Restoration of Information in On-Board Information and Controlling Complexes of Movable Objects in Emergency Situations

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Abstract. The technology of estimation of efficiency of methods of information recovery in on-board information-control complexes of moving objects in emergency situations caused by failures of hardware and software parts of on-board information-control complexes is offered. The proposed approach is considered as one of the steps of ensuring the functional stability of complex dynamic objects. Functional stability is considered as a property of a dynamic system, which is the ability to perform at least a set volume of its functions when failures in the information, computing, energy parts of the system, as well as external influences that are not foreseen by the operating conditions. It is proposed to provide functional stability in real time by performing the following actions: control of the state of functioning of a complex management system and detection of the fact of disturbances of its functioning (formation of the team "Accident"); identification of the cause of the fact of malfunctions in real time (localization of the place of damage of functioning and / or detection of unauthorized disturbances); shutting down the damaged parts or compensating for the effects of unauthorized disturbances on the general real-time control system; redistribution of system resources (information, computing, power) to ensure the functioning of the management system (possibly with impaired performance) in real time. It is determined that the implementation of functional stability can be achieved by the introduction into the complex dynamic system of various forms of redundancy (structural, functional, information, etc.) and the readiness of the operator of the dynamic object to control movement during a sudden reconfiguration of the complex. A mathematical model is proposed that allows you to build functional stability when using an automated control system for a complex dynamic object. The peculiarities of the application of the method of optimal filtration in emergencies caused by the evolution of structure and parameters are determined. The algorithm of discrete filtering in BICC in case of extraordinary situations related to distortion of information exchange is offered and the efficiency of methods of processing of measurement information in on-board information-control systems is evaluated. A recurrent algorithm of optimal discrete filtering is proposed to identify distortions related to information exchange distortion. Recommendations on practical neutralization of consequences of an emergency situation are offered.

Keywords: Filtering Algorithm, On-Board Information-Control Complex, Failures, Information Recovery, Dynamic System, Identification, Markov Chain, Emergency Situation, Optimal Filtration, Functional Stability.

1 Introduction and Literature Review

It is known that in the creation of aerospace technology, numerous information technologies and hardware are developed and used to ensure functional stability. Already since the 80s of the last century, intensive research has begun, related to the creation of methods of designing control systems capable of parrying possible freelance modes of operation. These methods are based on the principle of redundancy of hardware and their experimental testing. Then began scientific research aimed at exploring the potentialities of majoritarian ways of parrying the consequences of failures and emergencies.

The significant scale and uniqueness of these systems make them vulnerable to the effects of such destabilizing factors of functioning as various breakdowns, failures, failures, and in general - failures, crashes, catastrophes. All these anomalies testify to incomplete perfection of the created technical objects and, consequently, such components as control systems. The main reason for the imperfection is the low "intellectual level" of the control systems regarding the destabilizing factors - failures. An effective way to compensate for failures is to give the management system the properties of functional stability. Functional stability means the ability of a complex entity to restore system functions after failures occur. The realization of this property is possible using both the backup procedure and the procedure of redistribution of information, computing and energy resources in the control system. One of the productive ideas borrowed from nature experts is self-organization [1, 8-10]

Well-known traditional approaches to building adaptive systems do not in most cases ensure the functional stability of systems, so it is important to find new approaches, in particular, using the idea of self-organization. The problem of ensuring the functional stability of a complex object by means of self-organization is relatively new and relevant both in theoretical and applied plans [1, 6, 8-10].

In the work [14] introduced the scientific concept of the "functional stability" of a dynamic system, "as a property of a system that consists in the ability to perform at least a set volume of its functions in case of failures in the information, computing and energy parts of the system, as well as the environmental influences provided by the conditions". The functional stability is mathematically considered as the stability of the mathematical functional quality of the functioning of a complex system. This is a fundamental rejection of functional stability from dynamic Lyapunov stability. [8, 9]. Issues of information recovery in on-board information and control systems of moving objects are currently relevant, are addressed in research and practical development. [13-20]. In the works of Professor Kulik A.S. problems of development of scientific bases of rational management of efficiency of systems of automatic control of objects of aerospace technology in conditions of destabilizing actions are solved [6]. Organizations of the computational process in a multi-machine on-board computing complex are devoted to the works [8, 10]. In the writings of these scientists, decomposition methods were developed in the problems of distribution of computing resources of multi-machine aviation avionics complexes. In work [20] the problem of predicting the behavior of complex systems based on the use of fuzzy neural networks is investigated. In work [9], the principles of constructing an onboard multiprocessor computing system for fifth-generation avionics were proposed. In the works [11] a method of computer-aided design of on-board hardware has been developed, models and design methods for integrated modular avionics have been proposed [4]. A review of the current state and analysis of the prospects for the development of aircraft instrumentation integrated on-board computer systems made in [11]. The issue of reliability and functional safety of complexes of real-time programs was considered in work [7]. Prospects for the development of on-board equipment complexes based on integrated modular avionics are considered in work [12]. The principles of building a combined network topology for advanced on-board computer systems, the principles of organizing the architecture of advanced on-board digital computer systems in avionics, the organization of the on-board digital computer systems with support for reconfiguration and reliability assessment functions are considered in [11]. Algorithms and software for testing on-board digital computing systems of integrated modular avionics were proposed in [5]. The justification of the hardware reconfiguration of the structure of computing complexes, as well as evaluating the effectiveness of ensuring the restoration of the computing process after a failure in embedded systems, was considered in [2]. The issues of ensuring information and functional safety of special purpose airborne modular systems were considered in [2]. Fault-tolerant systems reconfigurable in integrated modular avionics are considered in [4, 13-17, 21].

2 Formulation of the Problem and its Relationship with Important Scientific and Practical Tasks

Recently, scientific opinion has come to the conclusion that there is a need for systematic consideration of issues of ensuring the functional stability of complex dynamic objects and information-control complexes. This is especially true of man-made and environmentally hazardous complexes that are hazardous to humans and the environment.

Unresolved parts of the common problem. An analysis of recent publications shows that there is an unresolved part of the problem, which is to investigate the issues of real-time bounce parsing in information-control systems in emergency situations.

The purpose of the work is to evaluate the efficiency of methods of information recovery in on-board information-control systems in emergency situations caused by failures in on-board information-control systems using the algorithm of discrete filtering in case of emergency situations related to the violation of information exchange.

Research methods. The following tasks were applied in the work: the theory of automatic control and system analysis for finding the algorithm of optimal filtration for the recovery of information in on-board information-control complexes of moving objects in emergency situations. Matrix theory, integral calculus, and simulation methods were also used using the Matlab computer program.

3 Materials and Methods

Research results are presented in sections 3.1-3.3. The application of the method of optimal filtration in emergency situations due to the evolution of structure and parameters is shown in subsection 3.1. The discrete filtering algorithm in the BICC in emergency situations related to the violation of the exchange of information is proposed in Section 3.2. Evaluation of the effectiveness of the methods of processing measurement information in the on-board information-control systems is made in subsection 3.3.

3.1 The Application of the Method of Optimal Filtration in Emergency Situations Caused by the Evolution of Structure and Parameters

Consider the problem of information recovery in on-board information and control systems (BIKS) in emergency situations caused by failures. We believe that the failures are modeled by the random vector $\gamma(k)$, which characterizes the evolution of the structure or BIKS parameters over time in the form of a Markov finite chain.

Let the BIKS equation be:

$$X(k+1) = F[X(k), \gamma(k), U(k), W(k)], \quad (1)$$

where $X(k)$- is the n-dimensional state vector of the system; $\gamma(k)$- random unknown vector of failure occurrence; $U(k)$ - is the m-dimensional control vector; $W(k)$ - random r-dimensional vector of Gaussian perturbations with zero mean and correlation matrix

$$M[W(k)W^T(j)] = Q(k)\delta(kj),$$

$\delta(kj)$ - is the symbol of Kronecker.

Observation equation:

$$y(k) = h[X(k), \gamma(k), V(k)], \quad (2)$$

where $y(k)$ - is the s-dimensional observation vector; $V(k)$ - is a p-dimensional random vector of Gaussian measurement errors

$$M[V(k)V^T(j)] = R(k)\,\delta\,(kj)$$

with zero mean and correlation matrix.

We assume that the values of the vector $\gamma(k)$ belong to a finite set R^N containing N elements:

$$R_N = \{\gamma: \gamma = \gamma_i,\ i = \overline{1,N}\}, \quad (3)$$

the sequence $\gamma(k)$ will in time produce a Markov chain with a known transition probability matrix:

$$P_{ij} = P[\gamma(k) = \gamma_i / \gamma(k-1) = \gamma_j] \tag{4}$$

from state γ_j at time k - 1 to state γ_i at the next k-th moment.

The task of filtering is to obtain an optimal estimate of the state vector $\hat{X}(k/k)$ by the observations Y_1^k = {y (k), y $(k$-$1)$,..., y (1)}, which satisfies the criterion for the minimum standard error. This criterion leads to estimates of the conditional average:

$$\hat{X}(k/k) = M\left\{X(k)/Y_1^k\right\}. \tag{5}$$

The quality of the estimates is determined by the conditional correlation matrix of the estimation errors:

$$P(k/k) = M\left\{[X(k) - \hat{X}(k/k)][X(k) - \hat{X}(k/k)]^T / Y_1^k\right\}. \tag{6}$$

The formulated problem is reduced to the problem of nonlinear filtering even in cases where the equations of state and BIKK observations are linear. This is due to the fact that in the process of filtering the state vector of the system, it is also necessary to estimate the random vector of parameters $\gamma(k)$. Moreover, estimating $\gamma(k)$ means identifying the type of BIKS structure at the present time.

Enter the notation:

$$\Gamma_i(k) \overset{\Delta}{=} \left\{\gamma(k) = \gamma_i\right\}, i = \overline{1, N} \tag{7}$$

$$\overline{\Gamma_i}(k) = \left\{\Gamma_{ik}(k), \Gamma_{ik-1}(k\text{-}1), \ldots, \Gamma_{i1}(1)\right\} = \left\{\gamma(k) = \gamma_{ik}, \gamma(k-1) = \gamma_{ik-1}, \ldots, \gamma(1)\right\}, \tag{8}$$

where each index i determines the number of the structure that BIKS may currently be in.

To determine all possible realizations of the vector of parameters $\gamma(k)$ from the beginning of the observation to the present moment, it is necessary to set $\Gamma_i(k)$ for all sets of the sequence of indexes {i_k, i_{k-1},..., i_1} ... Moreover, the total number of such realizations is N^k. Denote the space of these implementations containing N^k elements by Ω_k.

It is known that the estimate $X(k/k)$ can be reduced to the form [5]:

$$\hat{X}(k/k) = \sum_{i \in N^x} \hat{X}^{(i)}(k/k) P[\overline{\Gamma_i(k)} / Y_1^k], \tag{9}$$

$$\hat{X}_{(i)}(k/k) = M[X(k)/Y_1^k, \overline{\Gamma_i(k)}] \tag{10}$$

- the optimal estimate obtained for the specific implementation of the sequence $\overline{\Gamma_i(k)}$ and satisfying the criterion for the minimum of the root mean square error (separate estimate of the vector $X(k)$); $P[\overline{\Gamma_i(k)}/Y_1^k]$ - is the conditional probability of this realization.

Therefore, the optimal estimation of the BICK state vector is formed as a weighted sum of the individual estimates obtained for each realization of the sequence of values of the vector of parameters *γ(k)*, and the weighting coefficients are the posterior probabilities of these realizations. It should be borne in mind that the number of implementations $\overline{\Gamma_i(k)}$ increases over time, and the optimal filter requires an infinitely increasing amount of memory, which is perhaps unrealistic in the general case.

The posterior probabilities of sequences $\overline{\Gamma_i(k)}$ can calculated in a recurrent manner, using representations $\overline{\Gamma_i(k)}$ in the form:

$$\overline{\Gamma_i(k)} = \{ \Gamma_i(k), \overline{\Gamma_j(k-1)} \} = \{\gamma(k) = \gamma_i,\ \gamma(k-1) = \gamma_{jk-1},\ \ldots,\ \gamma(1) = \gamma_{j1}\}; \tag{11}$$

$$i, j_{k-1}, j_{k-2}, \ldots, j_1 \in I = \{i\colon i = \overline{1, N}\};$$

$$\overline{\Gamma_i(k-1)} = \{ \Gamma_j(k-1), \overline{\Gamma_l(k-2)} \} = \{\gamma(k-1) = \gamma_j,\ \gamma(k-2) = \gamma_{lk-2}, \ldots, \gamma(1) = \gamma_{l1}\} \tag{12}$$

$$j, l_{k-2}, l_{k-3}, \ldots, l_1 \in I = \{i\colon i = \overline{1, N}\};$$

consider Bayes formula:

$$P(\overline{\Gamma_i(k)} / Y_1^k) = P[\overline{\Gamma_i(k)} / y(k), Y_1^{k-1}] = \frac{f[y(k)\overline{\Gamma_i(k)}, Y_1^{k-1}] P[\overline{\Gamma_i(k)}, Y_1^{k-1}]}{f[y(k)/Y_1^{k-1}]}, \tag{13}$$

where $f[y(k)\overline{\Gamma_i(k)}, Y_1^{k-1}]$ - is the conditional density of the probability distribution of the measurements *y(k)*, calculated for the optimal filter, consistent with the specific implementation of the process $\overline{\Gamma_i(k)}$; $f[y(k)/Y_1^{k-1}]$ - conditional probability distribution density.

Expression (13) taking into account:

$$P(\overline{\Gamma_i(k)} / Y_1^{k-1}) = P[\Gamma_i(k), \overline{\Gamma_j(k-1)} / Y_1^{k-1}] = P[\Gamma_i(k) / \overline{\Gamma_j(k-1)}, Y_1^{k-1}] P[\overline{\Gamma_j(k-1)} / Y_1^{k-1}]; \tag{14}$$

$$P_{ij} \overset{\Delta}{=} P[\Gamma_i(k) / \Gamma j(k-1), \overline{\Gamma_l(k-2)}, Y_1^{k-1}] = P[\Gamma_i(k) \Gamma j(k-1)]; \tag{15}$$

is as follows:

$$P[\overline{\Gamma_i(k)} / Y_1^k] = \frac{f[y(k) / \overline{\Gamma_i(k)}, Y_1^{k-1}] P_{ij}}{\sum\limits_{n \in \Omega_k} f[y(k) / \overline{\Gamma_n(k)}, Y_1^{k-1}] P[\overline{\Gamma_n(k)} / Y_1^{k-1}]} \cdot P[\Gamma_j(k-1) / Y_1^{k-1}]; \tag{16}$$

We now find the correlation matrix of errors of optimal estimation:

$$P(k/k) = \sum_{n \in \Omega_k} P[\overline{\Gamma_n(k)} / Y_1^k] \left\{ P(k/k, \overline{\Gamma_n(k)}) + [\hat{X}^{(n)}(k/k) - \hat{X}(k/k)] \cdot [\hat{X}^{(n)}(k/k) - \hat{X}(k/k)]^T \right\} \tag{17}$$

Thus, the algorithm of optimal filtering in the case where the value of the vector of parameters *γ(k)*, describing the nature of the disturbances in the system, form a Markov chain, is reduced to the sequence of the following calculations:

1. On the basis of the accepted realization of the measurements *y(k)*, separate estimates of the state of the form of the form (10) are calculated. These estimates are based on the equations of state and observations of specific BICS and are consistent with the specific implementation of the sequence of violations $\overline{\Gamma_i(k)}$.

2. Using expression (16), the values of the weights are calculated $P[\overline{\Gamma_i(k)}/Y_1^k]$.

3. According to the formula (9) the resultant estimate of the state vector is calculated $\hat{X}(k/k)$.

4. According to formula (17), the correlation matrix of estimation errors is calculated, after which all calculations are repeated.

The need to have in the implementation of optimal filters an infinitely increasing amount of memory makes us look for algorithms of suboptimal (quasi-optimal) filtering, which, slightly inferior to the optimal in accuracy, would require significantly less computational cost for their implementation.

3.2 The Algorithm of Discrete Filtering in BIKK in Extraordinary Situations Related to the Violation of Information Exchange

Let the information message model be described by the equation of state:

$$X(k+1) = \Phi(k+1,k)X(k) + W(k), \tag{18}$$

where $\Phi(k+1, k)$ - is the dynamic matrix of the object.

Channel model of the measuring system - using the observation equation:

$$y(k) = \gamma(k)H(k)X(k) + U(k), \tag{19}$$

where *γ(k)* is a diagonal matrix whose elements are random variables that take only two values: $\gamma_i(k) = 1$ (normal operation mode) and $\gamma_i(k) = 0$ (failure mode caused by the disappearance of the information signal).

For a given BIKS model, we find practically implemented suboptimal algorithms for estimating the state vector, since the total number of possible realizations of sequences of values of *γ(k)* for each information channel is equal to two ($\gamma_i(k) = 1$ or $\gamma_i(k) = 0$), then, using by the general formula (9), the following expression can be obtained for the optimal filtering algorithm for the *j*-th channel:

$$\hat{X}_j(k/k) = \hat{X}_j^{(1)}(k/k)P(\gamma = 1/Y_1^k) + \hat{X}_j^{(0)}(k/k)P(\gamma = 0/Y_1^k), \tag{20}$$

where $\hat{X}_j^{(1)}(k/k)$ and - $\hat{X}_j^{(0)}(k/k)$ are separate estimates, provided that in the equation of observations (19) the value of *γ(k)* is 1 and 0, respectively.

And:

$$\hat{X}_j^{(1)}(k/k) = \hat{X}_j^{(1)}(k/k-1) + [P^{(1)}(k/k)H^T(k)R^{-1}(k)]\tilde{Z}_j^{(1)}(k/k-1), \qquad (21)$$

$$\hat{X}_j^{(0)}(k/k) = [\Phi(k,k-1)]\hat{X}_j^{(0)}(k-1/k-1), \qquad (22)$$

$$\tilde{Z}_j^{(1)}(k/k-1) = y_j(k) - H_j(k)\hat{X}^{(1)}(k/k-1). \qquad (23)$$

To calculate the weighting coefficients $P(\gamma = 1/Y_1^k)$ and $P(\gamma = 0/Y_1^k)$ representing the posterior probabilities of the corresponding values of the parametric variable γ, we should use the formula:

$$P(\gamma = 1/Y_1^k) = \Lambda(k)\frac{P(\gamma = 1/Y_1^{k-1})}{P(\gamma = 0/Y_1^{k-1})}[1 + \frac{P(\gamma = 1/Y_1^{k-1})}{P(\gamma = 0/Y_1^{k-1})}\Lambda(k)]^{-1}; \qquad (24)$$

$$\Lambda(k) = \left[\frac{\det P_{\tilde{Z}}^{(0)}(k)}{\det P_{\tilde{Z}}^{(1)}(k)}\right]^{-\frac{1}{2}} \exp\left\{-\frac{1}{2}\sum_{i=0}^{1}[\tilde{Z}(k)/k-1)^T[P_{\tilde{Z}}^{(i)}(k)]^{-1}\tilde{Z}(i)(k/k-1)\right\}; \qquad (25)$$

$$P[\gamma = 1/y(1)] = q.$$

Where $\Lambda(k)$ is the likelihood ratio, similar to that encountered in detection problems when using Wald's sequential analysis; q is the initial probability of a good channel condition.

A separate estimate $\hat{X}^{(1)}(k/k)$ is calculated using a filter according to algorithm (21). A separate estimate $\hat{X}^{(0)}(k/k)$ is according to algorithm (23).

Since the posterior probability $P(\gamma = 1/Y_1^k)$ under normal functioning conditions as the observation time increases, it tends to 1, and the value $P(\gamma = 0/Y_1^k)$ $\to$ 0, the scheme converted to a regular filter. If the information exchange channel is in a state of failure (γ = 0), then $\lim_{k\to\infty} P(\gamma = 1/Y_1^k) = 0$ and the resulting estimate is formed by the value $\hat{X}^{(0)}(k/k)$.

This structure can be considered as an adaptive system of general detection and evaluation of a random signal *X(k).*

Studies of the BIKS model of a dynamic object by mathematical modeling (Fig. 1) allow us to analyze the implementation of a random message *X(k)*, observations *y(k)*, and suboptimal estimates presented $\hat{X}(k/k)$ in dimensionless form. Arrows indicate the times in which the malfunction of the feed was modeled. The exact characteristics of the suboptimal algorithm under study are shown in Fig. 2 (curve 1). Ibid., For comparison, the time dependence of the filtration error dispersion (2) obtained for the same realizations *y(k)* as in the case of the suboptimal filter is shown. Both dependencies are calculated from 100 realizations for the slope angle of the trajectory of a dynamic object at a fixed sequence *γ(k)*, i.e. the disturbances were modeled for the same moments of time.

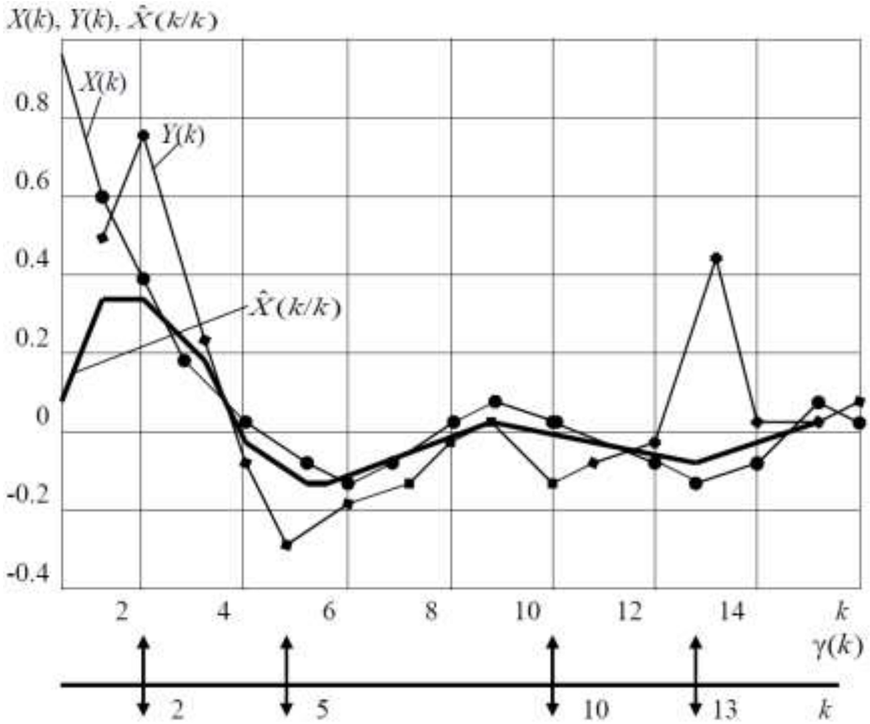

Fig. 1. Implementation of mathematical modeling

Comparison of the given accuracy characteristics makes it possible to conclude that with the appearance of failures in the information channel, the suboptimal nonlinear filter takes precedence over the usual optimal filter. The dependence of the posterior probabilities *P(1/k)* on the time of the proper state of the information channel for one implementation of *y(k)* and *q(k)* = 0.9 is shown in Fig. 3. This dependence uniquely determines the behavior of the filter gain. At the time of failure, the value of *P(1/k)* drops sharply, causing a corresponding decrease in the filter gain, which in turn leads to a loss of sensitivity to incoming new data, and, as a current estimate, produces an extrapolation estimate.

The suboptimal filtering algorithm for the information exchange channel model is as follows:

$$\hat{X}(k/k) = \hat{X}(k/k-1) + P(1/k)K_1(k)\tilde{Z}(k)(k/k-1); \quad (26)$$

$$\hat{X}(0/0) = M\{X(0)\}; \quad (27)$$

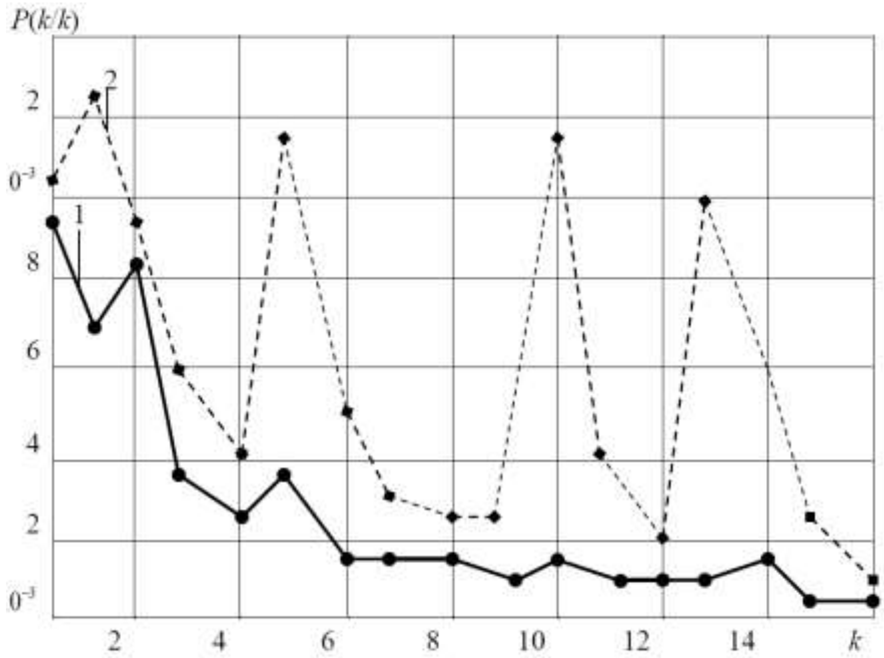

Fig. 2. Characteristics of the optimal algorithm

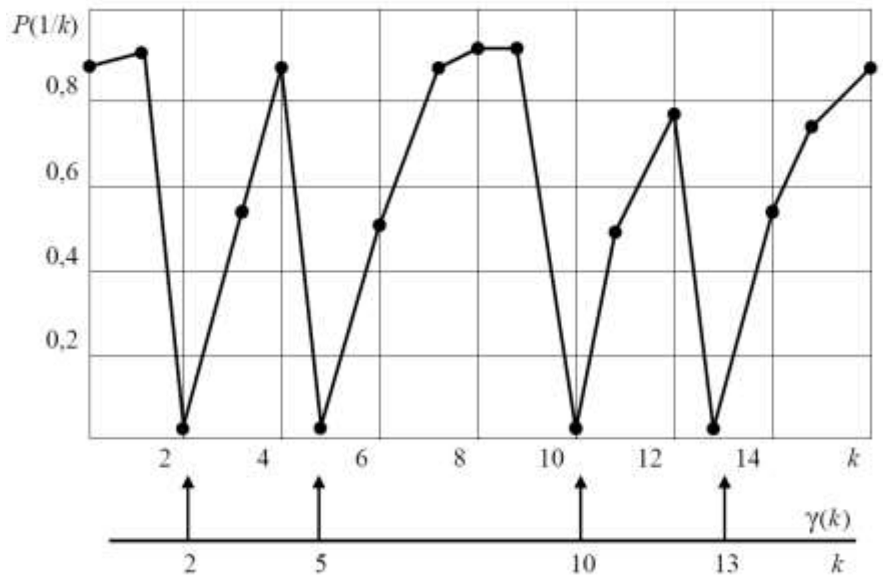

Fig. 3. Dependence of posterior probabilities *P(1/k)* on the time of the proper state of the information channel for one realization *y(k)* and *q(k)* = 0.9

$$\hat{X}(k/k-1) = \Phi(k,k-1)\hat{X}(k-1/k-1); \quad (28)$$

$$P(1/k) = \frac{f_1(k)q(k)}{f_1(k)q(k) + f_0(k)[1-q(k)]}; \quad (29)$$

$$f_i(k) = f[y(k)/\gamma(k) = i, Y_1^{k-1}]; \quad (30)$$

$$N\{iH(k)\hat{X}(k/k-1), iH(k)P(k/k-1)H^T(k) + R(k)\}, i = 0,1; \quad (31)$$

$$P(k/k-1) = \Phi(k,k-1)P(k-1/k-1)\Phi^T(k,k-1) + Q(k-1), P(0/0) = P_0; \quad (32)$$

$$P(k/k) = P(k/k-1) - P(1/k)K_1(k)H(k)P(k/k-1) + [1-P(1/k)]P(1/k)K_1(k)S(k)K_1^T(k); \quad (33)$$

$$K_1(k) = P(k/k-1)H^T(k)[H(k)P(k/k-1)H^T(k)R(k)]^{-1}; \quad (34)$$

$$S(k) = [y(k) - H(k)\hat{X}(k/k-1)][y(k) - H(k)\hat{X}(k/k-1)]^T. \quad (35)$$

The value of *P(1/k)* is a recurrent calculated probability that at a given observation vector Y_1^k, the value of *γ* at this step will acquire a value of 1, the measurement channel at this *k*-th instant is in working order.

In the above algorithm, in terms of practical implementation, there is a significant drawback associated with the a priori setting of the probabilities of the correct state of the information channel *q(k),* which is associated with the calculation of posterior probabilities *P(1/k)*:

$$P(1/k) = P\{\gamma(k) = 1/Y_1^k\} = \int_0^1 \frac{f_1(k)q}{f_1(k)q + f_0(k)(1-q)} f(q/Y_1^k)dq, \quad (36)$$

where $f(q/Y_1^k)$ is the posterior density probability distribution of *q*.

Using Bayes' formula, this density can easily represented in recurrent form:

$$f(q/Y_1^k) = \frac{f[y(k)/q, Y_1^{k-1}]f[q/Y_1^{k-1}]}{\int_0^1 f[y(k)/q, Y_1^{k-1}]f[q/Y_1^{k-1}]dq}, \quad (37)$$

with the initial condition $f[q(k)/y(0)] = 1$ at the interval [0,1].

The probability density $f[y(k)/q, Y_1^{k-1}]$ included in the numerator of the recorded expression (37) can written as:

$$f[y(k)/q, Y_1^{k-1}] = qf[y(k)/\gamma = 1, Y_1^{k-1}] + (1-q)f[y(k)/\gamma = 0, Y_1^{k-1}] = qf_1(k) + (1-q)f_0(k). \quad (38)$$

By typing:

$$\overline{q(k-1)} = M\{q/Y_1^{k-1}\} = \int_0^1 qf(q/Y_1^{k-1})dq,$$

given (37), (38), expression (36) can be represented as:

$$P(1/k) = \frac{f_1(k)\overline{q(k-1)}}{f_1(k)\overline{q(k-1)} + f_0(k)[1-\overline{q(k-1)}]}. \tag{39}$$

For practical calculations on a computer, the continuous density of distribution in $f(q/Y_1^{k-1})$, (37) is appropriate to approximate the discrete distribution at N nodes, the number of which generally determines the accuracy of the calculations:

$$f(q/Y_1^k) = \sum_{j=1}^{N} q_j \delta(q-q_j). \tag{40}$$

In this case, to calculate the posterior distribution density $f(q/Y_1^k)$, it is necessary to calculate each of the values of this density at the interval [0, l]

$$f(q/Y_1^k) = \frac{[q_j f_1(k) + (1-q_j) f_0(k)] f(q_j/Y_1^{k-1})}{\overline{q(k-1)} f_1(k) + [1-\overline{q(k-1)}] f_0(k)}, \tag{41}$$

where

$$\overline{q(k-1)} = \frac{1}{N}\sum_{j=1}^{N} q_j f\left(q_j/Y_1^{k-1}\right). \tag{42}$$

The results of mathematical modeling are shown in Fig. 4. However, the moments of occurrence of failures were not recorded. The analysis of the obtained results allows us to conclude that the accuracy characteristics of this algorithm are slightly higher than in the algorithm based on the a priori calculation of *P(1/k)* (Fig. 3), however, the proposed algorithm requires large computing capacities, which must be taken into account in practical implementation specific BIKS.

Therefore, the simplification of the algorithm should focus on reducing the procedure for calculating the posterior probability *P(1/k)* of the proper state of the information channel. And:

$$\hat{X}(k/k) = \hat{X}(k/k-1) + P(1/k)K_1(k)[y(k) - H(k)\hat{X}(k/k-1)]. \tag{43}$$

In order to obtain analytical results, we consider the case of scalar measurements at the observation matrix H = diag (1, 0, 0, ...) for the purpose of theoretical study. The posterior probability is:

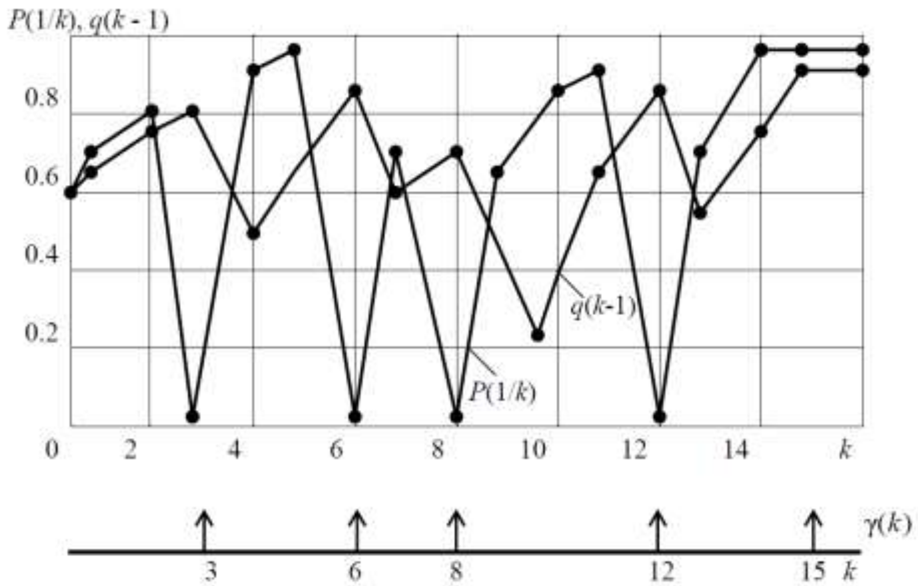

Fig. 4. The results of mathematical modeling

$$P(1/k) = q(k)R^{\frac{1}{2}}(k)\exp\left[-\frac{[y(k)-H(k)\hat{X}(k/k-1)]^2}{2\sum_1^2(k)}\right]\times$$
$$\times\left\{q(k)R^{\frac{1}{2}}\exp\left[-\frac{[y(k)-H(k)\hat{X}(k/k-1)]^2}{2\sum_1^2(k)}\right]+(1-q(k))\sum_1(k)\exp\left[-\frac{y^2(k)}{2R(k)}\right]\right\}^{-1}, \quad (44)$$

where $\sum_1^2(k) = H(k)P(k/k-1)H^T(k)+R(k)$.

Determine the limit value $y_{\text{пор}}(k)$, at which the magnitude of the posterior probability of the proper state of the BIKS information channel differs from unity by any small predetermined number $\varepsilon > 0$

$$y_{\text{пор}}(k)=\beta_1\sum\nolimits_1(k),$$

where β> 1 is a constant coefficient determined in the process of preliminary mathematical modeling.

Since the magnitude of the variance $\sum_1^2(k)$ is directly calculated in the process of forming the algorithm, finding boundary levels in this case does not require additional calculations, and the calculation of the a priori probability *P(1/k)* of the proper state of the BIKK information channel is simplified. If $y(k) \geq y_{por}(k)$, it is assumed that *P(1/k)* = 1. Otherwise, *P(1/k)* = 0.

Therefore, in the case of failure ($y(k) < y_{por}(k)$) of the BIKK information channel, the matrix gain K_1 (k) equals zero, and the algorithm (filter) calculates the extrapolated value of the BIKS state vector estimator without using the new incoming data.

3.3 Evaluation of the Efficiency of Measurement Information Processing Methods in Onboard Information and Control Systems

When choosing practical application methods for processing measurement information to ensure fault tolerance, two factors are usually taken into account - the precision characteristics and the amount of computation required to implement it.

In discrete systems, it is difficult to obtain a closed expression for the correlation matrix of the algorithm errors. Therefore, when comparing the accuracy of different methods and their algorithms, one has to resort to statistical modeling of them on a computer. Obviously, such modeling can only produce qualitative results for specific cases of interest to the BIKS developer.

To obtain theoretical results, we compare the efficiency of the above filtration algorithms. To improve the accuracy of the comparison, we will give the same implementation of the input process *y(k)* for all the filters studied, and the variance of the estimation errors will be calculated by 100 realizations in which the moments of occurrence of failures are fixed. The results of mathematical modeling (in one coordinate - angular slopes of the trajectory) are shown in Fig. 5.

This figure shows the time dependencies of the variance of the estimation errors *P(k/k)* for the following filters:

1. Linear optimal filter:

$$P(k/k-1)=\Phi(k,k-1)P(k-1/k-1)\Phi^T(k,k-1)+G(k,k-1)Q(k-1)G^T(k,k-1). \quad (45)$$

2. Suboptimal nonlinear filter:

$$P(1/k)=\frac{f_1(k)q(k)}{f_1(k)q(k)+f_0(k)[1-q(k)]}; \quad (46)$$

3. Adaptive filter.

The value of *P(1/k)* is determined by the relation:

$$P(1/k)=\frac{f_1(k)\overline{q(k-1)}}{f_1(k)\overline{q(k-1)}+f_0(k)[1-\overline{q(k)}]}. \quad (47)$$

The analysis of the results of the conducted researches leads to the conclusion that the appearance of the failure flow *γ(k)* significantly worsens (almost by an order of magnitude) the accuracy characteristics of the linear optimal filter, which loses to the adaptive filter by about 30-40 times. The suboptimal nonlinear filter at *k*> 10 is not inferior to the adaptive filter.

4 Recommendations for the Practical Elimination of the Consequences of the Emergency

Note that in the general case, the formulation of the decision-making problem to neutralize the consequences of an emergency situation is as follows.

Let there be a vector of the characteristics of the emergency $X = [x_1, x_2, \ldots, x_n]$, as well as a set of uncertainties $W = \{w_1, w_2, \ldots w_n\}$, which reflects the existence of qualitative factors, conditions, connections of systems and BIKS elements that are not formalized.

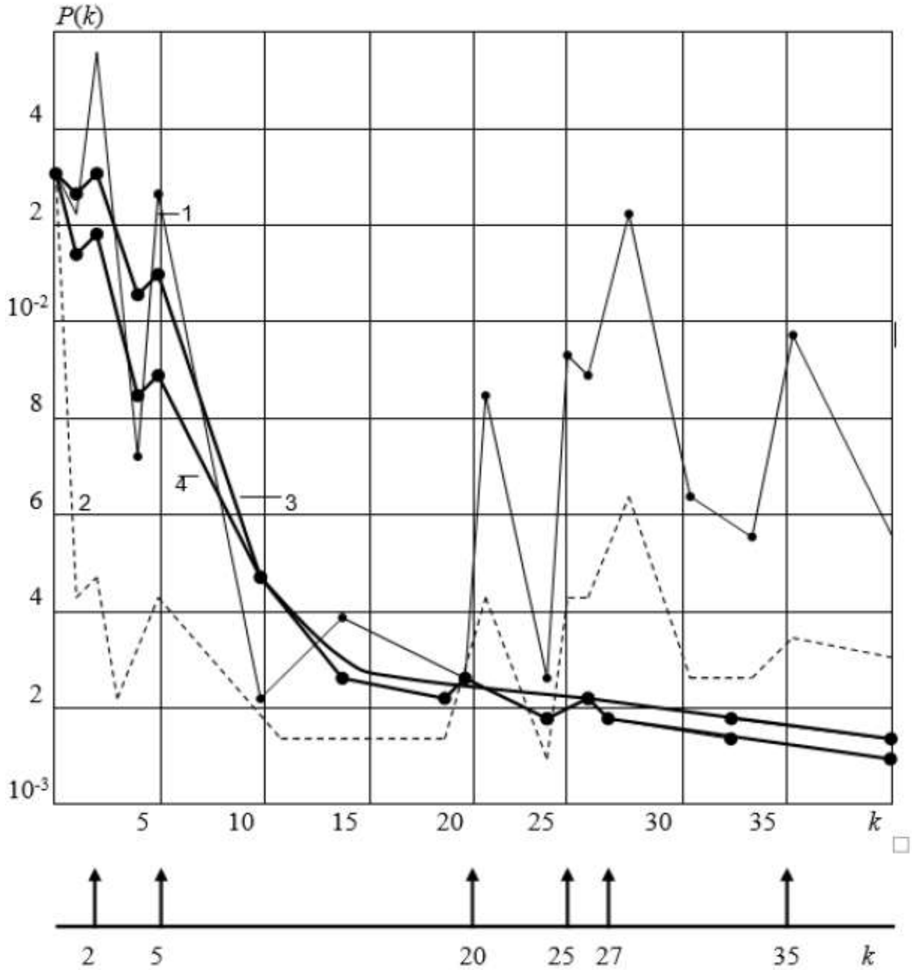

Fig. 5. Results of mathematical modeling of failure probability under conditions of failure flow

Introduce an integrated BIKS performance indicator

$$J = \sum_{i=1}^{m} \alpha_i \frac{f_i^u - f_i^p}{f_i^u}, \quad \sum_{i=1}^{m} \alpha_i = 1, \quad \alpha_i > 0, \tag{48}$$

where f_i^u, f_i^p - are the individual performance indicators of the ideally and really functioning BIKS; α_i- weighting factors that determine the "importance" of single indicators.

Each disturbance $< X, W >$ can matched by a set of control actions $U = \{u_1, \ldots u_p\}$. In other words, there is a finite algorithm A such that $A :< X, W > \rightarrow U$. In turn, any elementary control action u_i will transform the output characteristic σ , then the final algorithm of such conversion B will be $B : U \rightarrow \sigma$.

We will consider any perturbation $< X, W >$ random. Then the magnitude σ is random.

The task of neutralizing the consequences of an emergency situation is to find a control action that stabilizes the functioning of the BIKS, that is, it delivers a minimum of the variance of the magnitude σ and for a time interval τ not exceeding a predetermined interval of time $[t_1, t_2]$ at a known density of distribution $f(\sigma, t)$

$$D(\sigma) = \int \int_{-\infty}^{\infty} \sigma^2 f(\sigma, t) \ d\sigma dt \rightarrow \min \tag{49}$$

$$\tau \in [t_1, t_2]$$

The implementation of this task depends on the composition of the set W. If all parameters are defined in the problem, then the problem is solved by multicriteria optimization algorithms. If, due to the large amount of initial uncertainty, multicriteria optimization algorithms cannot be used, then the solution is sought in the space of hypotheses by proving the corresponding theorems. Based on the described principles of organization of work, it is possible to propose the structure of a functionally stable on-board information and control complex, presented in Fig. 6.

The specificity of a particular BIKS is determined in the knowledge base. The calculator integrates software complexes that simulate the logic of finding solutions, without taking into account the specific BIKK, which allows you to create unified software for BIKS decision making for various purposes.

For each type of BIKS tasks, a decomposition is performed, which results in a set of individual tasks. Each task is answered by an array of parameters, which are calculated in the decision process and are the initial data for the lower-level hierarchy tasks.

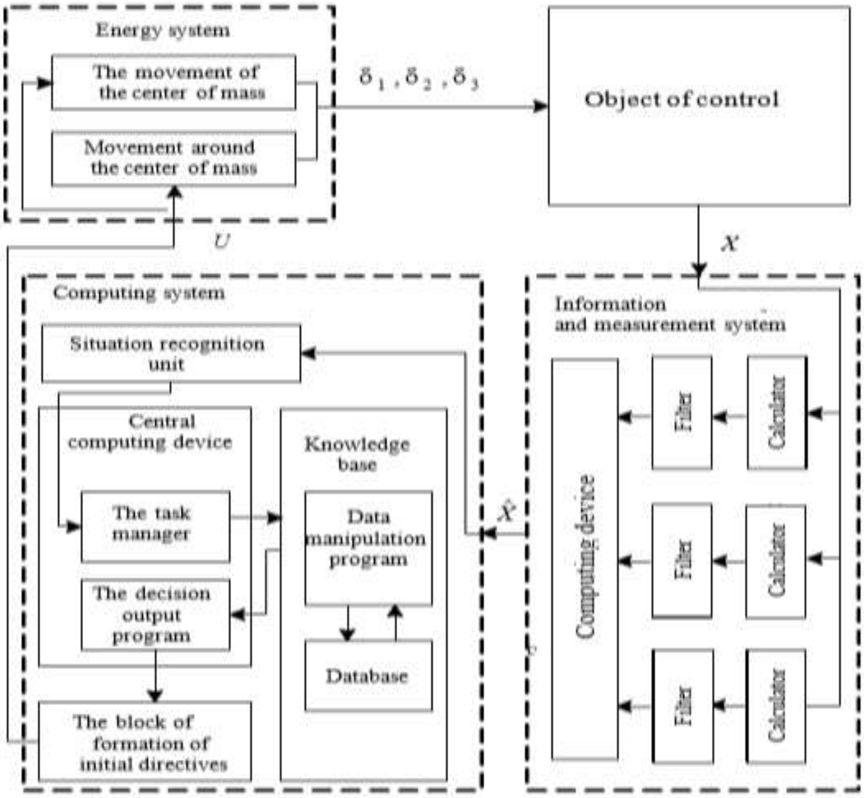

Fig. 6. Structural diagram of functionally stable BIKS

An analysis of the practical applications and complex tasks of a complex control object shows that, in order to be resilient to special (including emergency) situations, the following tasks should be addressed:

- Recognition of a special situation;
- Formation of the decision on the necessary measures in the form of a set of management actions aimed at neutralizing the consequences for the object of management of a special situation in a minimum time, with minimal loss of performance indicators.

A further stage of theoretical generalization and development - construction of functionally stable BIKS, is the development of software-algorithmic software on-board information and control systems to introduce the possibility of preventing emergency situations and (or) restoration of a working state in the condition of failure of hardware and software parts.

5 Conclusions

The paper offers an analytical evaluation of the effectiveness of methods of information recovery in onboard information and control systems in emergency situations caused by failures in onboard information and control systems. The implementation of the proposed approach is considered as one of the steps of ensuring the functional stability of complex dynamic objects. Functional stability is considered as a property of a dynamic system, which is the ability to perform at least a set volume of its functions when failures in the information, computing, energy parts of the system, as well as external influences that are not provided by the operating conditions.

The implementation of functional stability is achieved by sequential execution (if possible in real time) of the following steps:

1. Control of the state of functioning of a complex management system and detection of the fact of disturbance of its functioning (formation of the team "Accident").
2. Identification of the cause of the fact of malfunctions in real time (localization of the place of damage of functioning and / or detection of unauthorized disturbances).
3. Disconnecting damaged parts or offsetting the impact of unauthorized disturbances on the general real-time control system.
4. Redistribution of system resources (information, computing, energy) to ensure the functioning of the management system (possibly with poor performance) in real time.

Functional stability can achieved through the introduction into the complex dynamic system of various forms of redundancy (structural, functional, information, etc.) and the readiness of the operator of the dynamic object to control movement during the sudden reconfiguration of the complex. The proposed mathematical model allows you to build functional stability when using an automated control system for a complex dynamic object. Consider the features of applying the method of optimal filtration in extraordinary situations caused by the evolution of structure and parameters. The algorithm of discrete filtering in BIKK in extraordinary situations related to the distortion of information exchange is proposed.

The estimation of efficiency of methods of processing of measuring information in on-board information-control complexes is given. In order to identify out-of-state situations related to the distortion of information exchange, a recurrent algorithm of optimal discrete filtering is proposed in the case where the values of the vector elements of parameters γ (k) describing the nature of the disturbances in the system form a Markov chain. Based on comparison of linear optimal, simplified nonlinear, suboptimal nonlinear and adaptive filters, recommendations for implementation of filtration algorithms with increased resistance to failure are given. Recommendations on practical neutralization of consequences of an emergency situation are offered.

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