Efficiency Analysis of Predictive Monitoring and Control for Information and Communication System*

Oleksiy Zuiev[1,†], Oleksandr Solomentsev[1,†], Maksym Zaliskyi[1,*,†] and Alina Osipchuk[1,†]

[1] National Aviation University, 1 Liubomyra Huzara ave., 03058 Kyiv, Ukraine

Abstract

Information and communication systems used to meet the needs of flight activity consumers in civil aviation include communication, navigation, and surveillance equipment. During the operation of this equipment, its technical condition may change. In general, a distinction is made between normal, deteriorated, and non-serviceable conditions of equipment. Determination of technical conditions is usually performed by analyzing statistical data in the case of using diagnostic analytics. A promising direction of operation is predictive and prescriptive analytics technologies. This paper is devoted to the development of the data processing procedure during the implementation of predictive monitoring and control of the technical condition of equipment. The main attention was paid to obtaining formulas for the probabilities of making decisions regarding the future technical condition of the equipment. The initial information was the probability of being in a given condition at the current moment, the matrix of transition probabilities, and conditional probabilities of incorrect decisions. The results of the study can be used in the process of designing and improving the operation system for communication, navigation, and surveillance equipment during the monitoring and control of the technical condition.

Keywords

operation system, information and communication systems, classification, predictive control, veracity, decision-making

1. Introduction

Information and communication systems used to meet the needs of flight activity consumers in civil aviation include communication, navigation, and surveillance equipment [1, 2]. During the operation of this equipment, its technical condition may change. In general, a distinction is made between normal, deteriorated, and non-serviceable conditions of equipment [3]. Determination of technical conditions is usually performed by analyzing statistical data in the case of using diagnostic analytics. A promising direction of operation is predictive and prescriptive analytics technologies [4, 5].

Results of research [6–9] and practical experience in the operation of modern communication, navigation, and surveillance (CNS) aids show that there is a need for active use of information technology to process operational data on the use of these means and further modernization of the operation system (OS). It should be noted that, despite the possibilities of obtaining a large amount of information about the process of the operation and technical condition of radio equipment, this information is not used to its full extent. Insufficient use of data processing algorithms limits the possibilities of optimizing the processes of CNS systems operation [10, 11]. Thus, modern information technologies for the analysis of actual operational processes are not sufficiently used, which does not permit targeted and effective improvement of the OS [12, 13].

When building an operation system, a process and system approach can be applied [14, 15]. The conditions for the execution of all processes must be managed and controlled, and it is envisaged to

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* Corresponding author.
† These authors contributed equally.
0801zuiev@gmail.com (O. Zuiev); avsolomentsev@ukr.net (O. Solomentsev); maximus2812@ukr.net (M. Zaliskyi); alina.osipchuk2012@gmail.com (A. Osipchuk)
0000-0002-4520-3288 (O. Zuiev); 0000-0002-3214-6384 (O. Solomentsev); 0000-0002-1535-4384 (M. Zaliskyi); 0000-0002-9053-2072 (A. Osipchuk)

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perform operations to regulate the parameters of individual means and their components of the operation system [16]. This approach is adaptive to the operational processes management.

For realization of the adaptive approach, it is advisable to implement the following measures:

- Develop basic approaches to solving problems of classifying the technical state of CNS equipment.
- Reveal the key factors that it is desirable to take into account when implementing the classification process.
- Identify the main functions of the operation system of CNS means.
- Substantiate the main actions and operations that must be fulfilled during operation.
- Perform an analysis of the interaction of individual components of the OS in the classification process.
- Consider possible options for assessing the efficiency of adaptive operation [17–19].

Implementation of modern methods of processing statistical data and promising approaches to the construction of adaptive decision-making algorithms for managing the operational reliability of CNS means.

Modern approaches to the methods of operation of complex systems are based on the introduction of artificial intelligence technologies and robust methods of processing signals and data, special attention should be paid to the use of non-parametric detectors based on classical and consistent approaches to the use of the volume of the sample [20, 21].

Based on the conceptual tools of operations research, classification like any other measure (or system of actions), united by one idea and aimed at achieving a certain goal, is an operation.

The process of classifying objects consists of a set of elementary (indivisible under the conditions of this experiment) operations designed to perform certain functions on an object in a certain sequence by the selected classification algorithm [22]. The research objective determines the level of detail in elementary operations (EO). In the proposed model, classification is a sequence of transformation of a vector of states (VS) into a vector of realizations (VR) as a result of the joint action of a set of EO. Therefore, the quality performance of the object classification is determined by the quality of the performance of each of the studied sets of EO. Considering the above, the proposed procedure for forming a decision in the classification of objects will be based on the mathematical model of EO [23, 24].

Increasing the amount of a priori information taken into account leads to increasing the decision-making efficiency in the OS. Two types of data form ideas about the content and volume of a priori information. The first type involves knowledge of the background of the processes that are the object of research. In the second option, it is necessary to know the development of processes in the future. The data processing technologies differ when analyzing trends in parameter changes. The forecasting procedures are the most complex.

To conduct a prediction, the following tasks should be performed:

- Determine the goals of prediction.
- Determine the models of phenomena and processed data.
- Determine the efficiency indicator.
- Choose a prediction method.
- Solve the problems of synthesizing prediction algorithms.
- Solve the problems of analyzing prediction algorithms.
- Choose corrective actions in case of insufficient efficiency of the selected methods and corresponding algorithms.
- Directly execute the prediction.
- Assess the reliability of the prediction [25, 26].

2. Problem statement

The operation system can be represented as a system of systems. In terms of the system approach, its analysis requires describing the purpose, objectives, functions, content, organizational structure, relationships with the environment, and others [5, 6, 9].

The OS consists of the processes of using equipment for its intended purpose, maintenance, repair, diagnostics, control, monitoring, classification and prediction of technical conditions, resource extension, training and advanced training of personnel, and others [7, 14].

The main functions of the CNS equipment operation system are the following:

- Maintaining the reliability of equipment operation.
- Resource provision of operational processes.
- Analysis of compliance with regulatory documentation requirements.
- Formation and implementation of corrective and preventive actions.
- Control of the technical condition of equipment.
- Assessment of the effectiveness of the operation of the aviation enterprise, and others.

The active implementation and widespread use of information technologies of data processing for the formation and implementation of timely and accurate corrective and preventive actions characterizes the transition to the fourth industrial revolution [3, 16]. This trend particularly applies to all operational processes using artificial intelligence and Internet of Things technologies [23]. In conditions of a limited number of qualified operational personnel, remote control, diagnostics, and monitoring of technical conditions is a relevant scientific and technical task.

The efficiency of the operation system Ψ is determined by the set of actions $\left(\overrightarrow{Action}\right)$. The vector of possible actions is determined by the technical state of the CNS means—the vector $\overrightarrow{TS}$. The technical state of equipment can be classified according to trends in changes in key parameters and reliability indicators and can be two- and three-alternative. The technical state of the equipment is determined by procedures $\overrightarrow{Procedures}$ that depend on data processing algorithms $\overrightarrow{Alg}$ and models of determining parameters and reliability indicators $\overrightarrow{Models}$. Then the efficiency of the operation system can be written as

$$\Psi = \overrightarrow{Action}\left(\overrightarrow{TS} / \overrightarrow{Procedures}\left(\overrightarrow{Alg}, \overrightarrow{Models}\right)\right).$$

Therefore, the main scientific task of this research is to determine the dependence of the OS efficiency indicator on the parameters and characteristics of the process of classification and prediction of the technical state of communication, navigation, and surveillance means.

This paper aims to obtain analytical relations that describe the process of classifying the technical state of CNS means with subsequent prediction. Such relations can generally be used to solve the problems of increasing the reliability of decision-making during the implementation of predictive control.

To achieve the research objective, the following tasks will be considered:

- Development of a probabilistic decision-making graph for object classification with prediction (OCP).
- Synthesis of a classification model as a sequence of transformation of the VS into the VR as a result of the joint action of a set of EO and a further step-by-step method for determining the probabilities of making a decision based on the results of the OCP on the belonging of the CNS means to a certain classified state (CS).
- Analysis of stochastic graphs of decision forming with the selected OCP algorithm and taking into account errors.

3. Mathematical model of decision forming in object classification with prediction

The decision-forming operation during object classification with prediction (OCP) can be represented as a probabilistic graph (Fig. 1).

Fig. 1 contains the following notations:

1. $P(i,\tau_p)=P[E(i,\tau_p)], i=\overline{1,M}$ is the probability of radio-electronic means (REM) being in the i^{th} classified state at the prediction interval τ_n.
2. $\omega_{ir}(\tau_n)=P[(F(r,\tau_n))/(E(i,i_n))]$ is the conditional probability to decide on the belonging of the CNS mean to the r-th CS, if in fact, it was in the i^{th} CS.
3. $Q(i,\tau_p)=P[F(j,\tau_n)], i=\overline{1,M}$ is the probability of deciding on the belonging of the CNS mean to the j^{th} CS based on the results of the OCP.

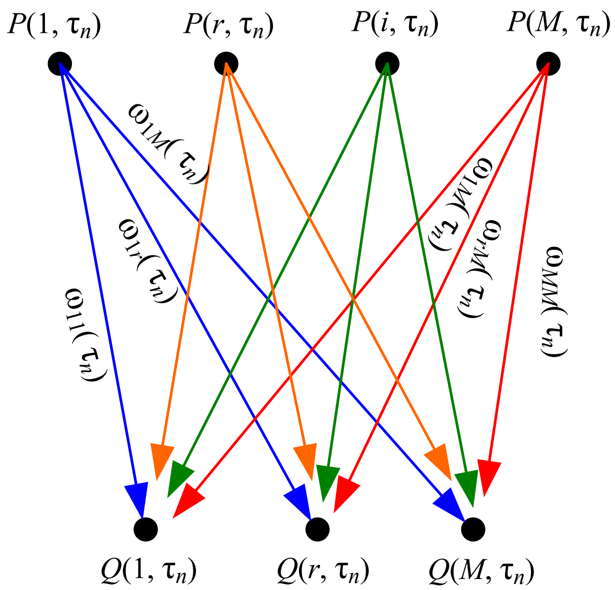

Figure 1: Probabilistic graph of the forming decisions during the object classification with prediction

The probabilities of making the decision based on the results of the OCP on the belonging of the CNS means to a certain CS, taking into account the accepted notations and by Fig. 1, are determined from the formula

$$Q(j,\tau_n)=\sum_{i=1}^{M} P(i,\tau_n)\omega_{ij}(\tau_n), j=\overline{1,M}. \quad (1)$$

Let us consider in more detail the process of forming a decision in the OCP.

According to the adopted mathematical model of the CNS means [4], changes in the time of the VS of objects set of the same type are described by an a priori vector random process, the characteristics of which are known on the time interval $[0,\tau_n]$. One of the implementations of this process, which corresponds to the VS of a specific instance of the CNS equipment, is observed using current classification (CC) at discrete moments of time $\tau_1,\tau_2,\ldots,\tau_n; 0<\tau_1<\tau_2\ldots<\tau_n<\tau_k$, preceding the prediction interval.

Given the discrete nature of the moments and results of observations of the VS, the set of its ordinates at the moments of observations $\tau_1, \tau_2, \ldots, \tau_n$ is conveniently represented in the form of a certain trajectory E_z—changes in its true values

$$E_z = \{E(i, \tau_1), E(i, \tau_2), \ldots, E(\omega, \tau_n)\}, (i, j, \ldots, \omega) = \overline{1, M}, z = \overline{1, z}, \quad (2)$$

where z is the set of the trajectories of the changes in the true values of the VS during the observation interval.

Each trajectory E_z is characterized by the probability of existence $P_z = P(E_z)$.

The quantitative results of observations (measurements, calculations for the VS $\vec{Y}^{(n)}_{(\tau_1)}, \ldots, \vec{Y}^{(n)}_{(\tau_n)}$) are converted by tools of a CC into the numbers of one of the M states, which differ:

$$F(i, \tau_1), F(j, \tau_2), \ldots, F(\omega, \tau_k), (i, j, \ldots, \omega) = \overline{1, M}. \quad (3)$$

Based on the set of results $F(i, \tau_1), \ldots, F(j, \tau_k)$, obtained in the observation interval $[\tau_1, \ldots, \tau_k]$, the prediction result is formed and a conclusion is given on the belonging:

$$F(\tau_n) = \psi[F(i, \tau_1); F(j, \tau_2), \ldots, F(\omega, \tau_n)] \quad (4)$$

of the CNS means to some l^{th} distinguishable out of n possible prediction results $(l = \overline{1, W}, W \leq M)$ in the prediction interval.

We will distinguish between the set of trajectories F_s formed by the results of observations using PCs of the change in the VS

$$F_s = \{F(i, \tau_1), F(j, \tau_2), \ldots, F(\omega, \tau_k)\}, \quad (5)$$

where $S = F_s \in S$ is a set of the trajectories formed by the results of observations using CC of the VS in the prediction interval. Each trajectory F_s is characterized by the probability of existence $P_s = P(F_s)$.

Due to the errors of the selected CC tools, the CS numbers of the CNS means obtained at the time of observations may differ from the numbers $E(i, \tau_1)$, $E(j, \tau_2), \ldots, E(\omega, \tau_n)$, $(i, j, \ldots, \omega) = \overline{(1, M)}$which contained the true values of the VS at the indicated points in time. In this regard, any Z trajectory of changes in the true values of the VS—E_z with probability $\omega_{zs}(\tau_k)$ can be perceived by prediction tools as any S of the possible trajectories formed by the results of the CC tools for changes in the values of the VS.

The prediction tool, due to implementation errors, decides on whether the CNS means belongs to the j^{th} CS with the probability:

$$\omega_{sj}(\tau_n) = P\left\{F(\tau_n) \in \frac{j}{F_s}\right\}; j = \overline{(1, W)}. \quad (6)$$

Graphically, the operation of forming a decision with the selected OCP algorithm for a VS belonging to the z-th trajectory, by [5] and taking into account the above, is presented in the form of a stochastic graph (Fig. 2).

According to [4], an elementary classification operation is characterized by a matrix of conditional probabilities of transitions from some states, which differ at the input of the operation, to other or the same states at its output. The unconditional probabilities of the states of the VS at the output of the EO are found by multiplying the specified matrix by the row matrix of the unconditional probabilities of the states of the VS at its input. The probabilistic characteristics of the VS at the output of an arbitrarily selected classification operation are found by successively multiplying the probability matrix at the input of the first in a series of operations that sequentially transform the VS values, by the transition probability matrix of all operations in the series, starting with the first and ending with the selected one.

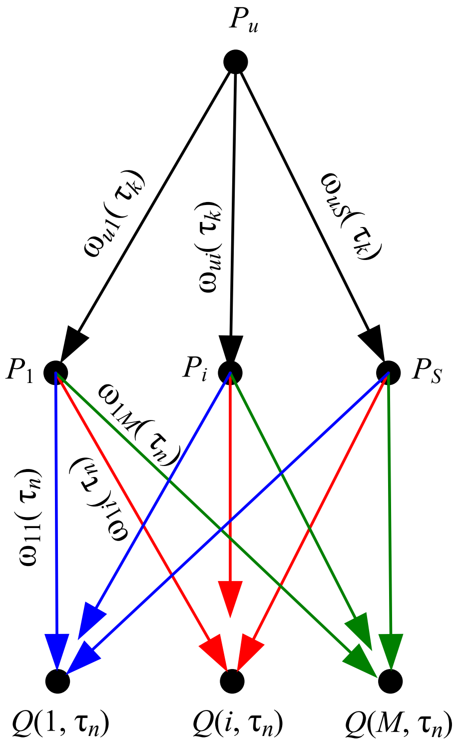

Figure 2: Stochastic graph of the forming decisions with the selected OCP algorithm

The latter circumstance allows us to find probabilistic characteristics of enlarged classification operations.

In this regard, all CC operations for elements of the observations at the VS can be replaced by one enlarged CC operation, characterized by a matrix whose elements are the probability of transitions of true trajectories into observed ones:

$$\left|W_{trs}^{T}\right|=\left\|\begin{matrix}\omega_{11}(\tau_k),\ldots,\omega_{1j}(\tau_k),\ldots,\omega_{1S}(\tau_k)\\ \omega_{z1}(\tau_k),\ldots,\omega_{zj}(\tau_k),\ldots,\omega_{zS}(\tau_k)\\ \omega_{z1}(\tau_k),\ldots,\omega_{zj}(\tau_k),\ldots,\omega_{zS}(\tau_k)\end{matrix}\right\|, \tag{7}$$

where $\sum_{S\in\dot{S}}\omega_{zS}=1;z=\overline{1,Z}$.

The set Z is characterized by a matrix row of probabilities of the existence of true trajectories of the VS, determined by the random process $\overrightarrow{\Xi_{(\tau)}^{(N)}}$, which is the input for the enlarged operation CC

$$\left|P_z^T\right|=\left\|P_1,P_2,\ldots,P_u,\ldots,P_z\right\|,\ \sum_{z\in Z}P_z=1. \tag{8}$$

The matrix-row of probabilities at the output of the enlarged CC operation, which is the result of multiplying matrices (7) and (8), contains as elements the probabilities obtained from the results of observations of each of the trajectories of the set S:

$$\left|P_S\right|=\|P_1,P_2,\ldots,P_i,\ldots,P_S\|=\left|P_z^T\,/\!/\,W_{trs}^T\right|, \tag{9}$$

The relationship of the certain components is shown on the probability graph.

According to Fig. 2, we can get

$$P_S=P(F_S)=\sum_{z\in Z}P_zW_{zs};s=\overline{1,S}. \tag{10}$$

The object classification with the prediction by the composition of operations differs from the CC in the presence of the EOs of a prediction, the resulting joint action of which can also be replaced by one enlarged prediction operation.

Its difference from the CC operation is that its input is not the probabilities of the states of the VS, but the probabilities of combinations of these states at discrete moments of observation.

Since the indicated combinations are characterized by the probabilities of the existence of trajectories of the set Z, which are input to the enlarged prediction operation, it is proposed to describe the probabilistic characteristics of this operation, similar to the CC operation, by the transition probability matrix $\left|W_{trs}^{n}\right|$

$$\left|W_{trs}^{n}\right|=\left\|\begin{matrix}\omega_{11}\left(\tau_{n}\right),\ldots,\omega_{1j}\left(\tau_{n}\right),\ldots,\omega_{1\omega}\left(\tau_{n}\right)\\ \omega_{s1}\left(\tau_{n}\right),\ldots,\omega_{sj}\left(\tau_{n}\right),\ldots,\omega_{s\omega}\left(\tau_{n}\right)\\ \omega_{s\omega}\left(\tau_{n}\right),\ldots,\omega_{s\omega}\left(\tau_{n}\right),\ldots,\omega_{s\omega}\left(\tau_{n}\right)\end{matrix}\right\|, \tag{11}$$

where $\sum_{j\in V} W_{sj}\left(\tau_{n}\right)=1$.

Probabilistic characteristics of the OCP are found by summing certain products of matrix elements. For example, the probability of making a decision based on the results of the OCP "The object belongs to the j-th CS" is determined by the expression

$$Q\left(j,\tau_{n}\right)=\sum_{z\in Z}\sum_{s\in S} P_{z}W_{zs}W_{sj}\left(\tau_{n}\right),\ j=\overline{1,M} \tag{12}$$

Conclusions

The need to implement modern information technologies for processing operational data on the operation of communication, navigation, and surveillance facilities and further modernization of the operation system is due to the results of research and practical experience in operating these facilities.

The paper considers the process of classifying CNS means, which consists of a set of elementary operations designed to perform certain functions, in a certain sequence by the selected classification algorithm. The article proposes a probabilistic graph of forming a decision during OCP, develops a classification model as a sequence of transformation of VS into VR as a result of the joint action of a set of EO and a further step-by-step method for determining the probabilities of making a decision based on the results of OCP on the belonging of a CNS means to a certain CS, analyzes stochastic graphs of decision forming with the selected OCP algorithm and taking into account errors. Analytical relations that describe the process of classifying the technical state of CNS means with subsequent prediction were obtained.

The results of the study can be used in the process of designing and improving the operational system for CNS means during the monitoring processes of the technical state.

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Declaration on Generative AI

While preparing this work, the authors used the AI programs Grammarly Pro to correct text grammar and Strike Plagiarism to search for possible plagiarism. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

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