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SOFTWARE TOOL FOR EVALUATION OF RELIABILITY AND SURVIVABILITY OF COMPLEX TECHNICAL SYSTEM BASED ON LOGICAL-PROBABILISTIC METHODOLOGY

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Abstract. The paper presents solutions for estimation and analysis of complex system (CS) reliability and survivability indicators based on the logical-probabilistic approach. Modified logical-probabilistic method and software tool for evaluating the reliability and survivability of onboard equipment (OE) of small satellites were developed (SS). The correctness of the suggested method and software tool was shown by computational experiments on some systems of CS SS similar to Belarusian SS, and later compared with the “Arbitr” software complex results.

Keywords: logical-probabilistic method, reliability, survivability, onboard equipment for small satellites, diagram of functional integrity, system operability function.

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Introduction

The evaluation of reliability and survivability of the complex technical systems, like OE for SS, is an important task of their safe and reliable design and operation.

Logic-probabilistic modeling is a method for analyzing the sensitivity of a complex system operating under conditions of uncertainty. The method boasts clarity and a wide range of possibilities to detect the influence of any argument on the reliability and survivability of the entire system.

In this paper the automated logical-probabilistic methodology and software tool for evaluating CS reliability and survivability is suggested. The logical-probabilistic software tool was combined with the CS SS telemetry data analysis software tool and some other methodologies and tools in the complex of methodologies and software tools for evaluating the reliability and survivability

of the CS SS. The complex was integrated into the software complex for multi-objective assessment, analysis, and prediction of values of reliability and survivability for CS SS developed in SPIIRAS.

The logical-probabilistic methodology

The usage of logical-probabilistic approach in evaluating the reliability and survivability of a structurally complex system provides sequential construction of two computational model types [1, 2]:

- boolean function of the system operability:

$$Y_F = Y_F(\{\tilde{x}_i\}, i = 1, 2, \dots, H). \quad (1)$$

- polynomial of the estimated probability function:

$$P_F = P_F(\{p_i, q_i\}, i = 1, 2, \dots, H). \quad (2)$$

Logical function of the system operability

In logic-probabilistic methodology a Boolean function as a logical model of system reliability and survivability is applied. It is called a logical function of the system operability that represents a set of states in which the system implements an appropriate criterion of its functioning (system health state). A logical criterion can be determined by different properties of the system.

The initial data for determining a logical FSO are:

- diagram of functional integrity (DFI),
- logical criteria of functioning (LCF) of system.

The features and restrictions of CS SS design allow to apply one of the simplest methods of direct analytic substitution for FSO construction.

It provides a consistent replacement in the logical FSO of all integrative functions by their equations selected from the system. Such substitution is performed until there are no undeclared functions y_i in the resulting expression. In other words, all integrative functions y_i will be replaced by simple logical variables x_i .

Computational probability model of system reliability

Polynomial of the estimated probability function (PF) P_F (2) is used as a computational probabilistic model of system reliability. The polynomial should clearly define (within limitations and assumptions) the probability of failure-free system operation, as well as all health states represented using the logical FSO Y_F (1).

In terms of physical meaning, P_F determines the probability of implementing the given logical criterion Y_F of system functioning. A polynomial P_F is a rule for aggregation of particular parameters of system elements, i.e. compositions of elementary probabilities p_i in a system probability characteristic. P_F defines an algorithm for calculating the probability of a complex event Y_F consisting of products, sums, and inversions of its simple random events, whose own probabilistic parameters p_i are known [1–3].

The parameters $p_i, q_i = 1 - p_i$ of the P_F polynomial are intrinsic probabilities of failure-free operation or availability coefficients of system elements.

As for P_F determining, the combined method is applied, one of the most effective and simplest approaches [1]. In general, two successive transformations of the original FSO are performed for accurate determination of P_F using a combined method:

- quasiorthogonalization of the FSO by a single logical variable;
- a symbolic transition to the P_F polynomial.

The conjunctions of a logical function are called orthogonal if their logical product is zero. Therefore, the events representing these conjunctions are inconsistent, and the probability of their sum equals a simple sum of their own probabilities of each event.

Assuming the independence in the aggregate of all elementary binary events $\tilde{x}_i, i=1,2,\dots,H$, the algorithm for performing these two steps is as follows.

Quasiorthogonalization by a single logical variable. All pairs of non-orthogonal conjunctions of the original FSO are checked for a possibility of their orthogonalization by the following rule

$$\gamma \tilde{x}_i \vee \gamma \cdot \varphi = \gamma \cdot x_i \vee \gamma \cdot \varphi \cdot \overline{\tilde{x}_i}, \quad (3)$$

where γ and φ are parts of the tested conjunctions, in which there is no variable \tilde{x}_i . Orthogonalization does not increase the total number of conjunctions in the original FSO. Having performed these transformations with the example illustrated over the function (3), we obtained

$$\begin{aligned} Y_p &= y_3 \cdot y_4 = x_3 \cdot x_4 \cdot x_1 \cdot x_2 \vee x_3 \cdot x_4 \cdot x_1 \cdot x_5 \vee x_3 \cdot x_4 \cdot x_2 \cdot x_5 = \\ &= x_3 \cdot x_4 \cdot x_1 \cdot x_2 \vee x_3 \cdot x_4 \cdot x_1 \cdot x_5 \cdot \overline{x_2} \vee x_3 \cdot x_4 \cdot x_2 \cdot x_5 \cdot \overline{x_1}. \end{aligned} \quad (4)$$

The resulting function is completely orthogonal, so all its conjunctions represent incompatible events.

A symbolic transition to P_F polynomial. A logical FSO is a rigorous analytical form of describing a complex random event in which:

- a conjunction is a product of random events;
- a disjunction is their sum;
- an inversion is the opposite outcome of an event whose probability is to be determined with the help of the desired P_F .

In order to obtain the P_F polynomial from the FSO, it is enough to perform some transformations to labeling of logical variables and operations in the labeling of probability variables and arithmetic operations. These symbolic transformations must be carried out in a strict accordance with the laws of probability theory for calculating the probabilities of products, sums, and additions of random events.

Operability (FSO), a logical function.

Having applied these rules to the orthogonalized FSO (4), we obtained the polynomial of the required

P_F :

$$P_p = p_F(y_3 \cdot y_4) = p_3 p_4 p_1 p_2 + p_3 p_4 p_1 p_5 q_2 + p_3 p_4 p_2 p_5 q_1. \quad (5)$$

Survivability model

Survivability [2] is an ability of a system to keep operating capacity at random damages of its elements owing to random emergence of the striking factors (blows, explosions, fires, etc.) In order to account for a random damaging factor in the structural model of the system survivability, another new event x_5 is added to the developed DFI: the emergence of the damaging factor (Fig. 1). The occurrence of this event is a prerequisite for a subsequent impact and accidental destruction of system elements 3 and/or 4. If a damaging factor does not arise, elements 3 and 4 are not significantly affected.

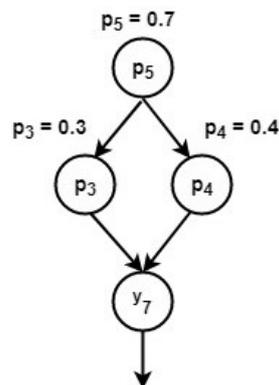


Fig. 1. The damaging factor for a two-element system

There is an operability persistence equation at the output of the fictitious vertex 7:

$$y_7 = \overline{y_3} \vee \overline{y_4}. \quad (6)$$

Operability persistence is sustained by at least one element, which is the criterion Y – the survivability of the system for accidental occurrence and impact of the damaging factor. If the onset of the damaging factor occurs with a probability of $p_5 = 0.7$, $p_3 = 0.3$, $p_4 = 0.4$, a polynomial of survivability probability function is as follows:

$$P_s = q_4 + p_4 q_5 + p_4 p_5 q_3 = 0.916. \quad (7)$$

It should be noted that the DFI of the total survivability of the considered two-element system (see Fig. 1) is nonmonotonic in construction. In particular, it means that an analogous structural model of total survivability cannot be constructed using standard block patterns or typical failure trees. At the same time, the obtained logical and probabilistic survivability functions are still monotonous, within the limits of the accepted substantive definitions for the used elementary events.

Method and software tool for estimating reliability and survivability

Method for calculating reliability and survivability

The software implementation of the considered methodology used for determining the logical FSO and P_F polynomials for the analysis of real structurally complex systems of CS SS with a large number of elements is difficult because of the complexity of automatic analytical simulation processes.

Therefore, we made a modification to the DFI graph while comparing with classical representation of DFI [1, 2]: in addition to the linking arcs and functional vertices, the logical vertices “AND” and “OR” were introduced instead of according arcs (Fig. 2).

Firstly, it helps to see more clearly which systems are redundant and which are not.

Secondly, logical vertices can be used more effectively in algorithms for automatic calculation of the probability of a failure-free operation and survivability of systems. In this case, the FSO Y_F and probability function P_F polynomials are computed implicitly for computing complexity reduction.

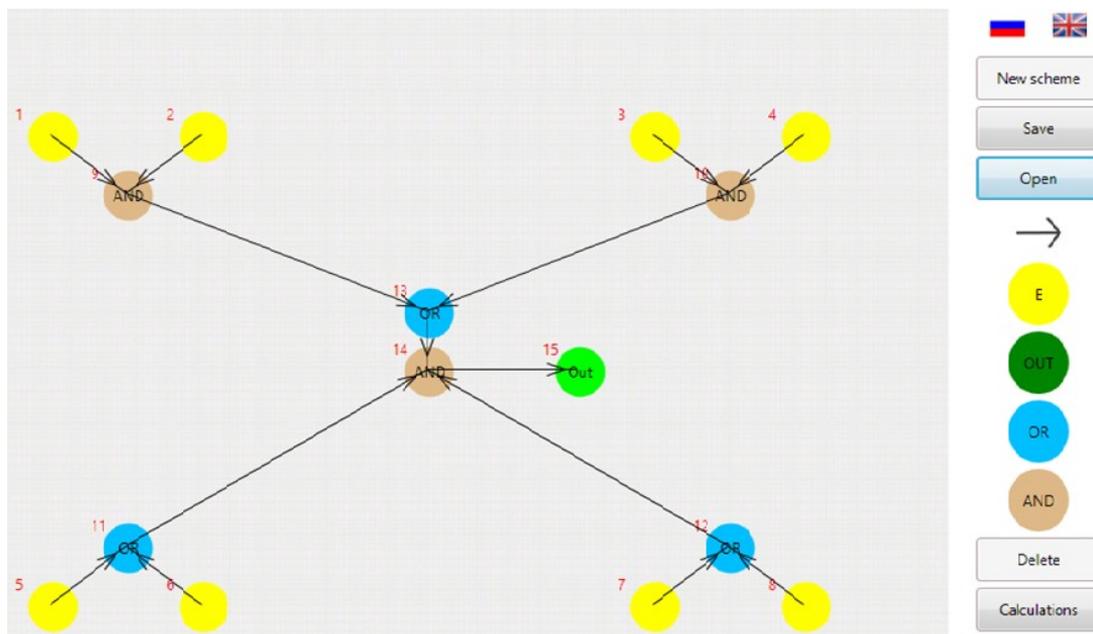


Fig. 2. Example of oriented graph as DFI of the multispectral camera subsystem (MCS) of the Belarussian SS, DFI graphical input window, desktop-version

Thirdly, there are systems consisting of X vertices that remain operative when any of the Y vertices work. For example, the flywheel group of satellite orientation system very often consists of 4 flywheels and in order to operate correctly, the presence of any three operable flywheels out of 4 is required. It is possible to create and analyze such systems using logical vertices.

The graph will be designed in such way that the functional elements commute with each other only through logical elements.

Introduction of these vertices does not change the probability of failure-free operation and the reliability and survivability of the systems at all. As a rule, the scheme is created on the basis of four logical constructions (Fig. 3). In order to create more complex structures, logical elements can be commuted with each other in any quantity. The width and depth search algorithms are used for graph navigation.

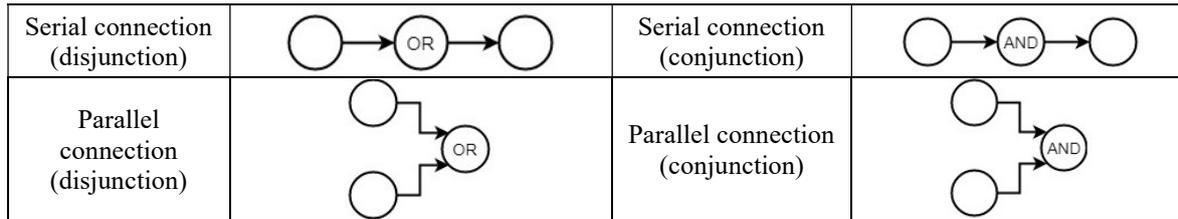


Fig. 3. Basic types of logical constructions

At each stage for each structural node, the probabilities of a failure-free operation and survivability are recalculated and transferred to the next vertex. Thus, each vertex contains information about the calculations on all previous vertices. And whenever we get to any vertex, we can always get the probabilities obtained for the previous vertices. Algorithm operation is finished when all final vertices are reached [4] (Fig. 4).

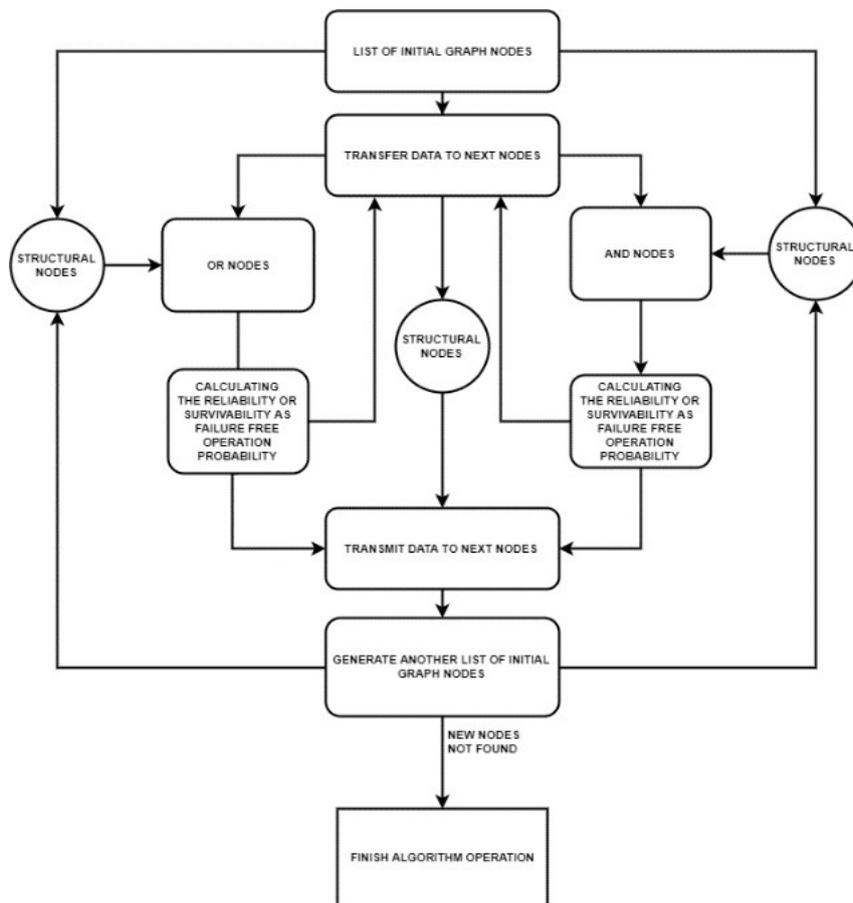


Fig. 4. The algorithm for calculating the probability of a failure-free operation and survivability

Software tool of logical-probabilistic estimating the reliability and survivability of system operating

Correspondent software tool, based on the logical-probabilistic approach and the proposed algorithm, was developed in two versions: a desktop version and a web one. The software tool was designed to automate the process of evaluating the reliability and survivability of CS SS systems. The tool implements the following functions:

- graphical input and editing DFI representing a device under analysis (Fig. 2, 6);
- input and editing the system element parameters including failure-free operation probabilities p_i and a redundancy level of the system elements;
- calculating the single value of the system reliability for the given single arguments of failure a free operation probability p_i for structural nodes;
- reliability analysis – calculating the values of the CS SS systems reliability for the series of element probability arguments and drawing graphics (Fig. 6, 7), in this case element probability parameters p_i are equally changed in the range ($p_{ini} > 0$; $p_{fin} \leq 1$) by step Δp . During the reliability analysis, failure free operation probabilities p_i of some elements could be fixed to the value in their properties by setting on according checkboxes in the elements list (Fig. 6, 7);

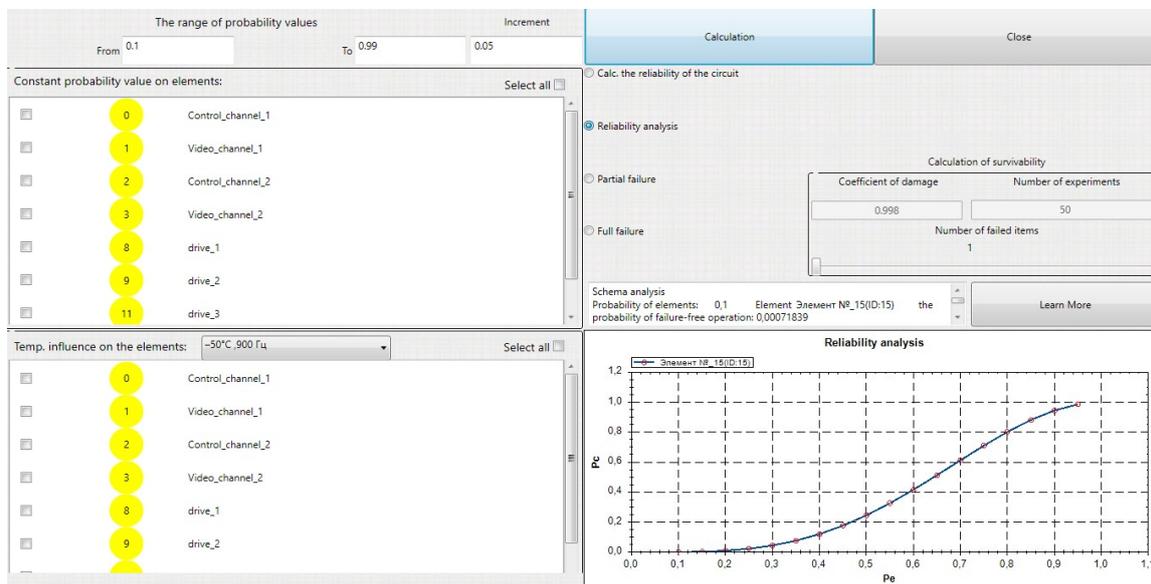


Fig. 5. Window for calculating, reliability analysis, desktop-version

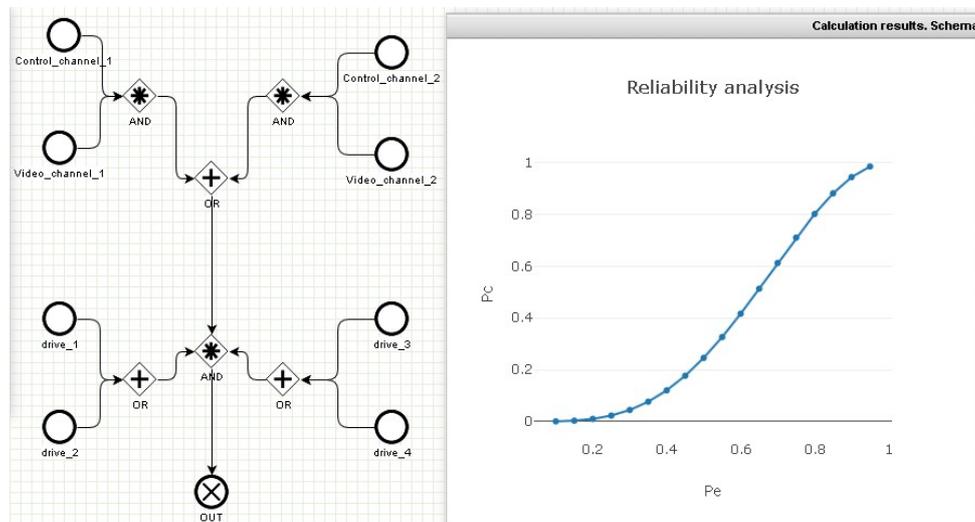


Fig. 6. Web-interface, example of graphical input and editing the DFI of the multispectral camera subsystem (MCS) of the Belarussian SS, reliability analysis results

– Survivability analysis – calculating the survivability of CS SS systems with full and partial failure and drawing a graphic. The damaging factor is applied to randomly selected k elements which reduces the probability of a failure-free operation p_i of these elements to 0 in case of full failure and in case of partial failure to $\tilde{p}_i < p_i$ that can CS set throw interface (Fig. 5, 6). The experiment is repeated N (50 by default) times (Fig. 7, 8). During survivability analysis some elements can be excluded from the impact of damaging factors by setting corresponding checkboxes in the elements list.

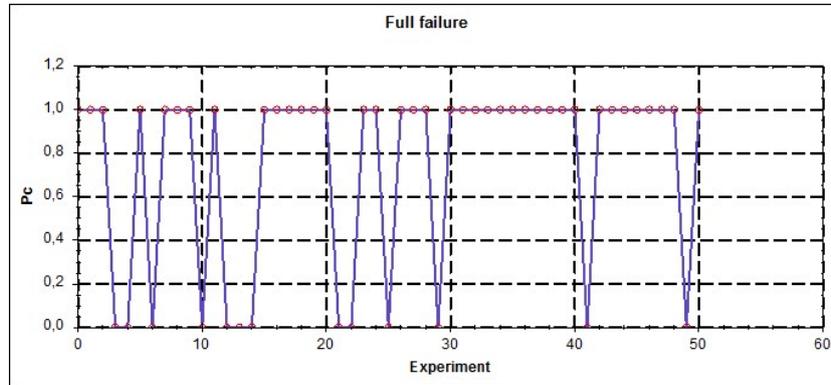


Fig. 7. Determining the survivability of the MCS under full failure

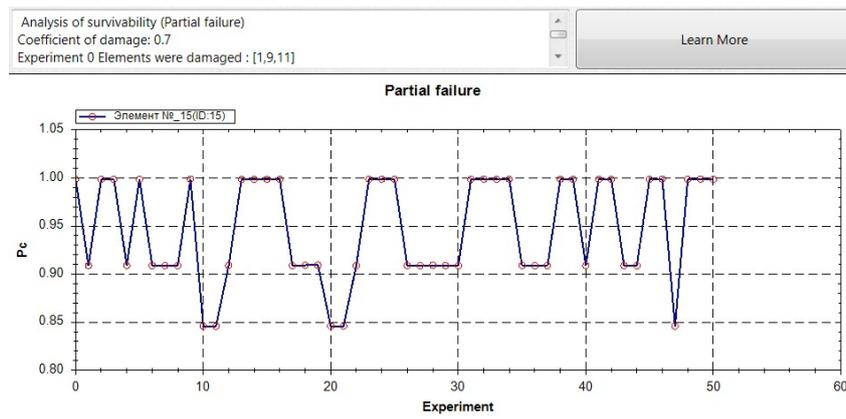


Fig. 8. Determining the survivability of the MCS under partial failure

Moreover, during the analysis of reliability and survivability of CS SS systems, the impact of thermal and mechanical factors on some system elements could be taken into account. It can be achieved through setting corresponding checkboxes in the elements list.

Computational experiments

The correctness of the developed methodology and software tool was tested on some test systems of CS for Belarusian SS, later compared with the “Arbitr” software complex results [1, 2], certified in 2007 by Rostekhnadzor (RF) for industrial application. In Tab. 1–3 the comparison results for MCS – the component of OE for Belarusian SS (Fig. 2) are represented. In Tab. 4 the reliability analysis comparison of the results for other three systems of OE SS similar to Belarusian SS are represented.

Table 1. Comparison results for MCS – component of OE of Belarusian SS. Single reliability index value

| | | |
|-------------------------|--|--|
| Reliability Calculating | Developed tool: Pc = 0.99940407919804 | Software complex “Arbitr”: Pc = 0.999404079 |
|-------------------------|--|--|

Table 2. Comparison results for MCS – component of OE of Belarusian SS. Reliability analysis

| Elements probability p_i | Pc, Developed tool | Pc, Software complex “Arbitr” | Term and mechanical influence on the elements: | Constant reliability on the elements: | Pc, Developed tool | Pc, Software complex “Arbitr” |
|----------------------------|--------------------|-------------------------------|--|---------------------------------------|--------------------|-------------------------------|
| 0.1 | 0.0007183 | 0.000718 | – | – | – | – |
| 0.3 | 0.0447111 | 0.044711 | – | – | – | – |
| 0.6 | 0.4165862 | 0.416586 | – | – | – | – |
| 0.8 | – | – | 3,6,7 | 1.8 | 0.88408152961 | 0.88408153 |
| 0.9 | – | – | 1 | 1 | 0.958474759968 | 0.95847476 |
| 1 | – | – | 1,2,3,4,5,6,7,8 | 2 | 0.999461280139 | 0.99946128 |

Table 3. Comparison results for MCS – component of OE for Belarusian SS. Survivability analysis.
The damaging factor 0,998, failure of 3 elements

| The following elements are failure ed: | Pc, Developed tool | Pc, Software complex “Arbitr” | Temperature influence on the elements: | Constant reliability on the elements: | Pc, Developed tool | Pc, Software complex “Arbitr” |
|--|--------------------|-------------------------------|--|---------------------------------------|--------------------|-------------------------------|
| 7,2,4 | 0 | 1,9404E-50 | – | – | – | – |
| 8,2,1 | 0.97020197 | 0.97020197 | – | – | – | – |
| 8,6,1 | 0.96059601 | 0.96059601 | – | – | – | – |
| 8,5,6 | – | – | 1,3 | 2.4 | 0 | 1.95869E-50 |
| 6,7,3 | – | – | 1,3 | 24 | 0.95291124192 | 0.952911242 |

Table 4. Comparison results for systems of OE SS similar to Belarusian SS. Reliability analysis

| Elements probability p_i | Navigation system equipment | | Multispectral camera system | | Orientation and stabilization system | |
|----------------------------|-----------------------------|-------------------------------|-----------------------------|-------------------------------|--------------------------------------|-------------------------------|
| | Pc, Developed tool | Pc, Software complex “Arbitr” | Pc, Developed tool | Pc, Software complex “Arbitr” | Pc, Developed tool | Pc, Software complex “Arbitr” |
| 0.60 | 0.027546 | 0.027546 | 0.064524 | 0.064524 | 0.090334 | 0.090334 |
| 0.70 | 0.087048 | 0.087048 | 0.164648 | 0.164648 | 0.214043 | 0.214043 |
| 0.80 | 0.228170 | 0.228170 | 0.347892 | 0.347892 | 0.417471 | 0.417471 |
| 0.90 | 0.512256 | 0.512256 | 0.630247 | 0.630247 | 0.693272 | 0.693272 |

Represented computational experiments show equality of the results for the developed methodology and software tool with the results of the software complex “Arbitr” and hence the correctness of the suggested method and developed tool.

Conclusion

In the paper an effective logic-probabilistic methodology and approach to estimating reliability of complex systems was considered. The methodology was applied to the problem of estimating the reliability and survivability of on-board equipment for small satellite systems. A modified logical-probabilistic method and a software tool for evaluating the reliability and survivability of OE SS systems were developed. The developed software tool automatizes the reliability and survivability estimating process. It also enables graphical input of DFI data and survivability analysis through drawing the graphics of obtained results. The correctness of the suggested method and software tool was shown by computational experiments on some systems of OE SS similar to Belarusian SS, later compared with the “Arbitr” software complex results. The logical-probabilistic software tool was combined with the OE SS telemetry data analysis software tool, represented in CSOC’2017 proceedings [3], and some other methodologies and tools in the complex of methodologies and software tools for evaluating the reliability and survivability of the OE SS.

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Authors' contribution

Skobtsov V.Yu. performed a full cycle of work, including problem statement, research and development of a modified logical-probabilistic method for analyzing the reliability and survivability of complex systems, work related to the software implementation of the method, and project management.

Lapitskaya N.V. took part in the problem statement and graphic-analytical investigation method to determine the logical FSO.

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