Method of Direct Diagnostic Problem Solution in UAV Operation System

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Abstract. The paper concentrates on solving the direct diagnostic problem of UAV radioelectronic equipment technical condition. Unmanned aerial vehicles play a large role in modern human life. Operation systems are applied for reliable intended use of UAVs. These systems contain main process (equipment intended use) and additional processes. Diagnostic is one of the operation system additional processes and is aimed at defining the failed UAV radioelectronic equipment element. The step by step method of solving the direct diagnostic problem is given. The method of direct problem solving includes the nine procedures. The probability density function of diagnostic procedure time is taken as an efficiency index. The example of direct diagnostic problem solving is given. The researched object in test example consists of seven functional elements The corresponding analytical equations are found and diagrams of probability density function of diagnostic time are built. Analysis showed that obtained probability density function of diagnostic time in general case has a multimodal nature. The research results can be used during the design and modernization of the UAV electronic equipment operation systems.

Keywords: operation system, diagnostics, UAV, Monte-Carlo simulation.

1 Introduction

Unmanned aerial vehicles (UAVs) began to play a large role in modern human life. UAVs are widely used in military field, agriculture, ecology. The UAVs tasks are: monitoring of the airspace, earth and water surfaces, ecological control, air traffic control, maritime traffic control, communication systems development, field logistics, etc. [1, 2].

Operation systems (OSs) are applied for reliable intended use of UAVs. In general OS includes: equipment, processes, resources, documents, personal, etc [3, 4]. OS processes include: intended use, maintenance and repair, diagnostic, monitoring, re-

source extension, etc. UAV technical condition diagnostic is an obligatory component during UAV intended use [5]. Technical diagnostic is a process of determining the technical condition of diagnostic object (DO). DO technical condition changes when elements in DO fail, that's why in fact technical diagnostic is a process of searching the failed element in DO. The failed objects search is made with the help of algorithms or diagnostic program (DP). DP development or synthesis is made with the help of diagnostic methods that define the DP creation sequence according to one or another efficiency index [6].

2   Literature Analysis and Problem Statement

UAV operation system can be considered as an object of design and update procedures [7]. During UAV OS design the following tasks are solved from the statistical data processing point of view: synthesis and analysis of data processing algorithms [8, 9], data statistical model substantiation [10], and efficiency index defining, etc.

Statistical data processing algorithms are connected with all operation processes. There is a possibility to make a data processing of UAV defining parameters and reliability indexes [11]. Choosing the optimal model of reliability indexes is an important phase of solving the design tasks. Using parametric, nonparametric and adaptive procedures of data processing is caused by variety of possible situations during UAV OS design, by the presence of many monitoring indexes and by antecedent uncertainty of initial data [12]. Analysis shows that the classical [13] and sequential [14] data processing algorithms are used in OS. First ones have fixed sample size, in second one's sample size is a random value.

In general, analysis shows [7, 15] that not enough attention is paid to data processing procedures in UAV technical condition diagnostic. So the topical scientific task of developing the data processing method during solving the direct diagnostic problem is concluded in this research.

3   Method of Direct Diagnostic Problem Solution

Direct problem solving method is based on principles of probability theory, mathematical statistics and differential calculus. Method is used for estimation the efficiency of current repairs procedures and data processing structure substantiation, during current repairs programs design, as well as during development of new and updating existing UAV operation systems. The main task is to find the efficiency index of performing the UAV diagnostic and current repairs process (direct problem).

Calculations initial data is:

1. The diagnosing and repair object structural diagram.

2. Time of inspection operations for diagnosing the separate blocks and object as a whole, as well as repair work time.

3. Probability of UAV structural elements faults.

4. Probability of the first α and second kind β errors.

During synthesis of this method we consider that separate element of current repair object is being replaced during its operability restoration that is repair time is equal to replacing time. In general case all durations are random values. Therefore, their full description requires the corresponding probability density functions. In the case of an approximate calculation it is enough to limit the first initial and second central moments of the random variable, that is, mathematical expectation and dispersion. Probability of each UAV element failure (Q_i) must be also known. Probability of making false decisions in the diagnosing process, probability of the first kind error α (when operable element is considered to be inoperable) and probability of the second kind error β (when inoperable element is considered to be operable) must be also known during direct problem solving.

Efficiency indexes during solving the direct problem can be the followings: distribution density of costs; time for diagnostic program implementation; mathematical expectation and variance of diagnostic time; probability density function (PDF) of diagnostic time.

Only a point estimate of a random value is used to determine the efficiency index in most scientific sources. However, such an approach may not take into account all the necessary information. Therefore, it is appropriate to use the PDF, which characterizes the random variable most fully. Point estimates can be found from known PDF.

Additionally, let's assume that only one element in the object failed during the diagnostic.

The method of direct problem solving includes the following operations.

1. Inspect the structural diagram of the current repair object.
2. Make a diagnostic model (DM).
3. Select diagnostic methods.
4. Make a diagnostic and current repair program if there are no first and second kind errors.
5. Select a strategy for replacing elements in case of the first and second kind errors during the technical condition inspection of the current repair object.
6. Make programs of the UAV current repair, the number of which is equal to the number of DM elements, if there are first and second kind errors.
7. Find the numerical values of the probabilities of a certain technological operations set (TOS) in case of each of the UAV elements failure possibility. These probabilities are functions of the parameters α and β.
8. Calculate the unconditional PDF of diagnostic time using the complete probability formula for given numerical values of the UAV elements failures probability Q_i.
9. Calculate the mathematical expectation and variance of the diagnostic procedure time for the obtained PDF.

At the stage of the current repair object inspection the followings are necessary: to define the structural and functional diagrams; to identify (take into account) possible first and second kind errors during the diagnostic procedure; to determine the probability of the DM structural elements failure at a given level; determine the inspection

operations time for each DM element; determine the TOS performing time and repair work.

At the stage of DM compilation it should be taken into account that DM is a main properties reflection of the object under control, at the level of structural, functional and principal diagrams. In the general case there may be several models at different levels of the diagnostic object representation (equipment frame, block, board, etc.).

Diagnostic method must be chosen to implement the third stage. Methods for diagnosing the UAV technical condition can be divided into two groups – statistical and analytical. Statistical methods are based on using the statistical data of faults and damages in UAV units and elements that are collected and analyzed in advance. As a result, a table is drawn up in which the signs of failures and damages are indicated, and a ranked list of reasons that led to them is given respectively for each of the sign. The ranking is carried out as the probability of the failure and damage reasons decreases. Analytical methods for diagnosing the UAV technical condition can be divided into two subgroups. The methods of the first subgroup specify a method for verifying the UAV operability. The methods of the second subgroup determine the sequence of the control and measuring operations.

The first subgroup of methods can include the followings: the method of intermediate measurements (using voltage maps, voltage diagrams, resistance maps, etc.); external examination; the method of replacing a checked unit, board, on a knowingly operable unit, board; comparison of the operable unit, board signals with the diagnosed equipment unit; simulation of input signals; supplying special test packages (signals) to the input; signature analysis, etc.

The second subgroup includes the following methods: probability/time; half decomposition; based on an information criterion; branches and boundaries; based on the dynamic programming; random search; engineering, etc. An example based on the engineering method is given in this methodology. Engineering methods are based on operation experience and can use the main potential of other methods for constructing DP that take into account the features of the elemental base, the constructional implementation of the UAV and a number of other UAV features.

At the fourth stage, the following works are necessary: 1) to develop the DP and 2) to develop a current repair program (CRP), using its DM. The diagnostic program shows the sequence of checking the DM elements to determine the faulty block.

The fifth stage requires the following works:

1. Determine the strategy of replacing DM elements. The simplest strategy is to consistently replace the elements from the first to the last. For example, if the third element is objectively failed, but the failure of the sixth element was diagnosed due to the false decisions, then after replacing the sixth element, the elements will be replaced in the sequence of the first, second, and third ones.

For certainty in this method, this rule is valid: if $Q_1 > Q_2 > \ldots > Q_n$, where n is the number of DM elements.

2. Two types of errors may occur in the process of the technical condition control and diagnosing: 1) when the operable object is defined as faulty (the first kind error); and 2) when the faulty object is determined to be operable (a second kind error). If there are no errors, then the technical condition control system works perfectly. The

errors presence reduces the efficiency of the operation system as a whole. Therefore, the key to effective design of the operation systems is to take into account the first and second kind errors.

At the sixth stage the following tasks need to be done:

1. Make several diagnostic programs, the number of which is equal to the number of the current repair elements. It is possible to perform not one TOS, but the whole set (the number of TOS is equal to the number of DM elements) in the case of failure of the DM i-th element if we assume that the probabilities of the first and second kind errors are not equal to zero. At the same time, one of these TOS will be correct, and all the others will be false.

2. The number of operations that will be part of the TOS that are related to the false detection of a fault element will be determined by the accepted strategy of the recovery work implementation. The following ones can be referred to such strategies: the repetition of the DP from the beginning; re-control DM elements that have bigger probability of fault. In this case, assume that the fact of element false detection will be found by the indirect method. This is due to the fact that the repair engineer will perform outgoing inspection of all current repair objects (CRO) operability and record its inoperable status. At the same time, we will assume that there are no first and second kind errors during the operability control of all CRO.

At the seventh stage, the following works must be performed:

1. It is necessary to analyze the diagnostic programs in the case of the first and second kind errors to find the probability of a TOS performing in the case of a certain CRO element possible fault. In the general case, these probabilities are functions from the probabilities of the first and second kind errors.

2. The probability of TOS performing is found by the graph-analytical method. At the same time it is equal to the product of all probabilities marked on the graph ribs, on the way from the control of the DP graph first element to the certain TOS. In the general case, the probability formula of a certain TOS performing will look like:

$$P(\text{TOS}i \, / \, j \text{ el. failure}) = \alpha^{n_1} \beta^{n_2} (1-\alpha)^{n_3} (1-\beta)^{n_4} \, ,$$

where n_1 is a number of the first kind errors, marked on the CRP graph ribs, on the way to the i-th TOS (its value can range from zero to k, where k is a number of hierarchical levels in the CRP); n_2 is a number of the second kind errors, marked on the CRP graph ribs, on the way to the i-th TOS (its value can range from zero to k); n_3 is a number of correct diagnostics regarding the TOS element operable condition, marked on the CRP graph ribs, on the way to the i-th TOS (its value can range from zero to k); n_4 is a number of correct diagnostics regarding the TOS element inoperable condition, marked on the CRP graph ribs, on the way to the i-th TOS (its value can range from zero to k).

The following works must be done at the eighth stage:

1. If for the i-th element failure the PDF of TOS performing time is known, must calculate PDF of diagnostic time for the i-th element failure by the total probability formula. If PDF is unknown, then we can assume that they have a Gaussian character.

If such an assumption cannot be made, then it is necessary to calculate the mathematical expectation of the diagnostic time based on the known values of the control and repair procedures average time.

2. Let's assume that we know the conditional PDF of the TOS performing time for the case of the i-th element failure – $f(t_D / i \text{ el. failure})$. Let's assume that for this conditional PDF the normalizing condition is following:

$$f(t_D / i \text{ el. failure}) = \sum_{j=1}^{n} P(\text{TOS } j / i \text{ el. failure}) f(t_{\text{TOS } j} / i \text{ el. failure}) ,$$

where n is a DM elements quantity.

3. The total probability formula is used to find the unconditional PDF. If the separate conditional PDF $f(t_D / i \text{ el. failure})$ is found it is possible to find the unconditional PDF of the object operability diagnostic program performing time in the following form:

$$f(t_D) = \sum_{i=1}^{n} Q_i f(t_D / i \text{ el. failure}).$$

The given formulas for conditional and unconditional PDFs are generalized in the case when there are n elements in the diagnostics object.

At the ninth stage, it is necessary to calculate the mathematical expectation and dispersion:

$$m_1(t_D) = \int_0^{\infty} t_D f(t_D) dt_D = \sum_{i=1}^{n} Q_i I_i.$$

$$\mu_2(t_D) = \int_0^{\infty} (t_D - m_1(t_D))^2 f(t_D) dt_D = m_2(t_D) - m_1^2(t_D).$$

In this case:

$$m_2(t_D) = \int_0^{\infty} t_D^2 f(t_D) dt_D = \sum_{i=1}^{n} Q_i J_i.$$

$$I_i = P(\text{TOS1} / i \text{ el. failure}) m_1(t_{\text{TOS1}} / i \text{ el. failure}) + ... + $$
$$+ P(\text{TOS}n / i \text{ el. failure}) m_1(t_{\text{TOS}n} / i \text{ el. failure}).$$

$$J_i = P(\text{TOS1} / j \text{ el. failure}) m_2(t_{\text{TOS1}} / j \text{ el. failure}) + ... + $$
$$+ P(\text{TOS}n / j \text{ el. failure}) m_2(t_{\text{TOS}n} / j \text{ el. failure}).$$

4   Example of Method Implementation

Let's consider test case of using a method for solving a direct problem.

1. Let the investigated object consists of seven functional blocks (Fig. 1).

2. We choose the engineering diagnostic method.

3. We will develop diagnostic and current repair programs in the absence of the first and second kind errors (Fig. 2).
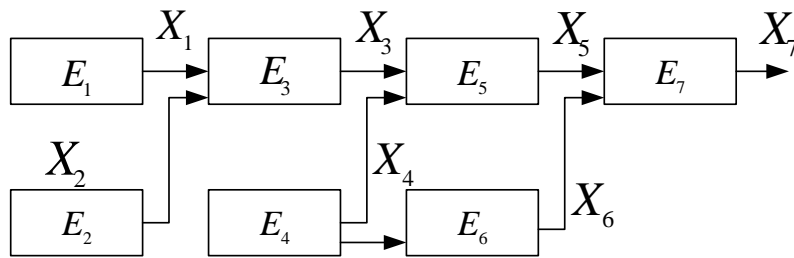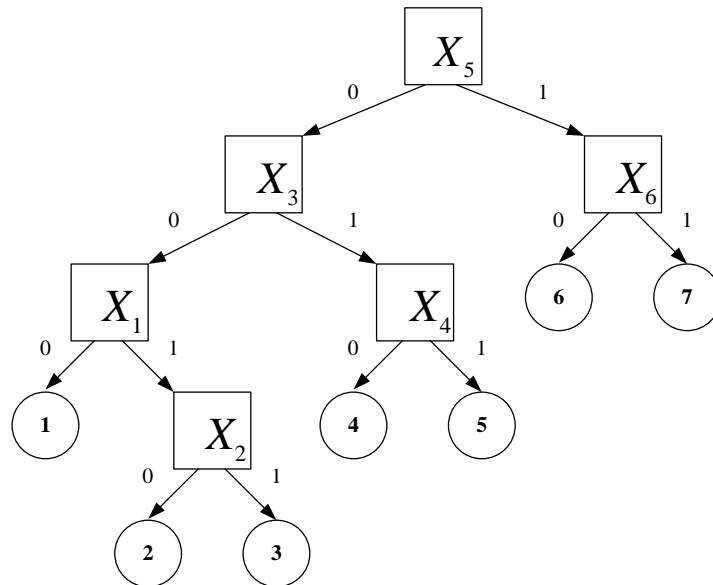

Fig. 1. Diagnostic model

Fig. 2. Diagnostic program based on engineering method

4. We choose the strategy of replacing elements during the technical condition inspection of the current repair object, in which the replacement of the elements is performed sequentially from the first in the case of an error.

5. Make a program of the current repair in case of the first and second kind errors presence. Since there are seven diagnostic object elements, then there will be seven

programs. A diagnostic program example in case of a first element of the object failure is shown in Fig. 3.

6. Will find the numerical values of the probabilities of a certain TOS performance in case of each of CRO the elements fault possibility. These probabilities are functions of α and β parameters.

In case of the first element failure:

$$P(\text{TOS1}/1\,\text{el. failure}) = (1-\beta)^3, \; P(\text{TOS2}/1\,\text{el. failure}) = \alpha\beta(1-\beta)^2,$$

$$P(\text{TOS3}/1\,\text{el. failure}) = \beta(1-\alpha)(1-\beta)^2, \; P(\text{TOS4}/1\,\text{el. failure}) = \alpha\beta(1-\beta),$$

$$P(\text{TOS5}/1\,\text{el. failure}) = \beta(1-\beta)(1-\alpha), \; P(\text{TOS6}/1\,\text{el. failure}) = \alpha\beta,$$

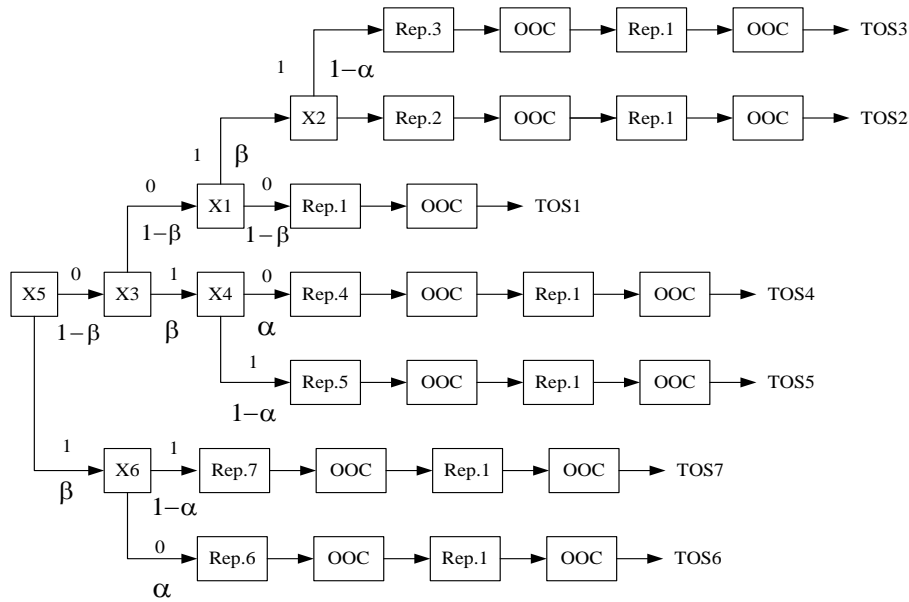$$P(\text{TOS7}/1\,\text{el. failure}) = \beta(1-\alpha).$$

Fig. 3. Diagnostic program in case of diagnostic errors and first element failure

In case of the second element failure:

$$P(\text{TOS1}/2\,\text{el. failure}) = \alpha(1-\beta)^2, \; P(\text{TOS2}/2\,\text{el. failure}) = (1-\alpha)(1-\beta)^3,$$

$$P(\text{TOS3}/2\,\text{el. failure}) = \beta(1-\alpha)(1-\beta)^2, \; P(\text{TOS4}/2\,\text{el. failure}) = \alpha\beta(1-\beta),$$

$$P(\text{TOS5}/2\,\text{el. failure}) = \beta(1-\beta)(1-\alpha), \; P(\text{TOS6}/2\,\text{el. failure}) = \alpha\beta,$$

$$P(\text{TOS7}/2\,\text{el. failure}) = \beta(1-\alpha).$$

In case of the third element failure:

$$P(\text{TOS1}/3\,\text{el. failure}) = \alpha(1-\beta)^2, \; P(\text{TOS2}/3\,\text{el. failure}) = \alpha(1-\alpha)(1-\beta)^2,$$

$$P(\text{TOS3}/3\,\text{el. failure}) = (1-\alpha)^2(1-\beta)^2, \; P(\text{TOS4}/3\,\text{el. failure}) = \alpha\beta(1-\beta),$$

$$P(\text{TOS5}/3\,\text{el. failure}) = \beta(1-\beta)(1-\alpha), \; P(\text{TOS6}/3\,\text{el. failure}) = \alpha\beta,$$

$$P(\text{TOS7}/3\,\text{el. failure}) = \beta(1-\alpha).$$

In case of the fourth element failure:

$$P(\text{TOS1}/4\,\text{el. failure}) = \alpha^2(1-\beta), \; P(\text{TOS2}/4\,\text{el. failure}) = \alpha^2(1-\alpha)(1-\beta),$$

$$P(\text{TOS3}/4\,\text{el. failure}) = \alpha(1-\alpha)^2(1-\beta), \; P(\text{TOS4}/4\,\text{el. failure}) = (1-\alpha)(1-\beta)^2,$$

$$P(\text{TOS5}/4\,\text{el. failure}) = \beta(1-\beta)(1-\alpha), P(\text{TOS6}/4\,\text{el. failure}) = \beta(1-\beta),$$

$$P(\text{TOS7}/4\,\text{el. failure}) = \beta^2.$$

In case of the fifth element failure:

$$P(\text{TOS1}/5\,\text{el. failure}) = \alpha^2(1-\beta), \; P(\text{TOS2}/5\,\text{el. failure}) = \alpha^2(1-\alpha)(1-\beta),$$

$$P(\text{TOS3}/5\,\text{el. failure}) = \alpha(1-\alpha)^2(1-\beta), \; P(\text{TOS4}/5\,\text{el. failure}) = \alpha(1-\alpha)(1-\beta),$$

$$P(\text{TOS5}/5\,\text{el. failure}) = (1-\beta)(1-\alpha)^2, \; P(\text{TOS6}/5\,\text{el. failure}) = \beta\alpha,$$

$$P(\text{TOS7}/5\,\text{el. failure}) = \beta(1-\alpha).$$

In case of the sixth element failure:

$$P(\text{TOS1}/6\,\text{el. failure}) = \alpha^3, \; P(\text{TOS2}/6\,\text{el. failure}) = \alpha^3(1-\alpha),$$

$$P(\text{TOS3}/6\,\text{el. failure}) = \alpha(1-\alpha)^2(1-\beta), \; P(\text{TOS4}/6\,\text{el. failure}) = \alpha^2(1-\alpha)^2,$$

$$P(\text{TOS5}/6\,\text{el. failure}) = \alpha^2(1-\alpha), \; P(\text{TOS6}/6\,\text{el. failure}) = \alpha(1-\alpha)^2,$$

$$P(\text{TOS7}/6\,\text{el. failure}) = (1-\alpha)(1-\beta).$$

In case of the seventh element failure:

$$P(\text{TOS1}/7\,\text{el. failure}) = \alpha^3, \; P(\text{TOS2}/7\,\text{el. failure}) = \alpha^3(1-\alpha),$$

$$P(\text{TOS3}/7\,\text{el. failure}) = \alpha^2(1-\alpha)^2, \; P(\text{TOS4}/7\,\text{el. failure}) = \alpha^2(1-\alpha),$$

$$P(\text{TOS5}/7\,\text{el. failure}) = \alpha(1-\alpha)^2, \ P(\text{TOS6}/7\,\text{el. failure}) = \alpha(1-\alpha),$$

$$P(\text{TOS7}/7\,\text{el. failure}) = (1-\alpha)^2.$$

7. Calculate unconditional PDF of diagnostic time by the total probability formula for given numerical values of the probability of CRO elements failures Q_i. Then

$$f(t_D/1\,\text{el. failure}) = P(\text{TOS1}/1\,\text{el. failure})f(t_{\text{TOS1}}/1\,\text{el. failure}) + ... +$$
$$+ P(\text{TOS7}/1\,\text{el. failure})f(t_{\text{TOS4}}/1\,\text{el. failure}).$$

The histogram of the diagnostic time obtained based on the Monte-Carlo statistical modeling method in the case of the first element failure, and the calculated theoretical conditional PDF for this example are shown in Fig. 4.

The unconditional PDF of the diagnostic program performance time:

$$f(t_D) = Q_1 f(t_D/1\,\text{el. failure}) + Q_2 f(t_D/2\,\text{el. failure}) + ... + Q_7 f(t_D/7\,\text{el. failure}).$$

The histogram of the diagnostic time obtained based on Monte-Carlo statistical modeling method, and the calculated theoretical PDF for this example are shown in Fig. 5.
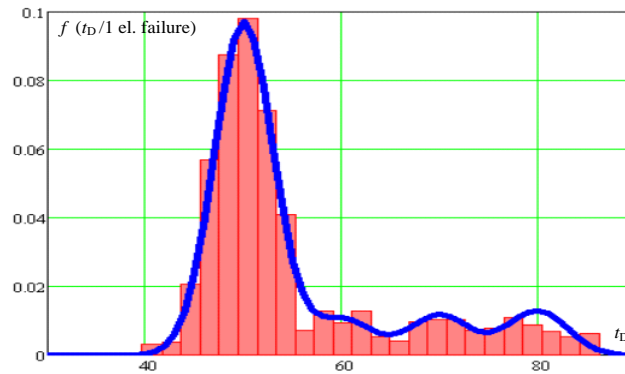

Fig. 4. Histogram of diagnostic time and calculated theoretical conditional PDF
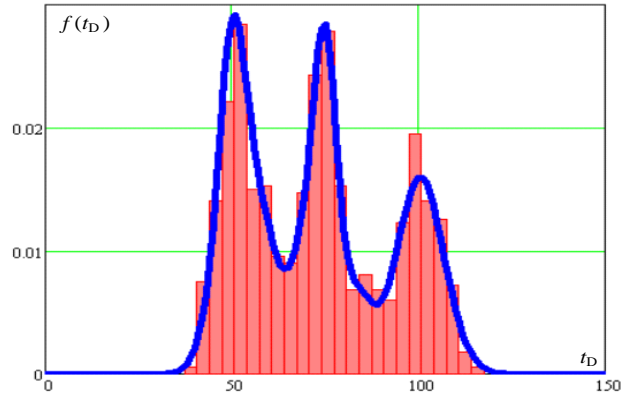
Fig. 5. Histogram of diagnostic time and calculated theoretical PDF

5 Conclusions

The article deals with the method of solving the direct problem of diagnosing the UAV radioelectronic equipment technical condition. This method includes nine steps, which are aimed at finding the probabilistic characteristics of efficiency index – the diagnostic time. The presence of the first and second kind errors distorts the PDF shape, which in the general case turns into a multimodal.

The research results can be used during the design and modernization of the UAV electronic equipment operation systems.

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