AVIONICS OF ZERO MAINTENANCE EQUIPMENT

Valentin BUKOV *, Vladimir KUTAHOV **, Azret BEKKIEV **
*** Institute Aircraft Equipment, Russia, ** State Corp. "Rostechnologii", Russia**

Keywords: *reliable airborne network, redundancy, localization of observed and unobserved failures, logic model apparatus*

Abstract

The conception and main directions of creating a new technology for avionics are considered. This technology is focused on approaches, demands, criteria, techniques, tools and materials for certification, which allow designing and producing avionics with architectural solutions based on essential redundancy of hardware and software. Parry of any airborne equipment failure assumes to be automatic by means of system reconfiguration using criteria of functionality loss minimizing. Therefore, a traditional human-aided service of equipment (disassembling, rebuilding and assembling) has to be realized at the time of routine maintenance only or, in the limit, has not to be realized during the life cycle of an aircraft.

This work is supported by RFBR, grant No 09-08-13564-офи_ц.

1 Problem Statement

Strategic Research Agenda (SRA), which was published in October 2004, contains in-depth analysis of different scenarios for evolution of European aviation, as well as proclaims the main impacts and strategic importance of air transport in Europe [1].

So, the third and the fourth impacts are:

<u>Safety</u> with goals –

- reduction of the accident rate by 80 %,
- reduction in human error and its consequences.

<u>Air Transport System efficiency</u> with goals –

- to enable the Air Transport System to accommodate 3 times more aircraft movements by 2020 compared with 2000,
- to reduce the time spent by passengers in airports to under 15 minutes for short-haul flights and to under 30 minutes for long-haul,
- to enable 99 % of flights to arrive and depart within 15 minutes of their advertised scheduled departure time, in all weather conditions.

These wordings imply some dispute: safety increasing demands more time for preflight action but commercial efficiency demands to shorten one.

Achievement of mentioned goals must be bear on balanced using of different resources including commercial, political and technological ones.

At the same time the great shot of airlines' recurrent expenses is an aircraft operation cost [2]. Now world airlines are spending more than $40 billion to suspect own aircraft fleet, where average expenses for operational availability take 20 % of sum total.

Facts mentioned above underline the urgency of finding cardinal ways to reduce both time and cost of aircraft maintenance including avionics maintenance [3].

So, a part of the NASA Aviation Safety Program, which is known as the project "Integrated Vehicle Health Management – IVHM", deals with developing tools and technologies to detect, diagnose, predict and mitigate adverse events occurring during the flight of an aircraft [4]. The technologies are developed with the intent of contributing to IVHM systems of the next generation aircraft. The full packet includes six bits: S – on-board health management systems, W – in-flight warnings to crew, R – system control reconfiguration, M – aircraft maintenance decision support, D – develop and sustain systems and T – advance technology.

Some goals and approaches (but not all) of the named project are similar to goals and approaches of this one, but for all that the authors of this work call attention to another view on the problem Safety + Maintenance.

2 Faces of Avionics of Zero Maintenance Equipment

Here it is proposed to change cardinally the conception of airborne electronics build-up. Principal essential components including level of microelectronics development, communication facilities and scientific achievements in area of automatic localization and parry failures in real time are ready to such changing.

One of a number of primary characteristic features of the new conception is realization of regular flight exploitation an aircraft fleet on the assumption of airborne system faultinesses being saved up in permissible limits.

This conception assumes presence and using on an aircraft board the following six components:

A. Reliable (faultless) airborne network with probability of failure in flight not more than 10^{-12}

A distributed network with a number of uniformed computation modules (UCMs) is assumed. Such UCM must be designed under perspective requirement specifications, possess internal operated redundancy and be produced on basis of modern technology "System on a Chip". It is supposed that combination a few UCMs and signal processors gives a platform to information handling on the whole. If area of application UCM is too big, utilization of failure UCM may be preferable than repairing.

B. Element wise redundancy of airborne equipment

It is assumed that in the future all functional (spatially segregated) systems have to contain "inside" a redundant number of independent sensors or execution units in combination with necessary controllers. Computing and communication facilities, which provides by UCMs, are "outside" of these systems in terms of priorities: these units are firstly elements of an airborne network and then parts of functional systems.

C. Advanced systems for gathering and generalization information about airborne equipment functioning for analysis during flight and taxi

It is assumed that airborne equipment will contain possible (physically feasible) built-in testing. Signals of corresponding units will be used for ground aids and firstly for urgent decisions in the interests of system reconfiguration and crew operation.

D. High-performance algorithms for search (localization) observed and unobserved failures

It is assumed that all airborne systems both accessible and inaccessible to built-in testing are checked with help of high-performance algorithms of "inverse logic", which based on using of logic models for propagation of failure in the system. Such algorithms must be added with algorithms of current analysis of system functioning efficiency, with allow optimizing of a system structure in real time.

E. Algorithms for profound reconfiguration of airborne systems on basis of element wise redundancy of functional systems and dual redundancy of an airborne network

It is assumed that results of failure localization will be used to make decision about exception (replacement) of failure airborne elements without or with minimal degradation of complex functionality. At the same time an element wise replacement allows achieving a high level of flight readiness under low surplus weight and expenses. The double redundancy of an airborne network (elements on a chip and chips in an airborne network) is planned to be used.

F. Systems and channels for distribution information about flight situation for the sake of making a timely decision

It is assumed that in any case a digital channel must be used to deliver operative information to the ground personnel for preparation extraordinary arrangements if it is necessary.

Definition: Zero Maintenance Equipment (ZME) is such airborne equipment that has been designed to recondition itself automatically without personnel in a given time.

3 Advantages for Producers and Carriers

The suggested conception allows achieving the following advantages:

for instrument-making companies:

- ✓ traditional division of applied tasks of airborne complex,
- ✓ universality, scalability and flexibility of computing facilities,
- ✓ certified high reliability and safety,
- ✓ supporting of multi-type interfaces,
- ✓ external reservation and reconfiguration for specific systems;

for aircraft construction companies:

- ✓ expected cost reduction for airborne electronics,
- ✓ substantial widening of functional capability,
- ✓ getting an hardware and software platform to satisfy actual and perspective requirements (including advanced version of Integrated Modular Avionics – IMA);

for airlines:

- ✓ reduction of service expenses for airborne equipment,
- ✓ possibility for realize more compact flight schedules,
- ✓ accessibility of aerodromes with poor ground equipment.

4 Feasible Direction: Airborne Network

4.1 Network Structure

A structure of airborne complex with spatially segregated and information integrated systems is shown in Fig. 1.

Here are a number of universal airborne Computers with Operated Redundancy (COR) produced as a System on a Chip (SoC).

COR's tasks, which are referred to second plan: two CORs or systems on basis of CORs are used as central cores of the complex (for left and right boards) and others are used in segregated systems for specialized functions. In ex-

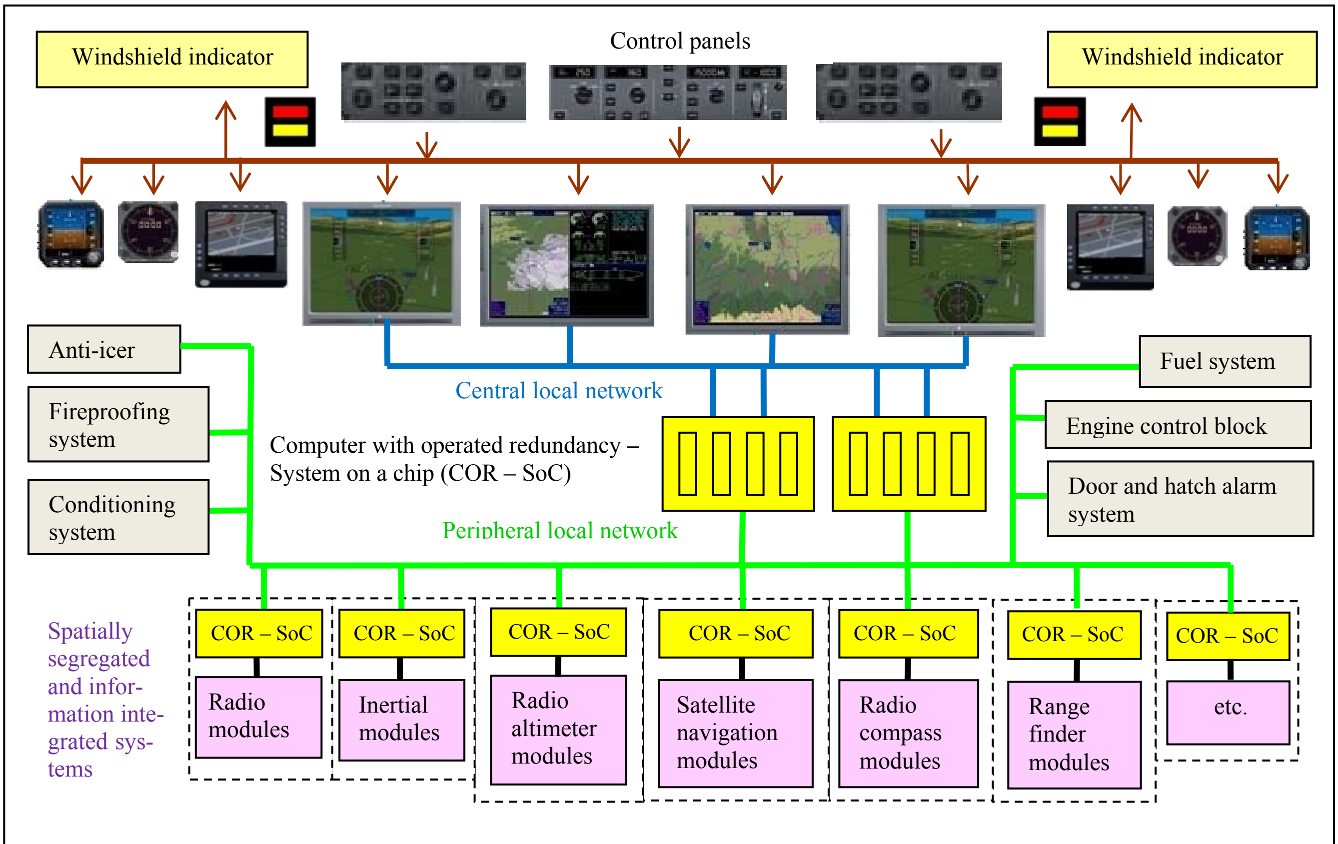

Fig. 1. Assumed Structure of Airborne Complex for the Day After Tomorrow.

treme case all CORs are the same and can be replaced either physically or with help of program controllers.

4.2 Structure of an Investigated Computer with Operated Redundancy

A variant of computer with operated redundancy, which has been designed and investigated in the frame of this project, is shown in Fig. 2.

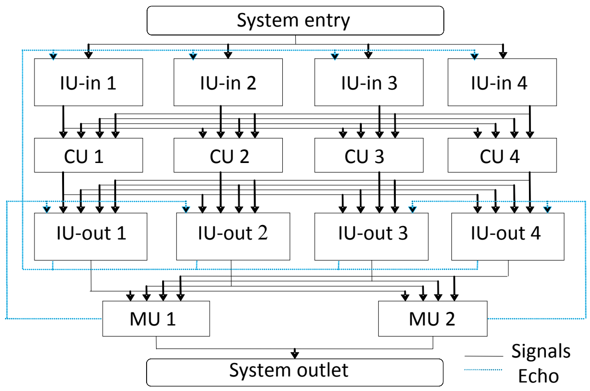

Fig. 2. Structure of COR.

The following abbreviations are used in this figure: IU stands for an Interface Unit, CU stands for a Computing Unit, and MU stands for a Multiplex Unit. Additional letter combinations stand for either entry or outlet parts of Interface Units. Numerals are used to name dubbed or four times reproduced identical units.

Such structure realizes the communication principle "each to each" as applied to units of COR. Combination of bimodal majority checking with threshold checking that are complied by every CU allows achieving the required reliability level of COR.

4.3 Estimated Economic Consequences for a Real Complex

Economical preeminence of an airborne network with CORs (only!) has been estimated on basis of existent procedures with reference to an aircraft Il-114. In this connection, annual expenses supposed to consist of an airborne network cost per year, a cost of repair packing located in all air bases and airports, costs of special tool sets and a wages fund for a maintenance staff.

The result shown in Table 1 holds true if fleet contains 50 aircrafts, air tracks include 25 airports, and ground equipment is distributed among 5 air bases.

Table 1. Estimated expenses.

Type of an airborne network	Cost ratio: Repair packing vs. Onboard network	Expenses ratio: Annual service vs. Purchase of sets
Traditional	1.02	1.68
Suggested	0.04	0.30

So, if one limits himself to using of CORs in his airborne network (without other suggested decisions) he will achieve five or six fold reduction of annual expenses for a network service.

5 Feasible Direction: Fault Localization

5.1 Scheme of Active Safety System

Igor Schagaev seems to be the first who has begun using the T-logic apparatus [5, 6] for description of safety processes in aviation [7, 8].

Later algorithms of Forward and Reverse Tracings based on static logic models as applied to active safety in aviation were published [9]. Then an approach with dynamic models (directed graphs) was described [10, 11].

A generalized scheme of Active Safety System taken from [12] is shown on Fig. 3.

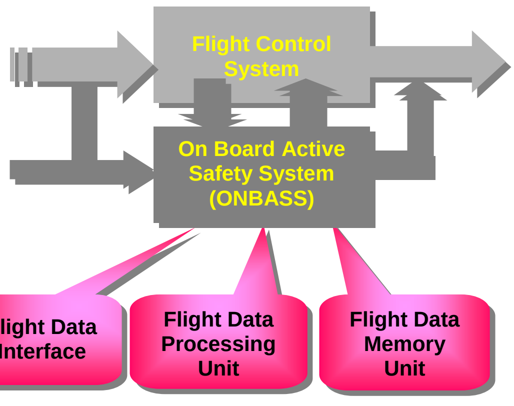

Fig. 3. ONBASS Conceptual Scheme.

Suggested (designed or planned to be designed) devices provide "activeness" of safety as well as gracefulness of degradation of the system (here an aircraft) when the full recovery is impossible. Diagnostic and test hardware units provide automatic on-board and on-ground supportive reliability tests.

5.2 Mathematical Apparatus

The problem is described by the following: to implement a procedure of search (localization) a reason – i.e. a source of a fault manifesting with logic and time latency.

These processes are provided with direct and inverse logics accordingly. It is assumed that any node of a graph has different logic operators at its input and output. Suitable logic tables for two logic operators OR and AND look like Table 2 and 3.

Note that some logical combinations are not defined, in the two last lines of Table 2 this

Table 2. Direct Logic

Symbol	Name	Formulae								
ORi	«OR» at the input	1+1=1	1+0=1	1+*=1	0+1=1	0+0=0	0+*=*	*+1=1	*+0=*	*+*=*
ANDi	«AND» at the input	1×1=1	1×0=0	1×*=*	0×1=0	0×0=0	0×*=0	*×1=*	*×0=0	*×*=*
ORo	«OR» at the output	~~1=1+1~~	1=1+0	~~1=1+*~~	1=0+1	0=0+0	*=0+*	~~1=*+1~~	*=*+0	*=*+*
ANDo	«AND» at the output	1=1×1	~~1=1×0~~	~~1=1×*~~	0=0×1	0=0×0	0=0×*	*=*×1	~~*=*×0~~	*=*×*

faulty element assuming multiple faults of aircraft equipment and using a mixed oriented graphs approach.

Additionally the difference between element faults and functional faults is implied. The is presented by red letter N.

Absence of some formulae in Table 2 creates conflict situations in Table 3. When conflict occurs, using this logic forces to exclude up nearest branching (and corresponding fault hy-

Table 3. Inverse Logic

Symbol	Name	Formulae								
iORi	inversion «OR» at the input	1=1+1	1=1+0	1=1+*	1=0+1	0=0+0	*=0+*	1=*+1	*=*+0	*=*+*
iANDi	inversion «AND» at the input	1=1×1	0=1×0	*=1×*	0=0×1	0=0×0	0=0×*	*=*×1	0=*×0	*=*×*
iORo	inversion «OR» at the output	conflict	1+0=1	conflict	0+1=1	0+0=0	0+*=*	conflict	*+0=*	*+*=*
iANDo	inversion «AND» at the output	1×1=1	conflict	conflict	0×1=0	0×0=0	0×*=0	*×1=*	conflict	*×*=*

last ones are the consequence of element faults and describe degradation of flight functions. However some element faults might not be followed by functional faults. In other cases functional faults present if the defined combinations of element faults exist while each element fault does not cause any functional fault separately.

Two processes are emphasized: detection of consequences that might lead to safety degradation of an aircraft and localization of a fault pothesis).

5.3 Models for Fault Propagation and Fault Localization

Models for description both spreading and localization of failures based on logic shown in Table 2 and 3 are very specific. Short form of equation for spreading failures looks alike following

$$x(k+1) = M\,x(k)\,,\ y(k) = E\,x(k)$$

where $x(k)$ is a system state vector with triple values of components before iteration of an expansion process ("0" stands for absence of a fault, "1" stands for existence of a fault, its manifestation or influence, "*" stands for anuncertain state), $x(k+1)$ is a vector with triple values of components after iteration. Number of component codes physical content and relation to category: fault, manifestation or internal variable.

A binary "matrix" M realizes the direct logic of failure spreading from Table 2 and looks like traditional matrices but in fact such construction is not a matrix in strict sense. The problem rises up from features of its rows and columns, which by definition connect with input and output logics for each node of a system graph. Everyone may make sure that such construction is not an algebra object since it does not save the initial feature after multiplication.

The last fact follows by the rule that formula for *k* steps

$$x(k) = \underbrace{MM \ldots M}_{k\ \text{tims}}\ x(0)$$

where $x(0)$ is an initial state vector, cannot be convert by multiplication of *M*. Rules for this «matrix» are described in [11].

A binary "matrix" *E* realizes a manifestation of a failure. A structure of this matrix is chosen under supposition that value "*" in a vector $x(k)$ is equal to value "1".

A corresponding inversed logic model without accounting of uncertainty looks alike

$$\hat{x}(0) = E^{\mathrm{T}} y(0)\,,\ \hat{x}(\tau+1) = \mathrm{inv}M\ \hat{x}(\tau)$$

where $\mathrm{inv}M$ is an inverse "matrix" M, which realizes the inverse logic from Table 3, $\hat{x}(\tau)$ is an estimation of a vector $x(k)$, τ is a number of steps in inverse direction, T is symbol of matrix transposition.

5.4 Localization Procedure

It is assumed that faults might be both simple (single fault) and complex (multiple faults). The only limitation assumption introduced here is in fact that fault does not change during algorithm action. On the whole a procedure of inversed transformation contains three steps:

<u>Firstly</u>, on basis of an observable manifestation vector $y(0)$ the created algorithm forms estimated value $\hat{x}(0)$ for the whole vector of state $x(0)$ of the system (logic variables of all the nodes in the graph). Common rules applied are: elements of the vector $\hat{x}(0)$ are assigned values

- "0" when a corresponding element is working certified;
- "1" when a corresponding element is not working certified;
- "*" when a state is undefined, a state of the element is impossible to determine using observable manifestation of faults.

A formal algorithm for this action is described with help of a formula

$$\{\hat{x}(0)\}_{\mu} = E^{\mathrm{T}} y(0) + \overline{E}^{R}\mu$$

where curly brackets denote a set of indistinguishable solutions, generated by variation of a vector μ of dimension $n-\mathrm{rank}E$ with elements presented as *; $\overline{E}^{R}$ is a right divider of zero for a matrix *E* with maximum rank, i.e. a matrix of dimension $n\times(n-\mathrm{rank}E)$ with maximum rank, for which the following condition stays:

$$E\overline{E}^{R} = 0\,.$$

<u>Secondly</u>, using the "matrix" $\mathrm{inv}M$, backward sequence (tracing) of fault influence are determined with help of a recurrent formula

$$\{\hat{x}(\tau)\}_{\mu} = \underbrace{\mathrm{inv}M\big(\mathrm{inv}M\big(\ldots\big(\mathrm{inv}M\,\{\hat{x}(0)\}_{\mu}\big)\big)\big)}_{\text{repeat using } \mathrm{inv}M\ \ \tau\ \ \text{tims}}$$

that can't be converted (presented as an algebraic equation) due to mentioned non-algebraic character of an $\mathrm{inv}M$-table structure. Number of iterations is selected either using a stop condition for transformation of a state vector $X(\tau+1) = X(\tau)$, or by limiting some value $\tau = \tau_{\max}$.

<u>Thirdly,</u> the potential faulty elements are defined by «1» values in the vector. «0» at the positions of the elements defines correct ele-

ments of vector of state. Presence of «*» defines the group of elements in the system that using existing information about possible faults and a structure of elements connection do not provide enough certainty about a fault or correctness.

6 Feasible Direction: Current Analysis of System Functioning Efficiency

The common concept of failure is not applicable to such compound system as, for example, a navigation system because an inner changing of their structure follows by not functional failure but some degradation of performance.

Technical condition of a navigation system is defined by an Indicator of Functioning Efficiency (IFE), which is an integral indicator depended on reliability, accuracy and adaptive property of its components. It is a probability of execution of navigation function with required accuracy [13]. Thus decrease IFE lower a given level is fixed as a condition close by failure.

An example of current estimation of Functioning Efficiency of a navigation system for a modern helicopter is shown in Fig. 4.

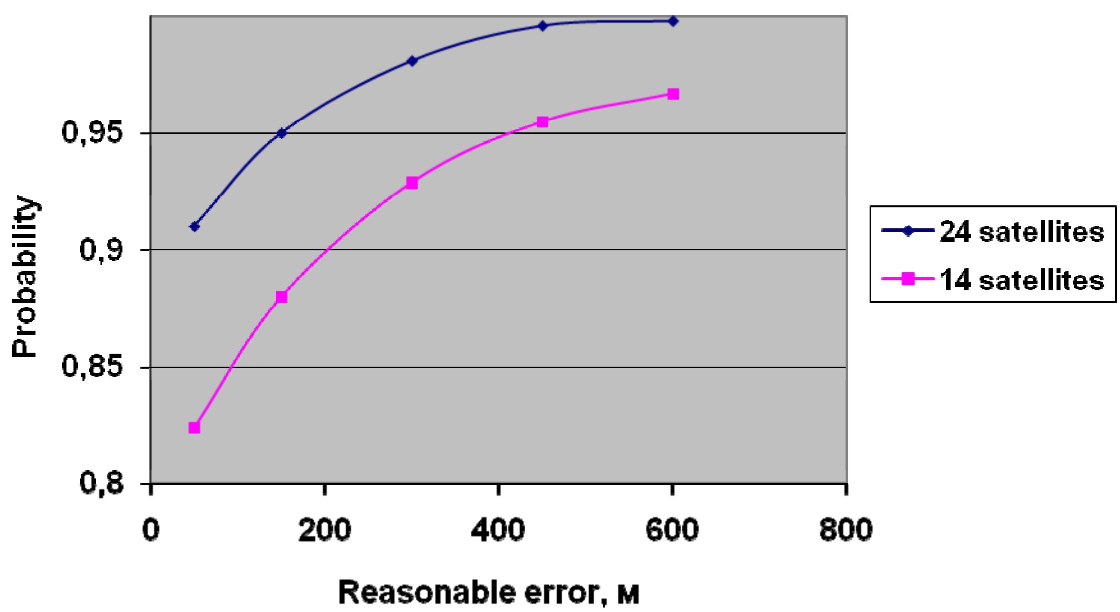

Fig. 4. Result of Current Analysis of Navigation System Functioning Efficiency.

Algorithms for diagnosis of a navigation system have to be conjugated to its regular algorithms as well as to solve the following tasks:

- ✓ determination of an error level of adjustors and autonomous navigation devices,
- ✓ determination of navigation system condition with reference to different decomposition levels,
- ✓ estimation of transition rates with reference to different decomposition levels,
- ✓ estimation of absolute probability for the all possible conditions of a navigation system for every mode of operation,
- ✓ checking of sufficient condition for balance in terms of IFE,
- ✓ determination of reasons of IFE imbalance.

Positive balance of a navigation system in terms of functioning efficacy is defined as its safety margin or accuracy margin on operating period until the next servicing, repair or writing off.

To determine reasons of IFE imbalance the method of automated estimation and diagnosis of navigation system functioning is created. This method is based on a Multilevel Discrete Model (MDM) and consists of three stages:

i. decomposition of functioning process as far as aggregates (top-down),

ii. numerical estimation of functioning (down-top),

iii. determination of imbalance reasons (top-down).

7 Conclusion

The core of future vehicle-borne systems assumes to process information for observable (in portion of a system that contains built-in self-tests) and unobservable (in portion of a system that does not contain ones) failures. These concern both an onboard data-processing network and other parts of vehicle (engine, fuselage, landing gear, etc.). Another version of onboard system analysis looks alike analysis of system functioning efficiency.

The information processing results immediate reconfiguration under the assumption that well-founded redundancy exists.

Reconfiguration realized both inside every chip and in scale of an airborne complex overall, is aimed to obtain the acceptable operational characteristics on condition that faults of elements, channels or systems are accumulated; and repairing either is deferred until a scheduled operation or is taken away.

Analysis has shown that only using a new reliable airborne network, which realizing principles of zero maintenance equipment, allows achieving five or six fold reduction of annual expenses of airlines for a network service.

Using of methods and technologies of current estimation and diagnosing of functioning efficiency of compound onboard systems is expected to be a baseline for the new run technology of zero maintenance airborne equipment.

Specific monitoring assumes existence of an automatic digital communication channel between an aircraft and some ground environment. This function allows airlines and aircraft producers to be informed in time about development of failure.

References

[1] *Strategic Research Agenda*, vol. 1, Advisory Council for Aeronautics Research in Europe (ACARE), 2004.

[2] Press release Boeing-717, http://www.avia.ru/pr/?id=984

[3] Do you find ways to make maintenance easier, safer and cheaper? http://www.emersonprocess.com/home/feature/pwu-maint1.html

[4] Gorinevsky D and Mah R. *NASA IVHM RTI Architecture: Working Document.* April 20, NASA NNA08BC21C, 2009.

[5] Allen J F. Towards a general theory of action and time. *Artificial Intelligence*, Vol. 23, pp 123-154, 1984.

[6] Gabbay D M, Hodkinson I and Reynolds M. *Temporal Logic. Mathematical Foundations and Computational Aspects*, Vol. 1, Oxford, Clarendon Press. 1994.

[7] Schagaev I. Concept of Dynamic Safety for Aviation. *Proc ISSC*, Seattle, pp 448-453, 1998.

[8] Schagaev I. Concept of Active System Safety. *Proc 15th IFAC Symp. on Automatic Control in Aerospace*, Bologna/Forli, Italy, 2001.

[9] Schagaev I, Kirk B and Bukov V. Applying the Principle of Active Safety to Aviation. *Proc 2nd European Conference for Aerospace Sciences (EUCASS)*, Brussels, Report 3_02_05, 2007.

[10] Bukov V N, Schagaev I and Kirk B. Analytical Synthesis of Aircraft Control Laws. *Proc 2nd European Conference for Aerospace Sciences (EUCASS)*, Brussels, Report 3_07_08, 2007.

[11] Bukov V N, Bronnikov A M and Selvesyuk N I. Algorithm of Fault Troubleshooting of Airborne Equipment Based on Mixed Directed Graph. *Safety Flight Problems*, No 2, pp 57-71, 2010 (in Russian).

[12] Bukov V, Chernyshov V, Kirk B and Schagaev I. Principle of Active System Safety for Aviation: Challenges, Supportive Theory, Implementation, Application and Future. *Proc Intern. Conf. "New Challenges in Aeronautics" (ASTEC'07)*, Moscow, 2007.

[13] Ksenofontov V.E. Design of Methods for Estimation and Diagnosis of Functioning Efficacy of Aircraft Navigation Complexes. *Control. Diagnostics*, No 11 (101), pp 50-53, 2006 (in Russian).

Copyright Statement