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MODELLING OF CONTROL SYSTEMS IN INFORMATION CONFRONTATION BASED ON THE APPLICATION OF NEUROPHYSIOLOGY, HYPERCOMPLEX NUMBER THEORY, AND CHAOS THEORY

Purpose of the article. *The purpose of this study is to investigate and define the conceptual foundations for an interdisciplinary synthesis of methods based on neurophysiology, cybernetics, and hypercomplex mathematics for the development of universal models of complex control systems in information confrontation. The study further aims to establish, grounded in the theory of hypercomplex dynamical systems and associative-projective structures, a framework for the practical formalisation of complex control system models with multidimensional, non-commutative interactions, enabling an adequate representation of their functioning as objects of information confrontation within a reflexive model of information conflict.*

Research methods. *The study employs methods of systems analysis, neuromorphic modelling, hypercomplex mathematics (in particular, quaternion algebra), chaos theory, and Lyapunov's direct method for stability assessment. The proposed methodological approach enables the formalisation of information-confrontation processes and the stability analysis of complex control systems without the need to solve the complex dynamic equations of motion of unmanned aerial vehicles.*

Research results. *For the first time, a concept for modelling complex control systems under conditions of information conflict is proposed, integrating neurophysiological approaches, hypercomplex number theory, chaos theory, and Lyapunov functions. The approaches to formalising processes of destructive information interaction and decision-making in complex control systems have been improved. The modelling of information confrontation has been further developed through the construction of a generalised model that integrates the interaction between opposing parties with the "cognitive" model of the control system. The effectiveness of the proposed approach is validated through a case study involving the interaction between unmanned aerial vehicle control systems and electronic warfare systems.*

Scientific novelty. *The scientific novelty of this work lies in the formalisation of information warfare processes as a nonlinear dynamic system with elements of chaotic behaviour, within which the influence of destructive factors is interpreted as a diffusive process of information energy degradation. A new approach to modelling complex control systems is proposed, based on a hypercomplex representation of states and neuromorphic associative-projective structures, enabling the integration of cognitive, informational, and technical components within a single formalised model.*

Theoretical and practical significance. *The theoretical contribution lies in developing a unified methodological framework for modelling complex control systems at a high level of abstraction. The practical significance lies in the applicability of the proposed models for assessing the stability of control systems, enhancing the effectiveness of electronic warfare systems, and supporting the development of decision-support systems in cybersecurity and military command and control.*

Keywords: *model, neural network, information warfare, cybersecurity, artificial intelligence, cyber influence, electronic warfare, stability, electronic communications.*

Introduction

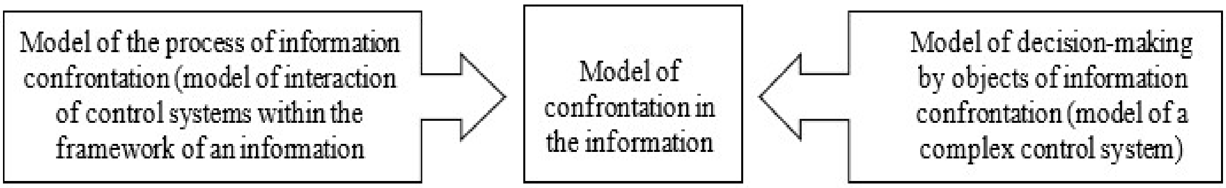
Problem statement. The present moment of time is characterised by intensive development of methodological foundations in the field of formalised description of complex control systems (CCS) in information confrontation (IC), which is caused by the evolution of hybrid wars and conflicts of high intensity of modernity towards rapid informatisation and robotisation of all processes of conducting armed struggle. A tendency has been formed and is becoming dominant, of rapid growth of the need to achieve superiority in the «confrontation for information» in all spheres of struggle for dominance – economic, military, political spheres, etc. This tendency is especially inherent in the sphere of conducting hybrid wars and military conflicts of high intensity, where dominance in the information space has become an integral condition of victory, a vivid example of which is the war of russia in Ukraine. He has caused active research of general-system and organisational problems in such important spheres of struggle for information as electronic warfare and information warfare [1; 2; 3; 4; 5; 6], introduction into practice of information confrontation of a new ideology of development based on the principle of asymmetric adequacy.

One of the priority directions of further research in the defined field is the development of mathematical apparatus and instrumental hardware-software means (complexes) of modelling objects, phenomena and processes of IC.

The model of confrontation in the information space, in the general case, contains two components, as shown in pic. 1:

model of the process of IC (model of interaction of the control system and the destructive influence of the adversary within the information conflict). This model allows for the description of the destructive influences of CCS on each other and actions for protection from such influence. For example, influence on the system of special electronic communications of the state control system by means and assets of EW or cyber influence of the adversary;

model of decision-making by objects of information confrontation (for example, a model of the state control system that describes how CCS «thinks»). This model allows formalising the internal processes of information generation and processing in control bodies, the corresponding destructive influences on these processes, and protection against them.



Picture 1 – The structure of the conflict model in information confrontation

Existing approaches to modelling CCS, taking into account the required level of abstraction of representation and the classes of problems being solved, do not fully make it possible to represent the structure of hierarchical transformation of information in them. This is explained by the fact that the description of any complex system in the form of physical, mathematical, logical, simulation, algorithmic and/or other models and formal descriptions constructed on the basis of any axiomatic theory is characterised by *fundamentally irreducible incompleteness and unproven consistency.*

The solution of this scientific problem, in the opinion of the authors, lies in the development of new approaches to modelling at a higher level of abstraction of representation, which arise as a result of solving a problem posed in one of the subject domains by methods and approaches from another subject domain. This will make it possible to represent in a generalised way the modes of functioning of real CCS, and, from unified positions, to identify and describe the mechanisms of their behaviour as participants in information confrontation.

Literature Review. Contemporary research in the field of modelling complex control systems under conditions of information confrontation is characterised by a multidisciplinary approach that integrates methods of cybersecurity, control theory, artificial intelligence, nonlinear dynamics, and digital information technologies.

In the works of Ukrainian scholars, considerable attention is devoted to the formalisation of information influence processes and the evaluation of the effectiveness of information operations. In particular, study [1] proposes models for the implementation and assessment of information operations, enabling the structuring of information confrontation as a research object. Study [2] addresses the modelling of psychological influence considering neuropsychological processes, thereby extending traditional approaches to information security through the inclusion of a cognitive component. Work [3] focuses on modelling the monitoring of the cognitive information space, which is essential for ensuring situational awareness and detecting destructive information influences in real time.

A significant contribution to the study of the security of complex technical systems is presented in [4], where approaches to the protection of cyber-physical systems are systematised, including classes of threats, vulnerabilities, and countermeasures. This allows complex control systems to be considered as integrated cyber-physical entities sensitive to multi-level impacts.

The theoretical foundation for modelling complex systems is formed by the principles of nonlinear dynamics and chaos theory, as described in [5]. These principles enable the description of unstable operating modes, critical transitions, and self-organization effects in complex dynamic systems. Additionally, modern approaches to neural network applications, particularly complex-valued neural networks [6], expand the capabilities for modelling multidimensional processes and hidden dependencies in complex control systems.

A separate research direction is associated with swarm systems and cooperative multi-agent control. Study [7] analyses the structure of swarm systems and interaction challenges, while [8] generalises modern approaches to cooperative control of unmanned aerial vehicle formations, including coordination algorithms, distributed decision-making, and ensuring the robustness of these complex distributed dynamic systems.

Significant progress has also been achieved in intelligent data analysis methods for cybersecurity tasks. Study [9] provides a comparative analysis of deep learning approaches for intrusion detection, confirming the effectiveness of machine learning techniques in processing large volumes of security events and detecting anomalies.

A promising direction is the application of the digital twin concept in the domain of information confrontation and cybersecurity [10]. The implementation of this approach enables the integration of real systems with their virtual counterparts for behaviour prediction, risk assessment, optimisation, and adaptive control to enhance overall system effectiveness.

Thus, the review of contemporary research demonstrates active development in several areas, including modelling of information influences, cyber-physical security, intelligent data analysis, multi-agent systems, and digital twins.

Despite the significant number of scientific works devoted to individual aspects of modelling complex dynamic systems, a number of unresolved scientific and applied problems remain.

First, existing approaches to modelling information confrontation [1–3] are mostly focused on individual components of influence (informational or cognitive) without integrating them into a unified formalised control system model.

Second, cyber-physical security models [4] do not fully account for the dynamic nature of information influences and their interaction with control processes in real time.

Third, theoretical approaches of nonlinear dynamics [5] and neural network modelling [6] are typically applied in isolation, without integration into applied security management systems.

Fourth, research results in the fields of swarm systems [7; 8] and machine learning methods for cybersecurity [9] are not sufficiently adapted to the management of complex information systems under destructive influences in information confrontation.

Fifth, although the digital twin concept [10] demonstrates significant potential, its application to security event management requires further formalisation, particularly in terms of integration with decision-making models, threat prediction, and adaptive response mechanisms.

Therefore, the above indicates that a pressing (relevant) scientific and applied problem is the development of an integrated approach to modelling complex control systems that combines nonlinear dynamics methods, intelligent data analysis, cognitive modelling, and digital twin technologies within a unified security event management framework.

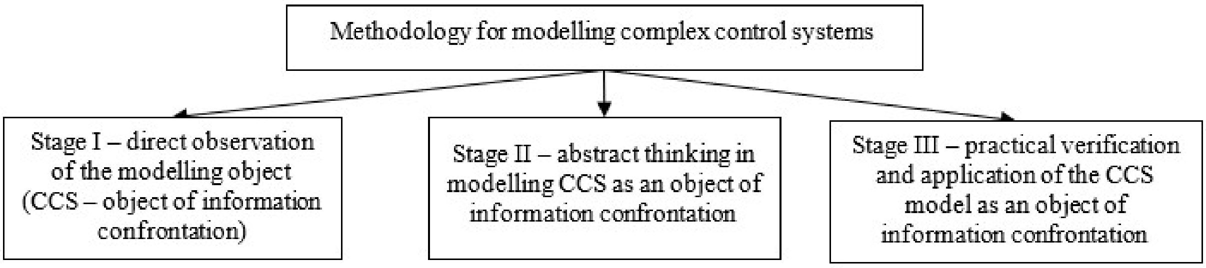
The purpose of the article is research and determination of conceptual foundations for interdisciplinary synthesis on the basis of methods of neurophysiology, cybernetics and hypercomplex mathematics of methods of development of universal models of *complex control systems* in information confrontation.

Determination on the basis of provisions of the theory of hypercomplex dynamic systems and associative-projective structures for practical formalisation of models of *complex control systems* with multidimensional, non-commutative interactions for description of the essence of their functioning as objects of IC within the framework of the reflexive model of information conflict

Research Results

Let CCS X in IC be modelled, in which the adversary applies measures and complexes (means) of destructive influence on information and electronic warfare. Under CCS we will understand an object of IC that exists in time, is subjected to various types of information and electronic influences, reacts to them by change of its states and has the ability to manifest these reactions in one form or another. CCS X within IC is characterised by nonlinearity, emergence, self-organisation (synergetic of I. Prigogine) and high interconnection. The object's external and internal connections are complex, diverse, multidimensional, nonlinear, and difficult to formalise using statistical methods. The methodology of modelling CCS as an object of IC must include stages known in the theory of cognition, pic. 2.

Let us consider in more detail the first and second stages of modelling. The task of the third stage is a separate complex scientific and technical problem, goes beyond the scope of this article, and ways of its solution will be considered by the authors in further research. In works [10; 11] conceptual foundations of modelling of human intelligence are developed and formulated. Generalization of results of into the field of modelling CCS – objects of IC made it possible to formalize CCS in IC as an object with functions of human intelligence [10; 11]. At the same time, the image for modelling CCS – object of IC has the following form, pic.2.



Picture 2 – General steps in the modelling methodology complex control systems – object information confrontation

According to pic.2, it is proposed to represent CCS in IC as a certain object endowed with its own «intelligence», subsystems of control objects and effectors, methods and means of control of a complex system and its interaction with an opposing control system (group CS). Control of CCS is carried out on the basis of operating with models of its states aimed at achieving the required effectiveness of functioning of the system within IC. Let us represent CCS in IC in the form of an interconnected set of subsystems that implement the main functions of CCS within the framework of the neurophysiological concept of brain activity of a human.

The structural-descriptive model (SDM) of CCS – object of IC is presented, pic.3. Let us specify the functional purpose of each of the subsystems of SDM, pic. 3 and the order of their interaction. In particular, in SDM the following subsystems can be distinguished:

Φ – subsystem of development of laws of formation of models of states and strategies of actions of CCS under conditions of information confrontation;

Ψ – subsystem of control bodies (decision-making) about the state of the complex control system;

$\Re$ – subsystem of sensors (receptors), which characterise the state of the system at discrete moments of time. The subsystem contains: sensors that register influences on the system from the external environment $\Re_1$ (information influences on CCS of the opposing side); eceptors of internal influences $\Re_2$ on the state of CCS;

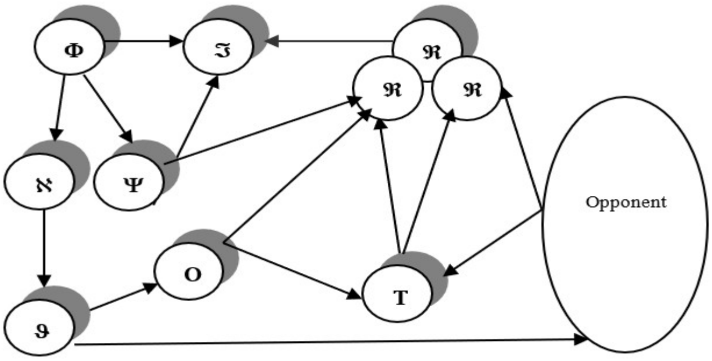
$\Im$ – subsystem of storage of models of a priori known states in which CCS can be during the process of IC;

T – subsystem intended for the transformation of external influences (types of energy), which are not perceived by sensors of the subsystem $\Re$, into those perceived;

O – subsystem of objects (elements) of control in CCS;

$\aleph$ executive subsystem, which forms, according to the indication of the decision-making subsystem Ψ, control influences on objects of control of CCS and elements of the opposing control system;

ϑ – subsystem that amplifies formed control influences to the level necessary for perception by control objects.



Picture 3 – Structural-descriptive model of a complex control system – an object of information confrontation

The structural-descriptive model, pic.3, by analogy with the model of neuro-brain activity of a human [10; 11] allows determining the procedure of creation of models of current states of CCS – object of IC of any level of state or military, etc. It also classifies and describes, in the language of a feature dictionary for recognition, possible states of CCS in IC.

The feature dictionary is formed on the set of reactions of sensors (receptors) subsystem $\Re$. Subsystem $\Re$ is an analogue of the receptor field of the human brain and determines the order of actions of CCS for each state (forms the set of rules «state – reaction»). Information about the results of formation of the description of the alphabet of classes of system states in the language of the alphabet of features, as well as about the formed set «state – reaction», is transferred to the decision-making subsystem Ψ.

In the decision-making subsystem Ψ, based on the obtained description of the current state of the system in the language of features subsystem $\Re$, a control influence is formed. his influence activates one of the models in the memory subsystem $\Im$, inhibiting (reducing the level of activity) of the others. As a result of the competition of activity of models, recognition of the current state of CCS under conditions of IC is carried out. Subsystem Ψ performs functions analogous to the system of excitation–

inhibition (SEI) of network intelligence [10].

Subsystem ℑ is a «storage» of a priori known states of the control system and can be identified with human memory. Models of new states of the system, created during the process of learning of CCS, are also placed in this subsystem. Coordination and amplification of external types of energy to the level of perception by sensors (receptors) is carried out by the corresponding subsystem T.

On the basis of the recognised current state of CCS, a command is issued to the subsystem 3 executive bodies ℵ, which forms influences on control objects of CCS (subsystem O) or elements of the opposing control system (group CS). The formed types of influence are amplified in the amplification subsystem ϑ to the required level. The set of connections between elements of SDM constitutes the information-communicative environment of CCS, which, in essence, is an analogue of the human nervous system.

For achieving the required unity of understanding of obtained results, let us formulate for CCS, presented at pic.3, and SDM.

Intelligence of CCS – a set of means and control bodies of CCS based on recognition of models of their current states in order to achieve the required effectiveness of their functioning within IC. Structurally, the intelligence of CCS includes the corresponding subsystems Ψ, Φ, ℑ , ℜ and the information-communicative environment Ψ and describes the model of interaction of the complex system with the opposing side.

Subconsciousness of CCS – the process of interaction of models of the memory subsystem ℑ, hat are weakened (inhibited) by the influence of the decision-making subsystem Ψ. Provides preparation of models for their transition into the area of consciousness of CCS and performs the formation of images for recognition of the current state of the system.

Thinking of CCS – the process of competitive struggle of active models in the process of decision-making, which is determined under control of the corresponding subsystems Ψ and Φ.

Idea of CCS – a model of the memory subsystem ℑ, strengthened by a control signal of the decision-making subsystem at a given moment of time.

The structural-descriptive model, pic. 3, can be concretised in relation to any complex control system in an information conflict at any level of abstraction. For this, it is necessary to fill each component of SDM with specific content, pic.3, CCS. Interconnections between subsystems SDM are described within the framework of the model of the information-communicative environment CCS. At the same time, models of a lower level of abstraction are the «building material» for the development of more general models SGU. Elements of each level are systems of the previous level of abstraction, in which properties of a higher-level system are already embedded.

A practical consequence of the application of the proposed approach was the possibility to formulate conceptual conditions of non-fulfilment by CCS of tasks according to their purpose (conditions of control disorganisation) under conditions of information confrontation using basic axioms of artificial intelligence:

axiom of resource. The intelligence of CCS functions only in the presence of a sufficient energy flow in the system. Energy $E(t)$ must always be greater than zero;

axiom of consistency. The intelligence of CCS can make correct decisions only under the condition of absence of internal contradictions in data. When making a decision in CCS, the same data (statements) cannot simultaneously be true and false;

Axiom of hierarchy of goals. The intelligence of CCS can act correctly if a uniquely defined priority goal (motivation of CCS intelligence) is determined. Motivation $M(t)$ must be either 0 or 1;

Axiom of synchronisation. The intelligence of CCS can make correct decisions only within the limits of a critical time interval for the fulfilment of the condition of operability. The delay Δt of decision-making by the intelligence of CCS must not exceed a critical value τ .

The proposed concept of modelling CCS in IC allows formalising CCS not simply as a hierarchy of orders and reporting documents that are operationally executed by subordinates, but as a substance that possesses «intelligence».

The intelligence of CCS is «fed» by four processes, random in the general understanding – energy $E(t)$, information $I(t)$, goal (will, motivation) $M(t)$ and time. It is required that the value of each process is normalised within the limits from 0 to 1. Such representation allows forming a generalized indicator of evaluation of effectiveness of control disorganization *D* the intelligence of CCS performs its functions only when the value of each of the listed processes exceeds a certain (for example, experimentally, through expert assessment, etc.) threshold value. For example, – 0.4 for energy, 0.4 for consistency of data, 0.5 for clarity of goal (motivation) and 0.6 for reaction rhythm. Let us call these indicators partial conditions of correct thinking of CCS. Then the intelligence of CCS performs its tasks (CCS thinks correctly) if and only if the conjunctive form of conditions of correct thinking of CCS has the value «TRUTH».

$$E(t) > E_{\min} \wedge I(t) > I_{\min} \wedge M(t) > M_{\min} \wedge T(t) > T_{\min} l , \tag{1}$$

where $E_{\min}, I_{\min}, M_{\min}, T_{\min}$ – threshold values of partial conditions are defined, reduction below which leads to impossibility of making correct decisions by the «intelligence» of CCS in IC.

$$D(t) \Leftrightarrow E < 0.4 V I < 0.4 M < 0.5 V T < 0.6 , \tag{2}$$

where $D(t)$ – A function of possibility of making correct decisions by CCS in IC.

Then it is possible to write a generalised criterion of «shutdown of intelligence» (generalised numerical criterion of control disorganisation) of CCS in information conflict in the following form:

$$D(t)=\begin{cases} 1, & E+I+M+T \geq 2.5(\text{action}) \\ 0, & E+I+M+T < 1.9(\text{paralysis}) \\ \text{undefined}, & 1.9 < E+I+M+T < 2.5(\text{chaos}) \end{cases} \qquad (3)$$

Application of expressions (1) – (3) allows formulating a general strategy of control disorganisation of the adversary in IC, such that in the control system of troops of the adversary, correct decisions are not made, that is, CCS enters a state of «intelligence shutdown». For this it is necessary artificially to achieve violation of one or several basic conditions of normal functioning of the neural network of the «brain» of CCS (1), (2).

Application of the proposed concept in practice allows modelling control systems of troops (forces) and weapons as a deep neural network, where each unit – is a layer of neurons, the headquarters – is an output classifier. Then «intelligence shutdown» (disorganization) of CCS based on AI – is a gradient collapse (or vanishing gradient) – this is a problem that arises during training of deep neural networks using gradient descent. It consists of the fact that gradients (derivatives of the loss function with respect to parameters of the model) become very small during propagation backwards through layers of the network.

This leads to the fact that weights in initial layers are updated very slowly or do not change at all, which complicates or makes impossible the training of deep models. In such a situation, CCS based on AI loses the ability to update weights of connections and make correct decisions and forecasts. Such an approach is a direction that ensures disruption of the functioning of artificial intelligence integrated into CCS, for example, CCS troops (weapons) equipped with integrated AI.

For software implementation of association-forming applications, associative-projective neuromorphic networks (APNmN) are used. In modelling of objects using such NmN formation of associations can be solved on the basis of the formation of NmN of connections and associations due to the intersection of subsets of neurons that are part of concepts [12; 13].

Neural networks that model the functioning of CCS as an object of IC must have a hierarchical associative structure, at each hierarchical level neurons are connected with each other by associative connections, forming neural ensembles (NE), and between levels connections are projective, the characteristics of which do not change during the functioning of the network. Such structures are known as associative-projective (AP-structures). The basis of hardware implementation of such APNmN-structures are AP-neurocomputers [12].

APNmN-structure, which formalises the structural-descriptive model of CCS, contains the following components:

input neural fields (implement subsystems of SDM of the complex control system). In them, ensembles are formed that correspond to different features (feature-ensembles) of situations and states of components and of CCS as a whole;

a block of formation of associative description of each feature and a «dictionary of neural ensembles-features» for recognition of situations and states, which are transmitted to the ensemble block;

a block of ensembles corresponding to combinations of elementary actions of opposing control systems on the basis of data from different receptors;

a block of recognition of situations of interaction;

a block of formation of images of situations and information relations;

a block of formation of ensembles corresponding to the main «concepts» that describe current states of the modelled CCS in the process of IC;

a block of higher levels, in which the behaviour of CCS in one or another state is described;

output neural fields (implement subsystems of SDM of CCS), which form ensembles corresponding to different sets of actions (reactions) of CCS determined by the results of recognition of its state. Within each sphere, neural ensembles are formed due to the existence of associative fields with variable synaptic connections between neurons, and exchange of information between spheres is carried out exclusively by means of projective connections that have an unchanged structure and synaptic weights.

Modelling of multidimensional connections between neural fields and multidimensional states of CCS is a separate scientific problem that is not solved in full. For its solution it is proposed to apply the mathematical apparatus of hypercomplex systematics and invariant modelling. This mathematical apparatus is expedient for modelling CCS with multidimensional, nonlinear, and non-commutative interactions, with a synergetic effect, where hypercomplex numbers (in particular, quaternions, octonions, sedenions, etc.) are used to model subsystems of CCS. Within the framework of the mathematical theory of hypercomplex dynamic CCS in IC, systems can be described in the form of decomposition into symmetric and skew-symmetric components, hypercomplex matrices, which gives a model in matrix form and operator form with emphasis on invariant modelling.

Without loss of generality of presentation, let us demonstrate the procedure of formalisation of processes of destructive influence on CCS in IC on an example. In this case, we will focus on the formalisation of the physics of the process of influence of electronic warfare (diffusion coefficient D), which «dissolves» the information energy of the APNN in real time. His approach assumes consideration of the system in a fixed state («instantaneous snapshot»), which makes it possible to evaluate its stability without the need to solve complex dynamic equations of motion.

Problem statement. Let the control system of a grouping of n UAVs in an information conflict in the electromagnetic spectrum be modelled. Each UAV transmits telemetric data about its own coordinates x, y, z and communication state (SNR) to m – control points (CP), which process the data and form commands for correction of routes and targets.

The control system is represented as an associative-projective neuromorphic network, where complex connections between neurons (UAVs and CPs) are described using hypercomplex (quaternion) weight coefficients. Let the modelling time be - t (hours).

A grouping of electronic warfare means, consisting of k units, influences the UAV control system, causing «diffusion degradation» of connectivity between its elements with the purpose of bringing the system into a bifurcation mode and to a complete loss of connectivity. The influence of electronic warfare means is modelled using the mathematical apparatus of hypercomplex systematics and the energy indicators of the stability function, as defined by the Lyapunov method. In such a formulation, it becomes possible to move from a primitive analysis of channel suppression by interference to a topological analysis of stability, in which the influence of electronic warfare can be modelled as diffusion (dissolution) of the Lyapunov function in a quaternion neural network.

It should be noted that it is possible to pose the problem of minimizing the «degradation» of associativity, connectivity, and hierarchy of the UAV control system in order to evaluate the effectiveness of electronic protection measures (the problem of maximizing protection effectiveness), or conversely, the problem of maximizing degradation for the effective use of electronic warfare means (the problem of maximizing EW effectiveness).

What needs to be found? It is necessary to develop a formalised description of the control system of a UAV grouping in information confrontation with an EW grouping as an associative-projective neuromorphic network using the mathematical apparatus of hypercomplex numbers to integrate spatial coordinates and energy parameters of the signal into a unified quaternion space. To formalise the influence of EW means on its properties (associativity, connectivity, hierarchy), modelling the influence of interference as diffusion (dissolution) of the Lyapunov function in a quaternion neural network. To evaluate the effectiveness of the disorganisation of the UAV control system (stability of the APNN) using the second (direct) Lyapunov method.

Solution of the problem. Let the complex control system of a grouping of n UAVs be considered as a neuromorphic structure, where each UAV is an active neuron, and the control point (CP) — is a processor of aggregation and decision-making. At the same time, the main principles of construction of the model are:

Implementation of the APNN concept in the control system model. Modelling of the control system as an APNmN structure is implemented through three fundamental principles:

1. Neuron as a projective processor. Each UAV in the model does not simply transmit data, but is a neuron-node of the APNN. The control point performs the role of an axonal field, where aggregation of states takes place. Mathematically, this is taken into account in that the output signal y_{res} is the result of the projection of the input state vector q_i onto the weight space w through the Hamilton product:

$$y_{res} = w \otimes q \qquad (4)$$

This is not linear addition, but precisely a projective transformation, where the phase and amplitude of the signal (SNR) are interdependent.

2. Associativity through quaternion weights. In the associative-projective neuromorphic network, «knowledge» or «stability» of the system is stored in weights w. Associativity here is the ability of the system to restore a correct control command even under noisy coordinates. In our model, this is taken into account through the components of the weight $w = w_0 + w_1 i + w_2 j + w_3 k$. If, under the influence of EW, the norm of the weight $|w|$ decreases below 0.5, associative connections are destroyed, and the neuron (UAV) can no longer «recognize» the command from the control point.

3. Unlike conventional neural networks, where weights are simply numbers, projective connectivity is used in APNN. A connectivity parameter λ_{conn} is introduced, which formalises the «distance» between the ideal state of the control system and the current state under the influence of EW. When multiplying $\lambda_{conn} \otimes w_{base}$, we model how the projection of the signal is distorted in hypercomplex space.

In such a formulation, it is possible to pose the problem of minimising the «degradation» of associativity, connectivity, and hierarchy of the UAV control system for evaluating the effectiveness of electronic protection measures (the problem of maximising protection effectiveness), as well as maximising degradation for effective use of EW means (the problem of maximising EW effectiveness).

The object of research is the control system for a group of n UAVs. The control system is considered as a neuromorphic structure, where each UAV is an active neuron, and the control point b (CS) – is a processor of aggregation and decision-making. The control system continuously resides in one of the functional states: $S_{stable}, S_{degraded}, S_{bifurcation}, S_{failure}$ (state of stable control, degradation, bifurcation, and disorganisation, respectively), depending on the metric of the input information field. The decision on transition between states is made on the basis of an analysis of the norm of resulting quaternion values.

Formalisation of states and functional dynamics of the UAV control system based on quaternions. The object of research is the control system as a neuromorphic structure, where each UAV is an active neuron, and the control point (CP) – is a processor of aggregation. The state of each neuron integrates spatial coordinates and energy into a unified quaternion space:

$$q_i(t) = s_i(t) + x_i(t)i + y_i(t)i + z_i(t)k\ , \qquad (5)$$

where $q_i(t)$ – quaternion of the state of the i-th UAV;

$s_i(t)$ – energy parameter (SNR);

x_i, y_i, z_i – spatial coordinates;

i, j, k – basis vectors of the quaternion basis.

Connections in the APNN structure are described through quaternion weights that reflect the hierarchy of control.

Intra-group connections (UAV–UAV): Model horizontal interaction and coherence of the group, the ability to self-organise. They are described by weights that ensure phase synchronisation between neighbouring UAVs. These connections attempt to maintain the system from collapsing when commands from the control point are lost, ensuring emergent stability of the swarm. In general form w_{ij} in the form of:

A. Intra-group connections (UAV–UAV): The following factors determine the swarm's horizontal stability

$$w_{ij} = C_{group} \cdot \left(w^0 + w^1 i + w^2 j + w^3 k\right) \qquad (6)$$

where C_{group} – group connectivity coefficient;

$w^0 \ldots w^3$ – internal components of the weight that ensure associative recovery of data.

B. Hierarchical connections (UAV–CP): Determine the vertical of control and the possibility of route correction:

$$w_{i,\text{ПУ}}(t) = \lambda_{conn}(t) \otimes w_{base}\ , \qquad (7)$$

where $\lambda_{conn} = a_{link} + b_{phase} i$ – dynamic connectivity parameter, where a – packet integrity, b – phase stability;

w_{base} – base hierarchical setting of the control point;

$\otimes$ – Hamilton product operator modelling nonlinear signal processing $y_{res} = w_{i,\text{ПУ}} \otimes q_i$.

This is a key operation for the model, since it describes how EW interference is «applied» to the UAV signal, changing its phase and coordinates.

Formalisation of destructive EW influence. The influence of EW is formalised as a nonlinear degradation operator $\hat{D}$, that changes the metric of the quaternion space. The influence is realised through:

1. Energy suppression: Dynamic decrease of the scalar component s_i (SNR).

2. Degradation of connectivity: exponential attenuation according λ_{conn} to the law:

$$\left|\lambda_{conn}(t)\right| = \left|\lambda_{conn}(0)\right| \cdot e^{-\gamma \cdot \epsilon(t) \cdot t}\ , \qquad (8)$$

where ϵ – interference intensity;

γ – vulnerability coefficient of the architecture.

General quaternion form of the solution (Hamilton's product). The process of decision-making and signal processing in a conflict environment is reduced to the general form of the Hamilton product:

$$y_{res}(t) = \hat{D} \otimes \left(w_{i,\text{ПУ}}(t) \otimes q_i(t)\right) \qquad (9)$$

Decomposition of components:

Scalar part $\left(y_{scalar}\right)$: Determines the overall confidence of the control system in the received data.

Vector part $\left(y_{vector}\right)$: Contains «vector rotation», caused by the skew-symmetric interference matrix, which leads to disorientation:

$$y_{vector} = w_0 v + s w + \left(w \times v\right) \qquad (10)$$

The vector product $\left(w \times v\right)$ models nonlinear cycles that are destroyed when entering the bifurcation mode.

Formalisation of the dynamics of the information conflict between the UAV control system and the electronic warfare grouping. The dynamics of the conflict can be described by the equation:

$$\frac{dq}{dt} = W \otimes q - D\nabla^2 q\ , \qquad (11)$$

where *D* – diffusion coefficient arising due to destructive EW influence (so-called rate of «dissolution» of the Lyapunov function);

$\frac{dq}{dt}$ – rate of change of the system state under conflict influence;

W – general matrix of weight coefficients APNN-structure;

$\nabla^2 q$ – Laplace operator that formalises dispersion (loss) of information energy in the network topology.

To evaluate stability, the second Lyapunov method is used (the Lyapunov function method or the energy function method):

$$V(q) = \frac{1}{2}\left\|q(t)\right\|^2\ , \qquad (12)$$

where $V(q)$ – Lyapunov scalar function, which expresses the overall «information energy» CS;

$\left\|q(t)\right\|$ – quaternion norm (the square root of the sum of the squares of all its components s, x, y, z);

$\dot{V}(q)$ – time derivative. If due to diffusion *D* value $\dot{V}(q) > 0$, the system loses stability energy.

Formalisation of functional states and dynamics of the associative-projective neuromorphic system that describes the UAV control system in information confrontation over time. Stability metrics. Without loss of generality of the presentation, in this example, we will focus on the formalisation of the physics of the process of influence of electronic warfare (diffusion coefficient D), which «dissolves» the information energy of the associative-projective neuromorphic network in real time. This approach assumes consideration of the system in a fixed state («instantaneous snapshot»), allowing evaluation of its stability without solving complex dynamic equations of motion.

The transition between functional states of the UAV control system in conflict with an EW grouping (from stable control to disorganisation) is determined by the metric of the resulting norm $\left\|y_{res}\right\|$, which is the Euclidean norm (or modulus) of the resulting quaternion $\left\|y_{res}\right\|$, and acts as a scalar measure of topological integrity and energy stability of the control system.

Since $\|y_{res}\|$ it is the result of the Hamilton product of the state quaternion q on the weight coefficient ω, it is itself a quaternion, and therefore the resulting norm $\|y_{res}\|$ is defined as the square root of the sum of squares of all its components:

$$\|y_{res}\| = \sqrt{S_{res}^2 + X_{res}^2 + Y_{res}^2 + Z_{res}^2} \ . \qquad (13)$$

Within the framework of the direct Lyapunov method, the resulting norm is an indicator of the «distance» of the system from the state of chaos. n essence, the norm reflects the amplitude of a coherent signal that has passed through hierarchical filters of the associative-projective neuromorphic structure and integrates both the quality of the communication channel $\left(a_{link}\ \text{та}\ b_{phase}\right)$ and group stability $\left(C_{group}\right)$, look (14).

The critical threshold is a certain value $\|y_{res}\| = 0.5$. This is the point of maximum entropy in the associative-projective neuromorphic structure. When this value is reached, the diffusion energy of EW completely neutralises hierarchical connections. From the point of view of mathematical statistics and information theory in hypercomplex spaces, at this point $\|y_{res}\| = 0.5$ the entropy of the system reaches a maximum. This means that the useful signal becomes indistinguishable from the diffusion interference of EW. his condition determines the radius of a sphere in quaternion space, beyond which the system retains the property of associativity. When crossing this threshold «inward», the Lyapunov function $V(q)$ loses its definiteness, and the system «breaks down» into a strange attractor of chaos.

The system passes through a bifurcation point – the control phase trajectory «breaks away» from the stable attractor and enters the region of action of a strange attractor of chaos. In this state, UAVs lose the ability to coordinate actions, which means complete loss of connectivity and disorganisation of the grouping.

The introduction of the diffusion influence of EW $\left(D\nabla^2 q\right)$ makes it possible to model the process of degradation of both types of connections. In this formulation, EW influence is considered as a gradual «dissolution» of the values of weights w_{ij} and W_H.

1. Initial phase: EW attacks vertical connections (W_H). The system transitions to a state of degradation $\left(S_{degraded}\right)$, but retains stability due to intra-group connections $\left(w_{ij}\right)$. The Lyapunov derivative $\dot{V}(q)$ fluctuates near zero.

2. Critical diffusion phase: When interference begins to dissolve horizontal UAV–UAV connections, emergence disappears. This leads to a sharp drop in the norm of the resulting signal.

3. Bifurcation point $(\|y_{res}\| = 0.5)$: This is the moment when diffusion of EW completely annihilates hierarchical and intra-group connectivity. The system energy $V(q)$ becomes uncontrollable $\left(\dot{V} > 0\right)$, and the grouping disintegrates into isolated elements that fall into a chaotic attractor.

The defined provisions make it possible to form stability metrics of the UAV control system under the influence of an electronic warfare grouping.

The resulting norm serves as a threshold indicator for transitions between states:

1) $\|y_{res}\| > 0.8$: Stable control state $\left(S_{stable}\right)$;

2) $0.5 < \|y_{res}\| \le 0.8$: Degradation state $\left(S_{degraded}\right)$; beginning of diffusion dissolution.

3) $\|y_{res}\| = 0.5$: Bifurcation point $\left(S_{bifurcation}\right)$;

4) $\|y_{res}\| < 0.5$: State of complete disorganization $\left(S_{failure}\right)$.

Dynamic model of degradation of the control system. Quaternion differential equation. To describe continuous change of the system state under the influence of EW, the dynamics of the state vector $q_i(t)$ s are represented in the form of a first-order quaternion differential equation:

$$\frac{dq_i(t)}{dt} = W_{APNM}(t) \otimes q_i(t) + \hat{D}(\epsilon, t), \qquad (14)$$

where $\frac{dq_i(t)}{dt}$ – rate of change of the intellectual state of the control system (change of SNR and spatial coordinates over time);

$W_{APNM}(t) \otimes q_i(t)$ – operator of the APNN, that describes the internal logic of the system, where W_{APNM} – the matrix of quaternion weights determines the ability of the network to self-recovery and associative thinking. The Hamilton product $(\otimes)$ ensures accounting of nonlinear connections between UAVs;

$\hat{D}(\epsilon, t)$ – operator of destructive influence, quaternion function of EW interference, which distorts the trajectory.

Analysis of system stability and transition to bifurcation. The use of the differential form allows applying the direct Lyapunov method for CS stability analysis. The system state is considered stable $\left(S_{stable}\right)$, as long as the energy function of the system (the quaternion norm $|q_i|$) satisfies the stability condition.

As soon as the intensity of EW reaches a critical value, the right-hand side of the equation becomes such that the eigenvalues of the system move into the right half-plane. This is the moment of bifurcation ($t = 2$ in our example), when the solution becomes chaotic.

Formalisation of the logic of decision-making through dynamics. The control system makes a decision about changing the functional state by analysing the rate of degradation $\frac{dq}{dt}$:

if $\left|\frac{dq}{dt}\right| < \delta$ – the system manages to adapt $\left(S_{degraded}\right)$ \$;

if $\left|\frac{dq}{dt}\right| > \delta_{crit}$ – the rate of destruction of connections exceeds the rate of recovery, the control system switches to the mode of autonomous survival $\left(S_{bifurcation}\right)$.

For visualisation of stability processes, an energy plane is used, where condition CS – is a ball moving on a surface, and attractors are bowls (zones of stability).

In the stable state $\left(S_{stable}\right)$ the ball is located at the bottom of a deep bowl «mission execution». Even under disturbances (interference), it returns to the centre due to high walls (associativity and hierarchy). The Lyapunov function $V(q)$ describes the depth of this bowl. The derivative $\dot{V}(q) \le 0$ indicates that the ball is still rolling toward the center. If $\dot{V}(q) > 0$, stability is lost, the walls disappear and the ball moves uncontrollably. EW acts as a process of «smoothing» the landscape. Diffusion D begins to «level» the basin, making it shallower.

Thus, the application of the APNmN – approach made it possible to identify the bifurcation point of the UAV control system under EW conflict. In conventional systems, degradation appears linear, whereas in APNmN, due to the non-commutativity of quaternions, a sharp «breakdown» (bifurcation) is observed upon reaching a critical threshold corresponding $\left|q_{r,i}\right| < 0.1$, to the neurophysiological principle of «all-or-nothing». At the same time, «APNmN – structure» describes interaction of UAVs and control points not as a set of robots, but as a unified intelligent network.

At a certain level of interference (D) the derivative of the Lyapunov function becomes positive. This indicates that even with fixed coordinates, the system loses structural integrity and stability. Such an analysis became possible precisely through the introduction and combination of a quaternion description of UAV states and a description of the control system as a neuromorphic structure, where stability is determined by the architecture's ability to withstand diffusion-induced degradation from electronic warfare at a given moment in time.

Conclusions

The obtained results do not contradict the well-known approaches to modelling control systems within the framework of neuromorphic cybernetics and make it possible to develop universal formalised descriptions that model the modes of functioning of real control systems of any level of complexity, and, from unified positions, to identify and analyse the mechanisms of their behaviour within the framework of various studies. The limits of applicability of the proposed approach extend far beyond the issues of modelling information confrontation. The interpretation of the neurophysiological concept of human brain activity, in combination with the theory of hypercomplex numbers and the Lyapunov stability function applied to the modelling of complex control systems, is a way to overcome the hypothesis of computational irreducibility proposed by S. Wolfram.

Prospects and directions for further work. The proposed approach creates a methodological basis for the development of models of control systems at a high level of abstraction under conditions of various destructive influences on information and channels of its transmission. At the same time, for a visual description of the stability processes of complex control systems, an energy plane is used, where the state of the system is represented as a ball moving over a surface, and attractors are represented as bowls (deep zones of stability).

The obtained practical results are focused on the formalisation of the physics of the process of influence of electronic warfare (diffusion coefficient D) on control stability based on the direct Lyapunov method. For the first time, the process of EW influence is formalised as a process that «dissolves» the information energy of the APNN in real time. At the same time, the complex control system was considered in a fixed state («instantaneous snapshot»), which made it possible to evaluate its stability without the need to solve complex dynamic equations of motion. Thus, the direction of further research should be the study of the stability of complex control systems under EW influence in dynamics with inertia, as well as its evaluation using the Lyapunov–Krasovskii functional that accounts for the accumulated influence of the past.

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Use of artificial intelligence (AI). This article draws only partially on certain theoretical concepts describing specific aspects of artificial intelligence to outline the fundamental principles of potential approaches to neuromorphic modelling of complex control systems in information warfare. Generative artificial intelligence systems were not used to obtain scientific results in this research paper. Artificial intelligence tools were used solely to assist in the search for literary sources and to partially edit and structure the text. All scientific findings, their interpretation, and conclusions are the sole responsibility of the authors.

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МОДЕЛЮВАННЯ СИСТЕМ УПРАВЛІННЯ В ІНФОРМАЦІЙНОМУ ПРОТИБОРСТВІ НА ОСНОВІ ЗАСТОСУВАННЯ КОНЦЕПЦІЇ НЕЙРОФІЗІОЛОГІЇ, ТЕОРІЙ ГІПЕРКОМПЛЕКСНИХ ЧИСЕЛ ТА ХАОСУ

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Мета статті. *Дослідження та визначення концептуальних основ для міждисциплінарного синтезу на основі методів нейрофізіології, кібернетики та гіперкомплексної математики, методів розроблення універсальних моделей складних систем управління в інформаційному протиборстві. Визначення на основі положень теорії гіперкомплексних динамічних систем та асоціативно-проєктивних структур для практичної формалізації моделей складних систем управління з багатовимірними, некомутативними взаємодіями для опису сутності їх функціонування, як об'єктів інформаційного протиборства в межах рефлексивної моделі інформаційного конфлікту.*

Методи дослідження. *Під час дослідження використано методи системного аналізу, нейроморфного моделювання, гіперкомплексної математики (зокрема, кватерніонної алгебри), теорії хаосу, а також прямий метод Ляпунова для оцінювання стійкості. Запропонований методичний підхід дає змогу формалізувати процеси інформаційного протиборства та здійснювати аналіз стійкості складних систем управління без необхідності розв'язання складних динамічних рівнянь руху безпілотних літальних апаратів.*

Огляд літератури. *У сучасних дослідженнях інформаційного протиборства значна увага приділяється формалізації інформаційних операцій та оцінюванню їх ефективності на основі математичних і ймовірнісних моделей. Окремий напрям становлять роботи, присвячені моделюванню когнітивних і нейропсихологічних процесів сприйняття інформації та аналізу інформаційного середовища. Активно розвиваються підходи до використання автономних технічних систем, зокрема безпілотних платформ, та методів штучного інтелекту для реалізації розподіленого управління і координації. У фундаментальних дослідженнях теорії складних систем і динаміки управління (зокрема, на основі підходів Ляпунова) закладено основи аналізу стійкості та поведінки складних систем. Водночас існуючі підходи здебільшого не враховують комплексну взаємодію когнітивних, інформаційних і технічних компонентів. Це зумовлює необхідність міждисциплінарного синтезу методів на основі нейрофізіології, гіперкомплексної математики та теорії хаосу для адекватного моделювання процесів інформаційного протиборства.*

Отримані результати дослідження. *Уперше запропоновано концепцію моделювання складних систем управління в умовах інформаційного протиборства, що базується на інтеграції нейрофізіологічних підходів, теорії гіперкомплексних чисел, теорії хаосу та функцій Ляпунова. Удосконалено підходи до формалізації процесів деструктивної інформаційної взаємодії та прийняття рішень у складних системах управління. Набуло подальшого розвитку моделювання інформаційного протиборства шляхом побудови узагальненої моделі, що поєднує модель взаємодії протиборчих сторін і модель «мислення» системи управління. Ефективність підходу підтверджено на прикладі взаємодії систем управління безпілотних літальних апаратів та засобів радіоелектронної боротьби*

Елементи наукової новизни. *Наукова новизна роботи полягає у формалізації процесів інформаційного протиборства як нелінійної динамічної системи з елементами хаотичної поведінки, у межах якої вплив* *деструктивних факторів інтерпретується як дифузійний процес деградації інформаційної енергії. Запропоновано новий підхід до моделювання складних систем управління на основі гіперкомплексного представлення станів та нейроморфних асоціативно-проєктивних структур, що дозволяє враховувати когнітивні, інформаційні та технічні компоненти в єдиній формалізованій моделі.*

Теоретичне та практичне значення. *Теоретичне значення зводиться до розвитку єдиного методологічного підходу стосовно моделювання складних систем управління на високому рівні абстракції. Практичне значення – можливості застосування запропонованих моделей для оцінювання стійкості систем управління, підвищення ефективності засобів радіоелектронної боротьби, а також розроблення систем підтримки прийняття рішень у сфері кібербезпеки та військового управління.*

Висновки і перспективи подальших досліджень. *Отримані результати узгоджуються з положеннями нейроморфної кібернетики та підтверджують можливість формалізованого моделювання складних систем управління різного рівня складності на єдиній методологічній основі. Запропонований підхід, що поєднує нейрофізіологічні принципи, гіперкомплексні числа та функції Ляпунова, створює універсальну основу для аналізу стійкості систем в умовах деструктивних інформаційних і радіоелектронних впливів. Уперше вплив засобів радіоелектронної боротьби формалізовано як дифузійний процес, що призводить до зниження «інформаційної енергії» системи та дозволяє оцінювати її стійкість у квазістатичному режимі. Перспективи подальших досліджень пов'язані з розвитком динамічних моделей стійкості з урахуванням інерційності процесів та застосуванням функціоналів Ляпунова–Красовського.*

Ключові слова: *модель, нейронна мережа, інформаційна зброя, кібербезпека, штучний інтелект, кібервплив, радіоелектронна боротьба, стійкість управління, електронні комунікації.*

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