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THE PRINCIPLE OF CONTROL BY DIAGNOSIS AS A RESULT OF THE SYSTEMATIC APPLICATION OF FUNDAMENTAL CONTROL PRINCIPLES

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The subject of study is the principle of control by diagnosis. The goal is to form a control principle based on a diagnosis as a result of the systematic application of fundamental management principles. Task: an excursion into history of mastering the principles of control. Analysis of features, positive and negative qualities of principles of control by setting influence, by disturbing influence and by deviation. Description of the principle of control by diagnosis. Presentation of diagnostic functional models of diagnostic objects. Giving an example of the application of the principle of control by diagnosis. The methods used are: retrospective analysis, the method of constructing graphic functional schemes, the method of the space of discrete states, the method of forming diagnostic functional models, methods of bench research and simulation modeling. The following results were obtained: the process of mastering control principles was decomposed into three stages: intuitive understanding of principles, mastering them in industry and scientific mastering. Features of the principles of control by setting influence, disturbing influence and by deviation are described. The principle of control by diagnosis and the functional scheme of a rational control system are proposed. Diagnostic functional models are presented that reflect the relationship between direct signs of destabilizing influences and indirect signs that are directly available for measurement. The results of experimental studies are presented, which testify to the possibility of rational control of the operability of sensors of flight parameters, in particular, of angular movements, during the action of various types of destabilizing influences. Conclusions. The scientific novelty consists in the formation of a new principle of control based on diagnosis and the development of a number of tools, the use of which allows to ensure the functionality of automatic control objects under the conditions of various types of destabilizing influences.

Keywords: principle of control, automatic control object, control by diagnosis, diagnosing, recovery of operability, state space, diagnostic functional model.

Introduction

The history of the development of automation is an integral part of the general history of the evolution of the material culture of mankind. The basic principles of automation are control principles. A principle (from *lat*. principium — beginning). The basic beginning on which anything is built (any scientific system, theory, policy, device, etc.) [1]. The mastery of the basic fundamental principles of automatic control continues throughout the history of the evolution of material culture, and this is evidenced by numerous examples of tools, devices, machines and systems, with the help of which the automation of certain technological processes was carried out in different periods of the development of civilization.

Learning, mastering and applying of the fundamental control principles underlying living and non-living nature is a long, complex, iterative process. The history of this process allows us to trace the main trends in the development of scientific knowledge and the ways of mastering and improving the fundamental principles of control by systematizing them to solve the current automation tasks caused by the challenges of scientific and technological progress.

One of the basic ones is the trend related to the further implementation of the control processes of complex automatic control objects with long period of autonomous functioning in conditions of uncertainty of influences that lead to impaired operability. Improvement of control processes takes place through the development of new control principles based on fundamental ones. Violation of the performance of automatic control objects occurs due to external influences: disturbance, noise, interference, and internal: malfunctions, failures and refusings. All these influences are uncertain events that destabilize operability, in other words, they are destabilizing influences. The significant uncertainty of destabilizing influences makes it necessary to develop procedures for identifying their specific physical types in order to make effective decisions how to parry it for restoring the operability of the automatic control object. Fundamental principles of control do not allow for the development of quality procedures for finding the causes of performance degradation, and therefore one of the possible ways to identify destabilizing influences is the development of a new principle of control based on diagnosis.

The article presents the results of research on the development of a new principle of control by diagnosis based on further systematization of the fundamental principles of control.

1. Excursion into history of mastering control principles

In the history of mastering the principles of control, three stages can be conditionally distinguished. The first is related to an intuitive understanding of control principles and their use in the simplest devices. The second stage is characterized by the further development of the principles and their applying in industry. The third stage is the scientific mastering of control principles, their formalization, solving the tasks of stabilization and positioning of objects of various physical nature, including the states when they are under uncertain operating conditions.

Man at the dawn of civilization realized his limited physiological capabilities in comparison with the capabilities of nature. Various tools and devices became the first means of expanding the physical capabilities of primitive people [2–4]. The need to catch fish, animals and birds created a need for new devices and devices in which the fishing process took place without direct human participation, i.e. automatically. The impressive penetration of the first inventors into the principles of control and its implementation in various tools for daily life and hunting amazes the imagination. The analysis of the first devices for fishing, from the point of view of the composition of functional elements, shows that such functional elements as sensitive and executive performed tasks without direct human participation, i.e., automatically, in accordance with the principle of control by setting influence.

Great interest in the early period is shown in the invention of various toys and devices used for entertainment and religious purposes. For example, the automatic signaling device of the ancient Greek philosopher Platon, a water vending machine, a device for opening temple doors, described by Heron of Alexandria, and a number of others that used the principle of control by setting influence.

Twenty centuries ago, in ancient Greece, Heron's oil lamp was used for lighting — it is a device that automatically feeds the wick when the oil level drops. The following elements were used in the lamp: a float to determine the oil level, a rack and pinion to transmit movement, a rack wrapped in wick to control the feed. In this device, the principle of control by deviation was implemented.

So, the first stage is characterized by the following features. First, the wide application of the principle of control by setting influence in various simplest automatic devices. Secondly, the use of various physical phenomena to build automatic devices. Thirdly, achieving an understanding of the main principle of building biological systems — the principle of control by deviation, and its practical use in non-production spheres of activity.

The second, most fruitful stage of the use of control principles was determined by the need for further improvement of the technique of industrial use of wind, water and, especially, steam. So, Agostino Romelli (1530–1590), an Italian military engineer, developed an automatic device that regulates the speed of rotation of the millstone when grinding grain in a mill. This device used the principle of control by disturbance. The appearance of the first steam engines by the Frenchman Papin, the Englishmen Sowery, Thomas Newcomen and John Kelly contributed to the development of automatic stabilization devices. In 1763, the outstanding Russian inventor I. Polzunov developed a project of a universal steam engine, which used an automatic stabilizer of the water level in the cauldron. In 1784, the Englishman James Watt received a patent for a centrifugal regulator of the angular speed of rotation of the shaft of a steam engine. In this regulator, the principle of control by deviation was used. In 1829, the French scientist J. Poncelet proposed a regulator of the angular speed of rotation of the shaft of a steam engine, based on controlling the supply of steam depending on the amount of load, that is using the principle of control by disturbance.

The inventions of I. Polzunov, J. Watt and J. Poncelet initiated a whole series of inventions of new automatic devices designed to stabilize the operation of steam engines using the principles of control by deviation and disturbance.

In 1676, the Dutch scientist Christian Huygene published a work on mechanics called «The Pendulum Clock», in which a cycloidal pendulum was presented. It was characterized by a constant oscillation period regardless of the amplitude due to the use of an anchor mechanism. The anchor mechanism provided undamped oscillations with the help of nonlinear negative feedback. This type of connection transforms the constant force acting on the anchor wheel into a variable periodic effect on the pendulum, which compensates for the effect of frictional forces. This invention started a new direction in technology — the development of clock mechanisms for accurate time measurement.

At the same stage, various automatic devices were developed that use the principle of control and by setting influence. For example, in 1929, the French inventor J. Jacquard proposed a device for a loom using a paper tape with holes — punched tape. The automatic device, with the help of feelers, recognized the location of the holes on each section of the punch tape and, in accordance with the received information, moved individual threads of the fabric base up or down so that the weft passing between them created the desired pattern programmed in the punch tape.

The second stage of the application of control principles is related to the creation of industrial regulators for machines using wind, water and steam energy, as well as various mechanisms and machines for the automation of technological operations of production processes. Regulators at this stage were built only on the basis of the intuition and experience of inventors who follow the path of trial and error. The importance of this stage in mastering the principles of control is difficult to overestimate, since the possibility of building various machines that perform their functions without human intervention has been practically proven.

The scientific development of control principles began at the third stage with the works of the English physicist J.C. Maxwell «On Regulators» (1868) [5] and the Russian mechanical scientist I.O. Vyshnegradskyi «On direct-acting regulators» (1876) [6]. The works of the Swiss professor A.B. Stodola in the field of configuration and calculation of heat engines, steam and gas turbines complete the creation of the classic linear theory of automatic regulation of the engines [7]. The scientific study of the possibilities of the principle of control by deviation led to the emergence of a number of new scientific tasks. Thus, a scientific approach to the mathematical description of transformation processes in a steam engine and a centrifugal regulator was needed. As a result of the conducted research, mathematical models of the first approximation were developed. The study of linear differential equations of the third order led to a new task — ensuring the stability of processes in a closed-loop control system. And the first solutions were the root criteria of stability. Then, the criteria of Raus-Hurwitz, Nyquist, Mikhailov, Kharitonov and a number of others were developed. For a closed-loop control system, in addition to the task of ensuring stability, which is a necessary condition of operation, it is necessary to solve the task of quality of control — a sufficient condition of operation. As a result of solving the problem of the quality of regulation, and in the future — the quality of control, a number of methods, theories, scientific directions appeared for the purpose of ensuring the specified accuracy of control, optimization of the transition process time, analytical design of regulators, dual control and others.

Further development of the principle of control by deviation in the class of nonlinear systems led to new scientific results and the emergence of scientific trends in the theory of stability, taking into account the fundamental results of O.M. Lyapunov.

The scientific development of the principle of control by disturbance, thanks to the works of H.V. Shchypanov, V.S. Kulebakin, B.M. Petrov, A.G. Ivakhnenko and A.I. Kukhtenko contributed to the creation of the theory of invariance. The further development of the theory of invariance led to the formation of a new scientific direction — combined control, which is based on the joint use of two principles of control — by deviation and by disturbance [8–11].

The trend of significant complication of control objects, caused by the expansion of their functions, scale, energy intensity and criticality, contributed to the development of many scientific directions regarding the joint use of fundamental principles of control. This trend has led to a revision of the classical approach to the design of control systems. It was necessary to take into account cost, weight and size, energy limitations and risks associated with the uncertainty of operating conditions, i.e. abnormal situations. Accidents and disasters in rocket and space engineering, nuclear technics and chemical production challenged the theory of automatic control. The increase in the structural and functional complexity of automation objects gives rise to the expansion of a multitude of influences, both external (disturbance, interference, noise) and internal (malfunctions, breakdowns, failures), which disrupt the performance of automatic control systems and lead to emergency situations. These disruptive actions, essentially destabilizing actions, cannot be fully defined and described at the stage of the control system design.

The problem of ensuring the guaranteed operability of autonomous control systems at a given time interval can be solved in the intensively developing class of adaptive systems. Thanks to the works of many scientists, such directions of automatic control have been formed as extreme control, combined control, control with a reference model, control with identification, control systems with self-adjustment and with the possibility of self-organization and self-learning, and a number of others [12–14].

Known approaches of adaptive control use fundamental control principles, mathematical models of automation objects, and a number of hypotheses regarding operating conditions. Among all possible hypotheses about destabilizing influences, the most difficult for practical use is the hypothesis about the uncertainty of the moment of their appearance, place of their appearance, type and specific physical form; in other words, the event uncertainty hypothesis.

The results of academician V.M. Kuntsevich's research on the use of fundamental control principles for adaptation in conditions of uncertainty of a non-stochastic nature initiated new scientific directions. Such directions expand the classes of automation objects up to objects of critical infrastructure and take into account more fully the peculiarities of their operation in order to ensure guaranteed operability over a long period of autonomous operation [15].

Therefore, the third stage in mastering the fundamental principles of control, thanks to the scientific approach, is characterized by a deeper penetration into the understanding of control processes in living and non-living nature and revolutionary automation of control processes of objects of various physical nature. This is accompanied by the involvement of advanced mathematical tools both for describing the processes of information transformation in control systems and for analytically solving the tasks of analysis and synthesis. At the third stage, unique control systems for autonomous objects with advanced adaptation capabilities to changing operating conditions are created. Intensive computer automation of the processes of analysis and synthesis of individual classes of control systems is taking place.

Increasing requirements for the quality of operation of control systems for various complex and critical objects and processes has contributed to the expansion of the front of research on the joint use of fundamental control principles with the aim of obtaining new system effects that provide more productive adaptation in uncertain operating conditions.

Let's consider the functional features of the fundamental principles of control in relation to modern and promising automation objects, the functioning of which is carried out in conditions that change in an uncertain manner.

2. The principle of control by setting influence

It is advisable to consider the features of the principle of control by setting influence with the help of a functional scheme that reflects the informational features of transformation processes (Fig. 1). The scheme uses the following notations: $U_S(t)$ — setting influence; $U_C(t)$ — control signal; $y(t)$ — output parameter; MCD — microprocessor control device; ACO — automatic control object; D — set of destabilizing influences.

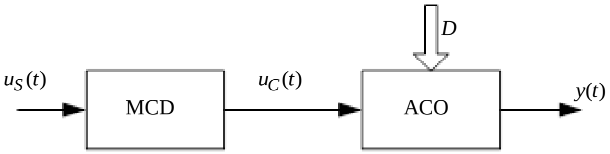


Fig. 1

The principle of operation of this automatic control system is obvious. When a setting influence $u_S(t)$ is applied to the MCD, a control signal $u_C(t)$ is formed, which is sent to the actuators of the ACO. As a result, appropriate technological operations are performed to obtain the desired value of the output signal $y(t)$.

D is a set of disturbances, noises and failures that disrupt the operational efficiency of the ACO. Failures mean malfunctions, refusings, degradations that lead to a significant change in technical characteristics. All the destabilizing effects of the set D lead to varying degrees of changes in the functional properties of the open-loop control system, which is a sequential connection of the functional elements of the MCD and ACO. A change in the functional properties of the control system is reflected in the result of its functioning — a signal $y(t)$.

Among the positive features of the principle of control by setting influence can be attributed:

— ideological and constructive simplicity;

— high operation speed of open-loop control system;

— preservation of operability under a number of destabilizing influences;

— satisfactory accuracy of output characteristics;

— ease of configuration and maintenance of open-loop control systems.

The negative features of this control principle include:

— high sensitivity to changes in open-loop control system parameters caused by failures;

— impossibility of obtaining high accuracy of initial characteristics in case of unknown disturbances and low accuracy of ACO models;

— impossibility of full compensation of disturbances for ACO with transport delay;

— inoperability of the open-loop control system in case of catastrophic failures and disturbances exceeding the design levels;

— impossibility of controlling an unstable ACO.

Therefore, the principle of control by setting influence can be applied to stable ACOs, the transforming properties of which are well studied and reflected in the corresponding models. Under the uncertain conditions of operation of the ACO, the principle of control by setting influence does not allow obtaining satisfactory output characteristics.

Examples of the productive use of the principle of control by setting influence are pneumatic and hydraulic valves, which open or close the supply of fuel, air or steam to actuators when an electric signal is applied, vending machines, information boards of stations and airports, and a number of others.

3. The principle of control by disturbance

There is much more information on the origins of the scientific development of the principle of control by disturbance influence than by the first principle. With the help of the simplest functional scheme, we will consider the features of this control principle (Fig. 2).

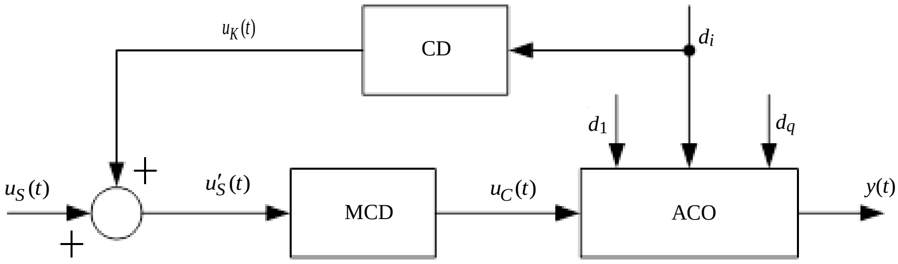


Fig. 2

There are many destabilizing influences $D=\{d_1,..., d_i,..., d_q\}$ on the ACO. Let the impact d_i significantly affect the process of operation of the ACO and can be measured, then with the help of a correction device (CD), it is converted into a correction signal $u_K(t)$ that enters the adder of the system. The corrected setting influence $u'_S(t)$ enters the MCD, where the control signal is formed $u_C(t)$. This signal compensates for the destabilizing impact d_i on the processes in the ACO and ensures the corresponding output parameter of the system — signal $y(t)$. So, the functional diagram shows a single-loop compensation system for one destabilizing impact d_i. A fundamental point is the possibility of measuring destabilizing influences. Not all destabilizing effects can be measured either because of the lack of appropriate sensors or because of the complexity and cost of their measurement. It is not possible to provide a measure of the magnitude of such destabilizing effects as failures. The formation of several contours of compensation for destabilizing influences leads to difficulties in coordinating their functioning and the complexity of technical implementation. For the organization of qualitative compensation of destabilizing influences, fairly accurate mathematical models of transformation processes in the ACO are required. Any changes in the operating conditions lead to a change in the compensation conditions and, as a result, a deterioration of the output characteristics. For the formation of an effective compensation circuit, knowledge of the maximum value of the destabilizing influence is required for the correct selection of the actuators in the ACO, which will ensure that the control signal is worked out on the working area of static characteristics.

These circumstances lead to the fact that it is practically impossible to ensure high accuracy of working out a setting influence in the conditions of destabilizing effects from the set D. It is possible to ensure control accuracy only for a limited subset of influences that can be measured under the condition of stability of ACO characteristics during operation.

The positive properties of the principle of control by disturbing influence in relation to the task of countering destabilizing influences are as follows.

1. Detection of all destabilizing influences only significant and measurable ones, the impact of which on the processes in the ACO can be fully compensated.

2. The use of fairly simple compensation algorithms that do not create the need to ensure the stability of the compensation loop.

3. Ensuring qualitative compensation of the impact of the measured destabilizing influences on the output characteristics of the ACO.

4. The operation speed of the compensation loop is comparable to the operation speed of the main ACO control channel.

5. The lack of complete information about the output characteristics of the ACO excludes the need to solve the problem of management stability.

The following can be attributed to the negative properties of the principle of control by disturbance.

1. Elimination of the influence of only those destabilizing influences for which compensation loops have been created.

2. The presence of a large number of uncontrolled destabilizing influences leads to a low level of output characteristics of the ACO, that is, to a violation of the system’ s operability.

3. When both the internal and external conditions of system functioning are changed, the conditions for compensation of measurable destabilizing influences are violated.

4. Impossibility to applicate this principle in the ACO, the properties of which change during operation.

5. There is a compensation for the impact of destabilizing influences on the operational efficiency of the ACO, rather than a countermeasure of the causes that gave rise to abnormal situations in the control processes.

The application of the principle of control by disturbance gives good results for stable ACOs, the properties of which are adequately reflected in the corresponding models.

4. Principle of control by deviation

The scientific development of this productive principle of control has been started with the fundamental works of J.K. Maxwell, I.A. Vyshnegradskyi and A.B. Stodola and continues to the present day through implementation in various fields of human activity. A graphic model in the form of the simplest functional scheme (Fig. 3) allows to display visually the features of this principle in relation to the ACO.

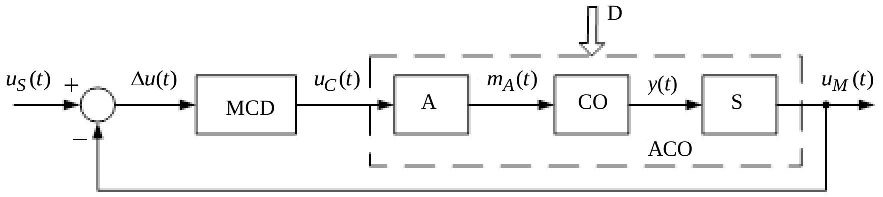


Fig. 3

A set D of destabilizing influences $d_i, i=\overline{1,q}$ which change arbitrarily, acts on the ACO. Information about the output parameter of the ACO is represented in the diagram by a signal $u_M(t)$ from the sensor (S). In the given scheme, the «adder» functional element is removed from the MCD as a key element in the implementation of the principle of control by deviation. A deviation signal $\Delta u(t)=u_S(t)-u_M(t),$ which contains information about the consequences of destabilizing influences from the set $D,$ is generated in the adder. The difference signal is converted into a control signal $u_C(t)$ in the MCD. It is sent to the actuator, which changes the state of the control object (CO), which is reflected in the output measurement signal $u_M(t)$ form the sensor. To implement this control principle, a signal from the system output to its input is used, that is, feedback. As a result, a closed control loop or a closed-loop control system is formed.

The principle of control by deviation is universal, it is applicable to objects and disturbances of any physical nature. This principle is quite effective, allows to achieve high-quality compensation of destabilizing influences from the set $D,$ which are constantly changing.

The following are the positive properties of the principle of control by deviation.

1. The ability to detect the appearance of any destabilizing influences in the control loop.

2. The ability to compensate for «small» deviations from the given behavior caused by destabilizing influences.

3. The ability to adjust the dynamic properties of the ACO using appropriate algorithms in order to ensure the necessary reserves of stability and quality indicators.

4. Low sensitivity to changes in parameters of functional elements in a closed-loop control circuit.

5. Low requirements for the adequacy of the mathematical description of the transformation processes in the functional elements of the system.

In the presence of such positive properties, the use of the principle of control by deviation does not allow to ensure fully the necessary and sufficient conditions for the operability of modern and promising control systems of long-term and autonomous functioning. The main reasons are as follows.

1. There is compensation for the consequences of destabilizing influences, rather than parrying the causes of influences that can be eliminated.

2. The internal inconsistency of the principle is due to the need to allow destabilization and then compensate for it.

3. When compensating for destabilization, workable functional elements are forced to work simultaneously with non-functional ones, and in costly, intensive modes, while spending additional energy and resources.

4. Destabilizing influences that lead to a significant change in system parameters and structure are not compensated.

5. It is impossible to localize destabilizing influences and target, flexibly and concretely neutralize them.

6. The period of detection and compensation of destabilizing influences is determined by the transition period of the closed-loop control system.

7. Destabilizing influences are uncontrollable and unmeasured inputs to the control system.

The application of the principle of deviation control allows to develop automatic control systems that have the ability to adapt in the «small». Such adaptation occurs due to the property of the system to detect and compensate for the limited effects of arbitrarily changing, uncontrolled destabilizing influences.

Further development and improvement of the considered control principles are possible in their systematic combination. Such a union should preserve their positive properties and eliminate their shortcomings in such a way as to ensure the possibility of adaptation in the «big» to real destabilizing influences. Such a systematic combination of basic principles is called the principle of control by diagnosis.

5. Principle of control by diagnosis

The development of the first instrumental means of signal-parametric diagnostics of automatic control systems [16] and means of restoration of operability [17] led to the need to find a control principle that allows adaptation to arbitrarily changing uncontrolled various types of destabilizing influences on a unified ideological basis in order to ensure the desired behavior of an autonomous control objects.

As a result of further research, it was possible to formulate the principle of control based on the diagnosis, which can be presented using the functional scheme shown in Fig. 4.

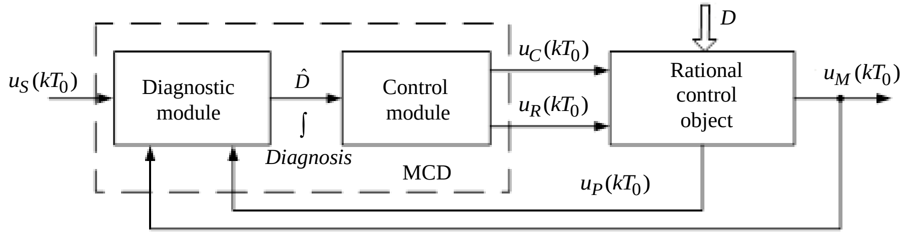


Fig. 4

The rational control object (RCO) is an object that has the properties of being diagnosed and restored. Diagnosability is the possibility of establishing the causes of destabilizing influences in finite time according to states available for measurement. Recoverability is defined as the possibility of transferring the RCO from an inoperable state to an operable one by neutralizing destabilizing influences $d_i \in D$ in a finite time interval. Two types of signals are received by the MCD diagnostic module from the rational control object: $u_M(kT_0)$ — discrete signals for measuring RCO parameters from sensors; $u_P(kT_0)$ — signals from check points; $k = 0,1,2,...$; T_0 — period of discretion. With the application of a setting influence $u_S(kT_0)$ in the diagnostic module, a diagnosis $\hat{D}$ is formed in the form of estimates of direct signs of destabilizing influences. The received diagnosis is sent to the control module, in which control actions are formed that restore operability of RCO: $u_C(kT_0)$ — signals that parry the destabilizing influences revealed as a result of diagnostics, and $u_R(kT_0)$ — signals that control the reconfiguration of hardware by disconnecting failed and connecting backup devices.

In the diagnostic module, the tasks of detecting destabilization are solved sequentially using the principle of control based on the deviation of the current signal $u_M(kT_0)$ relative to the reference behavior of the object. Next, the place of occurrence of destabilization is localized using local deviations of signals from their reference values. Identification of the type and kind of destabilization in accordance with the principle of control by disturbance allows to obtain estimated values of the magnitude of destabilizing influences. Thus, the diagnosis consists in estimating the moment of time when destabilization was detected, finding a specific structural part of the object where destabilization occurred, identifying the type of destabilization, and determining the estimated value of the destabilizing effect.

The positive properties of the principle of control by diagnosis include the following.

1. Ability to diagnose specific destabilizing influences and parry them.

2. Possibility of more accurate compensation of destabilizing influences on control processes.

3. The principle makes it possible to develop perfect adaptive systems that ensure a more accurate working out of a setting influence $U_S(t)$ during longer operation.

4. This principle is applied to diagnosed objects with incomplete or even missing information about destabilizing influences.

5. The principle of control by diagnosis helps to actively increase the resource and duration of active functioning of autonomous control systems.

The negative features of this principle are as follows.

1. The difficulties of creating scenarios of abnormal situations in control systems and the impact of their consequences on the performance of autonomous control functions.

2. The formation of the set D requires a deep knowledge of the features of the functioning of the automatic controling object.

3. The complexity of developing algorithms and programs for the processes of diagnosing and restoring the operability of objects.

4. At the current stage of mastering this principle, it is not possible to automate the development of diagnostic and recovery processes.

5. The work intensity of the formation of means of operability restoration, balanced with a set of destabilizations D.

So, in the principle of control by diagnosis, the principle of control by disturbance is applied in terms of obtaining information about destabilizing influences and in terms of compensating the action of destabilizing influences on the control process. The principle of control by deviation is applied to detect the fact of destabilization, detect the destabilized structural part of the object, and form stabilizing control influences. The principle of control setting effect is used in the part of the formation of control effects during the reconfiguration of hardware.

The application of the principle of control by diagnosis opens up the possibility of implementing better adaptive automatic control of objects with incomplete a priori information about destabilizing influences in the process of development, production and operation, and even in the absence of such information. Such adaptive control will allow in the future reduce ignificantly various resource costs for development, production and operation and significantly increase the periods of active functioning of autonomous control objects.

6. Diagnostic functional models

In the practical application of the principle of control by diagnosis, there is a need for mathematical models that reflect the relationship between the characteristics of destabilizing influences and the signals available by measurement. Such specific models are diagnostic functional models (DFM) [18]. Let's consider the main provisions regarding these models.

The process of functioning of the linearized diagnostic object in the time domain can be represented by the following system of equations:

$$\begin{gathered} x[(k+1)T_0] = Ax(kT_0) + Bu(kT_0);\ x(\mathrm{k}_0T_0) = x_0; \\ y(kT_0) = Cx(kT_0), \end{gathered} \qquad (1)$$

where $x(kT_0)$ — state vector of the control object, $x(kT_0) \in X^n$; $u(kT_0)$ — control vector, $u(kT_0) \in U^r$; $y(kT_0)$ — vector of measured parameters, $y(kT_0) \in Y^m$; A, B i C — matrices of appropriate dimensions; $k = 0, 1, 2, ...$ — discrete number; T_0 — period of discretion.

A set of possible destabilizing influences $D = \{d_1, ..., d_i, ..., d_q\}$ is used in the construction of the DFM. Each destabilizing influence is matched by a parameter λ_i whose value changes in the interval $\lambda_i \in [\underline{\lambda_i}, \overline{\lambda_i}]$. The perturbed motion of the diagnostics object for the parameter λ_i will take the following form:

$$\begin{gathered} \tilde{x}_i[(k+1)T_0] = A(\lambda_i)\tilde{x}_i(kT_0) + B(\lambda_i)u(kT_0);\ \tilde{x}_i(k_0T_0) = \tilde{x}_{i0}; \\ \tilde{y}(kT_0) = C(\lambda_i)\tilde{x}_i(kT_0), \end{gathered} \qquad (2)$$

where $\tilde{x}(kT_0)$ — the state vector of the object destabilized by the event d_i; $A(\lambda_i), B(\lambda_i)$ i $C(\lambda_i)$ — matrices of the corresponding dimensions, the coefficients of which depend nonlinearly on the parameter λ_i.

Equations of additional movements of the object caused by the appearance of destabilizing influence d_i can be obtained by applying reference models. Having chosen the simplest reference model in the form of the system of equations (1) for $x(k_0T_0) = 0$ and performing analytical linearization of nonlinear dependencies, we obtain

$$\begin{gathered} \Delta x_i[(k+1)T_0] = [A_i x(kT_0) + B_i u(kT_0)]\Delta\lambda_i;\ \Delta x_i(k_0T_0) = x_{i0}; \\ \Delta y_\mathrm{i}(kT_0) = C_i \Delta x_i(kT_0);\ i = \overline{1, q}, \end{gathered} \qquad (3)$$

where $A_i = \dfrac{\partial A(\lambda_i)}{\partial \lambda_i}, B_i = \dfrac{\partial B(\lambda_i)}{\partial \lambda_i}, C_i = \dfrac{\partial C(\lambda_i)}{\partial \lambda_i}$ — sensitivity functions of the corresponding matrices by parameter λ_i; $\Delta\lambda_i$ — a slight change in the parameter λ_i, such as $\Delta\lambda_i >> \Delta\lambda_i^2$.

The system of equations (3) reflects the functional relationship of the unmeasurable direct sign $\Delta\lambda_i$ of the destabilizing influence d_i with the measurable indirect sign $\Delta y_i(kT_0)$. Such a system of equations is the DFM for the direct sign $\Delta\lambda_i$ of the destabilizing influence d_i.

Diagnosability criteria are used to assess the diagnosability using DFM.

Criteria of structural diagnosability. For the structural diagnosability of the object according to the DFM, it is necessary and sufficient that the matrices $L_i,\ i=\overline{1,q}$ are linearly independent in all pairwise combinations.

$$L_i = \begin{bmatrix} A_i & B_i \\ C_i & 0 \end{bmatrix}. \tag{4}$$

Criteria of signal diagnosability. For signal diagnosability of an object by DFM, it is necessary and sufficient that the vectors $L_i^* v_i,\ i=\overline{1,q}$ are linearly independent in all pairwise combinations.

Matrices $L_i^*,\ i=\overline{1,q}$ are matrices of an object that has the property of structural diagnosability. Vector

$$v(kT_0) = \begin{bmatrix} x(kT_0) \\ u(kT_0) \end{bmatrix}, \tag{5}$$

where $x(kT_0)$ — state vector of the reference model.

The criteria of structural and signal diagnosability make it possible to form a DFM with an unambiguous connection of direct signs of destabilizing influences $\Delta\lambda_i$ with indirect signs $\Delta y_{\text{i}}(kT_0)$ and to determine the signal conditions for the manifestation of these connections.

7. An example of the application of the principle of control by diagnosis

As an object of research, let’ s consider a fragment of a block of gyroscopic sensors, which was used on flying models. Flying models are a research tool for obtaining reliable information about the behavior of the future aircraft in all designed flight modes [19]. The general view of the stand for the study of sensors in the course channel is shown in Fig. 5. An angle sensor (AS) and two angular velocity sensors (AVS) were used in this channel. In order to work out the models, algorithms and programs of the principle of managing the performance of sensors by diagnosis, a stand was developed according to the functional scheme shown in Fig. 6.

Fig. 5

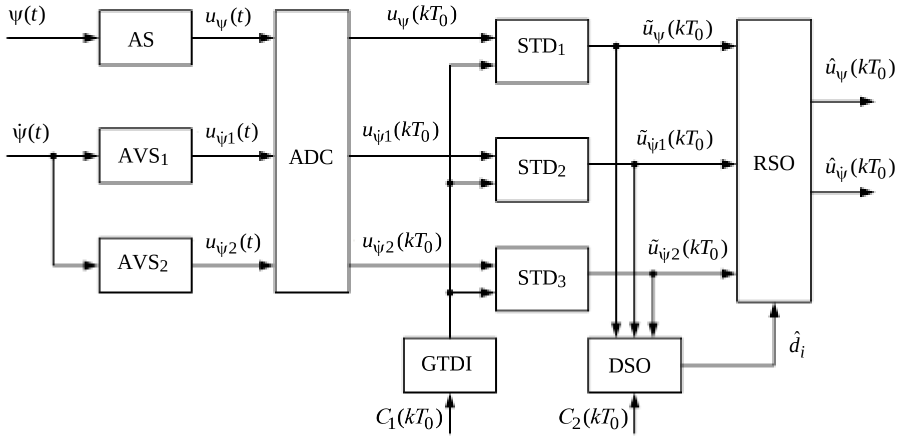
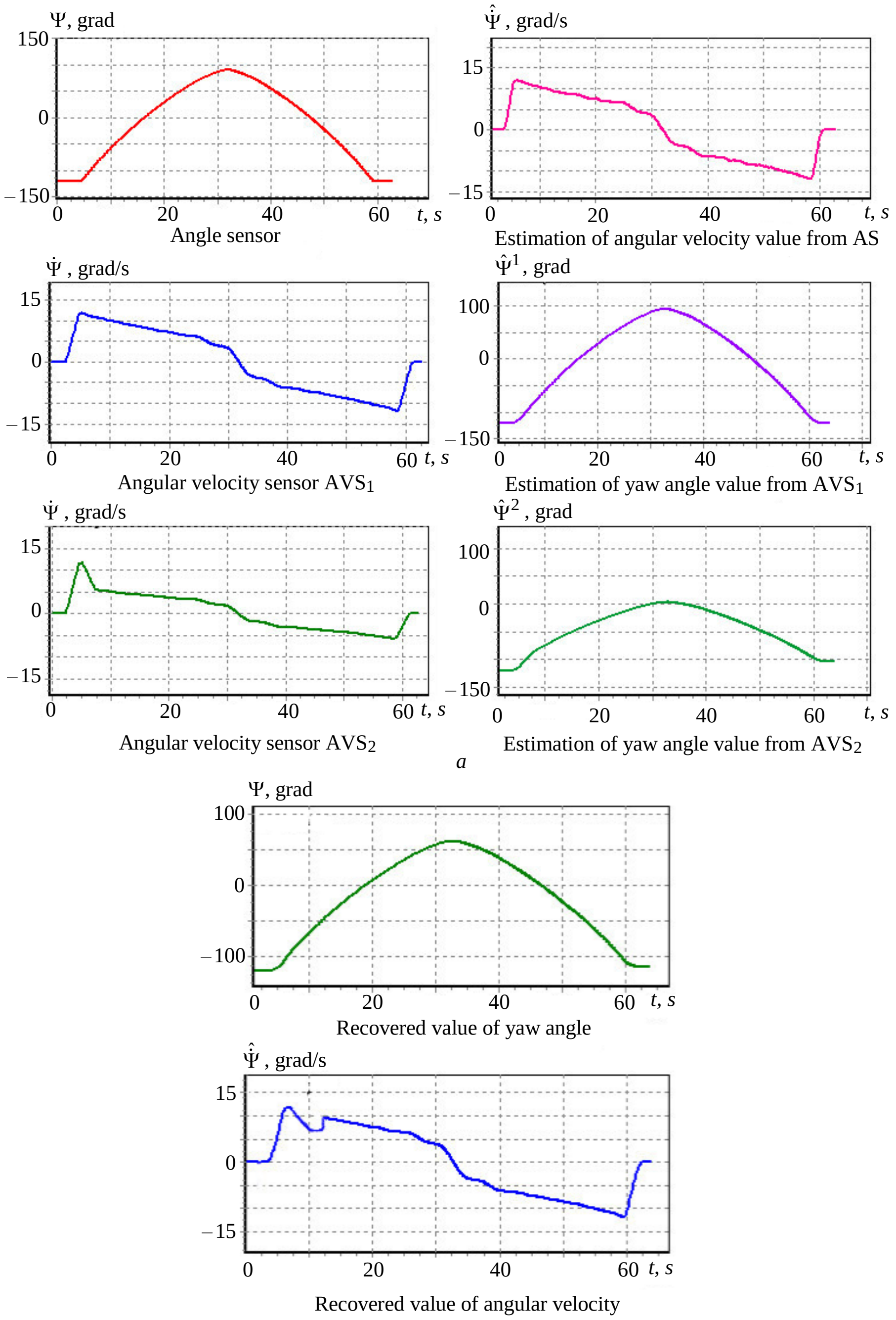


Fig. 6

Signals from the angle sensor (AS) and angular velocity sensors (AVS1 and AVS2) through the ADC are sent to the corresponding blocks of simulators of destabilization types SDT_i, $i=\overline{1,3}$. The blocks SDT_i work according to commands from the generator of types of destabilizing influences (GTDI). Blocks SDT_i together with GTDI carry out deformation of signals from sensors according to defined scenarios specified by the command $C_1(kT_0)$. Deformed signals, which reflect the result of the current destabilizing effect on the sensor, are sent to the unit for diagnosing the sensor operability (DSO). In this block, the cause of impaired operability is revealed by indirect signs and a diagnosis $\hat{d}_i$ is formed. The DSO unit is activated by the command $C_2(kT_0)$. The result of diagnosing — the diagnosis is sent to the unit, which performs the function of recovering the sensor operability (RSO). In the RSO block, according to the diagnosis and with the help of available means, the deformed signal distorted by the destabilizing influence is restored, and the estimated values of the signals $\hat{u}_\psi(kT_0)$ and $\hat{u}_{\dot\psi}(kT_0)$ are calculated.

The set of types of destabilization were generated for each sensor. For example, for AS the set $D=\{d_1, d_2, ..., d_{10}\}$, where d_1 — positive zero drift with the possibility of compensation, d_2 — negative zero drift with the possibility of compensation, d_3 — positive zero drift without compensation, d_4 — negative zero drift without compensation, d_5 — reduction of the conversion factor with the possibility of compensation, d_6 — reduction of the conversion factor with and without compensation, d_7 — break in the signal wire of the sensor, d_8 — break in the negative power wire, d_9 — break in the positive power supply wire, d_{10} — unknown type of destabilization.

For the stand, which contains three gyroscopic sensors, 30 scenarios of emergency situations were formed and algorithms and software were developed for diagnosing and restoring sensor operability. Graphs of processes during destabilization in AVS_2, which is caused by a rediction in the conversion factor is shown in Fig. 7. At the 5th second, a distortion of the sensor signal appeared due to destabilization from a reduction in the conversion factor with the possibility of compensation. The graph shows the distortion of the time characteristic of the signal compared to the time characteristic of AVS_1. From this moment, destabilization in the functioning of the sensors is detected. Then, as a result of the search, a faulty sensor is found. It is AVS_2. The type of destabilizing effect is established — reduction of the conversion factor, and the type of destabilizing effect — reduction of the conversion factor with the possibility of compensation is determined. At the 10th second, the diagnostic process was completed, and at the 12th second, the process of restoring measurements from AVS_2 by signal tuning was completed.



a

b

Fig. 7

Therefore, for each scenario, the graphs of the processes of diagnosing and restoring measurements of gyroscopic sensors were obtained. This indicates the fundamental possibility of adapting to various types of destabilizing influences and ensuring high-quality measurement of flight parameters, for example, yaw angle and angular speed, using the principle of control by diagnosis.

Conclusion

The presented description of the fundamental principles of control and the history of their scientific development testifies to their continuous development and improvement. One of the productive directions of development consists in their systematic combination and obtaining a new systemic effect.

Systematic combination of fundamental principles of control with the aim of obtaining information about uncontrolled destabilizing influences that change arbitrarily led to a new principle of control by diagnosis. In this control principle, it was possible to preserve the positive properties of the fundamental control principles, the combination of which made it possible to obtain a new property that ensures the controllability of destabilizing influences and the possibility of parrying them. This circumstance opens up new opportunities for the development of advanced control systems with wider adaptive properties for autonomous objects with a long period of active operation in harsh, not fully defined operating conditions.

А.С. Кулік

ПРИНЦИП КЕРУВАННЯ ЗА ДІАГНОЗОМ ЯК РЕЗУЛЬТАТ СИСТЕМНОГО ЗАСТОСУВАННЯ ФУНДАМЕНТАЛЬНИХ ПРИНЦИПІВ КЕРУВАННЯ

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Предметом вивчення є принцип керування за діагнозом. Мета полягає у формуванні принципу керування за діагнозом як результату системного застосування фундаментальних принципів керування. Зроблено екскурс в історію освоєння принципів керування. Проаналізовано особливості, позитивні та негативні якості принципів керування за задавальним впливом, за збурювальним впливом та за відхиленням. Описано принцип керування за діагнозом. Подано діагностичні функціональні моделі об'єктів діагностування. Наведено приклад застосування принципу керування за діагнозом. Використано ретроспективний аналіз, метод побудови графічних функціональних схем, метод простору дискретних станів, метод формування діагностичних функціональних моделей, методи стендових досліджень та імітаційного моделювання. Отримано такі результати — проведена декомпозиція процесу освоєння принципів керування на три етапи: інтуїтивного розуміння принципів, освоєння їх у промисловості та наукового освоєння. Описано особливості принципів керування за задавальним впливом, збурювальним впливом і за відхиленням. Запропоновано принцип керування за діагнозом та функціональну схему раціональної системи керування. Представлено діагностичні функціональні моделі, що відображають зв'язок прямих ознак дестабілізуючих впливів із непрямими ознаками, які безпосередньо доступні для вимірювання. Наведено результати експериментальних досліджень, які свідчать про можливість раціонального керування працездатністю датчиків параметрів польоту, зокрема кутових рухів, під час дії різнотипних дестабілізуючих впливів. Наукова новизна полягає у формуванні нового принципу керування за діагнозом та розробці низки інструментальних засобів, застосування яких дозволяє забезпечити працездатність об'єктів автоматичного керування в умовах дії різнотипних дестабілізуючих впливів.

Ключові слова: принцип керування, об'єкт автоматичного керування, керування за діагнозом, діагностування, відновлення працездатності, простір станів, діагностична функціональна модель.

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