Reliability Synthesis for UAV Flight Control System

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Abstract. This paper presents the models and methods for reliability synthesis for components of UAV flight control system: flight computer and navigation system. The developed reliability models depict different variants of fault-tolerant designs including designes for systems with complex reliability behavior. They have a high level of adequacy, since effectiveness of detection and switching devices was taken into account.
Based on the models, we proposed the reliability synthesis methods for flight control system components that allows making reasonable design decisions.
As an example of using these methods, the reliability requirements and recommendations for rational choice of fault-tolerant designs were developed to meet required reliability level of UAV flight computer and navigation system.

Keywords. Unmanned aerial vehicle (UAV), flight computer, navigation system, flight control system, reliability model of fault-tolerant system.

Key Terms. Model, Mathematical Modeling, Markov model.

1   Introduction

Although UAV's reliability has significantly increased for the last 15 years, this problem is still among the focus issues for manufactures and different branches of military [1-5]. The current UAV's failure and accident/mishap rates are much higher than that of manned air platforms. Approximately a quarter of all UAV's failures are caused by flight control system (FCS) failures [1-4]. This system contains three main components (Fig. 1) [1-3]: navigation system (NS), flight computer (FC) and autopilot (AP). All these components are failure-critical. In this paper, we choose NS and FC as research objects due to their complex reliability behavior. Based on the analysis of reliability measures and characteristics [1-5], the least reliable FC parts are microprocessors and the least reliable NS parts are gyroscopes and accelerometers.
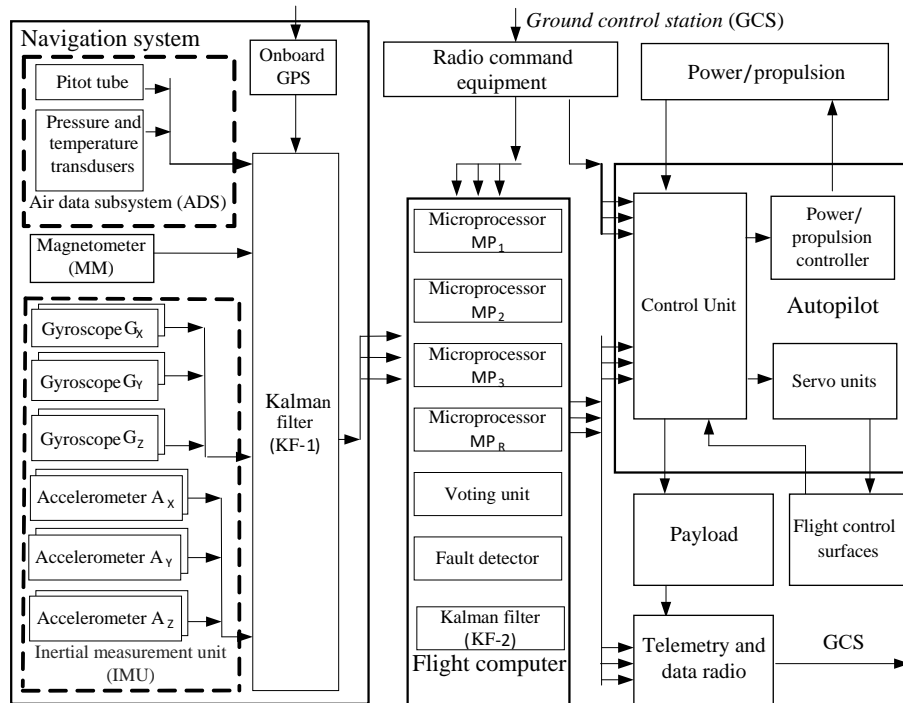
Fig. 1. UAV flight control system architecture

The researches, aimed to increase FCS reliability on the design stage, are important. It concerns reliability synthesis for navigation system and flight computer, namely, reasonable choice of their reliability parameters and fault-tolerant configurations to meet required reliability level. There are two major approaches for solving these issues [2-9]: fault avoidance with improvement of failure-critical subcomponents reliability, and fault tolerance based on redundancy with use of effective detection and switching devices (DSD). The second approach is used extensively for improving reliability of military UAVs [2-10]. For instance, the Russian UAV Forpost, which was shot down in Eastern Ukraine, has dual modular redundancy (DMR) for IMU, ADS, onboard GPS, FC, AP and other systems.

On the other hand, redundancy may not improve the reliability system if DSD have a failure rate below the acceptable mimimum level [11-14]. In addition, the number of the standby modules is limited to meet requirements concerning acceptable weight, size, power consumption, cost and other UAV characteristics.

Developers are often faced with complex problems as for making important decisions for systems design within a limited time. For example, it is necessary to choose the rational structure of FCS among many variants of its components redundancy and ensure achieving all critical requirements. In the absence of adequate reliability models answers to such questions are usually given based on either expert

evaluations or simplified models. For instance, to evaluate reliability of fault tolerant systems with N-modular redundancy the designers use models without considering real effectiveness of detection devices [6-9].

Reliability engineers usually perform reliability prediction of the military product using relevant procedures and methods presented in MIL-HDBK-217, other standards and reference books. The prediction methods are selected in view of reliability data availability, i.e., data about the distribution law for the product failure-free operation time [15-18]. There are specialized software tools (for instance, RAM Commander developed by ALD Reliability Engineering Ltd.) that support the reliability prediction procedures. Such software is oriented on the reliability analysis of series and parallel systems. Optionally, that software can also be used for computing the reliability of fault tolerant systems with complex reliability behavior, for example, a flight computer with implementation of majority-voting system 2-out-of-3 microprocessors and inherent standby microprocessor [10, 19]. For this purpose, engineers should develop and implement proper Markov reliability models with sufficient level of adequacy.

The reliability behavior of FCS and its components can be represented in form of discrete-continuous stochastic system [7, 9-14, 18]. The mathematical representation of Markov's model was proposed for reliability synthesis for FCS components. Hence, the modified space state methods [9, 19, 20] were used to develop reliability models of FCS components.

2   Rationale for Fault Tolerant Flight Computer Redundancy

2.1   Flight Computer Reliability Model with Account of Detection and Switching Effectiveness

In this paper, we investigated two variants of fault-tolerant flight computer (FTFC) design with implementation of majority-voting system (MVS) 2-out-of-3 microprocessors (MPs): 1) no additional standby MPs; 2) with inherent standby microprocessor as well as detection and switching devices.

A block-diagram of the second variant of FTFC design is depicted in Fig. 2, where MP is a microprocessor (there are three MPs in MVS core (MP_1, MP_2, MP_3) and one MP_R in standby mode),VU is a voting unit, FD is a fault detector and KF- 2 is a Kalman filter.
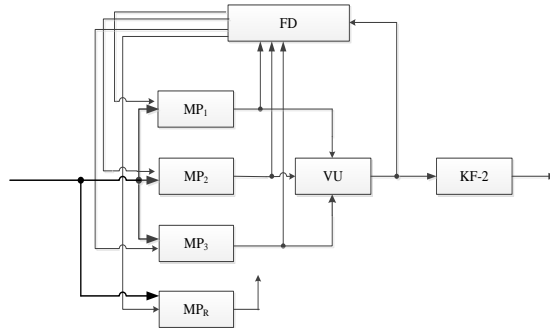
Fig. 2. Block diagram of flight computer with implementation of majority-voting system 2-out-of-3 microprocessors and inherent standby microprocessor

The fault detector provides failure detection of MVS core microprocessors. It compares MP's (MP_1, MP_2, and MP_3) out signals and the KF-2 input signal. If these signals are not identical, FD transfers a signal about failure of the certain MP and a command to the idle MP_R to switch to corresponding VU input.

The MP software failure rate is much higher than the MP hardware failure rate [19]. The detection procedure starts when the MP software failure is found. The MP software is restarted after this procedure. If the MP software restart is successful, the MP continues information processing. In case of unsuccessful software restart, FD determines a MP failure.

The Kalman filter KF-2 performs linear quadratic estimation of system state, thus its reliability is much higher, than for other components. The problem of providing its fault-tolerance was not considered in the paper.

On the first stage, the model was developed in the form of Markov Chain on the ground of basic events [9, 20].

1) The basic events (BE) definition: BE-1 "Failure of MP"; BE-2 "Failure of VU"; BE-3 "Completion of detection procedure"; BE-4 "Completion of MP_R switching procedure". Since durations of the detection procedure, T_D, and MP_R switching procedure, T_S, much less than the durations of failure-free operation of MP and VU, it is accepted that $T_D \approx 0$ and $T_S \approx 0$.

The detection and switching procedures are characterized by effectiveness measures: the probability of successful failure detection, P_D, and probability of successful completion of MP_R switching procedure, P_S. Their values are less than 1. Therefore, in the mathematical model the events BE-3 and BE-4 are concurrent with BE-1. For these events, we use notations: CBE-3 and CBE-4. For representation of consequences of these events, the probabilities of successful and unsuccessful detection and switching are taken into account. In addition, the model includes next measures: λ_{MP} – failure rate of MPs and λ_{VU} – failure rate of VU.

2) Rationale for components of state vector, which represent state of research object.

State vector consists of three components: V1; V2 and V3. Component V1 represents a current value of number of operating MPs in MVS core: V1 = 3 (three operating MPs); V1 = 2 (two operating MPs), V1 = 1 (one operating MP); initial

value V1 = 3. V2 represents a state of VU: V2 = 1 (operating), V2 = 0 (failed); initial value V2 = 1. V3 represents a state of MP_R: V3 = 1 (operating), V3 = 0 (failed); initial value V3 = 1. The system is in critical failure (CF) state, when there is one operating MP or the failed VU: (V1 = 1) OR (V2 = 0).

3) Development of state space diagram on the ground of basic events (Table 1).

The input data are the basic events of reliability behavior algorithm of FTFC; components of state vector; reliability measures of MPs and VU; measures of DSD effectiveness.

Table 1. State space diagram for flight computer

Step	Previous state and actual BE	Probability of alternative continuation of process	Next State after BE V1	V2	V3	State	Transition from State to State	Computational formula for the BE rate
1	Initial State	–	3	1	1	1	–	–
2	1BE-1 (CBE-3, CBE-4)	$1–P_d$	2	1	1	2	$1 \rightarrow 2$	$3\lambda_{MP}(1–P_d)$
		P_dP_s	3	1	0	3	$1 \rightarrow 3$	$3\lambda_{MP}P_dP_s$
		$P_d(1–P_s)$	2	1	1	2	$1 \rightarrow 2$	$3\lambda_{MP}P_d(1–P_s)$
3	1BE-2	–	3	0	1	CF	$1 \rightarrow CF$	λ_{VU}
4	2BE-1 (CBE-3, CBE-4)	$1–P_d$	1	1	1	CF	$2 \rightarrow CF$	$2\lambda_{MP}(1–P_d)$
		P_dP_s	2	1	0	4	$2 \rightarrow 4$	$2\lambda_{MP}P_dP_s$
		$P_d(1–P_s)$	1	1	1	CF	$2 \rightarrow CF$	$2\lambda_{MP}P_d(1–P_s)$
5	2BE-2	–	2	0	1	CF	$2 \rightarrow CF$	λ_{VU}
6	3BE-1 (CBE-3, CBE-4)	–	2	1	0	4	$3 \rightarrow 4$	$3\lambda_{MP}$
7	3BE-2	–	3	0	0	CF	$3 \rightarrow CF$	λ_{VU}
8	4BE-1 (CBE-3, CBE-4)	–	1	1	0	CF	$4 \rightarrow CF$	$2\lambda_{MP}$
9	4BE-2	–	2	0	0	CF	$4 \rightarrow CF$	λ_{VU}

On the second stage, FTFC structural-automaton model (SAM) was developed. The input data were the basic events and state space diagram. In accordance with methods presented in [9, 20], the following components of SAM were defined (Table 2):

Table 2. Structural-automaton model of fault-tolerant flight computer

Events	Formalized presentation of situations	CFER	RMC
BE-1.1	1. (V1=3) AND (V2=1) AND (V3=1)	$3\lambda_{MP}(1 - P_d)$	V1:=2
		$3\lambda_{MP}P_dP_s$	V3:=0
		$3\lambda_{MP}P_d(1 - P_s)$	V1:=2
BE-1.2	2. (V1=2) AND(V2=1) AND (V3=1)	$2\lambda_{MP}(1 - P_d)$	V1:=1
		$2\lambda_{MP}P_dP_s$	V3:=0
		$2\lambda_{MP}P_d(1 - P_s)$	V1:=1
BE-1.3	3. (V1=3) AND (V2=1) AND (V3=0)	$3\lambda_{MP}$	V1:=2
BE-1.4	4. (V1=2) AND (V2=1) AND (V3=0)	$2\lambda_{MP}$	V1:=1
BE-2	1. ((V1 = 2) OR (V1 = 3)) AND (V2 = 1) AND ((V3 = 0) OR (V3=1))	λ_{VU}	V2:=0

formalized description of all situations, in which each of the basic events can take place (BE-1 takes place in four separate situations: BE-1.1; BE-1.2; BE-1.3; BE-1.4);

computational formulas for the basic event rate (CFER);

rules of modification of components of state vector (RMC).

The third stage of development of FTFC reliability model is an automated building of state space diagram using SAM and specialized software "ASNA-1". Based on the verified state space diagram, the mathematical reliability model of FTFC in the form of system of differential Chapman - Kolmogorov equations (1) was formed

$$
\begin{cases}
\dfrac{dP_1(t)}{dt} = -P_1(t) \times \left(3\lambda_{MP} \times P_D \times P_S + 3\lambda_{MP} \times (1-P_S) \times P_D + 3\lambda_{MP} \times (1-P_D) + \lambda_{VU}\right), \\[2mm]
\dfrac{dP_2(t)}{dt} = -P_2(t) \times \left(2\lambda_{MP} \times (1-P_D) + 2\lambda_{MP} \times (1-P_S) \times P_D + 2\lambda_{MP} \times P_D \times P_S + \lambda_{VU}\right) + \\[1mm]
+ P_1(t)\left(3\lambda_{MP} \times (1-P_S) \times P_D + 3\lambda_{MP} \times (1-P_D)\right), \\[2mm]
\dfrac{dP_3(t)}{dt} = -P_3(t) \times \left(\lambda_{VU} + 3\lambda_{MP}\right) + P_1(t) \times 3\lambda_{MP} \times P_S \times P_D, \\[2mm]
\dfrac{dP_4(t)}{dt} = -P_4(t) \times \left(\lambda_{VU} + 2\lambda_{MP}\right) + P_2(t) \times 2\lambda_{MP} \times P_S \times P_D + P_3(t) \times 3\lambda_{MP}, \\[2mm]
\dfrac{dP_5(t)}{dt} = \lambda_{VU} P_1(t) + (\lambda_{VU} - 2\lambda_{MP} \times P_S \times P_D + 2\lambda_{MP}) P_2(t) + \lambda_{VU} P_1(t) + (\lambda_{VU} + 2\lambda_{MP}) P_4(t)
\end{cases}
\tag{1}
$$

where $P_i(t)$ is probability of system being in State i ($i \in 1,...,5$) at time t.
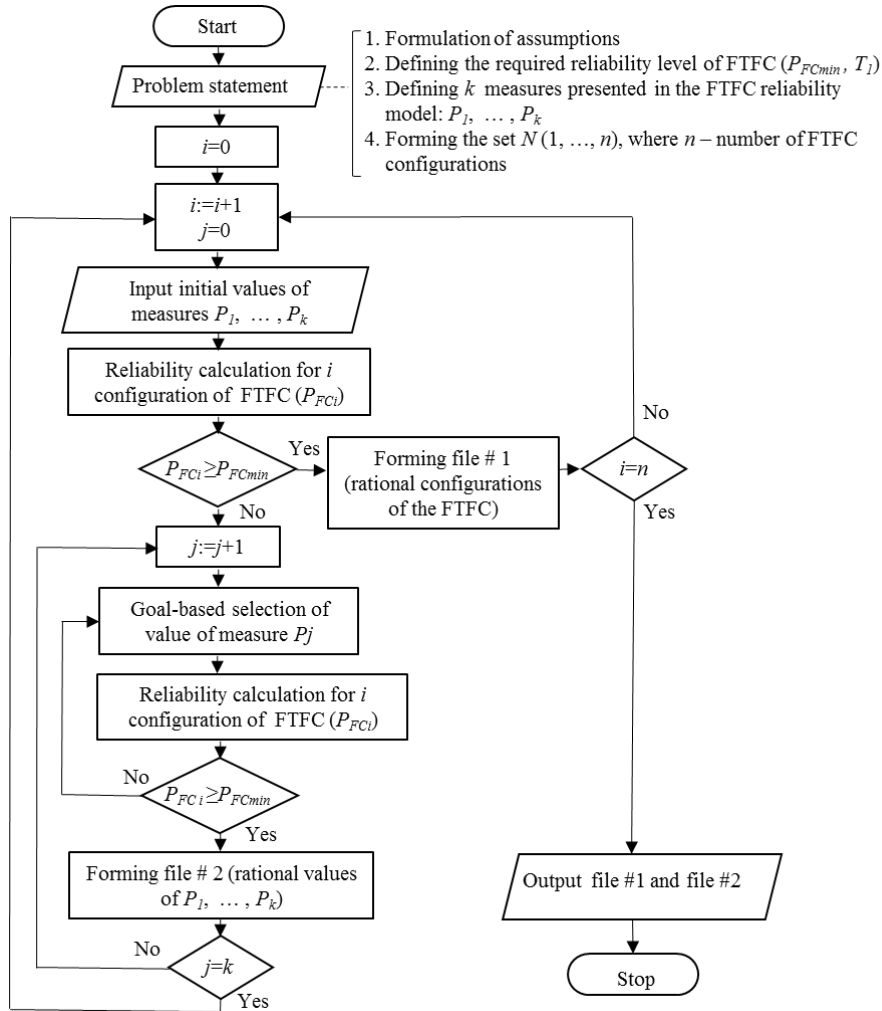
2.2 Reliability Synthesis Methods for Fault-Tolerant Flight Computer

Reliability synthesis for fault-tolerant flight computer focuses primary on solving two problems: 1) rationale for choice of FTFC design; 2) rationale for reasonable reliability measures of FTFC components. Proposed methods (Fig. 3) are developed to aid in solving these problems and based on reliability model of FTFC.

An example of practical use of proposed methods is given below.

The problem statement:

1) FC components and units have constant failure rates;

2) failure rates of MPs in MVS core equal MP_R failure rate;

3) required reliability level is a minimum allowable value of FC reliability P_{FCmin} during the time interval 0 to T_1;

4) four measures $P_j(t)$ ($j \in 1,...,4$), where $P_1 = \lambda_{MP}$, $P_2 = \lambda_{VU}$, $P_3 = P_D$, $P_4 = P_S$;

5) two above mentioned variants of FTFC design.

Fig. 3. Flowchart of reliability synthesis for fault-tolerant flight computer

We assumed that a designer uses following input data: T_1 = 500 hours (mean time of UAV's overhaul life is 500 hours); P_{FCmin} = 0,999; and initial values of measures: λ_{MP} = 1,8e-5 hr^{-1}; λ_{VU} = 2,9e-6 hr^{-1}; $P_D = P_S$ = 0,999.

The computation results (Fig. 4) reveal that during the time interval 0 to T_1 the value of FC reliability:

for the 1st variant of FTFC design $P_{FC}(500) = P_{FC1}$ = 0,99881 is less than P_{FCmin} that does not meet the set requirements;

for the 2nd variant of FTFC design $P_{FC}(500) = P_{FC2}$ = 0,99904 is more than P_{FCmin}.
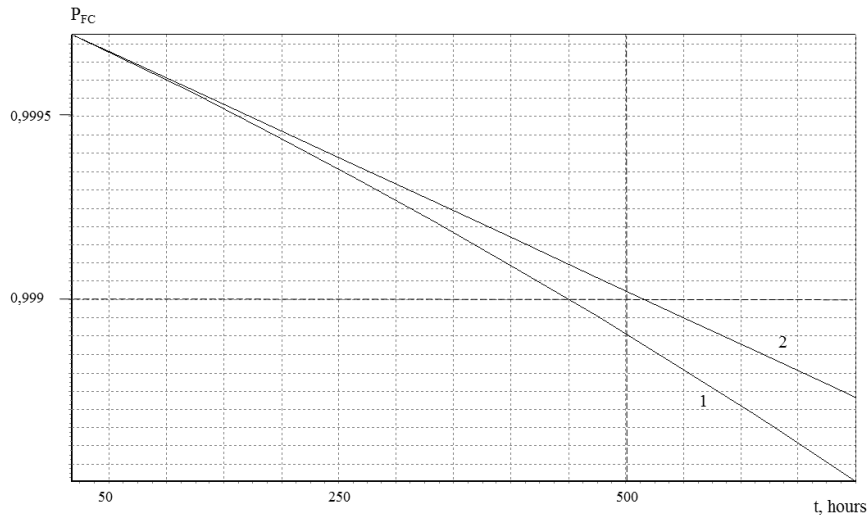
Fig. 4. Graphs of flight computer reliability: 1 – no additional standby microprocessors; 2 – with inherent standby microprocessor

The researches, using the above-mentioned input data, allow rationalizing reliability requirements to FTFC components and drawing next conclusions:

1. In order to maintain required reliability level of FTFC without standby MPs in MVS core, it is necessary to rise reliability requirements to MPs ($\lambda_{MP} \leq$ 8e-5 hr^{-1}) or VU ($\lambda_{VU} \leq$ 2,3e-6 hr^{-1}) reliability.

2. FTFC design with implementation of MVS 2-out-of-3 MPs and inherent MP as well as DSD allows increasing reliability to required level without changing requirements to reliability of MPs and VU. In addition, it is possible to scale back requirements to DSD effectiveness.

3. Using the proposed methods and set input data, we can advise the UAV designer two above examined variants of FTFC as its reasonable configurations.

3 Reliability Synthesis for Fault-Tolerant Navigation System Components

3.1 Rationale for Navigation System Components Redundancy

Reliability block diagrams for two navigation system configurations: 1) without redundancy; 2) with dual modular redundancy (DMR) for gyroscopes and accelerometers in inertial measurement unit (IMU), are depicted in Fig. 5. The denotation IS was used for the integrated subsystem, which includes two parts: air data subsystem (ADS); magnetometer (MM).
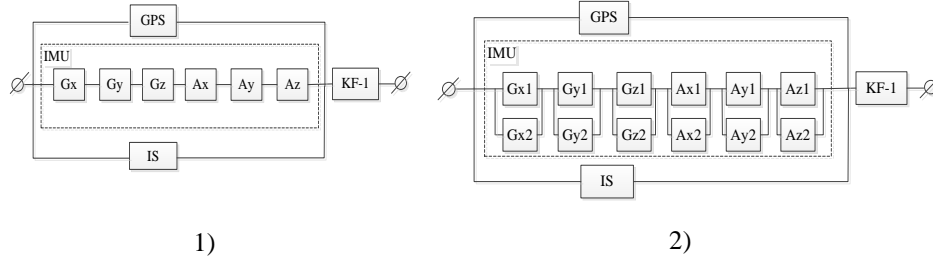
Fig. 5. Reliability block diagram of navigation system: 1) without redundancy for gyroscopes and accelerometers; 2) with dual redundancy for gyroscopes and accelerometers

Multi-sensor information redundancy is implemented in NS. It should provide required level of reliability. The task is to define the expedient values of reliability measures of NS components. Failure rates of NS components are chosen as reliability measures: λ_1 is failure rate of the onboard GPS; $\lambda_2 = \lambda_3 = \lambda_4 = \lambda_G$ – failure rates of gyroscopes (G_x, G_y, G_z); $\lambda_5 = \lambda_6 = \lambda_7 = \lambda_A$ – failure rates of accelerometers (A_x, A_y, A_z); λ_8 is failure rate of IS (sum of failure rates of ADS, MM and PS); λ_9 is failure rate of KF-1. Since main and standby gyroscopes and accelerometers have the same circuitry, so their failure rates are equal.

Kalman Filter KF-1 performs linear quadratic estimation and integration of the data from GPS, IMU and IS [12]. A failure of KF-1 causes a failure of navigation system. That is why there is a necessity to rationalize using KF-1 fault-tolerant design, for example, dual redundant Kalman Filter or implementation of majority-voting structure.

Onboard GPS is a main source of the navigation data [3, 4, 12]. It is accepted that a signal from global GPS comes securely. If onboard GPS is failed and IMU is in operating state, the navigation data comes from IMU. When onboard GPS and IMU are failed, integrated subsystem supplies the navigation data.

Reliability calculation was conducted for two above-mentioned variants of NS structure (Fig. 5). For the second configuration it considered that DSDs perform their functions with probability of successful failure detection $P_D = 1$ and probability of successful completion of switching procedure $P_S = 1$. It was assumed that duration of all processes and procedures, which take place in NS, are distributed according to an exponential law.

It considered that the designer uses the next input data for reliability synthesis for NS: time interval $T_1 = 500$ hours; minimum allowable value of NS reliability $P_{NSmin} = 0,999$; initial values of failure rates of NS components: $\lambda_1 = 3\text{e-}4$ hr^{-1}; $\lambda_G = 9\text{e-}5$ hr^{-1}; $\lambda_A = 6\text{e-}5$ hr^{-1}; $\lambda_8 = 4\text{e-}4$ hr^{-1}, $\lambda_9 = 1,6\text{e-}6$ hr^{-1}.

The computation results for two variants of NS proved expediency of DMR for gyroscopes and accelerometers in IMU. Reliability value for the 1st variant of NS is $P_{NS}(500) = P_{NS1} = 0,99411$ that less than P_{NSmin}. Implementation of dual redundancy for gyroscopes and accelerometers allows to increase NS reliability to the value $P_{NS}(500) = P_{NS2} = 0,99903$ and provide required reliability level on the interval of $T_2 = 845$ hr. These conclusions were drawn considering that DSD perform their

functions with probability equals 1. To raise adequacy of NS reliability model it was proposed to develop a reliability model of fault-tolerant unit with dual modular redundancy and taking into account the real DSD effectiveness: $P_D < 1$ and $P_S < 1$.

3.2 Reliability Model of Fault-Tolerant Unit with Dual Redundancy and Taking into Account Detection and Switching Devices Effectiveness

A reliability model was developed according to the methods presented in [9, 20]:

1) Forming a verbal model of fault-tolerant unit (FTU).

The model includes reliability measures (λ_M – failure rate of the main part and λ_R – failure rate of standby part of FTU) and DSD effectiveness measures (probability of successful completion of detection procedure – P_D and probability of successful completion of switching procedure – P_S).

A detection device controls continuously operability of the main FTU part. If detection procedure is successful (the detection device defines a failure of the main part), the detection device will transfer a signal to the switching device that unhooks the main part and hooks up the standby part.

If detection procedure is unsuccessful, fault-tolerant unit will come to state of critical failure. In addition, FTU will come to state of critical failure, if detection procedure is successful but the switching procedure is unsuccessful.

2) The state vector consists of two components: V1 – a state of main part (1, 0; initial value V1 = 1); V2 – a state of standby part (1, 0; initial value V2 = 1).

The basic events of reliability behavior of FTU: BE-1 – "Failure of main part"; BE-2 – "Completion of detection procedure"; BE-3 – "Completion of switching procedure"; BE-4 – "Failure of standby part".

3) The fault-tolerant unit is in critical failure state, when there is a failed main part and standby part is not hooked up: V1 = 0.

The developed state space diagram for the investigated FTU with dual redundancy and taking into account DSD effectiveness is presented in Table 3.

The model simplification was used on the basis that the research object is described by one group of procedures with long duration and another group of procedures with much less duration. This condition simplifies the model however reduces the degree of its adequacy. The detection procedure is auxiliary in the structure of FTU. If do not take into account duration of procedure in 20 ms, computation of FCS reliability for the UAV flight time interval (up to 10 hours) brings not significant error. For the proposed mathematical model, the next simplifications were done: duration of detection procedure $T_D = 0$ and switching procedure – $T_S = 0$. Accordingly, the basic events BE-2 and BE-3 are concurrent with BE-1 and got denotations CBE-2 and CBE-3.

Table 3. State space diagram for fault-tolerant unit with dual modular redundancy and taking into account detection and switching effectiveness

Step	Previous State and actual BE	Probability of alternative continuation of	Next State after BE	State	Transition from State to State	Computational formula for the BE rate

		process	V1	V2			
1	Initial state	–	1	1	1	–	–
2	1BE-1 (CBE-2, CBE-3)	$(1–P_D)$	0	1	CF	1 → CF	$\lambda_M(1–P_D)$
		$P_D P_S$	1	0	2	1 → 2	$\lambda_M P_D P_S$
		$P_D(1–P_S)$	0	1	CF	1 → CF	$\lambda_M P_D(1–P_S)$
3	1BE-4	–	1	0	2	1 → 2	λ_R
4	2BE-1 (CBE-2)	$(1–P_D)$	0	0	CF	2 → CF	$\lambda_M(1–P_D)$
		P_D	0	0	CF	2 → CF	$\lambda_M P_D$

It was taken into account that the duration of all procedures in research object are random variables having an exponential distribution, and a number of events on the observation interval is defined by the Poisson distribution. In accordance with the methods presented in [9, 20], the components of FTU structural-automaton model were formed (Table 4).

Table 4. Structural-automaton model of fault-tolerant unit with dual modular redundancy and taking into account detection and switching effectiveness

Basic event (concurrent basic events)	Formalized presentation of situations	CFER	RMC
BE-1 "Failure of main part" (CBE-2, CBE-3)	1. (V1=1) AND (V2=1)	$\lambda_M P_D P_S$	V2:=0
		$\lambda_M(1 – P_D)$	V1:=0
		$\lambda_M P_D(1 – P_S)$	V1:=0
	2. (V1=1) AND (V2=0)	$\lambda_M P_D$	V1:=0
		$\lambda_M(1 – P_D)$	V1:=0
BE-4 "Failure of standby part"	1. (V1=1) AND (V2=1)	λ_R	V2:=0

The mathematical reliability model of fault-tolerant unit (2) was formed

$$\begin{cases} \dfrac{dP_1(t)}{dt} = -(\lambda_M + \lambda_R)P_1(t), \\[2mm] \dfrac{dP_2(t)}{dt} = (\lambda_M P_D P_S + \lambda_R)P_1(t) - \lambda_M P_2(t), \\[2mm] \dfrac{dP_3(t)}{dt} = \lambda_M(1 - P_D P_S)P_1(t) + \lambda_M P_2(t). \end{cases} \tag{2}$$

where $P_i(t)$ is probability of system being in State i ($i \in 1,\dots,3$) at time t.

3.3 Estimation of Reliability Measures for Navigation System and its Components in view of Detection and Switching Effectiveness

The same assumptions and input data were used as in the section 3.1. Results of reliability estimation for the 2nd variant of NS and its components (units of gyroscopes

(UG) and accelerometers (UA)) with perfect and non-perfect DSD are presented in Table 5.

Table 5. Results of reliability estimation for the 2nd variant of NS and its components in view of detection and switching effectiveness

Input data			Output data		
DSD	P_S	P_D	$P_{UG}(500)$	$P_{UA}(500)$	$P_{NS2}(500)$
perfect	1	1	0,9981	0,9991	0,99903
non-perfect	0,999	0,999	0,9979	0,9989	0,99901
	0,99	0,99	0,9974	0,9982	0,99892
	0,94	0,99	0,9957	0,9978	0,99871
	0,98	0,98	0,9967	0,9979	0,99884

The graphs of UG reliability at different values of DSD effectiveness are shown in Fig. 6.
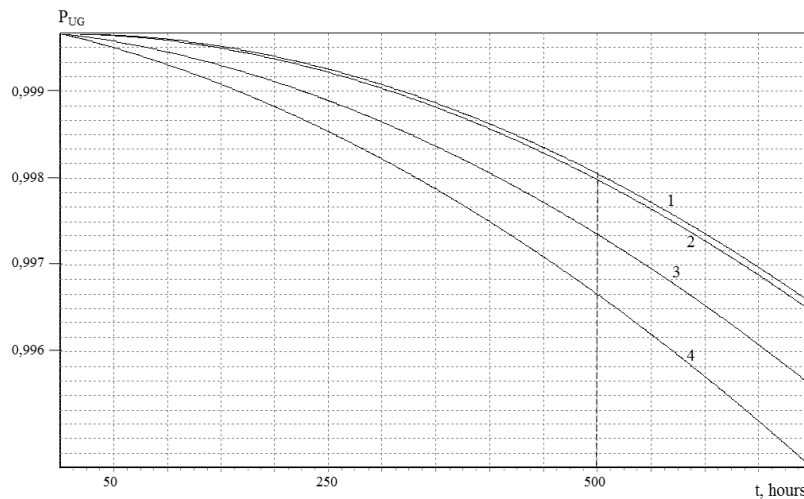
Fig. 6. Graphs of UG reliability at different values of P_D and P_S: 1 – $P_D = P_S = 1$; 2 – $P_D = P_S = 0,999$; 3 – $P_D = P_S = 0,99$; 4 – $P_D = P_S = 0,98$

The results, presented in Table 5 and Fig. 6, confirm that reliability depends on the detection and switching effectiveness. The proposed model gives an opportunity to rationalize necessary values of measures of DSD effectiveness.

3.4 Reliability Synthesis Methods for Navigation System Components

Proposed reliability synthesis methods are developed for fault-tolerant NS components. They are based on reliability models of NS components and use of

specialized software ASNA-1. The main difference of these methods from the mentioned above methods (section 2.2) is that for reliability synthesis for NS we can investigate rational variants of fault-tolerant modules (units). Using reliability synthesis methods for FC we evaluated fault-tolerant units with DMR for gyroscopes, accelerometers, Kalman Filter (KF-1). We used following input data: $T_l = 500$ hours; $P_{NSmin} = 0,999$. The computation results, which indicate reasonable reliability measures of NS components, are presented in Table 6.

Table 6. Rational reliability measures of NS components at different values of P_D and P_S

Input data		Output data		
P_S	P_D	λ_G , hr $^{-1}$	λ_A, hr $^{-1}$	λ_9, hr $^{-1}$
0,98	0,99	6,4e-5	3,7e-5	2,4e-5
0,96	0,99	5,5e-5	2,8e-5	1,7e-5
0,94	0,99	4,4e-5	2,4e-5	1,3e-5
0,92	0,98	3,7e-5	1,8e-5	9,1e-6
0,9	0,97	2,6e-5	1,6e-5	7,4e-6

Hence, these methods allow adjusting with designer the acceptable values of reliability measures of NS components as well as measures of DSD effectiveness.

4   Conclusions

1. A necessity and actuality of improvement of existent models and methods of reliability synthesis for fault-tolerant systems have been rationalized in making decisions on design of UAV flight control system.

2. The developed reliability models of navigation system and flight computer represent the different variants of fault-tolerant designs and have a high level of adequacy.

3. Based on the models, we proposed the reliability synthesis methods for components of UAV flight control system. Automation of multiple analysis procedures allows quickly (during a few hours) making reasonable design decisions.

4. Reliability requirements and recommendations for rational choice of fault-tolerant designs of navigation system and flight computer have been developed to meet required reliability level.

5. We are planning further research studies to investigate reliability of UAV autopilot and its fault-tolerant modules, availability of all FCS components as well as solving optimization problems.

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