Reliability-Oriented Approach for UAV Flight Control System Structural Optimization

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Abstract. This paper presents a reliability-oriented approach for solving structural optimization problem for UAV flight control system. The system and its components reliability is used as the basis for taking optimum design decisions. The proposed optimization technique is based on improved reliability models for the system components and their fault-tolerant configurations. It enables increasing results certainty to find an optimum variant of flight control system structure with minimum expenditure of technical resources, meeting required reliability level, flight duration and regularity of operations, observing principal constraints (weight, power consumption and overall cost), taking different maintenance and repair modes into consideration.

Keywords. Unmanned aerial vehicle (UAV), flight control system, structural optimization, reliability model, fault-tolerant system.

Key Terms. Structural Design Optimization, Mathematical Modeling, Markov model

1 Introduction

UAVs' reliability is one of the key factors that impacts on their effectiveness, which is characterized by their flight duration and regularity of operations. More than a quarter of all UAV failures are caused by flight control system (FCS) failures [1-3]. This system implements various degrees of UAV autonomy and its reliability does not satisfy requirements. Therefore, a vital task is to achive required FCS reliability level as early as on the design stage. There are three major approaches for solving these issues [1, 4-7]:

fault tolerance based on redundancy with use of effective detection and switching devices (DSD);

fault avoidance with improvement of failure-critical subcomponents reliability;

and forming expedient strategies and modes of maintenance and repair.

All these methods have own advantages and disadvantages, and their application should be validated in terms of all phases of the FCS life cycle. Above all, reliability improvement through fault-tolerant FCS configurations is limited to save resources and meet requirements concerning acceptable weight, size, power consumption, overall cost and other important UAV characteristics [1, 4-6]. In addition, the approach to use FCS components with higher reliability elements is very expensive. On the other hand, maintenance cannot improve the inherent reliability that is obtained during design and manufacture [4]. Different maintenance and repair modes (MRM), which vary with frequency, rate and volume of works, can only hold on the inherent reliability level.

Using flight control system with low reliability and without redundancy precipitates completing both operative and line maintenance. In turn, it causes extra staffing of unmanned aircraft system sections with highly skilled maintenance specialists. As result, this approach provides minimum time for UAV withdrawal from operation, and on the other hand, makes increasing in operating and support costs, and lowering mobility of unmanned aircraft system sections. Creation of centralized workshops in unmanned aircraft system units extends the time of UAVs withdrawal from operation that results in decreasing of UAV availability.

Using addition of redundancy can improve reliability as well as increase maintenance rate (interval between maintenance (operation restoring) works) to the needed value, for example, mean time of UAV's overhaul life. In this case, operation for flight control system can be reduced to the operative forms and its operating and support costs will diminish. Although, this advantage is accompanied by increasing of technical resources (weight, size and power consumption), as well as redundancy may not improve the system reliability if, for instance, DSD have a failure rate below the acceptable mimimum level [4, 5].

If simplified reliability models are used for redundancy amount calculation, then in practice the field FCS reliability will be often below expected level, which was determined during design. Moreover, if for FCS reliability estimation the conservative (for example, overestimated on 5-10%) values of reliability parameters are used, then amount of redundancy, and consequently system complexity, expenditure of technical resources, and cost of design, engineering and procurement will unreasonably increase.

Hence, the predicted FCS reliability must corresponds to required level with consideration for specified resource constraints and rationale for appropriate redundancy approach and redundancy amount. Accordingly, in order to make optimum decisions for FCS structure design within a limited time there is necessity to:

1) give grounds for expedient fault-tolerant configurations of FCS components;

2) develop reliability models for FCS fault-tolerant units with a high level of adequacy, in which besides reliability parameters of main and standby parts taken into account:

effectiveness parameters for detection equipment (probability of successful failure detection, rate of false alarm), and diagnostics and switching devices;

prediction on the amount of undetected software failures for computer-based modules, and variants of troubleshooting technics;

parameters for maintenance and repair strategies (repair duration and repairs amount);

maintenance organization effectiveness parameters;

3) have a structure optimization technique, which includes optimization methods, criteria and constraints. In essence, it is one of the desigh instruments that supports ensuring required reliability level and mission requirements package implementation, including expected UAV's flight duration and operations regularity, with a minimum expenditure of technical-economic resources, as well as observing accepted resources constraints. Moreover, the technique should be based on increasing automation in design decision-making procedures, since the permanent rapid updating of UAV avionics causes the time reduction on its development.

The conducted analysis has shown an absence of above-mentioned models as well as valuable optimization technique that defined actuality of this research.

2 Rationale for Flight Control System Redundancy

This system contains three main components (Fig. 1) [1-3, 7]: navigation subsystem, flight computer and autopilot. All these components are failure-critical and the least reliable elements for navigation subsystem – gyroscopes and accelerometers, flight computer – microprocessors and autopilot – all its main parts.

Based on structure analysis for UAVs' flight control systems with variety redundancy techniques, next variants of FCS components design were chosen for research:

1) three design variants for navigation subsystem:

the 1st – without redundancy;

the 2nd – with bimodal parallel/series redundancy for gyroscopes and accelerometers;

the 3rd – with bimodal series/parallel redundancy for gyroscopes and accelerometers;

2) two design variants for flight computer with majority voting redundancy 2-out-of-3 microprocessors (MPs):

the 1st – without additional standby MP;

the 2nd – with inherent standby MP;

3) three design variants for autopilot:

the 1st – without redundancy;

the 2nd – with simple parallel redundancy for main elements of control unit, three servo units and power controller, with use majority voting structure (MVS) 2-out-of-3 for each flight surfaces position sensors;

the 3rd – three parallel control units are used instead of two parallel control units additionally to the 2nd variant.

The well-known reliability models for systems with voting logic 2-out-of-3 without additional standby parts have a sufficient adequacy level [5, 8]. Therefore, only four types of fault-tolerant units (FTU) and their configurations were selected to raise adequacy level for their reliability models: bimodal parallel; bimodal series and three component redundancy, and majority voting redundancy 2-out-of-3 with inherent standby element.

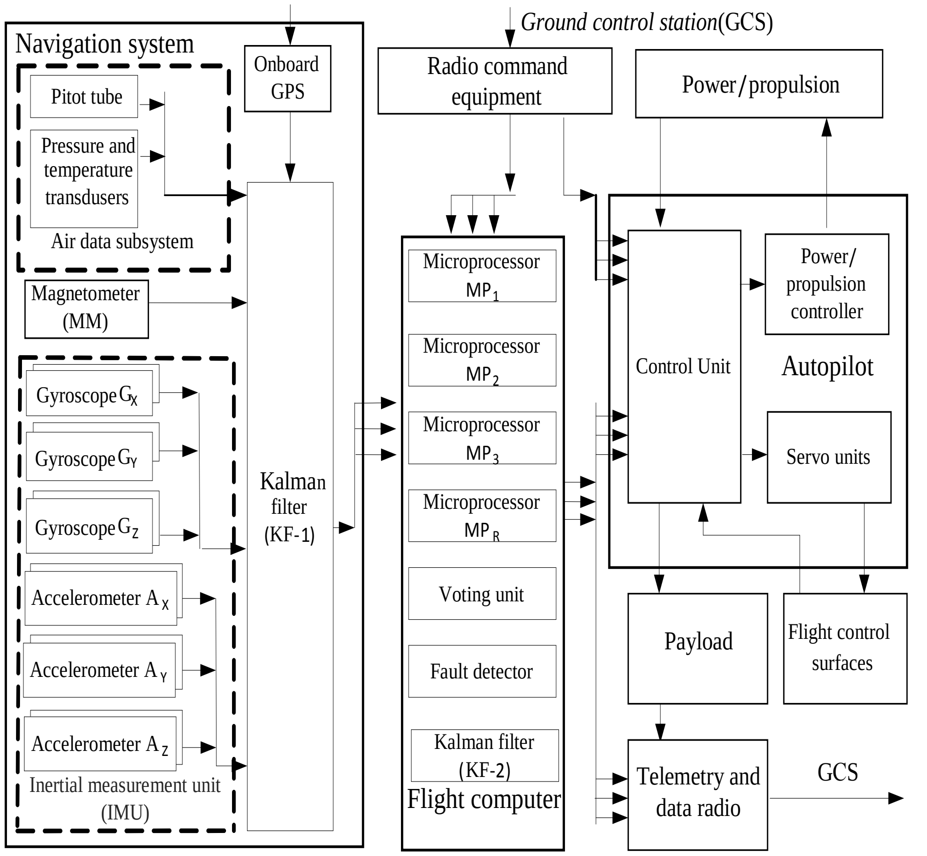

Fig. 1. Flight control system architecture

3 Improved Reliability Models for Flight Control System Fault-Tolerant Units

Reliability of fault-tolerant units depends not only on reliability of their main and stanby elements, redundancy technique and amount of redundancy. It also is affected by effectiveness of equipment, which detects faults, diagnoses and isolates them, reconfigures such units [4-6, 8].

Most of known reliability models for various types of hardware redundancy are obtained with assumption, that perfect DSD are used to support fault tolerance [5, 8-11]. Effectiveness of the ideal detection devices are mainly specified by false alarm rate $\lambda_{FA} = 0$ and probability of successful failure detection $P_D = 1$. Perfect switching equipment is characterized by probability of successful switching procedure completion $P_S = 1$.

In other models, only effectiveness of imperfect detection or switching devices is taken into account [9-11]. Furthermore, the above-mentioned models do not represent the performance features of equipment that connects backups. For instance, these approaches do not consider that switching procedure consists of two operations: unhooking main element (ME) and hooking standby element (SE). Consequently, it has four completion alternatives. One of such alternatives is named "opposing connection" (failed ME unhooking and successful SE hooking) and examined as a conflict situation which results FTU failure.

The reliability behavior of flight control system and its components can be represented in form of discrete-continuous stochastic system [12-14]. Hence, the Markov method and modified space states technology [12] were chosen to raise reliability models adequacy. This approach allows considering complex FTUs' reliability behavior and reducing the models development time. The technology stipulates the formalized representation of research object as structural-automaton model. Development of reliability models for the above-mentioned FTUs (Section 2), is broken down into five stages:

1) developing Markov model on the ground of basic events;

2) forming structural-automaton model in form of modification rules tree for state vector components;

3) structural-automaton model verification and validation;

4) automated building of state space diagram using structural-automaton model and specialized software ASNA-1;

5) forming differential Chapman – Kolmogorov equations set.

It was taken into account that all FCS components (elements) failures are independent and they are considered as critical failures (CF) if they result in complete or partial loss of the system performance. In addition, it was assumed that durations of all procedures in research objects are random variables having an exponential distribution, and a number of events on the observation interval is defined by the Poisson distribution.

3.1 Improved Reliability Model for Fault-Tolerant Unit with Bimodal Parallel/Series Redundancy

Reliability models for each of three FTUs with bimodal parallel/series redundancy for gyroscopes and accelerometers for the 2^{nd} navigation subsystem variant (discussed in Section 2), consist of two separate blocks. These blocks are gyroscopes unit and accelerometers unit with simple parallel redundancy (Fig. 2). Such approach allows initial building improved reliability model for FTU with simple parallel redundancy and on its basis forming mathematical model for FTU with bimodal parallel/series redundancy.

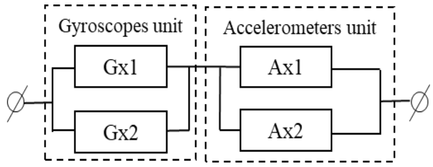

Fig. 2. Reliability block diagram of fault-tolerant unit with bimodal parallel/series redundancy for gyroscopes and accelerometers

On the first stage, according to the methods presented in [12, 13], the Markov model on the ground of basic events was developed. Active redundancy is used to provide continuous FTU performance with hooking standby element instead main element in case of its failure. The model includes elements reliability parameters: λ_M – ME failure rate and λ_R – SE failure rate.

Detection device continuously controls the ME state and does not control the SE operability. Detection procedure has two alternative completions:

successful – detection device defines the ME failure and transfers a signal to switching equipment with probability P_D;

failed (the 2nd type of control method errors) – detection device does not distinguish the ME failure with probability $(1 - P_D)$.

Detection device can give out a false alarm, which is classified as the 1st type of control method errors. In this case, detection device mistakes operating ME for failed with probability P_{FA}. False alarm rate λ_{FA} is defined as $1/T_{FA}$, where T_{FA} – mean time, when false alarm signal can be sent out from detection device with probability $P_{FA} = 1$.

If detection procedure is successful or in case of false alarm, the detection device will transfer a signal to switching device to start switching procedure. This procedure has four completion alternatives:

1) successful ME unhooking and hooking of operating or failed SE with probability P_S;

2) successful ME unhooking and failed SE hooking with probability P_{DN};

3) failed ME unhooking and SE hooking with probability P_{NN};

4) "opposing connection" with probability P_{NC}. Probability of successful switching procedure completion is determined from the formula:

$$P_S = 1 - \left(P_{DN} + P_{NC} + P_{NN}\right), \tag{1}$$

where $\left(P_{DN} + P_{NC} + P_{NN}\right)$ – probability of failed switching procedure completion.

Probability of successful procedure completion for ME isolation in case of its failure or false alarm is determined from the formula:

$$P_{SI} = 1 - P_{NC}\,. \tag{2}$$

The developed Markov model for fault-tolerant unit with simple parallel redundancy is shown in Fig. 3.

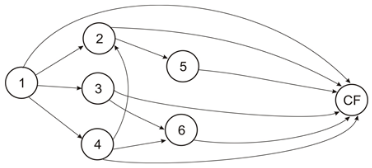

Fig. 3. Markov model for fault-tolerant unit with simple parallel redundancy

Mathematical reliability model for considered FTU is presented in form of differential Chapman – Kolmogorov equations set:

$$\begin{cases} dP_1(t)/dt = -(\lambda_M + \lambda_R + \lambda_{FA})P_1(t) \\ dP_2(t)/dt = (\lambda_M P_D P_S + \lambda_{FA} P_S)P_1(t) - (\lambda_M + \lambda_{FA}(1 - P_S + P_D))P_2(t) + \lambda_M P_D P_S P_4(t) \\ \dots \\ dP_6(t)/dt = \lambda_{FA} P_{NN} P_3(t) + \lambda_R P_4(t) - \lambda_M P_6(t) \end{cases} \quad (3)$$

where $P_i(t)$ is probability of system being in State i ($i \in 1$ ..., 7) at time t. State 7 corresponds to CF state in Fig. 3.

Here and in other stated below mathematical models, the equitations for critical failure states were replaced by the normalization requirement.

3.2 Improved Reliability Model for Fault-Tolerant Unit with Bimodal Series/Parallel Redundancy

Reliability block diagram of fault-tolerant unit with bimodal series/parallel redundancy (gyroscopes and accelerometers unit) is depicted in Fig. 4.

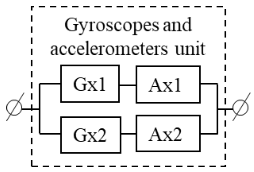

Fig. 4. Reliability block diagram of fault-tolerant unit with bimodal series/parallel redundancy for gyroscopes and accelerometers

Reliability model of such unit with active redundancy consists of two blocks: main block – two different-type main elements (ME1 and ME2) in series, and standby block – two standby elements (SE1 and SE2) in series. Two separate detection devices (DD1 and DD2) control respectively ME1 and ME2 operability and do not control the state of standby elements. Detection procedure for each main elements has two alternative completions:

successful – detection device DD1 or DD2 defines the main elements failure and transfers a signal to switching equipment with probabilitis P_{D1} and P_{D2};

failed (failure event ignoring) – detection device DD1 or DD2 does not distinguish failure of ME1 with probability $1 - P_{D1}$) or ME2 – with probability $(1 - P_{D2})$.

Detection devices also can give out false alarms with rate λ_{FA1}, λ_{FA2}.

In accordance with the technique presented in [12, 13]:

1) the corresponding Markov model (Fig. 5) was developed using main and standby elements reliability (λ_{M1}, λ_{M2}, λ_{R1} and λ_{R2}) and DSD effectiveness parameters (P_{D1}, P_{D2}, λ_{FA1}, λ_{FA2}, P_S, P_{DN}, P_{NC} and P_{NN});

2) mathematical model is formed as a differential Chapman – Kolmogorov equations set:

$$\begin{cases} dP_1(t)/dt = -(\lambda_{M1} + \lambda_{M2} + \lambda_{R1} + \lambda_{R2} + \lambda_{FA1}(P_S + P_{NN}) + \lambda_{FA2}(P_S + P_{NN}))P_1(t) \\ dP_2(t)/dt = (\lambda_{M1}P_{D1}P_S + \lambda_{M2}P_{D2}P_S + \lambda_{FA1}P_S + \lambda_{FA2}P_S)P_1(t) - \\ -(\lambda_{M1} + \lambda_{M2} + (\lambda_{FA1} + \lambda_{FA2})(P_S + P_{DN} + P_{NC}))P_2(t) + \\ + \lambda_{M2}P_{D2}P_S P_3(t) + \lambda_{M1}P_{D1}P_S P_4(t) + (\lambda_{M1}P_{D1}P_S + \lambda_{M2}P_{D2}P_S + \lambda_{FA2}P_S)P_5(t) + \\ + (\lambda_{M1}P_{D1}P_S + \lambda_{M2}P_{D2}P_S + \lambda_{FA1}P_S)P_6(t) + (\lambda_{M1}P_{D1}P_S + \lambda_{M2}P_{D2}P_S)P_{14}(t) \\ \ldots \\ dP_{20}(t)/dt = \lambda_{FA2}P_{NN}P_{16}(t) + \lambda_{FA1}P_{NN}P_{17}(t) + \lambda_{R2}P_{18}(t) + \lambda_{R1}P_{19}(t) - \\ -(\lambda_{M1} + \lambda_{M2})P_{20}(t) \end{cases} \tag{4}$$

where $P_i(t)$ is probability of system being in State i ($i \in 1$ ..., 21) at time t. State 21 corresponds to CF state in Fig. 5.

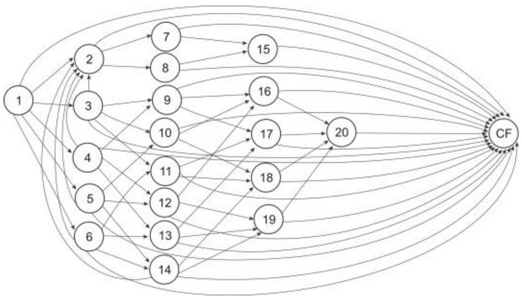

Fig. 5. Markov model for fault-tolerant unit with bimodal series/parallel redundancy

3.3 Improved Reliability Model for Fault-Tolerant Unit with Three-Component Redundancy

To achieve continuous performance of control unit and accordingly autopilot, the three-component active redundancy for this component was considered. This FTU includes main element, two standby elements (SE1 and SE2) in parallel and suitable detection and switching devices. Its fault-tolerant design enables the unit to continue operation with gradual reliability reducing after failure of main and two standby elements, which take ME position.

The reliability model is represented by reliability parameters (λ_{M1}, $\lambda_R = \lambda_{R1} = \lambda_{R2}$) and DSD effectiveness parameters (P_{D1}, P_{D2}, λ_{FA1}, λ_{FA2}, P_S, P_{DN}, P_{NC} and P_{NN}). The

Markov model for fault-tolerant unit with three-component redundancy is shown in Fig. 6.

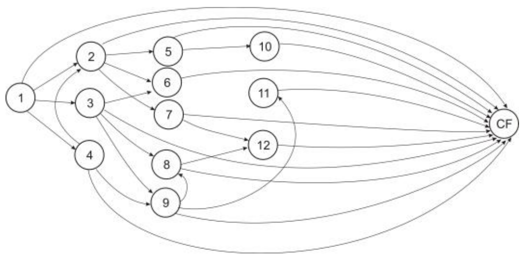

Fig. 6. Markov model for fault-tolerant unit with three-component redundancy

Mathematical reliability model for the considered FTU is presented in form of differential Chapman – Kolmogorov equations set:

$$\begin{cases} dP_1(t)/dt = -(\lambda_M + \lambda_R + \lambda_{FA})P_1(t) \\ dP_2(t)/dt = -(\lambda_M P_D P_S + \lambda_{FA} P_D)P_1(t) - (\lambda_M + \lambda_R + \lambda_{FA})P_2(t) + \lambda_M P_D P_S P_4(t) \\ \ldots \\ dP_{12}(t)/dt = \lambda_R P_7(t) + \lambda_{FA} P_{NN}(t) P_8(t) - \lambda_M P_{12}(t) \end{cases} \quad (5)$$

where $P_i(t)$ is probability of system being in State i ($i \in 1$ ..., 13) at time t. State 13 corresponds to CF state in Fig. 6.

3.4 Improved Reliability Model for Fault-Tolerant Flight Computer

The 2nd flight computer variant, presented in Section 2, was investigated in this paper. Its block-diagram is depicted in Fig. 7, where three MPs in majority voting structure core (MP_1, MP_2, MP_3) and one MP_R in standby mode, VU –voting unit, FD – fault detector and KF- 2 – Kalman filter.

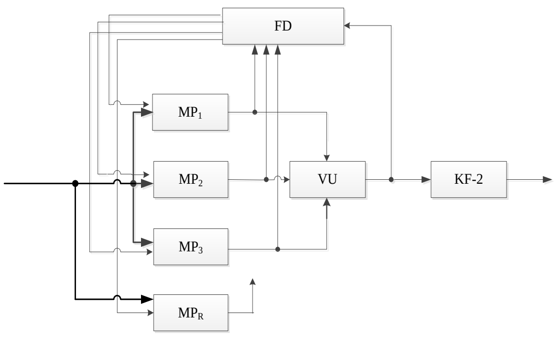

Fig. 7. Block diagram of flight computer with majority-voting redundancy 2-out-of-3 microprocessors and inherent standby microprocessor

Fault detector provides failure detection of MVS core microprocessors. It compares MP’s (MP_1, MP_2, and MP_3) out signals and 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 [8]. 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 failed 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.

The results of reliability model development for the 2[nd] flight computer variant:

1) the Markov model on the ground of basic events (Fig. 8);

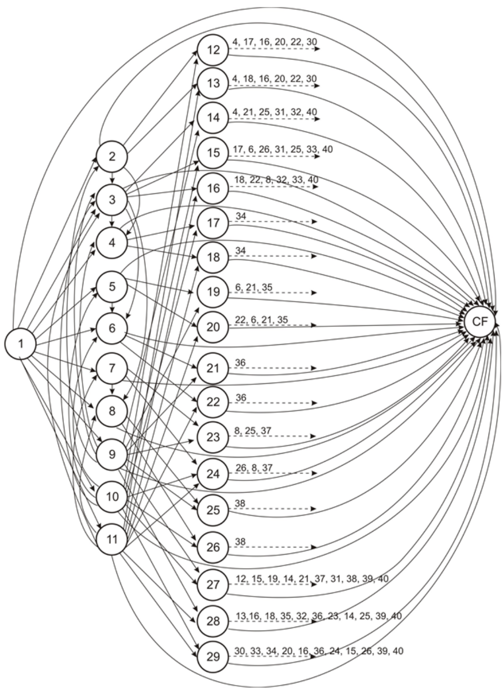

Fig. 8. Markov model for fault-tolerant flight computer with majority-voting redundancy 2-out-of-3 microprocessors and inherent standby microprocessor

2) mathematical reliability model in form of differential Chapman – Kolmogorov equations set:

$$
\begin{cases}
dP_1(t)/dt = -(4\lambda_{MP} + 3\lambda_{FA} + \lambda_{VU})P_1(t) \\
dP_2(t)/dt = (\lambda_{MP}(1 - P_D + P_D(P_{DN} + P_{NN}) + \lambda_{FA}P_{DN}))P_1(t) - \\
-(\lambda_{MP}(2P_DP_S + 3 - 2P_S) + 2\lambda_{FA} + \lambda_{VU})P_2(t) + \\
+(\lambda_{MP}(1 - P_D + P_D(P_{DN} + P_{NN}) + \lambda_{FA}P_{DN}))P_9(t) \\
\ldots \\
dP_{40}(t)/dt = \lambda_{FA}P_{NN}P_{31}(t) + \lambda_{FA}P_{NN}P_{32}(t) + \lambda_{FA}P_{NN}P_{33}(t) - (3\lambda_{MP} + \lambda_{VU})P_{40}(t)
\end{cases} \tag{6}
$$

where $P_i(t)$ is probability of system being in State i ($i \in 1$ ..., 41) at time t. State 41 corresponds to CF state in Fig. 8.

3.5 Reliability Estimation for Flight Control System Components

Using certain input data, we calculated reliability of FCS components. The reliability estimation results, presented in Tables 1, 2 and 3 and Fig. 9, confirm the known thesis that non-perfect detection and switching devices (in comparison with perfect equipment) decrease system reliability [4-6]. Such denotations are used in the Tables and Figure: T_{OP} – operation interval; $P_{UAV}(t)$, $P_{FC}(t)$, $P_{NS}(t)$ and $P_{AP}(t)$ – reliability accordingly for unmanned aerial vehicle, flight computer, navigation subsystem and autopilot. The variants of FCS components design are presented in Section 2.

Table 1. Calculated reliability of UAV flight computer (T_{OP} = 500 hr)

Graph # (Fig. 9)	Flight computer variants	Detection and switching devices	P_D	P_S	λ_{FA}, hr^{-1}	P_{FC} (500)	T, hours (at P_{FC}=0,99)
1	1st	–	–	–	–	0.95256	226
2	2nd	perfect	1	1	0	0.99084	518
3		non-perfect	0.96	0.97	4.5e-5	0.98728	447
4			0.92	0.94	1.5e-4	0.97643	342

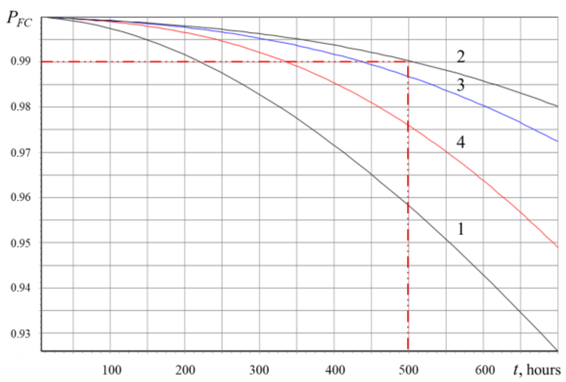

Fig. 9. Graphs of flight computer reliability (graphs #1-4 correspond to results presented in lines #1-4 in Table 1)

Table 2. Calculated reliability of UAV navigation subsystem (T_{OP} = 500 hr)

Navigation subsystem variants	Detection and switching devices	DSD effectiveness parameters			$P_{NS}(500)$
		P_D	P_S	λ_{FA}, hr^{-1}	
1st	–	–	–	–	0.97091
2nd	perfect	1	1	0	0.99188
	non-perfect	0.92	0.94	1.5e-4	0.98415
3rd	perfect	1	1	0	0.99012
	non-perfect	0.92	0.94	1.5e-4	0.98043

Table 3. Calculated reliability of UAV autopilot (T_{OP} = 500 hr)

Autopilot variants	Detection and switching devices	DSD effectiveness parameters			$P_{AP}(500)$
		P_D	P_S	λ_{FA}, hr^{-1}	
1st	–	–	–	–	0.82820
2nd	perfect	1	1	0	0.99067
	non-perfect	0.92	0.94	1.5e-4	0.95178
3rd	perfect	1	1	0	0.99128
	non-perfect	0.92	0.94	1.5e-4	0.95649

The considerable difference in UAV reliability results, obtained with the well-known and improved models (Table 4), indicates a significant overall impact of DSD effectiveness on the unmanned aerial vehicle reliability. The less effective detection and switching devices cause the bigger mentioned discrepancy. Consequently, it results in the considerable lowering of UAV employment effectiveness, including its flight duration and regularity of operations.

Table 4. Calculated reliability of unmanned aerial vehicle (T_{OP} = 500 hr)

Reliability models	Detection and switching devices	$P_{FC}(500)$	$P_{NS}(500)$	$P_{AP}(500)$	$P_{UAV}(500)$
well-known	perfect	0.99084	0.99188	0.99067	0.93338
offered	non-perfect	0.97643	0.98415	0.95178	0.87681

The achieved results certainty is validated by use of well-proven mathematical tools as well as reaching asymptotic agreement with results that were attained with application of the known models (Table 5). The obtained results have clear physical interpretation and do not contradict the well-known scientific theories.

Table 5. Calculated reliability of fault-tolerant units attained with use of the well-known and offered reliability models (t=500 hr)

Standards (scientific works) in which reliability models are given (reference number)	Types of redundancy				
	FTU with simple parallel redundancy		Majority voting redundancy 2-out-of-3		
			without standby elements	with inherent standby element	
	$P_S = 1$ $P_D = 1$ $\lambda_{FA} = 0$	$P_S = 0{,}96$ $P_D = 1$ $\lambda_{FA} = 0$	–	$P_S = 1$ $P_D = 1$ $\lambda_{FA} = 0$	$P_S = 0{,}96$ $P_D = 1$ $\lambda_{FA} = 0$
[9] (MIL-STD-756)	0.95941	0.95340	0.95256	–	–
[10] (OST 4G)	0.95942	0.95339	0.95255	–	–
[11]	–	–	0.95255	0.98883	–
[8]	–	–	0.95256	0.98989	0.98785
Offered models	0.95940	0.95342	0.95256	0.98976	0.98723

3.5 Rationale for Expedient Configurations of Flight Control System Fault-Tolerant Components

Rationale for expedient fault-tolerant configurations of FCS components is provided in the frame of flight control system reliability synthesis. The proposed synthesis technique [14] supports multiple analysis for different fault-tolerant configurations on condition of ensuring required reliability level with purposeful adjustment of FTU elements reliability and DSD effectiveness parameters, and taking maintenance and repair modes into account. It is based on use of specialized software ASNA-1 and MathCAd.

The improved FTU reliability models with the higher degree of adequacy comparatively to the well-known models determine the technique originality. Using of these models enables increasing certainty of reliability synthesis results.

One of the primary outcomes of application of the offered synthesis technique is forming up the sets of the rational fault-tolerant configurations of FCS components considering maintenance and repair modes. These sets appear as input data to solve optimization problem for FCS structure composition.

4 Reliability-Oriented Approach for UAV Flight Control System Structural Optimization

A key FCS design task is to realize the required field reliability level and ensure UAV effectiveness with necessary flight duration and regularity of operations, and save resources in achieving this objective [4, 15]. In order to avoid the main disadvantages of the known system structural optimization techniques (ignoring reliability or applying simplified reliability models), the proposed optimization technique is based on the FTUs' improved reliability models and results of FCS reliability synthesis with use of these models.

To complete the foregoing tasks and solve this multi-objective design problem, the resultant criteria method was applied [16]. It was admitted that expenditure of technical resources (weight, size, power consumption) is a dominant UAV design issue comparatively to its costs saving. Besides, weight of the FCS components and their elements can be reduced due to their high-density arrangement, maximum use of size. Hence, it was assumed that with addition of redundancy size FCS components would not change significantly. According to the above method the resulting scalar function was presented in form of integrated technical resources expenditure indicator. This measure for realization of fault-tolerant configuration *j* for FCS component *k* considering maintenance and repair mode *i* is determined from the formula:

$$Z_{kij} = \gamma_1 \cdot S_{kij} + \gamma_2 \cdot M_{kij} \tag{7}$$

where γ_1 γ_2 – weight coefficients for setting a balance expenditure state between 1 kW power consumption and 1 kg of equipment weight;

indexes – $i \in 1$ ..., r; for navigation subsystem – k=1; $j \in 1$ ..., n_{1i}; flight computer – k=2; $j \in 1$ ..., n_{2i}; autopilot – k=3; $j \in 1$ ..., n_{3i};

M_{kij} and S_{kij} – weight and power consumption for realization of fault-tolerant configuration *j* for FCS component *k* considering MRM i.

Accordingly, the optimization criterion is a minimum expenditure of technical resources that defined from the formula:

$$Z_i = \min \sum_{i=1}^{k} Z_{kij} \tag{8}$$

Since the reliability is the basis for making optimum design decision, the sets of the rational fault-tolerant configurations of FCS components with considering MRMs are the main input data for solving optimization problem and primary optimization constraint.

Thus, for each maintenance and repair mode *i* ($i \in 1$ ..., r), which is determined by the operation interval T_{OPi} (Table 6), can be formed three sets of rational fault-tolerant configurations for each of three FCS components accordingly: for navigation subsystem – N_{1i} (1,…, n_{1i}); flight computer – N_{2i} (1,…, n_{2i}); autopilot – N_{3i} (1,…, n_{3i}).

Table 6. Sets of rational fault-tolerant configurations for FCS components with taking maintenance and repair modes into account

Number of MRM	Maintenance and repair rate	Sets of rational fault-tolerant configurations		
		Navigation subsystem	Flight computer	Autopilot
1	T_{OP1}	N_{11} (1,…, n_{11})	N_{21} (1,…, n_{21})	N_{31} (1,…, n_{31})
2	T_{OP2}	N_{12} (1,…, n_{11})	N_{22} (1,…, n_{21})	N_{32} (1,…, n_{31})
…	…	…	…	…
r	T_{OPr}	N_{1r} (1,…, n_{1r})	N_{2r} (1,…, n_{2r})	N_{3r} (1,…, n_{3r})

In addition to reliability parameters, the normalized values of UAV flight duration and regularity of operations, and flight control system weight, power consumption and overall cost are defined as optimization constraints. The estimation of overall cost for FCS components is made on basis of analysis their cost of design, engineering, and procurement, as well as operating and support costs [4, 15].

As an example, the offered optimization technique was used for UAV flight control system design with selection of rational MRM from three basic maintenance and repair modes. It is considered that maintenance personnel should be used to restore the system operation: for the 1st MRM – after every UAV flight, and for the 2nd and 3rd modes – correspondingly after intermaintenance and overhaul period completion. The technique application allows choosing the expedient MRM that enables increasing mobility of unmanned aircraft system sections and declining requirements to qualification of maintenance specialists due to the grounded integration of FCS components with high reliability going from redundancy addition.

Based on the analysis of the optimization problem outcomes using the well-known and offered reliability models, it was concluded, that applying the well-known models determines making inefficient design decisions. It results in reduction of redundancy amount, and selection of less reliable elements. As experience has shown, it is practically one of main causes for development of technical systems with the field reliability level 10-15 % lower than was measured during design [4], as well as diminishing of flights duration and operations regularity below required values, and accordingly reducing UAV effectiveness performance.

5 Conclusions

1. The proposed reliability-oriented approach for UAV flight control system structural optimization enables increasing results certainty owing to improved reliability models for the system fault-tolerant configurations with high adequacy level.

2. The developed optimization technique ensures increasing non-failure UAV operating time with technical resources minimization for FCS design, meeting required system reliability level, flight duration and regularity of operations, observing principal constraints (weight, power consumption and overall cost), taking different maintenance modes into consideration.

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