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Method of improving the functional dependability of the control systems of an unmanned aerial vehicle in flight in case of failure in the onboard test instrumentation

Denis V. Morozov, *Kazan A.N. Tupolev National Research Technical University – KAI (KNRTU – KAI), Kazan, Russia*
Sergey F. Chermoshentsev, *Kazan A.N. Tupolev National Research Technical University – KAI (KNRTU – KAI), Institute for Computer Technologies and Information Protection, Kazan, Russia*

Denis V. Morozov

Sergey F. Chermoshentsev

Abstract. *The* **Aim** *of this paper consists in the development of a method of improving the functional dependability of the control systems of unmanned aerial vehicles (UAV CS) affected by electromagnetic effects in flight and failures within the functional component of the onboard test instrumentation (OBTI).That is achieved through the identification of the failed functional element, the functional component of OBTI, the capability of performing the target objective of the UAV CS and decision-making regarding the initiation of the flexible operation algorithm. The existing and future UAV CS under development use binary reliability models, i.e. two states are distinguished: up and disabled. Therefore, each in-flight failure is classified as the UAV CS failure regardless of the current mission. If we regard a CS as a multifunctional system, it becomes obvious that the failure of not any UAV CS functional element causes flight termination.* **Methods.** *Solving the problem involved the use of a CS diagnostic model in the form of binary relations between the control actions and combinatorial subsets of functional elements, risk of losses estimation method as part of improving the functional dependability of UAV CS in flight, decision theory and combined branch-and-bound method. The mission performance probability is used as the efficiency criterion. This criterion is applicable when changes in a UAV CS' characteristics cause only partial reduction of the functional efficiency.* **Results.** *The purpose of OBTI self-supervision is failure location with the depth that allows determining its ability to perform the basic operations with the probability not lower than required by the customer, as well as the allowed set of elementary checks (EC) in this case. Based on the current results of elementary self-checks (ESC), one of the following decisions can be taken: stop the checks and discard OBTI; continue location; stop failure location and continue UAV CS mission per modified algorithm. At each stage of failure location in OBTI, based on the results of ESC, the area of covering check (ACC) and part of set suspected of failure (PSSF) are analyzed, which includes verifying the ACC for sufficient coverage of the PSSF, based on which appropriate decisions are taken. The following areas are formed: the area of observable data (processes of changes in the ACC and PSSF areas), within which the decision is taken to continue the checks, and the area, within which it is finally decided to terminate the checks. If it is decided to continue the failure location, another ESC is selected, which is associated with the risk of loss. The probability of false discarding of OBTI due to ESC selected out of ACC is taken as the risk of loss. The moment of termination of OBTI self-supervision depends not only on the set of decisions, but their sequence as well. Thus, the task at hand comes down to designing the optimal ESC strategy that minimizes the probability of false discarding. The idea of combined branch-and-bound method (CBBM) as part of the design of the optimal OBTI self-supervision algorithm consists in the consecutive selection at each stage of ESC implementation process, out of the subset of minimum risk checks of the next ESC till a one-element subset is obtained and/or the corresponding decision is taken.* **Conclusions.** *The developed method allows continuing the performance of the target objectives of a UAV CS in flight when affected by failures in OBTI.*

Keywords: *unmanned aerial vehicle, control system, self-supervision, combinatory subsets of elements, part of set suspected of failure, binary diagnostic model, probability of false discarding, combined branch and bound method, risk of loss.*

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Introduction

In terms of the employed technological solutions, today's unmanned aerial vehicles (UAV) can be described as complex technical systems. The inclusion of a control computer (CC) into the control system (CS) enabled a significant extension of UAV functionality and missions. Not only the supervision and diagnostics functions were implemented onboard, but the flight of UAV was made completely automatic. Successful application of UAV depends on the reliable operation of all onboard systems. UAVs often operate in adverse electromagnetic environments caused by the presence of many characteristic external and internal factors [1, 2, 3]. That caused increased failure rate in UAV CS. The UAV CS [4, 5] consists of onboard test instrumentation (OBTI), its self-supervision system (SSS) and onboard mission equipment (OBE). The existing and future UAV CS under development use binary reliability models, i.e. two states are distinguished [4, 5]: up and disabled. Therefore, each in-flight failure is classified as the UAV CS failure regardless of the current mission. In this case the UAV interrupts mission performance and returns to the launch site (airfield) for the purpose of identification and replacement of the failed component. The replacement addresses either the failed unit or a line replacement unit.

However, if we regard a CS as a multifunctional system, it becomes obvious that the failure of not any UAV CS functional element [6, 7, 8] causes the impossibility of further mission performance. Thus, the unequal significance of the failures of different functional elements of UAV CS in terms of mission performance allows, by changing the CS operation algorithm, increasing the efficiency of UAV deployment. The flight plan can be modified based on the principle of exclusion of damaged areas with subsequent continuation of operation using the remaining functions. Since the completion of every task requires the fulfillment of a certain set of control and supervision operations implemented by the respective technical facilities, the CS OBTI includes supervisory equipment (SE) for up state supervision (USSE), operation (OSE) and emergency flight mode (EFMSE) of a UAV [7, 9].

The aim of this paper consists in the development of a method of improving the functional dependability of UAV CS affected by electromagnetic effects in flight and failures within the functional component of OBTI. That is achieved through the identification of the failed functional element, the functional component of OBTI, the capability to perform the target objective of the UAV CS and decision-making regarding the initiation of the flexible operation algorithm.

Definitions used in the method

In [10], it is proposed to use a binary hierarchical model (BHM) of UAV CS. It involves the subdivision of the CS into local functional components, which is caused by the requirement to evaluate their effect on the final results of UAV CS mission performance in flight and the capability to modify its operation algorithm. Each operation is implemented by its own set of elements that in the general case overlap [9, 11]. The overlapping of such elements subdivides the OBTI into non-overlapping combinatorial subsets of elements (CSE) each of which implements a precise set of elementary operations.

Definition 1. Elementary operation (EO) is the maximum set of operations on signals constant in all tasks (implemented completely with the execution of any task) performed under the control of a computer and/or human operator.

Definition 2. Elementary check (EC) is a set of EOs required and sufficient for the verification of an individual parameter (attribute) of the object of supervision.

Definition 3. Elementary self-check (ESC) is a set of EOs required and sufficient for the verification of an individual parameter (attribute) of the OBTI in the course of its self-supervision.

Definition 4. Supervised part of set (SPS, $\mathfrak{A}_i$) is a subset of OBTI CSE covered by the *i*-th EC (ESC)

$$\{b_1, \ldots, b_i\} \in \mathfrak{A}_i.$$

Definition 5. Part of set suspected of failure (PSSF, $\underline{\mathfrak{C}}$) is an area of CSE(a) formed by the overlapping of the $\overline{\mathfrak{A}}_i$ of the *i*-th ESC, in which a failure has been identified with $\mathfrak{A}_j$ of previous ESCs

$$\{b_j\} \in \overline{\mathfrak{A}}_i \cap \mathfrak{A}_j \in \mathfrak{C},$$

where $\overline{\mathfrak{A}}_i$ is the SPS of the *i*-th ESC in which a failure was identified,

$\mathfrak{A}_j, j = \overline{1, i-1}$ is the SPS of ESC performed before the *i*-th ESC that returned "OK".

In the course of ESC as part of OBTI self-supervision it may occur that $\mathfrak{A}_j = \varnothing$, i.e. PSSF is the same as the SPS of the *i*-th ESC.

Definition 6. ESC (π_i) is essential to $\mathfrak{C}_\gamma$, if simultaneously $\mathfrak{C}_i \cap \mathfrak{C}_\gamma \neq \mathfrak{C}_\gamma$ and $\mathfrak{C}_i \cup \mathfrak{C}_\gamma \neq \varnothing$.

Definition 7. Elementary checks (EC) that ensure UAV CS, control in emergency flight mode called basic.

The remaining ECs are auxiliary. Each EC corresponds with an ESC.

Problem definition

There is a UAV CS that consists of an OBTI, OBE and SSS. The components of this system are represented with a binary diagnostic model (BDM) [10]. For each functional element of the BDM there are known failure rates represented with row vectors.

Using EC (ESC), the operability of all CSEs of CS OBE (OBTI CSE) is supervised, therefore the EC (ESC) can have two definitive outcomes, i.e. "OK" and "not OK". The reliability of UAV CS must be ensured with the required probability P^*. The time of the latest supervision of CS OBE and self-supervision of OBTI is known. EC overlap per OBTI elements. Each EC is associated with an ESC in the course of self-supervision. The OBTI has a failure belonging to one CSE that does not allow executing a part of the EC (set of ECs) of CS OBE.

The purpose of OBTI self-supervision is the failure location with a depth that allows identifying its ability to perform the primary operations with the probability not lower than P^* and the allowed set of ECs in this case.

The π_γ (γ-th EC) returned "not OK". In this case the entire set $\boldsymbol{\Pi}$ of ECs (ESCs) is divided into two non-overlapping subsets (if $\gamma \neq 1$ and $\gamma \neq \mathcal{M}$):

$\boldsymbol{\Pi}_1 = \{\pi_1, \ldots, \pi_\gamma\}$ is the subset of implemented ECs (ESCs),

$\boldsymbol{\Pi}_2 = \{\pi 1, \ldots, \pi\gamma\}$ is the subset of non-implemented ECs (ESCs).

The following were defined: PSSF ($\mathfrak{C}$) that includes $\{\bar{b}_j\}$ CSEs of BTI and ACC ($\mathfrak{S}$), i.e. area of EC (ESC) that covers the PSSF. $\mathfrak{S} \subseteq \boldsymbol{\Pi}_2$ is sufficient for the failure location. In terms of functionality, ECs (ESCs) can be basic and auxiliary.

Based on the current ESC results a decision can be taken out of the following options:

– decision 1: stop the checks and reject the OBTI,

– decision 2: continue failure location,

– decision 3: stop the failure location and continue execution of UAV CS flight plan per modified algorithm.

At the final stage of OBTI self-supervision the second decision degenerates into the first or the third one. Due to that the set $\mathfrak{D}$ contains two basic elements: d_c, decision to continue the failure location and d_s, decision to stop the failure location. The second and third decisions define the depth of OBTI self-supervision.

At each stage t_i of failure location in OBTI, based on the results of ESC, the ACC and PSSF are analyzed, which includes verifying the ACC for sufficient coverage of the PSSF ($\mathfrak{C} \subseteq \mathfrak{S}$), based on which the appropriate decisions are taken. In this case areas $\mathfrak{G}_c^\phi$, $\mathfrak{G}_\psi$: $\mathfrak{G}_c^\phi(t_i)$ are formed, i.e. the area of observable data (processes of changes in the areas $\mathfrak{C}$, $\mathfrak{S}$), within which the following decisions are taken

$$d_c = \left(d_c^{11},\ d_c^{10}\right) \text{ and } d_c^\phi,$$

where d_c^{11} is the decision to continue the failure location, as in PSSF there are $\{b_j\} \in$ SE, OBTI EFMSE,

d_c^{10} is the decision to continue the failure location, as in PSSF $\{b_j\} \in$ OBTI SE, provided $P_{MP} < P^*$,

P_{MP} is the mission performance probability used as the criterion of UAV CS efficiency. It is applicable when changes in an object's characteristics cause only partial reduction of the functional efficiency. We understand this indicator [7] as the a posteriori probability of absence of failures in the CS equipment required and sufficient for successful completion of UAV CS mission.

$d_c^{\phi i}$ is the decision to next implement the i-th ESC,

$_\psi(t_i)$ is the area within which final decisions are taken

$$d_s = \left(d_s^{01},\ d_s^{10}\right),$$

where d_s^{01} is the decision to stop the checks and discard the OBTI, as in PSSF there are only $\{b_j\} \in$ OBTI EFMSE,

d_s^{10} is the decision to stop location and allow OBTI to continue the mission per a modified functional program of CS, since in PSSF $\{b_j\} \in$ SE and $P_{MP} \geq P^*$.

Decision $d(t_i) = \delta_{t_i}\left(\mathfrak{C}^{t_i}, \mathfrak{S}^{t_i}\right)$ that conform to the general sequential rule $\delta = \left\{\delta_{t_i}\left(\mathfrak{C}^{t_i}, \mathfrak{S}^{t_i}\right), \mathfrak{C}, \mathfrak{S} \in \mathfrak{G}(t_i), i \geq 0\right\}$ with planning of observations, has the form

$$\delta_{t_i}\left(\mathfrak{C}^{t_i}, \mathfrak{S}^{t_i}\right) = \begin{cases} d_s^\varphi \ \text{if} \ \mathfrak{C}^{t_i}, \mathfrak{S}^{t_i} \in \mathfrak{G}_s^\varphi(t_i), i \geq 0, \\ d_\psi \ \text{if} \ \mathfrak{C}^{t_i}, \mathfrak{S}^{t_i} \in \mathfrak{G}_\psi(t_i), i \geq 0. \end{cases} \quad (1)$$

If it is decided to continue the failure location, another ESC is selected, which is associated with the risk of loss [11, 12]. The probability of false discarding of OBTI due to ESC selected out of ACC is taken as the risk of loss. It is identified according to formula

$$P_{FD}^*(i) = P_{FD}(i) + P_{PP}(i)\hat{P}_{FD}^{\max}(M - i), \quad (2)$$

where $\hat{P}_{FD}^{\max}(M - i)$ is the estimation of the probability of false discarding in the course of remaining ESCs,

$P_{PP}(i)$ is the probability that as the result of implementation of the i-th ESC, in C there will be both elements of SE and EFMSE.

$P_{FD}(i)$ is the probability of false discarding of OBTI in the course of the i-th ESC.

The moment of termination of OBTI self-supervision depends not only on the set of decisions $\mathfrak{D}$, but their sequence as well

$$\tau\left(\delta_{t_i}\right) = \inf\left\{\tilde{\gamma}\left(\delta_{t_i}\right) : d(t_i) \in \mathfrak{D}_n\right\}$$

and is a random value.

Thus, the task at hand comes down to designing the optimal ESC strategy that minimizes the probability of false discarding

$$\bar{\gamma}(\delta) = \min P_{FD}^*(i) \ \text{if} \ P_{MP} \geq P^*. \quad (3)$$

Description of the solution method

We assume that there is one failed CSE within the OBTI. Based on the properties of the binary diagnostic model of the OBTI the initial PSSF and ACC are generated. They are then analyzed using the obtained results. For the ACC it consists in the definition of the functional composition of the ESC that can be basic and auxiliary, while for the PSSF it leads to the corresponding decision d_c or d_s. If the results of analysis fell within the area $\mathfrak{G}_s^\phi$, the next ESC is selected out of the initial ACC. The application of the i-th ESC for failure location in OBTI can be regarded as the subdivision of the PSSF set into two subsets $\mathfrak{C}_j$ and $\bar{\mathfrak{C}}_i$, with the result of π_i implementation of the i-th ESC unambiguously defining the belonging of the failed CSE to one of these subsets: subset $\mathfrak{C}_j$ if the result is "OK" and subset $\bar{\mathfrak{C}}_i$ if the result is "not OK". Further failure location, obviously, can only involve ESCs essential to the current PSSF. Therefore, in the process of selection of the i-th ESC the ACC is specified, where upon the implementation of such ESC only essential ones must remain. The selection of the next ESC is based on the

Table 1. Components of the model of BTI failure location in the course of self-supervision

Numbers of graph nodes	ESC classification			ESC result hypothesis		PSSF-SPS			Solution		$P_{\text{FD}}(i)$	$P_{\text{PP}}(i)$	$Q_{EFSME}(M-i)$	$P_{\text{FD}}(i)$
	δ_1	δ_2	1-δ_2	H	$\overline{\text{H}}$	δ_3	δ_4	δ_5	δ_6	δ_7				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
8.4	1	0	1	1	0	1	-	0	1	0	0	$P_{EFSME_i} R_{EFSME_i}$	0	0
8.5	1	0	1	1	0	1	-	0	0	1	0	0	0	0
8.6	1	0	1	1	0	0	-	1	1	0	0	$P_{EFSME_i} R_{EFSME_i}$	$1-e^{-\sum \lambda_{\text{EFMSE}} t}$	$P_{EFSME_i} R_{EFSME_i} \times \times Q_{\text{EFMSE}}(M-i)$
8.1	1	0	1	0	1	-	-	-	0	0	0	0	0	0
8.2′	1	0	1	0	1	1	-	0	0	0	$P_{\text{EFMSE}_i}(1-R_{\text{EFMSE}_i})$	0	0	$P_{\text{EFMSE}_i}(1-R_{\text{EFMSE}_i})$
8.2′′	1	0	1	0	1	0	-	1	0	0	$P_{\text{EFMSE}_i}(1-R_{\text{EFMSE}_i}) \times \times \Phi^*_{\text{EFMSE}}$	0	$1-e^{-\sum \lambda_{\text{EFMSE}} t}$	$P_{\text{EFMSE}_i}(1-R_{\text{EFMSE}_i}) \times \times \Phi^*_{\text{EFMSE}}$
8.7	0	1	0	0	1	-	-	-	1	0	0	$1-P_{\text{SE}_i}$	0	0
8.8	0	1	0	0	1	-	-	-	0	1	0	0	0	0
8.12	0	1	0	0	1	1	0	0	1	0	0	$P_{\text{SE}_i}(1-R_{\text{SE}_i})$	0	0
8.13	0	1	0	0	1	1	0	0	0	1	0	0	0	0
8.15	0	1	0	0	1	0	0	1	1	0	0	$P_{\text{SE}_i}(1-R_{\text{SE}_i}) \times \times (\Phi^*_{\text{EFMSE}}(1-\Phi^*_{\text{SE}})+\Phi^*_{\text{SE}})$	0	0
8.16	0	1	0	0	1	0	0	1	0	1	0	0	0	0
8.9	0	1	0	0	1	0	1	0	1	0	0	$P_{\text{SE}_i}(1-R_{\text{SE}_i})$	0	0
8.10	0	1	0	0	1	0	1	0	0	1	0	0	$1-e^{-\sum \lambda_{\text{EFMSE}} t}$	0
8.19	0	1	0	1	0	1	0	0	1	0	0	$P_{\text{SE}_i} R_{\text{SE}_i}$	0	0
8.20	0	1	0	1	0	1	0	0	0	1	0	0	0	0
8.21	0	1	0	1	0	0	0	1	1	0	0	$P_{\text{SE}_i} R_{\text{SE}_i}$	$1-e^{-\sum \lambda_{EFM} t}$	$P_{\text{SE}_i} R_{\text{SE}_i} \Phi^*_{\text{EFMSE}} \times \times Q_{\text{EFMSE}}(M-i)$
8.18	0	1	0	1	0	0	1	0	0	0	$P_{\text{SE}_i} R_{\text{SE}_i} \Phi^*_{\text{EFMSE}}$	0	$1-e^{-\sum \lambda_{\text{EFMSE}} t}$	$P_{\text{SE}_i} R_{\text{SE}_i} \Phi^*_{\text{EFMSE}}$
8.22-8.25	0	0	1	0	1	-	-	-	1	0	0	$P_{\text{EFMSE}_i}+P_{\text{SE}_i}- -2P_{\text{EFMSE,SE}_i}+ +P_{\text{EFM,SE}_i} \times \times (1-R_{\text{EFMSE}_i})$	$1-e^{-\sum \lambda_{\text{EFMSE}} t}$	$(P_{\text{EFMSE}_i}+P_{\text{SE}_i}- -2P_{\text{EFMSE,SE}_i}+ +P_{\text{EFMSE,SE}_i} \times \times (1\text{-}R_{\text{EFMSE}_i})) \times \times Q_{\text{EFM}}(M-i)$
8.28	0	0	1	1	0	1	0	0	1	0	0	$P_{\text{EFMSE,SE}_i} \times \times R_{\text{EFMSE,SE}_i}$	0	0
8.29	0	0	1	1	0	1	0	0	0	1	0	0	0	0
8.27	0	0	1	1	0	0	1	0	0	0	$P_{\text{EFMSE,SE}_i} \times \times R_{\text{EFMSE,SE}_i} \Phi^*_{\text{EFMSE}}$		$1-e^{-\sum \lambda_{\text{EFMSE}} t}$	$P_{\text{EFMSE,SE}_i} \times \times R_{\text{EFMSE,SE}_i} \Phi^*_{\text{EFMSE}}$
8.30	0	0	1	1	0	0	0	1	1	0	0	$P_{\text{EFMSE,SE}_i} \times \times R_{\text{EFMSE,SE}_i}$	$1-e^{-\sum \lambda_{\text{EFMSE}} t}$	$P_{\text{EFMSE,SE}_i} \times \times R_{\text{EFMSE,SE}_i} \times \times Q_{\text{EFMSE}}(M-i) \times \times \Phi^*_{\text{EFMSE}}$

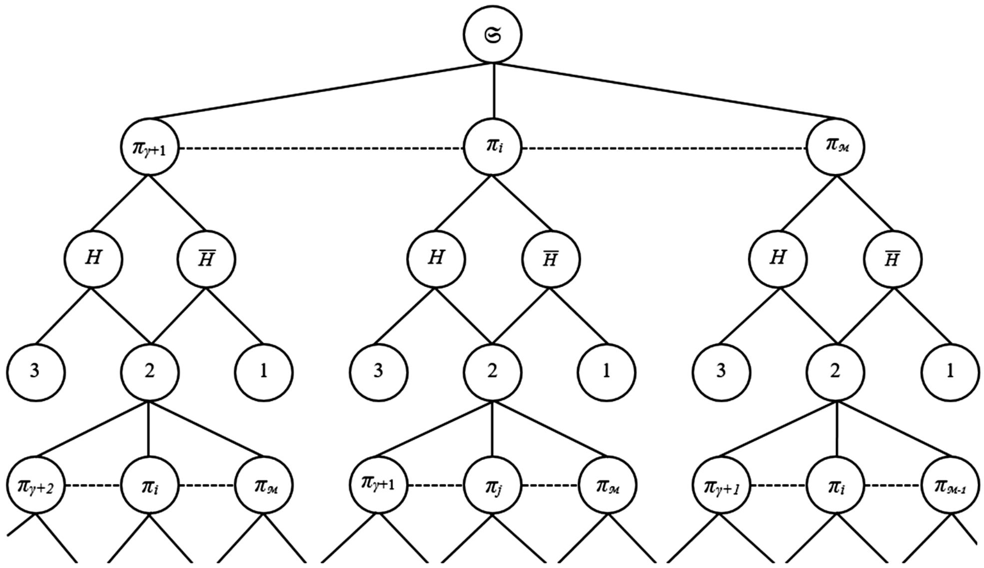

Figure 1. Graph of the failure location process in the course of OBTI self-supervision

prediction of the risk of loss from its implementation. The probability of false discarding of OBTI per the *i*-th ESC is taken as the risk of loss [9, 11, 12]. $P^*_{FD}(i)$ is calculated based on the procedure of risk of loss identification is part of improving the functional dependability of UAV CS in flight [9, 11] according to formula (2). The implementation of the next ESC in the course of OBTI self-supervision may cause a probability of its false discarding. For that reason this probability is estimated for each ESC that make the ACC of the current step of location. In formula (2) $\hat{P}^{\max}_{FD}(M-i)$ can be estimated through the probability of failure of the self-supervision facilities of the functional component of the OBTI EFMSE per the remaining ESCs of the ACC. In this case formula (2) is as follows:

$$P^*_{FD}(i) = P_{FD}(i) + P_{PP}(i) Q_{EFMSE}(M-i), \qquad (4)$$

where $Q_{EFSME}(M-i)$ is the probability of failure of self-supervision facilities of the functional component of the OBTI EFSME.

The components of formula (4) are calculated based on the procedure of risk of loss identification as part of improving the functional dependability of UAV CS in flight [9, 11] and is shown in Table 1. The selection of the *i*-th ESC itself and construction of the optimal strategy of failure location is based on the application of the combined branch-and-bound method (BBM). When the combined BBM is used, for the purpose of constructing optimal conditional self-supervision programs the sequential use of ESCs in the process of self-supervision is considered as a multistage process, and the application of any ESC at a random stage is considered as the subdivision of the set of the states of OBTI allowable at such stage into two parts, to one of which belongs the true state.

The idea of combined BBM as part of the design of the optimal OBTI self-control algorithm consists in the consecutive selection at each stage of ESC implementation process, out of the subset $\mathfrak{S} = \{\pi_{\gamma+1}, \dots, \pi_{\mathcal{M}}\}$ per the minimal $P^*_{FD}(i)$ of the next *i*-th ESC till a one-element subset is obtained and/or the corresponding decision is taken.

This process is represented by a graph in Figure 1 where the apexes of the corresponding subset $\mathfrak{S} = \{\pi_{\gamma+1}, \dots, \pi_{\mathcal{M}}\}$ are the results of ESC implementation, corresponding decisions, while the arcs are the logical connections between the apexes. Decisions 2 and 3 correspond to the ESC result "OK", while the decisions 1 and 2 correspond to the result "not OK". Let us examine the left branch of the graph. Let us assume that based on the analysis of the initial ACC per the minimal $P^*_{FD}(\gamma+1)$ the $(\gamma+1)$-th ESC was selected. Its implementation can return "OK" or "not OK", but decision d_c was taken, i.e. continue failure location. On this basis the ACC is specified and in this case $\mathfrak{S}^{t_1} = \{\pi_{\gamma+2}, \dots, \pi_{\mathcal{M}}\}$.

At stage t_1 of failure location $P^*_{FD}(i)$ is calculated, $i = \overline{\gamma+2, M}$, *i*-th ESC of $\mathfrak{S}^{t_1}$, and per the minimal $P^*_{FD}(i)$ the next ESC is selected for implementation. The branching process continues until decision 1 or 3 is taken.

Conclusion

The method of improving the functional dependability of UAV CS allows defining the strategy of in-flight UAV application:

a) if the failure belongs to OBTI EFMSE, abort the UAV mission and bring it back to LS.

b) implementing the procedure of modification of the UAV CS algorithm, if the failure belongs to OBTI SE; location in the course of the self-supervision must have the optimal depth.

If it is decided to continue the failure location, another ESC is selected, which is associated with the risk of loss. The probability of false discarding of OBTI due to ESC selected out of ACC is taken as the risk of loss.

The paper proposes a BBM-based solution that consists in sequential selection at each stage of ESC implementation process, out of the ACC subset per minimal $P^*_{FD}(i)$ of the next ESC till a one-element subset is obtained and/or the corresponding decision is taken.

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About the authors

Denis V. Morozov, post-graduate student, Kazan A.N. Tupolev National Research Technical University – KAI(KNRTU – KAI), Institute for Computer Technologies and Information Protection,Kazan, Russia, e-mail: i_am_morozov@mail.ru

Sergey F. Chermoshentsev, Doctor of Engineering, Professor, Head of Chair of Computer-Aided Design Systems, Kazan A.N. Tupolev National Research Technical University – KAI(KNRTU – KAI), Institute for Computer Technologies and Information Protection, Kazan, Russia

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