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RATIONAL CONTROL OF OBJECTS WITH UNCERTAIN DYNAMICS

The reasons causing uncertainty in the dynamics of objects are considered on the example of aerospace engineering. Objects of automatic control, consisting of control objects, servo drives, and sensors, are subjects to the influence of indefinite external and internal disturbing influences, which destabilize their performance. Classical methods of automatic control of such objects do not allow obtaining the desired quality indicators. For the rational control of such objects with uncertain dynamics, a new approach has been proposed, which is based on a deep diagnosis of the causes of destabilization and flexible restoration of working capacity. The main provisions of the method of rational control are described. A new class of mathematical models called diagnostic is presented. In-depth diagnostic procedures are formed using formalized and weakly formalized models of the processes of regular and abnormal operation of the control system. For the formation of a priori and a posteriori knowledge of the causes of malfunctioning, structures of developing dichotomous trees are used, representing a kind of product knowledge bases with a design in nodes "if ... then ...", with logical rules for obtaining a diagnosis of the causes of destabilizing effects. A method for solving diagnostic problems for objects with uncertain dynamics is described. To restore the performance of objects with uncertain dynamics, the use of redundant means has been proposed: signal and parametric adjustment, reconfiguration of algorithms and hardware. The process of parrying destabilization, which was diagnosed, is formed using the second method A. M. Lyapunov. This method ensures the stability of the system and the specified quality control. Rational adaptation to destabilizing effects is based on the use of intelligent procedures for in-depth diagnosis of the causes of a malfunction of the control system and a flexible restoration of working capacity in real time. Such procedures allow for productive training in order to preserve the efficiency of the control system throughout the entire life cycle. The results of applying the method of rational control to a number of model samples of aircraft are given.

Keywords: rational control; objects with uncertain dynamics; the event uncertainty destabilizing impact efficiency; diagnostic model; deep diagnostics; flexible recovery; dichotomous tree; Lyapunov function.

Introduction

The growth of consumer requirements for the quantity and quality of functions of control systems of autonomous objects is in contradiction with the growth of a priori and an aposteriori uncertainties of the conditions of their functioning. The uncertainty of the conditions is due to the action of disturbing influences in the design. Thus, in aerospace engineering, the functional properties of automatic control objects (ACO) consisting of an aircraft, actuators and sensors substantially depend on the flight conditions. The functional properties of ACO are influenced by external conditions (pressure, density, turbulence, temperature, etc.) and internal (malfunction, breakdowns, damages, failures, etc.). These conditions are, in fact, destabilizing effects on the functional properties of ACO, i.e. destabilize their performance. Destabilizing effects can occur at any time during the flight, in any part of the ACO, with an unknown pattern of manifestation. There are a number of destabilizing effects models based on various hypotheses regarding their properties. At the same time, tools of probability theory, interval analysis, etc. are used to describe it. Describing of destabilizing effects as indefinite events seems to be the most adequate.

In models and methods of adaptive control, as a rule, probabilistic and interval descriptions of destabilizing effects are used [1, 2]. These descriptions do not fully correspond to the real nature of destabilizing influences. The presentation of destabilizing effects in the form of models with event uncertainty reflects their properties more adequately. Therefore, it is not possible to resolve effectively the contradiction between the growth of consumer requirements and the growth of uncertainties in the conditions of operation with the help of classical adaptive tools. More complete resolution of the contradiction requires the search of new approaches.

The rapid progress in the production of real-time digital signal processing equipment and software contributes to the expansion of the functionality of automatic control systems for autonomous objects. This circumstance makes it possible to attempt to automate such functions of human professional activity, like diagnosing inoperable control systems, and restoring lost functions. Diagnosis and restoration of control systems are based on professional competencies – experienced

knowledge. The tools of artificial intelligence allow forming knowledge bases in established areas of activity with the help of experts. The formation of knowledge bases for new objects of control, especially with properties that change in an indefinite way, is problematic.

An effective resolution of the contradiction seems to be an approach to adaptation through rational control based on a deep diagnosis of the causes of destabilization of control objects and flexible restoration of lost functions. Rational management should be formed using a priori knowledge obtained in the design process and an aposteriori knowledge acquired through diagnostic procedures in the operation of objects with uncertain dynamics.

Thus, the scientific problem of adaptive control of autonomous objects with uncertain dynamics caused by destabilizing effects seems to be relevant.

The article proposes an approach to solving this problem through rational control based on the procedures of deep diagnostics and flexible recovery of working capacity in real time.

1. Main Issues of Rational Control Approach

Rational control is a new and developing trend that emerged from the study of fault-tolerant control systems [3-8].

1. The control system of an object with uncertain dynamics can be represented as consisting of two interrelated subsystems. The first named as automatic control object (ACO) includes a control object, actuators and sensors. This subsystem is a heterogeneous formation, since it consists of components that are different in physical principle and functional properties, which determines its vulnerability to various kinds of disturbing influences.

The second subsystem named as automatic control unit (ACU) is a controller with the appropriate hardware interface. The perfection of the hardware and software of the subsystem has led to a high level of its reliability and survivability compared with the first subsystem, and therefore it can be assumed that it is invulnerable to various disturbing influences.

2. External disturbing effects on the object and internal acting on the first subsystem (malfunctions, failures, failures, breakdowns, noise and interference) are effects that destabilize the performance of the entire control system. Such impacts are destabilizing effects.

3. Destabilizing effects are one-time uncertain events characterized by the appearance at an unknown point in time, in an unknown structural part of a subsystem, with unknown properties. Event uncertainty of destabilizing effects is due to the peculiarities of the life cycle of objects with uncertain dynamics as unique

products operating in changing and partly defined conditions.

4. The event uncertainty of destabilizing effects can be reduced by indirectly detecting their occurrence due to a malfunction of the control system. And then, by the consequences of their actions, find the cause that gave rise to a malfunction. Such a procedure for finding the causes of a malfunction can only be a deep diagnosis procedure.

5. The procedure of deep diagnostics should allow forming in real time on indirect signs, using the principle of sequential removal of uncertainty, the diagnosis i. e. the conclusion about an avoidable cause that has impaired the performance of the control system.

6. Procedures of deep diagnosing are formed using formalized and weakly formalized models of the processes of regular and abnormal operation of the control system. For the formation of a priori and an aposteriori knowledge of the causes of a malfunction, structures of developing dichotomous trees are used, which are a type of production knowledge bases with a design in nodes "if ... then ..." with logical rules for obtaining a diagnosis of the causes of destabilizing effects.

7. For flexible restoration of the performance of the management system for objects with uncertain dynamics, built-in redundant, heterogeneous types of means are created, ensuring the ability to maintain performance throughout the entire life cycle. The choice of excess funds for the current recovery of health is made on the basis of the diagnosis and on the principle of "stinginess", namely, the least "popular" means are selected from those currently available.

8. The classical principle of adaptation is based on the use of information about the deviation of the current characteristics of the control object from the reference ones. Instrumental design tools for adaptive control, as a rule, are formed on linearized representations of information transformation processes in the system. Linearized models reflect the features of management processes in the "small". Destabilizing effects lead, in some cases, to significant changes in the structure and parameters of the ACO, which makes it necessary to consider management processes "in large", following the terminology of A. M. Lyapunov [9]. Accidents and disasters in aerospace engineering convince of the need to consider performance as a dynamic state that needs to be managed "in large" throughout its life cycle in order to stabilize it.

9. Rational adaptation to destabilizing effects is based on the use of intelligent procedures for in-depth diagnosis of the causes of impaired control system performance and flexible real-time restoration of performance, allowing for productive training in order to preserve the control system's performance throughout the entire life cycle.

10. Rational adaptation is implemented comprehensively both at the component and system levels on a single methodological basis using the same type of models and tools according to the system criterion of the minimum adaptation time.

11. The further development of the classical principle of adaptation is to use throughout the entire life cycle of deeply diagnosing the causes of destabilization and flexible restoration of working capacity. In fig. 1 a block diagram of a rational control of an object with an indefinite dynamics is presented [10]. The block diagram consists of two interconnected subsystems. The first subsystem is an automatic control object (ACO) consisting of a control object, an actuator unit (AU) and a sensor unit (SU). The subsystem is affected by many uncontrolled destabilizing effects D, which significantly affect the performance of the ACU.
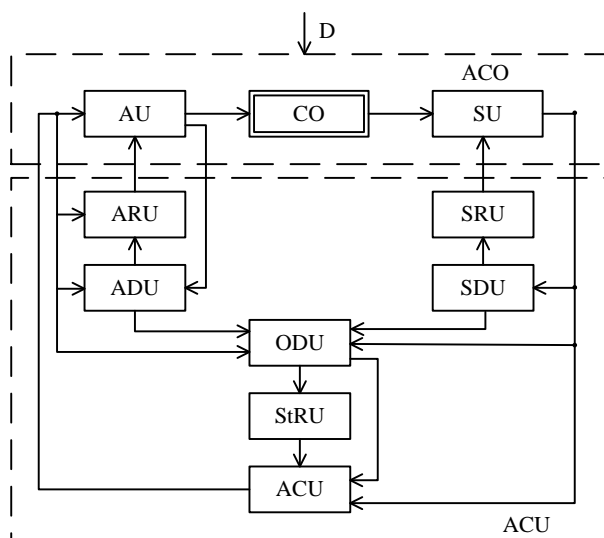

Fig. 1. Block diagram of rational control system
of an automatic control object with uncertain dynamics

The second subsystem is the device of rational control (URU). So, in order to ensure the efficiency of the AU, the actuator diagnostics unit (ADU) is used. The results form the control signals to restore the performance of the AU. For diagnostics of SI, a sensor diagnostics unit (SDU) is used, in which the cause of non-operability is identified, and the result of the diagnosis enters the sensor recovery unit (SRU). In this block, control actions are formed on the SU, restoring its measurements.

As the restoration of the AU and the measurements of the SU is completed, the enabling signals are received by the object diagnostics unit (ODU), in which the signals from the input and output of the OAU are diagnosed. The diagnosis of the state of the object enters the system recovery unit (StRU), in which changes in the structure and parameters of the automatic control unit (ACU) are formed. In this device, control actions

are formed on the ACO, ensuring the restoration and stabilization of the performance of the entire system of automatic motion control of an object.

In the absence of destabilizing effects, the diagnostics blocks ADU, SDU and StDU consistently issue corresponding signals that allow the normal mode of functioning of the ACU, ensuring the operability of the closed-loop automatic control system.

To implement the rational control of objects with uncertain dynamics a new technology for conceptual design is needed. The productivity of the technology of conceptual design of rational control of objects with uncertain dynamics depends on the used tools. The classical tools used in the traditional technology of conceptual design of motion control systems do not fully correspond to the goals and objectives of rational control. This circumstance led to the development of new conceptual design tools.

2. Problems of Diagnostic and Solution Tools

The tasks of diagnosing objects with uncertain dynamics and their connection with each other can be represented using a block diagram (Fig. 2).
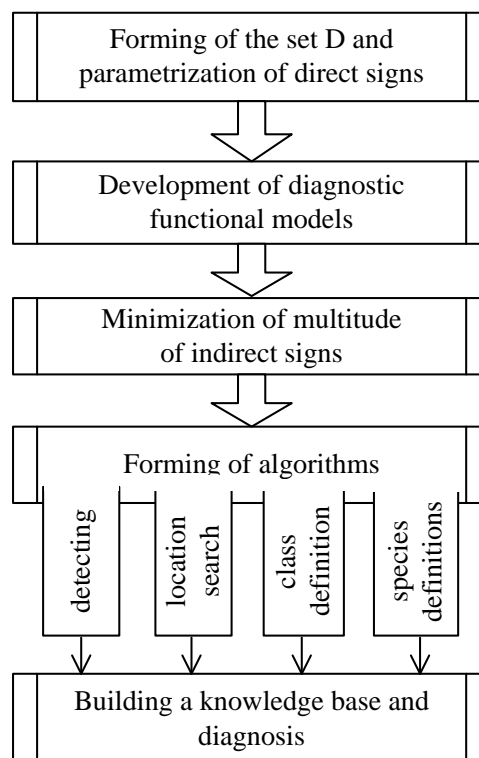

Fig. 2. Block diagram of a set of diagnostic tasks

A lot of destabilizing effects D is formed at the stage of preliminary design of the system of rational control. Based on the features of the ACO, the condi-

tions of the life cycle of the control system, the available depth of diagnosis and possible redundant means of restoring health, the developers form a compromise list of destabilizing effects that can affect the performance of the ACO at all stages of the life cycle. Each destabilizing effect is associated with three parameters that characterize its appearance in ACO – α_i, the place of manifestation – β_i and the class – γ_i. The parameters describe such destabilizing effects that must be established in the process of diagnosing ACO.

To describe the processes of influence of destabilizing effects on the dynamics of ACO, a new class of diagnostic functional models (DFM) is used. DFM reflect the connection of direct signs of destabilizing effects with indirect ones. The simplest DFMs are developed on the basis of linearized ideas about the processes of signal conversion to ACO [11]. So, in a discrete space of states DFM in a generalized form can be represented as follows:

$$\Delta x_i\left[(k+1)T_0\right] = \left[A_i x\left(kT_0\right) + B_i u\left(kT_0\right)\right]\Delta\lambda_i;$$
$$\Delta x_i\left(0\right) = \Delta x_{i0};$$
$$\Delta y_i\left(kT_0\right) = C\Delta x_i\left(kT_0\right) +$$
$$+\left[C_i x\left(kT_0\right) + N_i u\left(kT_0\right)\right]\Delta\lambda_i; \qquad (1)$$
$$i = \overline{1,q},$$

where $\Delta x_i\left(kT_0\right)$ – n-dimensional vector of deviations caused by the destabilizing effects of $d_i, \Delta x_i\left(kT_0\right) \in \Delta X^n$; $x\left(kT_0\right)$ – n-dimensional vector of the nominal state of OCO, $x\left(kT_0\right) \in X^n$; $u\left(kT_0\right)$ – r-dimensional vector control effects of ACO, $u\left(kT_0\right) \in U^n$; $\Delta y_i\left(kT_0\right)$ – m-dimensional vector of indirect signs of destabilizing effects, $\Delta y_i\left(kT_0\right) \in \Delta Y^m$; $\Delta\lambda_i$ – direct signs of destabilizing actions $\Delta\lambda_i \in \left\{\Delta\alpha_i, \Delta\beta_i, \Delta\gamma_i\right\}$, C – ($m \times n$)-ACO measurement matrix; A_i, B_i, C_i and N_i – matrix of sensitivity functions of the corresponding matrices of ACO nominal model on generalized parameters $\Delta\lambda_i$. $\Delta\lambda_i \in \left\{\Delta\alpha_i, \Delta\beta_i, \Delta\gamma_i\right\}$, generally describes a destabilizing impact properties $d_i \in D, i = \overline{1,q}$; T_0 – sampling period $k = \overline{1,1}$.

The quality assessment of the developed DFMs is performed using diagnostic criteria. Diagnosability refers to the property of equations (1), which consists in the presence of a unambiguous connection of direct signs of destabilizing effects $d_i \in D$ with indirect

$\Delta y_i\left(kT_0\right)$, $i = \overline{1,q}$, and the possibility of their determination on a finite time interval.

Criterion for structural diagnosability. For the structural diagnosability of ACO, it is necessary and sufficient that the matrices

$$L_i = \begin{bmatrix} A_i & B_i \\ C_i & N_i \end{bmatrix}, i = \overline{1,q}, \qquad (2)$$

where linearly independent in all pairwise combinations.

Criterion of signal diagnosability. Structurally diagnosable ACO $- L_i^*$ will be signal diagnosed if and only if vectors $L_i^* w\left(kT_0\right), i = \overline{1,q}$ are linearly independent in all pairwise combinations. Here $w^T\left(kT_0\right) = \left[x\left(kT_0\right) \ u\left(kT_0\right)\right]$.

The use of diagnosability criteria allows for designing the ACO to form such a structure and select such modes of operation, which provide using DFM described by equations (1), solving problems of detection, localization and identification of one-time destabilizing effects.

The vector of indirect signs of destabilizing effects $\Delta y_i\left(kT_0\right)$, as a rule, contains an excessive amount of components. It is possible to eliminate the redundancy of indirect features through logical tables and minimization procedures. Logical tables are formed by passing from indirect signs in the form of discrete functions of time $\Delta y_i(kT_0)$ to indirect signs in the form of Boolean variables z_i obtained using two-digit predicate equations:

$$z_i = S_2\left\{\left|\Delta y_i(kT_0)\right| - \delta_i\right\}, \qquad (3)$$

where $S_2\{\cdot\}$ – symbol of two-digit predicate; δ_i – thresholds.

To ensure the efficiency of diagnosis, it is necessary by means of minimization to form a non-redundant number of components in the Boolean form. In solving this problem, diagnostic logic models (DLM) are used. DLM reflect the qualitative connection of direct signs $\Delta\lambda_i$ with indirect signs $z_j, j = \overline{1,m}$ using a Boolean variable. In form, these are tabular models linking a vertical q-dimensional column of signs $\Delta\lambda_i$ with an m-dimensional horizontal row using a variable. The variable takes the value "1" if there is a connection and the value "0" if there is no connection between the signs. To minimize the following recurrent procedure is used:

$$M_1 = \left\{ z'_{j1} \right\};$$

$$M_2 = \left\{ \min_{\left\{ z'_{j2} \right\}} \left[\left\{ z'_{j2} \right\} \wedge M_1 \right] \right\}, \qquad (4)$$

where z'_{j1} – signs z_j, containing "1" in the i-th row of the table; M_1 – a set of indirect Boolean attributes containing "1" in the first line of the table; $\wedge$ – symbol of the conjunction; M_2 – the set of minimal conjunctions at the second step.

At the last q-th step of the recurrent procedure, all minimal conjunctive forms are obtained using the equation

$$M_q = \left\{ \min_{\left\{ z'_{jq} \right\}} \left[\left\{ z'_{jq} \right\} \wedge M_{q-1} \right] \right\}. \qquad (5)$$

The choice of a rational set of indirect signs is made on the basis of the conditions of a specific problem of diagnosing through a technical and economic analysis of the obtained minimum sets of sets M_q and the choice of the appropriate one. A suitable set of minimum Boolean features allows you to create a new table linking the direct signs of destabilizing effects $\Delta\lambda_i$ with a minimum set of indirect ones z_i. Such a relationship in tabular form allows you to create effective machine production knowledge bases.

When solving the problems of forming algorithms for detecting, localizing and identifying destabilizing effects, the corresponding canonical DFMs are used, which have the property of complete diagnosability and minimality of indirect signs. The calculation of direct signs $\Delta\lambda_i \in \left\{ \Delta\alpha_i, \Delta\beta_i, \Delta\gamma_i \right\}$ of destabilizing effects is reduced to the sequential solution of inverse problems.

Consider in the general form of the tools of direct evidence of the formation of estimates. DFM in the canonical form can be represented by the following equations:

$$\Delta x'_i \left[(k+1)T_0 \right] = \left[A'_i x'(kT_0) + B'_i u(k) \right] \Delta\lambda_i;$$
$$\Delta x'_i (0) = x'_{i0};$$
$$\Delta y'_i (kT_0) = C' \Delta x'_i (kT_0) + \qquad (6)$$
$$+ \left[C'_i x'(kT_0) + N'_i u'(kT_0) \right] \Delta\lambda_i;$$
$$i = \overline{1, q},$$

where designation " x' " and others refer to the new variables and matrices satisfying the canonical conditions.

In the presented system of algebraic equations, the unknown parameter will be $\Delta\lambda_i$. Of all the equations of system (6), the simplest in structure equation is chosen, from which the algorithm of step-by-step determination of values $\Delta\lambda_i (kT_0)$ for a number of quantization cycles $k = \overline{1, \eta}$ is formed. Further, according to the formula of the arithmetic mean value

$$\hat{\Delta\lambda_i} = \frac{1}{\eta} \sum_{k=1}^{\eta} \Delta\lambda_i (kT_0) \qquad (7)$$

finds an estimation of the direct sign d_i of destabilizing effects.

A more accurate estimation of the direct sign $\hat{\Delta\lambda_i}$, if necessary, can be calculated using batch or recurrent algorithms for arithmetic mean estimation.

The formation of a priori and an aposteriori knowledge of the direct signs of destabilizing effects lies in such a machine representation of them, so that, by operating with them, a complete diagnosis of an emergency situation caused by the current destabilizing influence can be obtained in real time.

Through the canonical DFM described by the system of equations (6) at the stage of preliminary design of rational systems, the equations form algorithms for obtaining estimated values of direct signs of supposed destabilizing effects.

To formalize knowledge of destabilizing effects, products are used based on rules that allow knowledge to be presented in the form of a "if ... then ..." sentence. When forming a set of products, two-digit predicate equations of this type are used:

$$z_i = S_2 \left\{ \hat{\Delta\lambda_i} \right\} = \begin{cases} 1, \text{ if } \hat{\Delta\lambda_i} \in \Omega_i; \\ 0, \text{ if } \hat{\Delta\lambda_i} \notin \Omega_i, \end{cases} \qquad (8)$$

where $\hat{\Delta\lambda_i}$ – estimated value of the i-th direct sign; Ω_i – the set of values of the i-th sign.

More detailed two-digit predicate equations have the following form:

$$z_i = S_2 \left\{ \left| \hat{\Delta\lambda_i} \right| \geq \delta_i \right\}, \qquad (9)$$

where δ_i is the interval value of the sign;
or this one:

$$z_i = S_2 \left\{ \delta_i - \left| \hat{\Delta\lambda_i} \left[(k+1)T_0 \right] - \Delta\lambda_i (kT_0) \right| \right\};$$
$$k = \overline{1, n_i}; \; \rho_i = 0,85, \qquad (10)$$

where n_i is the number of measurements on the diagnostic interval; ρ_i – trust ratio.

Other forms of knowledge representation using predicate equations are also used.

For the formation of correct logical conclusions, the method of ordering products using dichotomous trees is used. A dichotomous tree is a means of a hierarchical organization of knowledge, where each node contains specific knowledge and references to left or right descendants. The node at the very top is called the root. Nodes without descendants are leaves. The organization of knowledge through dichotomous trees can significantly reduce the time of formation of the current diagnosis. The search for knowledge in the linear structures of knowledge is carried out by sequential enumeration of all elements of this structure. A search on a tree represents a directed search; therefore it takes much less time, thus ensuring the speed of diagnosis.

To ensure the maximum possible efficiency of diagnosis, dichotomous trees are balanced according to various criteria, which make it possible to form a rational tree structure that satisfies the requirements of the speed of diagnostic processes.

The nodes of a dichotomous tree are formed using two-digit predicate equations of current knowledge of direct signs of destabilizing effects. At the root of a dichotomous tree is knowledge about the detection of a destabilizing effect. Next is the knowledge of the place of it appearance. Below are the predicate equations for classes and specific types of destabilizing effects. Leaves of a tree are specific physical types of destabilizing effects.

3. Problem of Recovery and Solution Tools

The cause of destabilization identified in the process of diagnosing is required to be neutralized by using the appropriate redundant means to achieve the main goal of rational management – ensuring the operability of the ACO.

ACO must have the property of recoverability. Recoverability is a property of ACO, which characterizes the possibility of its transfer from an inoperable state to a healthy state by means of parrying destabilizing effects $d_i \in D$ on a finite time interval.

An ACO is called recoverable if the means of restoration are formed that allow compensating for the influence of destabilizing effects $\Delta y_i\left(kT_0\right) \to 0$ in such a way that the final time interval is acceptable.

The set of tasks arising from the restoration of ACO working capacity and their connections can be represented using the following scheme (Fig. 3).

The first task of recovery is to choose the means of restoring the ACO on the basis of:

1) the current knowledge base about the tools and current recovery criteria;

2) the current conditions for the performance of functional tasks assigned to the ACO;

3) the stage and status of fulfilment of the mission of control object.
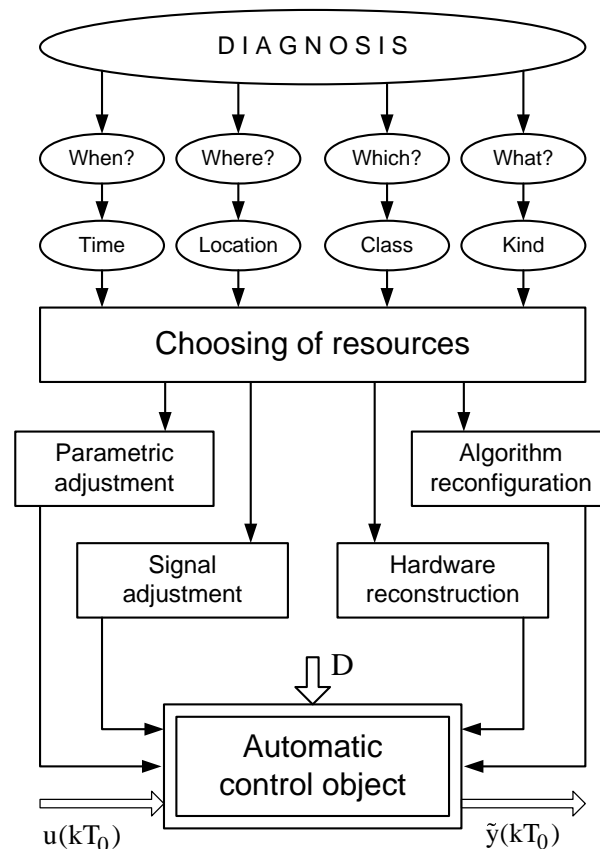

Fig. 3. Block diagram of aggregate recovery tasks

The choice of redundant recovery tools is based on the current knowledge base [12]. The base of knowledge about the means of restoration can be represented using table 1, where types of destabilizing effects d_i, $i = \overline{1,q}$ are placed horizontally, and the means of recovery effects v_j, $j = \overline{1,q}$ used to parry them are placed vertical.

When designing ACO, such means are chosen that can fend off several species d_i, which is reflected by a variable σ_{ij} taking the value "1" if it is possible to neutralize the type of destabilization d_i by means of a recovery tool v_j, or the value "0" if it is not possible.

Parameters l_j, $j = \overline{1,\mu}$ numerically equal to the number "1" in the column characterize the recovery

rank. The more types of destabilization d_i you can fend off by using the tool v_j, the higher its rank.

Table 1

Base of knowledge about the means of restoration

Types of effects	Recovery tools				Level
	v_1	v_2	$\cdots$	v_μ	
d_1	σ_{11}	σ_{12}	$\cdots$	$\sigma_{1\mu}$	c_1
d_2	σ_{21}	σ_{22}	$\cdots$	$\sigma_{2\mu}$	c_2
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
d_i	σ_{q1}	σ_{q2}	$\cdots$	$\sigma_{q\mu}$	c_q
Rank	l_1	l_2	$\cdots$	l_μ	

The parameter c_i numerically equal to the sum of "1" in the line characterizes the level of recoverability of the destabilization type d_i. The bigger c_i, the more resources can be used to restore the operation. The table is formed from the condition of satisfying the following criteria for recoverability: $\forall c_i \geq c_T$, $i = \overline{1,q}$ and $\forall l_j \geq l_D$, $j = \overline{1,\mu}$. Here c_T is the required level of recoverability, and l_D is the allowable rank of the recovery tool.

In the process of evolution ACO table 1 should reflect the current state of the cash recovery, i.e. each time a recovery tool is selected and used, the corresponding column is deleted from the table. In essence, the table represents the dynamic structure of the knowledge base of the recovery tools. Production rules in the equivalent format of the production knowledge base on the restoration of working capacity are formed according to the lines of the table like this: "if the diagnosis is d_i and among all the means for which $\sigma_{ij} = 1$, l_j has a minimum value, then a means of recovery is chosen".

For full restoration of the ACO working capacity, a procedure is required to introduce the selected agent in the process of countering the type d_i of destabilization, in order to ensure the sustainability of the transfer process from inoperable to operational condition, and its quality.

Signal or parametric adjustment, reconfiguration of algorithms and devices can be acceptable means of recovery for many objects. For the formation of procedures that ensure the sustainability and quality of recovery processes, an approach is used based on the Lyapunov functions. The specificity of the recovery tools generates the corresponding methods for the synthesis of recovery algorithms.

The recovery process is described by the following system of recurrent equations:

$$\Delta y_i\left[(k+1)T_0\right] = R\Delta y_i\left(kT_0\right) + h\varphi\left[\sigma\left(kT_0\right)\right];$$
$$\sigma\left(kT_0\right) = c^T\Delta y_i\left(kT_0\right); \; \Delta y_i\left(0\right) = \Delta y_{0i}, \quad (11)$$

where $\Delta y_i\left(kT_0\right)$ is the vector of deviations of the object of adaptation caused by the destabilizing effect $d_i \in D$; R, h, c – matrices of the corresponding dimensions; $\varphi\left[\delta\left(kT_0\right)\right]$ – nonlinear discrete scalar function.

The task of synthesis of recovery algorithms is reduced to the problem of synthesis of control actions for nonlinear discrete systems described by equations (11) using the discrete analogue of the direct Lyapunov method, based on the task of a special auxiliary function $V\left[\Delta y_i\left(kT_0\right)\right]$ and the formation by means of equation (11) of a function $V\left[kT_0,(k+1)T_0\right]$ that satisfies the condition

$$\Delta V\left[kT_0,(k+1)T_0\right] = V\left[\Delta y(k+1)T_0\right] - V\left[\Delta y\left(kT_0\right)\right], \quad (12)$$

where $V\left[\Delta y\left(kT_0\right)\right]$ and $V\left[\Delta y(k+1)T_0\right]$ are definitely positive functions for discrete values of arguments kT_0 and $(k+1)T_0$.

From the condition of providing a certain negativity of functions $\Delta V\left[kT_0,(k+1)T_0\right]$, an algorithm is formed that ensures the asymptotic stability of the recovery process [11, 12].

The described tools allow to formalize the implementation of individual stages of the process of designing a rational adaptation of motion control systems of objects with uncertain dynamics.

4. Experimental Research

Studies of the possibility of rational control of object operation were carried out for a prototype of the block of electro-flywheel drives of a micro-satellite. In space flight, aircraft has external perturbing effects of gravitational, magnetic, aerodynamic, electric, solar and other forces and moments. In addition, destabilizing actions appear due to various malfunctions, defects, failures, failures of instrumentation equipment of orientation and stabilization systems. Electro-flywheel drives and flywheel engines are widely used as executive unit of orientation and stabilization systems, from which drive blocks are constructed that produce control vec-

tors of kinetic moments. The structure of three such drives, placed along the axes of the orthogonal coordinate system, allows only external disturbing influences to parry, and blocks with an excessive structure of electromechanical drives – internal block disturbances caused by failures. To provide these properties, the blocks of drives with redundant structure need to be constructed so as to ensure not only the necessary and sufficient conditions for their performance in nominal modes of operation, but also to maintain performance in abnormal modes. The principle of control by diagnosis allows for the design to ensure diagnosability and recoverability with respect to the a priori and an aposteriori sets of destabilizing effects.

For experimental studies of the possibility of rational control of the block of electro-flywheel drives of excess structure, a prototype model of a microsatellite with electro-flywheel drives of a pyramidal structure was used (Fig. 4). A series of experimental studies on the static and dynamic properties of the functional elements of the positioning systems with kinetic moments were carried out on a workbench.

As a result of linearization of the obtained static characteristics, linear mathematical models of functional elements and ACO, as well as a priori sets of destabilizing influences for objects of control, are formed.

In Matlab/Simulink, a modelling complex was developed for studying an ACO, which includes a power amplifier, an electric DC-motor with a flywheel and a tachometer. Various modes of its operation with destabilizing effects were researched. On this complex, diagnostic software has been developed and implemented to detect destabilizing effects, localize their sites and identify a specific type. Computational experiments conducted on the complex, allowed to work out the structure and parameters of the detection algorithms, localization of destabilizing effects from the generated a priori set and their identification. The experiments witnessed the fundamental possibility of obtaining a complete diagnosis during the transient process of the object of automatic control caused by destabilizing effects from the a priori set.

Based on the multitude of destabilizing effects, a lot of resources have been formed to restore the efficiency of an electro-flywheel ACO. Then algorithms were developed for the inclusion of excess resources on the results of diagnosis. The testing of recovery algorithms for destabilizing effects was performed on the software package. Computational experiments on the study of procedures for the restoration of the efficiency of an electro-flywheel automatic control object have provided confirmation of the fundamental possibility of restoring performance in real time during the transition process caused by the appearance of destabilization.

The study of the possibility of rational control of the operation of the sensor units was carried out on the laboratory bench of the channel yaw sensors (Fig. 5).
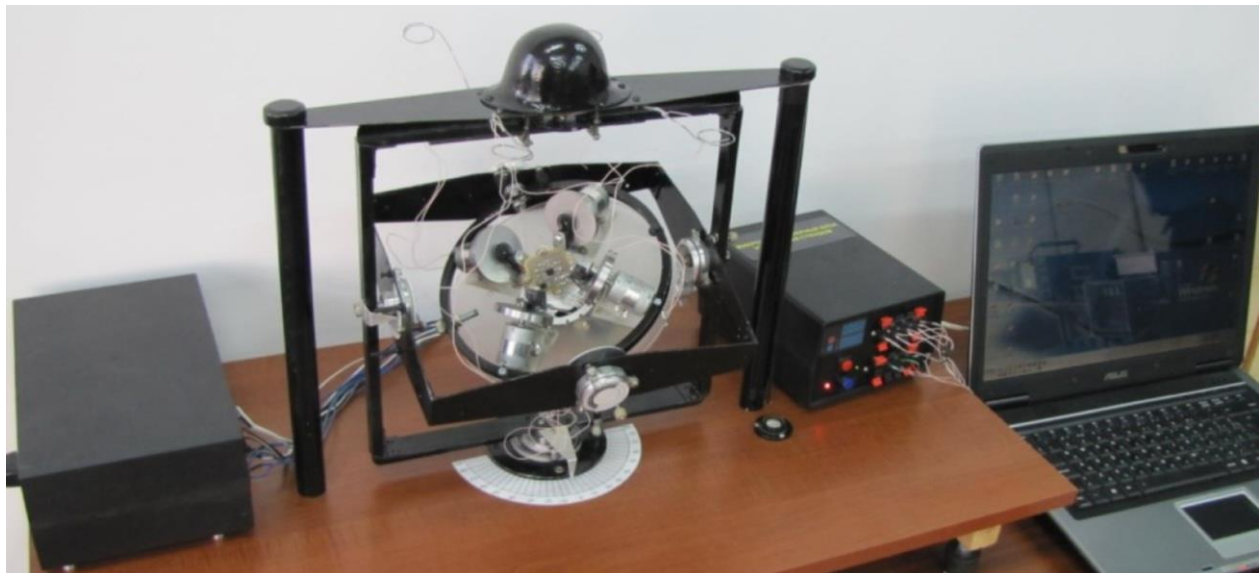

Fig. 4. Overall view of micro-satellite prototype

Fig. 5. General view of the stand for the study
of sensors in the yaw channel

In the yaw channel of the flying models of the projected aircraft, one gyroscopic angle sensor and two angular velocity sensors were used. Static characteristics were experimentally obtained for the sensors, they were linearized and linear mathematical models were compiled. As a result of studying their operating experience, an a priori set of 32 types of failures has been formed.

Corresponding DFMs for the problems of detecting, localizing and identifying failures of the formed set are constructed. Based on diagnostic functional models using diagnostic methods, algorithms, flowcharts, and computer diagnostics programs for course channel sensors have been developed. After debugging the software, a series of experimental studies on the imitation of types of destabilizing effects and their diagnosis was carried out on the stand. Then, a lot of redundant resources and the corresponding algorithms, flowcharts and programs were formed to restore the operation of the sensors. The software was debugged and field experiments were carried out, which confirmed the effectiveness of the procedures for restoring the functionality of the yaw channel sensors in real time.

Conclusion

The use of the proposed approach for adaptation with the event uncertainty of the ACO is based on a priori and an aposteriori knowledge. The tasks and tools presented in the article are the results of the first steps in solving the problem of adaptive control of an object with uncertain dynamics through rational control. Fur-ther steps are needed to improve the knowledge and knowledge-based model representations.

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РАЦІОНАЛЬНЕ УПРАВЛІННЯ ОБ'ЄКТАМИ З НЕВИЗНАЧЕНОЮ ДИНАМІКОЮ

А. С. Кулік, В. Г. Джулгаков

Розглянуто причини, що породжують невизначеність в динаміці об'єктів на прикладі аерокосмічної техніки. Об'єкти автоматичного управління, що складаються з об'єктів управління, сервоприводів і датчиків, схильні до впливу невизначених зовнішніх і внутрішніх збурювальних впливів, що дестабілізують їх працездатність. Класичні методи автоматичного управління такими об'єктами не дозволяють отримати бажані показники якості. Для раціонального управління об'єктами з невизначеною динамікою запропонований новий підхід, який базується на глибокому діагностуванні причин дестабілізації і гнучкому відновленні працездатності. Описано основні положення методу раціонального управління. Представлений новий клас математичних моделей - діагностичних. Процедури глибокого діагностування формуються з використанням формалізованих і слабоформалізованних моделей процесів штатного і нештатного функціонування системи управління. Для формування апріорних і апостеріорних знань про причини порушення працездатності використовуються структури у вигляді дихотомічних дерев, що розвиваються, які представляють собою різновид продукційних баз знань з конструкцією у вузлах «якщо ..., то ...», з логічними правилами отримання діагнозу про причини дестабілізуючих впливів. Описана методика рішення діагностичних задач для об'єктів з невизначеною динамікою. Для відновлення працездатності об'єктів з невизначеною динамікою запропоновано використання надлишкових ресурсів: сигнального і параметричного підстроювання, реконфігурації алгоритмів і апаратних засобів. Процес парирування дестабілізації, яка була діагностована, формується за допомогою другого методу А. М. Ляпунова. Даний метод забезпечує стійкість системи і задану якість управління. Раціональна адаптація до дестабілізуючих впливів базується на використанні інтелектуальних процедур глибокого діагностування причин порушення працездатності системи управління і гнучкого відновлення

працездатності в реальному масштабі часу. Такі процедури дозволяють здійснювати продуктивне навчання з метою збереження працездатності системи управління протягом всього життєвого циклу. Наведено результати застосування методу раціонального управління до ряду макетних зразків літальних апаратів.

Ключові слова: об'єкти з невизначеною динамікою; подійно-залежна невизначеність; дестабілізуючі впливи; працездатність; діагностичні моделі; глибоке діагностування; гнучке відновлення; дихотомічне дерево; функції А. М. Ляпунова.

РАЦИОНАЛЬНОЕ УПРАВЛЕНИЕ ОБЪЕКТАМИ
С НЕОПРЕДЕЛЕННОЙ ДИНАМИКОЙ

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Рассмотрены причины, порождающие неопределенность в динамике объектов на примере аэрокосмической техники. Объекты автоматического управления, состоящие из объектов управления, сервоприводов и датчиков, подвержены влиянию неопределенных внешних и внутренних возмущающих воздействий, дестабилизирующих их работоспособность. Классические методы автоматического управления такими объектами не позволяют получить желаемые показатели качества. Для рационального управления такими объектами с неопределенной динамикой предложен новый подход, который базируется на глубоком диагностировании причин дестабилизации и гибком восстановлении работоспособности. Описаны основные положения метода рационального управления. Представлен новый класс математических моделей – диагностических. Процедуры глубокого диагностирования формируются с использованием формализованных и слабоформализованных моделей процессов штатного и нештатного функционирования системы управления. Для формирования априорных и апостериорных знаний о причинах нарушения работоспособности используются структуры развивающихся дихотомических деревьев, представляющих собой разновидность продукционных баз знаний с конструкцией в узлах «если…, то…», с логическими правилами получения диагноза о причинах дестабилизирующих воздействий. Описана методика решения диагностических задач для объектов с неопределенной динамикой. Для восстановления работоспособности объектов с неопределенной динамикой предложено использование избыточных средств: сигнальной и параметрической подстройки, реконфигурации алгоритмов и аппаратных средств. Процесс парирования дестабилизации, которая была диагностирована, формируется с помощью второго метода А. М. Ляпунова. Данный метод обеспечивает устойчивость системы и заданное качество управления. Рациональная адаптация к дестабилизирующим воздействиям базируется на использовании интеллектуальных процедур глубокого диагностирования причин нарушения работоспособности системы управления и гибкого восстановления работоспособности в реальном масштабе времени. Такие процедуры позволяют осуществлять продуктивное обучение с целью сохранения работоспособности системы управления в течение всего жизненного цикла. Приведены результаты применения метода рационального управления к ряду макетных образцов летательных аппаратов.

Ключевые слова: объекты с неопределенной динамикой; событийная неопределенность; дестабилизирующие воздействия; работоспособность; диагностические модели; глубокое диагностирование; гибкое восстановление; дихотомическое дерево; функции А. М. Ляпунова.

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