14. Blahut, R. Theory and Practice of Error Control Codes [Text] / R. Blahut. – Moscow: Myr, 1986. – 576 p.
15. Ahmad, A. Selection of polynomials for cyclic redundancy check for the use of high speed embedded – an algorithmic procedure [Text] / A. Ahmad, L. Hayat // Wseas Transactions on Computers. – 2011. – Vol. 10, Issue 1. – P. 16–20.
16. Semerenko, V. P. Estimation of the correcting capability of cyclic codes based on their automation models [Text] / V. P. Semerenko // Eastern-European Journal of Enterprise Technologies. – 2015. – Vol. 2, Issue 9 (74). – P. 16–24. doi: 10.15587/1729-4061.2015.39947

На прикладах успішних реалізацій технологій у проектах ненаселених привязних та автономних підводних апаратів (АПА) показано ефективність автоматизованих систем управління (АСУ) з гібридною системою підтримки прийняття рішень (СППР). Поставлена та розв'язана задача аналітичного визначення залежності похибки від властивостей АПА та параметрів процесу, як кількісного критерію вибору альтернатив моделі, алгоритму, керуючих правил у ході фукціюнування АСУ підводних технологій

Ключові слова: координаційне управління, оцінка похибки моделі, гібридна СППР, АСУ підводних технологій

На примерах успепешных реализаций в проектах необитаемых привязных и автономных подводных аппаратов (АПА) показана эффективность автоматизированных систем управления (АСУ) с гибридной системой поддержки принятия решений (СППР). Поставлена и решена задача аналитического определения зависимости ошибки от свойств АПА и параметров процесса, как количественного критерия выбора альтернатив модели, алгоритма, управляющих правил в ходе функционирования АСУ подводних технологий

Ключевые слова: координационное управление, оценка ошибки модели, гибридная СППР, АСУ подводных технологий

UDC 519.816:009. 826:629.585
DOI: 10.15587/1729-4061.2016.85585

CRITERIA FOR THE EVALUATION OF MODEL'S ERROR FOR A HYBRID ARCHITECTURE DSS IN THE UNDERWATER TECHNOLOGY ACS

A. Trunov
PhD, Associate Professor, First Vice-Rector
Department of automation and computer-integrated technologies
Petro Mohyla Black Sea National University
68 Marines str., 10, Mykolayiv, Ukraine, 54000
E-mail: trunovalexandr@gmail.com

1. Introduction

The inability of classic methods of the theory of automatic control to effectively resolve the problems of automation of enterprises and their management has been paid more and more attention to in the technical literature [1–3]. An analysis of negative results and the reasons that caused them indicates that the coordination, coordinational control [1], as the main principle of functioning in the overall management system, plays a role of a subsystem in the stabilization process in relation to the predetermined strategy [4]. When defining the role of coordination in the process of control, it should be noted that for any intellectual, industrial, social and everyday human activity, mandatory is a typical procedure for making a decision [1–3, 5, 6]. At present, scientists, based on the study and systematization of technologies [7–28], including underwater technology [4, 7–15, 29, 30], determined and formed a generalized structure of underwater technological complex and generalized models of the technological process (TP) automation control system (ACS). In addition, an analysis of the methods of control over complex automated systems was carried out [4, 7, 13–15, 17–20]. As evidenced by the results of analysis, structural constituents of such systems are mostly designed with automatic or automated control systems [15, 17]. It is established that the application of methods of designing control system processes that are suitable for the functioning in the surface marine technologies, is complicated in the underwater technology [30]. The latter is due to the fact that the magnitude of time of the transition process in the executive mechanisms is comparable to the magnitude of the system transition from one state to another and to the magnitude of time necessary for decision making [7, 30]. In addition, it is predetermined by nonlinearity of the processes of interaction with the environment and complexity of the adequate modeling, which is caused by insufficient exploration of dynamics of underwater apparatus, manipulators and technological equipment [8]. A significant obstacle is also the problem of changing the angular position of the device, as the carrier of technological equipment in space, which occurs when implementing the control algorithms and is caused by a change in the centers of mass and the moments of inertia [7]. Another obstacle is the unknown features of the implementation of technologies and a lack of methods that enable the prediction of possible changes, while under design, in the functional purpose of the entire complex [30]. This particularly, concerns individual components of the complex, which is why to design it being capable of such adaptive changes and resettings directly in the course of technological operations, without lifting to the surface, is an important task [7]. No less important is the problem of reprogramming during ACS operation of such technological complexes and the provision of transparency of these processes representation. The latter task is further exacerbated by the level of training of staff and a constant requirement to reduce operational costs. In the literature, it is more and more argued [7, 29, 30] that a more effective solution to this problem should be sought in the creation of branching mathematical models of the technological process with a natural language description of technological transitions and additions that allow the implementation of programming languages of the higher level on the natural language operators and the automation of this process.

In addition, it is now often are demonstrated [7, 8, 30] that the construction of TP ACS, effective in operation, including those for deep-water complexes, is not possible without the creation of DSS. Their effectiveness can be provided by the existence of criteria of estimation of the transition error from the models represented in the form of systems of nonlinear differential equations with partial derivatives or a system of nonlinear boundary problems to the sequence of algebraic expressions of recurrent approximation and logical terms, as well as a list of behavioral rules and algorithms. The choice between alternatives is carried out by means of quantitative [29] or qualitative [5, 30] comparison with the help of calculating the criteria values. In the majority of the cases, this process is complicated and time-consuming, it complicates or renders their application impossible [28, 29]. Thus, the construction and representation of such criteria in analytical form, suitable for rapid calculation, is one of the relevant tasks of building hybrid DSS of underwater technologies. For the practical implementation of these criteria, a relevant task is to provide for their capability to link the quantitative variables with those qualitative and linguistic ones, with the help of which the productive-controlling rules are formed and which are operated by the person, who makes decisions.

2. Literature review and problem statement

The experience of design works and operation of unmanned (U) underwater vehicle (UV) in many countries of the world proves [8–15] that successful implementation of underwater technologies requires complete information about interacting structural elements of the technological functional chain. Data on the properties of the underwater complex in general and on the condition of structural elements at this particular moment and on the predicted behaviour of each of them, as well as full information about the solution of the reverse problem of dynamics for each of the interacting elements, are the relevant tasks of operation. The development and structural improvement of both the vehicles and the onboard equipment are intrinsically linked to the development of automated control systems of such complexes for the implementation of tasks of underwater technologies [8–10]. In most implementations of the automation problems, their solution used to be provided for by creating TP ACS. They have especially specific features in the underwater technology. Thus, in these systems, consistent work of UUV will be provided using the floating cable-rope [8, 10–15]. Regardless of the weather, it is used comprehensively, enabling power supply, transmission of operator commands and video signals from the UUV board to aboard the ship and in the reverse direction. Cable rope also performs the function of a reliable means of lifting the UUV from water. One, and sometimes even two, operators control the hydraulic manipulators with a set of technological equipment. At the same time they also manage the motion and positioning of the vehicle. The process control when conducting repair works [8, 10–15] practically does not differ from the control in other types of technological processes. Manipulators are used for mechanical displacement operations. They include, for example, such tasks as: opening or closing the valves of pipes passes; or maintaining the control of their condition to fill the casings when submerged. They also inspect cavities when the appropriate equipment is available, lift the drilling tools, acoustic beacons [11, 12]. An outer shell that has a streamlined shape, improves the UV hydrodynamic characteristics, as well as compensates for the negative floatage. Material for its manufacturing is spheroplastic. Dimensions of the glass micro balls and their concentration play significant role in determining the magnitudes of working depths – these magnitudes are associated with each other inversely proportionally [8, 10–15]. To ensure the UV stability, the main volumes of floatage are formed at the top of the vehicle, or its frame, which are used for placing the propulsion engines and control engines, cameras, sonars, with a high resolution capacity for detecting obstacles and preventing collision. The frames also hold the manipulators, putting them maximally forward in the nose of the hull, which provides enlargement of their working area and expansion of mechanical features when moving the working body with a tool or a part. To ensure their operation, practically all UUV design implementations make use of the automated control systems that contain basic features of TP ACS.

ACS of the most tethered UUV [9, 10, 15] control their motion direction by adjusting the speed of rotation of propulsion engines or other means of active creation of controlling forces and moments. One of the commonest forms of transfer of commands of the tethered UVs is multichannel joysticks, since the motion speed of the device does not exceed 1.5 meters per second. The movements themselves are alternately linear, which is why they provide for an uninterrupted solution of the tasks assigned to them.

One of the most effective realizations of such complexes that implement the benefits of the principles of automated systems is the remotely controlled UV AN/SLQ-48. Its purpose is to search, observe and neutralisation of mines [15]. The structure of its search systems includes hydroacoustic station of/direct observation (HAS/DO) with two television (TV)-cameras. For the disposal of bottom mines it uses additionally two mechanical cutters and blasting charge that contains a device for remote blasting. High resolution of HAS/DO provides for the device's approach directly to the mine. Blasting charge is placed next to the mine and is activated by the encoded hydroacoustic signal that is sent after receiving a message from aboard the ship carrier about UV dispatch at a safe distance. Propulsion mode of the motion is enabled by two engines of capacity 18 kW, while the manoeuvres realizes by two additional maneuvering engines. Power supply and coordinated control over the vehicle and equipment is carried out by a cable-rope from aboard the ship.

There are also modifications of these systems, which make use of semi-submerged UV. Their guidance is carried out by a signal that is transmitted over radio channel. One of the representatives of such systems is AN/WLD-1(V)1 RMS (Remote Minehunting System, USA) [15]. Their design includes semi-submerged UV and towed HAS AN/AQS-20 with variable depth of submersion. A vehicle of mass 7.3 t, length 7 m and diameter 1.2 m is equipped with a retractable device for underwater work of diesel engine (UWDE) and diesel engine of capacity 370 HP, which provides for the motion speed of 16 knots on the move, and when maneuvering while performing tasks – 10–12 knots [13, 14]. Over the tower above the deck house, there are antennas and TV cameras for observing the surface. On the nose, HAS/DO is installed to search for underwater objects and possible obstacles. Data from mobile HAS AN/AQS-20 and HAS/DO are continuously sent to the control post of the ship-carrier, or helicopter, by broadband, digital VHF radio channel, and beyond horizon line – broadband low-frequency radio channel. In future it may be possible to use SW channels and satellite communication. UV is controlled both by using the digital channel and autonomously by the pre-installed programs.

Another example of logical development from a simple UV to a complex with the ACS use in underwater technology that is brought to perfect implementation is the French system FDS3 (Forward Deployed Side Scan Sonar) [14, 15]. It uses one or two remotely controlled UV "Dorado" that are equipped with towed multiray HAS/DO "Aurora" at depths from 6 to 200 m. Remotely controlled tethered UV (RCTUV) and towed HAS/DO provide for an overview of the underwater area by the ship-carrier course in the nose sector at a distance of up to 3 nautical miles. The UV in full gear is equipped with power plant with diesel engine of capacity 200 kW, which gains speed on the move of 17.5 nodes. The searching speed is reduced to 10–12 knots. The search can be performed continuously for 28 hours. The vehicle is of length 8.24 m and mass 5.9 t, it is equipped with a device for UWDE, which, together with radio antenna and TV-cameras of surface surveillance and observation when passing by the obstacles on the surface move, is located on the tower. UV control, exchange and transfer of data from it are carried out by analogy with the American system RMS [15].

Thus, one of the important problems of designing and further improvement of TP ACS for the provision of underwater technology is to create effective DSS. As evidenced by studies over the past 30 years [16–25], the development and implementation of DSS in underwater technology and other sectors is based on such principles as [15, 16–25]: flexibility, adaptivity and hybridity in the architecture for heterogeneous elements, including the systems of effect modeling and prediction of their behaviour under the influence of external factors. Controlling the systems, in which measuring devices, mechanisms, drives, subsystems that exchange streams of continuous and digital signals [15] operate simultaneously, should be performed based on the experience of DSS implementation in other sectors, for example [15, 17–25]. According to papers [5, 21–23, 28, 29], an important element that enables the functioning of DSS regardless of the area of application is the criteria for the qualitative and quantitative selection of alternatives.

An analysis and systematization of the models and determinining the most effective methods for the provision of information substantiation of the decisions made were conducted in article [28]. Results of the study confirmed that the existence of quantitative assessments of the predicted characteristics of an object's model and the estimation of error is crucial for constructing and functioning of DSS. An attempt at resolving the problem of decision making support through the accumulation of information in the form of a database does not warrant solving analogous problems, while it is especially complicated for dynamic systems [24]. It should be noted that devising and implementing the methodology for the evaluation of alternatives by several standards [29], when there are quantitative and linguistic variables, also comes down to the problem of rapid assessment of the alternatives regardless of their type.

Thus, constructing quantitative estimates of error by a single metric that allows the prediction of model's behavior and the estimation of prediction error is a promising problem, not solved as yet. Its solution clears the way for the construction of selection criteria of alternative models, algorithms, controlling rules and provides for the efficient functioning of hybrid DSS. For the underwater technologies, with regard to nonlinearity and dynamism in behavior of the system and commensurate periods of time for the prediction and time of transition processes, the task of constructing such evaluations in analytical form is especially promising.

3. The aim and tasks of the study

The aim of the study is to construct analytical expressions for the evaluation of norm of error in the description of nonlinear object, applicable for using in DSS of hybrid architecture of underwater technology ACS.

To achieve the set goal, it is necessary to solve the following tasks:

– to establish using the methods of finite-integral transforms analytical relation between the norm of error in the predicted behavior of nonlinear model and an error of approximation of its nonlinear component and properties of the object for arbitrary linear operator and arbitrary conversion kernel;

– to receive an expression for the evaluation of maximum possible error at the infinite number of eigenvalues;

– to perform the simulation for finite, limited number of own numbers, and at the change in the structure of the model for the sine and cosine transform.

4. Generalization of architecture of hybrid DSS of adaptive complexes for the underwater technology. Formulation and solution of the problem on the model's error

By summing up results of analysis of development of the underwater technologies and examples of the best practices that are presented above, we shall generalize TP ACS structure, which is depicted in Fig. 1. As can be seen from Fig. 1, such a system implies the existence of external and internal data storage 1. It separates internal 2, external 3 sources of information, which are controlled by using control system 4, resulting in the exchange of data with the database. These processes are also administered by the central coordinating system (CCS) 5.

The communication of CCS 5 is provided via system of dialogue organization 6 with operator 7, as well as with models base 8, algorithms base 9, rules base 10 and directly with a decision maker 16. Structuring of models base 8 and rules base 10, accordingly, intended for UUV and separately for the technological equipment of UUV simplifies their control processes in the course of technological operations. The existence of criteria for rapid evaluation of the models, algorithms, controlling rules is a key tool that enables the performance of control systems [8–10].

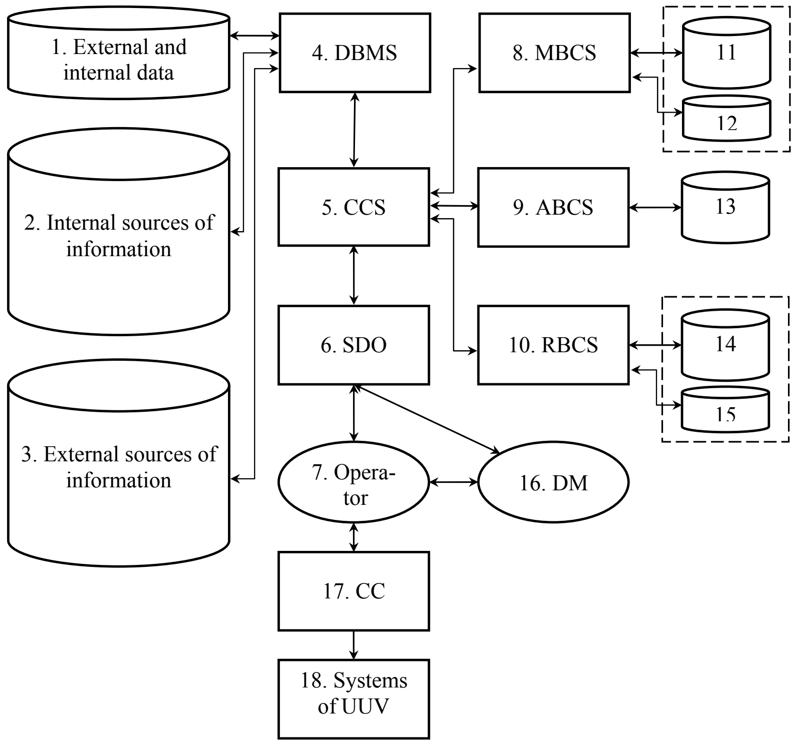

Fig. 1. Generalized architecture of hybrid DSS of adaptive complexes for the underwater technology: 1 – external and internal data; 2 – internal information sources: archive; gismeteo; centralized DB of the vessel and ground-based services; distributed enterprise systems; life-support systems of the vessel; life-support systems of UUV; systems for gathering underwater information; systems of management and control over parameters of technological process; 3 – external sources of information: CD ROM; Internet; statistical bodies; government structures; 4 – DBMS; 5 – central coordinating system; 6 – system of dialogue organization; 7 – operator; 8 – models base CS; 9 – algorithms base CS; 10 – rules base CS; 11 – models base of UUV; 12 –models base of technological equipment of UUV; 13 – algorithms base; 14 – rules base of UUV; 15 – base of rules of technological equipment of UUV; 16 – Decision maker; 17 – communication channels; 18 – systems of UUV

4. 1. Formulation and solution of the problem on the evaluation of effect of linearization error on the model's error

Assume that V is the assigned n-dimensional region of points whose position is determined by radius vector r. Assume that S is the boundary surface and l is the boundary curve of the intersection between region V and the coordinate surfaces. Let us denote by P(r,t) an unknown function that satisfies equation:

$$L_1(P) = L_2(P) + f(r,t); \qquad (1)$$

$$\lambda_j\left(P(r,0)\right) = \beta_j(r);\ B_i\left(P(r,t)\right) = b_i(r,t);$$

$$(j = 1,2,...M;\ \forall r \in V);\ (i = 1,2,...N;\ r \in S, t \geq 0),$$

where $L_1(P)$ is the linear function of P and its derivatives, and $L_2(P)$ is the nonlinear. Assume λ_j and B_j are the linear functions of P(r, t) and its derivatives. We assume as well that the D is the region of defining operators L_1 and L_2 and function f(r, t) belongs to the Banach space R, and the values of these operators are mapped into general Banach space of values W. We shall continue to assume that P is continuous and integrated with the square, that is, there is a norm:

$$\|P\| = \sqrt{\int_0^1 P^2\left(x_j\right) dx_j},$$

in addition, we shall assume that there is a direct finite integral transform of function P, as well as there is reverse transformation:

$$\tilde{P} = \int_a^b K_{nj}\left(x_j\right) P\left(x_j\right) dx_j$$

and

$$P\left(x_j\right) = \int_0^\infty K_{nj}\left(\sigma_j\right) \tilde{P}\left(\sigma_j\right) d\sigma_j,$$

where a and b are the boundaries of change in coordinate x_j, and σ_{nj} are the eigenvalues of the corresponding boundary problem. Let us consider a general case when a linear operator is presented in the form

$$L_1(P) = \sum_{k=0}^{l} a_{l-k} \frac{d^k P}{dx_j^k}.$$

Now let us also assume that linear differential operator L_1 as the operator has the following properties:

– operator from the sum of functions is the sum of operators from these functions, that is,

$$L_1\left(\sum_1^n c_i P_i\right) = \sum_1^n c_i L_1\left(P_i\right);$$

– finite integral transformation of image $L_1(P)$ is the linear function from the transformed with the same kernel K_{nj} and own numbers σ_{nj}, function P, that is,

$$\int_a^b K_{nj} L_1(P) dx_j = \sum_{k=0}^{l} a_{l-k} \sigma_{nj}^k \int_a^b K_{nj} P dx_j = \tilde{P} \sum_{k=0}^{l} a_{l-k} \sigma_{nj}^k.$$

Let us define nonlinear differential operator L_2 as the operator that has the following properties:

– operator from the sum of functions is not equal to the sum of operators of these functions, that is,

$$L_2\left(\sum_1^n C_i P_i\right) \neq \sum_1^n C_i L_2\left(P_i\right);$$

– operator L_2 is such that L_2 (P) is uninterrupted over the entire definition region and is n+1 differentiated by Fréchet, in this case, its derivatives are also defined on D;

– operator L_2 is such that L_2 (P) on D is integrated and is integrated with the square, that is, there is a norm from L_2 (P) on D, and it also allows the integral transform with kernel K_{nj}. Below we will demonstrate and prove the need to have the specified properties. As shown in paper [4, 7], this model describes most of the processes that implement the ACS principles in the underwater technology.

Assume known maximum and minimum values of the unknown function, then P_1 is the approximate solution of boundary problem that satisfies linearized equation:

$$L_1(P_1)=L_3(P_1)+f(r,t) \quad (2)$$

with initial and boundary conditions of the original problem. Absolute error $\Delta=P-P_1$ satisfies the zero original and boundary conditions and differential equation:

$$L_1(\Delta)=\delta(r,t), \quad (3)$$

where $\delta=L_2(P)-L_3(P_1)$ is the error in linearization. Let us introduce notation for the norm of function f that integrates with the square on interval [0, 1]

$$\|f\|=\sqrt{\int_0^1 f^2(x_j)dx_j}.$$

Applying finite integral transform to (3) gives:

$$\tilde{\Delta}\sum_{k=0}^{1} a_{1-k}\sigma_{nj}^k=\int_a^b K_{nj}\delta dx_j. \quad (4)$$

Let us apply the theorem of evaluation for upper estimate of the right part and let us use the properties of the Cauchy-Bunyakovsky inequalities:

$$\left|\int_a^b K_{nj}\delta dx_j\right|\le\|K_{nj}\|\cdot\|\delta\|\le|\delta|_{max}. \quad (5)$$

Let us apply inverse finite integral transform to (4), we will receive from calculations (5) and assuming that Δ integrates with the square:

$$\|\Delta\|\le|\delta|_{max}\left\|\sum_{n=1}^{\infty}\frac{K_{nj}}{\sum_{k=0}^{1}a_{1-k}\sigma_{nj}^k}\right\|$$

or approximately

$$\|\Delta\|\le|\delta|_{max}\sum_{n=1}^{\infty}\frac{|K_{nj}|_{max}}{\left|\sum_{k=0}^{1}a_{1-k}\sigma_{nj}^k\right|_{min}}. \quad (6)$$

An analysis (6) reveals that under the same conditions of the synthesized regulator, error is generated by the error of approximation of the nonlinear part of the model and the number of eigenvalues and the choice of the kernel type. Examining sensitivity separately to each of these factors is an important practical task for the final formation of analytical criteria for selection.

4. 2. Formulation and solution of the problem on the impact of the nonlinearity properties on the model's error

Let us consider problem (1) with all the assumptions and properties that were introduced in chapter 4. 1. and determine the impact of each factor – sources of error. In addition, using the recurrent approximation method [4, 7], we shall decompose the images formed by their action in the vicinity of prototype P_1. Let us choose as P_1 approximate solution of the boundary problem that satisfies linearized equation (2). As a result of the transform with regard to (2), we shall write down:

$$L_1(\Delta_m)=\delta(r,t)+\left.\frac{\partial L_2(P)}{\partial\Delta}\right|_{P_1}\Delta_m+\left.\frac{\partial^2 L_2(P)}{\partial\Delta^2}\right|_{P_1}\frac{\Delta_m\Delta_{m-1}}{2}, \quad (7)$$

where Δ_m and Δ_{m-1} is the error in the solution of the m-th and m-1-th approximation.

Applying finite-integral transform to (7), we shall write down:

$$\tilde{\Delta}_m\sum_{k=0}^{1}a_{1-k}\sigma_{nj}^k=\int_a^b K_{nj}\delta dx_j+$$

$$+\int_a^b K_{nj}\left[\left.\frac{\partial L_2(P)}{\partial\Delta}\right|_{P_1}\Delta_m+\left.\frac{\partial^2 L_2(P)}{\partial\Delta^2}\right|_{P_1}\frac{\Delta_m\Delta_{m-1}}{2}\right]dx_j. \quad (8)$$

Let us apply the Cauchy-Bunyakovsky inequality properties to equation (8) and transform it into the inequality:

$$\tilde{\Delta}_m\le\frac{\left|\int_a^b K_{nj}\delta dx_j\right|_{max}+\left\|\left[\left.\frac{\partial L_2(P)}{\partial\Delta}\right|_{P_1}+\left.\frac{\partial^2 L_2(P)}{\partial\Delta^2}\right|_{P_1}\frac{\Delta_{m-1}}{2}\right]\right\|_{max}\int_a^b K_{nj}\Delta_m dx_j}{\sum_{k=0}^{1}a_{1-k}\sigma_{nj}^k} \quad (9)$$

or

$$\frac{\left|\int_a^b K_{nj}\delta dx_j\right|_{min}}{\sum_{k=0}^{1}a_{1-k}\sigma_{nj}^k-\left\|\left[\left.\frac{\partial L_2(P)}{\partial\Delta}\right|_{P_1}+\left.\frac{\partial^2 L_2(P)}{\partial\Delta^2}\right|_{P_1}\frac{\Delta_{m-1}}{2}\right]\right\|_{min}}\le$$

$$\le\tilde{\Delta}_m\le\frac{\left|\int_a^b K_{nj}\delta dx_j\right|_{max}}{\sum_{k=0}^{1}a_{1-k}\sigma_{nj}^k-\left\|\left[\left.\frac{\partial L_2(P)}{\partial\Delta}\right|_{P_1}+\left.\frac{\partial^2 L_2(P)}{\partial\Delta^2}\right|_{P_1}\frac{\Delta_{m-1}}{2}\right]\right\|_{max}}. \quad (10)$$

We shall introduce a three-component vector-indicator $\bar{V}$ and recurrent decomposition, similar to [7], and apply the reverse finite integral transform to equation (8) to receive:

$$\Delta_m=\int_0^{\infty}K_{nj}(\sigma_j)\frac{\int_a^b K_{nj}|\delta|V_1dx_j+\int_a^b\Delta_m K_{nj}\left[\left|\frac{\partial L_2(P)}{\partial\Delta}\right|_{P_1}V_2+\left|\frac{\partial^2 L_2(P)}{\partial\Delta^2}\right|_{P_1}V_3\frac{\Delta_{m-1}}{2}\right]dx_j}{\sum_{k=0}^{1}a_{1-k}\sigma_{nj}^k}d\sigma_j. \quad (11)$$

Expressions (9), (10) allow the upper estimation of error magnitude, and expression (11) allows us to track its changes for different values of parameters of the state. A detailed analysis of these expressions demonstrates that their practical application might be attained in two ways. According to the first one, gradually finding estimates for each of their own numbers and substituting preliminary approximations lead to the transformed values of the error. After that, by the set of their own numbers, the error is found by reverse transform. Then this expression is assumed to be a preliminary approximation, and the algorithm is repeated.

According to the second approach, by the set of own numbers, by expression (11), the m-th approximations of errors are found, at the zero value of the preceding m-1st approximation. Then, upon completing the operation of integration, this result is used again, after the substitution to expression (11). In order to find the next approximation of inverse transformation, we take the received result. And then by this algorithm, the process is repeated until achieving convergence of sequences with the required accuracy. It also should be noted that the introduction of vector indicator links qualitative and linguistic variables, with the help of which production-controlling rules are formed and a decision maker operates, with quantitative variables. The latter enables connection between the modules of hybrid DSS with the modules, that are built by the principles of neural networks, including the recurrent ones.

5. Modeling the influence of the number of their own numbers and model's parameters and discussion of results

For clarity and ease of representation of the process of modeling, we shall consider the model, for which the linear operator is simplified. Let us consider a finite integral transform of simplified operator $L_1(P)$ for such a case, assuming that the transform is a linear function from the transformed with the same kernel K_{nj} and own numbers σ_{nj},, function P, that is:

$$\int_a^b K_{nj} L_1(P) dx_j = \sigma_{nj}^2 \int_a^b K_{nj} P dx_j = \sigma_{nj}^2 \tilde{P}.$$

We shall also consider a special case of own numbers [7], $\sigma_n = \pi n$, where n runs over a series of natural numbers. Then the estimate takes the form:

$$\|\Delta\| \le \frac{|\delta|_{max} |K_{nj}|_{max}}{\pi^2} \cdot \sum_{n=1}^{\infty} \frac{1}{n^2} = |K_{nj}|_{max} |\delta|_{max} B_1, \tag{12}$$

where B_1 is the Bernoulli number and $B_1 = 1/6$, or relative error is determined by

$$\varepsilon = \frac{\|\Delta\|}{|P|_{max}} \le \frac{1}{6} \frac{|\delta|_{max}}{|P|_{max}} |K_{nj}|_{max}, \tag{13}$$

but it is an approximate estimate, it can be obtained more accurately if one uses reverse transform:

$$\|\Delta\| \le \left\| \int_0^{\infty} \frac{K_{nj}}{\sigma_{nj}^2} d\sigma_{nj} \cdot |\delta|_{max} \right\|.$$

Consequent estimate is possible only for specific kernels. Thus, for example, for the most common sine- and cosine Fourier transformation, estimation of error for these transforms will equal:

– sine transformation

$$\|\Delta\| \le |\delta|_{max} \cdot \left| \sqrt{\frac{2}{b-a}} \int_0^{\infty} \frac{\sin \sigma_n x_j}{\sigma_n^2} d\sigma_n \right|_{max} =$$

$$= |\delta|_{max} \sqrt{\frac{2}{b-a}} \times$$

$$\times \left| x_j \left[\ln|x_j \sigma_n| - \frac{\sin \sigma_n x_j}{\sigma_n x_j} + \sum_{n=1}^{\infty} \frac{(-1)^n (\sigma_n x_j)^{2n}}{2n \cdot (2n)!} \right]\Bigg|_{\sigma_n=0}^{\sigma_n=\infty} \right|_{max}; \tag{14}$$

– cosine transformation

$$\|\Delta\| \le |\delta|_{max} \cdot \left| \sqrt{\frac{2}{b-a}} \int_0^{\infty} \frac{\cos \sigma_n x_j}{\sigma_n^2} d\sigma_n \right|_{max} =$$

$$= |\delta|_{max} \sqrt{\frac{2}{b-a}} \left| x_j \left[\sum_{n=1}^{\infty} \frac{(-1)^{(n)} (\sigma_n x_j)^{(2n-1)}}{(2n-1) \cdot (2n-1)!} - \frac{\cos \sigma_n x_j}{\sigma_n x_j} \right]\Bigg|_{\sigma_n=0}^{\sigma_n=\infty} \right|_{max}. \tag{15}$$

An analysis of rough and more accurate evaluations demonstrates that if linearization error is the finite magnitude, then the estimation of error of the solution is also finite magnitude. The most interesting is the fact that if a number of own numbers is limited only from the bottom, then the evaluations of errors reduce sharply and the upper only restriction simplifies the calculation of sums of the series (14), (15).

Thus, analyzing expression (13), we can conclude about the possibilities of applying the methods of finite integral transformations to nonlinear problems, if there are

$$\sigma_n \ge \sqrt{\frac{|\delta|_{max}}{|P|_{max}}}.$$

A special choice of kernels only with the eigenvalues, which satisfy this inequality, allows us to obtain approximate solution with relative error, much less than unity. The choice of coefficients of linearization for constrained unknown functions from the top and bottom is conveniently conducted by the introduction of dimensionless unknown function $P/|P|_{max}$ based on the criterion of equality to zero of both the deviation in one of the points or in some of their set and the deviation of integrals from its dimensionless value in the interval. However, an analysis of expressions (5) reveals that if we linearize integral from the square of discrepancy, then the error is significantly reduced.

Thus, we substantiated a technique that will allow obtaining the estimation of error of solutions, which also enables us to use expressions of evaluation of the norm as the criteria. Thus, for example, for a hybrid decision support system, models database control system 8, algorithms base control system 9 including by the magnitude of estimation of the maximum error, will make it possible to choose the type of model or algorithm by the magnitude of the assigned accuracy. In order to explore influence of the quantity of own numbers n on the rate of error and relative error $\|\Delta\|$ and relative error ε, we shall consider a model of the second order for a set of values of the ratio of coefficients a_1/a_0. Modeling results are presented in Table 1.

Table 1

Analysis of influence of the quantity of own numbers on the estimation of magnitude of the norm of error

n	a_1/a_0=0,05		a_1/a_0=0,5		a_1/a_0=1	
	$\|\Delta\|$	ε	$\|\Delta\|$	ε	$\|\Delta\|$	ε
1	0.909091	–0.36864	0.5	–0.45	0.333333	–0.49714
2	1.147186	–0.20328	0.666667	–0.26667	0.458333	–0.30857
3	1.254713	–0.12861	0.75	–0.175	0.525	–0.208
4	1.315689	–0.08626	0.8	–0.12	0.566667	–0.14514
5	1.354904	–0.05902	0.833333	–0.08333	0.595238	–0.10204
6	1.382227	–0.04005	0.857143	–0.05714	0.616071	–0.07061
7	1.402347	–0.02607	0.875	–0.0375	0.631944	–0.04667
8	1.41778	–0.01536	0.888889	–0.02222	0.644444	–0.02781
9	1.42999	–0.00688	0.9	–0.01	0.654545	–0.01257
10	1.439891	0.005688	0.909091	0.008333	0.662879	0.010549

As evidenced by analysis of the results of the modeling, the effect of increasing the quantity n of own numbers from one to ten reduces the maximum possible error from tens of percent to the unities. Such an influence when compared with the effect of factors a_1/a_0 is more significant. A change by the order of ratio a_1/a_0 by twenty times leads to an increase in error practically only by two times. The latter indicates that the factor of the quantity of own numbers for the formation of kernels of integral transformations is more significant and it first of all determines the magnitude of error when modeling the processes. Analyticity of expressions for the estimation of error in the predicted model's behavior makes them fit for simple rapid calculations. The latter renders such estimations advantage for selecting them as the criteria for DSS of hybrid architecture of the underwater technology.

6. Conclusions

1. Analytical expressions for the evaluation of the norm of error in the description of nonlinear object are constructed using the methods of finite-integral transforms for continuous models and can be applied as criteria for the selection of type of the model of hybrid DSS in the underwater technology ASC.

2. Evaluations of the error norm in the solution of the problem of simulation for infinite and finite quantity of own numbers do not depend on the type of the transformation kernel and are determined largely by the number of the problem's own numbers and error of approximation of nonlinear terms and properties of an object for arbitrary operator and arbitrary transform kernel.

3. Results of the analytical and numerical modeling for finite and limited number of own numbers and when changing the structure of the model demonstrate practical applicability and ease of evaluation of the norm of maximum possible error for sine- and cosine transform. Such analytical assessment makes them suitable for selecting the type of the model and the algorithm, as well as productive-controlling rules at the assigned maximum possible error in the solution for the problem of modelling hybrid DSS in ASC for the underwater technologies.

References

1. Petrov, E. G. Koordynacijne upravlinnja (menedzhment) procesamy realizacii' rishen' [Text] / E. G. Petrov // Problemy informacijnyh tehnologyj. – 2014. – Issue 02 (016). – P. 6–11.
2. Hodakov, V. Je. Pro rozvytok osnov teorii' koordynacii' skladnyh system [Text] / V. E. Hodakov, N. A. Sokolova, D. L. Kyryjchuk // Problemy informacijnyh tehnologyj. – 2014. – Issue 02 (016). – P. 12–21.
3. Gorshen'ova, K. Ju. Modeljuvannja dynamichnyh procesiv vitrovoi' elektrychnoi' stancii' u seredovyshhi gpss [Text] / K. Ju. Gorshen'ova, M. T. Fisun // Problemy informacijnyh tehnologyj. – 2015. – Issue 01 (017). – P. 145–149.
4. Trunov, A. Realization of the paradigm of prescribed control of a nonlinear object as the problem on maximization of adequacy [Text] / A. Trunov // Eastern-European Journal of Enterprise Technologie. – 2016. – Vol. 4, Issue 4 (82). – P. 50–58. doi: 10.15587/1729-4061.2016.75674
5. Krjuchkovskyj, V. V. Razvytye metodologyy ydentyfykacyy modelej yntellektual'noj dejatel'nosty [Text] / V. V. Krjuchkovskyj, K. E. Petrov // Problemy informacijnyh tehnologij. – 2011. – Issue 9. – P. 26–33.
6. Hodakov, V. E. Harakterne osobennosti odnogo klassa social'no-jekonomichnyh sistem [Text] / V. E. Hodakov, A. K. Vezumskij // Problemy informacijnyh tehnologij. – 2013. – Issue 2. – P. 10–14.
7. Trunov, A. N. Rekurentna aproksymacija u zadachah modeljuvannja ta proektuvannja [Text]: monografija / A. N. Trunov. – Mykolai'v, 2012. – 270 p.
8. Trunov, O. M. Dynamika avarijno-rjatuval'nogo aparatu v umovah reguljarnogo hvyljuvannja i shkvaliv [Text] / O. M. Trunov // Zbirnyk naukovyh prac', NUK. – 2007. – Issue 6. – P. 30–41.
9. Blincov, V. S. Pryv'jazni pidvodni systemy [Text] / V. S. Blincov. – Kyiv: Naukova Dumka, 1998. – 231 p.
10. Blincov, V. S. Suchasni zavdannja stvorennja pidvodnyh robotiv dlja Azovo-Chernomors'kogo basejnu [Text]: nauk.-tehn. konf. / V. S. Blincov // Innovacii' v sudnobuduvanni ta okeanotehnici. – Mykolai'v: NUK, 2010. – P. 8–9.
11. Bocharov, L. Nezaseleni pidvodni aparaty: Stan i zagal'ni tendencii' rozvytku [Text] / L. Bocharov // Elektronika: Nauka, Tehnologija, Biznes. – 2009. – Issue 7. – P. 62–69.
12. Bjelousov, I. Suchasni i perspektyvni nezaseleni pidvodni aparaty VMS SShA [Text] / I. Bjelousov // Zakordonnyj vijs'kovyj ogljad. – 2013. – Issue 5. – P. 79–88.
13. Mosalev, V. Dystancijno kerovani ta avtonomni pidvodni aparaty VMS zarubizhnyh krai'n [Text] / V. Mosalev // Zakordonnyj vijs'kovyj ogljad. – 2006. – Issue 6. – P. 56–66. – Available at: http://pentagonus.ru/publ/27-1-0-431

14. FDS3 (Forward Deployed Side Scan Sonar) Jane's International Defense Review [Electronic resource]. – Available at: http://www.janes.com/
15. Bremer, R. H. Unmanned surface and underwater vehicles [Text] / R. H. Bremer, P. L. Cleophas, H. J. Fitski, D. Keus. – Netherlands, 2007. – 126 p.
16. Kazeli, H. An Intelligent Hybrid Decision Support System for the Management of Water Resources [Text] / H. Kazeli, T. Christofides, E. Keravnou // ACM Digital Library. – 2002. – P. 272–276. – Available at: http://dl.acm.org/citation.cfm?id=708464
17. Blincov, V. S. Keruvannja prostorovym ruhom pidvodnogo aparata z urahuvannjam vzajemozv'jazkiv mizh skladovymy ruhu po riznym osjam koordynat [Text]: nauk.-tehn. konf. / V. S. Blincov // Innovacii' v sudnobuduvanni ta okeanotehnici. – Mykolai'v: NUK, 2010. – P. 406–408.
18. Boguslavs'kyj, A. B. Planuvannja ruhiv intelektual'nyh robotiv na osnovi tehnologii' ekspertnyh system [Text] / A. B. Boguslavs'kyj, V. M. Lohin, S. V. Man'ko // Teoretychni i prykladni problemy modeljuvannja predmetnyh oblastej v systemah baz danyh ta znan'. – Kyiv: Concept Ltd, 1994. – P. 21–25.
19. Boguslavs'kyj, A. B. Formuvannja znan' dlja planuvannja ruhiv robotiv v seredovyshhi z pereshkodamy na osnovi tehnologii' ekspertnyh system [Text] / A. B. Boguslavs'kyj, V. M. Lohin, S. V. Man'ko // Shtuchnyj intelekt v systemah avtomatychnogo keruvannja. – Kyiv: Concept Ltd, 1995. – P. 12–23.
20. Boguslavs'kyj, A. B. Planuvannja cilesprjamovanyh ruhiv manipuljacijnyh robotiv [Text] / A. B. Boguslavs'kyj, S. V. Man'ko, S. A. Peresleni // Pytannja upravlinnja v skladnyh tehnichnyh systemah. – Moscow: MIREA, 1992. – P. 79–87.
21. Kondratenko, Y. P. Decision-Making Based on Fuzzy Estimation of Quality Level for Cargo Delivery [Text] / Y. P. Kondratenko, I. V. Sidenko // Studies in Fuzziness and Soft Computing. – 2014. – P. 341–344. doi: 10.1007/978-3-319-06323-2_21
22. Kondratenko, Y. P. Distributed computer system for monitoring and control of thermoacoustic processes [Text] / Y. P. Kondratenko, V. V. Korobko, O. V. Korobko // IEEE 7th International Conference on Intelligent Data Acquisition and Advanced Computing Systems (IDAACS). – 2013. doi: 10.1109/idaacs.2013.6662682
23. Kondratenko, Y. P. Slip displacement sensors for intelligent robots: Solutions and models [Text] / Y. P. Kondratenko, L. P. Klymenko, V. Y. Kondratenko, G. V. Kondratenko, E. A. Shvets // IEEE 7th International Conference on Intelligent Data Acquisition and Advanced Computing Systems (IDAACS). – 2013. doi: 10.1109/idaacs.2013.6663050
24. Nahavndi, S. A Dynamic Decision Making System For Manufacturing Control [Text] / S. Nahavndi, H. Abachi, M. Abdollahian // First Conference on systems Thinking in Management. – 2000. – P. 475–480.
25. Mikstiene, R. Legal decision support system application possibility in corporate governance [Text] / R. Mikstiene, V. Kersuliene // 9th International Scientific Conference "Business and Management 2016". – 2016. doi: 10.3846/bm.2016.39
26. Mansoul, A. A Hybrid Decision Support System: Application On Healthcare [Electronic resource] / A. Mansoul, B. Atmani, S. Benbelkacem // Available at: https://arxiv.org/ftp/arxiv/papers/1311/1311.4086.pdf
27. Rogachov, G. M. Produkcionnyj metod opisanija, analiza i sinteza avtomaticheskih reguljatorov nepreryvno-diskretnyh sistem upravlenija [Text] / R. M. Rogachov // Elektronnij zhurnal Cloud of Science. – 2014. – Vol. 1, Issue 1. – P. 17–40. – Available at: https://cloudofscience.ru/sites/default/files/pdf/CloudOfScience01011740.pdf
28. Kovalenko, V. I. Analiz i systematyzacija modelej i metodiv pryjnjattja rishen' [Text] / V. I. Kovalenko // Visnyk HNTU. – 2005. – Issue 1. – P. 25–30.
29. Trunov, O. M. Methodology of evaluation alternatives on the basis several etalons [Text] / O. M. Trunov // Naukovi praci. – 2014. – Vol. 237, Issue 225. – P. 99–104.
30. Trunov, O. M. Rozvytok metodiv ocinky efektyvnosti system upravlinnja robotyzovanymy kompleksamy u glybokovodnyh tehnologijah [Text] / O. M. Trunov // Visnyk Hersonskogo nacional'nogo tehnichnogo universyteta. – 2013. – Issue 1 (46). – P. 328–337.