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Session H. Methods of Navigation and Ground Navigation Equipment

Intelligent Control System Against Aircraft's Structural Damage in the Flight

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***Abstract*—In this paper, intelligent flight control system for recovering controllability of the aircraft when an unexpected problem (such as faults or failures to the actuators/sensors or structural damage) occurs during a flight is proposed.**

***Keywords*—aircraft; faults or failures to the actuators/sensors or structural damage; reconfiguration; flight control system; loss of control in flight; survivability**

I. INTRODUCTION

In the past ten years, 59% of the fatal airliner aircraft accidents were caused by loss-of-control in flight and another 33% by controlled flight into terrain [1]. The accident reports published by NTSB (National Transportation Safety Board) have revealed that most in-flight loss-of-control accidents were triggered by faults including subsystem/component failures, external hazards, and human errors [2]. With hindsight, it is easy to say that most of these accidents could have been prevented if the maintenance were performed better to avoid component failures, or if the aircraft had not entered the hazardous region, or if the flight crews had not made mistakes, but it is impossible to eliminate all the faults that may threaten flight safety.

II. PROBLEM STATEMENT

Malfunction or jam of aircraft control surfaces like elevators, rudders, ailerons can be very dangerous since these faults not only result in the reduction of control authority, but they also impose persistent disturbances on the aircraft. The jammed control surface position can be anywhere in the operational range and is not known a priori. If the jam position is not too far away from the trim condition, the remaining control authority may be enough to be utilized to maintain a safe flight. However, if the jam occurs near an extreme position, the available control authority may not be able to offset the effect of the persistent disturbance caused by the jam. The first fault the Flight 261 crew members encountered was a horizontal stabilizer jam at 0.4°, which was near the trim condition. This fault was not severe and the pilots were able to keep the aircraft aloft at 31,050 feet preparing for an emergency landing. But about twenty minutes later, the horizontal stabilizer was moved by an excessive force with huge noise from 0.4° to a new jam position, 2.5° airplane nose down, and the airplane began to pitch nose down, starting a dive. Things got worse after that – pilots lost control of the pitch axis, and the aircraft crashed into the ocean 11 minutes and 37 seconds later [3]. Flight 232 DC–10 in Sioux City, Iowa 1989 (which suffered a tail engine failure that caused the total loss of hydraulics) [5, 6], the Kalita Air freighter in Detroit, Michigan, October 2004 (where engine No: 1 was shed but the crew managed to land safely without any casualties) and the DHL A300B4, Baghdad, November 2003 (which was hit by a missile on its left wing and lost all hydraulics, but still landed safely using only the engines) [5], represent some examples of successful landings using clever manipulation of the remaining functional redundant control surfaces (Fig. 1).

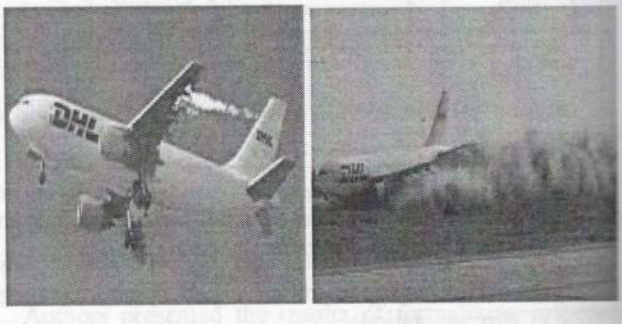

Fig. 1. Emergency landing sequence using engines only and left wing structural damage due to surface-to-air missile impact, DHL A300B4-203F, Baghdad, 2003.

Here it can be seen that one of the main factors that enabled safe landing after faults/failures is the clever manipulation of the redundant control surfaces to achieve the desired level of acceptable degraded performance. In the event of an emergency due to faults/failures, pilots will use all the available resources to help in a safe landing. The 1989 Sioux City DC-10 incident is an example of the crew performing their own reconfiguration using asymmetric thrust from the two remaining engines to maintain limited control in the presence of total hydraulic system failure. The crash of a Boeing 747 freighter aircraft (Flight 1862) in 1992 near Amsterdam (the Netherlands), following the separation of the two right-wing engines, was potentially survivable given adequate knowledge about the remaining aerodynamic capabilities of the damaged aircraft [4]. Adaptive or reconfigurable flight control strategies might have prevented the loss of two Boeing 737s due to a rudder actuator hardover and of a Boeing 767 due to inadvertent asymmetric thrust reverser deployment.

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III. REVIEW

In the literature, most of the motivation and research work in fault tolerant control involves solving problems encountered in safety critical systems such as aircraft. To design active fault tolerant control systems (AFTCS), one of the important issues to consider is whether to recover controllability of aircraft under adverse flight conditions. AFTCS is a complex combination of three major research fields, fault detection and isolation (FDI), robust control, and reconfigurable control [7]. Patton [8] also discussed the relationship between these fields of research. For a typical AFTCS scheme, when a fault/failure occurs either in an actuator or sensor, the FDI scheme will detect and locate the source of the fault. The reconfigurable controller will try to adapt to the fault, therefore providing controllability and stability. Both the FDI and reconfigurable controller need to be robust against uncertainty and disturbance [7]. Reference [9] is given a good bibliographical review of reconfigurable fault tolerant control systems. The paper also proposes a classification of reconfiguration methods which is based on a few categories (the mathematical tools used, the design approach used, the way of achieving reconfiguration, reconfiguration mechanisms, control structures etc.). It also provides a bibliographical classification based on the design approaches and the different applications, discussing open problems and current research topics in AFTCS.

Development of methods and models of reconfiguration of controlling influences aboard the airplane in the conditions of origin special situations in flight operation [10] is devoted. For reconfiguration of controlling influences in case of failures of drives and governing bodies two approaches [10] are used: parametric and structural. Parametric change of feedback factors of the executive mechanisms taking into account a technical status of the airplane, for improving of efficiency of their functioning. Structural – control redistribution between operational governing bodies for recovery of acceptable characteristics of controllability and stability in the conditions of unexpected situations in flight. Patton [8], classify FTC into two major groups: passive fault tolerant control systems (PFTCS) and active fault tolerant control systems (AFTCS). In passive fault tolerant control systems, the controller is designed to be robust against faults and uncertainty. Therefore when a faults occurs, the controller should be able to maintain stability of the system with an acceptable degradation in performance. PFTCS does not require FDI and does not require controller reconfiguration or adaptation.

IV. PROBLEM SOLUTION

At first let us clarify the terminological distinction between a fault and a failure [7], [11] – [13]:

- fault is an undesired change in a system parameter that degrades performance: a fault may not represent a component failure;
- failure is a catastrophic or complete breakdown of a component or function (to be contrasted with a fault which may be a tolerable malfunction.

A reconfigured flight control system is required to perform failure detection, identification, and accommodation following a battle damage and/or failure to a critical control su[illegible] implement a failure accommodation strategy, a variety of control surfaces (speed brakes, wing flaps, differential dihedral canards, spoilers, etc.) and thrust mechanisms (differential thrust, thrust vectoring) can be used. This means, most control surfaces will have triple redundancy. In terms of the control surface itself, there exist secondary control surfaces that can be used in an emergency or in an unconventional way to achieve the same effect as the primary control surface. In large passenger transport aircraft for example, the spoilers which are typically deployed to reduce speed, can also be used differentially to create roll which normally is achieved by using ailerons; also engines can be used differentially to create yaw, which is typically achieved by using the rudder; and finally the horizontal stabilizer (Figs 2 and 3) which is normally used to set the angle of attack, can also replace elevators for pitch movement [7].

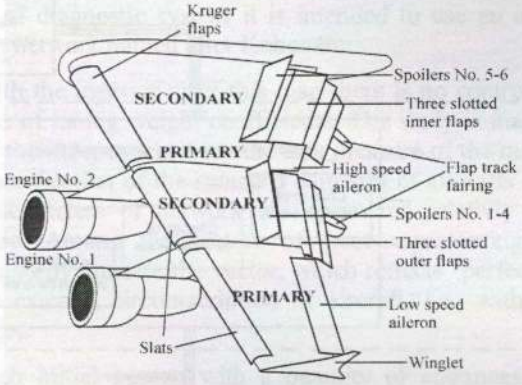

Fig. 2. Large transport aircraft: typical control surfaces.

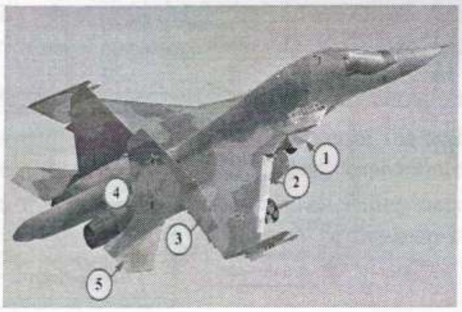

Fig. 3. SU-34 flight control surfaces scheme: *1* are two consoles canards; *2* are two sections rotary wing socks; 3 are two sections flaperons; 4 are two sections rudder; 5 are two consoles horizontal tail.

The proposed intelligent control system (ICS) is shown in Fig. 4. It consists of the parametric and structural reconfiguration, block of choice the program flight and block of classification of the special situations (BCSS). In the conditions of considerable uncertainty arising from the sudden failures or faults elements of automatic control system, damages the external contour of the aircraft, changes in the external environment, decision of choosing the tactics and strategies of extension the flight is possible with crew or probabilistic models. However, in both cases, traditional approaches are characteristic unacceptably high decision-making time, which may lead to undesirable shift the current flight situation to emergency of flight, and in some cases even a catastrophic situation. Based on the above, scientific task is to restore the aircraft controllability and stability in the unexpected flight conditions based on the reconfiguration methods and intelligent technologies.

The failures/faults elements of automatic control system, assessment of the dangerousness of the refusals and operational decision-making by the method of further flight control are very essential tasks. The basis of reconfiguration is the fixed possibility of organization of structural and functional surplus of elements of the system, that is used as organs of control: wing flaps, interceptors, spoilers, engines etc, giving additional, not peculiar for the regular mode mission-controls of function to them, that allows to redistribute managing influences after the new algorithm of management.

Introduction of configuration manager to the system of automatic control fundamentally distinguishes it from the existent systems. A configuration manager consists of two modules – module of objective, structural, self-reactance and having a special purpose reconfiguration, and also module of exposure, authentication and classification of typical refuses/of damages. In case of origin of refuse/damage the module of exposure and authentication classifies a damage and forms a command on including of the module of reconfiguration, except that, he passes in the module reconfigurations of managing actions all information about the classified refuse/of damage (this is forms the model of refuse/of damage). The module of objective, structural, self-reactance and having a special purpose reconfiguration forms new managing influences for beating back, and at impossibility of the complete beating back, maximally possible decline of consequences of refuse/of damage.

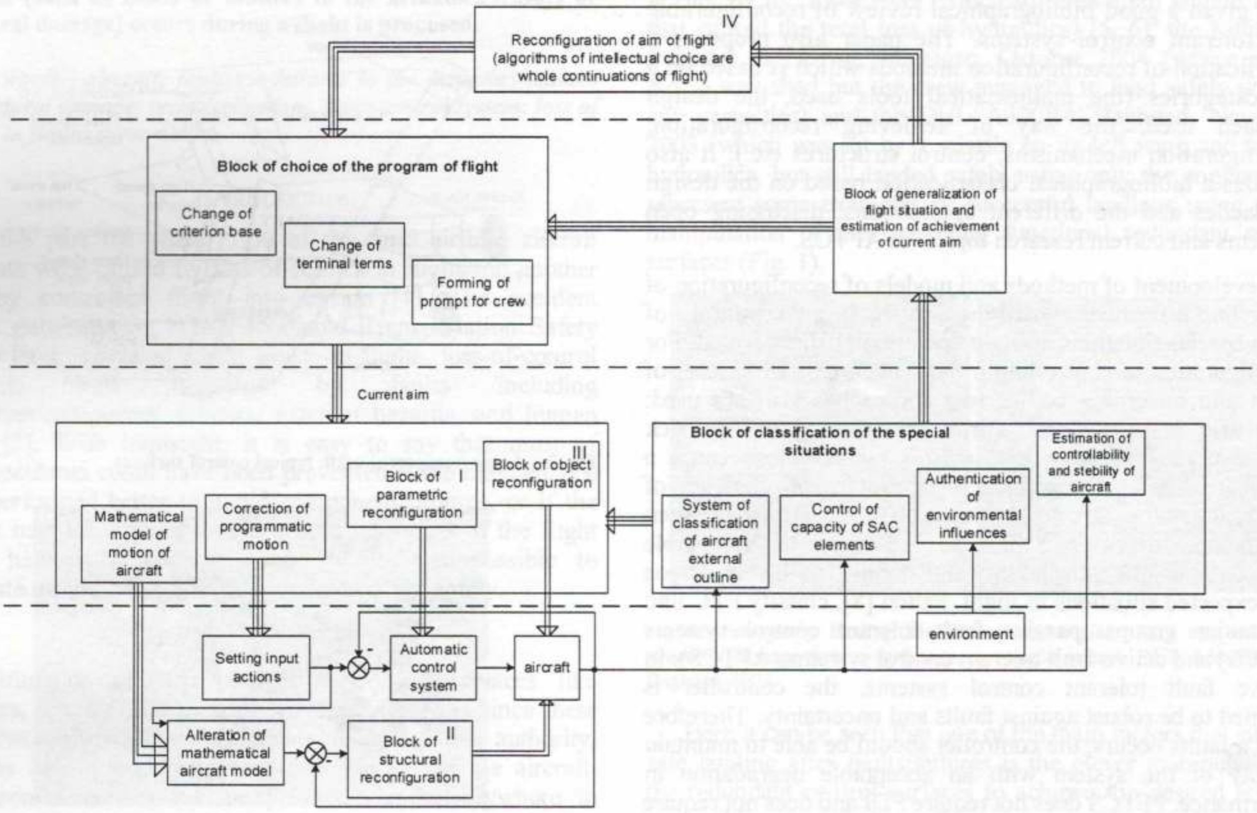

Fig. 4. Flow diagram of intelligent control system of aircraft in the conditions of origin of exception condition on wing.

Depending on the specific situation in flight offered the following algorithms:

- parametric reconfiguration is to change the gains of the regulator;
- structural reconfiguration is to the redistribution of control on a serviceable actuators or control surfaces;
- reconfiguration flight program and its criteria;
- changing purpose of the flight;
- bailout.

Let's suppose that movement of the aircraft is described by a differential equation:

$$x = F(x, a, q, u, t) + \xi_x,$$

where x – n is the dimensional state vector of object defined in space X ; a – r is the dimensional vector of parameters accepting values from a A-set and defined by properties of the environment; q is the vector of integrity of external contour of the airplane in the flight, considering influence of standard damages on aerodynamic properties of the airplane, and the m-dimensional vector of controlling influences created by reconfigured control system and belonging to the set U ; t – the current time belonging to a segment $[t_0, t_f]$ on which unexpected situation in flight is defined; ξ_x - n is the dimensional vector of uncontrollable perturbations (noise, measurement noises etc.); F - n is the dimensional vector function of the specified arguments known, according to the assumption, on the basis of theoretical and pilot studies. Observation over movement of the airplane is carried out by means of a complex of the sensors measuring components of a status of object and control, and also integrity of its external contour in flight:

$$z = h(x, a, q, u, t) + \xi_z,$$

where z - l is the dimensional vector of observations in space Z ; ξ_z - l is the dimensional vector of the additive noises distorting indications of sensors; h - l is the dimensional vector function of the specified arguments known on the basis of theoretical and pilot studies of sensors of information. Results of measurements arrive in reconfigured management system where are used for determination of response characteristics of the airplane and optimum (suboptimal) estimation of its status.

The following stage of functioning of the offered reconfigured management system is process of parametric identification of response characteristics of the airplane in the conditions of unexpected situation origin in flight which in a general view is described by the operator:

$$\hat{a} = H(z, \bar{a}, \bar{q}, t).$$

Thus, in considered structure it is necessary that identification is carried out in some neighborhood of program value of a vector of parameters. In the course of identification the reconfigured management system considers the factors influencing dynamic properties of the airplane (unfavorable external factors and degrading internal processes).

On the basis of signals of sensors and estimates of parameters of object it is carried out optimum (or suboptimal) estimation of a status of the object, allowing substantially to increase accuracy of information on a vector:

$$\hat{x} = N(z, \hat{a}, \hat{q}, t),$$

where $\hat{x}$ - n is the dimensional vector of an assessment of parameters of a vector x.

Total procedure of reconfigured management system is optimization of controlling impacts on airplane executive bodies on a basis, set the purposes of control and criteria of optimization for preventing of development of unexpected situation in flight. The operator describing formation of a vector of optimum controls, looks like:

$$u = \Omega(z, \hat{a}, \hat{q}, t).$$

The optimality criterions created beforehand, define a measure, leaning on which control algorithm selects an optimum way of achievement by object of the given status. The structure of the operator depends on a method of the job of the purpose of the control, minimized criteria and a choice of a method of the optimization, to unexpected situation had time development in flight, and also an aerodynamic status of external contour of the airplane.

The task of the unit of BCSS is the classification of the standard damages of external circumscriptions in flight, and also the tracking of the appearance of destructive processes in the structure of composite skin materials. Examples of the standard damages: the damage of skin and mechanization of wing and of tail assembly, which they lead to a change in the forces and moments, which act on the aerodynamic surfaces, with the subsequent course deviation; collision with the birds; the impacts of stones with the takeoff and the landing. As the block of diagnostic system it is intended to use an artificial neuron network named after Kohonen.

With the instruction of this map there is no control of the process of tuning weight coefficients. The study is made with use of the independent from the task measure of the quality of the classification of the standard damages of aircrafts outline. The parameters of network are optimized relativly to this measure. Among the vectors of those representing study, compulsorily must be the vector, which reflects "perfect" state of the external circumscription of aircraft, i.e., without the damages.

Each initial neuron with a quantity of entrances of the elements of input vector equal to a quantity, gives an output one of the values D. Initial neuron with the maximum value will determine the class, to which belongs the input information description of the integrity of the external circumscription of the aircraft $\max D(x(\omega)) = R_k(\omega)$.

That is, by neuron conqueror is considered the neuron, which has at the entrance of the function of the activation n^1 maximum value. Activation function appropriates to this neuron at the output a^1 values 1, all other neurons have original value the equal to zero. Study of the map is achieved according to the principle:

$$_iIW_{11}(q) = {}_iIW_{11}(q-1) + \alpha(x(q) - {}_iIW_{11}(q-1)),$$

where i is the number of that line of the matrix of weights, which is corrected; $_iIW_{11}$ is the i -number-concealing the line of the matrix of weights; q is the number of the step of instruction; α is the parameter of the speed of instruction; $x(q)$ is the input vector of the information description of the integrity of the external circumscription of aircraft.

The weight coefficients of neurons adjacent to the conqueror change according to the rule named after Kohonen:

$$_iw(q) = (1-\alpha) \cdot {}_iw(q-1) + \alpha x(q),$$

here $,w(q)$ is the weight coefficients of neurons i -number line of the matrix of weights. By the essential advantage of the map of Kohonen there is that the fact that it insensitive to the correlation of the elements of the vector of the information description of the technical state of the aircrafts outline, since the competing principle of instruction is used.

Before the instruction in neuron network of Kohonena it is necessary to conduct the procedure of rate setting the values of the vectors of information description for guaranteeing the identical speed of the instruction of weights.

Rate of vectors can be achieved in a next way:

1) For each of the elements of the vector of the information description x_i we should determine the minimum and maximum b value.

2) Each of the elements of the vector of information description to normalize to the interval [- 1, 1] according to the equation:

$$x_i^{\text{norm}} = 2(x_i - a)/(b - a) - 1.$$

As a result we will obtain the collection of values from the interval [- 1, 1] with the proportional to the original values of rate setting.

Weight coefficients of the network w_{ij} we will consider the components of the nuclei of the classes $\{c_k\}$ describing the standard damages of the external circumscription of aircraft.

In the stage of instruction the map of Kohonen builds mapping the collections of the values of the set of the current information descriptions of the technical state of the external circumscription of aircraft into the map of the states of the system $\{|\, x(\omega_h)\,|_{h=1}^{m}\} \to R_k\,(\omega)$. In the stage of operation the map ensures the classification of the current state of the external circumscription of the aircraft: $\{|\, x_i(\omega)\,|_{i=1}^{n}\} \to k$ or $\{|\, x_i\,(\omega)\,|_{i=1}^{n}, |\, z_j\,(\omega)\,|_{j=1}^{q}\} \to k$, $k \in K$.

The network of neurons of Kohonen gives the possibility to obtain the map of the classes of the technical state of the external circumscription of aircraft.

The unit of main algorithm control functional represents the main control loop which includes the longitudinal and lateral control channels. The functional of main control loop determine dynamic and static characteristics of the flight in certain range before operation of ultimate modes limiter. Adjustment of gear ratios and the functional parameters of the basic control loop is performed using software based on air-speed aircraft flight parameters and is adjusted by self-tuning block. Self- tuning of control system parameters, first of all, is required for improvement of the dynamic characteristics of aircraft.

The reserve algorithms control surface actuator use the identity principle of parametric self-tuning, according to this principle the "pure" object with possible typical failures / damages without control system is evaluated. The obtained data change gear ratios in the control algorithm to keep the optimum stability and control characteristics in conditions emergency flight. The unit of parametric and structural reconfiguration is used to provide failure tolerance of automatic control systems in case of damages or failures of control units. Reconfiguration is based on possibility of arrangement of structural and functional excess which are used as actuators: wing flaps, interceptors, spoilers, engines etc., providing additional (not peculiar for nominal flight control mode) functions that allow to redistribute control signals according to new control algorithm and to save the stability and controllability of the aircraft in conditions of in-flight emergency.

V. CONCLUSION

Real-time intelligent control system is a main element of the strategy change the configuration of the control actions. It can take the initial information about the existing laws the aircraft flight control and redistribute the initial commands intact control surfaces in terms of emergency situations. In addition, important elements of intelligent control system flight control system is element of identification fault/failure. In this material proposed concept to recovering the survivability of aircraft in terms of fault/failure control surfaces or flight control system will maintain acceptable flight and technical characteristics and safe implementation flight task.

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