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An Approach to Substantiating the Composition of the Reconnaissance-Firing Systems

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Abstract:

An approach to justifying the composition of the reconnaissance-firing systems is proposed, which would consider the appropriate type of redundancy for each subsystem. Reconnaissance subsystems have a triple modular redundancy because this type of redundancy has a high degree of reliability of the received signal and a high probability of faultless work at the initial stage of operation. For the control subsystem, the most appropriate type of redundancy is passive redundancy, because this subsystem, as a rule, has the lowest failure rate among the elements of other subsystems. For the fire support subsystem, the most appropriate type of redundancy is sliding redundancy, because this type of redundancy allows you to ensure the redundancy of a larger number of main elements with a smaller number of spare ones. The application of the mentioned types of redundancy for these subsystems increases the probability of faultless work and saves the resource of redundancy elements.

Keywords:

reconnaissance-firing systems, operational stability, active redundancy, passive redundancy, triple modular redundancy, sliding redundancy

1 Introduction

The analysis of recent military conflicts, especially the Russian-Ukrainian war, showed that the unification of the separate functional elements of reconnaissance, control, and fire support into a single one, the reconnaissance-firing systems (RFSs), is gaining more and more popularity [1, 2].

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The experience of using such systems has shown the importance of their use on the battlefield. RFSs make it possible to detect potential threats in advance and minimize the risk, due to the fact that information about these threats is sent directly to the actors, which reduces the response time.

RFSs ensure the speed and mobility of troops, accurate hitting of targets at a considerable distance, as all elements of these systems are mobile, and the systems themselves have a high degree of autonomy. The high accuracy is explained by the use of intelligence tools both during target detection and during the correction of fire exposure.

An important advantage of RFSs is the possibility of providing information about both the target and the situation in the areas of reconnaissance. A short chain of information transmission ensures the relevance of the received information [1, 2].

The disadvantage of these systems is high cost, relative to existing systems, because separate mutually sufficient chains are created in RFSs, which requires a larger number of elements.

The next disadvantage is vulnerability of these systems to electronic interference, because data exchange between the elements of these systems is carried out via radio channels [3].

The next shortcoming is the need for high-quality information, because RFSs perform the task of hitting a target on certain objects. At the same time, insufficient information awareness can lead to destruction of civil infrastructure, which is unacceptable in the conditions of modern war [1, 2].

An important factor that affects the functioning of RFSs is the need for constant technical support [1, 2], the fact that each of the elements of this system is important, because the failure of this element will lead to the failure of the entire system and failure to complete the task.

In general, the highlighted advantages and disadvantages of RFS indicate both the growing interest in these systems and the need for further research.

2 Problem Formulation

One of the main problems of using RFSs is the low stability of their functioning. This is due to a number of factors, in particular, the combination of elements with different functional purposes into one system, failure related to the influence of the enemy, limited tests, and technical conditions [4, 5].

Of course, the practice of applying RFS allows identifying certain sources of these causes and partially preventing them from happening. To avoid a decrease in the stability of functioning, reserves of spare parts [4] and reserve of forces and means [5] are created, and duplicate systems for the performance of the same task [4] are used. The specified measures are effective, but all of them require a substantial stock of the elemental base and, accordingly, substantial material costs. Moreover, in case of failure of the entire RFS, or its subsystem (element), it takes some time to include spare parts or to introduce a duplicate system (subsystem) to restore its functioning.

At the same time, the approach to ensuring the stability of functioning, which minimizes the loss of operational efficiency and resources, is the redundancy of elements (subsystems) [6, 7]. This is explained by the fact that reserve elements are usually included in the RFS, which leads to a reduction in the time of their inclusion. At the same time, redundancy allows for replacing only the element that failed, which grants saving the spare part element base.

However, it is necessary to consider that there are several types of redundancy, such as active and passive redundancy [8, 9], elemental and general, triple modular [10], sliding redundancy [11], and others. The choice of the type of redundancy is influenced by certain factors, in particular, the time of the operation, the importance of the task, the presence of certain functional elements, and some others. That is, the same RFS with different types of redundancy will have different operational stability.

It should also be noted that according to the existing approaches, the type of redundancy for RFS is selected of the same type for all subsystems. However, taking into account the different functions of each of the subsystems and the different conditions for the implementation of these functions, the same type of redundancy is not appropriate.

Thus, the purpose of the article is to substantiate the composition of the RFS, which would consider the appropriate type of reservation for each subsystem.

3 Basic Material and Results

The study examines the stage of creating the RFS for combat missions. The scientific hypothesis in the work is as follows: the application of the types of redundancy for subsystems corresponding to the operating conditions is more expedient than the use of one type of redundancy for all subsystems. The limitations of the study are: all elements in the subsystem are the same, and the failure intensity rate is subject to the exponential law of the distribution of random variables.

The main factors that affect the functioning of the RFS are the number of separate elements by subsystem, the influence of the enemy, the technical reliability of the elements, the period of operation of the elements, the time of execution of the combat task, and the importance of the task.

To determine the appropriate type of redundancy for each subsystem, an analysis of the functioning of each of them was carried out. Thus, the main feature of the functioning of the reconnaissance subsystem is the importance of the received reconnaissance information. That is, the information received by this subsystem represents the input data for other subsystems, and the success of the combat mission depends on the accuracy and reliability of this information. The next feature is functioning in close proximity to the enemy or directly in his battle formations. This causes the failure intensity rate to increase due to the influence of the enemy.

Regarding the control subsystem, it should be noted that this system has, as a rule, fewer separate functional elements than other subsystems. That is, each of the functional elements of the control subsystem becomes more important compared to the elements of other subsystems. In addition, the elements of the control subsystem are the link that connects the reconnaissance subsystem with the fire support subsystem. That is, failure of the functional element of the control subsystem will lead to the loss of the entire chain from the reconnaissance subsystem to the fire support subsystem.

A review of the functioning of the fire support subsystem shows that the elements of this subsystem, as a rule, have the largest number of functional elements. In addition, the functioning of this system is associated with such unmasking signs as artillery fire and rocket launches. That is, the intensity of tasks performed by the enemy in terms of damage to the elements of this subsystem is, as a rule, greater than the elements of other subsystems.

The influence of the main factors was also analyzed. Thus, the number of individual elements by subsystem affects the possibility of allocating a certain part of these elements for redundancy. That is, if there are fewer backup elements than the main ones, then it is not possible to apply general redundancy, but it is necessary to carry out element redundancy.

Regarding the influence of the enemy, it should be noted that it characterizes the failure intensity rate of individual functional elements of subsystems from the performance of tasks as a result of this influence. At the same time, the technical reliability of elements characterizes the failure intensity rate of individual functional elements of subsystems from performing tasks due to technical malfunctions. The service life of elements characterizes the failure intensity rate of individual functional elements of subsystems from the performance of tasks due to the limit of working.

In this study, it is proposed to consider the failures from the performance of tasks, taking into account the results of these events, and not the source of their occurrence. After all, it is clear that the nature of these failures will be different, but the result will be the same. Therefore, it is suggested to consider them in a generalized indicator - the failure intensity rate from the performance of the task, is

$$\Lambda = \lambda_{\mathrm{en}} + \lambda_{\mathrm{tr}} + \lambda_{\mathrm{lw}} \tag{1}$$

where λ_{en} is the failure intensity rate related to the influence of the enemy; λ_{tr} is the failure intensity rate related to technical reliability; λ_{lw} is the failure intensity rate related to the limit workings.

With regard to such factors as the time of the combat mission and its importance, it should be noted that they directly determine the level of necessary stability of the RFS functioning.

Considering the peculiarities of the RFS functioning and the factors affecting it, the approaches of the theory of probabilities and the theory of reliability were chosen. The probability of faultless work was taken as the main indicator of the stability of RFS functioning. Accordingly, the basic calculation dependence for determining this probability [6, 7], taking into account the accepted assumptions (1), is

$$P(t) = \mathrm{e}^{-\Lambda t} \tag{2}$$

where t is the time of the combat mission (the operation time).

Next, the existing types of redundancy were analyzed regarding the feasibility of their application in the RFS. The main types of redundancy include active and passive redundancy.

The essence of passive redundancy is that the reserve element is in the RFS structure but does not function. That is, to replace the main element that failed, it takes time to turn on the backup element.

The basic calculation dependence for determining the probability of faultless work with passive redundancy [6, 7, 9] taking into account (1) is

$$P(t)_{\mathrm{pr}} = \mathrm{e}^{-\Lambda t} \sum_{i=0}^{n_e} \frac{\left(\Lambda t\right)^i}{i!} \tag{3}$$

where n_{e} is the number of redundant elements.

The schematic diagram of the application of passive redundancy is shown in Fig. 1a.

The essence of active redundancy is that the backup element is in the RFS structure and works by duplicating the functions of the main element. That is, to replace the main element that failed, no time is needed to turn on the backup element, but the working resource before the failure of the backup element decreases.

The basic calculation dependence for determining the probability of faultless work with active redundancy [6, 7, 9] taking into account Eq. (1) is

$$P(t)_{\mathrm{pr}} = 1-\left(1-\mathrm{e}^{-\Lambda t}\right)^{n_{\mathrm{e}}+1} \tag{4}$$

The schematic diagram of active redundancy application is shown in Fig. 1b.

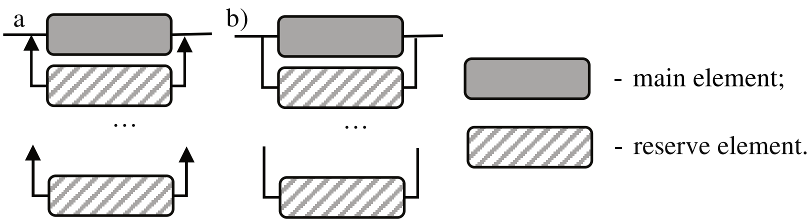

Fig. 1 Passive (a) and active (b) redundancy [6, 7, 9]

In addition, triple modular redundancy and sliding redundancy types were analyzed. The essence of triple modular redundancy is that instead of one element (channel), three identical elements are included, the outputs of which are fed to the majority-voting gate. If all elements of this reserve group are working, then three identical signals are received at the input of the majority-voting gate, and the same signal is sent to the external circuit. The advantages of this type of redundancy are the high degree of reliability of the received signal because to receive unreliable information, 2 out of 3 elements must fail.

The basic calculation dependence for determining the probability of faultless work with triple modular redundancy [6, 7, 10] taking into account Eq. (1) is

$$P_{\mathrm{mr}}(t) = \left(3\mathrm{e}^{-2n\Lambda t} - 2\mathrm{e}^{-3n\Lambda t}\right)\mathrm{e}^{-\lambda_{\mathrm{mg}} t} \tag{5}$$

where λ_{mg} is the failure rate of the majority-voting gate (control subsystem), n is the number of elements in the chain.

The schematic diagram of the use of triple modular redundancy is shown in Fig. 2a.

The most expedient place of application of this type of redundancy is the reconnaissance subsystem. This is because information about enemy facilities is the input for the entire RFS, so the reliability of this information is of the utmost importance.

With regard to sliding redundancy, it should be noted that the essence of this redundancy is the possibility of replacing any primary element with any backup element. It is clear that such a redundancy is possible in the case when all the elements are the same. The advantage of this redundancy is the ability to ensure the redundancy of a large number of main elements with a small number of reserve elements.

The basic calculation dependence for determining the probability of faultless work with sliding redundancy [6, 7, 11] taking into account Eq. (1) is

$$P_{\mathrm{sr}}(t) = \sum_{i=n_e}^{n_{\mathrm{e}}+n} C^{i}_{n_{\mathrm{e}}+n} \mathrm{e}^{-\Lambda i t} (1-\mathrm{e}^{-\Lambda t})^{n_{\mathrm{e}}+n-i} \tag{6}$$

where $C_{n_e+n}^i$ is a combination, which is defined as $C_{n_e+n}^i = \frac{(n_e+n)!}{i!\left[(n_e+n)-i\right]!}$

The schematic diagram of the use of triple modular redundancy is shown in Fig. 2b.

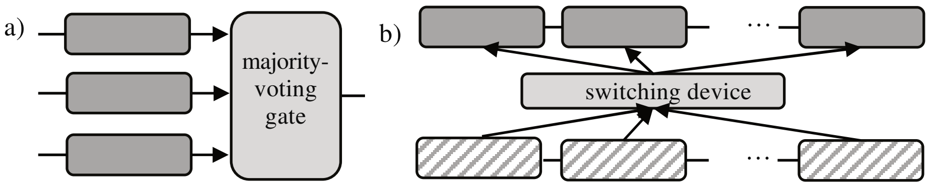

Fig. 2 Triple modular redundancy (a) sliding redundancy (b) [6, 7, 11]

The most appropriate place for sliding redundancy is the fire support subsystem. This is explained by the fact that, as a rule, the fire support subsystem has a larger number of elements than other subsystems. At the same time, usually, the fire support subsystem has fewer backup elements than the main ones.

The existing approaches to choosing an appropriate type of redundancy [8-12] allow you to choose exactly the type of redundancy that ensures the performance of the task and minimizes the loss of resources. However, the task of this study is to select the optimal universal set of types of redundancy, which would allow, in the future, to develop a new principle of RFS construction. For comparison, it is proposed to consider several options for creating RFS, in particular without redundancy, with redundancy according to the existing approaches, and by choosing the optimal type of redundancy for each subsystem.

A typical composition was chosen to compare different approaches to RFS redundancy. With regard to the reconnaissance subsystem – 1 main element of the multicopter UAV type ($n_r = 1$) and 2 reserve elements of the same type ($n_{e,r} = 2$). The failure intensity rate of the reconnaissance element from the execution of the task is 0.12 failures per hour according to (1) ($\lambda_r = 0.12$ h^{-1}). The control subsystem – 1 main element of the control point type using the geoinformation platform "GIS-Art" ($n_c = 1$) and 1 reserve element of a similar type ($n_{e,c} = 1$). The failure intensity rate of the control element from the execution of the task is 0.1 failures per hour according toEq. (1) ($\lambda_c = 0.1$ h^{-1}). The fire support subsystem – 4 main elements of the M119 105 mm howitzer type ($n_f = 4$) and 2 reserve elements of the same type ($n_{e,f} = 2$). The failure intensity rate of the fire support subsystem element from the completion of the task is 0.21 failures per hour according to (1) ($\lambda_f = 0.21$ h^{-1}). The task completion time is 2 hours ($t = 2$).

The general view of the structural and functional scheme of the RFS without redundancy is shown in Fig. 3.

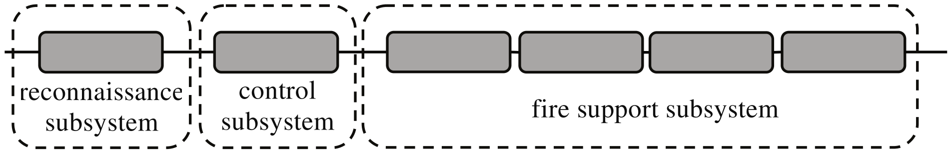

Fig. 3 Structural and functional scheme of RFS without redundancy

Applying formula (2) and the rule for determining the resulting probability for serially connected sections, the dependence for the proposed RFS structural-functional scheme without redundancy is obtained

$$P(t)_1 = \mathrm{e}^{-n_\mathrm{r}\lambda_\mathrm{r}t}\mathrm{e}^{-n_\mathrm{c}\lambda_\mathrm{c}t}\mathrm{e}^{-n_\mathrm{f}\lambda_\mathrm{f}t} \tag{7}$$

where, using the original data, the dependence was obtained

$$P(t)_1 = \mathrm{e}^{-0.12t}\mathrm{e}^{-0.1t}\mathrm{e}^{-4t0.21} \tag{8}$$

Regarding the creation of RFS according to the existing approaches, it should be noted that depending on the time of the task, active redundancy is chosen - in the case of limited time and passive redundancy, when there is enough time. At the same time, the type of reservation is the same for all subsystems. In the study, a variant with passive redundancy was considered, since this type of redundancy is more common. The general view of the structural and functional scheme of the RFS created according to the existing approaches is shown in Fig. 4.

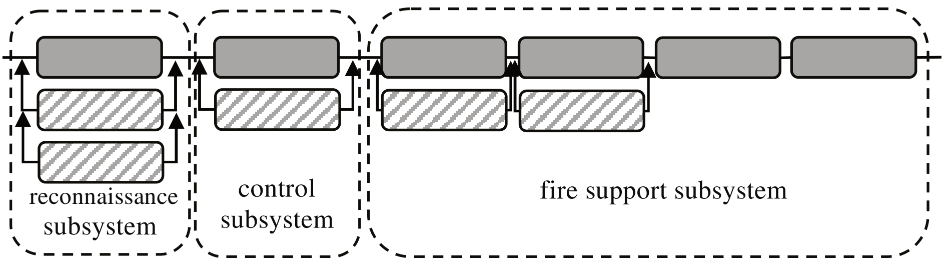

Fig. 4 Structural and functional scheme of RFS created according to existing approaches

Applying formulas (2), (3) and the rule for determining the resulting probability for serially connected sections, the dependence for the proposed structural-functional RFS scheme (Fig. 4) without redundancy is obtained

$$P(t)_2 = \mathrm{e}^{-\lambda_\mathrm{r}t}\sum_{i=0}^{n_{\mathrm{e,r}}}\frac{(\lambda_\mathrm{r}t)^i}{i!}\mathrm{e}^{-\lambda_\mathrm{c}t}\sum_{i=0}^{n_{\mathrm{e,c}}}\frac{(\lambda_\mathrm{c}t)^i}{i!}\left(\mathrm{e}^{-\lambda_\mathrm{f}t}\sum_{i=0}^{n_{\mathrm{e,f}}}\frac{(\lambda_\mathrm{f}t)^i}{i!}\right)^{n_{\mathrm{e},f}}\mathrm{e}^{-n_{\mathrm{e,f}}\lambda_\mathrm{f}t} \tag{9}$$

where using the original data, the dependence was obtained

$$P(t)_2 = \mathrm{e}^{-0.12t}\sum_{i=0}^{2}\frac{(0.12t)^i}{i!}\mathrm{e}^{-0.1t}\sum_{i=0}^{1}\frac{(0.1t)^i}{i!}\left(\mathrm{e}^{-0.21t}\sum_{i=0}^{2}\frac{(0.21t)^i}{i!}\right)^2\mathrm{e}^{-2t0.21} \tag{10}$$

With regard to the proposed approach to the creation of the RFS, in particular, regarding the application of triple modular redundancy to the reconnaissance subsystem, passive redundancy for the control subsystem, and sliding redundancy for the fire support subsystem, a structural and functional scheme was created for the accepted initial conditions (Fig. 5).

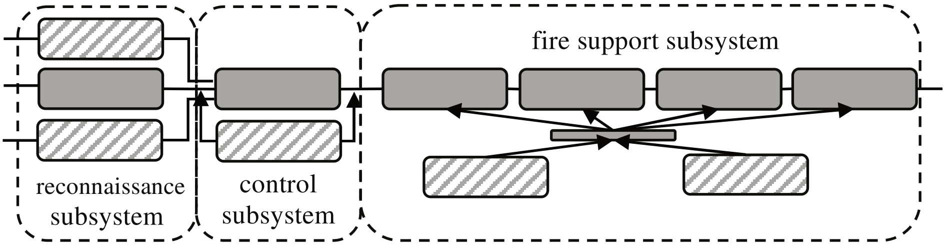

Fig. 5 Structural and functional scheme of RFS created according to the proposed approach

Applying Eqs (2), (3), (5), (6) and the rule for determining the resulting probability for serially connected sections, the dependence for the proposed structural-functional RFS scheme (Fig. 5) according to the proposed approach

$$P(t)_3 = \left[\left(3\mathrm{e}^{-2n_\mathrm{r}\lambda_\mathrm{r}t} - 2\mathrm{e}^{-3n_\mathrm{r}\lambda_\mathrm{r}t}\right)\mathrm{e}^{-\lambda_\mathrm{c}t}\right]\left(\mathrm{e}^{-\lambda_\mathrm{c}t}\sum_{i=0}^{n_\mathrm{e,c}}\frac{(\lambda_\mathrm{c}t)^i}{i!}\right)\left[\sum_{i=n_\mathrm{e,f}}^{n_\mathrm{e,f}+n_\mathrm{f}} C^i_{n_\mathrm{e,f}+n_\mathrm{f}}\mathrm{e}^{-\lambda_\mathrm{f}it}\left(1-\mathrm{e}^{-\lambda_\mathrm{f}t}\right)^{n_\mathrm{e,f}+n_\mathrm{f}-i}\right] \quad (11)$$

where, using the original data, the dependence was obtained

$$P(t)_3 = \left[\left(3\mathrm{e}^{-6t0.12} - 2\mathrm{e}^{-9t0.12}\right)\mathrm{e}^{-0.1t}\right]\left(\mathrm{e}^{-0.1t}\sum_{i=0}^{1}\frac{(0.1t)^i}{i!}\right)\left[\sum_{i=2}^{2+4} C^i_{2+4}\mathrm{e}^{-0.21it}\left(1-\mathrm{e}^{-0.21t}\right)^{2+4-i}\right] \quad (12)$$

When calculating the probability of faultless work for three variants of the RFS structural-functional scheme (8), (10), and (12), the operating time was taken in increments of 15 min (0.25 h). The results of the calculations are presented in Tab. 1.

Tab. 1 Results of probability of faultless work calculation for three variants of RFS structural-functional scheme

Operation time [h]	Probability of faultless work		
	non redundancy $P(t)_1$	existing approaches $P(t)_2$	proposed approach $P(t)_3$
2.00	0.120	0.416	0.378
1.75	0.156	0.466	0.449
1.50	0.204	0.522	0.527
1.25	0.266	0.584	0.612
1.00	0.346	0.652	0.703
0.75	0.452	0.727	0.794
0.50	0.589	0.809	0.881
0.25	0.767	0.900	0.955
0.00	1.000	1.000	1.000

For a better interpretation, the results of the probability of faultless work calculation for three variants of the RFS structural and functional scheme are presented in the graph (Fig. 6).

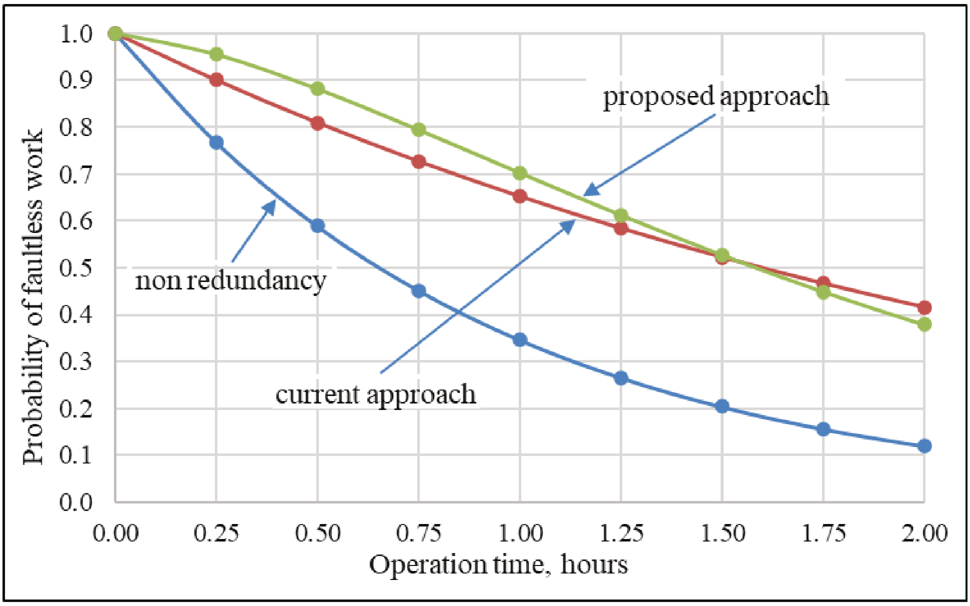

Fig. 6 Graph of dependence of probability of faultless work of RFS on the operation time

Analysis of the results of the calculation of the probability of faultless work (8), (10), (12) for three variants of the structural and functional scheme of the RFS (Tab. 1, Fig. 6) shows that the proposed approach to the creation of the RFS is better than the variants without redundancy and with redundancy according to existing approaches. This is explained by the fact that the type of redundancy is selected for each subsystem by the functioning of this subsystem. It should be noted that when operating for up to 1 hour, the proposed RFS has a probability of faultless work higher on average by 6 % than the system reserved according to the existing approach and by 31 % for the system without redundancy. At the same time, when operating from 1 hour to 2 hours, this advantage is slightly reduced, so the advantage of the proposed approach is 29 % for the system without redundancy. This is explained by the fact that the applied triple modular redundancy in the reconnaissance subsystem ensures high stability of functioning only for a short period. It is clear that to increase the time of operation, you can try to replace this type of redundancy with another, in particular, active, passive, or sliding redundancy. In this way, the operating time will increase, but the probability of faultless work at the initial stage will decrease, which can lead to the failure of the reconnaissance subsystem and, as a result, the failure of the entire system.

4 Conclusions

Thus, a structural and functional scheme of the RFS is proposed, which takes into account the appropriate type of redundancy for each subsystem. Hence, the most appropriate type of redundancy for the reconnaissance subsystem is triple modular redundancy because this type of redundancy has a high degree of reliability of the received signal and a high probability of faultless work at the initial stage of operation. This ensures faultless work of the entire system. For the control subsystem, the most appropriate type of redundancy is passive redundancy. This is explained by the fact that this subsystem, as a rule, has the lowest failure intensity rate among the elements of other subsystems. Therefore, the use of this type of redundancy allows you to save the resource of reserve elements. For the fire support subsystem, the most appropriate type of redundancy is sliding redundancy, because this type of redundancy allows you to ensure the redundancy of a larger number of main elements with a smaller number of spare ones. This fully corresponds to the conditions of operation of the fire support subsystem. Moreover, it should be noted that the fire support subsystem has, as a rule, the highest failure intensity rate among the elements of other subsystems.

The results of modeling the operation of the RFS according to three variants of the structural-functional scheme, in particular without redundancy, redundancy according to the existing approaches, and according to the proposed approach, indicate the superiority of the proposed approach. Thus, the average increase in the probability of faultless work according to the proposed approach relative to the existing one is 6 %, and relative to the scheme without redundancy is 30 %. This allows us to claim that the proposed approach to backup is more appropriate.

The further direction of the research is the substantiation of ways to increase the stability of the functioning of the reconnaissance subsystem by combining triple modular redundancy with other types of redundancy.

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