives us the potential for the alternatives in much more variety of ways, by the flexible surfaces with many simplex actuators or by the deforming structures.

3.2 Actuation Computer System

The segmented or the separated control surfaces more than conventional configuration for the aircraft might be designed to meet with the system reliability requirements.

The each of the effectors is grouped to the control category in the 3 axes, with the high priority for conventional usage and low for the specific usage. One of effectors could belong to several groups of the control, according to the capabilities of the effectors. The capability is functioned by the actuation control computer. For example, the both elevator are actuated for the pitch control, and the differential elevator is applied for the roll control. The pitch input by the column or the flight control computer activates the effectors in the pitch control group according to the priority. The priority level would be defined by the way for high for the case the only conventional effectors are applied in normal condition, and for gradually low for the case the unusual application level increased.

The secondary flight control devises, and the engine thrust are positioned in 2nd or 3rd priority effectors. And the aircraft response sensed by the common motion sensors is applied for the feedback control to the actuation computer.

4. Example Simulation

4.1 Capability Check for Reflex Control

The author carried out some example calculations for the basic layer reconfiguration control to check the capabilities for the concept.

The applied model is a large type of the civil transport. The flight condition is M=0.8, H=30,000ft in cruise.

The figure 5 explains the stabilator capability in the pitch control for recovering the altitude in case of the altitude loss due to a failure at the elevators. And the figure 6 shows the rudder capability in the roll control for the step input. Those figure only show that the alternative effectors could be effective in case of the failure of the ordinary surfaces. Although this one example explains a small portion of the facts, it could tell the enough capability of the alternatives as a tool for the failure cases.

The calculation demo was carried out by MATLAB, with the block diagram shown in the figure 7, where the simple rate feedback in SAS control or the reference value hold in AFCS control is applied.

4.2 Sequence Test for the Concept by Flight Simulator

The column or pedal controls which are applied with the unconventional effectors or surfaces in

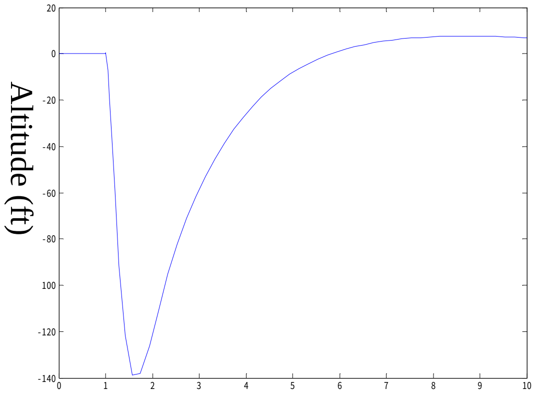

Fig. 5 Altitude Recovery by Stabilator

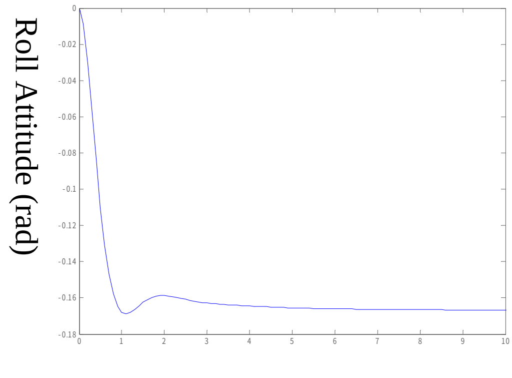

Fig. 6 Differential Elevator Capability

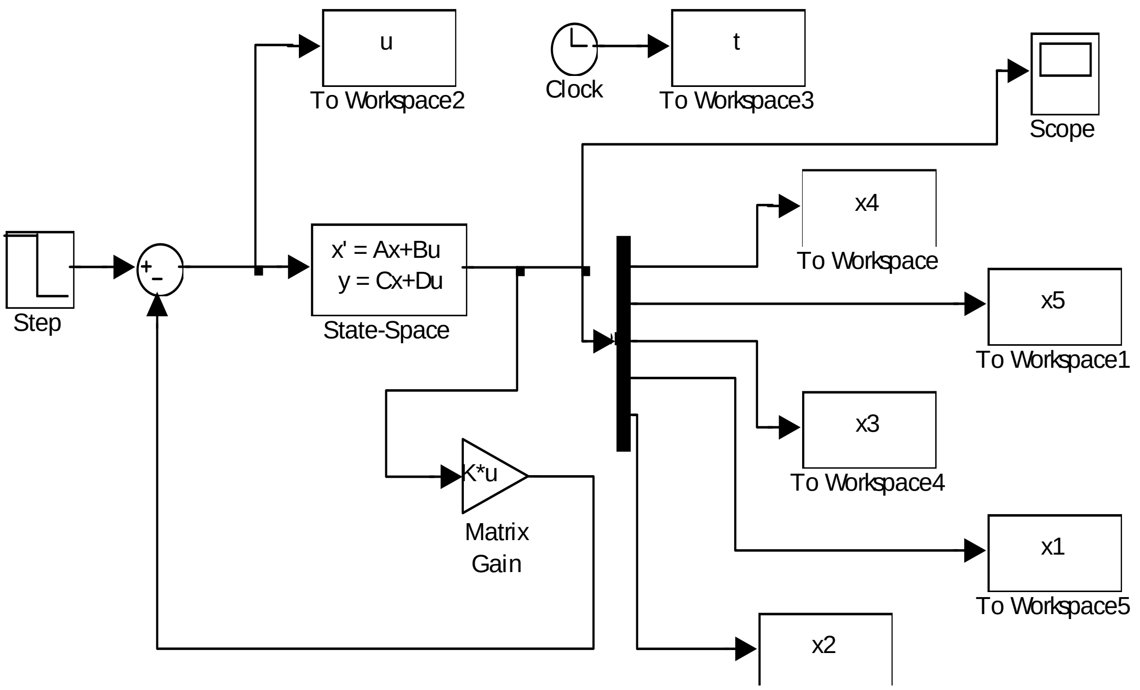

Fig. 7 MATLAB Block Diagram

the low priority in the flexible actuation system are checked by the fixed base flight simulator at the Nishinippon Institute of Technology (cf. Figure 8).

The test is carried out the way the control effectors are switched to the alternatives, during a normal flight by the normal usage of the conventional control surface.

According to the pilot comments for the tests, the lateral movements of the control column by the differential elevators are smooth enough to control the roll of the aircraft. The jerk of the column for the movement of the

Fig. 8 NIT Flight Simulator

stabilator was felt with a bit sluggish for a smooth maneuvering. And the pitch control by the thrust is possible, when it has a pitch up moment for increasing the thrust.

Although there might be a bit of problem, the step 2 in the figure 4 is recognized controllable by the alternatives through a column input by a pilot.

5 General Discussions on the Faults Immune Flight Control System

5.1 General

The general concept for the system is shown in the figure 1 and figure 2. The more detailed concept for the core system is shown in the figure 9. The fault immune flight control system is consisted of the highly reliable hardware

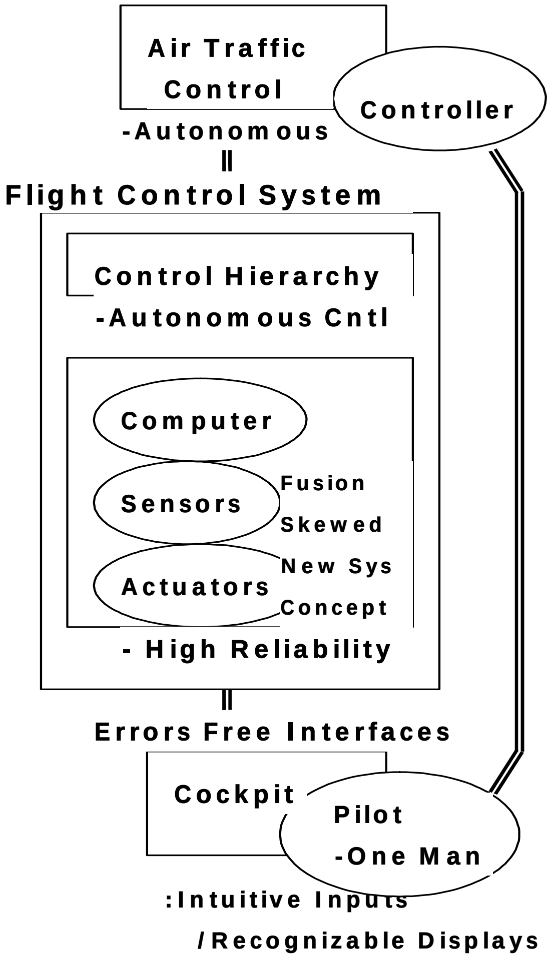

Fig. 9 Structure for Fault Immune FCS

systems for the wider definition, the control laws hierarchy for the full time flight control for the system safety and the autonomous operation, with the new flexible concept of the actuation system, and the smooth pilot interfaces to eliminate the human errors in the control.

The hardware system for the flight control system of the aircraft is structured by the sensors system, the computers system, the actuators system, the data bus system, and so forth. The paper includes the cockpit system with the pilot, and the relating aircraft traffic control system with the controllers as well, to the system. The flight control system in this wider definition should be designed under the same concept for the ultra high reliable system to conform really high reliable system to cope with the critical condition, including to a human interfaces problems.

The key words are autonomous, and safety for the control, high reliability for the hardware system, and error free for the pilot interfaces.

5.2 Control System

5.2.1 Flight Control Hierarchy

The flight control is structured in the form of a hierarchy, like in the figure 10, where the system controls in many ways with many layers, from the basic movement of the system operation, to the augmented controls or the active controls, to improve the original characteristics of the system, and to the automated control of AFCS (Automatic Flight Control System) and FMS (Flight Management System), and to the autonomous control for the mission or the safety flight with the intelligent.

The author asserts that the flight command system positions over the flight management system, and presides over the autonomous control for the aircraft, coordinating with the traffic control controllers.

The safety control in the basic layer behaves like the inherent characteristics to the aircraft. The reconfiguration control in this layer is positioned in the basic layer, which is the lowest, while the actual control circuitry for SAS, or AFCS is applied, with the application

Autonomous	Flight Command System
	: Mission Control
	: Air Traffic Communicatn/Action
	: Flt Safety / Reconfiguratn

<Conventional Control Hierarchy>

Automation*	Flt Managemt System AFCS
Improvement (for the system characteristics)	SAS /CAS / Active Control Tech.
Sys.Operation*	Basic FCS

Safety	Reflex Control
	:Reconfiguration with Flex. Actuation
(as inherent function)	

* : Conscious Control Level

Fig. 10 Flight Control Hierarchy

of the flexible actuation system at the basic layer in this case.

5.2.2 Autonomous Control

The autonomous control is a key factor to cope with the human errors. The most effective and necessary measures to take for the fault immune flight control is to apply the autonomous control in the end to cope with the human errors which occupy nearly 70% of the causes for the critical aircraft accidents.

The autonomous control covers the normal flight mission control, and the flight safety control, as well. Those are carried out under the communication with the ATC (Air Traffic Control).

The pilot plays a role for a supervisor, when the autonomous laws are taking place for the aircraft control. Whenever a pilot is required to take over the control, he must react promptly and correctly. It is very difficult and necessary to keep the pilot in his alertness, which leads to the discussions of the interfaces.

The autonomous control should be carried out in several ways. One is under the unconscious level, such as the reconfiguration control. The other is for the mission controls under the conscious level, such as the system condition judgment through the communication with the other relating system like the ATC.

5.2.3 Autonomous Avoidance Control

The author presented the autonomous traffic avoidance sequence, applying a fuzzy expert logic at the former meeting.[5)] The example showed the autonomous capabilities for the flight plan change in the case of the aircraft on the collision course, communicating with the ground controller. The recent many papers developed some intelligent ways for the see and avoid capability.[6)]

The most important factor the author introduced was that the communication between the pilot and the ground controller could be treated in sequence type of control, if the communication patterns are coded well and the ATC is improved to accept the digital coordination. Although the sequence control requires the complete preset for the sequence chart, the fuzzy control could make up for the deficiency. [5)]

5.2.4 Autonomous Landing Approach

The recent FMS has been developing to take the control of the aircraft in almost all of the flight, except take-off, and landing phase. As for the landing approach, there seems to be a problem FMS could not carry out the flight, other than the airport facility problem.

The main reason the pilot cannot rely on the automatic landing might come from the facts that the phase requires a very much precise and meticulous control with the care of other traffic and a direction from a ground controller as well.

The author showed the fuzzy expert logic could control the target aircraft to take the middle position between the former and later aircraft on the approach course during the approach phase, after getting the approach sequence from the controller, which is the common practice for a pilot control at the approach.[7)]

Through these discussions, it is obvious that the autonomous control throughout the flight mission would be possible.

5.2.5 Pilot and Autonomous Control

The autonomous control is carried out in an unconscious level. However, if the pilot on board could admit the situation, the pilot could accept the results and the process by the autonomous control, and could override the control correctly.

We recognize that the most of our human behaviors are controlled unconsciously and the conscious brain control admits the situation as a controller of oneself. This is because we are very much limited to keep our attentions in time or in area, and we could admit the unconscious behaviors as natural one.

The author asserts that the pilot and the autonomous control can coexist, from the discussion above.[8)]

5.2.6 Autonomous Air Traffic Control System

The above discussion requires that the ATC system can communicate with the autonomously controlled aircraft system. This means that the ATC system itself should be digitally communicative and autonomously controlled. The ATC System has also the resembled problems with the aircraft that the human factors should be avoided in the control as much as possible.

The ATC is to go to the autonomous control with the supervising actions by the controllers.

5.3 Hardware System

The hardware system for the flight control is composed from the sensors, computers, actuators, etc. The current design regulation for the system reliability is 10^{-9} per flight hour for a critical failure due to FAR Part 25.

Although we are still confronting the reliability problems to realize the figure in the regulation, it is the right time to promote the requirement to much more stringent level. That is 10^{-12}.

5.3.1 Sensors System

The current reliability level by the statistics for the sensor hardware is about 10^{-4} per flight hour. The triple redundancies would be a plenty enough configuration to attain the 10^{-13} level of the sensor system reliability, if the system would be structured with the analytical redundancies by sharing the outputs of the sensors group, as a result of the sensor fusion, and with the minimum parts number alignment technology, applying the skewed arrangement in sensor space.

5.3.2 Computers System

Again, the current technology level for the area in the reliabilities is 10^{-4} per flight hour. The complete triplex, including the software, is the most advanced computer system for the moment. The triplex computer system seems to be a limit to retain the complication.

However, the critical portion of the computer is so limited that the reliable back up could be easily structured to get the 10^{-13} level as a computer system.

5.3.3 Flexible Actuators System

The flexible actuation system above mentioned has a tremendously high level of operation reliability as a system.

The level of 10^{-13} would be easily within our reach.

5.4 Pilot Interface

As long as a pilot controls the aircraft, the human errors are inevitably derived from the aircraft operation circumstances. The point to confront the problem is to minimize or eliminate the chances for the errors as a system by applying an autonomous control way, as well as to minimize the effects by the error itself, or the chances of the errors through smoothing the human interfaces.

The intuitively recognizable displays and intuitively smooth control inputs are required to give proper situation awareness and correct counter-actions to a pilot, in any time and in any conditions, because only the instinctive behavior could be fit in well to the autonomous control circumstances in the unconscious level.

As the examples for the intuitively recognizable displays, the 3 dimensional displays for the aircraft position over the mapping, or the cross section of height and range with the mapping information, just like the display for the EGPWS (Enhanced Ground Proximity Warning System), and other devices are considered.

As for the examples of the intuitively smooth control inputs method, the flight path controls instead of the rate control for the column inputs are considered.

The author confirmed that the deflection control of the stick for the pitch control and the bank angle control, and of the pedals for the yaw control were very useful for the flight situation with the large time lag in the system operation under a condition of big cross-wind at the flight tests of the QF-104J.

5.5 One Man Pilot

Although the fault immune flight control system is realized with the autonomous control, the control is not matured enough to get rid of the human pilot. Even the system is leveled up to be an alternative to a pilot, the system would require a pilot as a final authority to be accepted in the society.

However, the reliability for the system reaches to the level of as high as 10^{-12} per flight hour, the system could be treated as one of the redundancies for the controlling pilot. In the other world, the unmanned freighter, which has no pilot on board, would be realized in near future. For this sense, the one-man pilot should be possible for the airline operation, with the combination of the highly reliable autonomous machine and the pilot.

According to the opinions of the airline, we have to consider the situation of no man condition at the loss of the one man through the illness, or a crime. When the unmanned air freighter system would be realized and operated, the one man pilot system for the transport would have the counter measures for that kind of the problems, and would be also accepted from our society, in near future.

6 Proposal for Change of Design Regulation

If the design regulation for the transport could be changed to require the 10^{-12} for a critical failure, the aircraft safety would be enhanced to the level for the actual world of almost no failure in real time scale. The figure is to be attainable level now, like the discussions above.

7 Conclusions

The reconfiguration control of the aircraft is very important for the safety operation of the aircraft at the critical failures. The most effective ways for the control is to have a dual layer control for the flight control hierarchy. There should be the controls, which are required in a very quick manner in the responses, or which are required for safe reactions and to fix the following flight path. The reflex type of reconfiguration at the basic control layer is necessary for that former purpose, and capable enough to keep the aircraft safe.

The author presented the general discussion on the fault immune flight control system, which is composed from the ultra-highly reliable system, the autonomous control system, and smooth interface system with a pilot to get free from a critical failure at the aircraft operations. And the design regulation change for the transport type of the aircraft is proposed as the 10^{-12} per flight hour for a critical failure, and one-man pilot system for the transport operation is also proposed as a next step and realizable target in near future.

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