NATIONAL ACADEMY OF SCIENCES OF UKRAINE
INTERNATIONAL RESEARCH AND TRAINING CENTER FOR INFORMATION TECHNOLOGIES AND SYSTEMS OF THE NAS OF UKRAINE AND OF MES OF UKRAINE
V.M. GLUSHKOV INSTITUTE OF CYBERNETICS OF THE NAS OF UKRAINE

# Cybernetics and Computer Engineering

3 (205)/2021

SCIENTIFIC JOURNAL ▪ FOUNDED IN 1965 ▪ PUBLISHED 4 TIMES PER YEAR ▪ KYIV

## CONTENTS

NATIONAL ACADEMY OF SCIENCES OF UKRAINE
INTERNATIONAL RESEARCH AND TRAINING CENTER FOR INFORMATION TECHNOLOGIES AND SYSTEMS OF THE NAS OF UKRAINE AND OF MES OF UKRAINE
V.M. GLUSHKOV INSTITUTE OF CYBERNETICS OF THE NAS OF UKRAINE

# Cybernetics and Computer Engineering

3 (205)/2021

SCIENTIFIC JOURNAL ▪ FOUNDED IN 1965 ▪ PUBLISHED 4 TIMES PER YEAR ▪ KYIV

## CONTENTS

НАЦІОНАЛЬНА АКАДЕМІЯ НАУК УКРАЇНИ
МІЖНАРОДНИЙ НАУКОВО-НАВЧАЛЬНИЙ ЦЕНТР
ІНФОРМАЦІЙНИХ ТЕХНОЛОГІЙ ТА СИСТЕМ НАН УКРАЇНИ І МОН УКРАЇНИ
ІНСТИТУТ КІБЕРНЕТИКИ ІМ. В.М. ГЛУШКОВА НАН УКРАЇНИ

# Кібернетика та обчислювальна техніка

3 (205)/2021

НАУКОВИЙ ЖУРНАЛ ▪ ЗАСНОВАНИЙ У 1965 р. ▪ ВИХОДИТЬ 4 РАЗИ НА РІК ▪ КИЇВ

## ЗМІСТ

DOI: https://doi.org/10.15407/kvt205.03.005

UDC 681.3.



**GRITSENKO V.I.[1],** Corresponding Member of NAS of Ukraine,
Director of International Research and Training Center
for Information Technologies and Systems
of the National Academy of Sciences of Ukraine
and Ministry of Education and Science of Ukraine
ORCID: 0000-0003-4813-6153, e-mail: vig@irtc.org.ua
**GLADUN A.Ya.[1],** PhD (Engineering),
Senior Researcher of the Department of Complex Research
of Information Technologies and Systems
ORCID: 0000-0002-4133-8169, e-mail: glanat@yahoo.com
**KHALA K.O.[1],** Researcher of the Department of Complex Research
of Information Technologies and Systems
ORCID: 0000-0002-9477-970X, e-mail: cecerongreat@ukr.net
**MARTÍNEZ-BÉJAR R.[2],** PhD (Informatics),
Professor at the Department of Information and Communication Engineering
and Artificial Intelligence
ORCID: 0000-0002-9677-7396, e-mail: rodrigo@um.es
[1] International Research and Training Center
for Information Technologies and Systems of the National Academy of Sciences
of Ukraine and Ministry of Education and Science of Ukraine
40, Acad. Glushkov av., Kyiv, 03187, Ukraine
[2] University of Murcia
CP 30180 Bullas, Spain


## SEMANTICAL SIMILARITY EVALUATION METHOD OF CONCEPTS FOR COMPARISON OF ONTOLOGIES IN APPLIED PROBLEMS OF ARTIFICIAL INTELLIGENCE


***Introduction.*** *The expediency of reapplication of ontology in applied intelligent information systems (IIS), which are focused on functioning in the open Web environment on the basis of Semantic Web technologies, is substantiated in the work. Features of ontology storage and management platforms and their metadata are analyzed. Possibilities of searching in ontology repositories and their reuse in IIS are considered. The mechanisms of ontology search based on semantic processing of their metadata, analysis of ontology structure using metrics of semantic similarity between their concepts related to the current user task are presented.*

***The purpose*** *of the paper is to develop algorithms and methods for evaluating semantic models, which consist in combining qualitative (ontological) representation of knowledge with quantitative (numerical) evaluation of ontologies and their parameters (semantic proximity, semantic distance, semantic affinity) aimed at finding similarities different ontologies.*

***Methods.*** *Methods of ontological analysis of objects of the subject area, theoretical and multiple approaches to determine the degree of closeness of two objects by comparing their properties (feature matching) and traditional methods of statistical analysis are used to solve the tasks set in the work.*

***Results.*** *The proposed method of estimating semantic similarity allows on the basis of semantic analysis of natural annotations of metadata both ontologies and data (including Big Data) to perform the task of their interpretation and selection to the problem to be solved by the applied IIS or application. The obtained results allow to create original IIS for artificial intelligence in economics, medicine, national security, defense and social sphere.*

***Conclusion.*** *The proposed original approach to the evaluation and analysis of metadata (ontologies, data) is based on semantic analysis of metadata and determining the semantic similarity of structural data models (ontologies, data) and the formation of a ranked set of related ontologies to solve problems of artificial intelligence. The application of methods for defining semantically similar concepts is presented as a tool for semantic comparison of the structure of ontologies, which were found in the repository under formal conditions, with a poorly structured PM-description. At present, there is no generally accepted standard for presenting metadata, so the proposed methods of analysis of PM annotations are the most adequate means of comparing the semantics of ontologies, data with the problems for which they can be used.*

***Keywords:*** *semantic similarity, formal ontology model, metadata, metadata standards, intelligent information system, ontology repository.*

## INTRODUCTION

The construction and implementation of modern intelligent information systems (IIS) based on the formalization and reuse of knowledge is a promising area of research and practical application of artificial intelligence methods. The development of intelligent information technologies (IIT) provides for the creation of a new class of IIS based on a formalized representation of knowledge about the subject area (SA). These new information technologies must be able to analyze the environment based on its figurative perception, by using models of knowledge about its objects, phenomena, processes; obtaining the necessary data to achieve the set tasks; structuring this data into certain categories, allow computer processing of these models for solving applied task.

We suggest to solve the problem of reliability, relevance, persistence of information resources (IR) based on a semantically approach to the analysis of metadata that accompanies the information resources and analytically information processing about these resources. Metadata contains a large amount of information about IR, including significant descriptive textual information, the understanding of which by machines would improve the problem of relevance of the applied information objects (data, ontologies, texts etc.).

Nowaday, a huge number of ontologies have already been created in various SA. These ontologies often use one of the standardized presentation languages (OWL or RDF) that designed for multiple repeated reuse, but they have different complexity, structure and quality [1]. Modern means allow searching for the desired ontology among them only according to some formal parameters (for example, by keywords) and not at the level of their semantics. Therefore, it is quite often easier to create a new ontology than searching and selecting a readymade one, which is extremely inefficient and time-consuming. The solution to such problems could be provided by ontology repository [2], which processes knowledge not of the ontologies themselves, but knowledge of ontologies.

In our work, the interest in creating ontology repositories is related the need to search for ontologies that could be reused to create artificial intelligence applications. Until now, such a search was carried out by users manually, but the ensuring automated generation of estimates of available ontologies, the availability of a single metadata standard for describing ontologies and their processing will greatly facilitate this work and increase the persistence of search and selection. The first step in solving the problem will be the semantic binding of the ontology to a certain SA (or several SA), to assess its depth and structural complexity.

Ontologies and dictionaries are key resources for creating interoperable metadata in the Semantic Web. To simplify and accelerate the task of identifying and use relevant ontologies, we using the idea of ontology repositories, they are formed as ontological systems, which has been currently implemented in many international projects [3]. Ontological systems operate wiht ontology models and form of their repositories .

Today, there is an urgent need to use specialized ontologies repositories of different classes, each of which can be focused on different types of *user needs specifications (user profile)*, *different ontology profiles* selected according to a certain topic and *different requirements of organizations*, as they can not be submitted as a common and unique implementation.

Each ontology repository is a separate information system with its own user interfaces and APIs. Ontologies use dynamically-variable languages such as OWL, OWL2, SKOS (Simple Knowledge Organization System), RDF Schema etc. SKOS provides an easy, intuitively comprehensible standard language for developing and disseminating the new knowledge management systems and transferring them to the Semantic Web. This language can be used separately or in combination with a formal knowledge representation language such as OWL.

Semantic technologies based on logic, databases and the Semantic Web can solve the problem of efficient access to data and integration of data that have been created both today and long ago — for decades and centuries. The international project Open Ontology Repository [4] is an initiative to develop and deploy a new interaction infrastructure, called an open ontology repository (OOR).

In this regard, global search, update and inference in repositories are today a difficult and generally poorly implemented task. As a result, it becomes quite difficult effectivelly search and reuse of existing ontologies. Thus, there is a need for knowledge engineers in the ontology analysis tool to be able to evaluate a particular ontology for reuse.

Using a certain taxonomy, the user iteratively identifies the SA of his interests, and the search is not reduced to rearrangement of keywords, although they are used at the initial stage. If more than one ontology is found for user purposes, their parameters must be evaluated. The values of these parameters are calculated automatically (or automated) for each ontology when it is placed in the repository. In particular, the parameters may be the completeness of the ontology, the number of classes and instances in it, the date of creation, the authors, the confirmation certificate (authenticity) of the knowledge contained in it. The user needs to specify the relative weight of the various criteria.

The lack of mechanisms and standards for storing and presenting ontologies affects the process of recognizing, identifying and accessing ontological resources. Thus, the urgent problem is to create new methods to support efficient access and reuse of ontologies with greater scalability and more reliable infrastructure the so-called *ontology repositories*.

Ontology repositories require additional knowledge of ontologies as metadata, which must also be managed together with the ontologies in the repository. Metadata of ontologies — knowledge that contains information about the possibilities of working with the ontology, a description of the ontology itself, ways of its functioning, structure, methods of knowledge extraction, interaction of components etc.

The purpose of the paper is to develop algorithms and methods for evaluating semantic models, which consist in combining qualitative (ontological) representation of knowledge with quantitative (numerical) evaluation of ontologies and their parameters (semantic similarity, semantic proximity, semantic distance, semantic affinity) and aimed at finding different similarities.

## RESEARCH OBJECTIVE

Modern intellectual applications require the use of external sources of knowledge, which determines the relevance of the problem of searching ontologies. For reusing ontologies from repositories, it is necessary to develop tools for semantizing their search and analysis, which provide a comparison of metadata and ontology structure with the current user's tasks that require knowledge from these ontologies. For this purpose it is proposed to use such standards for presenting of metadata on ontologies, that allow structuring this information, and methods for determining the semantic proximity between concepts as a tool for quantifying the similarity between ontologies and natural description of the user's task.

## BASIC CONCEPTS AND CHARACTERISTICS OF DATA REPOSITORIES AND ONTOLOGIES

In the historical tour, repositories specializing in the preservation of ontologies were developed on the basis of the concept of data warehouses. There are many different values and definitions of data repositories in the literature, so first we will discuss what we will mean by the data warehouse in the future.

The **data repository** is a set of the digital data that is available to one or more entities (or users of systems) for various purposes (training, administrative procedures, research) and has the characteristics offered in [5]:

• the content is placed in the repository by its creator or owner – a third party;

• the repository architecture allows you to manage both content and metadata;

• the repository offers a minimum set of basic services, such as receiving, searching, access control;

• the repository must be stable and reliable, well maintained and well managed.

The term "Data warehouses" became popular in the early 1990s. The purpose of the data warehouse is to analyze the stored data for management decision-making. Data is periodically entered into this data repository, and is usually only added to existing ones. The data repository, however, does not necessarily have to support data warehouse functionality such as analysis.

Like the data repository, there are also many different definitions for the term "knowledge base"(KB). However, in the general case, the knowledge base is a centralized repository of knowledge artifacts. Typically, the KB can use ontologies to formally submit the content and classification schemes, but it can also include unstructured or informal information presented in natural language or procedural code. In addition, unlike the data repository, usually the purpose of the KB is the possibility of automatically deductive inference from the accumulated knowledge.

The Semantic Web community is interested in using repositories to preserve semantic content (for example, ontologies).

Initial projects to organize a base of existing ontologies proposed the creation of library systems that proposed various functions for the managing, adapting and standardizing of ontology groups. These systems are important tools for grouping and reorganizing ontologies for further reuse, integration, maintenance, display and versioning. They defined a model for evaluating the library system based on functionality. Examples of library ontology systems are: WebOnto, Ontolingua, DAML Ontology Library System, SchemaWeb etc. Today, efforts are being made to create ***ontology repositories***. The ontology repository is most similar to the library ontology system defined by [6], but there are some differences.

The term "ontology repository" can be considered as a development of the term, which came from the classical understanding of data repositories [7]. Otherwise, you can rely on the following understanding into the ontology repository and their corresponding control systems.

The ontology repository (OR) is a set of ontologies accompanied by metadata describing individual ontologies and sets of ontologies, their properties and the relationships between them.

Metadata can characterize various aspects of ontologies related to access to ontologies and related to their preservation. The general requirement is that the ontology repository should support the entire ontology lifecycle, from the ontology development process to its use in any intelligent application through specialized tools and tasks. In addition, one of the most important tasks of the ontology repository is the long-term preservation of knowledge.

Ontological KB are a key element of IIS based on Semantic Web. The increase in the number of such applications determines the rapid increase in the number of ontologies that are suitable for use in more than one IIS. In this regard, the problem of organizing effective ontological repositories knowledge bases — ontologies repositories is relevant.

For automatically processing shared knowledge, the consortium *W3C* has developed common standards for their presentation: *RDF (Resource Description Framework) and OWL (Ontology Web Language).*

The basic construction of the *RDF* language is a statement given by the triple <subject> <predicate> <object>. Using *URI* to specify subjects and properties allows to be bind individual statements into complex semantic networks that have a single interpretation in an open environment.

The most common form of saving ontologies is an OWL file. When reading such a file in RAM, a model (set of statements) is created, with which further work is performed. However, this approach has the disadvantages associated with information processing: a significant increase in RAM costs when working with large ontologies due to the full load of the OWL file, as well as a significant increase in loading time of OWL files as the number of ontologies used increases. This does not allow the use of this approach when creating large IIS. An alternative to it is construction of RDF-repositories based on relational databases, which are also designed to store ontological information, but in a different view.

The RDF-repository is an information system designed to store RDF-triplets and execute queries to them. The main functions of the repository are to manage the functions of saving and searching for ontologies in a relational database, provision of a software interface for retrieving knowledge from ontologies stored using the structured query language SPARQL or a special API, and support for the administration of preserved ontologies: adding, deleting, modifying and allocating access rights [8].

Efficient storage must meet the following requirements:

• high productivity — minimization of query execution time;

• minimum memory consumption (disk space) for saving ontologies;

• universality of the approach — the possibility to preserve ontologies of any structure.

There are two basic approaches to the organization of saving ontologies in RDF-repositories:

1) using a single table to store all triplets;

2) mapping the hierarchy of ontological entities (classes, properties, instances) into the RDB scheme.

A feature of another approach is the definition of the DB scheme in accordance with the specific SA, which allows you to optimize the execution of queries. The implementation of this approach for large ontologies involves the creation of a large number of DB tables with complex relationships between them. We present the generalized scheme of RDF-storage as follows (Fig. 1).

The use of RDF repositories is also directly related to the use of metadatafor searching and reusing the ontological knowledge contained in such repositories.

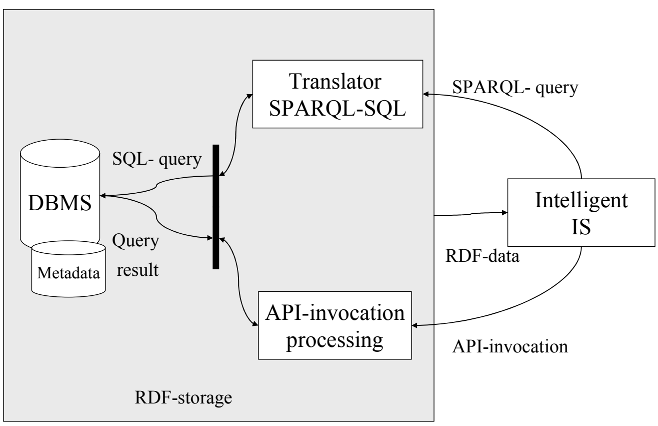



***Fig. 1.*** Generalized *RDF-storage schema*

Metadata is information that makes data useful and should provide access to information [9]. The metadata is defined as structured data that containing the characteristics of the entities they describe for the purposes of their identification, retrieval, evaluation and management of them. Metadata can be used to determine the semantics of information, and therefore to improve its searching and sampling, understanding and using. For example, considers the use of ontologies and thesauruses for semantic annotation of IR and their elements, which is the basis for machine learning and knowledge acquisition from data [10]. Depending on the purposes of annotation, ontologies of different complexity can be applied (from controlled dictionaries and glossaries to ontologies with complex relationship of inversion, non-intersection etc.).

For today in Ukraine, three international standards concerning metadata (ISO 15489-1: 2016 [11], ISO 15836-1: 2017 [12], ISO 15836-2: 2019 [13]) are accepted as national standards by confirmation method [14], [15]. These standards can be applied to display the main properties of Big Data with provision of a common universal language for creating and analyzing metadata, as well as describing the general properties of metadata elements required for basic interoperability between different programming languages and their SA.

For metadata semantic analysis in ontology repositories, we use NL annotations, which are part of the metadata. Semantic processing of metadata information allows to obtain implicit knowledge about the data itself.

## ONTOLOGIES EVALUATION CRITERIA

Many different and alternative criteria can be used to evaluate ontologies. Analysis of the literature on ontological analysis [16, 17] allowed to form a set of the most common criteria for evaluating Web-ontologies in the ontologies repository and principles for creating qualitative ontologies.

Gómez-Pérez [18] introduces two terms of ontology verification and validation to describe the ontology evaluation: ontology verification deals with the creation of a correct ontology, that is, ensures that its definitions implement the correct requirements. Ontology validation refers to the content (values) of the definitions of how real they model the SA for which the ontology was created. Ontology validation is an important part of assessing the quality of an ontology and is usually a way to guarantee the correctness of the knowledge encoded in the ontology.

But most approaches to ontology validation require close collaboration with SA experts and cannot be performed automatically [19].

Other criteria for ontologies evaluating are:

• ***Sequence:*** fixation of both the logical sequence (i.e. no contradictions can be logically deduced) and the sequence between the formal and informal description (i.e. comments and formal correspondence of descriptions);

• ***Completeness:*** all knowledge that is expected to be in the ontology, either explicitly declared or deduced from the ontology;

• ***Brevity:*** when the ontology is free from any unnecessary, useless, or excessive axiom;

• ***Extensibility:*** the ability to add new definitions without changing the already established semantics;

• ***Sensitivity:*** refers to how small changes in the axiom change the semantics of the ontology.

Thomas Gruber identified the following criteria:

• ***Clarity:*** the ontology should effectively provide the meaning of the term being defined. The Definitions must be objective. Sometimes the definition can be established using logical axioms. Wherever possible, the definition should take precedence over the description. All logical objects must be documented in natural language.

• ***Consistency:*** the statements must be correct. At least, certain axioms must be logically consistent. In addition, natural language documentation should be consistent with formal statements.

• ***Extensibility:*** the ontology should cover the conceptual foundation for the range of expected tasks and its presentation should be processed so that everyone, if necessary, could expand and specialize the ontology. At the same time, new terms can be introduced without the need to revise existing axioms.

Other researchers [20] identified the following criteria:

• ***coverage of a specific domain*** and completeness, complexity and level of detail through this coverage;

• ***clarity*** for people (users);

• ***legality and reasonableness***;

• for performing an ontology evaluation, the following should be developed: specific uses, scenarios, requirements, applications and ontology data sources;

• sequence;

• completeness;

• the type of logical conclusions for which they can be used;

• adaptability and reuse for broader purposes;

• display at the top level or other ontologies.

Gangemi [21] defines the following criteria:

• ***Cognitive ergonomics:*** these are the fundamental properties of ontology, thanks to which it can be easily understood and managed;

• ***Transparency:*** properties of the ontology, thanks to which it can be analyzed in detail, with a rich formalization of conceptual sets and motivations;

• ***Computational integrity and efficiency:*** ontology properties, thanks to which it can be successfully/easily processed by a reasoner (reasoner, logical inference mechanism, classifier etc.);

• ***Integrity level mark:*** ontology properties through which it maintains a certain order of criteria that are accepted as qualitative characteristics.

• ***Flexibility:*** ontology properties that allow it to be easily adapted to many applications and evaluations.

• ***Consent to the examination:*** properties of the ontology, due to which it is suitable for use by one or more users;

• ***Consent to the procedures of extension, integration, adaptation etc.:*** ontology properties, thanks to which it can be easily understood and managed for multiple use and adaptation;

• ***Universal availability:*** ontology properties that allow you to easily access it for effective use by the application;

• ***Organizational suitability:*** ontology properties that allow it to be easily deployed within the organization and it has the correct annotation of the context.

For different applications, the importance of these criteria may vary significantly, but it is advisable to provide the values of these criteria in the metadata of the repository ontologies (or at least allow them to be automatically generated formed based on other metadata).

For qualitative evaluation and comparison of ontologies in the repository, it is advisable to use quantitative evaluations of its individual aspects with their subsequent integration. Such aspects of the ontology (applicable in the assessment) are:

• ***Dictionary.*** An ontology dictionary is a set of all names in that ontology, URI, or character constants that denote a data type or identify a language. This aspect deals with the different sets related to the URIs or literals used.

• ***Syntax.*** Web ontologies can be described using many different syntaxes: RDF/XML, OWL etc.

• ***Structure.*** Web ontology is described by an RDF or OWL graph. The ontology structure is a graph. The structure can dramatically change even the semantic description of the same ontology. These differences can be assessed based on this aspect.

• ***Semantics.*** A consistent ontology describes a non-empty, usually infinite set of possible models. The ontology semantics is a general characteristic of all these models. This aspect of semantics determines the distinctive hallmarks (features) of the ontology.

• ***Submission.*** This aspect captures the relationship between structure and semantics. Aspects of representation are typically evaluated by comparing the metrics calculated on a simple RDF or OWL graph with the features of possible models as defined by the ontology.

• ***Context.*** This aspect is about the features of an ontology when compared to other artifacts that may be present, such as an application using ontology, a data source describing ontology, different data representations within an ontology, or formalized ontology requirements in the form of competence questions.

## ONTOLOGY REPOSITORIES CONCEPTUAL STRUCTURE

From a technical point of view, the practical implementations of ontology repositories differ from each other. However, components and services at the conceptual level are reusable for various technical solutions. As a result, consider the conceptual structure for ontology repositories (Fig. 1). Based on the various implementations of ontology repositories [22], it is possible to determine a set of relevant components and services that should be built into a scalable and reliable structure.

The Ontology Repository Management System (ORMS) is a system for storing, organizing, updating and retrieving knowledge from an ontology repository. An example of using such a program is the Generic Ontology Repository Framework (GORF) [23], which contains a special module to support ontology knowledge. GORF is based on the experience gained in the implementation of the ontology repository "Ontology" and ontology metadata vocabulary (OMV). One of the main requirements for ORMS is scalability and the ability to interact with other repositories — for example, using Web-services.

*Table 1.* **Sample for OMV metadata element:**

| ***Name*** | **The name of the metadata element (entity)** |
|---|---|
| *Type* | The type of ontological primitive used to represent an element in OWL: Class, ObjectProperty or DatatypeProperty |
| *Identifier* | The unique identifier used for this element |
| *Occurrence Constraint* | One of the following: required, optional or extensional |
| *Category* | Content-dependent category to which belongs the element |
| *Definition* | A short definition of the goal, which can be described in detail in the comment tags |
| *Domain* | OMV element subject area (for OWL properties) |
| *Range* | OMV entity element rank (for OWL properties) |
| *Cardinality* | OMV element power (MIN: MAX) |
| *OMV version* | The version of OMV in which the element is presented |
| *Comments* | Element's detailed description |

The ontology repository framework includes such conceptual levels:

1. Access to knowledge, according to the concept of the Semantic Web, for people and machines with support for individual views of users and various visualizations to perform personalized queries.

2. Processes and services for processing the knowledge accumulated in the repository, providing analysis of the quality of ontologies, their comparison, evaluation of their adequacy and reliability.

3. Organization of knowledge processing in the repository taking into account the modular approach [24] for reuse and using metamodel based on open standards: metadata, considered as a metamodel, helps to improve the availability and reuse of ontologies and provide useful information about resources to support maintenance.

4. Ontology repository management should support search, view and navigation in the repository with support for content semantics and the use of various specialized ontologies [25].

Creating metadata for ontologies based on standards and metaontologies. Both specialized standards and universal standards for describing metadata can be used for this purpose. An example of a universal standard is Dublin Core, which is used for various types of documents, the use of which is difficult because it does not take into account the specifics of ontologies. An example of a specialized standard is OMV [26], which is the first metadata standard for ontologies and related entities. It is formalized as an OWL ontology. OMV [27] represents metadata model for ontologies that reflects key aspects of ontology metadata information, such as origin and availability (Table 1). Metadata categories are distinguished between the following three limitations of occurrence for metadata elements, according to their impact on the evaluation of reuse of the described ontological content: 1) mandatory — mandatory metadata elements; any missing entries in this category result in an in-complete description of the ontology; 2) additional — important, but not mandatory, facts of metada-ta; 3) advanced — specialized metadata elements that are not considered core part of the metadata schema.

## USING OF SEMANTIC SIMILARITY BETWEEN CONCEPTS FOR ANALYSIS OF METADATA IN ONTOLOGY STORAGE

In order to compare not only the properties of ontologies that related to their quality, validity, scope etc., but also their relevance to a particular user task, it is advisable to the quantitative characteristics of ontology evaluation, namely to compare the semantic component of their metadata with the metadata of the task to be solved or with the metadata of those data whose processing is the user's goal (for example, Big Data metadata). A direct comparison of ontologies will give a more accurate result, but the problem is that:

1) direct comparison of ontologies is a time-consuming and resource-intensive task;

2) in many cases, the purpose of such a comparison is to find the ontology that is most pertinent to the user's task and therefore it is necessary to compare the ontology repositories with a structured or natural (unstructured) description of the task.

Using formal ontology estimates allows you to filter out ontology repositories, among which you search and proceed to the analysis of metadata of these ontologies. Using the same metadata standards to describe tasks, data, and ontologies greatly simplifies the task and compares only semantically related fields.

However, it should be borne in mind that different terms and terminological systems can be used in NL descriptions, and therefore there is a valuation problem the semantic proximity between two independently created NL entities used in metadata.

**Semantic similarity and semantic proximity metrics between the concepts of ontology and their parameters.** Semantic similarity is a special case of semantic proximity. Semantic similarity takes into account only the hierarchical relationships between the elements of the ontology, while semantic proximity allows us to analyze arbitrary relationships in the ontology. Some researchers suggest that the assessment of similarity in semantic networks should be considered involving only taxonomic connections, excluding other types of connections; but the relationships between the parts can also be seen as attributes that influence the definition of similarity. Many similarity criteria have been identified in the scientific literature, but they are rarely accompanied by an independent characterization of the phenomenon they measure: their value lies in their usefulness for a particular task.

*Semantic similarity concepts* (SSCs) is a fuzzy set that includes a set of concepts for which the quantitative value of semantic proximity with the selected concept is above a given threshold [28]. Measures for determining the semantic proximity of concepts based on ontologies use a variety of semantic characteristics of these concepts — their properties (attributes and relationships with other concepts), the mutual position in ontological hierarchies. The complexity of the problem of constructing a set of SPC in an ontology is associated with its poor scaling: the increase in the number of concepts in the ontology and the complexity of its structure significantly increase the search space.

The semantic distance between concepts depends on the length of the shortest path between the vertices and the general specificity of the two vertices. The shorter the path from one node to another, the more semantic similar they are. If there are several paths between the elements, the shortest of them is used. The length of the shortest path in this taxonomy between the corresponding concepts, which is determined by the number of vertices (or edges) in the shortest path between the two corresponding vertices of the taxonomy, taking into account the depth of the taxonomic hierarchy (the smaller length of the path between the vertices, the semantically closer in distance). Unfortunately, uniform distance in taxonomy is difficult to determine and even more difficult to control.

The similarity of concepts is also related to their information content. *Information content* of the concept *c* can be quantified as: $-\log \mathrm{p(c)}$, the higher the concepts in the hierarchy, the lower its informativity. Thus, the higher the level of abstraction of the concept, the less its information content. If there is a unique top concept in a taxonomy, then its information content is 0. One of the key factors in the similarity of the two concepts is the degree to which they share the information specified in the IS-A taxonomy by a highly specific concept that applies to both of these concepts. The edge-counting method takes this into account indirectly, because if the minimum path of IS-A connections between two nodes of a graph is long, it means that it is necessary to rise high in taxonomy to more abstract concepts in order to find the smallest upper bound — the concept to which both concepts are analyzed. Such quantitative characterization of information provides a new way of measuring semantic similarity based on the extensional concepts.

In the process of processing natural language information, there is often a need to measure the similarity of words rather than concepts. Using to represent words from the set *W* through the set of concepts in the taxonomy, which are the meanings (contents) of the word *w*, a function $s(w)$ such that $s: W \rightarrow C$, that is $s(w \in W) = \{c_k \in C,\ k = \overline{1,m}\}$, it can determine

$$sim\_w(w_1, w_2) = max\, sim(c_i, c_j) \text{ where } c_i \in s(w_1),\ c_j \in s(w_2).$$

The similarity of words is evaluated by finding the maximum information content over all concepts for which both words can be an instance. This allows you to create sets of *semantically similarity words* (SSW), that is words whose semantic distance between which is less than the selected threshold value.

Many ontology-based proximity measures are based on Tversky's set-theoretic approach [29], which determines the degree of similarity of two objects by *feature matching*. The similarity measures *S(a, b)* between objects *a* and *b* is a function of the three sets of properties of these objects *A* and *B* — their intersection $A \cap B$ and complements *A–B* and *B–A*. The attributive proximity measures is based on the proximity of the values of common attributes of concepts, whose ranges are literals, numbers, rows and other data types.

Using these proximity measures allows to evaluate the similarity of the values of concept parameters (the properties of data instances of ontology classes), which in semanticized Wiki-resources correspond to the values of semantic properties that are not links to other Wiki-pages.

The analysis of the existing approaches to the quantitative assessment of the semantic similarity of concepts shows the appropriateness of using taxonomies for this purpose and the distance in these taxonomies between the concepts whose similarity is assessed of their common superclass. Taking into account other types of ontological relationships between concepts and comparing their semantic properties allow to refine these estimates in accordance with the specifics of SA. Existing approaches and metrics for assessing semantic similarity, as well as methods of their application to unstructured natural language texts are considered in more detail in [30].

Measures of semantic similarityreflect the semantics of ideas about SA, which is reflected in a certain ontology. Thus, it can be assumed that for ontologies that reflect a similar view of SA, the sets(plurality) of SSC should also be similar. The following approach to searching for ontologies in repositories based on the analysis of their metadata and their structure is based on this assumption.

## METHOD OF SEMANTIC SIMILARITY EVALUATION OF ONTOLOGY TO THE USER'S TASK

For searching a pertinent ontology, it is necessary to solve the problem inverse to the search task using semantic similarity metrics: a set of SSCs is formed for a set of ontologies that have passed the first stage of filtering, and we compare these sets with the NL description of the user task. The criterion of similarity is the number of matches (the number of points by coincidence) of the studied ontology with the description of the current task, i.e. the most pertinent will be the ontology whose SSC contains the most matches with the description of the task. It should be noted that the final choice of the most pertinent ontology should be made by the user who is offered a ranked set of ontologies with the highest scores.

The developed method of evaluation of semantic similarity concepts (semantic closeness of ontology to user request) is aimed at solving the problem of searching for natural language text in ontologies at user's request. It should be noted that the search for ontology is usually performed at the first stage of IIS development, for which you need to find an ontology, which can already determine the basic requirements for ontology – its scope, representation language and expressive complexity (it is important not to use too complex and large ontologies in tasks that do not require it, because it complicates the calculation and increases the processing time), but it is difficult to assess the relative importance of different concepts of SA.

Proposed method of assessing the semantic similarity of ontologies comprises the following main stages.

***Stage I.*** It is to determine the conformity of the basic concepts of the ontology under investigation with the query conditions. At this stage, the set K is formed – a set of keywords that characterize the most important concepts of the SA task. The ontology repository searches for these keywords. Ontologies that do not contain all relevant concepts are not considered further. If no ontology in the repository meets the conditions of the query, you need to use another repository or make changes to the set of K (for example, specify a concept in another language or delete some concepts). If more than one ontology is found, you must proceed to stage II.

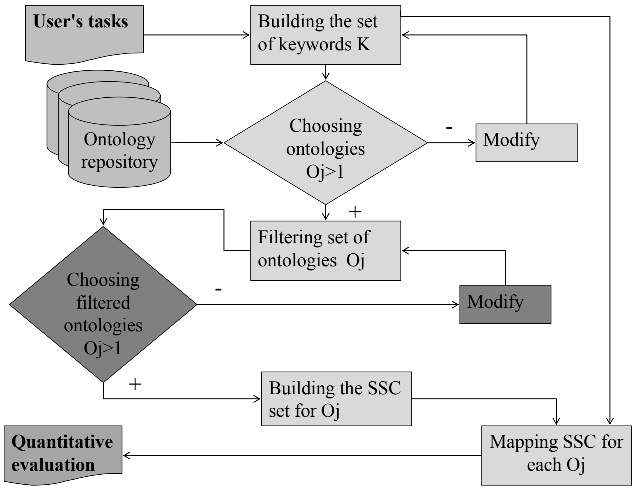



***Fig. 2.*** Algorithm for assessing semantic similarity of the ontology to the problem of artificial intelligence to be solved by the user

***Stage II.*** It is filtering the set of ontologies according to main characteristics. Filtering of a set of ontologies is carried out by volume, presentation language, expressiveness etc. For example, a user can search for taxonomies submitted in OWL 2 that contain between 300 and 1,000 concepts. If no ontology in the repository meets all the selected query conditions, you need to use another repository (filtering is performed in stages I and II, but as a result has different solutions) or weaken the search conditions according to the formal characteristics of the desired ontology. If at this stage more than one ontology is found, then you need to pass to the III stage.

***Stage III.*** It is an assessment of the semantic similarity of the investigated ontology of the user's task description. For each concept $k_i \in K, i = \overline{1,n}$ required in each of the selected ontologies $o_j \in filter(O) \subseteq O, j = \overline{1,m}$ build a set of SSC:

$$t_{i_j} \subseteq T(o_j) \in K, i = \overline{1,n}, j = \overline{1,m},$$

where $t_{i_j}$ is a concept (class or instance of a class) from a non-empty set *T*, taken from *m* terms for an ontology $o_j$ from a non-empty set of selected ontologies of n elements and compare it with NL description of the user's task. Comparison parameters and thresholds for the concept to belong to the SSC are completely determined by the specifics of the task, but these quantitative evaluation are based on the metrics for assessing semantic similarity, analyzed above. Combinatorial methods, linguistic and statistical analysis tools can be used to compare SSC with the task description [31]. The results of comparing individual SSCs for each ontology are summed and normalized (methods and parameters of calculations also depend on the specifics of the task). An algorithm was developed using this method (Fig. 2).

As a result of using this algorithm, each ontology receives a quantitative evaluation of the proximity to the description of the query:

$$x(o_i) = f(s(t_{i_j}, K)), \quad i = \overline{1,n}, \quad j = \overline{1,m},$$

where s($t_i$, $K$) is the result of a comparison $t_i$ from $K$.

Visualization of the described algorithm is given at Fig. 2.

## MODULE FOR SEMANTIC SIMILARITY EVALUATION OF CONCEPTS IN INTELLECTUAL APPLICATIONS OF CYBERSECURITY

Today, the issue of information security (IS) is becoming a cornerstone in the activities of each organization or individual. Information security means the protection of information and the entire organization from intentional or accidental actions that lead to damage to its owners or users.

Cybersecurity is the process of applying security measures to ensure the confidentiality, integrity and availability of data. Cybersecurity protects resources (information, computers, servers, businesses, individuals). Cybersecurity is designed to protect data during its exchange and storage. Such security measures include access control, training, audit and risk assessment, testing, management and authorization security.

Despite the high interest in big data, their analytics for cybersecurity and the availability of various technological means of their storage and processing them, today there are no relevant methods for selecting a pertinent subset of external big data units based on semantic description of metadata suitable for this task. To solve this problem, a module for assessing the semantic similarity of concepts has been proposed, which will be a part of the Cybertrack, the main task of which is to monitor, search and analyze social media on cybersecurity and Big Data technology, in particular, including Elastic Stack components and graph DBMS Neo4j.

The proposed method is implemented in the structure of the module for assessing the semantic similarity of concepts in intellectual applications used to solve information security problems of organizations based on the recognition, selection and interpretation of Big Data units. The module consists of the following units (Fig. 3).

*The unit for forming of an array of researched subjects ontologies*, which provides selection of key features (words) that characterize the most important concepts of SA tasks, and the definition of the corresponding features in the researched technologies.

*The unit for processing the natural description of the user's task*, which provides analysis of the text of the user's task and the formation of a set of keywords (thesaurus) of the task.

*The Big Data and Metadata Repository* is storing external data unit and metadata for their subsequent semantic analysis.

Besides, the analysis is performed at the request of user with the following characteristics: unstructured or weakly structured natural language text, the presence of explicitly or implicitly described SA, input information, processing methods and desired results to be achieved as a result of such processing. Also, the task description in the query may contain references to similar developments and their shortcomings, which need to be eliminated in a new solution of the task. An example of a weakly structured description of the user's task may be a request for the discovery of scientific work, which indicates the thematic direction of scientific research and technical developments, keywords, justification for the feasibility of the work, purpose and objectives, its relevance, tasks solving, experience and refinement authors, structure and stages of work, expected results etc. — use of standardized unit's names allows for better comparison such a description with the metadata of resources and data.

The ontology set filtering unit provides the first stage of selecting relevant ontologies to solved the user's task.

The unit for determining quantitative evaluation of semantic similarity of the investigated ontology of user's task description (selection of ontology closest to the context with user's request). Combinatorial methods, linguistic and statistical analysis tools can be used to compare SSC with the description of the task. The results of comparing individual SSC for each ontology are summarized and normalized by calculation methods and parameters, which also depend on the specifics of the task. Analysis of the semantic similarity of concepts is a cyclical (iterative) task to obtain the greatest semantic similarity).

The module for semantic similarity of concepts assessing works in interaction with external to the module blocks, namely: the repository of ontologies, external repositories of Big Data and metadata.

The development prospects of the proposed method are the formation of means of structuring NL descriptions using background knowledge of the structure of the task/query, but without SA knowledge, because only by performing the above comparison the user gains access to pertinent SA ontologies. If such a search is iterative, knowledge of the ontology that the user wants to replace with a more suitable one for the purpose can be used to search for more pertinent ontologies.

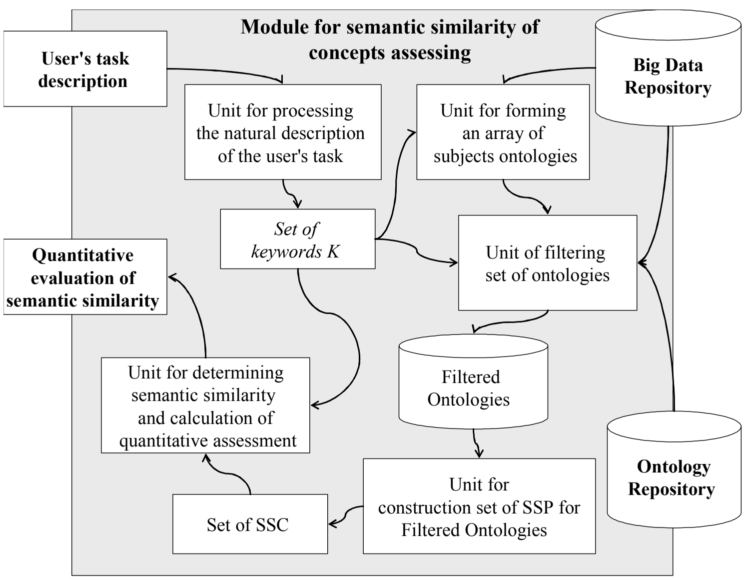



***Fig. 3.*** Module for semantic similarity of concepts assessing for an intelligent cybersecurity system.

Proposed method implements the components of the theory of semantic recognition, interpretation, selection and structuring of data and allows creating so-called adaptive ontologies, which are most optimized for a specific applied task of artificial intelligence, and also allows more accurate structuring and selection of data for intelligent applications. The method involves designing ontology classes of a subject area or information object for the current situation (task) and introducing metrics within the ontology of a metric, with which to search for the required semantic distance.

## CONCLUSIONS

The proposed approach to data integration and structuring in an intelligent information system is based on semantic analysis of metadata and semantic similarity determination of structural data models (ontologies, data), as well as the formation of a set of similar ontologies for solving problems of artificial intelligence.

The application of the created method of definition/evaluation of semantic similarity of concepts, which provides formation of an array of query features and researched ontologies, filtering of these features and closeness degree determination of researched ontology to user query characteristics, it is a tool for semantic comparison of ontologies found in repository under formal conditions with poorly structured natural language description.

Currently, there is no generally accepted standard for presenting metadata, so the proposed methods of analysis of NL annotations are the most adequate means of comparing the semantics of ontologies, data with those tasks for which they can be applied.

The scope of the developed method and module can be used in artificial intelligence systems for big data processing, cybersecurity, competence analysis when creating a team for the project implementation, human resource management, field of finance and business, companies working with dynamically-modified content of documents (jurisprudence, finance, standardization, public authorities etc.).

REFERENCES

1. Vasyukov V.L. Formal ontology and artificial intelligence. Moscow: IP RAS, 2006. 140 p. (In Russian)
2. Gladun A.Ya., Rogushina Yu.V. Ontology repositories as a means of reusing knowledge for recognizing information objects. *Design Ontology*.2013, No. 1 (7), pp. 35–50. (In Russian)
3. Torsten Hahmann Ontology repositories: A treasure trove for content ontology design patterns. *Proceedigs of 8th Inter. Workshop on Modular Ontologies* (WoMO-2014), Rio de Janeiro, Brazil, 2014.
4. Kenneth Baclawski, Todd Schneider. The open ontology repository initiative: Requirements and research challenges. *Proc. 8th International Semantic Web Conference*, ISWC 2009, Chantilly, VA, USA, 2010.
5. Rachel Heery and Sheila Anderson. Digital repositories review, February 2005.
6. William H. Inmon and W. H. Inmon. Building the Data Warehouse, 3rd Edition. Wiley, New York, 2002.
7. Jens Hartmann, York Sure, Raul Palma, Peter Haase, Mari Carmen Suarez-Figueroa, Rudi Studer, Asuncion Gomez-Perez. Ontology metadata vocabulary and applications. *Int Conf on Ontologies, Databases and Applications of Semantics. Workshop on Web Semantics (SWWS)*, Oct 2005.
8. Vekhorev M.N., Panteleev M.G. Construction of repositories of ontological knowledge bases. *Software products and systems*. 2011, No. 3 (3), pp.67–89.

9. Taylor C. An Introduction to Metadata. The University of Queensland, Australia. URL: http://www.libraty.uq.edu.au/papers/ctmeta4.html (Last accessed: 17.03.2018)
10. Corcho O. Ontology based document annotation: trends and open research problems. *Intern. Journal of Metadata, Semantics and Ontologies*. Vol. 1, Issue 1, January 2006. URL: http://www.dia.fi.upm.es/~ocorcho/documents/IJMSO2006_Corcho (Last accessed: 21.05.2020)
11. ISO 15489-1:2016 Information and documentation — Records management — Part 1: Concepts and principles.
12. ISO 15836-1:2017 Information and documentation — The Dublin Core metadata element set — Part 1: Core elements.
13. ISO 15836-2:2019 Information and documentation — The Dublin Core metadata element set — Part 2: DCMI Properties and classes.
14. DSTU ISO 15489-1: 2018 Information and documentation. Records management. Part 1. Concepts and principles (ISO 15489-1: 2016, IDT). (In Ukrainian)
15. DSTU ISO 15836-1: 2018 Information and documentation. Dublin Core Metadata Element Set. Part 1. Basic elements (ISO 15836-1: 2017, IDT). (In Ukrainian)
16. Gladun A., Khala K., Subach I. Ontological Approach to Big Data Analytics in Cybersecurity Domain. *Collection "Information Technology and Security"*. 2020, Vol. 8, No. 2, pp.120–132. DOI: https://doi.org/10.20535/2411-1031.2020.8.2.222559. URL: http://its.iszzi.kpi.ua/article/view/222559 (Last accessed: 11.12.2020)
17. Obrst, L., Ceusters, W., Mani, I., Ray, S., & Smith, B. (2007). The evaluation of ontologies. In Semantic web (pp. 139–158). Springer, Boston, MA.
18. Gómez-Pérez, A. (2004). Ontology evaluation. In Handbook on ontologies (pp. 251–273). Springer, Berlin, Heidelberg.
19. Leo Obrst, Werner Ceusters, Inderjeet Mani, Steve Ray, Barry Smith. The evaluation of ontologies. In Christopher J.O. Baker and Kei-Hoi Cheung, editors, *Revolutionizing Knowledge Discovery in the Life Sciences*, chapter 7. Springer, Berlin, 2007, pp. 139–158.
20. Obrst L. Ontologies for semantically interoperable systems. *Proceedings of the 12th International Conference on Information and knowledge management*, 2003, pp. 366–369.
21. Gangemi A., Catenacci C., Ciaramita M., Lehmann J. Modelling ontology evaluation and validation. *European Semantic Web Conference*. Springer, Berlin, Heidelberg, 2006, pp. 140–154.
22. Jens Hartmann, Raul Palma, Asunci´on Gomez-Perez "Ontology Repositories". Chapter in *Handbook on Ontologies*. Springer, 2009, pp 551–571.
23. Yimin Wang, Jie Bao, Peter Haase, and Guilin Qi. Evaluating formalisms for modular ontologies in distributed information systems. *Proc. of the First Inter Conf on Web Reasoning and Rule Systems* (RR2007), LNCS 4524, (June, 2007, Innsbruck). Innsbruck, Austria, pp. 178–182.
24. Jens Hartmann, Raul Palma. OMV – Ontology Metadata Vocabulary. *Semantic Web*. 2006, Vol. 2.0, URL: http://omv.ontoware.org/ (Last accessed: 17.12.2020)
25. Palma R., Hartmann J., Haase P. OMV Ontology Metadata Vocabulary. *SemanticWeb*. 2009, 76 p. URL: http://kent.dl.sourceforge.net/project/omv2/OMV%20Documentation/OMV-Reportv2.4.1.pdf. (Last accessed: 12.09.2017)
26. Jens Hartmann, Raúl Palma, Peter Haase, Asunción Gómez-Pérez. "Ontology Metadata Vocabulary and Applications." *OTM Workshops*, 2005, pp. 906–915.
27. Welcome to OMV — Ontology Metadata Vocabulary — http://omv2.sourceforge.net/. (Last accessed: 28.07.2020)
28. Gladun A.Y.,Khala K.A. Ontology-based semantic similarity to metadata analysis in the information security domain. *Prombles in programming*. 2021, №2, pp.34-41. DOI: htpps://doi.org/10.15407/pp2021.02.034. URL: http://pp.isofts.kiev.ua/ojs1/article/view/459 (Last accessed: 08.01.2021)
29. Tversky A. Features of Similarity. *Psychological Rev*. 1977, V. 84, P. 327.
30. Rogushina J. Use of Semantic Similarity Estimates for Unstructured Data Analysis. CEUR Vol-2577, *Selected Papers of the XIX International Scientific and Practical Conference "Information Technologies and Security"* (ITS 2019), Kyiv, 2019, pp. 246–258. URL: http://ceur-ws.org/Vol-2577/paper20.pdf. (Last accessed: 11.10.2019)
31. Gladun A.Y., Rogushina Y.V. Development of domain thesaurus as a set of ontology concepts with use of semantic similarity and elements of combinatorial optimization. *Prombles in*

*programming.* 2021, №2, pp. 3–15. DOI: htpps://doi.org/10.15407/pp2021.02.003. URL: http://pp.isofts.kiev.ua/ojs1/article/view/456 (Last accessed: 08.01.2021)

Received 11.01.2021

ЛІТЕРАТУРА

1. Васюков В.Л. Формальная онтология и искусственный интеллект. Москва: ИФ РАН, 2006. 140 с.
2. Гладун А.Я., Рогушина Ю.В. Репозитории онтологий как средство повторного использования знаний для распознавания информационных объектов // Онтология проектирования, № 1 (7), 2013. С.35–50.
3. Torsten Hahmann Ontology repositories: A treasure trove for content ontology design patterns. *In Proceedigs of 8th Inter. Workshop on Modular Ontologies* (WoMO–2014), Rio de Janeiro, Brazil, 2014.
4. Kenneth Baclawski Todd Schneider The open ontology repository initiative: Requirements and research challenges. In *Proc. 8th International Semantic Web Conference*, ISWC 2009, Chantilly, VA, USA, 2010.
5. Rachel Heery and Sheila Anderson. Digital repositories review, February 2005.
6. William H. Inmon and W. H. Inmon. Building the Data Warehouse, 3rd Edition. Wiley, New York, 2002.
7. Jens Hartmann, York Sure, Raul Palma, Peter Haase, Mari Carmen Suarez-Figueroa, Rudi Studer, Asuncion Gomez-Perez. Ontology metadata vocabulary and applications. *In Int Conf on Ontologies, Databases and Applications of Semantics.* In Workshop on Web Semantics (SWWS), Oct 2005.
8. Vekhorev M.N., Panteleev M.G. Construction of repositories of ontological knowledge bases. *Software products and systems*. 2011. No. 3 (3). P. 67–89.
9. Taylor C. An Introduction to Metadata. The University of Queensland, Australia. http://www.libraty.uq.edu.au/papers/ctmeta4.html
10. Corcho O. Ontology based document annotation: trends and open research problems. *Intern. Journal of Metadata, Semantics and Ontologies.* Volume 1. Issue 1. January 2006. URL: http://www.dia.fi.upm.es/~ocorcho/documents/IJMSO2006_Corcho (Дата звернення: 21.05.2020)
11. ISO 15489-1:2016 Information and documentation — Records management — Part 1: Concepts and principles.
12. ISO 15836-1:2017 Information and documentation — The Dublin Core metadata element set — Part 1: Core elements.
13. ISO 15836-2:2019 Information and documentation — The Dublin Core metadata element set — Part 2: DCMI Properties and classes.
14. ДСТУ ISO 15489-1:2018 Інформація та документація. Керування записами. Частина 1. Поняття та принципи (ISO 15489-1:2016, IDT).
15. ДСТУ ISO 15836-1:2018 Інформація та документація. Набір елементів метаданих Дублінського ядра. Частина 1. Основні елементи (ISO 15836-1:2017, IDT).
16. Gladun A., Khala K., Subach I. Ontological Approach to Big Data Analytics in Cybersecurity Domain . *Collection "Information Technology and Security"*. 2020. Vol. 8 No. 2. P.120–132. DOI: https://doi.org/10.20535/2411-1031.2020.8.2.222559. URL: http://its.iszzi.kpi.ua/article/view/222559 (Дата звернення:11.12.2020)
17. Obrst, L., Ceusters, W., Mani, I., Ray, S., & Smith, B. (2007). The evaluation of ontologies. In Semantic web (pp. 139–158). Springer, Boston, MA.
18. Gómez-Pérez, A. Ontology evaluation. *In Handbook on ontologies*. Springer, Berlin, Heidelberg, 2004. P. 251–273.
19. Leo Obrst, Werner Ceusters, Inderjeet Mani, Steve Ray, Barry Smith. The evaluation of ontologies. In Christopher J.O. Baker and Kei-Hoi Cheung, editors, *Revolutionizing Knowledge Discovery in the Life Sciences*. Chapter 7. 2007. P. 139–158.
20. Obrst L. (2003, November). Ontologies for semantically interoperable systems. *In Proceedings of the twelfth international conference on Information and knowledge management* (pp. 366–369).

21. Gangemi, A., Catenacci, C., Ciaramita, M., & Lehmann, J. (2006, June). Modelling ontology evaluation and validation. *In European Semantic Web Conference*. Springer, Berlin, Heidelberg. P. 140–154.
22. Jens Hartmann, Raul Palma, and Asunci´on Gomez-Perez "Ontology Repositories". *Chapter in Handbook on Ontologies*. Springer, 2009. P. 551–571.
23. Yimin Wang, Jie Bao, Peter Haase, Guilin Qi. Evaluating formalisms for modular ontologies in distributed information systems. *In Proc of the First Inter Conf on Web Reasoning and Rule Systems* (RR2007), LNCS 4524, Innsbruck, Austria, Jun 2007. P. 178–182.
24. Jens Hartmann and Raul Palma. OMV — Ontology Metadata Vocabulary for the Semantic Web, 2006. v. 2.0, URL: http://omv.ontoware.org/. (Дата звернення: 17.12.2020)
25. Palma R., Hartmann J., Haase P. OMV Ontology Metadata Vocabulary for the SemanticWeb. 2009. 76p.URL: http://kent.dl.sourceforge.net/project/omv2/ OMV%20Documentation/OMV-Reportv2.4.1.pdf. (Дата звернення: 12.09.2017)
26. Jens Hartmann, Raúl Palma, Peter Haase, Asunción Gómez-Pérez. Ontology Metadata Vocabulary and Applications. *OTM Workshops*, 2005, P. 906–915.
27. Welcome to OMV – Ontology Metadata Vocabulary. URL: http://omv2.sourceforge.net/. (Дата звернення: 28.07.2020)
28. Gladun A.Y., Khala K.A. Ontology-based semantic similarity to metadata analysis in the information security domain. *Prombles in programming*. 2021. №2. P. 34–41. DOI: htpps://doi.org/10.15407/pp2021.02.034. URL: http://pp.isofts.kiev.ua/ojs1/article/view/459 (Дата звернення:08.01.2021)
29. Tversky A. Features of Similarity. *Psychological Rev.* 1977. V. 84. P. 327.
30. Rogushina J. Use of Semantic Similarity Estimates for Unstructured Data Analysis // CEUR Vol-2577, *Selected Papers of the XIX International Scientific and Practical Conference "Information Technologies and Security"* (ITS 2019), Kyiv, 2019. P. 246–258. URL: http://ceur-ws.org/Vol-2577/paper20.pdf. (Дата звернення: 11.10.2019)
31. Gladun A.Y., Rogushina Y.V. Development of domain thesaurus as a set of ontology concepts with use of semantic similarity and elements of combinatorial optimization. *Prombles in programming*. 2021. №2. P. 03–15. DOI: htpps://doi.org/10.15407/pp2021.02.003. URL: http://pp.isofts.kiev.ua/ojs1/article/view/456 (Дата звернення: 08.01.2021)


Отримано 11.01.2021

*Гриценко В.І.*[1], член-кореспондент НАН України,
директор Міжнародного науково-навчального центру
інформаційних технологій та систем НАН України та МОН України
ORCID: 0000-0003-4813-6153, e-mail: vig@irtc.org.ua
*Гладун А.Я.*[1], канд.техн.наук, старш. наук. співроб.,
відд. комплексних досліджень інформаційних технологій та систем
ORCID: 0000-0002-4133-8169, e-mail: glanat@yahoo.com
*Хала К.О.*[1],
наук. співроб., відд. комплексних досліджень інформаційних технологій та систем
ORCID: 0000-0002-9477-970X, e-mail: cecerongreat@ukr.net
*Мартінез-Бежар Р.*[2], д-р. філософії (інформатика),
професор каф. інформаційно-комунікаційних технологій та штучного інтелекту
ORCID: 0000-0002-9677-7396, e-mail: rodrigo@um.es
[1] Міжнародний науково-навчальний центр інформаційних
технологій та систем НАН України та МОН України,
пр. Академіка Глушкова, 40, м. Київ, 03187, Україна
[2] Університет Мурсії,
CP 30180 Буллас, Іспанія

## МЕТОД ОЦІНЮВАННЯ СЕМАНТИЧНОЇ БЛИЗЬКОСТІ ПОНЯТЬ ДЛЯ СПІВСТАВЛЕННЯ ОНТОЛОГІЙ В ПРИКЛАДНИХ ЗАДАЧАХ ШТУЧНОГО ІНТЕЛЕКТУ

**Вступ.** Розвиток інтелектуальних інформаційних технологій (ІІТ) передбачає створення нового класу систем на основі формалізованого подання знань про предметну область.

Нині в різних предметних областях вже створено велику кількість онтологій. Сучасні засоби дають змогу шукати серед них бажану онтологію лише за деякими формальними параметрами (наприклад, за ключовими словами), а не на рівні їхньої семантики. Вирішення проблем пошуку необхідної онтології може бути забезпечено сховищем онтологій, яке уможливлює оброблення знань онтологій.

**Мета статті** — розроблення алгоритмів та методів оцінювання семантичних моделей, що полягають у поєднані якісного (онтологічного) подання знань з кількісним (числовим) оцінюванням онтологій та їхніх параметрів (семантична близькість, семантична відстань, семантична спорідненість), що спрямовано на віднайдення подібності між елементами різних онтологій.

**Методи.** Для розв'язання поставлених завдань використані методи онтологічного аналізу об'єктів предметної області, теоретико-множинні підходи до визначення міри близькості двох об'єктів шляхом зіставлення їхніх властивостей (feature matching) та традиційні методи статистичного аналізу.

**Результати.** Запропонований метод оцінювання семантичної подібності дає змогу на основі семантичного аналізу природномовних анотацій метаданих як онтологій, так і даних (зокрема великих даних), уможливлює виконання завдання їхньої інтерпретації та відбору. Отримані результати надають можливості створення оригінальних інтелектуальних інформаційних систем для економіки, медицини, національної безпеки, оборони та соціальної сфери.

**Висновки.** Запропонований оригінальний підхід до оцінювання та аналізу метаданих (онтологій, даних) базується на семантичному аналізі метаданих та визначенні семантичної подібності структурних моделей даних (онтологій, даних) і формуванні ранжованого набору близьких онтологій для розв'язання завдань штучного інтелекту. Застосування методів визначення семантично близьких понять подано як інструмент для семантичного зіставлення структури онтологій, які було знайдено у репозиторії за формальними умовами, зі слабо структурованим описом природною мовою (ПМ). Запропоновані методи аналізу ПМ-анотацій є адекватним засобом зіставлення семантики онтологій, даних з тими задачами, для розв'язання яких вони можуть застосовуватися.

***Ключові слова**: метадані, стандарти метаданих, семантична подібність, формальна модель онтології, інтелектуальна інформаційна система, репозиторій онтології.*

DOI: https://doi.org/10.15407/kvt205.03.026

UDC: 004.9:911.5/.9:528.94

**CHABANIUK V.S.**[1, 2], PhD (Phys.-Math.),
Senior Researcher of the Cartography Department, Institute of Geography,
Director of "Intelligence systems-GEO" LLC,
ORCID: 0000-0002-4731-7895
email: chab3@i.ua, chab@isgeo.kiev.ua.
**KOLIMASOV I.M.**[2],
Head of Production of "Intelligence systems-GEO" LLC,
ORCID: 0000-0002-4927-4200
email: kolimasov@ukr.net.
[1] Institute of Geography, National Academy of Sciences of Ukraine
44, Volodymyrska str., 01054, Kyiv, Ukraine
[2] "Intelligence systems-GEO" LLC,
6/44, Mykilsko-Slobidska str., 02002, Kyiv, Ukraine

# CRITICAL SYSTEMIC PROPERTIES OF ELECTRONIC ATLASES NEW GENERATION. PART 2: RESEARCH RESULTS

***Introduction***. *Part 2 discusses three critical systemic properties (CSP) of Electronic atlases (EA) new generation. With their help are determined fundamentally new, systemic EA. Compared with classic systems, new EA have much more opportunities to model spatial systems of actuality.*

***The purpose*** *of the paper is to describe and to prove the criticality of three CSP for a new generation of EA — systemic EA.*

***Results***. *Three CSP are described: CSP1.System, CSP2.Tree, CSP3.View. CSP1.System means that systemic EA should be models of spatial systems of actuality. These models are primary in contrast to the classic EA models, which are secondary. CSP2.Tree means that the contents/solutions tree of the systemic EA must classify the modeled spatial system of actuality. CSP3.View should model the visualization needs of users, in particular through interactivity. The methods of Conceptual Frameworks and Solutions Frameworks of Relational cartography, as well as facts from Model-Based Engineering were used for proof.*

***Conclusions***. *Three CSP of systemic EAs are described and it is proved that each of them is a necessary property of EA new generation.*

***Keywords***: *Electronic atlases new generation, critical systemic property, Conceptual Framework, Solutions Framework, Relational cartography.*

## INTRODUCTION

Part 2 takes into account the content of Part 1 [1] two main sections. The first presents the evolution of Electronic atlases (EA) over more than four decades: from the mid-1980s to our time. It is argued that in our time the evolution of EA leads to a revision of the cartographic and systemic foundations of EA until their revolutionary changes. The authors suppose that revolutionary changes should be considered in the context of a fundamentally new EA class, named Systemic (SEA). In general, the problem both Parts 1 and 2 of this article is formulated in the first main section of Part 1.

Part 1 second main section describes research methods. They are architectural patterns, which in computer science are called frameworks. The first is named the Conceptual Frameworks (CoFr) method valid for the Spatial Information Systems (SpIS) of the defined classes. This fact is proved for the SpIS, which are EA or, more generally, AtS = EAAtIS (AtIS — Atlas information system). CoFr determines, in a fixed period of information technologies stability, the structure of defined SpIS (for example, EA) in the so-called broader sense (SpISb). SpISb include the SpIS of end users also named the systems in the narrow sense — SpISn. And also all models of SpIS (SpISn) which exist both at phases of its development and operation. Some of them are created physically. As a method, CoFr provides the interaction between the SpS of actuality and the SpISb. In particular, this method is designed to transform MEA (modern EA) into SEA. It is used to identify the first critical systemic property (CSP1) — CSP1.System.

The second is named the Solutions Frameworks (SoFr) method. There are several SoFr for each CoFr, as SoFr provide interaction between the knowledge about the SpISb (components) of users who belong to neighboring "echelons". There are four echelons in each particular Formation. Formation is associated with a period of stability of information technologies in the atlas context. CoFr of some SpISb for each Formation identifies four echelons of users who must have knowledge of the respective four strata of the system. Examples of adjacent echelons are Operational and Application, which in SpISb correspond to strata with similar names. The Operational is the echelon of end users. The Application is mainly the echelon of developers. AtlasSF1.0 SoFr mentioned below is used between Application and Operational echelons of users or between components (elements, systems) of the corresponding EAb (SpISb) strata. SoFr is more specific than CoFr. This specificity is determined by: 1) the strata between which SoFr is used, 2) the solution components, to which SoFr is applied. In this work the SoFr method is used to identify two CSPs: CSP2.Tree (solutions/contents tree) and CSP3.View (view). The second section of Part 1 is finished by the explaination why CoFr and SoFr can be used in conjunction with Model-Based Engineering (MBE).

The main sections of Part 2 from the first to the third consider three critical systemic properties (CSP). They are easier to explain with CoFr. The first CSP (CSP1) is determined by the relations between the modeling system SEAb and the corresponding modeled system SpS of actuality. The second CSP (CSP2) is determined by the classification relation of subject area by using the CoFr Datalogics of such SEAb construction as a solutions/contents tree. The third CSP (CSP3) is determined by the relations between the hierarchical knowledge of the users of the Operational and Application echelons and the corresponding

SEAb views. It is easy to see that CSP1 refers to SEA (SEAb) as a system in a whole, CSP2 refers to SEA (SEAb) Datalogics of a two-dimensional system second "dimension", and CSP3 also refers to SEA (SEAb) Uselogics of a two-dimensional system second "dimension".

The first section of Part 2 uses the CoFr method to identify the first, and main, critical systemic property of SEA — CSP1, which is called CSP1.System. CSP1.System — SEA must model the Spatial systems (SpS) of actuality.

Germany (Europe) autobahns Atlas is used as the SEA example. This Atlas has both paper and electronic variants. Its de facto used to interpret the MBE concepts in (Kühne, 2006) [2]. We used Kühne's inferences and extended them to the representation of the Germany autobahns Atlas in accordance with the SEA CoFr.

The second section of Part 2 uses the AtlasSF SoFr method to describe CSP2, which is called CSP2.Tree and consists of three interrelated CSPs:

- CSP2.Tree.DA — Datalogics of the solutions tree is a critical systemic property.
- CSP2.Tree.DA-DO — The rigid relation between the Datalogics of contents and solutions trees (Operational and Application strata) is a critical systemic property.
- CSP2.Tree.DO — Datalogics of the contents tree is a critical systemic property.

Simply speaking, CSP2.Tree argues that the SEA should classify the subject area. For this classification, it is sufficient to perform data classifications for the SEA application, i.e., for the component models and/or systems of the SEA CoFr Operational and Application strata. This Datalogical Epistemological classification can be called ontological according to [2]. The ontological (or Datalogical Epistemological) classification is responsible for the epistemological relations between the contents and solutions trees. This classification is well known in IT. It's called instanceOf (instanceOfSomething) or classification. The inverse relation is called instantiation (exemplarisation).

The third section of Part 2 discusses CSP3, which is called CSP3.View and consists of two interrelated CSP:

- CSP3.View.State — Preservation of several SEA states in the operation session.
- CSP3.View.Interaction — Interactive view of SEA to users with different qualifications.

The information in this section is very important to explain the SEA's relation to the "live" world of users. It uses maps interactivity, which on the one hand is a substantive feature of modern electronic maps, and on the other hand, more importantly, it represents the views of users of the respective groups on atlas maps and the atlas as a whole. Maps interactivity has been extended to atlas interactivity and its place in AtlasSF is shown. It uses a view pattern, which is a logical combination of views of the main components of the SEA and/or AtlasSF.

The "Conclusions" section provides the conclusions of Part 2.

## RELATIONS BETWEEN SEA AND SPS OF ACTUALITY: CSP1.SYSTEM

The most important, the first SEA critical systemic property CSP.System, is formulated as follows:

- CSP1.System — SEA must model the spatial systems (SpS) of actuality.

It implies that SEA should not be just collections or sets of pre-created maps (to be a secondary model of actuality), but be a model of actual system (to be a primary model of actuality). Examples of such systems/models are Classic dynamic atlas systems and Atlas geographic information systems (AGIS) [3].

Geographic (spatial) system (geo-system (spa-system, SpS)) is an ordered pair (A, R), where A is a set of things (entities), among which are geographic (spatial), and R is a set of relations between things (entities) of the set A, which form a unity or organic whole. The term 'geo-system' is left to synchronize with the physical geography and topography that studies the Earth's surface. The concept of 'relations' is understood as in systemology. There it includes the whole set of related concepts, such as constraint, structure, information, organization, cohesion, interaction, coupling, linkage, interconnection, dependence, correlation, pattern etc [4].

Somebody may disagree with the criticality of CSP1.System, because it depends on how the researcher understands the concept of "system". For example, B. Gaines [5; p. 1] uses the following definition: "A system is what differs as a system". That is, the system by this definition can be everything. At first glance, it seems like an unnecessary statement. However, then B. Gaines argues that this definition of the system is meaningful and rich in systems theory. In particular, he argues that "In this lies the essence of systems theory: that to distinguish some entity as being a system is a necessary and sufficient criterion for its being a system, and this is uniquely true for systems. Whereas to distinguish some phenomenon (entityies) entity as being anything else is a necessary criterion to its being that something but not a sufficient one" (ib.; p. 2).

This work does not consider the relations between "information" EAb or SEA and "general" EAb or SEA. Note in passing that the "information" EAb here means a subset of SpISb, which is shown in [1; Fig. 2] on the example of ElNAUb. "Information" SEA are also a subset of SpIS, although this is not shown in [1; Fig. 2]. "General" EAb are the subset of the General SpS, as shown in [1; Fig. 2] on the example of General NAUb. "General" SEA is also a subset of the General SpS, although this is not shown in [1; Fig. 2]. Among the relations between "information" and "general" SEA are also critical, which are especially important in the design of SEA. However, for the actual introduction into the SEA issue, we need simpler, "non general system" CSP. CSP.View is such an example.

Consideration of CSP1.System will begin with the fact that the modeled systems of actuality should be not arbitrary systems, but spatial systems (SpS) of (or "on") the Earth. Their perception, in contrast to arbitrary systems, is not so arbitrary, because the concept of "space" in "earth" systems has both scientific and universal interpretations. Among modern scientific interpretations, we hold the view that in reality it is possible and necessary to distinguish "Relational space — the viewpoint of space as a product of relations between entities (objects). Space in this viewpoint arises at the same time as the entities (objects) in it, which contrasts with absolute space" [6; p. 280]. In our constructions, relational space is associated primarily with the concrete space of A. Aslanikashvili [7].

Between T. Cresswell and A. Aslanikakshvili works is almost 40 years apart, but so far the question of the inquiry domain (research subject, subject domain, cognition or research subject) of modern cartography and the related definition of cartography has not been resolved. This issue is particularly acute for the SEA (EA/AtIS). Thus, the International cartographic association (ICA) still cannot change the definition of cartography to a more modern one. To be able to respond to modern challenges to cartography in the monograph [8; p. 9] the definition of the latter is changed as follows:

- **Classic** (or Subject) **cartography** — the arts, sciences and technologies of making and using maps. This is a slightly modified definition from [9]. A. Aslanikashvili criticized such definitions and therefore put forward his understanding of the subject of cartography. We agree with his thoughts and from our part introduced the concept of two-dimensional system cartography, determining the first dimension as subject cartography, and the second dimension as relational cartography.
- **Relational** cartography (RelCa) — coordinated arts, sciences and technologies of making and using relations in cartographic systems and between cartographic systems.
- (**System(ic)** or Geomatic or simple) **cartography** — coordinated and uncoordinated arts, sciences and technologies of making and using maps, cartographic relations and cartographic systems.

We can not be tolerant in the definition of cartography by ICA, because according to this classic definition, neither modern electronic atlases, nor modern atlas information systems, nor their domains are not in fact the subject of knowledge (research) of (modern) cartography. On the other hand, it is quite difficult to name the fields of science that would be concerned with SEA (EA/AtIS). It is assumed that the domains of SEA (EA/AtIS) could be attributed to the inquiry domains of CIS or GIS. However, there are some problems that are not addressed in this article.

Below we have described two variants of the SEA relations with spatial systems of actuality: simpler and more complicated. In the simpler variant, the CoFr method is essentially not used. It is almost entirely proved using facts from Model-Based Engineering (MBE, see for a start [10]). In a more complicated variant, in addition to MBE, CoFr and the theory of Relational cartography are also significantly used [8].

**Simpler variant.** The relations of SEA with actuality systems are explained in Fig. 1. This figure is obtained by the logical combination of the Physical World and the Application and Operational strata of CoFr EAb (ElNAUb) [1; Fig. 2] with “Fig. 2 Kinds of model roles” [2]. [1; Fig. 2], in turn, is logically aligned with “Fig. 6 Linguistic metamodels” [2]. We did not complicate the figure by showing the correspondence between the CoFr elements and the language (linguistic) elements shown on the right in Fig. 1. In Fig. 1 marked:

- token modelOf: Holds between a system and a model, representing the system in a one-to-one fashion (one system corresponds to one model); model elements can be considered as determinants of system elements,
- type modelOf: Holds between a system and a model, classifying the system in a multi-to-one way (many systems correspond to one model); model elements can be considered as classifiers of system elements,

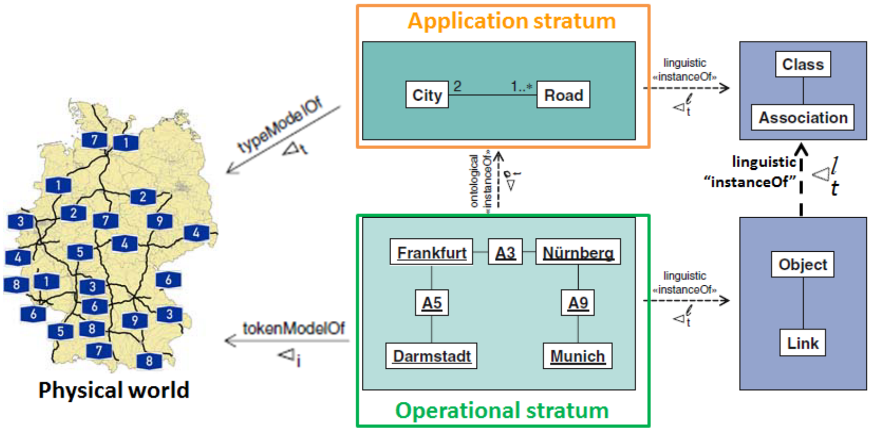



***Fig. 1.*** The relation between the actual SpS of the physical world and the ElNAUb Application and Operational strata. Used (Kühne, 2006) [1; Fig. 2, Fig. 6]

- instanceOf relation was used by us to denote the bottom-up relations between the elements of two adjacent strata. Use of this relation in practice is called classification. The reverse use is called instantiation or exemplification. Fig. 1 shows two classifications: ontological and language. So far, we have used the generalized terms "epistemological" to denote the relations between the elements of the strata in the bottom-up direction and "reduction" to denote the relations in the top-down direction. Recall the definition of ontology and epistemology. "Ontology (from the greek. on — genus n. ontos — being and ... logy) — a section of philosophy, the doctrine of existence (as opposed to epistemology — the doctrine of cognition), which explores the general basics, principles of existence, its structure and regularities; the term was introduced by the german philosopher R. Goklenius (1613)" (LED, 1993; p. 933) [11 p. 933]. "Theory of cognition (epistemology) — a section of philosophy, which studies the regularity and possibilities of cognition, the relations of knowledge (feelings, ideas, concepts) to objective reality, explores the degrees and forms of the process of cognition, conditions and criteria of its reliability and truth. Summarizing the methods and techniques used by modern science (experiment, modeling, analysis and synthesis, etc.), the theory of cognition acts as its philosophical-methodological basis" (LED, 1993; p. 1321) [11; p. 1321].

Recall the definition of ontology and epistemology: "ontology: a particular theory about the nature of being or the kinds of things that have existence", "epistemology: the study or a theory of the nature and grounds of knowledge especially with reference to its limits and validity" [11].

These definitions allow us to conclude that ontological relations should be given in an actual real spatial system, and in a modeling spatial system these relations should be called epistemological. Therefore, in our work we use the term "epistemological" relations instead of the term "ontological" relations in (Kühne, 2006) [1]. That is, instead of "ontological instanceOf" in Fig. 1 "epistemological instanceOf" should be used in our constructions. For Web 1.0 Atlases, the bottom-up relations ("epistemological instanceOf") between the elements of the Application and Operation strata is called "classification". The inverse relationship is called "instantiation".

However, the "linguistic" relations between the elements of the strata are also called by us and are in fact epistemological. Therefore, for example, instead of “linguistic instanceOf” between vertical elements belonging to adjacent strata (Fig. 1) it is possible to use epistemological “instanceOf”. In this article, we went further and divided the epistemological relations into three groups, using three levels of the Conceptual framework: Datalogical (or Technological context), Infological (or Language (Linguistic) context) and Organizational (or Usage context). The epistemological relations between the Datalogical components are called the Datalogical Epistemological relations and they coincide with the Ontological relations in (Kühne, 2006) [2]. Epistemological relations between Infological components are called Infological Epistemological relations and they include linguistic instanceOf (Kühne, 2006) [2]. Finally, the Epistemological relations between Organizational components is called the Organizational Epistemological relations and they include both the relations between the elements of the system and the relations between user knowledge.

In [2] the Germany autobahns network is used as an example of an actual spatial system of the physical world. The model of each autobahn is denoted by An (Autobahn n), where n = 3, 5, 9 within Fig. 1. To represent this spatial system in Fig. 1, apparently used “landkarte deutschland (autobahnnetz) / map of germany (street map)” from [12]. Although it may be a map from [13].,

If you take a closer look, it turns out that in [2] the model of the Germany autobahns network is supplemented with a representation of the cities through which individual autobahns pass. Representation without cities is shown in Fig. 2.

It turns out that cities appear only in the model in Fig. 1 (in the middle, Operational and Application strata). For a better understanding of the Germany autobahns network, we use a representation of the required system [15] on the Google map (Fig. 3).

Google Maps uses almost the same autobahn notations from the maps above. Therefore, thanks to Google Maps, the interested reader can get a fully available online idea of the actual spatial system of the physical world being research.

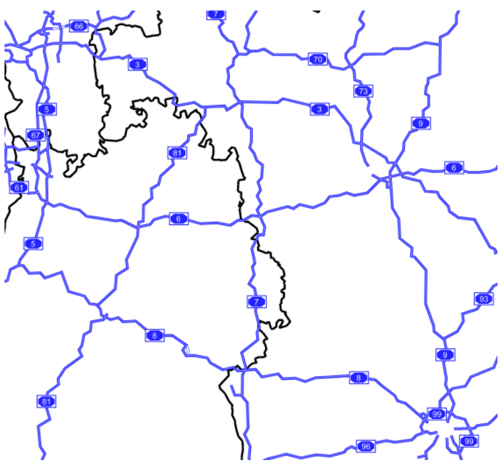


***Fig. 2.*** Representation of the part of the Germany autobahns (highways) we need from the website [14]. Cities not shown

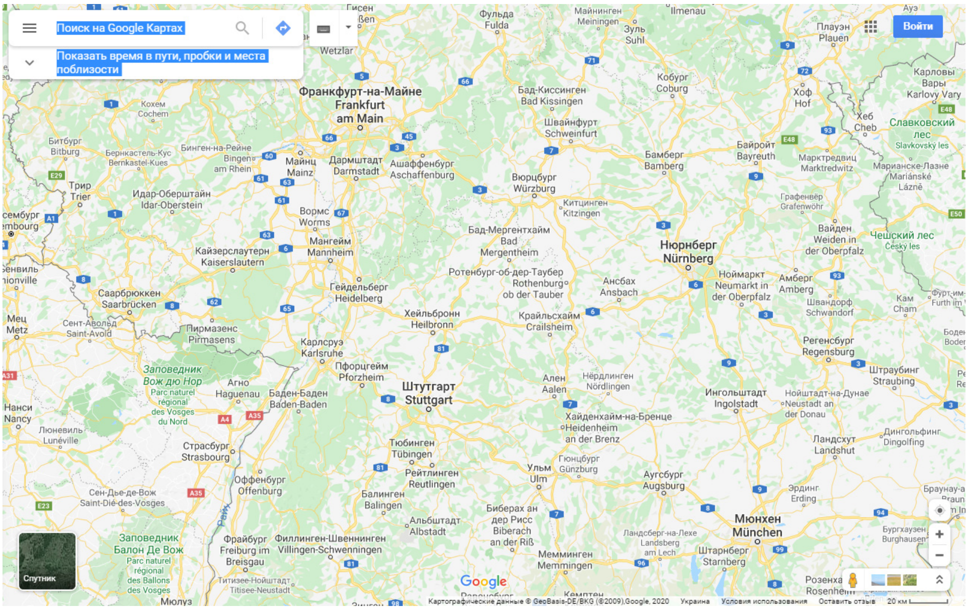



***Fig. 3.*** Representation of the actual SpS of the physical world from Fig. 1 on the Google map

To bring this example as close as possible to the topic of this article, we can say that T. Kühne [2] could even consider the actual SpS of the Germany autobahns, which is modeled by the Germany autobahns atlas. It is clear that the actual SpS for this atlas is somewhat more complex than shown in the previous figures. However, the main things (entities) in this system are settlements, and the main relations between them are fragments of autobahns

Fig. 1 shows two models of actual SpS: language (linguistic) and ontological. The language model is perceived by us as a highways paper atlas, which usually consists of sheets of a book. The user must find a (paper) sheet with the highways that interest him at the moment. Finding this sheet corresponds to moving on the base map of the atlas.

In contrast to the language model, the ontological model allows us to first find the value of the entity or relation that interests us, and only then perform positioning on the desired base map. Obviously, such operations are best performed with an electronic version of the atlas.

In Fig. 1 under the map of Germany autobahns the "Physical world" is signed. In this case, it means that the map only represents part of the actual SpS and is not this system. The language model of a part of the actual SpS is referred to the CoFr Operational stratum, and the ontological one is referred to the CoFr Application stratum. This is because both models are also representations, only in this case of the specific EA/AtIS of the Operational stratum and its class of the Application stratum, respectively. The electronic implementation of the language model is EA/AtIS of the Operational stratum. For example, in the case of the National atlas of Ukraine project, it was the Electronic version of the National atlas of Ukraine on DVD (ElNAU2007/2010). This atlas did not allow editing, but an editable version of the same atlas was created on the Application stratum, which was called ElNAU_Edited. In essence, ElNAU2007/2010 was a language model of the actual SpS of Ukraine, and ElNAU_Edited was an ontological model of the actual SpS of Ukraine

At the end of this paragraph, we draw readers attention to the clear presence in the actual spatial system of the physically existing relations "autobahn" and "at least one autobahn passes through the city". This example shows the fundamental difference between atlases as a collection of maps and atlases as a system. A collection (set) of maps can be created by collecting maps that are made without paying attention to systemic issues. If the researcher is based on classic cartography, then the most important thing for him is a separate map - usually a model of a field of the same type entities of actuality. Then other fields are modeled in the same way. After that, the created maps are collected in a collection of maps and the result is called an atlas. It turns out that this collection is unlikely to be a modern atlas.

Interestingly, this collection will not be an atlas, even from the classic viewpoint, which is set out in the monographs [16], [17], [18]. After all, in the definition of the geographic atlas by K. Salishchev there is such a phrase: "performed according to the general program" [17; p. 185]. Thanks to the Conceptual framework, we now know that the "general program" of creating an atlas is an element of the Conceptual stratum, which is closely related to the elements of the Application stratum and, through them, to the elements of the Operational stratum. Let's recall about the epistemological relations between the elements of strata, which primarily materialize knowledge between the elements.

More complicated variant. Our interpretation of some picture elements of [2] on Fig. 1 is not entirely accurate, namely:

1. The ontological model in UML terminology is called a class diagram, which is the result of the conceptual design stage of the AtIS development phase. It is quite obvious that the class diagram does not model the SpS of the physical world, but in the terminology of CoFr - the abstract-physical world.

2. The language model in UML terminology can be called an object diagram, which is also the result of the conceptual design stage of the AtIS development phase. Like the class diagram, the object diagram does not model the SpS of the physical world, but in the terminology of the CoFr, the abstract-physical world.

3. Fig. 2 of [2] will be accurate provided that the author meant the map of Germany autobahns, which is then modeled on UML. Therefore, to prevent inaccuracies in interpretation to represent actuality, we use satellite images. For a more accurate representation of the Germany autobahns network, it is possible to use Google images Fig. 4 [19].

Taking into account the above, as well as using the CoFr method, the specified part of Fig. 1 looks like in Fig. 5.

As a paper map of autobahns in Fig. 5 used a map of the territory we need from a paper atlas of European highways. We will not specify the concept of "Cartographic image" in Fig. 5. These can be Ontological and Language (Linguistic) models of the map from Fig. 1, but not required. Here we pay attention to the existence of two types of relations between the Conceptual stratum and the Abstract world, as well as the Abstract-physical world.

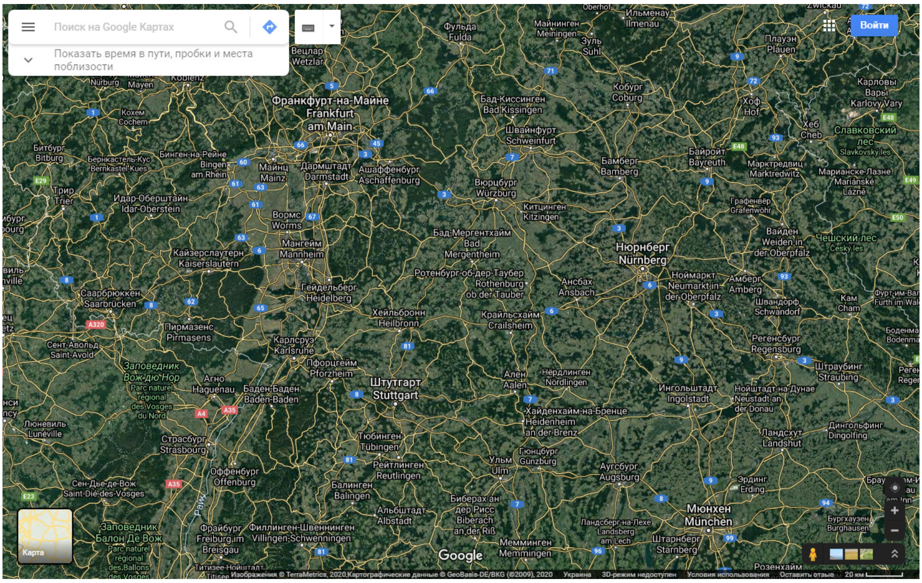



***Fig. 4.*** Representation of the Germany autobahns network using Google images

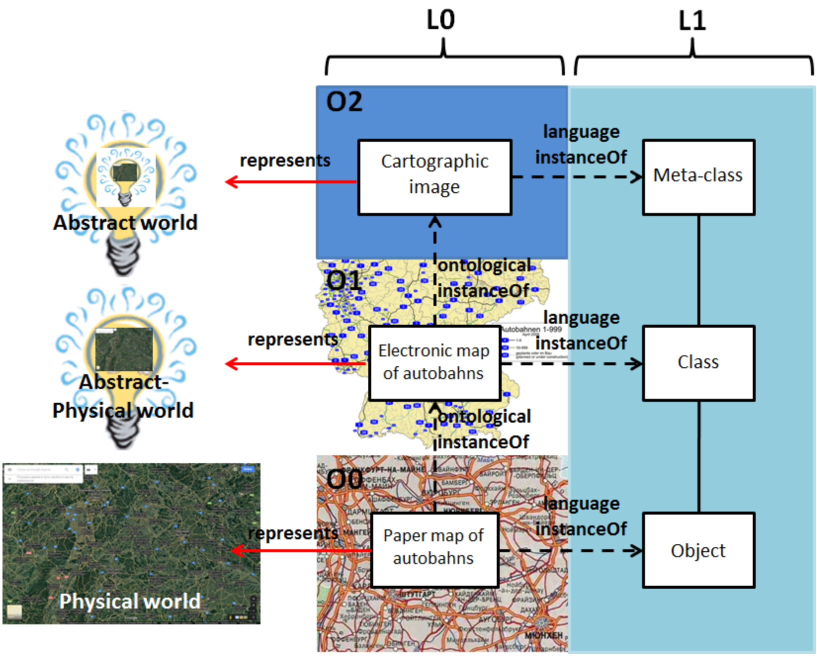



***Fig. 5.*** Clarification of the left and middle parts of Fig. 1

Again, at the end of the section, we note that the described discussion is impossible at all, if the subject of cognition (research) of cartography to leave the maps. The inquiry domain of modern atlases, including the subject of cognition (research) of cartography, changes de facto if their most important critical systemic property will be fulfilled: CSP1.System. The SEA must model actual Spatial systems (SpS). However, there is a question about the practical implementation of this CSP. Therefore, we further consider two more critical systemic properties: CSP2.Tree and CSP3.View. These CSP are correlated with the relational and subject properties of atlases as systems.

## RELATIONS BETWEEN SOLUTIONS/CONTENTS TREES IN ATLASSF: CSP2.TREE

In the main sections of Part 1, the "systematic collection", "systematized set", "simple atlas system", "real atlas system" terms were used to denote certain "systemic" subjects. The concepts corresponding to these terms and denoted subjects were formally or informally defined there. All these subjects can be obtained by performing "systematization", which is defined in the Cambridge dictionary as "the act of planning a system for something or organizing something into a system: (such as) the systematization of a set of ideas" [20]. Since the term "system" is not defined here, from the cited definition it is possible to draw a conclusion about its applicability to the "systemic" subjects listed here.

However, to find practically useful CSP we need to understand better the essence of systematization. To do this, we use a more detailed definition from [21; p. 259] : "Systematization" (from the greek systema — a whole consisting of parts) is defined as "mental activity in which the studied objects are organized into a certain system based on the selected principle. The most important kind of S. is classification, that is, the distribution of objects into groups on the basis of establishing similarity and differences between them (for example, the classification of animals, plants, and chemical elements). To S. leads also the establishment of causal relations between the facts under study (for example, in the course of history) and the allocation of the main units of material, which allows considering a specific object as part of the whole system. S. is preceded by analysis, synthesis, generalization, and comparison".

This definition clarifies the meaning of the phrase "systematic collection of maps" from the K. Salishchev's atlas definition. We see that to obtain this "collection of maps" you need to perform systematization, the most important kind of which is the classification. In addition, according to Philosophical encyclopedic dictionary [22] "Systematics (from the Greek sistematikos — ordered) — the science and art of systematization. Systematic — set out in the form of a certain system, which forms a certain system" [23].

In the work [24], we considered the systematics of atlas basemaps in Web 2.0 epoch. There we used the following definition: "Systematics (from the Greek συστηματικός — ordered, relating to the system) — bringing into the system, as well as a systemic classification of the study subject. Often, systematics is an auxiliary discipline that helps to organize the objects studied by this science; for example, biological systematics, language systematics" [25]. For us, the most useful is the following explanation from the article "Systematics" of Yu.V. Tchaikovsky [26; Vol. III: pp. 557–558]:

"Systematics — the doctrine of the principles and methods of ordering sets of objects that have essential similarities (systematics of stars, systematics of chemical elements, systematics of animals etc.). The objects of systematics are individuals and their groups. The group legalized in this system is called a taxon and is itself an object of the system. According to K. Behr (1822), the taxon is defined not by boundaries, but by the nucleus of typical forms; this principle was put into practice by W. Wawell (1840), who put forward the thesis ‘Class is given precisely, though not clearly limited'. Tasks of systematics: 1) classification (description of objects in terms of their essential similarities and differences), 2) nomenclature (assigning a name to each object of the system), 3) definition (finding the name of the object on the presented individual), 4) addressing (finding the object by its name). A system that solves the problem of classification is called natural, and a system that does not pose such a problem is called artificial. The main principles of organization: (1) row (address is an alphabetical order or number), (2) table (address — row and column numbers, if the table is two-dimensional), (3) map (address — coordinates), (4) hierarchy, is graphically expressed by a tree (address — a list of branching points, starting from the top of the tree, indicating the number of the branch at each such point). One set can be arranged in several ways: so, a chemical element can be specified by its number and the intersection of a row of the Periodic Table with a column (both techniques are natural), house — by its coordinates, and hierarchically (postal address). According to S.V. Meyen (1978), systematics — a part of the diversity (diatropics) science, complementary morphology (the doctrine of the plan of structure, common to the objects of the group), and classification is possible due to the natural order of the objects of nature. The principle of classification should be sought, not postulated. On the contrary, it is most convenient to carry out the determination once and for all by the established technique — the dichotomous key (M. Yoreniy, 1710), introduced into the practice by J.-B. Lamarck (1778): if there is a sign, read on, if not, see something there.

**CSP2.Tree: DA — Datalogics of solutions tree, DA-DO — Relations between Datalogics of solutions and contents trees, DO — Datalogics of contents tree.** It follows from the above that the "ontological classification" may be the first practical CSP. Probably, if the transformations are carried out from an actual spatial system to its "complete" atlas model. The "complete" atlas model for a particular stratum consists of Datologics, Infologics and Organologics (Uselogics). In the graphic images of the atlas model, the transformation is shown to be performed from left to right: actual SpS → AtS Datalogics → AtS Infologics → AtS Uselogics [27]. We name the ontological classification by the Datalogical Epistemological classification. Based on this, the classification of the subject area of each specific atlas should start from top to bottom relative to the graphic images of the strata, in particular, from the Application to the Operational strata. If possible, the Datalogical Epistemological classification for the Conceptual and Application strata should be performed first. Although the classification must be performed from the bottom up, the result of these actions must be a class, not a single instance of that class.

In the Atlas Solutions Framework (AtlasSF) systematics, in the sense of the quoted above Yu.V. Tchaikovsky's article, provides several patterns, including: (A2) solutions/contents tree and (A8) view. In this section, we formulate critical systemic properties only for the (A2) pattern. At once we will notice that in practice we used some of these patterns and all of them are Solutions frameworks. In Web 1.0 Formation, we used three versions of the (A2) pattern, which were components of the corresponding versions of AtlasSF1.0 SoFr, produced every five years since 2000. And in the Web 1.0x1.0 Formation yet one pattern (A2) has been developed and is used so far, which is a component of AtlasSF1.0+ SoFr. From the experience of using AtlasSF1.0 to create about 20 EA/AtIS, we draw the following conclusions:

- CSP2.Tree.DA — Application Datalogics (DA) of the solutions tree is CSP. It is necessary to start the classification of the subject area for the purpose of further implementation with the Application stratum.
- CSP2.Tree.DA-DO — The rigid relations between Datalogics of solutions and contents trees (DA-DO) is CSP.
- CSP2.Tree.DO — Operational Datalogics (DO) of the contents tree is the CSP. In no case do you need to start the classification of the subject area from the Operational stratum. That is, from the available maps.

We are not able to disassemble CSP2.Tree.DA, CSP2.Tree.DA-DO and CSP2.Tree.DO in detail. Therefore, we present Fig. 6 for explaination what we are talking about. In addition to the already used arguments about the top-down start, you need to use the following simple proof: if there is a CSP2.Tree.DO, then there must be a CSP2.Tree.DA, and without CSP2.Tree. DA-DO it is impossible.

**Some static properties of the solutions/contents tree in AtlasSF1.0.** In the first Atlas of Ukraine 2000 created by us, the Contents Tree was called the Table Of Contents (TOC). This atlas was also a prototype of ElNAU2007/2010 [28], so it can be designated ElNAU2000. ElNAU2000 TOC was used to navigate the contents and access the content of EA — first ElNAU2000, and then several more EA and AtIS in the first half of the first decade of the 21st century. The framework of these solutions was called AtlasSF1.0(1).

From a software viewpoint, TOC implementations on the Operational stratum in the first period (2000–2005) were ActiveX components. Such ActiveX started and supported manipulation of an XML-like .hhc contents file. However, we should not forget about the software system HTML Help Workshop, which allowed to perform the necessary actions on the Application stratum with the component element that was to become the TOC on the Operational stratum. We call this whole componentlex the "solutions tree" for the elements of the Application stratum. The term "table of contents" denotes a set of elements of the Operational stratum.

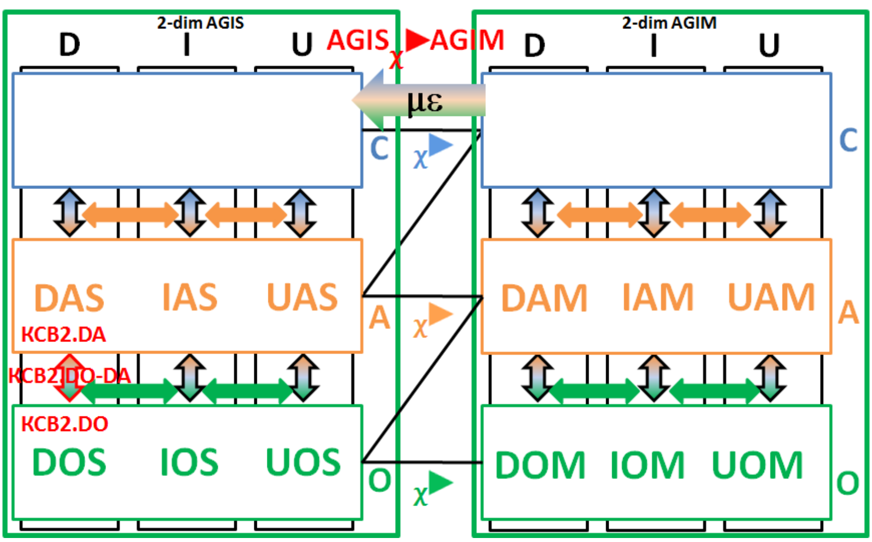



***Fig. 6.*** CSP of the solutions/contents tree in the context of SoFr and CoFr

In the first decade of this century, EA/AtIS end-user products were produced on optical media and did not allow any changes. After the producing of several EAs/AtIS, it was realized that the solution for this component may be replicated and applied not only in end-user products — in operation, but also earlier — in development — to build the Solutions Tree/Table of Contents that best suits to the end user EA/AtIS. Finally, recent research has shown that this element should be a pattern of the AtlasSF SoFr and is better called the Solutions/contents tree".

HTML Help Workshop was a powerful software system. After its forced replacement by our solution, several of its important properties were lost. In particular, in the updated solutions of edition 2 the ability to search the contents tree was not realized. Although, we repeat that between AtlasSF1.0(1), AtlasSF1.0(2) and AtlasSF1.0(3) there are relations that we call refactoring. However, at the turn of the decade, the 2010 atlas problem arose, which boils down to the fact that now we need to talk not about refactoring, but about reengineering - that is, about a complete rebuild of the solution.

The TOC below are based on the EA/AtIS examples created from 2000 to 2015. The TOC of all these AtS were fixed, immutable components in which the developers reflected the final solutions on structuring the research subject of a particular EA/AtIS on the Operational stratum.

Classification. Table Of Contents (TOC). If we draw an analogy between a paper atlas (PA) published in the form of a book and an Electronic atlas (EA) on CD/DVD or on the Internet, in both cases the contents and content of the atlas must be communicated to the user. Usually the Table Of Contents consists of sections, subsections, paragraphs, subparagraphs. In the case of EA, they are branches and/or leaves of the contents tree. By selecting the appropriate item in this tree, the user can gets access to a certain element of EA content - map pages, texts, photo-video materials etc. In contrast to the PA contents in working with the EA contents there are additional advantages: search in the contents, the function "go to the previous/next viewed item/page" and so on.

Fig. 7a shows the contents of ElNAU. The Left-Right arrows at the top of the figure implement the "go to the previous/next item/page viewed" function. In the case of a PA, you will need to remember the viewed page or make some bookmarks to repeat this operation is an example of searching for the word “terms” in the contents tree of the Atlas of radioactive contamination of Ukraine (RadAtlas2014, online version). In the PA version, this is almost impossible to implement.

Relations between the elements (components) of the atlas. We should note the relations between the elements (components) of the atlas, which existed since the first activity period of 2000–2005. Fig. 8 illustrates the organization of relations and connections between the elements of RadAtlas2014, although this property was implemented in RadAtlas2002 and in RadAtlas2008. In the table of contents in the left window the letter "Content" leaf is selected. In the right window we have a specific element of the content of the atlas. When you select a map or text, a certain element is loaded, and in the contents tree the cursor moves to the corresponding sheet leaf of the tree. Thus we have a convenient way to "travel" the atlas, using the relationship between its elements.

**Dynamic properties of the solutions/contents tree in AtlasSF1.0+**. For dynamic Solutions/contents trees of the Web 1.0x1.0 Formation AtS, all critical systemic properties of the Web 1.0 Formation must be met.


a) b)

***Fig. 7.*** a) Contents of ElNAU, b) Contents of RadAtlas2014 (at the top of TOC — search field)

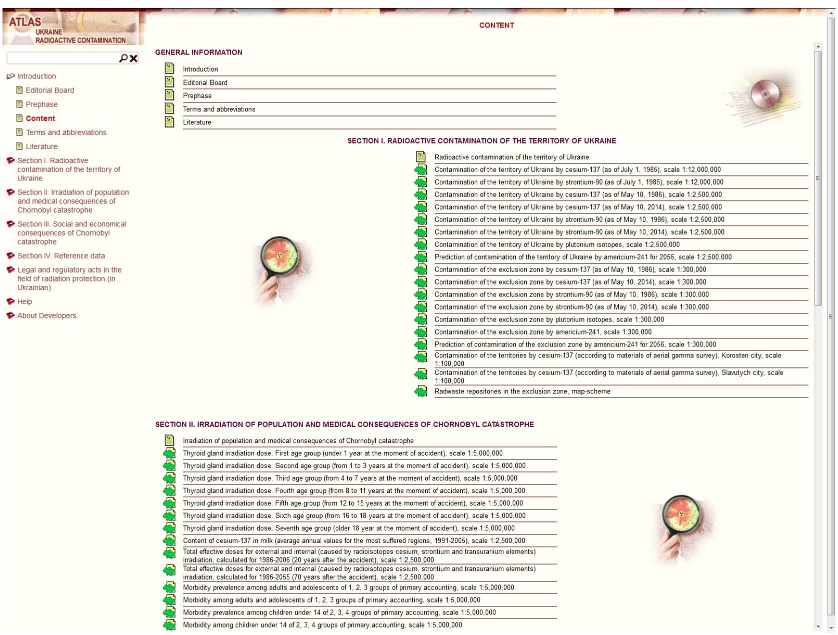



***Fig. 8.*** Organization of relations and links of RadAtlas materials

Dynamic systemic properties of the pattern (A2) can be divided into two groups: 1) the evolution of static properties, 2) the creation of new properties. They are not called critical, because some of them have not been yet implemented in any of the actual AtS. Below are two examples of such properties.

1. The evolution of static properties is providing dynamics in current versions of the solutions/contents tree SoFr in AtlasSF1.0+. It is based on Mikowski's software architecture [29], which is used in the current implementation of AtlasSF1.0+, and on its ability to use external modules. In the case of the main tree, AtlasSF1.0+ uses the jsTree library. Fig. 9 shows the interface of the test version AtlasSF1.0+ (0.0.33), Fig. 10 shows the activation of dynamic changes in the properties of a tree leaf with text. The right mouse button activates the operations Create, Rename, Delete, Edit > Cut, copy, paste. To do this, in the asf1plus.toc.js module, a context menu plugin has been added to the jsTree library: plugins: ["search", "contextmenu"]. The search tree plugin implements a local search of (A7) search pattern.

2. The example of new properties creation can be found in the monograph [8]. There are formulated three new patterns for Web 1.0x1.0 Formation AtS: (A9) GeoCollager, (A10) GeoComposer and (A11) GeoRelator. We will not describe now the essence of these new patterns. The simplest of them is GeoCollager, which is already used in the practice of AtS creation. We use an example from the site [30] (Fig. 11).

In the contents tree window (Navigation) on the basemap are selected: 1) UNESCO World Heritage Sites, 2) Monuments of national importance: a) archeology, b) historical, 3) Historical and cultural reserves, 4) Public cadastral map of Ukraine: a) boundaries and numbers of cadastral quarters of urban and land cadastres.

All themes selected in contents tree (Navigation) are displayed at once in the map window (Content). We hope that many people have recognized the displayed territory: it is the central part of Kyiv. The accumulation of monuments in the lower part of the map near Demiivka is explained simply: it is the Baykove cemetery, where there are many immovable monuments of Ukraine.

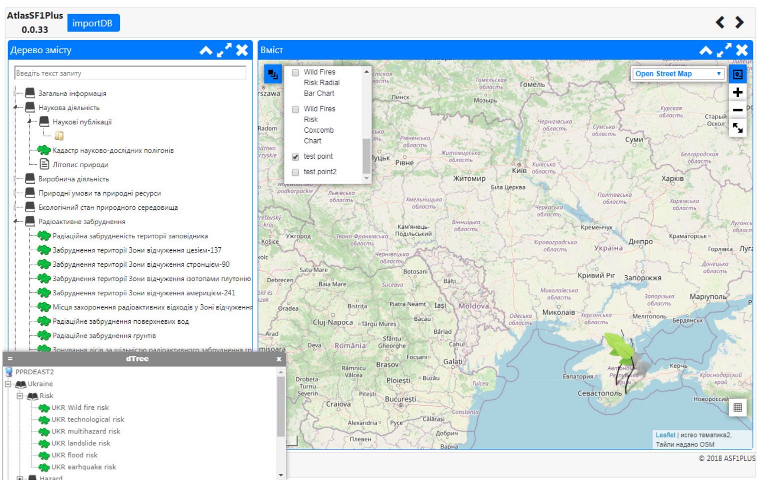



***Fig. 9.*** Test version of AtlasSF1.0+(0.0.33)

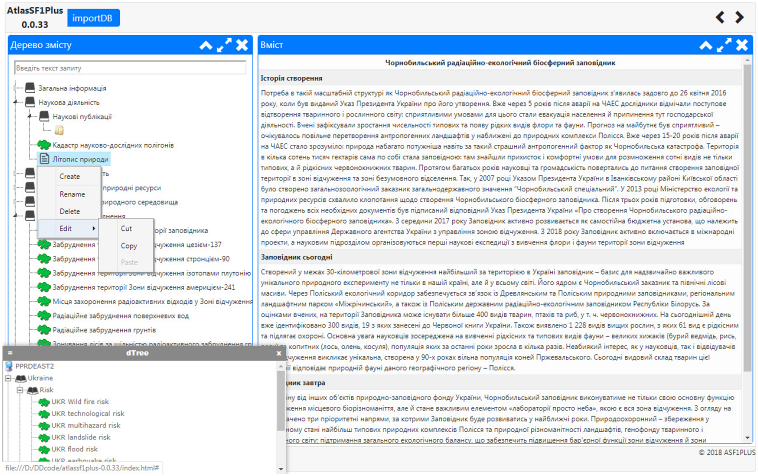



***Fig. 10.*** Dynamic properties of a tree thanks to jsTree

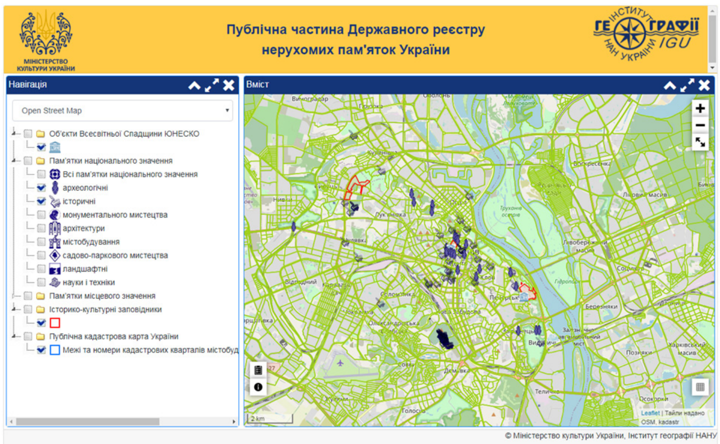



***Fig. 11.*** GeoCollager pattern in the Public register of immovable monuments of Ukraine

We have presented the simplest case of GeoCollager, when there are no relations between the topics. However, we hope that the reader will understand the power of this pattern, provided that we begin to define specific relations between themes.

## VIEW PATTERN RELATIONS: CSP3.VIEW

This section substantiates the CSP3.View (Fig. 12), which we associate with the state (CSP3.View.State) and interactivity (CSP3.View.Interaction) of atlases. CSP3.View is presented in all "old" patterns (A1) – (A8), in "new" patterns (A9) – (A11), as well as in both architectures A0.F1 (Formation Web 1.0) and A0.F1$^2$ (Formation Web 1.0$^2$). Thus first of all it is necessary to address to (A8) View pattern. This pattern is a logical pattern that consists of views of other patterns. View in AtlasSF1.0 was understood by analogy with the *.WOR (workspace) file of MapInfo Professional. In AtlasSF1.0+ this concept was evolved.

**CSP3.View.State** explains the following example, which is also related to SoFr (A2) Solutions/contents tree, (A4) Thematic layers and (A0) Architecture. Through (A0) Architecture communication with the atlas software modules is carried out. This property is understood by all as obvious, but it is often forgotten. Its explanations are shown in Fig. 13 and Fig. 14, which are obtained as follows. First, we displayed the "Migration (urban settlements)" map. To do this, in the tree window we found the name of the map — selected the tree leaf "Migration (urban settlements)" — scaled the map displayed in the map window to the desired scale — opened and placed the drop-down windows "Legend" and "Map Description". This is a description of Fig. 13.

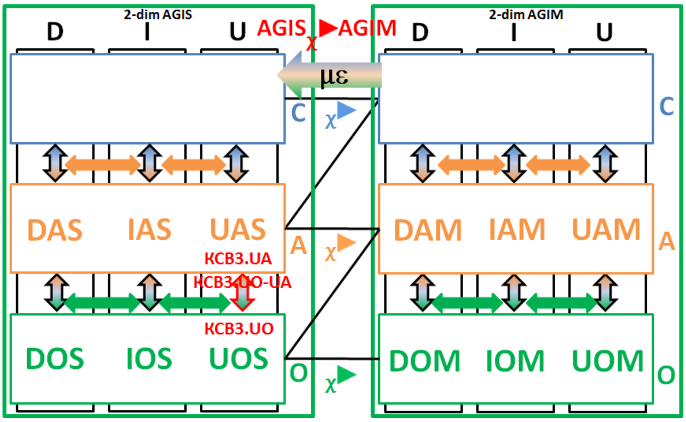



***Fig. 12.*** CSP.View in the context of SoFr and CoFr

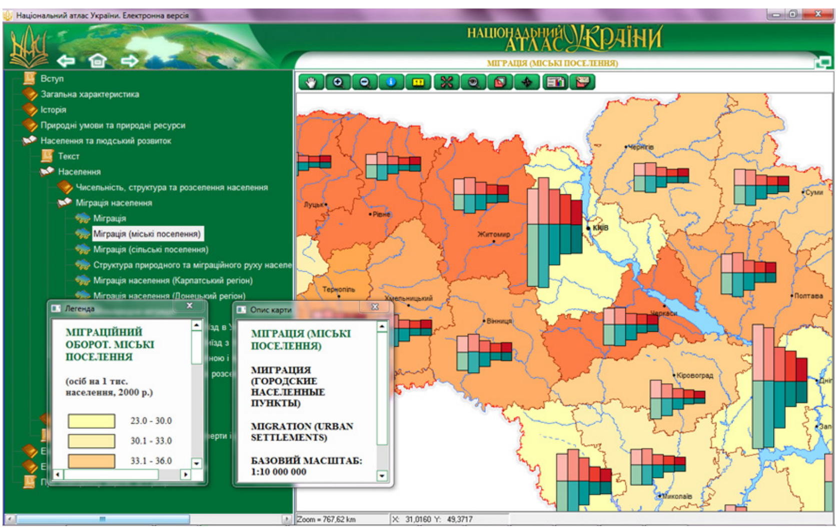



***Fig. 13.*** ElNAU2007. Migration (urban settlements)

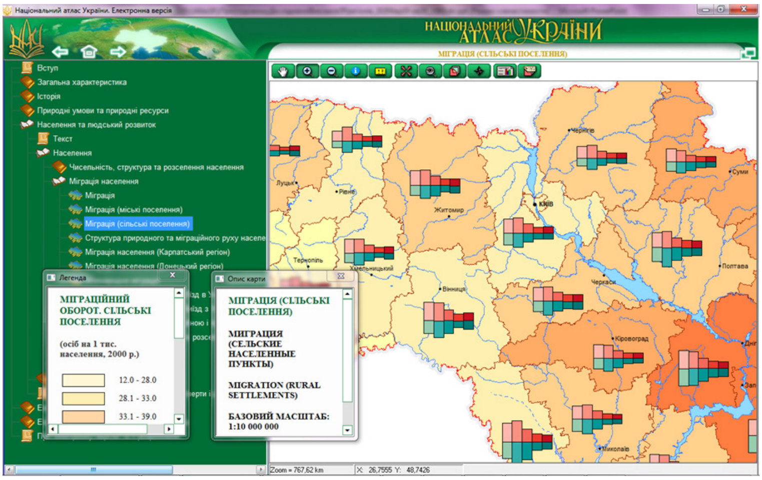



***Fig. 14.*** ElNAU2007. Migration (rural settlements)

Then in the tree window we chose a leaf with the name of the "Migration (rural settlements)" map and immediately received the image in Fig. 14. That is, one click got four new images: 1) in the contents tree window a white rectangle highlights the name of the "Migration (rural settlements)" map, 2) in the map window is displayed the "Migration (rural settlements)" map, 3) in the drop-down window "Legend" is reflected the "Migration turnover. Rural settlements" legend, 4) in the drop-down window "Map description" the description of the "Migration (rural settlements)" map is displayed.

The described critical property refers to the (A8) View pattern (SoFr). It is clearly systemic. We formulate it as follows:

- CSP3.View.State. Saving the state of the atlas in the operation session.

**CSP3.View.Interaction**. In the work [27] we proved that in modern atlas conditions the usual notion of cartographic interactivity should be extended to a certain systemic notion. In this systemic notion of interactivity it is necessary to consider the interactivity of the elements of Operational, Application and Conceptual strata, as well as the relations between them. If we consider the user echelons related to strata, it has been shown that cartographic interactivity cannot be considered in relation to a single user group, fixed, static, single map. On the contrary, it is necessary to consider interactivity for several maps, organized according to existing knowledge and targeted at different user groups. The minimum set of interactivity of such maps should include the interactivity of three dynamically changing maps: operational, application, conceptual.

This set should be consistent with the interactivity of the three *O* considered by R. Roth [31], [32] in the context of three approaches to interactivity: (1) based on objectives (Objective (first *O*) — at the stage of Forming the Intention), (2) based on operators (Operator (second *O*) — at the stage of Specifying an Action) and (3) based on operands (Operand (third *O*) — at the stage of execution and evaluation, between the stages of Executing the Action and Perceiving the State of the System). For example, when using an operand-based approach (third *O*), the focus is on the operand or the digital/virtual object with which the (end) user interacts. When creating a future user interface, the developer must ensure proper feedback regarding changes to the operand (third *O*) depending on the operator execution results (second *O*).

R. Roth in his doctoral dissertation [31] describes "cartographic interactivity" as a dialogue between a person and a map, performed using a computer device and understands it as a supplement to the cartographic representation. This fairly general interpretation allows us to consider many aspects of cartographic interactivity that arise in makingand using interactive maps. In particular, R. Roth [31], [32] argues that cartography is in another crisis ("identity crisis" in origin), named by us the "2010 cartography crisis". He suggests a way out of this crisis, which is to use the so-called "Growth perspective". R. Roth [31; Fig. 1.4] believes that all major cartographic paradigms can be included in the Growth perspective. It is depicted as a square with sides (bottom clockwise): cartographic interactivity — making maps — cartographic representation — using maps (Fig. 15).

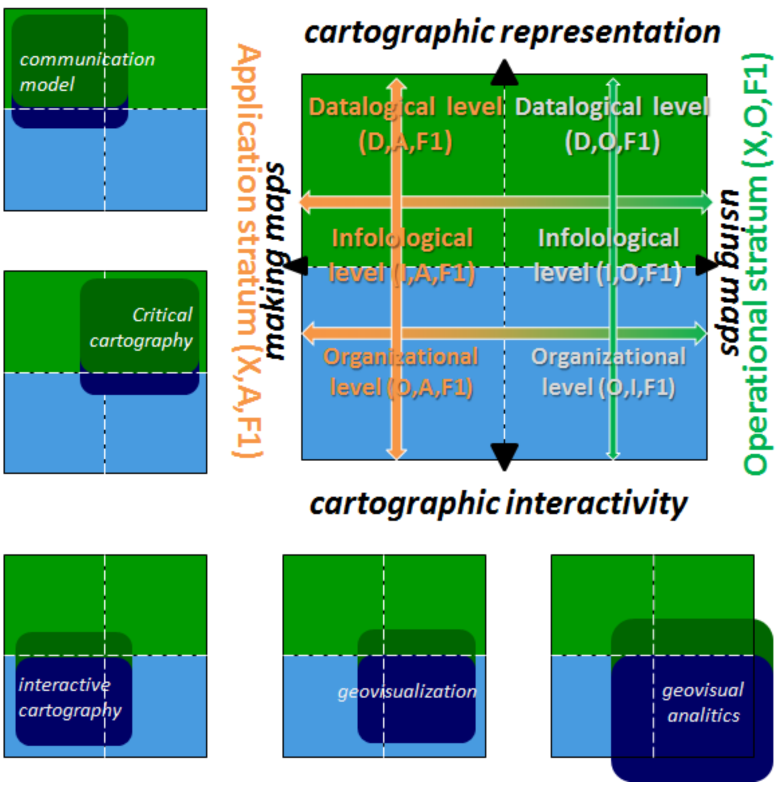
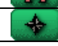



***Fig. 15.*** Relationship of the R. Roth's Growth perspective with the Operational and Application strata of AtS CoFr

*Tabl. 1.* **Navigation menu of the prototype library of web mapping patterns, which organizes the existing design patterns by sections: "*start work*", "*data*", "*map elements*", "*view*", "*interactivity*" [34; p. 124]. The line of designations D, I, U and *ElNAU* column are added by us**

| D | | I | U | |
|---|---|---|---|---|
| ***start work*** | ***data*** | ***view*** | ***interactivity*** | ***ElNAU*** |
| template code page template | data download | tile base map | moving (pan) |  |
| | storage | vector base map | zoom (decrease, increase) |   |
| | export | choropleth | extraction |  |
| | map elements | proportional symbol | overlay/switching (toggle) |  |
| | cartographic grid | density of points | filter |  |
| | legend | isoline/surface | ordering (arrange) |  |
| | | flow | reexpress |  |
| | | cartogram | sequence | -+ |
| | | bivariate/ multivariate | resymbolization | + |
| | | animation | redesign | - |
| | | graph/diagram | search |  |
| | | | calculation |  |

In work [33], we showed the relations between the web mapping patterns library of R. Roth's student — Richard Donohue [34] — and the constructions of Relational cartography [8]. In particular, we worked with the original table from [34; p. 124] and obtained Tabl. 1. The symbols of columns "D", "I" and "U" added by us show the correspondence between the columns of R. Donahue's table and the levels of AtS CoFr. In blue, we usually denote elements of the Conceptual stratum. This is a correct action, because R. Donahue created a table of design patterns painted in blue, which in [8] are also called conceptual patterns. The patterns of the application stratum are called application, and the patterns of the Operational stratum are called operational. In the work [33] the column of ElNAU was also painted blue. There we described the correspondence between the interactivity operands implemented in ElNAU and the design patterns of R. Donahue from the column "interactivity".

It would be more correct to describe the design patterns that were implemented in the operands of ElNAU (or operational patterns AtlasSF1.0(2)), and then compare the elements of the same epistemological stratum. However, such an action would lead to an unnecessary increase in the volume of the article and would not provide fundamentally new knowledge. With this in mind, we left a line of symbols D, I, U and the column *ElNAU* in Tabl. 1 unpainted.

We have repeated the evidence that map interactivity in Formation Web 1.0+ is systemic. This systemic property is also critical, because without it is impossible to develop modern AtSs. It follows from the above material that the interactivity of the maps refers to the presentation of the results of computer-human interaction to the user of the maps. Finally, the presentation of maps is a logical part of the presentation of AtS to the user. Therefore, this CSP can be called as follows:

- CSP3.View.Interaction. Interactive presentation of modern AtS to users with different qualifications.

## CONCLUSIONS

The work considers not the subject, but the systemic and relational properties of modern AtS. Subject properties are reduced to the properties of the maps included in the AtS. Electronic atlases (EA) and Atlas information systems (AtIS) were perceived (understood) mainly because of these properties before and, unfortunately, are perceived nowadays.

Relational properties are orthogonal to subject properties. Together they form systemic properties. Relational properties do not depend on the subject, so if we fix the latter, we will again have systemic properties, which here are called systemic-relational. For the purposes of the work, only three CSPs were selected, which belong to two types: purely systemic (CSP1.System) and systemic-relational (CSP2.Tree and CSP3.View). The systemic properties of AtS are nowadays such an urgent problem that now it is appropriate to talk even about critical systemic properties (CSP), without which it is impossible to talk about AtS as a system.

Purely systemic properties include the representation of AtS as a system of some SpIS class— CSP1.System. Representation of AtS as SpIS is a fundamental issue in the field of research of such a science as cartography. Unfortunately, the field of cartography research still remains such subjects as maps. At the same time, such cartographic works as atlases in all previous years belonged to the field of cartography research. Therefore, the contradictions in the definition of cartography are quite obvious, to the field of research of which either EA (and AtIS) belong or do not belong. At the moment, it makes no sense to say that there is another science, the field of research of which includes the field of research of Electronic atlases and Atlas information systems. GIScience immediately comes to mind, although this is just the name of the undertheory — may be paradigm. This and other paradigms, despite the names, are not yet theories, so the corresponding sciences should be considered with some clarification of the name — for example, "applied".

Systemic-relational properties include such critical properties as "tree" and "view". The "tree" consists of trees of contents and solutions and the relations between them. The main property of the contents tree and the solutions tree is their ability to implement the classification relations in the sense of the article [2]: ontological and possibly language (linguistic, both epistemological). Classification is not only a relation, but also, perhaps, the most famous method of research and design of systems. CSP2.Tree systemic-relational critical property is related to a CSP1.System purely systemic property. This CSP does not say anything about subjects — maps.

"View" systemic-relational property consists of the AtS state as a system at a given time moment and of the relations between these states. The state of the system (CSP3.View.State) is a representation of AtS for the end user at a given time. From the end user's viewpoint, changes between system states occur by performing interactivity operands. Atlas interactivity is a combination of the interactivity of its main components. The essential AtS components are the maps included in the AtS, as well as their interactivity. The work [27] proves the correspondence between the constructions of Relational cartography and the constructions of interactivity of the new paradigm of cartography, which its author R. Roth called the (cartographic) Growth perspective paradigm. One of the important properties of this paradigm is its basis. According to [31], this basis, in addition to cartographic interactivity, includes the main actual in 2010 paradigms of cartography.

REFERENCES

1. Chabaniuk V., Kolimasov I., Krakovskyi S. Critical systemic properties of Electronic atlases new generation. Part 1: Problem and research methods. *Cybernetics and Computer Engineering*. 2021, № 2(204), pp. 20–49.
2. Kühne Thomas. Matters of (meta-)modeling. *Softw. Syst. Modeling*. 5, 2006, pp. 369–385.
3. Chabaniuk V., Polyvach K. Critical properties of modern geographic information systems for territory management. *Cybernetics and Computer Engineering*. 2020, № 3(201), pp. 5–32.
4. Klir G.J. Architecture of Systems Problem Solving. New York: Springer, 1985.
5. Gaines Brian R. General systems research: quo vadis? *General Systems: Yearbook of the Society for General Systems Research.* 1979, Vol. 24, pp. 1–9.
6. Cresswell Tim. Geographic Thought: A Critical Introduction (Critical Introductions to Geography). Wiley-Blackwell, 2013. 298 p. (290 (300) p.)
7. Aslanikashvili A.F. Metacartography. Main problems. Tbilisi: Metsniereba, 1974. 126 p. (in Russian)
8. Chabaniuk Viktor. Relational cartography: Theory and practice. Kyiv: Institute of Geography of the NAS of Ukraine, 2018, 525 p. (in Ukrainian)
9. URL: https://icaci.org/mission/ [Last accessed 10.07.2021].
10. Brambilla Marco, Cabot Jordi, Wimmer Manuel. Model-driven Software Engineering in Practice (Synthesis Lectures on Software Engineering). Morgan & Claypool Publishers, 2nd Ed., 2017, 209 p.
11. Dictionary by Merriam-Webster, https://www.merriam-webster.com/ [Last accessed 17.09.2021]
12. URL:https://www.weltkarte.com/europa/landkarten-und-stadtplaene-von-deutschland/landkarte- deutschland-autobahnnetz.htm [Last accessed 10.07.2021].
13. URL:http://www.autobahntourismus.de/ [Last accessed 10.07.2021].
14. URL:https://ru.wikipedia.org/wiki/Автомагистрали_Германии [Last accessed 10.07.2021].
15. URL:https://www.google.com.ua/maps/@49.3402178,9.6836355,8z?hl=ru [Last accessed 10.07.2021].
16. Salichtchev K.A., Ed. Complex Regional Atlases. M.: MSU Publishing, 1976, 638 p. (in Russian)
17. Salichtchev K.A. Cartography. Textbook. M.: MSU Publishing, 1990, 3rd Ed, 400 p. (in Russian)
18. Svatkova T.G. Atlas cartography. Textbook. M.: Aspect Press, 2002, 203 (210) p. (in Russian)
19. URL:https://www.google.com.ua/maps/@49.3402178,9.6836355,258690m/data=!3m1!1e3?hl=ru [Last accessed 10.07.2021].
20. URL: https://dictionary.cambridge.org/ru/словарь/английский/systematization [Last accessed 27.08.2020].
21. Pedagogical Encyclopedic Dictionary. / Ch. ed. B.M. Bim-Bad. M., Large Russian Encyclopedia, 2002, 528 p. [Last accessed 30.04.2021], URL: https://pedagogical_dictionary.academic.ru/2945/Систематизация

22. Philosophical encyclopedic dictionary, 2010. [Last accessed 11.07.2021], URL: http://philosophy.niv.ru/doc/dictionary/philosophy/index.htm.
23. URL: http://philosophy.niv.ru/doc/dictionary/philosophy/fc/slovar-209-2.htm#zag-2490 [Last accessed 10.07.2021].
24. Chabaniuk V., Dyshlyk O. Atlas Basemaps in Web 2.0 Epoch. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, V. XLI-B4, 2016 *XXIII ISPRS Congress*, (12–19 July 2016, Prague), Prague, Czech Republic, pp. 611–618.
25. URL: https://uk.wikipedia.org/wiki/Систематика [Last accessed 03.07.2021].
26. New Philosophical Encyclopedia: In 4 volumes / Institute of Philosophy RAS, Nat. general scientific fund; Scientific ed. Council: Chairman V.S. Stepin, Deputy Chairmens: A.A. Guseinov, G.Yu. Semigin, Scientific Secretary A.P. Ogurtsov. M.: Thought, 2010. ISBN 978-2-244-01115-9. V. I. 2010. 744 p. ISBN 978-2-244-01116-6. V. II. 2010. 634, [2] p. ISBN 978-2-244-01117-3. V. III. 2010. 692, [2] p. ISBN 978-2-244-01118-0. V. IV. 2010. 736 p. ISBN 978-2-244-01119-7. (in Russian)
27. Chabaniuk V.S, Rudenko L.G. Software solutions in the processes of creating and using atlas interactive maps. *Journal of the Belarusian State University. Geography. Geology*. 2019, No. 2, pp. 25–39. Russian. https://doi.org/10.33581/2521-6740-2019-2-25-39
28. Bochkovska, et al. Electronic version of the Pilot Project “The National Atlas of Ukraine”. *Ukrainian Geographic Journal*, 2000, № 1, pp. 48–61 (in Ukrainian)
29. Mikowski Michael, Powell Josh. Single Page Web Applications: JavaScript end-to-end.- Manning Publications. 2014, 407 (433) p.
30. URL: http://publicregistry.heritage.in.ua/ [Last accessed 07.07.2020].
31. Roth Robert E. Interacting with Maps: The science and practice of cartographic interaction. The Pennsylvania State University, Doctor of Philosophy (Geography) Dissertation, 2011. 215 (225) p. DOI: 10.1179/1743277412Y.0000000019.
32. Roth Robert E. Interactive Maps: What We Know And What We Need To Know. *Journal of Spatial Information Science*. No. 6, 2013, pp. 59–115. DOI: 10.5311/JOSIS.2013.6.105.
33. Interactive maps: essence and software solutions for creation and use, pp. 21–35, in Rudenko L., ed. Actual directions of cartography development in Ukraine. Kyiv, Institute of Geography of the National Academy of Sciences of Ukraine, 2019. 88 p. (in Ukrainian)
34. Donohue Richard G. Web Cartography with Web Standards: Teaching, Learning, and Using Open Source Web Mapping Technologies. University of Wisconsin-Madison, Doctor of Philosophy (Geography) Dissertation, 2014, 167 (173) p.

Received 22.03.2021

ЛІТЕРАТУРА

1. Chabaniuk V., Kolimasov I., Krakovskyi S. Critical systemic properties of Electronic atlases new generation. Part 1: Problem and research methods. *Cybernetics and Computer Engineering*, 2021, № 2(204), pp. 20–49.
2. Kühne Thomas. Matters of (meta-)modeling. *Softw. Syst. Modeling*, 2006, 5, pp. 369–385.
3. Chabaniuk V., Polyvach K. Critical properties of modern geographic information systems for territory management. *Cybernetics and Computer Engineering*, 2020, № 3(201), pp. 5–32.
4. Klir G.J. Architecture of Systems Problem Solving. New York: Springer, 1985.
5. Gaines Brian R. General systems research: quo vadis? *General Systems: Yearbook of the Society for General Systems Research*, Vol. 24, 1979, pp. 1–9.
6. Cresswell Tim. Geographic Thought: A Critical Introduction (Critical Introductions to Geography). Wiley-Blackwell, 2013. 298 p. (290 (300) p.)
7. Асланикашвили А.Ф. Метакартография. Основные проблемы. Тбилиси: Мецниереба, 1974. 126 с.
8. Чабанюк В.С. Реляційна картографія: Теорія та практика. Київ: Інститут географії НАН України, 2018. 525 с.
9. https://icaci.org/mission/, accessed 2021-jul-10.

10. Brambilla Marco, Cabot Jordi, Wimmer Manuel. Model-driven Software Engineering in Practice (Synthesis Lectures on Software Engineering).- Morgan & Claypool Publishers, 2nd Ed., 2017. 209 p.
11. Большой Энциклопедический Словарь. Гл. редактор Прохоров А.М. Советская Энциклопедия, 1993. 1628 с.
12. https://www.weltkarte.com/europa/landkarten-und-stadtplaene-von-deutschland/landkarte- deutschland-autobahnnetz.htm, accessed 2021-jul-10.
13. http://www.autobahntourismus.de/, accessed 2021-jul-10.
14. https://ru.wikipedia.org/wiki/Автомагистрали_Германии, accessed 2021-jul-10.
15. https://www.google.com.ua/maps/@49.3402178,9.6836355,8z?hl=ru, accessed 2021-jul-10.
16. Салищев К.А., ред. Комплексные региональные атласы. М.: Изд-во МГУ, 1976. 638 с.
17. Салищев К.А. Картоведение. Учебник. М.: Изд-во МГУ, 1990, 3-е изд. 400 с.
18. Сваткова Т.Г. Атласная картография. Учебное пособие. М.: Аспект Пресс, 2002. 203 (210) с.
19. https://www.google.com.ua/maps/@49.3402178,9.6836355,258690m/data=!3m1!1e3?hl=ru, accessed 2021-jul-10.
20. https://dictionary.cambridge.org/ru/словарь/английский/systematization, accessed 2020-aug-27
21. Педагогический энциклопедический словарь. / Гл. ред. Б.М. Бим-Бад. М., Большая российская энциклопедия, 2002. 528 с. Доступ 2021-июл-10, https://pedagogical_dictionary.academic.ru/ 2945/Систематизация)
22. Философский энциклопедический словарь, 2010.- Доступ 2021-июл-10, http://philosophy.niv.ru/doc/dictionary/philosophy/index.htm.
23. http://philosophy.niv.ru/doc/dictionary/philosophy/fc/slovar-209-2.htm#zag-2490, accessed 2021-jul-10.
24. Chabaniuk V., Dyshlyk O. Atlas Basemaps in Web 2.0 Epoch. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, V. XLI-B4, 2016 XXIII ISPRS Congress, 12–19 July 2016, Prague, Czech Republic, pp. 611–618.
25. https://uk.wikipedia.org/wiki/Систематика, accessed 2020-jul-03.
26. Новая философская энциклопедия: В 4 т./Ин-т философии РАН, Нац. общ.-научн. фонд; Научно-ред. совет: предс. В.С. Степин, заместители предс.: А.А. Гусейнов, Г.Ю. Семигин, уч. секр. А.П. Огурцов. М.: Мысль, 2010.-ISBN 978-2-244-01115-9. Т. I. 2010. 744 с.-ISBN 978-2-244-01116-6. Т. II. 2010. 634, [2] с. - ISBN 978-2-244-01117-3. Т. III. 2010. 692, [2] с.- ISBN 978-2-244-01118-0. Т. IV. 2010. 736 с. - ISBN 978-2-244-01119-7.
27. Чабанюк В.С., Руденко Л.Г. Программные решения в процессах создания и использования атласных интерактивных карт. *Журнал Белорусского государственного университета. География. Геология*, 2019, No. 2, с. 25-39. https://doi.org/10.33581/2521-6740-2019-2-25-39
28. Бочковська, та ін. Електронна версія пілотного проекту «Національний атлас України». *Український географічний журнал*, 2000, № 1, с. 48-61.
29. Mikowski Michael, Powell Josh. Single Page Web Applications: JavaScript end-to-end.- Manning Publications, 2014. 407 (433) p.
30. http://publicregistry.heritage.in.ua/, access 2020-jul-07
31. Roth Robert E. Interacting with Maps: The science and practice of cartographic interaction. The Pennsylvania State University, Doctor of Philosophy (Geography) Dissertation, 2011. 215 (225) p. DOI: 10.1179/1743277412Y.0000000019.
32. Roth Robert E. Interactive Maps: What We Know And What We Need To Know. *Journal of Spatial Information Science*, No. 6, 2013, pp. 59–115. DOI: 10.5311/JOSIS.2013.6.105.
33. Інтерактивні карти: сутність та програмні рішення при створенні та використанні, с. 21–35 // Руденко Л., ред. Актуальні напрямки розвитку картографії в Україні. Київ, Інститут географії НАН України, 2019. 88 с.
34. Donohue Richard G. Web Cartography with Web Standards: Teaching, Learning, and Using Open Source Web Mapping Technologies. University of Wisconsin-Madison, Doctor of Philosophy (Geography) Dissertation, 2014. 167 (173) p.


Отримано 22.03.2021

*Чабанюк В.С.*[1, 2], канд. фіз.-мат. наук,
старш. наук. співроб. відд. картографії Інституту географії НАН України,
директор ТОВ «Інтелектуальні системи-ГЕО»,
ORCID: 0000-0002-4731-7895
e-mail: chab3@i.ua, chab@isgeo.kiev.ua.
*Колімасов І.М.*[2],
начальник виробництва ТОВ "Інтелектуальні системи-ГЕО",
ORCID: 0000-0002-4927-4200
e-mail: kolimasov@ukr.net, van@isgeo.kiev.ua.
[1] Інститут географії НАН України,
вул. Володимирська, 44, м. Київ, 01030, Україна
[2] ТОВ «Інтелектуальні системи-ГЕО»,
вул. Микільсько-Слобідська, 6/44, м. Київ, 02002,Україна

КРИТИЧНІ СИСТЕМНІ ВЛАСТИВОСТІ ЕЛЕКТРОННИХ АТЛАСІВ НОВОГО ПОКОЛІННЯ. ЧАСТИНА 2: РЕЗУЛЬТАТИ ДОСЛІДЖЕННЯ

**Вступ.** У Частині 2 розглядаються три критичні системні властивості (КСВ) Електронних атласів (ЕА) нового покоління. За допомогою цих КСВ визначаються принципово нові, системні ЕА. Порівняно з класичними, системні ЕА мають набагато більше можливостей моделювати просторові системи дійсності.

**Метою** статті є опис і доведення критичності трьох КСВ для нового покоління ЕА — системних ЕА.

**Результати.** Описано три КСВ: КСВ1.Система, КСВ2.Дерево, КСВ3.Подання. КСВ1.Система означає, що системні ЕА повинні бути моделями просторових систем дійсності. Ці моделі є первинними на відміну від моделей класичних ЕА, які є вторинними. КСВ2.Дерево означає, що дерево змісту/рішення системного ЕА має класифікувати просторову систему дійсності, що моделюється. КСВ3.Подання має моделювати візуалізаційні потреби користувачів, зокрема, за допомогою інтерактивності. Для доведення використано методи Концептуальних каркасів і Каркасів рішень Реляційної картографії, а також факти з Базованої на моделях інженерії.

**Висновки.** Описано три КСВ системних ЕА і доведено, що кожна з них є необхідною властивістю ЕА нового покоління.

***Ключові слова***: *Електронні атласи нового покоління, критична системна властивість, Концептуальний каркас, Каркас рішень, Реляційна картографія*

DOI: https://doi.org/10.15407/kvt205.03.052

UDC 519.8.812.007



**ARALOVA N.I.[1]**, DSc (Engineering), Senior Researcher,
Senior Researcher of Controlled Processes Optimization Department,
ORCID 0000-0002-7246-2736, e-mail: aralova@ukr.net
**KLYUCHKO O.M.[2],** PhD (Biology), Associate Professor,
Associate Professor of Air Navigation Faculty,
ORCID 0000-0003-4982 7490, e-mail: kelenaXX@nau.edu.ua
**MASHKIN V.I.[1],** PhD (Engineering), Senior Researcher,
Senior Researcher of Controlled Processes Optimization Department,
ORCID 0000-0002-4479-6498, e-mail: mashkin_v@ukr.net
**MASHKINA I.V.[3],** PhD (Engineering), Associate Professor,
Associate Professor of Information Technology and Management Faculty
ORCID 0000-0002-0667-5749, e-mail: mashkina@kubg,edu.ua
**RADZIEJOWSKI P.A.[4],** DSc (Biology), Professor,
Professor of Management Faculty, Department of Innovations
and Safety Management Systems
ORCID 0000-0001-8232-2705, e-mail: pawel.radziejowski@ pcz.pl
**RADZIEJOWSKA M.P.[4],** DSc (Biology), Professor
Professor of Management Faculty, Department of Innovations
and Safety Management Systems
ORCID 0000-0002-9845-390X, e-mail: maria.radziejowska@pcz.pl
[1] V.M. Glushkov Institute of Cybernetics of National Academy of Sciences of Ukraine.
40, Acad.Glushkov av., Kyiv, 03187, Ukraine
[2] Institute of Electronics and Telecommunications, National Aviation University,
1, Lubomyr Huzar av., Kyiv, 03058, Ukraine
[3] Borys Grinchenko Kyiv University,
18/2, Bulvarno-Kudriavska str., Kyiv, 04053 Ukraine, 04053
[4] Czestochowa University of Technology
19b, Armii Krajowej str., 42-200, Częstochowa, Poland


# MATHEMATICAL MODEL OF CONFLICT-CONTROLLED PROCESSES IN SELF-ORGANIZATION OF RESPIRATORY SYSTEM


***Introduction***. *Various processes going in surrounding environment are controlled, i. e. their states are determined depending on the specific influence of controlling party. At the same time, it is natural to try to choose the optimal controlling influence that would be the best in comparison with other possible controlling methods. Intensive development of the theory of optimal solutions with computers use has obtained the ability to perform complex calculations and realize the rules of control due to the development of computational technology.*

*The problem of identifying and studying of the nature of self-organization mechanisms of processes going in organism, the disclosure of the laws of control that operate in it actually arises during the investigation of living systems. Problem solution of self-organization process knowing for these controlled objects should be carried out using the methods of mathematical modeling. Peculiarities of setting problems of control for functionally-organized systems can be conveniently examined on the example of processes going in living organism when the achievement of certain goals is ensured.*

***The purpose*** *of the paper is to create the mathematical model of functional respiratory system for the investigation of self-organization mechanisms in human organism in response to extreme disturbances.*

***Methods.*** *The usual nonlinear differential equations are used for process description; they describe the mass transfer and mass exchange of respiratory gases flowing along all their ways in organism.*

***Results.*** *Mathematical model of functional respiratory system has been developed to study the current functional state and to predict the mechanisms of self-organization of respiratory system in adapting to the disturbing influences of external and internal environment based on the problem of optimal control and taking into account the conflict situation between the self-regulating organs — controlling and executing.*

***Conclusions.*** *Mathematical model of functional self-organization of respiratory and blood circulatory systems is proposed, which takes into account the interaction and inter-influence of organism functional systems, conflict situations between controlling and executive elements of self-regulation; it is based on the assumption of optimal regulation of oxygen regimes. The model may be useful for solving a number of applied problems of physiology and medicine.*

***Keywords***: *Functional respiratory system, controlled dynamic system, self-organization of respiratory system, operators of continuous interaction system, disturbing influence of environment.*

## INTRODUCTION

Mathematical modeling is a unique and powerful tool used for the investigation of physiological processes. It allows to deepen significantly our knowledge of studied phenomena, to form fundamentally new ideas about these phenomena, to identify a wide range of system responses during model parameters changing, to propose new hypotheses that could be studied experimentally and to identify new fundamental classes of phenomena. It can even be argued that along with experimental physiology, an independent branch of physiology is developing already — mathematical physiology, which is a specific source of a new knowledge about the nature of physiological processes. Even relevant textbooks have been written now on this subject [1]. Let's note that realistic computer models are the means of integrative description of a single subsystem and they take into account the relationships and interactions between different functional systems at different levels and time scales.

Taking into account as well that the possibilities of experimental approaches applying to the study of processes occurring in the respiratory and blood circulatory system are significantly limited, the development of effective software and algorithmic tools for numerical modeling and conducting of a full-scale computational experiment is particularly important.

Widespread computerization has substantiated the base for the development of theoretical bases for any phenomenon or process by simulating that phenomenon or process using computer. It is clear that the development of computer model follows the development of mathematical model. This is especially true for physiology and medicine. If in physics and chemistry the experimenter deals with inanimate objects with which any experiments could be carried out, then in addition to ethical norms, there are many other limitations associated with the impossibility of experimenting with various extreme perturbations and limitations of modern invasive methods. The complexity of the problem of mathematical models constructing for functional systems of organism is primarily due to the extreme complexity of examined biological system, the functioning of which nonlinearly depends on many factors, almost every element of living organism and these dependencies remain informal even at physiological level of description. Therefore, analytical methods of solutions have a rather narrow sphere of their use, and the main means for investigation of real problems linked with the respiratory and blood circulatory systems studying are computational methods of problems solving by computer.

## PROBLEM STATEMENT

The determining factors for choosing and formulating a mathematical model are the object, purpose, method and means of modeling [2]. Methods of dynamic systems theory are used for mathematical modeling. Means are differential and difference equations, methods of qualitative theory of differential equations, computer simulation. The purposes of mathematical modeling of organism functional systems are represented on Fig.1.

The main principle of complex systems mathematical modeling is the principle of optimality [3]. In [4] works related to extreme principles in mathematical biology were observed.

According to [5], two approaches are used for mathematical analysis of physiological functions — data models and system models. In the first case, the task is to build a mathematical function that describes as accurately as possible a set of input data, like statistical data model. This does not take into account the physiological features of structural and functional organizations of modeled object.

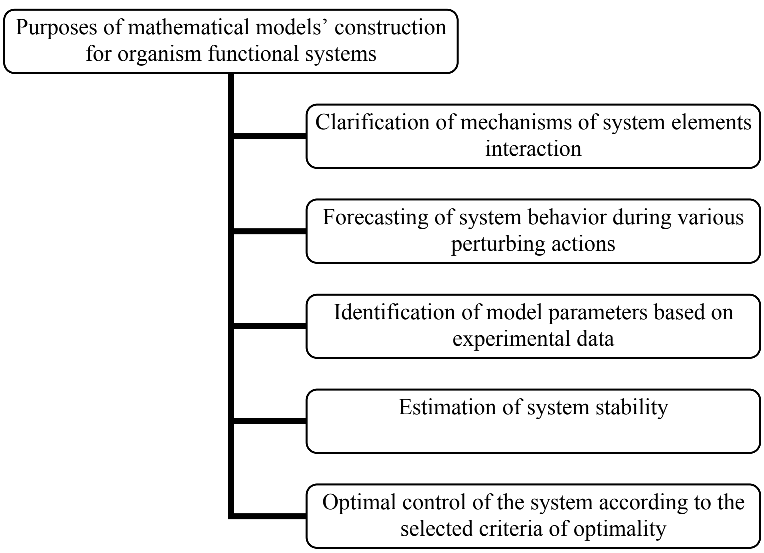



***Fig. 1.*** Purposes of organism functional systems modelling

Models of the second type are based on physiological principles and hypotheses about the structural and functional organization of modeled object. The purpose of modeling is to check the physiological hypothesis in base of the model and to elucidate the physiological mechanisms that underlie studied phenomenon or process. It should be noted that usually the results of physiological experiment analysis with the construction of data models are used as initial data for the next stage of research — the system analysis of these data models and development of mathematical model of the system functioning; it is directed on studying of the fundamental physiological mechanisms put in base of its functioning.

We would like to emphasize the following item. It has been already mentioned above that there is a lot of publications linked with modeling of separated subsystems as well as a whole organism [1]. Following papers have been published recently concerning mathematical models of respiratory and blood circulatory systems [6–25]. However, all these studies were based on complex mathematical apparatus, that was very difficult in practical use. These studies were rather more theoretical and they could be attributed to recently formed field — mathematical physiology. An approach to modeling, which supposes the use of developed models to solve applied problems in physiology and medicine has been proposed in present article.

As a rule, biological systems are self-organized systems that have controlling subsystems developed in the process of evolution; which provide the normal course of processes occurring in the system and executing of their functions within appropriate limits of disturbances. Classical theory of control offers now the whole class of mathematical models that describe the type of control of moving objects, if there is known the ultimate goal of control to be achieved by these objects, limited region of control parameters, as well as criterion of quality of control.

The self-organized systems are distinguished in the class of controlled dynamical systems, i.e. the systems that have the ability to transform the system into a state in which this influence becomes insignificant in response to the disturbing influence. The biosystems and homeostatic systems belong to such systems. Stationary solutions of dynamic systems of such objects are asymptotically stable. And, although the optimality of such systems is denied by some authors, it is always possible to define the purpose of self-organization as the ability to maintain an equilibrium state during disturbances coming to this system.

## PURPOSE OF THE PAPER

Purpose of the paper is to develop a mathematical model of functional systems of respiration and blood circulation; the model that take into account the interaction and inter-influence of organism functional systems, conflict situations between controlling and executive organs of self-regulation and based on the assumption about the optimality of regulation of organism oxygen regimes.

## PROBLEM SOLUTION

Methods of the theory of optimal control of respiration have aroused the constant interest of researchers of physiological systems, primarily due to the ideas about perfection of regulatory mechanisms in living systems. The specificity of application of the methods of optimal control theory into the study of physiological systems is that the criteria for their optimality are unknown. The task of the study is to determine whether a given physiological system is an optimal control system and what is the criterion for its optimality. Accordingly, such studies include the following steps:

– selection of object under the control and creation of its mathematical model;

– selection of hypothetical criterion of optimality basing on the data of experimental studies;

– creation of mathematical model of the system of optimal control, which includes the controlling subsystem (optimizer) and object of control;

– examination of the model of control in order to verify its adequacy.

Significant difficulties appear at each stage they were both of experimental and theoretical nature.

Therefore, the number of the works on this issue is insignificant and they have appeared recently [26].

The criterion of optimality are most often the indicators that are somehow related to the energy of organism, because the efficiency of physiological functions is not in doubt in general case. The model of regulation of parameters of organism external respiration and blood supply developed by Yu. N. Onopchuk was based on the assumption of optimality in system regulation by organism oxygen regimes [27].

Let's observe a class of nonlinear dynamic systems, the structure of which contains $m$ regions of utilization and creation of matter, linked with the system by transport pipeline network, which delivers this matter to the regions with special carrier. Usually, mathematical models that describe the processes that occur in such systems are balance-type models. It is assumed that in the pipeline system, the delivery of the substances, which can be both in dissolved form and chemically bound to other substances of the carrier, is carried out by forced convection. The transitions of the carrier to the region, or from the region to carrier are occurred by diffusion.

Let's denote by $x$ the concentration of the substance in carrier, $x_{i+1}$ in a given region ($i$ — are negative indices), $u_{i+1}$ — volumetric velocity of carrier in the region. Then the technological process of delivery and utilization of this substance in the chain "carrier-region" under consideration can be written by the system of differential equations [28]:

$$\frac{dx_i}{d\tau} = \frac{a_{1_i} u_i (y - x_i) + a_{2_i} u_i (\varphi(y) - \varphi(x_i)) - a_{3_i} (x_i - x_{i+1})}{V_i \cdot (\alpha_i + \beta_i \cdot \varphi'(x_i))} \tag{1}$$

$$\frac{dx_{i+1}}{d\tau} = \frac{a_{3_i} (x_i - x_{i+1}) - q_{i+1}^0 q(x_{i+1})}{V_{i+1} \left(\alpha_{i+1} + \beta_{i+1} \phi'(x_{i+1})\right)}, \tag{2}$$

where $V_i$ and $V_{i+1}$ is the carrier volumes in the region; $y$ is the concentration of the substance in the main pipeline; $q_{i+1}$ is the maximum rate of substance utilization in the region; $q(x_{i+1})$ is a function that adjusts the intensity of utilization of the substance in the region, $\varphi(x_i)$, $\phi(x_{i+1})$ is the chemical activity of organic compounds to the substance under consideration in the carrier and region, $\alpha_{1_i}, \alpha_{2_i}, \beta_{1_i}, \beta_{2_i}, a_{1_i}, a_{2_i}, a_{3_i}$ are positive coefficients that characterize the solubility of the substance in the carrier and region, diffusion of the substance between the carrier and region, chemical properties of the compounds of the carrier and the environment of the region.

Let's suppose that $\varphi(z)$, $\phi(z)$ $q(z)$ — nonlinear functions of $S$ type. In this case, let's assume that $\mu(z)$ — nonlinear function in the domain $z \geq 0$ refers to $S$ type, if in this domain it is smooth, non-decreasing and

$$\lim_{z \to +0} \mu(z) = 0, \quad \lim_{z \to +\infty} \mu(z) = 1, \tag{3}$$

$$\lim_{z \to +0} \mu'(z) = 0, \quad \lim_{z \to +\infty} \mu'(z) = 1. \tag{4}$$

In addition, it is assumed that among $m$ regions there is one region (for certainty, we assume that the first, i.e. the one for which $i = 1$) which is responsible for ensuring the circulation of the carrier in closed network of magisterial pipelines with volumetric velocity

$$u = \sum_{i=1}^{m} u_i. \tag{5}$$

Let's assume as well that the utilization of the substance in the region is accompanied by a given amount of work performed in the region. So, it is natural to assume that the rate of utilization of the substance in the first region is a function of the rate provided by this region:

$$q_2^0 = f(u) \tag{6}$$

and the rate of utilization of the substance $q_{i+1}^0$ ($i = 3, 5, ....$) for other regions is constant, which corresponds to the given level of energy consumption in the region.

Thus, we suppose a system of regions connected by the network of pipelines to ensure the delivery of energetic substance, and utilization of this substance in the regions is carried out to perform their functions. The external perturbation for this system is the concentration of the substance in the main pipeline and ensuring the directional movement of the carrier in it is placed on the first region.

Models of this type describe many of technological, physical, chemical, environmental processes that are usually stable. The questions of the existence, unity and stability of the solutions of the model (1), (2) are practically important, especially at the stage when the idea of trust in the results of modeling of particular process or system is formed.

In article [29] the following properties of the solutions of the system (1), (2) at $\varphi(x), \phi(x), q(x) \in C^2[0, \infty)$, were proved, which satisfy (3), (4) under the conditions: $y = \text{const} > 0$, $n_i = \text{const} > 0$, $i = 2k - 1$, $k = \overline{1, m}$.

Under the given at initial time $\tau_0 x_i(\tau_0) = x_i^0 \geq 0$, $\tau_0 x_{i+1}(\tau_0) = x_{i+1}^0 \geq 0$, $i = 2k - 1$, $k = \overline{1, m}$ the system (1), (2) has a unique solution $x\left(\tau, x_i^0, x_{i+1}^0, i = 2k - 1, k = \overline{1, m}\right)$.

The solution of the system (1), (2) is non-negative under non-negative initial conditions.

The solution of the system (1), (2) with non-negative initial data is limited from above.

The system (1), (2) has a single stationary solution $\{\overline{x}_i, \overline{x}_{i+1}, i = 2k-1, k = \overline{1,m}\}$.

The stationary solution (1), (2) is asymptotically stable.

The dynamic system (1), (2) can be considered as controlled, if the control effects cause the volumetric velocities $u_i$, $i = \overline{1,2m-1}$ of the carrier in the pipeline system.

Concerning the system (1), (2), we should not talk about controllability, but about the self-organization of the system, which is aimed at maintaining of some states of the system. The choice of $u_i$ in this type of systems should cause the compensation of disturbing effects on the system, to its transfer to some other stationary motion, which corresponds to influences on the system.

Let's write the conditions of stationarity for the system (1), (2). Any stationary trajectory satisfies the condition

$$x_i - x_{i+1} = \frac{q^0}{a_{3_i}} q_{i+1}(x_{i+1}), \quad i = \overline{1,2m-1},$$

which means that the positive difference $x_i - x_{i+1}$ in stationary motion is set in accordance with the level of utilization of the substance in this region. Therefore, any change in the value of $q^0_{i+1}$ should be perceived as perturbation influence on the system, and the problem of control can be considered as a problem of optimal (for example, in time) response of the system to the transition to a new stationary motion. The change in the concentration of the substance $y$ in the main pipeline can be interpreted similarly.

To solve the control problem in practice, it suffices to require that in the presence of perturbations the system (1), (2) to be transited into such a motion (close to stationary), which is determined by the set $M(t)$ that for all $\tau > t$ for all $\tau$ at the same time the condition below was satisfied

$$\frac{q^0_{i+1}}{a_{3_i}} q_{i+1}(x_{i+1}) - \varepsilon < x_i(\tau) - x_{i+1}(\tau) \le \frac{q^0_{i+1}}{a_{3_i}} + \varepsilon. \tag{7}$$

It can be shown [30] that under the influence of constant perturbations $q^0_{i+1} > 0$, $y > 0$ on the system (1), (2), any set $n_i > 0$ will transform the system in $M(t)$ for a finite time.

In process of examination of physiological and biological processes, it is advisable as a criterion for quality of control to choose an integrated criterion of following type

$$I(u) = \int_{\tau}^{\infty} \sum_i \sigma_i [a_{3_i}(x_i - x_{i+1}) - q^0_{i+1} q(x_{i+1})]^2 \, d\tau \tag{8}$$

and to solve the optimization problem with simple constraints for the control:

$$n_i \le n_i \le \overline{n}_i . \tag{9}$$

The coefficients $\sigma_i$ in (8) can be considered as the values of sensitivity of the region to deficit or excess of the substance, because in square brackets there is the expression of the differences between the rates of entry and utilization of the substance in the region.

Since the control task is to output the perturbations of the system in the $\varepsilon$-tube of stationary trajectory, the upper limit in (8) can be replaced by a finite number $T$.

Let's suppose that in the system with forced ventilation there are the mass transfers of three substances. One of them was utilized in the region, and the others were produced. The concentration of these three substances transported in the dispersed medium of main channel is maintained at constant levels. The dispersed medium contains two carriers-adsorbents, which form the dispersed phase of circulating mixture. One carrier carries only one substance, the other one — two substances simultaneously.

The third substance is transported only in dissolved form. All three substances can diffuse through the phase distribution surface. Sorbent located in a region, can bind a substance that is carried by only one carrier in regional channel, and that is utilized in parallel with the production of another substance. One example of such a system may be the blood gas transfer system to the tissues.

Let's consider the blood of regional channels as circulating mixture - generalized tissue capillaries, in regions — tissue cylinders, substances that transport oxygen, carbon dioxide and nitrogen. So, the state of this system will be characterized by the levels of partial pressures of these gases in dispersed medium, i.e. blood plasma and tissue reservoirs, which depending on the rate of oxygen utilization can be regulated under the given conditions of internal or external environment by changing the volumetric flow rate of the circulating mixture (blood in the main and regional channels). Experimental studies have demonstrated that in some disturbances of the environment — reducing the partial pressure of gases, increasing the rate of oxygen utilization and etc. — the role of mechanisms that regulate circulation, in stabilizing the system parameters is the main. The methods of mathematical modeling and apparatus of the theory of automatic regulation are successfully used in studying the rules of these mechanisms functioning under the different conditions. Studies also have shown that any of known basic regulatory schemes cannot explain the compensating reaction, regulation of self-organization of processes occurring in the system – direct or feedback control, perturbation control and etc.

In general, the equations of the dynamics of partial pressures and stresses of respiratory gases $pO_2$, $pCO_2$ and $pN_2$ in respiratory tract, alveolar space, arterial and mixed venous blood, blood tissue capillaries and tissues were built on the principles of material balance and continuity of flow are as follows [31] – [33]:

$$\frac{dp_iO_2}{d\tau} = \varphi(p_iO_2, p_iCO_2, \eta_i, \dot{V}, Q, Q_{t_i}, G_{t_i}O_2, q_{t_i}O_2) \tag{10}$$

$$\frac{dp_iCO_2}{d\tau} = \psi(p_iO_2, p_iCO_2, \eta_i, \dot{V}, Q, Q_{t_i}, G_{t_i}CO_2, q_{t_i}CO_2), \qquad (11)$$

where the functions φ and $\psi$ were described in detail in [31] – [33]; $\dot{V}$ is the ventilation; η is the degree of oxygen saturation of hemoglobin; $Q$ is the volumetric rate of systemic and $Q_{t_i}$ local blood circulation; $q_{t_i}O_2$ is the rate of oxygen consumption by $i$ th tissue reservoir; $q_{t_i}CO_2$ is the rate of carbon dioxide release in $i$ th tissue reservoir. The flow rate $G_{t_i}O_2$ of oxygen from the blood into the tissue, and $G_{t_i}CO_2$ carbon dioxide from the tissue into the blood is determined by the ratio

$$G_{t_i} = D_{t_i}S_{t_i}(p_{ct_i} - p_{t_i}),$$

where $D_{t_i}$ is the gas permeability coefficients through the air barrier, $S_{t_i}$ is the gas exchange surface area.

The participation of biochemical structures — hemoglobin, myoglobin and buffer bases in processes of mass transfer of gases add significant nonlinearity in the system of differential equations. Naturally that all these cause serious difficulties for mathematical analysis of dynamic system, but there is very powerful mechanism for maintaining of gas homeostasis of organism, and from the standpoint of theory of control — the mechanism of control.

All the values that characterize the process of mass transfer of gases in living organism are non-negative and limited, moreover, the limits of changes of some of them are quite narrow. The theory of mathematical modeling requires usually a qualitative study of the models to determine the area of adequate description of the studied process. We need to be sure in the existence and unity of the solutions of the system of equations and to study the nature of these solutions.

In article [30] the following statements were proved.

1) For given at the initial moment of time $\tau_0$ $p_{j_{ct_i}}(\tau_0) = p^0_{j_{ct_i}} > 0$, $p_{j_{t_i}}(\tau_0) = p^0_{j_{t_i}} > 0$, $j = \overline{1,3}$, $i = \overline{1,m}$ there is only one solution of the system (10), (11) $p(\tau, p^0_{j_{ct_i}}, p^0_{j_{t_i}}, j = \overline{1,3}, i = \overline{1,m}$.

2) If $\lim_{p_{j_{t_i}} \to 0} q_{j_{t_i}} = 0$, $q_{j_{t_i}} = 0$, when $p_{j_{t_i}} = 0$ then the solution of the system (10), (11) is positive under positive initial conditions.

3) The solution of system (10), (11) is limited from above in the conditions of statement 1.

4) The system (10), (11) has a unique stationary solution for $p_{j_a} = \text{const}$, $j = \overline{1,3}$, $Q_i = \text{const}$, $i = \overline{1,m}$.

5) The stationary solution of the system (10), (11) is asymptotically stable.

There are two main types of models of regulation of blood circulation are possible to be selected [27], [29]. To the first one it is expedient to relate those models at which construction the principles of the theory of automatic regulation were used. The choice of values of systemic and local blood circulation as control parameters is aimed on the eliminating of respiratory gas stresses deviations from the "setpoint" values that occur when the system is disturbed. It is necessary to know these values for each specific type of environmental conditions, the level of functional loading etc. Such models are effective in practice, but they do not allow revealing the causal-consequential links of regulation. The second type of models includes more general models of gas dynamics control in organism using the principle of maximum by Pontryagin [34].

However, the calculated data differed from those obtained experimentally. In addition, the calculated data did not answer a number of theoretical and applied questions. For example, they did not explain the reasons of tissue hypoxia during muscle work of low intensity, staying in hypoxic environment (when the reserves for the growth of systemic circulation are present still), the role of hypercapnic regulatory stimulus at hypoxia of loading known in physiology, hypoxic hypoxia etc.

The model proposed in [31] – [33] and developed for these problems solutions was based on following principles:

– modeled system is considered as self-organized, respectively, the model was also formulated as a model of blood circulation self-organization. Self-organization means the ability of the model when the perturbations to change the system parameters were such as, that the effect of perturbations was insignificant. At the same time, certain quality criteria should be minimized.

– the control in such systems should be carried out with the resolution of conflict situations of various natures that appear.

We formulate the problem of system control (10), (11) as follows. It is necessary to transmit the perturbed dynamical system (10), (11) into the multitude

$$M(\tau)=\begin{cases} \dfrac{\dot{q}_{t_i}\mathrm{O}_2\cdot\tau-\varepsilon_i^{\mathrm{O}_2}}{n_{t_i}\mathrm{O}_2\cdot k_{t_i}\mathrm{O}_2\cdot S_{t_i}}\le\displaystyle\int_{\tau_0}^{\tau_0+\tau}(p_{ct_i}\mathrm{O}_2-p_{t_i}\mathrm{O}_2)d\xi\le\dfrac{\dot{q}_{t_i}\mathrm{O}_2\cdot\tau+\varepsilon_i^{\mathrm{O}_2}}{n_{t_i}\mathrm{O}_2\cdot k_{t_i}\mathrm{O}_2\cdot S_{t_i}}, \\ \dfrac{\dot{q}_{t_i}\mathrm{CO}_2\cdot\tau-\varepsilon_i^{\mathrm{CO}_2}}{n_{t_i}\mathrm{CO}_2\cdot k_{t_i}\mathrm{CO}_2\cdot S_{t_i}}\le\displaystyle\int_{\tau_0}^{\tau_0+\tau}(p_{ct_i}\mathrm{CO}_2+p_{t_i}\mathrm{CO}_2)d\xi\le\dfrac{\dot{q}_{t_i}\mathrm{CO}_2\cdot\tau+\varepsilon_i^{\mathrm{CO}_2}}{n_{t_i}\mathrm{CO}_2\cdot k_{t_i}\mathrm{O}_2\cdot S_{t_i}}, \\ -\varepsilon_i^{N_2}\le\displaystyle\int_{\tau_0}^{\tau_0+\tau}(p_{ct_i}N_2-p_{t_i}N_2)d\xi\le\varepsilon_i^{N_2}, \end{cases} \quad (12)$$

with minimum of functional:

$$I=\int_{\tau_0}^{\tau_0+T}\sum_{i=1}^{m}[\rho_1\lambda_1(G_{t_i}O_2-q_{t_i}O_2)^2+\rho_2\lambda_2(G_{t_i}O_2+ q_{t_i}CO_2)^2+\rho_3\lambda_3(G_{t_i}N_2)^2]d\tau, \quad (13)$$

where $\rho_1,\rho_2,\rho_3$ are coefficients that characterize the sensitivity of particular organism to oxygen deficiency, excess of carbon dioxide, and increase of nitrogen concentration, respectively; $\lambda_t$ are coefficients that reflect the functional and morphological features of particular region.

Restrictions are imposed on control parameters:

$$0 \le Q_i \le Q , \quad i = \overline{1,m} . \tag{14}$$

The multitude $M(\tau)$ is a terminal multitude of states of the system, which has a homeostatic property — gas stresses were set at certain level, the rates of oxygen utilization and carbon dioxide removal corresponded to the rates of oxygen utilization and carbon dioxide removal in all tissue regions of organism. In this case, the moment of time $\tau$ is precisely the moment at which this homeostatic property of the system is manifested. Functional (13) is a quality criterion of accepted law of control.

In this problem's formulation of the process of gases mass transfer regulating, we can speak about the optimal choice of volumetric velocity of organism blood circulation in relation to criterion (13). The accepted form of setting the problem of control is consistent with the conceptual models that currently exist in contemporary respiratory physiology. It is important to make sure that the set of solutions to formulated problem is not empty. Also in [30] it was proved that when the system (10), (11) is affected by constant perturbations $\dot{q}_{t_i} O_2$, $\dot{q}_{t_i} CO_2$, $p_a O_2$, $p_a CO_2$, $p_a N_2$ a number of constants $\dot{Q}_i$, $i = \overline{1,m}$, which satisfy (14) will deduce the trajectories of the system in $M(\tau)$ during finite period of time.

$$q_{ск.м} = \sigma \dot{Q} \gamma , \tag{15}$$

where $\sigma, \gamma > 0$.

Let's note that the formulation of the optimal control problem (10), (11), (9), (12), (13) is such that gas homeostasis is understood as the relative constancy of oxygen, carbon dioxide and nitrogen stresses. It consists on the compromise formation of corresponding homeostasis levels to the disturbance in resolution of conflicts of both regional and systemic nature. The Fick ratio can be used to calculate how much it is necessary to increase the volume of blood circulation through the working skeletal muscles in order to maintain oxygen tension in them at constant level. When comparing the calculated data with the experimental ones, it was appeared that the first ones exceed the experimental values significantly. According to the proposed model, this is due to ignoring the nature of conflict that arises in organism between the groups of functioning tissues and the heart muscle, which provides the necessary cardiac output. In fact, such situations occur every time with the changes of organism living conditions. An increase in muscle intensity requires corresponding increase in blood circulation in muscles (otherwise there will be oxygen deficiency in the muscles) and it can be achieved by changing the systemic circulation or its redistribution. In the first case, the intensity of the heart muscle increases (because oxygen deficiency arise in it), in the second — the decrease in blood circulation in tissue reservoirs of other organs appears, which at a constant rate of oxygen consumption causes hypoxia development in tissue. Thus, changing the conditions of external or internal environment to maintain gas homeostasis in one muscle group requires the blood circulation increase, which is contrary to the interests of other tissues, because it causes oxygen deficiency. This conflict resolution is in finding a compromise, in which all tissues, on average, feel oxygen deficiency, and their average oxygen tensions decrease. In the model, this is represented by introduction of heart muscle oxygen consumption rate dependence on the volumetric rate of systemic circulation

$$q_{sc.m} = \sigma \dot{Q} \gamma, \tag{16}$$

where $\sigma, \gamma > 0$. The dependence of the rate of oxygen consumption in tissues of brain, kidneys, liver is determined by Michaelis–Menten ratio

$$q_t \, O_2(\tau) = q_t^0 \, O_2 \frac{p_t \, O_2}{k + p_t \, O_2}, \tag{17}$$

where $k$ is Michaelis constant.

In skeletal muscles, including peripheral tissues, the oxygen consumption rate is determined by the ratio

$$q_t \, O_2(\tau) = q_t^0 \, O_2 \frac{\eta(\tau)}{\eta}, \tag{18}$$

where $q_t^0 \, O_2$ is a rate of oxygen consumption under normal environmental conditions at known intensity of physical activity; $\eta$ is the degree of saturation of hemoglobin with oxygen in these conditions; $\eta(\tau)$ is the degree of saturation of hemoglobin with oxygen under altered experimental conditions.

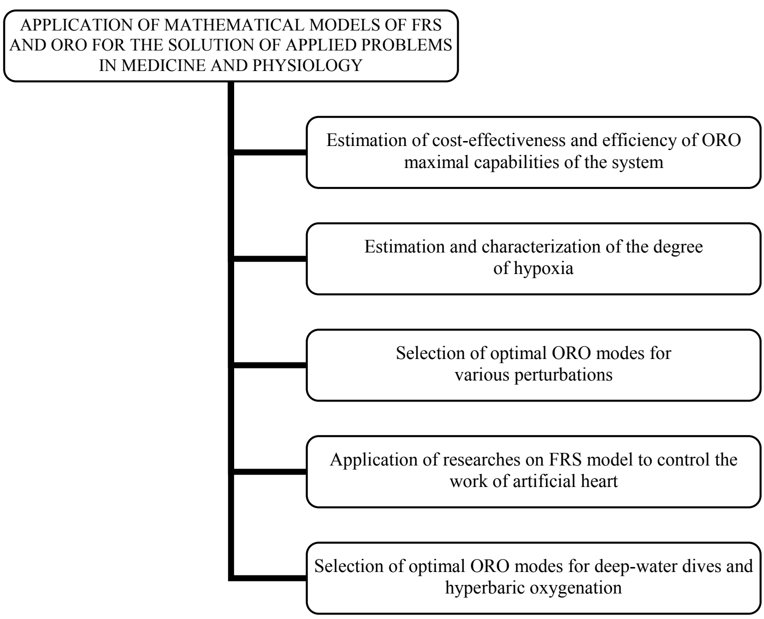



***Fig. 2.*** Application of mathematical models of respiratory system self-organization for the solution of applied problems in medicine and physiology

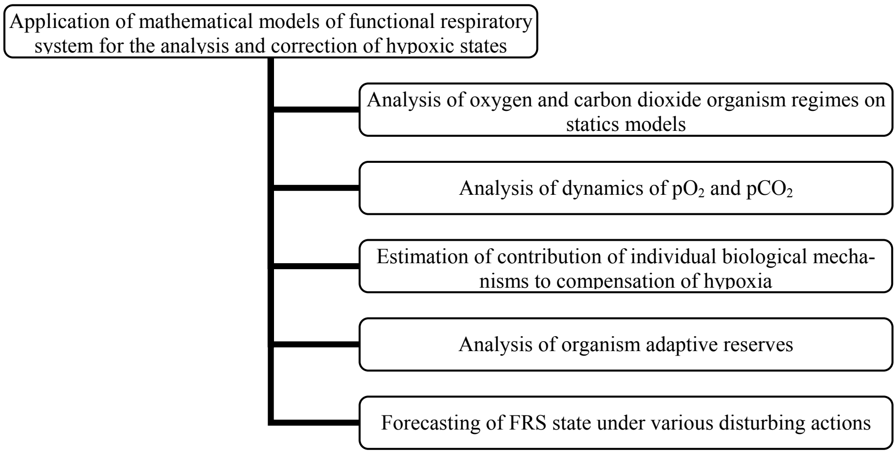



***Fig. 3.*** Application of mathematical models of FRS for analysis and correction of hypoxic states

This model also permits the resolution of conflicts that arise between organism subsystems, which provide hypercapnic, hyperazotic stimulation of respiration due to the quality criterion in the form of criterion (13), which provides a compromise minimization of inconsistencies in flows and utilization (release) of gases in tissues.

This approach to the problem of optimal control for the investigation of self-organization process of the functional respiratory system in adaptation to extreme disturbances has been widely used to solve practical problems in occupational medicine and sports (Fig. 2). In particular, in the authors' investigations with determining the parameters of self-organization of mountain rescuers respiratory systems at mid-term and short-term adaptation to hypoxic hypoxia [35] – [37], and athletes specialized in combat sports [38], [39]. Also, the proposed models could be used for the analysis and correction of hypoxic states as well (Fig. 3).

## CONCLUSIONS

The mathematical model of functional system self-organization, which is based on the taking into account the conflict situation between the controlling and executive organs of self-regulation is described in present article. The purposes of the functioning, resource of control, criteria of effective self-organization are defined in present study. This approach has made it possible to solve a number of problems in occupational medicine and sports of the highest achievements, related to the prediction of parameters of self-organization of respiratory and blood circulatory systems in adaptation to extreme environmental disturbances.

REFERENCES

1. Keener J., Sneyd J. Mathematical physiology. Springer-Verlag New York, 1998.
2. Anokhin P.K. Fundamental questions of general theory of functional systems. The principles of systemic organization of the functions. Moscow: Nauka, 1973, 258 p. [In Russian]
3. Balanter B.I. Introduction to mathematical modeling of pathological processes. M .: Medicine, 1980, 262 p. [In Russian]
4. Fursova I.V. Extreme principles in mathematical biology. *Advances in contemporary biology.* 2003,123, 2, pp. 115–117. [In Russian]

5. Mesentseva L.V., Pertsov S.S. Mathematical modeling in biomedicine. *Journal of new medical technologies*. 2013, XX, 1, pp.11–14.
6. Diekman C.O., Thomas P.J., Wilson, C.G. Eupnea, tachypnea, and autoresuscitation in a closed-loop respiratory control model. *J. Neurophysiol*. 2017, 118, pp. 2194–2215. doi:10.1152/jn.00170.2017
7. Duffin, J. Model validation and control issues in the respiratory system. *Mathematical Modeling and Validation in Physiology Lecture Notes in Mathematics*, eds J. J. Batzel, M. Bachar, F. Kappel (Berlin; Heidelberg; Springer), 2013, pp.133–162.
8. Fincham W. F., Tehrani F. T. A mathematical model of the human respiratory system. *J. Biomed. Eng*. 1983, 5, pp. 125–133. doi: 10.1016/0141-5425(83)90030-4
9. Serna Higuita L.Y., Mañanas M.A., Hernández A.M., Marína Sánchez J., Benito S. Novel modeling of work of breathing for its optimization during increased respiratory efforts. *IEEE Syst. J.* 2014, 10, pp. 1003–1013. doi: 10.1109/JSYST.2014.2323114
10. Serna L.Y., Marín J., Hernández A.M., Mañanas, M.Á. Optimization techniques applied to parameter estimation in respiratory control system models. *Appl. Soft Comput*. 2016, 48, pp. 431–443. doi: 10.1016/j.asoc.2016.07.033
11. Tsai N. C., Lee R. M. Interaction between cardiovascular system and respiration. *Appl. Math. Model*. 2011, 35, pp. 5460–5469. doi: 10.1016/j.apm.2011.04.033
12. Serna L.Y., Mañanas M.A., Hernández A.M., Rabinovich R.A. An Improved Dynamic Model for the Respiratory Response to Exercise. *Front. Physiol*. 2018, 9.69. doi: 10.3389/fphys.2018.00069
13. Ellwein Fix L., Khoury J., Moores R.R.Jr., Linkous L., Brandes M., Rozycki H.J. Theoretical open-loop model of respiratory mechanics in the extremely preterm infant. *PLoS ONE* .2018, 13(6): e0198425. https://doi.org/10.1371/journal.pone.0198425
14. Ebrahimi Nejad S., Carey J.P., McMurtry M.S., Hahn J.-O. Model-based cardiovascular disease diagnosis: a preliminary in-silico study. *Biomech Model Mechanobiol.* 2017, 16, pp. 549–560 (2017). https://doi.org/10.1007/s10237-016-0836-8
15. Quarteroni A, Formaggia L. Mathematical modelling and numerical simulation of the cardiovascular system. *Handb Numer Anal.* 2004, 12:7–9. DOI: 10.1016/S1570-8659(03)12001-7
16. Quarteroni A., Manzoni A., Vergara C. The cardiovascular system: mathematical modelling, numerical algorithms and clinical applications. *Acta Numer.* 2017.26.365–590. DOI: https://doi.org/10.1017/S0962492917000046
17. Capoccia M., Marconi S., Singh S.A., Pisanelly D.M., De Lazzari C. Simulation as a preoperative planning approach in advanced heart failure patients. A retrospective clinical analysis. *BioMed Eng OnLine.* 2018, 17, 52 . https://doi.org/10.1186/s12938-018-0491-7
18. Korobov A.A., Frolov S.V., Aliyev N.E., Rodionova I.E. Dual-contoured model of cardiovascular system regulation. *J. Phys.: Conf. Ser.* 2020, 1553 012006 DOI:10.1088/1742-6596/1553/1/012006
19. Albanese A., Cheng L., Ursino M., Chbat N.W. An integrated mathematical model of the human cardiopulmonary system: model development. *Am J Physiol Heart Circ Physiol.* 2016, Apr 1;310(7):H899-921. doi: 10.1152/ajpheart.00230.2014.
20. Cheng L., Albanese A., Ursino M., Chbat N.W. An integrated mathematical model of the human cardiopulmonary system: model validation under hypercapnia and hypoxia. *Am J Physiol Heart Circ Physiol.* 2016, Apr 1;310(7):H922-37. doi: 10.1152/ajpheart.00923.2014
21. Sarmiento C.A., Hernández A.M., Serna L.Y., Mañanas M.Á. An integrated mathematical model of the cardiovascular and respiratory response to exercise: model-building and comparison with reported models. *Am J Physiol Heart Circ Physiol.* 2021, Apr, 1;320(4):H1235-H1260. doi: 10.1152/ajpheart.00074.2020.
22. Trenhago P.R., Fernandes L.G., Müller L.O., Blanco P. J., Feijóo R.A. An integrated mathematical model of the cardiovascular and respiratory systems. *Int. J. Numer. Methods Biomed. Eng.* 32 2016, no. 1, e02736, 25 pp.
23. Zhou S, Xu L, Hao L, Xiao H, Yao Y, Qi L, Yao Y. A review on low-dimensional physics-based models of systemic arteries: application to estimation of central aortic pressure. *Biomed Eng Online.* 2019, Apr 2;18(1):41. doi: 10.1186/s12938-019-0660-3.

24. Maury B. The Respiratory System in Equations. Springer. 2013, 278 p. DOI:10.1007/978-88-470-5214-7
25. Fouchet-Incaux, J. Artificial boundaries and formulations for the incompressible Navier–Stokes equations: applications to air and blood flows. *SeMA*. 2014, 64, pp.1–40. https://doi.org/10.1007/s40324-014-0012-y
26. Bobryakova I. L., "Sensitivity of mathematical model and optimality of regulation of the functional respiratory system," *diss. Candidate of Physical and Mathematical Sciences Sciences*, Kyiv, 2000, 179 p. [In Russian]
27. Onopchuk Yu.N. About one scheme of regulation of external respiration modes, minute blood volume and tissue blood flow at oxygen request. *Cybernetics*. 1980, No. 6, pp. 110–115 [In Russian]
28. Onopchuk Yu.N. On the construction of model for optimal distribution of blood flow in human tissues and organs — In the book: *Theory of optimal solutions.* Kyiv, 1979, pp. 80–86 [In Russian]
29. Onopchuk Yu.N. Controlled models of organism gas dynamics and their numerical analysis. Dis ... ..doct. phys.-mat. sciences. Kyiv, 1984, 208 p. [In Russian]
30. Onopchuk Yu. N., "Equilibrium states and transients in the systems of external respiration and blood circulation. Research on a mathematical model," *Cybernetics*. 1981, no. 1, pp. 136–139. [In Russian]
31. Onopchuk Yu. N. Homeostasis of functional respiratory system as a result of intersystem and system-medium informational interaction. *Bioecomedicine. Uniform information space. Ed. by V. I. Gritsenko*. Kyiv*,* 2001, pp. 59–84. (In Russian).
32. Onopchuk Yu. N. Homeostasis of the functional circulatory system as a result of intersystem and system-medium informational interaction. *Bioecomedicine. Uniform information space. Ed. by V. I. Gritsenko.* Kyiv, 2001, pp. 85–104. (In Russian).
33. Aralova N. I. Mathematical models of functional respiratory system for solving the applied problems in occupational medicine and sports. Saarbrücken: LAP LAMBERT Academic Publishing GmbH&Co, KG. 2019, 368 p. (In Russian). ISBN 978-613-4-97998-6
34. Pontryagin L.S., Boltyansky V.G., Gamkrelidze R.V., Mishchenko E.F., Mathematical theory of optimal processes. Moscow: Nauka. 1983, 392 p.
35. Aralova N. I. Mathematical model of the mechanism short- and medium-functional adaptation of breath of persons work in extreme conditions high. *Kibernetika i vychislitelnaya tekhnika.* 2015, V. 182, pp. 15–25.
36. Onopchuck Y. N., Beloshitsky P. V., Aralova N. I. To problem of reliability of functional systems in organism. *Kibernetika i vychislitelnaya tekhnika.*1999, V. 122, pp. 72–82. ISSN - 0454-9910. (In Russian).
37. Beloshitsky P. V., Onopchuk Yu. M., Aralova N. I. Mathematical methods for the investigation of the problem of organism functioning reliability at extreme high mountains conditions. *Physiol. Journal.*2003,V. 49, № 3, pp. 47–54 (in Russian).
38. Aralova N. I. Information technologies of decision-making support for rehabilitation of sportsmen engaged in combat sport. *J. Automation Information Sci.* 2016, V. 3, pp. 160–170. https://doi:10.1615 / JAutomatInfScien.v48. i6.70
39. Onopchuk Yu.N., Aralova N.I., Beloshitsky P.V., Podlivaev B. A., Mastycash Yu. I. Forecasting of wrestler' state in the combat on the base of mathematic model of functional respiratory system. *Computer mathematics.* 2005, № 2, pp. 69–79 (In Russian)

Received: 27.05.2021

ЛІТЕРАТУРА

1. Keener J., Sneyd J. Mathematical physiology. Springer-Verlag New York, 1998.
2. Анохин П.К. Принципиальные вопросы общей теории функциональных систем. Принципы системной организации функций. М.: Наука, 1973. 258 с.
3. Балантер Б.И. Введение в математическое моделирование патологических процессов. М.: Медицина, 1980. 262 с.
4. Фурсова И.В. Экстремальные принципы в математической биологии. *Успехи современной биологии.* 2003. 123, 2. С. 115–117.

5. Мезенцева Л.В., Перцов С.С.Математическое моделирование в биомедицине. *Вестник новых медицинских технологий.* 2013. XX, 1. С.11–14.
6. Diekman C.O., Thomas P.J., Wilson C.G. Eupnea, tachypnea, and autoresuscitation in a closed-loop respiratory control model. *J. Neurophysiol*. 2017.118. C. 2194–2215. doi: 10.1152/jn.00170.2017
7. Duffin, J. Model validation and control issues in the respiratory system. *Mathematical Modeling and Validation in Physiology Lecture Notes in Mathematics*, eds J. J. Batzel, M. Bachar, F. Kappel (Berlin; Heidelberg; Springer). 2013. C. 133–162.
8. Fincham W. F., Tehrani F. T. A mathematical model of the human respiratory system. *J. Biomed. Eng*. 1983.5. C. 125–133. doi: 10.1016/0141-5425(83)90030-4
9. Serna Higuita L.Y., Mañanas M.A., Hernández A.M., Marína Sánchez J., Benito S. Novel modeling of work of breathing for its optimization during increased respiratory efforts. *IEEE Syst. J.* 2014. 10. C. 1003–1013. doi: 10.1109/JSYST.2014.2323114
10. Serna L.Y., Marín J., Hernández A.M., Mañanas, M.Á. Optimization techniques applied to parameter estimation in respiratory control system models. *Appl. Soft Comput*. 2016. 48. C. 431–443. doi: 10.1016/j.asoc.2016.07.033
11. Tsai N. C., Lee R. M. Interaction between cardiovascular system and respiration. *Appl. Math. Model*. 2011. 35. C. 5460–5469. doi: 10.1016/j.apm.2011.04.033
12. Serna L.Y., Mañanas M.A., Hernández A.M., Rabinovich R.A. An Improved Dynamic Model for the Respiratory Response to Exercise. *Front. Physiol*. 2018. 9.69. doi: 10.3389/fphys.2018.00069
13. Ellwein Fix L., Khoury J., Moores R.R.Jr., Linkous L., Brandes M., Rozycki H.J. Theoretical open-loop model of respiratory mechanics in the extremely preterm infant. *PLoS ONE 2018*. 13(6): e0198425. https://doi.org/10.1371/journal.pone.0198425
14. Ebrahimi Nejad S., Carey J.P., McMurtry M.S., Hahn J.-O. Model-based cardiovascular disease diagnosis: a preliminary in-silico study. *Biomech Model Mechanobiol.* 2017. 16. C. 549–560. https://doi.org/10.1007/s10237-016-0836-8
15. Quarteroni A, Formaggia L. Mathematical modelling and numerical simulation of the cardiovascular system. *Handb Numer Anal.* 2004.12:7–9. DOI:10.1016/S1570-8659(03)12001-7
16. Quarteroni A., Manzoni A., Vergara C. The cardiovascular system: mathematical modelling, numerical algorithms and clinical applications. *Acta Numer.* 2017.26.365–590. DOI: https://doi.org/10.1017/S0962492917000046
17. Capoccia M., Marconi S., Singh S.A., Pisanelly D.M., De Lazzari C. Simulation as a preoperative planning approach in advanced heart failure patients. A retrospective clinical analysis. *BioMed Eng OnLine.* 2018. 17. 52 . https://doi.org/10.1186/s12938-018-0491-7
18. Korobov A.A., Frolov S.V., Aliyev N.E., Rodionova I.E. Dual-contoured model of cardiovascular system regulation. *J. Phys.: Conf. Ser.* 2020. 1553 012006 DOI:10.1088/1742-6596/1553/1/012006
19. Albanese A., Cheng L., Ursino M., Chbat N.W. An integrated mathematical model of the human cardiopulmonary system: model development. *Am J Physiol Heart Circ Physiol.* 2016. Apr 1. 310(7):H899-921. doi: 10.1152/ajpheart.00230.2014.
20. Cheng L., Albanese A., Ursino M., Chbat N.W. An integrated mathematical model of the human cardiopulmonary system: model validation under hypercapnia and hypoxia. *Am J Physiol Heart Circ Physiol.* 2016. Apr 1. 310(7):H922-37. doi: 10.1152/ajpheart.00923.2014
21. Sarmiento C.A., Hernández A.M., Serna L.Y., Mañanas M.Á. An integrated mathematical model of the cardiovascular and respiratory response to exercise: model-building and comparison with reported models. *Am J Physiol Heart Circ Physiol.* 2021. Apr 1. 320(4):H1235-H1260. doi: 10.1152/ajpheart.00074.2020.
22. Trenhago P.R., Fernandes L.G., Müller L.O., Blanco P. J., Feijóo R.A. An integrated mathematical model of the cardiovascular and respiratory systems. *Int. J. Numer. Methods Biomed. Eng.* 2016. 32. no. 1, e02736, 25 pp.
23. Zhou S, Xu L, Hao L, Xiao H, Yao Y, Qi L, Yao Y. A review on low-dimensional physics-based models of systemic arteries: application to estimation of central aortic pressure. *Biomed Eng Online.* 2019. Apr 2. 18(1):41. doi: 10.1186/s12938-019-0660-3.

24. Maury B. The Respiratory System in Equations. Springer. 2013. 278 c. DOI: 0.1007/978-88-470-5214-7
25. Fouchet-Incaux, J. Artificial boundaries and formulations for the incompressible Navier–Stokes equations: applications to air and blood flows. *SeMA* 64. 2014. С. 1–40. https://doi.org/10.1007/s40324-014-0012-y
26. Бобрякова И.Л. Чувствительность математической модели и оптимальность регуляции функциональной системы дыхания. дисс. канд.физ.-мат. наук, Киев, 2000. 179 с.
27. Онопчук Ю.Н. Об одной схеме регуляции режимов внешнего дыхания, минутного объема крови и тканевого кровотока по кислородному запросу. *Кибернетика.*1980. № 6. С. 110–115.
28. Онопчук Ю.Н. К вопросу о построении модели оптимального распределения кровотока по тканям и органам человека. В кн.: Теория оптимальних решений. Киев, 1979, с. 80–86.
29. Онопчук Ю.Н. Управляемые модели газовой динамики организма и их численный аналіз Дис…..докт. физ.–мат. наук. Киев, 1984. 208 с.
30. Онопчук Ю.Н. Равновесные состояния и переходные процессы в системах внешнего дыхания и кровообращения. Исследования на математической модели.*Кибернетика.* 1981, № 1. С. 136–139.
31. Онопчук Ю.Н. Гомеостаз функциональной системы дыхания как результат внутрисистемного и системно-средового информационного взаимодействия. *Биоэкомедицина. Единое информационное пространство*.Киев. 2001. С. 59–81.
32. Онопчук Ю.Н. Гомеостаз функциональной системы кровообращения как результат внутрисистемного и системно-средового информационного взаимодействия *Биоэкомедицина. Единое информационное пространство.* Киев.2001. С. 82–104.
33. Аралова Н.И. Математические модели функциональной системы дыхания для решения прикладных задач медицины труда и спорта. Saarbrücken: LAP LAMBERT Academic Publishing GmbH&Co, KG. 2019. 368 с.ISBN 978-613-4-97998-6
34. Понтрягин Л.С., Болтянский В.Г., Гамкрелидзе Р.В., Мищенко Е.Ф. Математическая теория оптимальных процессов. М.: Наука. 1983.392 с. ИБ № 12370.
35. Аралова Н.И. Математическая модель механизмов краткосрочной и среднесрочной адаптации функциональной системы дыхания лиц, работающих в экстремальных условиях Кибернетика *и вычислительная техника.* 2015. Вып. 182. С. 15–25.
36. Онопчук Ю.Н., Белошицкий П.В, Аралова Н.И. К вопросу о надежности функциональных систем организма. *Кибернетика и вычислительная техника.*1999. Вып. 122. С. 72–82.
37. Білошицький П.В., Онопчук Ю.М., Аралова Н.І. Математичні методи дослідження проблеми надійності функціонування організму за екстремальних умов високогір'я *Фізіол.журнал.* 2003.Т. 49. № 3. С. 47–54.
38. Aralova N. I. Information technologies of decision-making support for rehabilitation of sportsmen engaged in combat sport. *J. Automation Information Sci.* 2016. V. 3. P. 160–170. https://doi:10.1615 / JAutomatInfScien.v48. i6.70
39. Онопчук Ю.Н., Аралова Н.И., Белошицкий П.В., Подливаев Б.А., Мастыкаш Ю.И. Прогнозирование состояния борца в процессе поединка на основе математической модели функциональной системы дыхания. *Компьютерная математика.* 2005. № 2. С. 69–79.

Received: 27.05.2021

*Аралова Н.І.*[1], д-р техн. наук, старш. наук. співроб.
старш. наук. співроб. відд оптимізації керованих процесів
ORCID 0000-0002-7246-2736, e-mail: aralova@ukr.net
*Ключко О.М.*[2], канд. біол. наук, доцент
доцент факультету аеронавігації
ORCID 0000-0003-4982 7490, e-mail: kelenaXX@nau.edu.ua
*Машкін В.Й.*[1] канд. техн. наук, старш. наук. співроб.
старш. наук. співроб. відд. оптимізації керованих процесів
ORCID 0000-0002-4479-6498, e-mail: mashkin_v@ukr.net
*Машкіна І.В.* [3], канд. техн. наук, доцент
доцент факультету інформаційних технологій та менеджменту
ORCID 0000-0002-0667-5749, e-mail: mashkina@kubg,edu.ua
*Радзієвський П.О.* [4], д-р біол. наук, професор
професор факультету менеджменту,
відд. систем керування інноваціями та безпекою
ORCID 0000-0001-8232-2705, e-mail: pawel.radziejowski@ pcz.pl
*Радзієвська М.П.*[4], д-р біол. наук, професор
професор факультету менеджменту,
відд. систем керування інноваціями та безпекою
ORCID 0000-0002-9845-390X, e-mail: maria.radziejowska@pcz.pl
[1] Інститут кібернетики імені В.М. Глушкова НАН України
пр. Глушкова, 40, Київ, 03187, Україна
[2] Інститут електроніки та телекомунікацій Національного авіаційного університету
пр. Любомира Гузара, 1, Київ, 03058, Україна
[3] Київський університет імені Бориса Грінченка
вул. Бульварно-Кудрявська, 18/2, Київ, 04053, Україна,
[4] Czestochowa University of Technology
19b, Armii Krajowej str., 42-200, Częstochowa, Poland

# МАТЕМАТИЧНА МОДЕЛЬ КОНФЛІКТНО-КЕРОВАНИХ ПРОЦЕСІВ ПРИ САМООРГАНІЗАЦІЇ СИСТЕМИ ДИХАННЯ

**Вступ.** Різноманітні процеси, які відбуваються в середовищі, є керованими, тобто їх стан визначається в залежності від конкретного впливу системи, яка керує. Водночас природним є намагання вибрати оптимальний керуючий вплив, найкращий у порівнянні з іншими можливими способами керування. Розв'язок проблеми пізнання процесу самоорганізації цих об'єктів керування має здійснюватися за допомогою методів математичного моделювання на прикладі перебігу процесів у живому організмі у разі забезпечення досягнення заданих цілей.

**Метою роботи є** побудова математичної моделі функційної системи дихання для дослідження механізмів самоорганізації організму людини при екстремальних збуреннях.

**Методи.** Процес транспорту та масообміну респіраторних газів на їх шляху в організмі описується за допомогою системи звичайних нелінійних диференційних рівнянь.

**Результати.** Розроблено математичну модель функційної системи дихання для дослідження поточного стану та прогнозування параметрів самоорганізації системи дихання при адаптації до збурюючих впливів зовнішнього та внутрішнього середовищ, яка ґрунтується на задачі оптимального керування з урахуванням конфліктних ситуацій між керуючими та виконавчими органами саморегуляції.

**Висновки.** Запропоновано математичну модель функційної самоорганізації системи дихання та кровообігу, яка враховує взаємодію та взаємовплив функційних систем організму, конфліктність ситуацій між керуючими та виконавчими органами саморегуляції, яка ґрунтується на припущенні щодо оптимальності регуляції кисневих режимів організму та дозволяє прогнозувати параметри самоорганізації організму людини при екстремальних збурюючих впливах. Модель може виявитися корисною для розв'язку прикладних задач фізіології та медицини.

***Ключові слова:*** *функційна система дихання, керована динамічна система, самоорганізація системи дихання, збурюючий вплив середовища.*

DOI: https://doi.org/10.15407/kvt205.03.070

UDC 577.169; 616.1 — 616.7

**DANILOVA V.A.**[1],
Senior Lecturer of the Biomedical Engineering Department
ORCID: 0000-0003-3009-6421
e-mail: valnaa@ukr.net
**SHLYKOV V.V.**[1], DSc (Engineering), Associate Professor,
Head of the Biomedical Engineering Department
ORCID: 0000-0001-8836-4658
e-mail: v.shlykov@kpi.ua
**DUBKO A.G.**[2], PhD (Engineering), Associate Professor,
Researcher of Department of Welding and Related
Technologies in Medicine and Ecology
ORCID: 0000-0001-6070-3945
e-mail: ndreyies17@gmail.com
[1] National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
37, Peremogy av., Kyiv, 03056, Ukraine
[2] "E.O. Paton Electric Welding Institute"
11, Kazimir Malevich str., Kyiv, 03150, Ukraine,

# DETERMINATION OF INFLUENCE PARAMETERS OF HIGH FREQUENCY CURRENT ON LIVING TISSUES

***Introduction.*** *High-frequency electric welding of biological tissues is an effective method of treatment in surgery. This is an electrosurgical method that minimizes the possibility of the destructive effect of electric current on soft living tissues. The welding method is widely used in general surgery for joining soft tissues where a weld is created when a high frequency electric current is passed through the tissue. With this method, it is possible to carry out serious operations, such as welding of liver tissue, retina, resection of tumor tissue and many other operations. For operations in surgery, it is important to know the optimal parameters of HF-welding, such as welding temperature, mechanical stress on tissues, welding time and voltage.*

***The purpose*** *of the paper is to determinatethe optimal conditions for high-frequency welding of living tissues, such as welding temperature, mechanical stress on tissues, welding time and voltage. To determine these parameters, the liver tissue fusion was simulated in the Sinda and Comsol software.*

***Results.*** *As a result of modeling and research, model dependencies were obtained that determine the optimal parameters of high-frequency welding for performing surgical operations for resection and welding of liver tissue. In the place of direct contact of the electrodes with the tissue, the temperature does not exceed +70 ° C, and at a distance of 2 mm in the adjacent tissues does not exceed +50 ° C, which provides a tissue-preserving electrosurgical effect.*

***Conclusions.*** *The studies have shown that mathematical modeling of heating biological tissue by a split electrode, through which a high-frequency current passes, practically coincides with a real experiment. The optimal conditions for high-frequency welding of living tissues obtained as a result of modeling, such as welding temperature and welding time make it possible to reduce the recovery period after applying the HF-welding method by choosing the optimal coagulation modes.*

***Keywords:*** *welding of biological tissues, mathematical modeling, temperature, liver, surgery, modeling in Sinda, modeling in Comsol.*

## INTRODUCTION

The use of welding of living tissue for hemostasis in surgical operations reduces blood loss, cost and time of surgery [1–3]. The use of live tissue fusion for hemostasis in surgical procedures reduces blood loss, cost and time of surgery. For hemostasis, bipolar forceps and clamps are used. Monopolar electrodes are used for welding and hemostasis in ophthalmology. Instruments with split electrodes are used for bloodless tissue cutting, hemostasis of the surface of wounds, and in thoracic surgery. With the help of special clamps with narrow electrodes and welding modes, bloodless tissue cutting is possible with simultaneous hemostasis and an increase in the ablasticity of the surgical operation.

The voltage and duration of welding are automatically changed depending on the condition and thickness of the fabric, the degree of contamination of the electrodes and the force of their compression. The relative impedance value is used as information about the state of the tissue Z. At the start of welding, the impedance drops to the $Z_{min}$ value due to heating of the fluid in the tissue, and then begins to rise due to protein coagulation and tissue drying. The high-frequency welding control system by regulating the voltage stabilizes the impedance at the level (1,3–1,5)*$Z_{min}$ (Fig. 1) [4].

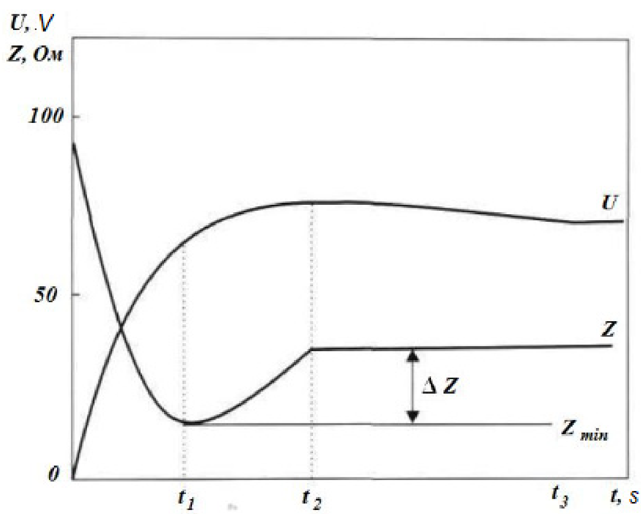



***Fig. 1.*** The dependence of voltage and impedance $Z_{mir}$ with automatic control of welding: $t_1$, $t_2$, $t_3$ — high-frequency heating stages relative to impedance value.

The operating modes of electro-welding exposure in the physiological range, worked out in the course of many years of clinical practice, made it possible to register structural events at the molecular and nanostructural levels. In particular, it was shown that during high-frequency welding, more labile globular proteins undergo thermal denaturation: an increase in temperature causes a structural transition of the "globule-coil" type, resulting in the formation of glue-like substances. The advantage of the method of high-frequency (HF) welding of living tissues is that it is possible to avoid the presence of foreign material and problems of immune incompatibility [5].

## PROBLEM STATEMENT

On the basis of the obtained experimental and clinical data [1–5], the ability of tissue exposed to high-frequency welding to maintain its viability, restore physiological properties and functions through regeneration processes has been demonstrated.

In the study [5], it was shown that when an electric current passes through the tissue between the electrodes, the temperature of the tissue in the center of the welded joint rapidly rises to a temperature 60–70°C coagulation of proteins and denaturation of cells, and then, after turning off the current, the temperature gradually decreases exponentially to the initial values 15–20°C (Fig. 2).

To find the optimal conditions for HF-welding of living tissue, it is important to know the optimum welding parameters such as welding temperature, mechanical stress on tissue, welding time and voltage. To determine these parameters, the welding of biological tissues was simulated in special software. The simulation was carried out by the finite element method in the Sinda and Comsol software environments. [6, 7].

To simulate the welding of biological tissues, the real values of biological tissues (Young's modulus, Poisson's ratio) and electrode characteristics (material, electrical and thermal conductivity) were used. After the selection of materials, research was carried out. In the model, the current was transmitted through biological tissue when the electrode interacted with the tissue. A certain pressing force was applied to the electrode. To find the optimal welding parameters during the experiment, a constant value of the force applied to the electrode, the welding time and the electric voltage were set. The safe welding temperature is 60–90°C.

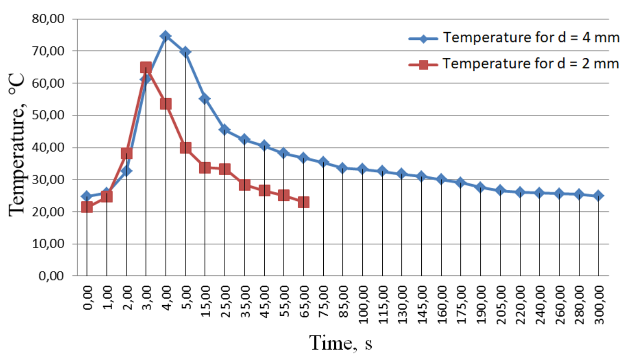



***Fig. 2.*** Temperature change in muscle tissue with a thickness of 2 mm and 4 mm during HF-welding and cooling relative to the initial temperature 15°C.

To find the optimal temperature, a sample of the study parameters was carried out. As a result, model dependencies were obtained that can determine the optimal parameters of HF-welding.

## THE PURPOSE STUDY

A model of welding in liver tissues was built in the environment of Sinda and Comsol. For welding it is necessary to find safe conditions of welding process and to define optimum parameters. Thanks to the Sinda and Comsol software, it is possible to perform experiments without the use of clinical experiments.

The study of the optimal parameters of HF-welding of living tissues will allow surgery in the future to non-invasively control the temperature of nearby tissues and determine the quality of the weld.

The purpose of the paper is to determinatethe optimal conditions for high-frequency welding of living tissues, such as welding temperature, mechanical stress on tissues, welding time and voltage. To determine these parameters, the liver tissue fusion was simulated in the Sinda and Comsol software.

## METHODS AND MEASURES OF THE RESEARCH

Liver tissue temperatures during high frequency welding are measured using a thermograph FLIR ThermaCAM E300, which has temperature sensitivity 0,1°C and measurement error ±1% of the measurement range. The technical capabilities of the thermograph allow to determine the minimum temperature difference between the nearby tissues from 0,5°C to 10°C.

Finite element modeling was performed in the Sinda and Comsol programs. The maximum welding temperature is 90 °C. To simulate the process of high-frequency welding, a constant value of the application of force to the electrode, the welding time and the electrical voltage between the electrodes are set.

To determine the optimal temperature of high-frequency welding of liver muscle tissue, the study parameters (current in the electrode, voltage, tissue temperature) were selected, which allows to determine the optimal welding parameters.

## RESEARCH OF TEMPERATURE GRADIENTS ON THE LIVER SURFACE

For high-frequency welding of tissues in research and execution model used a bipolar electrosurgical instrument with a split electrode (Fig. 3), which allows to destroy the muscle tissue of the liver with an electric current while stopping bleeding.

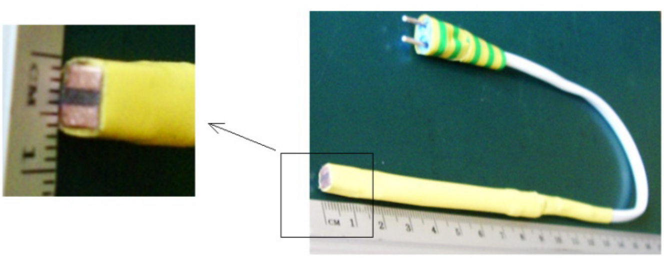


***Fig. 3.*** A bipolar electrosurgical instrument with a split electrode

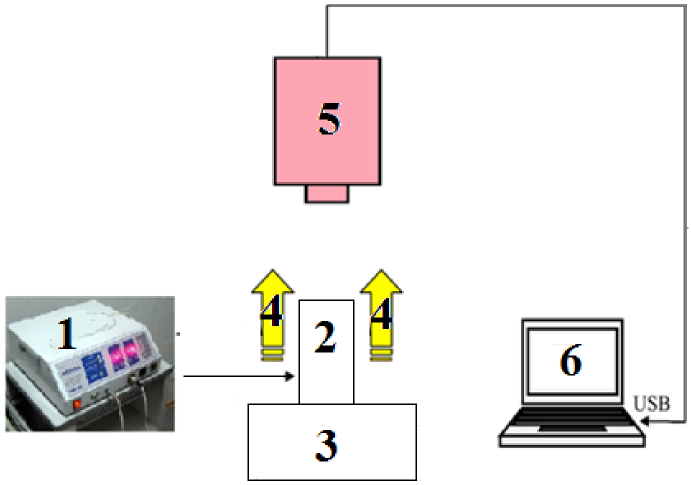



***Fig. 4.*** Research block diagram

The block diagram of the studies performed is shown in Fig. 4. And it consists of 1 — power supply EKVZ-300 "Patonmed", 2 — bipolar electrosurgical instrument with a split electrode, 3 — research object (biological tissue), 4 — infrared radiation, 5 — thermographic system based on the thermal imager ThermaCAM E300, 6 — personal computer with specialized software.

During the research, the coagulation mode was used at 75% of the power of the EKVZ-300 apparatus. The object of research is the temperature change in tissues isolated porcine liver (Fig.5).

Non-invasive temperature control in liver tissues was performed with a thermograph ThermaCAM E300 in the mode of ablation by high-frequency current using the EKVZ-300 "Patonmed" apparatus. The temperature of the tissues between the electrodes was measured using a thermography system. The spectral range of the infrared thermograph was from 7.5μm to 13 μm. The distance between the object and the lens of the thermograph was from 0.1 m to 1 m. The temperature measurement error was no more than ±2% in the temperature measuring range from 0°C to 80°C, temperature sensitivity of the thermograph 0,1°C.

The change in the temperature of liver tissue with a thickness of up to 4 mm in the center of application of the split electrode and in the area of nearby tissues (with a radius of up to 2 mm) during high-frequency welding is shown in Figure 7.

The input data for modeling the process of heating and cooling the tissues of the isolated liver in the process of high-frequency heating are the temperature data measured with a thermal imager with a time interval of 1 s (Fig. 6).

Obviously, the cooling process of the tissues of the isolated liver after high-frequency welding has an exponential relationship, and thus the estimated time for re-ablation of a tissue site can be determined from the expression:

$$\Delta t \approx 3{,}14 \cdot T, \qquad (1)$$

where $T \leq 1$ is a time of high-frequency welding of a tissue section, sec.

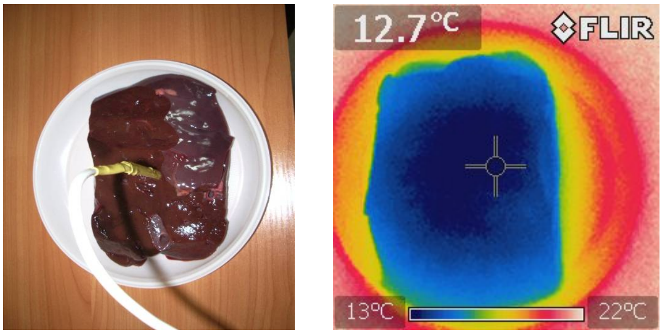



***Fig. 5.*** Object of research: a) pork liver with an installed split electrode, b) pork liver in the infrared spectrum.

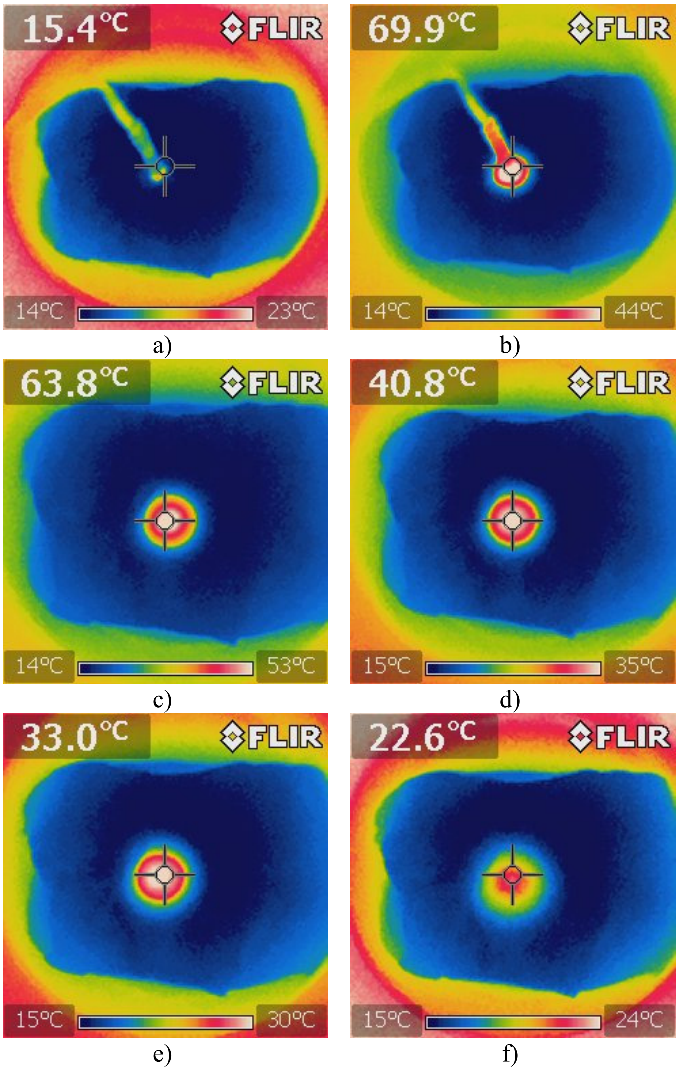



***Fig. 6.*** Pork liver in the infrared spectrum during HF-welding: temperature data with a time interval of 1 s.

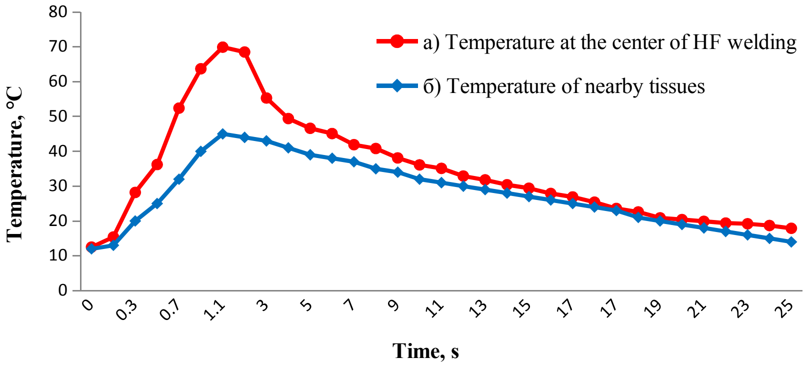
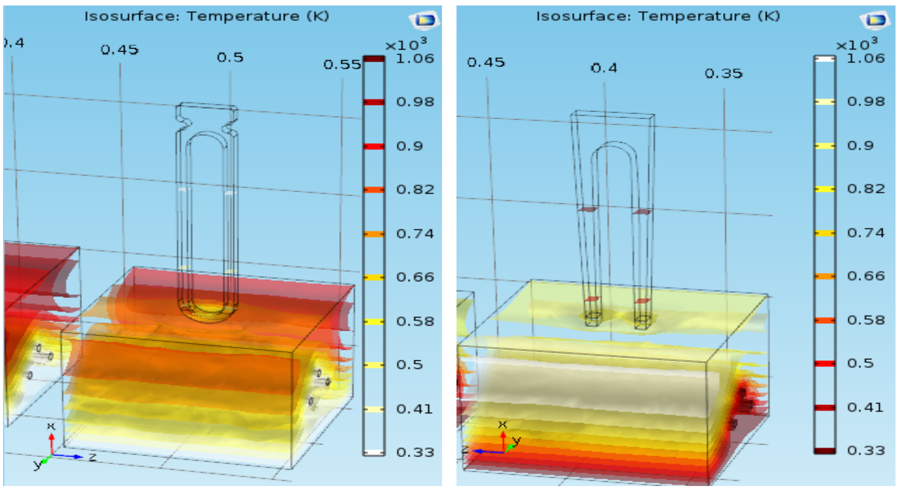



***Fig. 7.*** Change in liver tissue temperature: a) in the center of application of the split electrode, b) in the area of nearby tissues with a radius of up to 2 mm.




a) b)

***Fig. 8.*** Model of high-frequency welding in the Comsol environment for different types of electrodes: a) model with a closed electrode, b) model with a split electrode.

In the implemented model of the high-frequency welding process, a constant value of the application of force to the electrode, the welding time and the electric voltage between the electrodes were set. The model in the Comsol environment is built for two types of electrodes: a model with a closed electrode and a model with a split electrode (Fig. 8).

The distribution of high-frequency current in the electrodes of electrosurgical instruments has been shown in previous studies [8, 9]. Mathematical modeling of the stationary distribution of temperature fields in a two-phase medium (electrode — biological tissue) at a frequency of 440 kHz is considered in detail [10]. The presented model makes it possible to study the non-stationary distribution of the temperature field using an infrared thermograph, with a tissue-preserving technology of welding biological tissues.

The temperature distribution in the material is described by the thermal conductivity equation, which has the form:

$$c \quad \frac{\partial T}{\partial t} - \nabla\left(k \nabla T\right) = Q, \tag{2}$$

where $\rho$ is a density; $C$ is a specific heat; $k$ is a coefficient of thermal conductivity; $\rho$ is a nabla operator; $Q$ is a heating source distribution function; $T$ is a temperature; $t$ is a time.

To solve this problem of heat transfer, first of all, it is necessary to solve the electromagnetic problem and, as a result, find $Q$ − distribution function of heating sources.

From Maxwell's equations [11] follows an equation that describes electromagnetic processes in conducting media.

$$-\nabla\left(\frac{1}{\mu}\nabla E\right) + \left(j\omega\sigma - \omega^2\varepsilon\right)E = 0, \tag{3}$$

where $E$ is a electric field strength; $\mu$ is a magnetic permeability of a conductive medium; $j$ is a imaginary unit; $\omega$ is a angular frequency; $\sigma$ is a specific conductivity; $\varepsilon$ is a dielectric constant of the conducting medium.

Equation (2) makes it possible to determine the electric field strength $E$ and the distribution of heating sources $Q$ when a high-frequency current flows in conducting media:

$$Q = \sigma \cdot E^2. \tag{4}$$

In clinical practice, in order for the restoration of the physiological functions of an organ to proceed quickly enough and not to entail complications, the thermal input should be minimal, but sufficient for the formation of a high-quality compound [12].

## RESULTS OF MODELING FOR HIGH-FREQUENCY HEATING OF TISSUES

To solve the differential equation of heat conduction in the MSC Sinda system, the thermal network method is used (TNM — Thermal Network Method) [13], wherein the thermal conductivity of the system of equations is represented as a cell — centered nodes and resistances between the nodes using the method of finite differences (Fig. 9).

Application of the TNM method to the heat equation gives the following discrete form of the equation [14]:

$$\frac{\partial T_i}{\partial t} \approx \frac{1}{(m \cdot c)_i}\left[\sum_{j=1}^{N} C_{i,j}(T_j - T_i) + \sum_{j=1}^{N} R_{i,j}(T_j^4 - T_i^4)\right], \quad i = 1,\ldots,N \tag{5}$$

where $(m \cdot c)_I$ is a node capacity in the $I$ is a node, $N$ is the total number of diffusion nodes of the network, $R_{i,j}$ is athermal radiation from the resistance between the nodes $i$ and $j$, $C_{i,j}$ is the capacity of the linear conductor between the nodes $i$ and $j$.

The MSC Sinda system allows to perform thermal analysis of the model and all types of heat transfer: thermal conductivity, free or forced convection, advection, radiation, as well as to take into account such effects as ablation and thermal contact between nearby tissue layers (Fig. 10).

In high-frequency welding of liver tissues, more labile globular proteins undergo thermal denaturation — an increase in temperature causes a structural transition, as a result of which adhesive-like substances are formed.

The course of thermal denaturation processes depends on the temperature distribution in the depth of the fabric, which can be determined from the results of modeling high-frequency welding in Comsol (Fig. 11).

In the model, the heat transfer coefficient for free convection in the surface layer of the fabric corresponds to the natural model of laminar flow convection (ID = 701 for Convection Correlation Lib MSC Sinda) through the surface of the object of study with a characteristic length.

As a result, the nature of the process of heating the surface layer of liver tissue during high-frequency welding has the form shown in Figure 12.

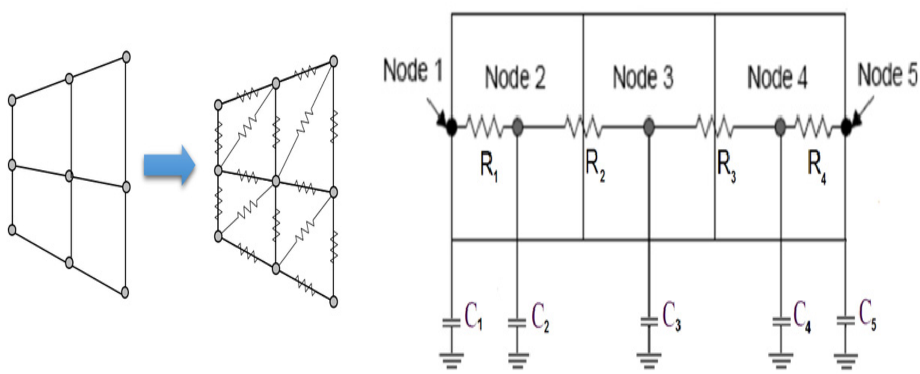



***Fig. 9.*** Thermal RC-network based on the equivalent electrical circuit:
Node — network nodes,
R — resistances equivalent to thermal radiation,
C — capacity equivalent to thermal conductivity between network nodes.

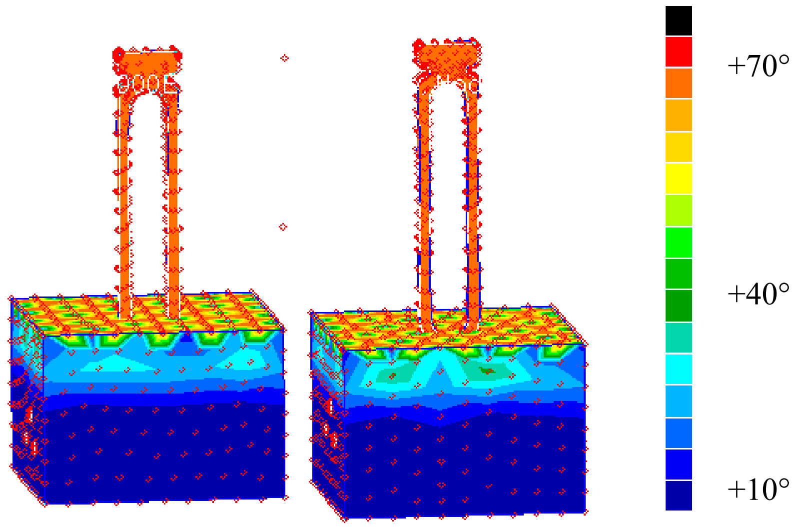
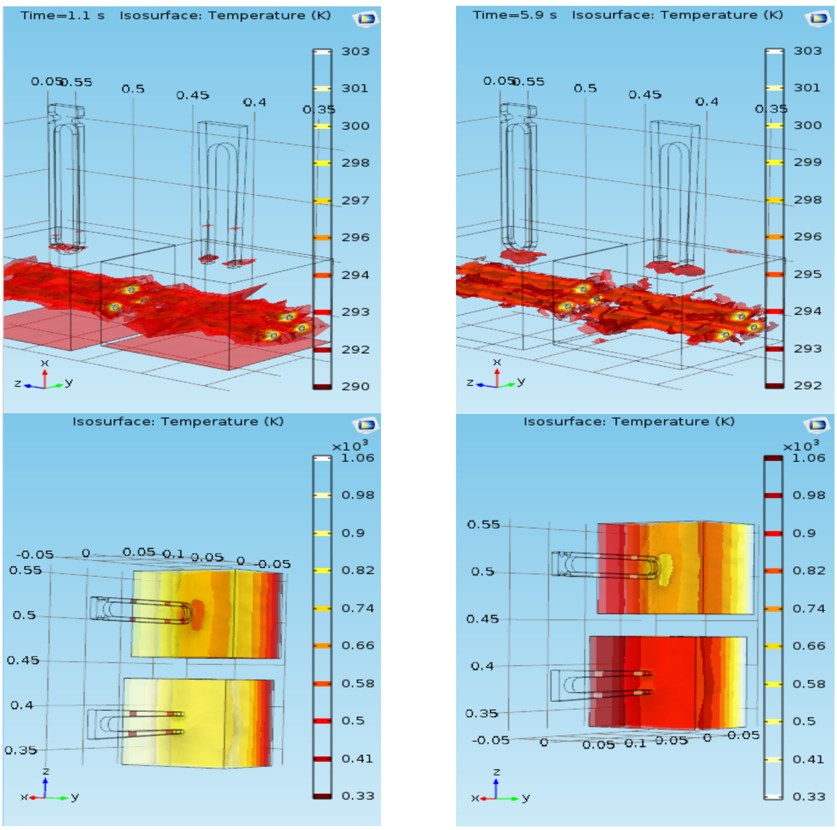



***Fig. 10.*** Model of high-frequency welding process in MSC Sinda system




a) b)

***Fig. 11.*** Model of temperature distribution in tissue in Comsol: a) after 1.0 s. at a temperature of +70° C on the surface, b) after 6.0 s. at a temperature of +70 °C at a depth of 4 mm.

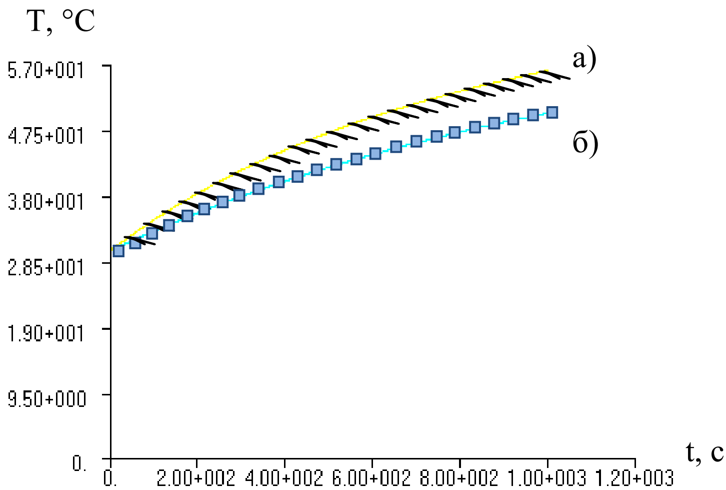



***Fig. 12.*** The nature of the process of heating the surface layer of the fabric during high-frequency welding: a) on the surface, b) at a depth of 4 mm.

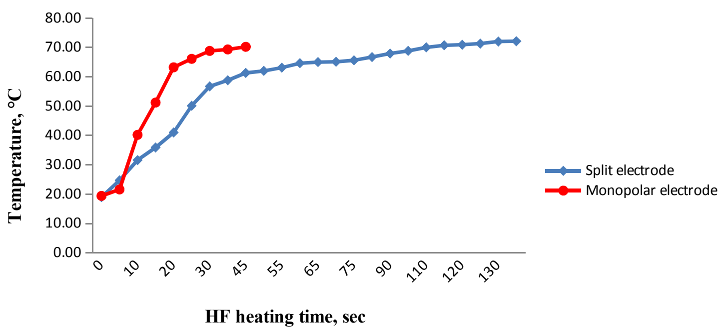



***Fig. 13.*** Temperature change in liver tissue based on Comsol models for temperature distribution in the field of application of the welding electrode: a) monopolar electrode, b) split electrode.

The dynamics of the change in the temperature of the liver tissue, obtained on the basis of the model of temperature distribution in the software Comsol in the field of application of the monopolar and split electrode for the high-frequency welding process is presented in Figure 13.In the place of direct contact of the electrodes with the tissue, the temperature does not exceed +70°C, and at a distance of 2 mm in the adjacent tissues does not exceed +50°C, which provides a tissue-preserving electrosurgical effect.

At high-frequency welding of living tissues both by a monopolar electrode, and the split electrode full sealing of connection of fabric (weld) and asepsis of an operating field due to bloodless cutting and welding by high-frequency current, preservation of a hemostasis of a wound surface is provided.

The parameters of the welding mode are set and maintained based on the results of identification of the type of fabric, its condition etc. As a result of the use of coagulation modes, in this study mode 1–100% power and mode 3–50% power, the optimal effect of HF-current on the operated tissue is achieved, which ultimately leads to a high quality connection.

## CONCLUSIONS

Thus, the study of non-stationary temperature field distribution using an infrared thermograph is an effective example of the use of tissue-preserving HF-technology — welding of biological tissues in surgery.

The results of modeling the temperature distribution during electrosurgical exposure for the gentle mode of high-frequency heating of the liver tissue coincide with the experimental results and show that the maximum temperature at the place of direct contact of the electrodes with the tissue does not exceed +70°C, and at a distance of 2 mm in the adjacent tissues does not exceed +50°C. The temperatures reached in the process of high-frequency heating exclude overcoagulation (overheating) of tissues, which provides a tissue-preserving electrosurgical effect on soft biological tissues.

Studies have shown that the mathematical modeling of the heating of biological tissue by a split electrode, through which a high-frequency current passes, practically coincides with a real experiment. This approach will further allow the development of new electrosurgical instruments for specific surgical operations on different types of tissues.

The proposed method of non-invasive temperature control of soft biological tissues allows increasing the efficiency of treatment of surgical patients by determining the optimal parameters of high-frequency welding based on modeling of heat transfer processes during welding of living tissues.

The optimal conditions for high-frequency welding of living tissues, such as welding temperature, welding time and stress, obtained as a result of thermographic studies and modeling, allow reducing the recovery period after the application of the high-frequency welding method by choosing the optimal coagulation regimes.

REFERENCES


1. Lebedev, A.V., Dubko, A.G. Use of Electric Welding of Living Tissues in Surgery (review). *Biomed Eng.* 2020, 54, pp.73–78. https://doi.org/10.1007/s10527-020-09977-3.
2. Molotkovets, V.Y., Medvediev, V.V., Korsak, A.V. et al. Restoration of the Integrity of a Transected Peripheral Nerve with the Use of an Electric Welding Technology. *Neurophysiology.* 2020, 52, pp. 31–42 (2020). https://doi.org/10.1007/s11062-020-09848-3.
3. Vazina, A.A., Vasilieva, A.A., Lanina, N.F. et al. Study of molecular and nanostructural dynamics of biological tissues under the influence of high-frequency electrosurgical welding. *Bull. Russ. Acad. Sci. Phys*. 2013, 77, pp.146–150. https://doi.org/10.3103/S1062873813020391.
4. Paton B.E., Lebedev V.K., Lebedev A.V. et al. Method for welding soft tissues of animals and humans: RU229417. Application number: 2003135514/14. Publication date: 2007.02.27 (In Russian)
5. Shlykov V., Kotovskyi V., Dubko A., Visniakov N., Šešok A. Temperature monitoring for high frequency welding of soft biological tissues: A prospective study. *Technology and Health Care*, 2019, vol. Pre-press, no. April, pp. 1–7.
6. Astrium. SINDA User Manual, ver. 3.2., 2003, 895 p.
7. COMSOL Multiphysics Reference Manual, ver.5.5, 2019, 1742 p.
8. Sydorets, V., Dubko, A. The current distribution in the electrodes of electrosurgical instruments during welding of biological tissues. *Eastern-European Journal of Enterprise Technologies*. 2015, 3(5), pp. 24–28.
9. Sydorets, V., Lebedev, A., Dubko, A. Mathematical modeling of the current density distribution in a high-frequency electrosurgery. *Proceedings - 2015 16th International Conference on Computational Problems of Electrical Engineering, CPEE*, 2015, pp. 215–217.

10. Dubko, A., Sydorets, V., Bondarenko, O. Simulation of the Temperature Distribution with High-Frequency Electrosurgical Heating. *38th International Conference on Electronics and Nanotechnology (ELNANO – 2018)*, Kyiv, Ukraine. 2018, p. 394–397.
11. Zoya Popovic, Branko D. Popovic. Introductory Engineering Electromagnetics. Prentice Hall, 1999, 548 p.
12. Vazina, A.A., Lanina, G. S. Marinsky et al. Influence of high-frequency electrosurgical welding on the functional stability of the structure of biological tissues. Welding of soft living tissues. Current state and development prospects: materials of the Sixth International Seminar: edited by O. N. Ivanova. Kyiv: E.O. Paton Electric Welding Institute, 2011. p. 53. (In Russian)
13. MSC Sinda 2017 User's Guide: ID DOC11364. MSC Software Corporation. 2017, 451 p.
14. Vitaliy B., Maksymenko V., Danilova A., Shlykov V. The Discrete Model for the System of the Myocardium and Coronary Vessels.*KPI Science News*. 2017, No 1, pp. 54–60.

Received: 05.04.2021

*Данілова В.А.*[1], старш. виклад.,
кафедра біомедичної інженерії
e-mail: valnaa@ukr.net
ORCID: 0000-0003-3009-6421
*Шликов В.В.* [1], д-р техн. наук, доцент,
зав. кафедри біомедичної інженерії
e-mail: v.shlykov@kpi.ua
ORCID: 0000-0001-8836-4658
*Дубко А.Г.* [2], канд. техн. наук, доцент,
наук. співроб. відд. зварювання
та спорідненихтехнологій в медицині та екології
e-mail: ndreyies17@gmail.com
ORCID: 0000-0001-6070-3945
[1] Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
пр. Перемоги, 37, Київ, 03056, Україна
[2] Інститут електрозварювання ім. Є.О. Патона
вул. Казимира Малевича, 11, Київ, 03150, Україна

## ВИЗНАЧЕННЯ ПАРАМЕТРІВ ВПЛИВУ ВИСОКОЧАСТОНОГО СТРУМУ НА ЖИВІ ТКАНИНИ

**Вступ.** Високочастотне електрозварювання біологічних тканин є ефективним методом лікування в хірургії. Це метод електрохірургічного впливу, який мінімізує можливість руйнівної дії електричного струму на м'які живі тканини. Метод зварювання широко використовується в загальній хірургії для з'єднання м'яких тканин, коли зварений шов виникає при проходженні електричного струму високої частоти через тканину. За допомогою цього методу можна проводити серйозні операції, такі як зварювання тканин печінки, сітківки, резекція пухлинної тканини і багато інших операцій. Для операцій в хірургії важливим є знання оптимальних параметрів ВЧ-зварювання, таких як температура зварювання, механічне навантаження на тканини, час зварювання і напруга.

**Метою статті є** визначення оптимальних умов для високочастотного зварювання живих тканин, таких як температура зварювання, механічне навантаження на тканини, час зварювання і напруга. Для визначення цих параметрів було проведено моделювання зварювання тканин печінки в програмному забезпеченні Sinda і Comsol.

**Результати.** В результаті моделювання і досліджень були отримані модельні залежності, які визначають оптимальні параметри високочастотного зварювання для виконання хірургічних операцій по резекції та зварювання тканин печінки. У місці безпосереднього контакту електродів з тканиною температура не перевищує +70°C, і на

відстані 2 мм в довколишніх тканинах не перевищує +50°C, що забезпечує нетравматичний електрохірургічний вплив.

**Висновки.** Дослідження показали, що математичне моделювання нагріву біологічної тканини розщепленим електродом, через який проходить струм високої частоти, практично збігається з реальним експериментом. Отримані в результаті моделювання оптимальні умови для високочастотного зварювання живих тканин, такі як температура зварювання і час зварювання, дозволяють зменшити відновний період після застосування методу ВЧ-зварювання за рахунок вибору оптимального режиму коагуляції.

***Ключові слова:*** *зварювання біологічних тканин, математичне моделювання, температура, печінка, хірургія, моделювання в Sinda, моделювання в Comsol.*

DOI: https://doi.org/10.15407/kvt205.03.084
УДК 004.942:001.57+004.03+519.85+612.5

**ЄРМАКОВА І.Й.,** д-р біол. наук, проф.,
провід. наук. співроб.,
ORCID: 0000-0002-9417-1120, e-mail: irena.yermakova@gmail.com
**БОГАТЬОНКОВА А.І.,** канд. техн. наук,
старш. наук. співроб.
ORCID: 0000-0002-7536-5958, e-mail: bogatonkova@gmail.com
**НІКОЛАЄНКО А.Ю.,** канд. техн. наук,
наук. співроб.
ORCID: 0000-0002-2402-2947, e-mail: n_nastja@ukr.net
**ТАДЕЄВА Ю.П.,** канд. техн. наук,
старш. наук. співроб.,
ORCID: 0000-0001-5418-2848, e-mail: jbest0207@gmail.com
**ГРИЦАЮК О.В.,** молодш. наук. співроб.,
ORCID: 0000-0002-9019-4894, e-mail: olegva11@gmail.com
**СОЛОПЧУК Ю.М.,** наук. співроб.,
ORCID: 0000-0001-9712-6045, e-mail: jul.bast@gmail.com
Міжнародний науково-навчальний центр
інформаційних технологій та систем НАН України та МОН України,
відділ комплексних досліджень інформаційних технологій,
пр. Акад. Глушкова 40, м. Київ, 03187, Україна

# M-HEALTH ТЕХНОЛОГІЯ ДЛЯ ПРОГНОЗУВАННЯ СТАНУ ЛЮДИНИ В ЕКСТРЕМАЛЬНИХ УМОВАХ СЕРЕДОВИЩА

***Вступ.*** *До засобів мобільної медицини (m-health), які стрімко розвивається, належать мобільні телефони, пристрої спостереження за пацієнтами, персональні цифрові помічники та інші бездротові пристрої для відстеження певних даних, наприклад, рівня фізичної підготовки, частоти пульсу, дозування ліків , циклів сну тощо. Це допомагає пацієнтам контролювати своє здоров'я, що важливо через нестачу медичних працівників. Пристрої та застосунки допомагають надавачам медичних послуг дистанційно збирати дані про пацієнтів. Актуальним засобом орієнтованої на особу медицини є створювані комбіновані інформаційно-комп'ютерні системи, які надають можливість пацієнтам самостійно контролювати життєво важливі показники власного здоров'я, а лікарям — відстежувати стан здоров'я пацієнтів за віддаленого доступу та аналізувати результати спостереження за допомоги мобільних застосунків для своєчасного та ефективного корегування лікувальних і профілактичних заходів.*

***Метою роботи*** *є розроблення m-health технології для оцінювання ризику погіршення здоров'я людини в екстремальних умовах середовища. Для цього розроблено комп'ютерний модуль визначення впливу навколишнього середовища на тепловий стан людини.*

***Результати.*** *Розроблено m-health технологію для прогнозу стану людини в екстремальних умовах середовища, основу якої становить комплекс математичних моделей терморегуляції людини, який дає можливість визначити низку важливих фізіологічних параметрів. Технологія враховує понад 490 показників людини та середовища, серед яких: антропометричні дані, анатомічні параметри, біофізичні харак-*

*теристики, базові фізіологічні характеристики, адаптаційні властивості людини, характеристики середовища та тривалість перебування людини у вибраних умовах.*

***Висновки.*** *Використання комплексного методу моделювання в поєднанні із сучасними комп'ютерними технологіями дає змогу дослідити процеси теплообміну між людиною та середовищем, враховуючи безліч регуляторних реакцій та фізіологічних процесів. Основне завдання розробленої m-health технології для прогнозу стану людини в екстремальних умовах — запобігти ураженню здоров'я людини в екстремальних умовах середовища за фізичного навантаження. Застосунок дає змогу прогнозувати динаміку терморегуляторних фізіологічних реакцій людини за спеки. Мобільний застосунок видає висновок про небезпеку або безпеку виконання планованого фізичного навантаження за заданих умов середовища.*

***Ключові слова:*** *моделювання, комп'ютерний модуль, екстремальний вплив, навколишнє середовище.*

## ВСТУП

До Mobile health (m-health), що стрімко розвивається, належать мобільні телефони, пристрої спостереження за пацієнтами, персональні цифрові помічники та інші бездротові пристрої відстеження певних даних [1], наприклад, рівня фізичної підготовки, частоти пульсу, дозування ліків, циклів сну [2] тощо. Це допомагає пацієнтам контролювати своє здоров'я, що важливо при все більшій нестачі медичних працівників. Пристрої та застосунки допомагають надавачам медичних послуг проводити віртуальні відвідування/зустрічі і збирати дані про пацієнтів.

Розробники пропонують велику кількість медичних гаджетів та мобільних застосунків для вимірювання окремих фізіологічних та вербальних показників, які характеризують стан здоров'я людини: пульс (Instant Heart Rate, Runtastic Heart Rate Monitor), артеріальний тиск (Blood Pressure Monitor), рівень глюкози в крові, спірометричні показники, якість слуху та зору тощо [3–4]. За допомогою мобільних засобів також можна визначати емоційний стан людини та рівень стресу (Stress Check); контролювати фізичну активність (Googlefit, moves) та кількість спалених калорій; фази та якість сну (Sleep Time) тощо [1–5].

Актуальними засобами орієнтованої на особу медицини є створювані комбіновані інформаційно-комп'ютерні системи, які надають можливість пацієнтам самостійно контролювати життєво важливі показники власного здоров'я, а лікарям — відстежувати стан здоров'я пацієнтів у режимі віддаленого доступу та аналізувати результати спостереження за допомогою спеціальних мобільних застосунків для своєчасного та ефективного корегування лікувальних та профілактичних заходів [6].

До категорії m-health застосунків також належать багатопараметричні системи моніторингу, носимі, тканеві та імплантовані сенсори життєвоважливих показників здоров'я, системи експрес-аналізу, застосунки контролю вживання ліків, системи тренінгу для стабілізації емоційного стану, покращення когнітивних функцій та працездатності. Активно розробляють системи віддаленого контролю та підтримки у разі хронічних захворювань (Care Innovations, Visi Mobile, hWear (ЕКГ), SugarSenz (діабет) тощо).

На основі аналізу функційних і аналітичних можливостей сучасних засобів вимірювання та оцінювання психофізіологічних функцій за допомогою медичних сенсорів, гаджетів і мобільних застосунків для смартфонів розроблена концепція створення інноваційної мобільної інформаційної системи зі зворотним зв'язком на базі інтелектуального мобільного навігатора з сервісною платформою тривалого спостереження, аналізу і корекції інтегральних показників фізичного здоров'я людей, а також методи її практичної технічної реалізації для систем з ОС Android [7–8].

На основі запропонованої концепції розроблено модульну структуру, алгоритмічну базу та програмне забезпечення інноваційної мобільної інформаційної системи. Інформаційно-аналітична система містить медичні гаджети, мобільний навігатор, сервісну платформу та комплекс тестових програм, які дають змогу користувачам оцінити їхні основні фізіологічні та ментальні показники, а також визначити кореляцію показників з такими факторами, як тривалість сну, фізична активність, харчові звички, адекватне насичення тіла киснем на основі електронного щоденника, створеного у смартфоні.

**Метою роботи** є розроблення m-health технології для оцінювання ризику погіршення здоров'я людини в екстремальних умовах середовища. Для цього розроблено комп'ютерний модуль визначення впливу середовища на тепловий стан людини.

## ІНФОРМАЦІЙНА ТЕХНОЛОГІЯ

Об'єднання можливостей комплексу математичних моделей терморегуляції людини і сучасних засобів мобільної медицини дає змогу розробити унікальну інформаційну технологію прогнозування стану людини за різних умов середовища.

Запропонована інформаційна технологія надає нові можливості для підтримання здорового способу життя, оскільки дає змогу виявити і попередити фактори ризику для погіршення здоров'я людини, яка знаходиться чи опинилася в екстремальних умовах середовища.

Результати прогнозування можна використати для розв'язання завдань, пов'язаних з підтриманням здорового способу життя, перевіркою безпеки умов навколишнього середовища, розрахунку часу безпечного перебування людини в екстремальних умовах, підбору одягу і захисного спорядження, оцінювання резервних можливостей організму за фізичних навантажень високої інтенсивності та організації підготовчого етапу тренувань спортсменів.

**Клієнт-серверна архітектура.** Архітектура інтелектуальної інформаційної технології має клієнт-серверне рішення, яке передбачає доступ користувачів за допомогою застосунку на смартфоні до комплексу математичних моделей, централізованої бази даних і централізованого електронного сховища інформації (Рис. 1.). Термін «клієнт-сервер» тут означає мережеву архітектуру, в якій завдання логічно розподілені між постачальниками послуг (серверами) та замовниками послуг (клієнтами).

У цьому випадку клієнт — це програма для смартфона, яка взаємодіє з сервером через телекомунікаційну мережу за допомогою мережевих протоколів. Клієнт дозволяє вводити, первинно контролювати і передавати дані на сервер, а потім приймати і відображати результати на смартфоні. На сервері розміщено програмне забезпечення, яке серед іншого керує даними (приймає, обробляє, передає та зберігає у відповідних базах даних), автоматично контролює цілісність і несуперечливість отриманої та збереженої інформації. За допомогою серверу здійснюють керування доступом багатьох користувачів, дотримуючи конфіденційність баз даних користувачів, ведення журналу системних подій тощо.


***Рис. 1.*** Структурна схема смартфон технології

Під час роботи інформаційної технології клієнт і сервер обмінюються пакетами даних (у разі доступного з'єднання і отриманої згоди користувача). Клієнт направляє запити по мережі серверу й обробляє отриману у відповідь інформацію. Сервер отримує і обробляє запити, робить відповідні запитам дії і передає клієнтові відповідні дані.

Відмінна риса розробленої технології — це комплекс математичних моделей для прогнозування стану людини на основі введених умов. Результати прогнозування аналізують і за результатами аналізу виявляють можливі чинники ризику погіршення здоров'я. На цій підставі формується висновок про резервні можливості організму або попередження про небезпеку їх вичерпання. Можливість автоматичного аналізу і ухвалення рішення дає підставу розглядати розроблену технологію як інтелектуальну інформаційну технологію.

**Клієнт.** Клієнтську програму написано мовою Java для смартфонів під операційну систему Android. Графічний інтерфейс складається з вікон для введення даних і відображення результатів на екрані. Інтерфейс автоматично адаптується до розміру екрана смартфона. Після встановлення програми новому користувачу пропонується зареєструватися, або увійти в систему, якщо користувач був зареєстрований раніше. Під час реєстрації надається анкета для реєстрації персональних даних і індивідуалізації математичних моделей: ім'я, дата народження (для розрахунку віку), стать, вага, зріст. Користувач може зареєструватися в системі за допомогою акаунтів соціальних мереж Twitter, Facebook, Google+ або електронної пошти. Залежно від профілю соціальної мережі і дозволу користувача, система може автоматично отримувати доступні персональні дані. Підключення до системи соціальних мереж сприяє популяризації програми.

Для прогнозування функційного стану людини використано або індивідуальні дані, введені користувачем, або усереднені показники. На основі введених даних ваги, зросту та статі розраховано індекс маси тіла і процентний вміст жирової тканини в організмі, що є необхідним для прогнозування стану людини в екстремальних умовах. Меню застосунка надає доступ до всіх його функцій: вибір середовища для прогнозування, відповіді на поширені запитання, наявна можливість переглянути збережені результати тощо.

Якщо застосунок встановлений, користувач зареєстрований, то вхід в систему відбувається автоматично і на екрані виводиться вікно вибору середовища: відкрите повітря, вода чи приміщення. Для кожного середовища перебування закріплене вікно введення вихідних даних. Вікна введення вихідних даних розділене на області: вид фізичної активності, її тривалість та інтенсивність, одяг чи захисне спорядження; умови середовища. Надано можливість вибрати вид фізичної активності: спокій, ходьбу, біг, їзду на велосипеді, плавання різними стилями і багато іншого. За даними геолокації застосунок автоматично отримує від кліматичних сервісів поточну температуру, вологість, швидкість руху повітря. Реалізовано можливість ручного введення характеристик середовища за бажанням користувача, що дає змогу прогнозувати стан людини у будь-яких умовах.

Введені дані передаються на сервер, де розміщено комплекс математичних моделей. Попередній прогноз стану людини автоматично аналізується, виявляються фактори ризику погіршення здоров'я і відображаються на екрані вибрані користувачем показники (система пропонує користувачу перелік прогнозованих даних). Потім на сервері формується і передається клієнтові відповідь на запит. Отримана відповідь обробляється у підсистемі клієнта і відображається у вікні результатів прогнозування.

У налаштуваннях програми користувач може вибрати показники стану людини, які будуть отримані після оброблення вихідних даних комплексом математичних моделей. У отриманій користувачем інформації надано всі доступні для відображення показники: значення загальної і локальних температур, кровотоки, теплопродукції, втрати тепла і води та інші показники.

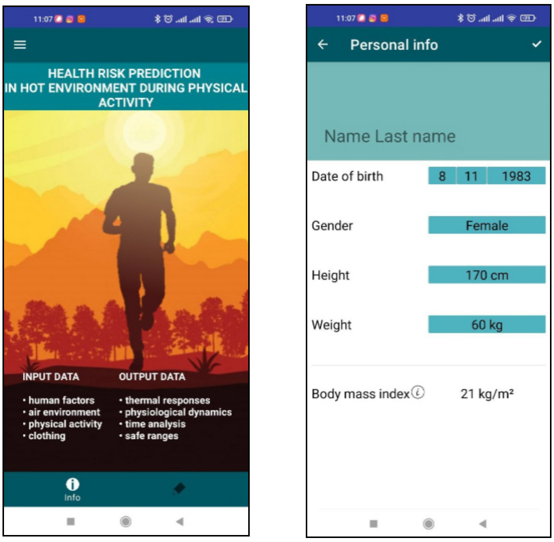
На екрані смартфона у вікні результатів виводяться попередження про характер ризиків (якщо такі виявлені), практичні рекомендації, спрямовані на попередження екстремальних впливів, а також бажані значення фізіологічних показників до кінця заданого періоду часу. За бажанням користувач може переглянути графік зміни вибраного показника в динаміці, що дає змогу відстежувати перехідні процеси і безпечний термін перебування в заданих умовах. Отримані результати користувач може зберегти на сервері та подивитися пізніше за необхідністі.

**Сервер.** Сервер системи складається з програми керування потоками даних, комплексу математичних моделей, бази персональних даних і бази збережених показників прогнозування («Архів»). Після з'єднання на сервер надходить ідентифікатор (ID) клієнта, який порівнюється з ID вже наявних облікових записів. Якщо запису в системі немає, то в базу даних додається запис щодо нового користувача, в іншому разі відбувається автентифікація.

Сервер допускає одночасне обслуговування великої кількості клієнтів. Розрахований на багато користувачів доступ накладає на сервер вимоги щодо дотримання конфіденційності, розмежування прав користувачів і убезпечення даних від несанкціонованого доступу. Тому після успішної автентифікації користувача в системі здійснюється перевірка прав. Після авторизації сервер надає клієнтам доступ до своїх ресурсів.

На сервер надходять запити від клієнтських програм і, залежно від типу запиту (наприклад, на зміну персональних даних), виконуються такі функції:

— збереження змін персональних даних;




а б

***Рис. 2.*** Екранна форма застосунку: опис вхідних та вихідних даних (а) та надання особистих даних користувача (б)

— обчислення комплексом математичних моделей вибраних користувачем умов перебування та виду фізичної активності людини, аналіз результатів прогнозування, формування результатів залежно від персональних налаштувань користувача та відповідь клієнту;

— формування і збереження за запитом користувача результатів прогнозування в «Архів» сервера;

— передача клієнту результатів прогнозування з «Архіву».

Відповідно до запиту сервер передає клієнту дані або підтвердження виконаної операції, після чого повертається до режиму очікування запиту від клієнта. У разі завершення роботи клієнта з'єднання завершується до наступного запиту на вхід у систему.

**Титульне вікно** (Рис. 2). Надано можливість введення *початкових даних* (Рис. 2а): характеристик людини, умови навколишнього середовища, вид і рівень фізичної активності людини, біофізичні властивості одягу та *заключних даних* (Рис. 2б): теплові реакції людини, динаміка фізіологічних показників, часовий аналіз, висновок — «безпечно/небезпечно».

**Особисті дані користувача:** ім'я та прізвище, дата народження, стать, зріст, вага, індекс маси тіла (розраховується автоматично) — вага/площа поверхні тіла людини.

Для аналізу і прогнозування стану людини за різних умов надано можливість введення початкових даних (антропометричні дані людини, дані площі поверхні тіла людини, вік) та заключних даних (характеристики середовища та фізичного навантаження).

**Характеристиками середовища** (Рис. 3) для виду середовища «Повітря (Air environment) є: температура повітря (temperature), вологість повітря (humidity), швидкість руху повітря (velocity).

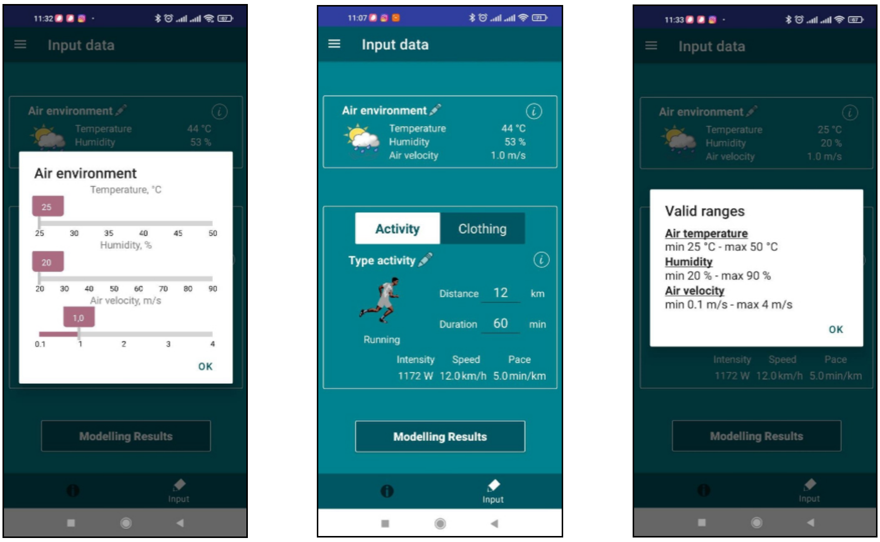



***Рис. 3.*** Екранна форма для введення характеристик середовища

Передбачено аналіз для таких **видів фізичної активності** людини, як: спокій (Rest), ходьба (Walking), біг (Running), навантаження (Exercise).

**Характеристики навантаження** містять (Рис. 4): віддаль прогулянки/ пробігу (Distance), тривалість фізичної активності (Duration), напруженість фізичної активності (Intensity), швидкість ходьби/бігу (Speed), темп ходьби/бігу (Pace).

Для аналізу впливу захисного одягу задають його характеристики як початкові дані (Рис. 5): теплоізоляція одягу (Thermal resistance), випарний опір одягу (Evaporative resistance), ступінь/ відсоток покриття тіла одягом (Covered body), одяг (Clothes), взуття (Shoes).

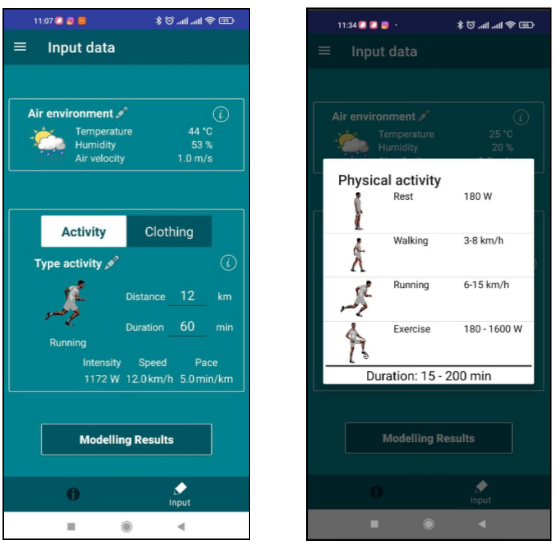



***Рис. 4.*** Екранна форма для введення характеристик навантаження

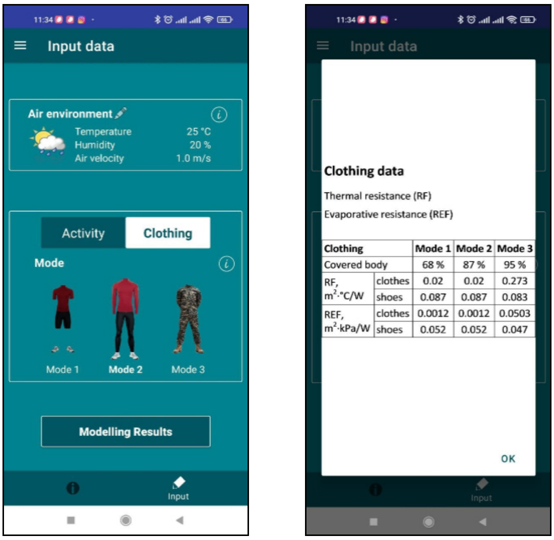



***Рис. 5.*** Екранна форма для введення характеристик захисного одягу

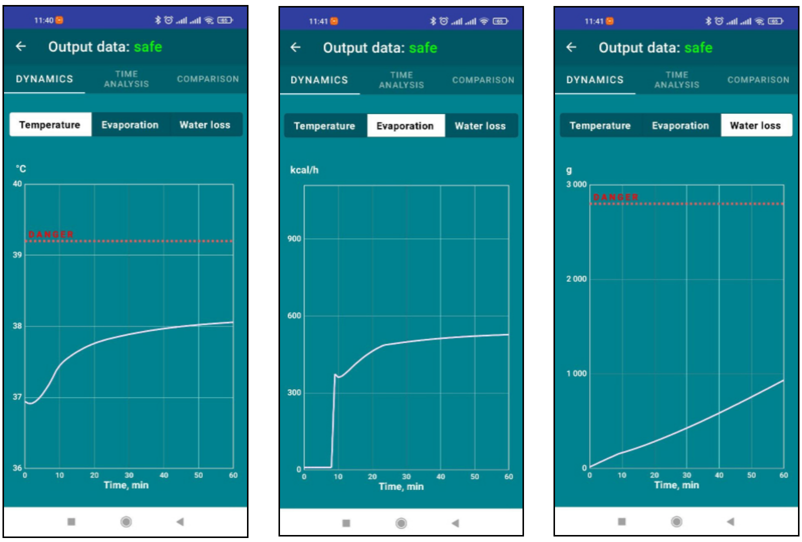



***Рис. 6.*** Динаміка температури, випаровування поту і втрати води у людини під час навантаження — скріншоти з мобільного

Використання розробленої ІТ, реалізованої у мобільному застосунку, надає можливість проаналізувати результати моделювання, визначивши динаміку температури, випаровування поту і втрати води у людини під час навантаження.

**Часовий аналіз** забезпечує визначення таких показників функційного стану людини під впливом чинників навколишнього середовища та різного виду фізичної активності (Рис. 7):


а б

***Рис. 7.*** Результати моделювання — часовий аналіз — показники функційного стану людини: температура тіла людини за безпечних (а) та небезпечних (б) даних

— температура внутрішніх органів (Body temperature);
— втрати води в % від маси тіла (Water loss in % of body mass);
— серцевий викид (Cardiac output);
— швидкість крові в м'язах (Muscle blood flow);
— швидкість випаровування поту (Evaporation sweat rate);
— швидкість стікання поту (Dripping sweat rate);
— смуга прокрутки шкали часу для зміни експозиції (Scroll time).

## ВИКОРИСТАННЯ РОЗРОБЛЕНОЇ ІТ ТА МОБІЛЬНОГО ЗАСТОСУНКА

Розроблена технологія, реалізована у мобільному застосунку, надає змогу провести аналіз та порівняння результатів модельних експериментів за різних умов як середовища, так і характеристик фізичної активності чи захисного одягу. У цих експериментах задано однакові умови середовища, однаковий одяг, але різна потужність навантаження, а саме 1172 Вт та 828 Вт.

Розглянемо детальніше початкові дані цих експериментів та результати аналізу за допомогою розробленої ІТ.

**Експеримент №1.** Початкові дані, відображені на Рис. 8, містять характеристики середовища: температура 35°C, вологість 70%, швидкість руху повітря 1 м/с; а також активність: потужність навантаження 800 Вт, тривалість 60 хвилин.

Ансамбль одягу № 1 (тренувальні шорти, футболка, кросівки, характеристики): теплоізоляція одягу — 0,02 $m^2C$ / W, опір одягу — 0,0012 $m^2kPa$ / W, теплоізоляція взуття — 0,087 $m^2C$ / W, опір взуття — 0,052 $m^2kPa$ / W, ступінь вкривання одягом — 68%.

Заключні дані експерименту №1 (Рис. 9.) охоплюють аналіз динаміки та прогноз досліджуваних показників, за якими зроблено висновок щодо безпечності такої активності — «безпечно»!

**Експеримент №2**. Початкові дані (Рис. 10) містять такі характеристики середовища: температура 35°C, вологість 70 %, швидкість руху повітря 1 м / с; активність: потужність навантаження 1200 Вт, тривалість 60 хвилин та результати аналізу.

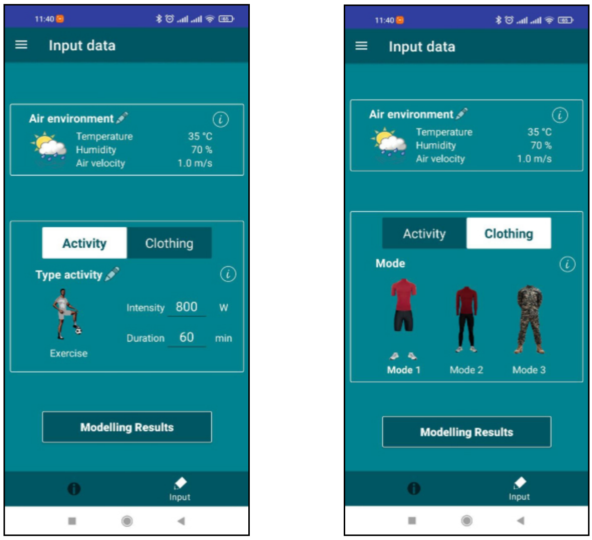



***Рис. 8.*** Екранна форма для введення початкових даних експерименту 1

температура: випаровування: втрати води: часова шкала:

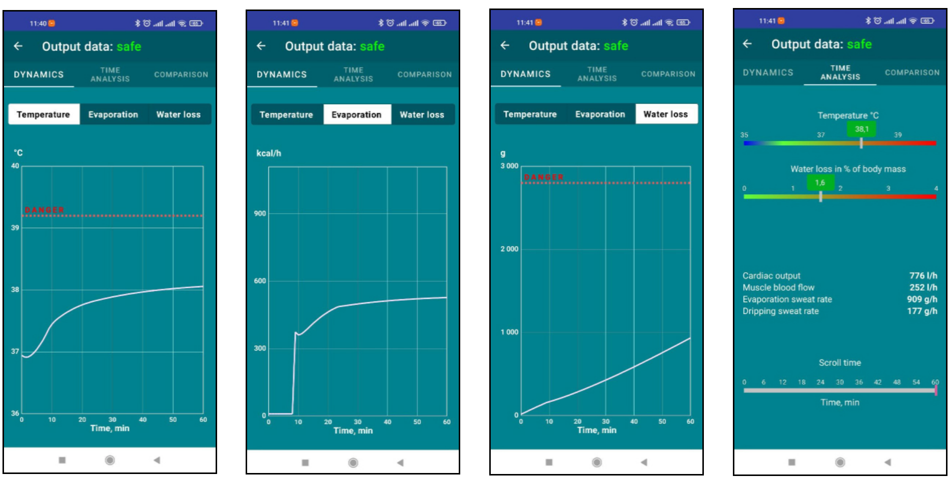



***Рис. 9.*** Результати визначення динаміки досліджуваних показників та висновок щодо безпечності такої активності

Ансамбль одягу № 1 (тренувальні шорти, футболка, кросівки, характеристики): теплоізоляція одягу — 0,02 $m^2C/W$, опір одягу — 0,0012 $m^2kPa/W$, теплоізоляція взуття — 0,087 $m^2C/W$, опір взуття — 0,052 $m^2kPa/W$, ступінь вкривання одягом — 68 %.

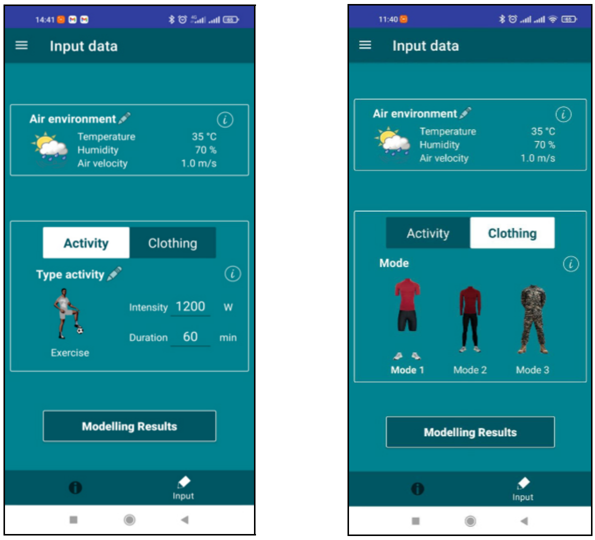



***Рис. 10.*** Екранна форма: початкові дані експерименту 2

Динаміка температури: Динаміка випаровування: Динаміка втрати води: Часова шкала:

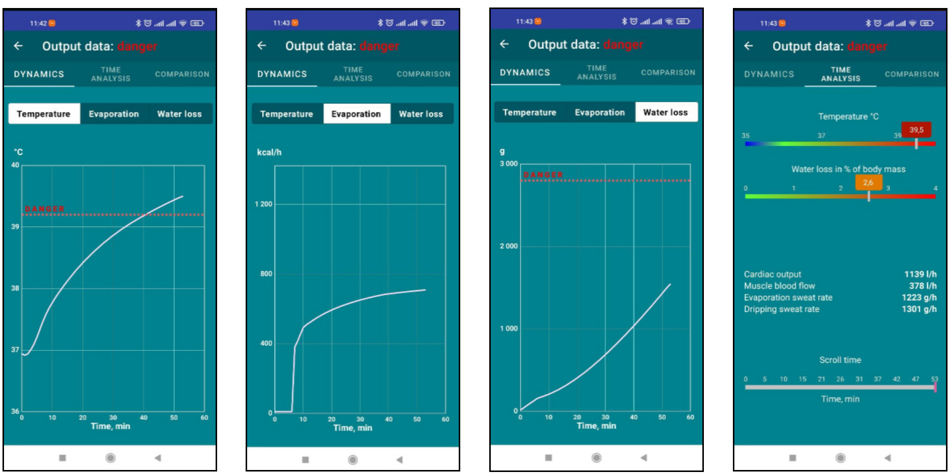



***Рис. 11.*** Результатами проведеного дослідження (експеримент 2)

За результатами проведеного дослідження (Рис. 11) зроблено висновок — «небезпечно!» і надається застереження на екран: «Увага! Гіпертермія! Ви можете виконувати вправи лише 53 хв.».


***Рис. 12.*** Порівняння результатів двох експериментів

Отже, враховуючи результати проведеного аналізу та надані попередження, експеримент було перервано на 53 хвилині — виявлено загрозу теплового удару (температура тіла 39,5°С).

**Порівняння двох експериментів.** Технологію створено таким чином, що її використання дає змогу переглянути та порівняти два модельних дослідження (Рис. 12). У верхніх частинах скриншотів зазначено таблиці вхідних даних двох описаних експериментів, а під ними — графіки порівняння. Білою лінією зображено результати попереднього експерименту (експеримент № 1), зеленою — поточного (експеримент № 2). Як було зазначено вище, поточний експеримент було перервано на 53 хвилині через загрозу теплового удару.

Запропонована ІТ, реалізована у мобільному застосунку, становить інтерес для військових, служб порятунку, організаторів спортивних змагань (чемпіонати, Олімпійські ігри тощо), тренерів, спортсменів та людей, які працюють в екстремальних умовах середовища.

## ВИСНОВКИ

Використання комплексного методу моделювання як основи розробленої інформаційної технології m-health у поєднанні з комп'ютерними технологіями дає змогу дослідити процеси теплообміну між людиною та середовищем, враховуючи велику кількість регуляторних реакцій та фізіологічних процесів. Основне завдання ІТ — попередити ураження здоров'я людини в екстремальних умовах середовища під час фізичного навантаження.

Мобільний застосунок, який реалізує ІТ, забезпечує введення початкових даних про умови діяльності конкретної особи, аналіз та прогнозування стану людини за введених даних та видає висновок про **небезпеку** або **безпеку** виконання планованого фізичного навантаження в заданих умовах середовища.

Мобільний застосунок у модельному експерименті дає змогу здійснювати порівняльний аналіз змін стану людини за різної фізичної активності людей, які працюють в екстремальних умовах середовища.

ЛІТЕРАТУРА / REFERENCES


1. Абдулаев В.Г., Аскеров Т. К., Чуба И. В. Мобильные приложения для здоровья. *Радиоэлектроника и информатика*. 2014. Т. 1, № 64. [Abdulaev V.G., Askerov T.K., Chuba I.V. Mobilnyie prilozheniya dlya zdorovya. Radioelektronika i informatika. 2014. T. 1, № 64. (In Russian)]
2. McCarthy M., Spachos P., "Wellness assessment through environmental sensors and smartphones", Communications (ICC) 2017 IEEE International Conference on, 2017, pp. 1–6.
3. Khudetskyy I., Antonova-Rafi Yu. Development of the module for data processing psycho-physiological indicators based on the Android OS*Materials of the XII International Scientific and Methodical Conference "Physical Education in the Context of Modern Education,"* Kyiv, 2016, pp. 115–116.
4. Hotra O., Boyko O., Zyska T. Improvement of the operation rate of medical temperature measuring devices *SPIE Proceedings*. Vol. 92914, 2014, pp. 92910A.
5. Holyaka R., Kostiv N. Energy-efficient signal converters of thermocouple, temperature sensors *Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska,* 2011, pp. 26–28.
6. Yermakova I., Nikolaienko A., Tadeieva J., Bogatonkova A., Solopchuk Y., Gandhi O., Computer model for heat stress prediction during physical activity. *Proceedings of the 40th International scientific conference electronics and nanotechnology* Institute of Electrical and Electronics Engineers, Kyiv, Ukraine, 22–24 April 2020. pp. 569–573
7. Hrytsenko V., Nikolaienko A., Solopchuk Y., Yermakova I., Regan M. Dynamics of Physiological Responses during Long Distance Run: Modelling. *Proceedings of the 38th International scientific conference electronics and nanotechnology.* Institute of Electrical and Electronics Engineers, Kyiv, Ukraine, 24–26 April 2018, pp. 439–442. ISBN 978-1-5386-6382-0. doi:10.1109/ELNANO.2018.8477470.
8. Dorosh N., Ilkanych K., Kuchmiy H., Boyko I., Yermakova I, Dorosh O., Voloshyn D. Measurement modules of digital biometrie medical systems based on sensory electronics and mobile-health applications. *Proceedings of the 14th International Conference on Advanced Trends in Radioelecrtronics, Telecommunications and Computer Engineering (TCSET).* IEEE, Slavske, Ukraine, 20–24 February 2018, pp. 687–691. doi:10.1109/TCSET.2018.8336294.


Отримано 03.06.2021

*Yermakova I.I.,* Doctor of Biological Sciences, Full Professor,
Leading Researcher of Department of Complex Research
of Information Technologies
ORCID: 0000-0002-9417-1120, e-mail: irena.yermakova@gmail.com
*Bogatonkova A.I.,* Ph.D (Engineering), Senior Researcher,
Department of Complex Research of Information Technologies
ORCID: 0000-0002-7536-5958, e-mail: bogatonkova@gmail.com
*Nikolaienko A.Yu.,* Ph.D (Engineering), Researcher,
Department of Complex Research of Information Technologies
ORCID: 0000-0002-2402-2947, e-mail: n_nastja@ukr.net
*Tadeeva J.P.,* Ph.D (Engineering), Senior Researcher,
Department of Complex Research of Information Technologies
ORCID: 0000-0001-5418-2848, e-mail: jbest0207@gmail.com
*Hrytsaiuk O.V.,* Junior Researcher,
Department of Complex Research of Information Technologies
ORCID: 0000-0002-9019-4894, e-mail: olegva11@gmail.com
*Solopchuk J.M.,* Researcher,
Department of Complex Research of Information Technologies
ORCID: 0000-0001-9712-6045, e-mail: jul.bast@gmail.com
International Research and Training Center for Information Technologies
and Systems of the National Academy of Sciences of Ukraine
and Ministry of Education and Science of Ukraine,
40 Acad. Glushkov av., Kyiv, 03187, Ukraine

# M-HEALTH TECHNOLOGY FOR THE FORECAST OF THE HUMAN CONDITION IN EXTREME ENVIRONMENTAL CONDITIONS

**Introduction.** Rapidly evolving Mobile health (m-health) includes mobile phones, patient monitors, personal digital assistants, and other wireless devices for tracking certain data, such as fitness level, heart rate, medication dosage, sleep cycles, and more. This helps patients control their health, which is important in the face of growing medical shortages. Devices and applications help healthcare providers make visits / appointments and collect patient data. An important means of person-centered is the creation of combined information and computer systems that allow patients to independently monitor vital indicators of their own health, and doctors — to monitor the health of patients remotely and analyze the results of monitoring using mobile applications for timely and effective adjustment of treatment and prevention measures.

**The purpose** of the paper is to develop m-health technology to assess the risk of deterioration of human health in extreme environmental conditions. To do this, a computer module for determining the impact of the environment on the thermal state of man has been developed.

**Results.** M-health technology for forecasting the human state in extreme environmental conditions, based on a set of human thermoregulation mathematical models, which allows to determine a number of important physiological parameters, has been developed. The technology takes into account more than 490 human indicators and the environment parameters, including: anthropometric data, anatomical parameters, biophysical characteristics, basic physiological characteristics, human adaptive properties, environmental characteristics and duration of human stay in selected conditions.

**Conclusions.** The use of a complex method of modeling in combination with modern computer technology makes it possible to study the processes of heat exchange between humans and the environment, given the huge number of regulatory reactions and physiological processes.

The main task of the developed m-health technology for forecasting the human state in extreme environmental conditions is to prevent damage to human health in these conditions during physical activities. The application makes it possible to predict the dynamics of thermoregulatory physiological reactions of a person during heat. The mobile application issues a conclusion about the danger or safety of the planned physical activity under the given environmental conditions.

***Keywords:*** *simulation, computer module, extreme impact, environment.*

# ДО УВАГИ АВТОРІВ!

У журналі надано результати досліджень у галузях теорії та практики інтелектуального керування, інформатики та інформаційних технологій, а також біологічної і медичної кібернетики.

Цільова аудиторія — науковці, інженери, аспіранти і студенти вищих навчальних закладів відповідного фаху.

**Вимоги до рукописів статей**

1. Рукопис надають на папері у двох примірниках (мова — англійська, українська, 17–22 с.) та електронна версія. До рукопису додають:

• анотації — українською та англійською мовами (прізвище, ініціали автора/ів, науковий ступінь, звання, посада, місце роботи, адреса організації, назва статті, текст 250–300 слів, з виділенням рубрик: вступ, мета, результати, висновки, ключові слова);

• список літератури мовою оригіналу — у порядку згадування у тексті, за стандартом ДСТУ 8302:2015;

• список літератури — переклад джерел англійською мовою, прізвища та ініціали авторів — транслітерація:

• ліцензійний договір;

• відомості про автора/ів українською та англійською мовами повинні містити: ПІБ, науковий ступінь, вчене звання, посада, відділ, місце роботи, поштова адреса організації, телефон (для зв'язку редактора), E-mail, авторські ідентифікатори ORCID або ResearcherID.

2. Текст статті подається з обов'язковими рубриками: вступ, постановка завдання/проблеми, мета, результати, чітко сформульовані висновки.

**Вимоги до текстового файлу**

Формат файлу * .doc, * .rtf. Файл повинен бути підготовлений за допомоги текстового редактора Microsoft Word.

Використовувані стилі: шрифт Times New Roman, 12 пт, міжрядковий інтервал — 1,5. Формат паперу А4, всі береги — 2 см.

Формули набирають у редакторах формул Microsoft Equation Editor 3.0. чи MathType 6 Опції редактора формул — (10,5; 8,5; 7,5; 14; 10). **Ширина формул — до 12 см**.

Рисунки повинні бути якісними, створені вбудованим редактором рисунків Word Picture або іншими Windows-застосунками (рисунки надають окремими файлами відповідних форматів). **Ширина рисунків — до 12 см**.

Таблиці виконують стандартним вбудованим у Word інструментарієм «Таблиця». **Ширина таблиці — до 12 см**.

**Передплату на журнал (друкована версія) в Україні здійснюють**:

— за «Каталогом видань України», індекс передплати друкованої версії — 86598;

— за допомоги передплатної агенції «Укрінформнаука» НАН України, ukrinformnauka@gmail.com, індекс журналу — 10029.