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

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

ЗМІСТ

УШАНУВАННЯ ПАМ'ЯТІ АКАДЕМІКА Б.Є. ПАТОНА

Редакційна колегія з глибоким сумом повідомляє, що 19 серпня 2020 р. на 102-му році пішов з життя Президент Національної академії наук України академік **Борис Євгенович Патон**.

Найважливішим напрямом науково-організаторської діяльності Патона-президента був розвиток широкого спектра фундаментальних досліджень і створення на їх основі новітніх технологій для масштабного промислового застосування, орієнтування академічних інститутів на цей шлях.

Видатний український вчений в галузі металургії, технології металів, електрозварювання та матеріалознавства, організатор науки та державний діяч, Борис Євгенович Патон був однією з найвеличніших особистостей, за якими сприймається Україна у світі.

Світла пам'ять…

The editorial board informs with deepest sorrow that on August 19, 2020, at the age of 102, the President of the National Academy of Sciences of Ukraine, Academician **Borys Yevhenovych Paton** passed away.

The focus of B.E. Paton's organizing activities as the President of the Academy was on promoting a broad range of fundamental research, developing cutting-edge technologies on its basis for large-scale industrial applications, and guiding Academy institutions towards those goals.

A prominent Ukrainian scientist in the field of metallurgy, metal technology, electric welding and materials science, science development leader and statesman, Borys Yevhenovych Paton was one of the greatest personalities for whom Ukraine is perceived in the world.

May he rest in peace…

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CRITICAL PROPERTIES OF MODERN GEOGRAPHIC INFORMATION SYSTEMS FOR TERRITORIAL MANAGEMENT

Introduction. *The issue of the "geographic information system" (GIS) definition is important both for the theory and practice of creating modern GIS of large territories. An analysis of modern studies has shown that most of the currently publicly available GIS definitions don't meet the needs of modern territorial GIS.*

The purpose *of the paper is to prove the claim that for the management of territories in modern conditions should be used not GIS in the "narrow" sense, but GIS of the new generation, in particular GIS in the "broader" (extended) sense, for example Atlas Geoinformation Systems (AGIS), which correspond to a predetermined structure — Conceptual framework of Atlas Systems of Relational Cartography.*

Results. *The term Atlas Geoinformation System is defined as GIS of large territories of a new generation. The concept of Atlas Geoinformation System (AGIS) is described. An example of AGIS of a certain class is given. We believe that it is important and useful for practitioners to use the results of this article in the creation of GIS of large territories. Theorists will get a better understanding of the field of geoinformatics research of the next generation, which would satisfy the requirements of modern times.*

Conclusions. *Inductive and/or deductive inferences on the fairness of main critical properties in modern GIS of large territories are given. In the absence of one of the properties, we can say that there is a corresponding critical disadvantage of the GIS project of a large territory. The criticality is that in the absence of an appropriate property, the GIS project is likely to fail.*

Keywords: *Atlas geoinformation system, territory management, Conceptual framework, Solutions frameworks, critical property.*

INTRODUCTION

The article [1] substantiates the need to implement four critical properties (CP) in geoinformation systems (GIS) designed to manage "large" territories:

- CP1. Availability of education-scientific, production and management components in each large territorial GIS.
- CP2. Availability of an atlas solution (or Atlas system — AtS), relatively independent of other elements of the large territory GIS, which could work offline.
- CP3. Portal as the means of building GIS in some broader sense (GISb) with GIS in the narrow sense (GISn) and other elements, as well as to provide on-line teamwork with all elements-systems.
- CP4. GIS of large territory must have a metasystem extension, which must necessarily include meta-products and meta-processes for their creation. All elements of the system must be consistent with the particular Solutions Framework of the project in which the system was created.

In this article, we want to prove that for the management of territories under modern conditions should not be used “classic” GISn, but GIS of some new generation. For these GIS, in addition to CP1–CP4, the following critical property must also be implemented:

- CP5. The need to create in modern conditions not GISn, but GISb and, in particular, Atlas geo-information systems (AGIS), which correspond to a certain predetermined structure — Conceptual framework of Relational Cartography [2], as well as CP1–CP4.

“Classic” GISn refers to systems that are ultimately defined according to one of four approaches to the definition of GIS, oriented accordingly to: processes, applications, databases, tools [3]. A process or process-oriented approach to GIS definition has become the most popular. This is evidenced by definitions from the Russian [4], Ukrainian [5] and English [6] sectors of Wikipedia. In the late 1990s, process-oriented definition of GIS became essential to us thanks to a monograph [7], where GIS was defined as an information system (IS) designed to work with spatial or geographical data. IS, in turn, was defined as a set of subsystems that implement data collection and input processes; their pre-processing; data manipulation; data and information analysis; generating results. In particular, it was used in the Conception of Multipurpose National GIS (NGIS) of Ukraine [8].

The terms "in the narrow sense" and "in the broader sense" were defined in [9] for IS. Since GIS is an IS specialization for us, GISb can be defined through IS in the broader sense (ISb): “The totality of all formal and informal data representation and processing activity within an organization, including the associated communication, both internally and with the outside world”.

To prove the "criticality" of CP1–CP4 for the GIS of “large” territory, we used the experience of creating the Radioecological GIS (RGIS) and the experience of coordinating three large projects of the French-German Chornobyl Initiative (FGI) [1]. In general, this is the work of the decade from 1996 to 2005 and this period coincides with the life cycle of the RGIS. As a result of the Chornobyl accident in 1986, 12 of 25 oblasts of Ukraine are considered to be victims, which is why we have a “large” territory here. Our method of proof was based on the so-called "abductive" inferences [10], [11]. To remove possible objections to their correctness, it should be noted that RGIS was the first implementation of the GIS of "large" territory (or national-level GIS), and there are no other such implementations in Ukraine. Because of this, there are no other abductive inferences for or against, so we believe that in all GIS implementations, CP1–CP4 must be taken into account for managing large territories. For our part, we further analyze the current GIS-solutions available to us, which could be attributed to large territorial ones, to further verify the correctness of CP1–CP4. To this end, we use the theoretical methods of proof based on inductive and deductive inferences.

We always perceive territories through spatial phenomena and processes that allow GIS modeling. In this case, before applying such modeling, we separate spatial phenomena and processes, which in reality can be represented by spatial systems or spatial entities. An example of a spatial system is the hydrography of the Ukraine territory. In GIS, these spatial systems are often modeled by systems of map layers, and the spatial layers themselves are, in reality, appropriate to be called in the field. Examples of spatial entities are those of material cultural heritage. In GIS, these spatial entities are modeled by spatial objects. It is clear that objects of one type can form map layers, and map layers can fall into spatial objects of the same type. Because of this, geoinformatics have even decided to separate the layer and object approaches to GIS.

In the years following the creation and operation of the RGIS and associated "Chornobyl" GIS, since the middle of the first decade of the 21st century, we have been implementing GIS mainly in the commercial sectors of the national economy: oil and gas, telecommunications, banking, transport. In general, these systems should be called object GISs, even if the object of study is entities distributed by territory (systems of entities). For example, the spatial entities of the network of the national telecommunications operator "Vodafone Ukraine" (VF Ukraine) were modeled using a GIS called the VF Automated Information System (AIS) (life cycle from 2008 to 2020). It must be acknowledged that not all CP1–CP4 are valid for such object GISs. For example, the purpose of the VF AIS was to support the operational state of entities of the VF network, such as, for example, base stations. Such systems automate predefined business processes, so CP1 should not be considered, unless the "certainty" of business processes is questioned. There is no need to consider also and CP2. However, in our view, the need for CP1 and CP2 for object GIS is explained by the purpose, which in the case of territorial GIS is different from object GIS.

If we go to the heart of our study, it must be said that most common-sense GIS definitions now do not meet the needs of current territorial GIS. If we take the deeper look at the most up-to-date definitions, we will see the following. The authors of the textbook [12] adhere to the definition of GIS from the textbook [13]: "information systems providing the collection, storage, processing, display and dissemination of data, as well as obtaining on their basis new information and knowledge about spatially coordinated phenomena". Process-oriented definition is adhered to [14; p. 1]: "A geographic information system (GIS) is a computer system for capturing, storing, querying, analyzing, and displaying geospatial data". Shipulin V. in the textbook [15; p. 29] after considering several variants, the definition goes: "GIS is a system that:

- first, there is a set of interacting five components, consisting of computer tools, software, geographic data, regulations and users;

- second, it performs the functions of input, integrating, storing, processing, analyzing, modeling and visualizing geographical information".

It seems that based on the title of the textbook [16; p. 78] Karmanov, et al. could deviate from the process-oriented definition of GIS. Yes, they initially consider different types of territorial IS, but in the section "Concept of GIS territorial management" still define GIS as "a system for management of geographical information, its analysis and mapping", that is, adhere to process-oriented definition of GIS. Interestingly, in the next section, called "GIS as a Distributed System", they de facto recognized that territorial GISs should be integral systems made of GIS of several kinds. To do this, use the ecosystem ArcGIS version 9.x, which is still: 1) dating back to the first decade of the 21st century, and the textbook cited dates from 2015; 2) as early as the first decade of the 21st century, it consisted, at least, of desktop, server-based, portal and mobile elements, each of which could be used to construct an appropriate GIS.

We can state that the definition of GIS from textbooks is different from professional and scientific definitions. Yes, the current definition of GIS for ESRI is: «A framework to organize, communicate, and understand the science of our world. A geographic information system (GIS) is a framework for gathering, managing, and analyzing data. Rooted in the science of geography, GIS integrates many types of data. It analyzes spatial location and organizes layers of information into visualizations using maps and 3D scenes. With this unique capability, GIS reveals deeper insights into data, such as patterns, relationships, and situations — helping users make smarter decisions» [17].

Yang, et al. [18; p. 25] recall that, «GIS originates from several domains and refers to the system designed to capture, observe, collect, store, and manage geographic data, and to provide tools for spatial analyses and visualization [19]. GIS can help obtain geographic data to be used for decision making, such as choosing routes for emergency response». Further Yang, et al. [18; p. 26] indicate that «Coined by Mike Goodchild, the term GIS can also refer to the field of geographic information science or *GIScience* — the study of the scientifically applied GIS principles and technologies [20]. According to GIS scientists, *GIScience* involves remote sensing, global navigation satellite systems, and GIS. Additionally, in various domains, *GeoInformatics* may be applied to remote sensing, global navigation satellite system, and GIS information».

Longley, et al. in the second edition of the monograph [21; p. 16] consider, in contrast to the above definition from the first edition [19], several definitions, among which are the interpretation of GIS as a Spatial Decision Support System (SDSS). As a result of the discussion there, the definitions of Longley, et al. [21; p. 31] point to the importance of the social context, which, in their view, was beautifully expressed by N. Chrisman in his definition of GIS [22; p. 13]: «The organized activity by which people: 1) measure aspects of geographic phenomena and processes; 2) represent these measurements, usually in the form of a computer database, to emphasize spatial themes, entities, and relationships; 3) operate upon these representations to produce more measurements and to discover new relationships by integrating disparate sources; and 4) transform these representations to conform to other frameworks of entities and relationships. These activities reflect the larger context (institutions and cultures) in which these people carry out their work. In turn, the GIS may influence these structures».

Finally, GIS is synonymous with SDSS, the latter being defined as «computer-based system that combines conventional data, spatially referenced data and information, and decision logic as a tool for assisting a human decision-maker. It usually includes a user interface for communicating with the decision-maker. A SDSS does not actually make a decision, but instead assists and analyzing data and presenting processed information in a form that is friendly to the decision-maker» [23].

PROBLEM AND METHODS OF SOLUTION

Consideration of GIS definitions is not a purely academic issue. To explain the importance of this question both for theory and practice of creating modern GIS overlarge territories, let us consider the stages of GIS development in general, which, for example, H. Ottens [24] defined for Europe as follows:

1. Pioneering (innovation): 1965/70 – 1980/85.
2. Maturity (use by specialists and commercialization): 1980/85 – 1990/95.
3. Usage (widespread use and stabilization): 1990/95 – 2000/05.

In article [8], we argued that Ukraine lags behind Europe in terms of GIS development phases by at least ten years. At the same time, H. Ottens [24] considered that the countries of Eastern Europe were not less than twenty years behind. However, there are now signs that even Ukraine has entered phase 3 — the usage of GIS. At the same time, both in the world and in Ukraine, the necessity of changing the definition of GIS, which would correspond to the phase of its development, was not given due consideration. The need for such a change for the usage phase is apparent even from the analysis of the above definitions. Indeed, all four approaches to the definition of GIS from [3] relate, in extreme cases, to the first two phases of development and are, in fact, definitions of GISn. The definitions of GIS in [21; p. 16], [22; p. 13], [23] allow to depart from the definition of GIS in the narrow sense (GISn). However, Yang, et al. [18; p. 26] actually reduce geoinformation science (GIScience) to the use of a slightly extended set of geoinformation technologies. Unfortunately, this is not a mistake. We also suppose that geoinformation science has not yet been created, as, incidentally, cartographic science has not been created. There are also no serious arguments to consider GIS definitions that are different from GISn definitions satisfactory from the viewpoint of the new generation GIS – or from the GIS phase of usage [24].

We cannot provide a direct and complete argumentation for the absence of geoinformation or cartographic sciences. Let's just clarify that for [25], each science has the following components: 1) a domain of inquiry; 2) a body of knowledge regarding the domain; 3) a methodology (a coherent collection of methods) for the acquisition of new knowledge within the domain as well as utilization of the knowledge for dealing with problems relevant to the domain.

According to [26; p. 58], by theory we mean the "'rigid' representation that comes from classical logic and the theory of knowledge of the XX century. From this point of view, the **theory** *is a deductively organized set of judgments formulated in a closed system of concepts*. In other words, each theory in its exact (explicated) form should include at least the following components: basic undefined notions, derivative motions, axioms (postulates in terms of basic and derivative notions that are not derived within the framework of this theory) and theorems, ie, judgments derived by rules from certain axioms".

For partial argumentation of the lack of geoinformation and cartographic sciences, we use facts for a subset of their common domains of inquiries, bodies of knowledge regarding the domains and methodology for the acquisition of new knowledge within the domain. This subset is defined by the knowledge about Atlas GIS (AGIS) that can be obtained from the results of the monograph [2]. Since AGIS is a broader Atlas system (AtSb), the statements made in this monograph are valid, including statements about the absence (before the monograph [2]) of cartographic theory and statements about the presence of much weaker forms of scientific knowledge, which are generally called paradigms. Therefore, it can be argued that there are no geoinformation theories in the above understanding of Rozov V. [26] that could possibly be used for AGIS.

The following two examples allow for a better understanding of the above. In the monograph [2], relatively new mapping phenomena such as geo- or carto-platforms (the example is OpenStreetMap) have been analyzed. These platforms do not belong to the field of research in "classic" cartography, which is defined as "the art, science and technology of making and using maps" [27]. The same can be said about geoinformatics, which is defined, for example, as "science, technology and applied activities related to the collection, storage, processing, analysis and display of spatial data, as well as to the design, creation and use of GIS" [28]. The point here is the question of the geo-/carto- platforms themselves: are they GIS and if so, which one? Or maybe they are geo-information technologies used to create end-user GIS?

Another unclear example is the attempt to identify the geoinformation products of business firms. The monograph [2] outlines the products of MapInfo Corp.: mi-Aware (2003) and MapInfo Envinsa (2006). There these products are also called platforms. However, in the ESRI definition above, GIS is called "A framework to organize, communicate, and understand the science of our world". The term "framework" is not very clear here. Maybe the ESRI framework is a platform from former MapInfo Corp. And in general, to what definition of GIS does ESRI's definition apply?

To finish the description of the problem, let us refer to the article [29] and Abstract: “Many visions for geospatial technology have been advanced over the past half century. Initially researchers saw the handling of geospatial data as the major problem to be overcome. The vision of geographic information systems arose as an early international consensus. Later visions included spatial data infrastructure, Digital Earth, and a nervous system for the planet. With accelerating advances in information technology, a new vision is needed that reflects today’s focus on open and multimodal access, sharing, engagement, the Web, Big Data, artificial intelligence, and data science. We elaborate on the concept of geospatial infrastructure, and argue that it is essential if geospatial technology is to contribute to the solution of problems facing humanity”. In our opinion, the cited authors (by the way, very famous persons in the field of GIS) are talking about the same as we are: modern GIS is a new generation GIS, in which it is very important to use spatial data infrastructure (SDI) as one of the elements for the study territory.

The main method of our study is shown in the example of AGIS (Fig. 1.) The domain of inquiry is "large" territories in which spatial phenomena and processes are defined (Ph&Pr, which, when used in a GIS, are called domain/context). These are primarily the relational spaces defined in the studied territories or their corresponding spatial (territorial) systems, which also include the so-called spatial object systems (or models of Ph&Pr spatial entities), if Ph&Pr is some investigated spatial entity of reality. The "large" territories for us here are (for example, in Ukraine): country, oblast, community (modern association of several village councils, which are determined by the current COATOU), rayon or protected area. However, for territories smaller than the oblast, another additional integration territorial echelon (or tier/stratum) will have to be introduced.

The prerequisite of AGIS is the Electronic version of the National Atlas of Ukraine (ElNAU) [31] in broader sense (ElNAUb). The concept of "broader sense" comes from the fact that ElNAU, like any spatial information system (SpIS), is a specialization of IS, and IS in the broader sense is defined in [9]. In this case, the ElNAU, which was first produced on CD (ElNAU2000onCD) and then on DVD (ElNAU2007onDVD), is IS in a narrow sense [9] — ElNAUn. It turned out that the structure of ElNAUb is not arbitrary, but corresponds to the model, which, because of its repetitiveness in the "atlas" context, is called by the Conceptual Framework (CoFr) not only for ElNAU but also for all Atlas systems [2]. The structure of the AGIS on the example of ElNAU is shown (Fig. 2).

ElNAU Atlas GIS (AGIS) is a hierarchical integrated echeloned GIS or a system of spatial systems where the elements of each echelon (stratum) have the following meaning:

1. ωAGIS (Operational AGIS) is a set of (national) electronic atlases (EA) and other operational models. Examples of EA are ElNAU2007onDVD and a pilot version of ElNAU (ElNAU2000onCD), known as the Atlas of Ukraine [32]. An example of an operational model is the ElNAU2007onDVD master disk, which is used for producing the ElNAU2007onDVD circulation.

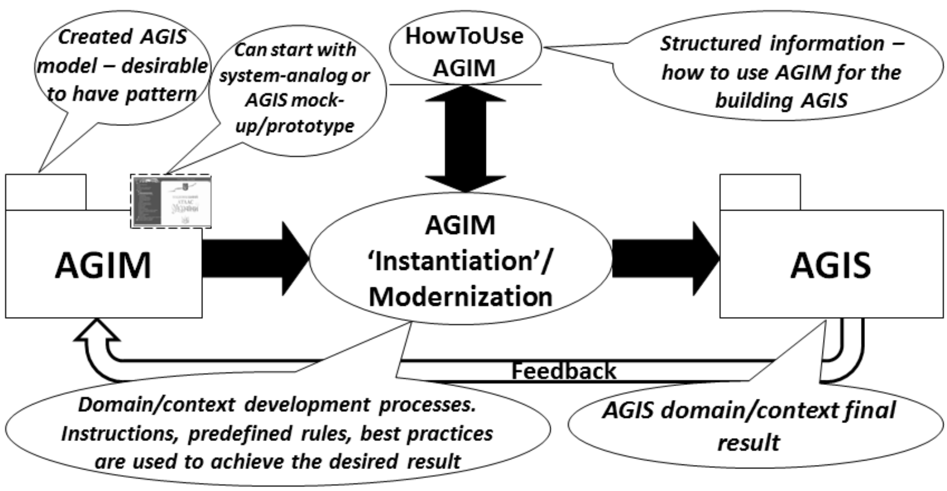

Fig. 1. The process of using AGIM to build AGIS in [30; Fig. 7.1]

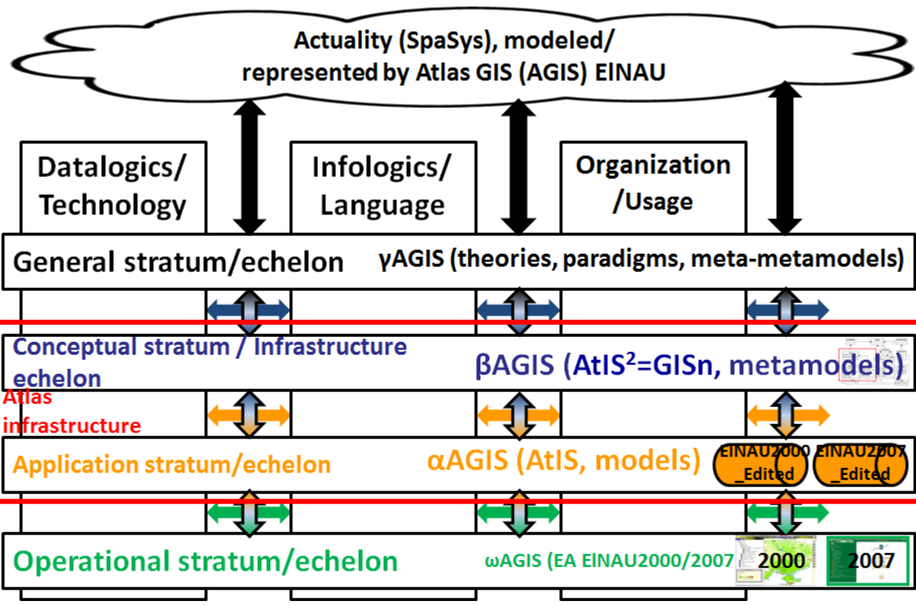

Fig. 2. Structure of the Atlas GIS on the example of ElNAU according to [30; Fig. 7.18]

2. αAGIS (Application AGIS) is a set of Atlas Information Systems (AtIS) and other application models. An example of AtIS is ElNAU2007_Edited, described in [2]. ElNAU2007_Edited is used by the developers of ElNAU2007onDVD to make the latter. An example of an application model is the AtlasSF (Atlas Solutions Framework). A description of the first and subsequent versions of AtlasSF (AtlasSF1.0, AtlasSF1.0+) is contained in [2].

3. βAGIS (Conceptual or Infrastructure AGIS) is a set of specialized GISn and other conceptual models (or application model metamodels). An example of such GIS is the internal ISGeo system, which is designated $AtIS^2$ and was used to develop and support EA and AtIS. An example of a metamodel is the GeoSF (GeoSolutions Framework). The standard version of GeoSF (GeoSF0) is described in [33], [34].

4. γAGIS (General AGIS) is a set of theories, paradigms, and meta-models that are used in the work with lower stratum/echelon elements. γAGIS refers to the most complex stratum/echelon of AGIS. It contains both theoretical and practical elements. An example of a theoretical element is the paradigm of Analytical Cartography [35]. Practical elements are often metamodels of conceptual models.

There are few important remarks according AGIS ElNAU shown in Fig. 2:

1. The notion of model and the relation between models/systems is quite complex. A *model* here is a simplification of a *system* built with an intended goal in mind. The model should be able to answer questions in place of the actual system [36]. We can use the record ωAGIS ► αAGIS ► βAGIS ► γAGIS ► SpaSys, keeping in mind that each relation ► is another very general "model-of" relation between the SpaSys spatial system and its models. Both the elements involved in the relation and the relation themselves need clarification. Thus, [37] distinguishes such varieties of models that are present in many shown in *Fig. 2* constructions: model-as-example (model), model-as-type, model-as-exemplar, model-as-mold.

2. The types of relations in [37]. The relations of these varieties are included in the sets of relations shown in Fig. 2 by vertical and horizontal two-way arrows:

- δ — **DecomposedIn**, **composite/part**. A *system* is very often defined as a complex set of more elementary parts. This relation represents the decomposition of systems in subsystems, and so on. For instance, the country Ukraine is a part of the planet Earth.
- μ — **RepresentationOf**, **model/sus**. A *model* is a representation of a *system under study* (sus for short). This relation is the key of modelling. Sometimes the distinction is made between specification models, which represent a system to be build and descriptive models that describe an existing system [38]. These associations could be introduced as specialization of μ if required.
- ε — **ElementOf, element/set**. This relation corresponds to the notion of set in the Set Theory. For instance, Ukraine is an element of the set of all countries.
- χ — **ConformsTo**, **metamodel/model**. This relation defines the notion of metamodel with respect to a model. A model must conform to its metamodel. In fact, χ is derived from the μ and ε.

3. The AGIS of ElNAU is called and is at present, in fact, a weak integrated system of systems or models, if the term "system" is left for the spatial system of reality, and all other structures are called models. Here we are implicitly using Model-Based Engineering (MBE, [39]). In MBE "everything is a model", and in systemology [25] "everything is a system". The concept of "weak integration" is introduced to encompass relation that exist in the IS in the broader sense but are not implemented in the IS in the narrow sense. For example, ELNAUonDVD(ωAGIS) χ▶ ElNAU_Edited(αAGIS), that matches the phrase "ElNAUonDVD conforms to ElNAU_Edited". This relation exists, but it is not implemented in any IS in the narrow sense. In other words, strong integration between systems is not implemented, so in real time (automated or dynamic) it is impossible to get one system from another — only by the developer manually. Moreover, the relation χ▶ in the above example does indeed consist of the relations μ▶ and ε▶, which further complicates the possible strong integration.

4. We pay attention to the captions Datalogics/Technology, Infologics/Language, Organization/Usage (Fig. 2). They denote, respectively, the Datalogical Level/Technological Context, the Infological Level/Language Context, the Organizational Level/World of Usage Context [2]. There are (horizontal) one-way transformation relation and reverse verification relations between the elements of these levels. We call these bilateral relations generically transformational.

5. It is necessary to emphasize additionally the necessity of using atlas models on the Operational (Electronic Atlases) and Application (Atlas Information Systems) Strata. These models somehow model real-world systems with multiple layers of maps. The preference is given to the so-called "layer" approach, when in the real world they are looking for explicit or hidden thematic fields. Compared with the more common object approach used in GIS, the layer approach greatly simplifies the model of the real system, while still being very powerful. Finally, it must take into account the fact that well-known geo- and/or carto- platforms (such as Google Maps, OpenStreetMap) have accustomed humanity to a layer approach, at least in map representation.

6. The internal nature of strata/echelons is disclosed in [40], as well as their importance and obligation for modern atlas systems. In particular, the relation between the elements of the neighboring strata is called epistemological. At the same time, the knowledge about the modeled spatial phenomenon is realized from the bottom-up — the higher the stratum, the more we know. In our case, the phenomenon is the sustainable development of the territory.

ElNAU2000onCD and ElNAU2007onDVD are AtSn of the classic static type. They were created in the first decade of the 21st century and earlier. In the second decade of the 21st century (and beyond), we need to consider AtS (AtSn), which we might call AtSn of the classic dynamic type. Non-classic type AtS (AtSn) are too early to consider because there is no relevant theory for this consideration. Therefore, the CoFr AtSn of the classical dynamic type can be obtained from Fig. 3 (additional explanations can be found in [2] and further).

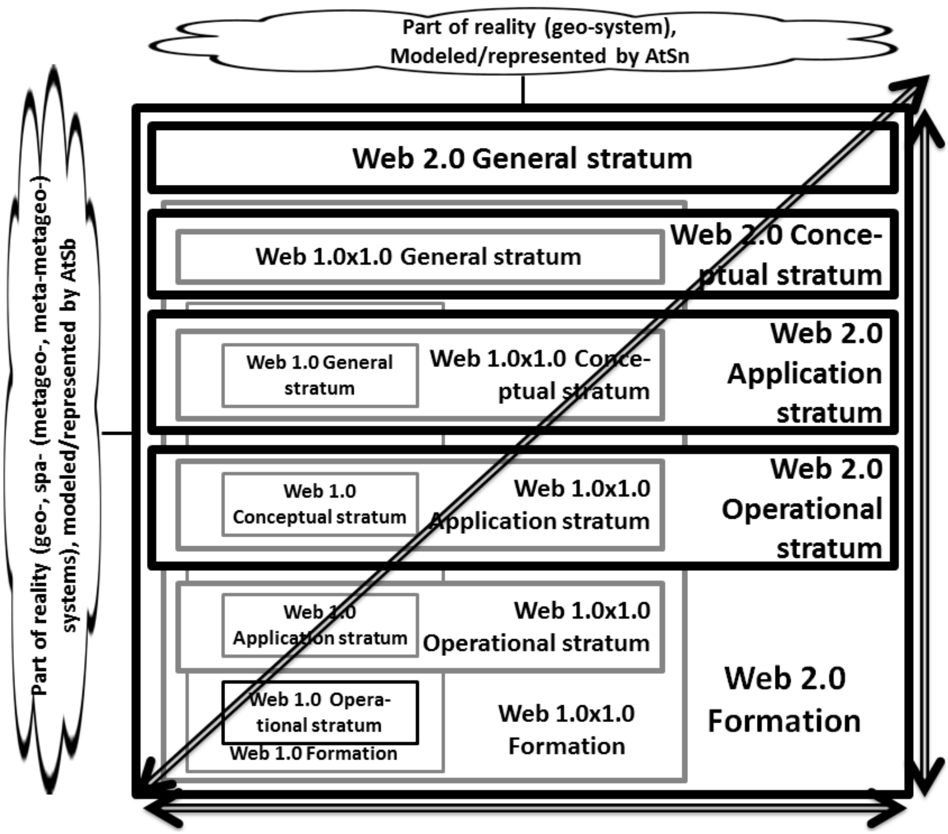

Fig. 3. Classic dynamic type AGIS (highlighted color)

Diagonal arrow in Fig. 3 shows the so-called evolutionary/devolutionary relation between classes of systems of different formations. Above we have used the term "AtS of the classic static type" to identify the class of AtS of Web 1.0 formation. The next evolutionary formation is called Web 1.0x1.0 (Web 1.0^2). It corresponds to the class "AtS of the classic dynamic type". Formation Web 2.0 has been poorly studied, so only the two previous formations are shown in green. However, elements of earlier formations are "embedded" into later formations. For example, the CoFr AtSn of the classic static type in the example of ElNAU (Fig. 2) corresponds to the Web 1.0 formation. Using Fig. 3, it is quite easy to get a representation CoFr AtS of the classic dynamic type. These five-stratum classic dynamic type CoFr (highlighted color in Fig. 3) are the AGIS models that are discussed below.

Horizontal arrows in Fig. 3 show the transformation/verification relations between the elements of the three levels: Datological, Infological and Organizational (Fig. 2). We will not stay on them further. The vertical arrows show the most important for us the epistemological/reduction relations between the elements of the four strata for the class of systems of fixed formation Web 1.0^2. We will stay on the interpretation of these relations in the consideration of AGIS further.

AN EXAMPLE OF A MODERN ATLAS GIS (AGIS)

The concept of AGIS was first introduced in a monograph [30]. It describes the concept and relation of AGIS with the Atlas geo-information model (AGIM). This relation is shown in the simplest (slightly modernized) form (Fig. 1), where, compared to [30; Fig. 7.1], material cultural heritage (CH) has been replaced with an arbitrary domain/context. In addition, the main result [30] is AGIM-CH, which can be a model of the system of sustainable development of the country in the terminology adapted to Ukraine [41].

The description of AGIS, stated above as the Critical property 5 (CP5) for GIS of large territory, begins with an example of AGIS hypothetical "large" territory (AGIS-LT, Fig. 4). The structure of AGIS-LT was developed using the method shown in Fig. 1. There, the ElNAU AtSn of classic static type (see the ElNAU image as the AGIM parameter in Fig. 1), was used as an initial model parameter. The initial model itself is an extension of the ElNAU to the ElNAUb (AtSb), which is shown in Fig. 2. Then, the evolutionary relation Web 1.0 $\nearrow$ Web 1.0^2 was used to obtain the modern structure now the AtSb of the classic dynamic type (Fig. 3). The final result of the method usage (Fig. 1) (referred to in [2] by the method of AtS Conceptual Frameworks) is shown in Fig. 4. In addition to the theoretical results from [30], during the Instantiation/Modernization of AGIM (Fig. 1), the practical experience of developing the pilot project of the AGIS Cultural heritage (AGIS-CH) was used [42]. In particular, the domain of inquiry of (physical) reality is replaced. Instead of (spatial system of) the entities of the material CH, spatial phenomena and processes of reality (Ph&Pr), which are studied under the jurisdiction of the organizational structure responsible for the territory, are shown.

Fig. 4 shows five echelons that are called strata from a system perspective. For a specific AGIS, there are three "own" echelons/strata on which there are spatial systems such as: AtIS, $AtIS^2$ and GIP (geoinformation platform). On the external Operational echelon EA is shown. On the external Infrastructure echelon, no SpIS are shown so as not to overload the figure with information that we do not need in this article. We hope it is easy to see that Fig. 4 corresponds to Fig. 2, and Fig. 3. The designation "GIP" is used for the Spatial Data Infrastructure (SDI), which shall exist on the Infrastructure echelon for each system of AGIS type. We did not use the term GISn here because the geoinformation platform term is better suited for this subject. Turning again to the analogy with the base map, we can say that in the Web 1.0^2 formation it is necessary not to use separate base maps, but platforms that have to dynamically connect to spatial systems of the lower echelons.

Other explanations for Fig. 4:

- Development is carried out by phases. The phases consist of stages. The green and red colors in the AGIS-LT rectangle indicate the elements that are proposed to be created in the first and second stages of the first phase, respectively.
- "SpaSys" means a Spatial system (SpS) or a Relational space of actuality modeled using AGIS-LT. In fact, this SpS includes systems of three "worlds": physical, abstract-physical, and abstract. The abstract-physical world is intended to describe the SpS that will/can be created in the form of computer systems.

The third arrow from the cloud "Actuality, ..., etc." top-down means that other information systems of Ukraine already created outside of AGIS-LT (spatial) information systems (usually referred to as UkrSys) may exist and be used. For example, these could be NCS (National cadaster system) or arbitrary AtIS (Atlas information system). This arrow also points to AGIM-LT (see below), which is an education-scientific component of AGIS-LT.

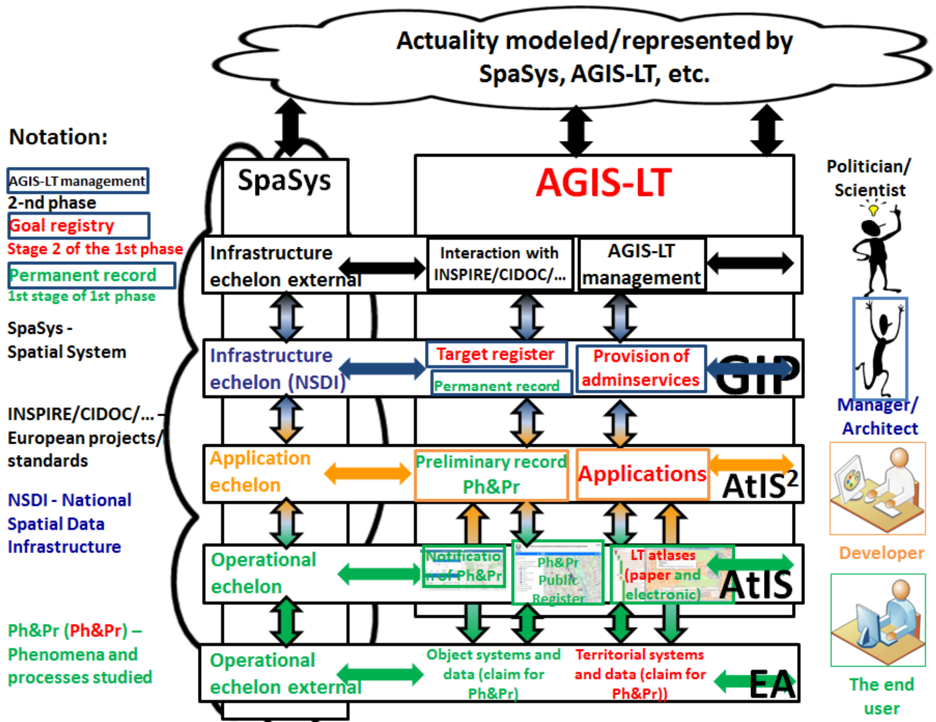

Fig. 4. Conceptual structure of AGIS-LT with the notations of the stages of the 1st phase and user echelons

“LT atlases (paper and electronic)” are shown outstanding beyond AGIS-LT, as may include second phase atlases. The atlases of the second and subsequent phases can be an essential element of the sustainable development systems of the region, which in this case is the territory domain of inquiry.

- The main elements of the second (and subsequent) phase of AGIS-LT are the "Interaction with INSPIRE/CIDOC/..." and "AGIS-LT management". INSPIRE is a well-known regional EU SDI [43]. The CIDOC Conceptual Reference Model [44] or CIDOC CRM provides an extended ontology for concepts and information in cultural and museum documentation. It is an international standard ISO 21127: 2014 [45]. "..." means that there are other European standards that should be determinative for AGIS-LT.

The first phase of AGIS-LT is the system of recording and protection of spatial phenomena and processes (Ph&Pr), managed by the responsible organization in accordance with its provisions. The first stage of the first phase of the AGIS creation project consists of those shown in Fig. 4 items (bottom-up):

1. "Object systems and data (claim for Ph&Pr)". The object is an information mapping of the Ph&Pr entity. This element is external to AGIS-LT. It is appropriate only if AGIS-LT makes significant use of AGIM-LT [30] and the latter includes the territory's SDI. It can be, in principle, any model of a separate spatial entity of the territory. The most popular such model is the use of the WGS84 coordinate system for spatial anchoring of the Ph&Pr. However, it is not yet known in this element whether the claimed substance is a phenomenon or a process to be studied by an organization in accordance with its provisions. Perhaps the entity of the object (original) in reality (actuality) is not a Ph&Pr at this time.
2. "Notification of Ph&Pr". The main difference between the "Ph&Pr notification" and the "claim for Ph&Pr" is that the notification is an element of AGIS-LT and is executed, in particular, on a datum controlled topographic map and corresponds to a known administrative-territorial division up to the address, if any. If there is electronic pre-recording or permanent recording, then the operator with verification permission practically immediately sets three options for what it is: 1) Ph&Pr is recorded, 2) Ph&Pr to be pre-recorded and dealt with later, 3) not Ph&Pr.
3. "Preliminary record of Ph&Pr". This is a set of CRUDL (Create, Read, Update, Delete, List) activities of electronic Preliminary recording of Ph&Pr. In the AGIS-CH pilot project, this is the Declaration module. It must maintain a Public register and ensure that the assets are permanently registered. It must be adapted for use in AGIS-LT.
4. "Permanent record". It is in fact a database of permanently registered Ph&Pr. To put it simply, only with such Ph&Pr can all other automatic AGIS-LT operations be performed and perform some automatic data conversion.
5. "Ph&Pr Public Register". It is currently characterized by the Public register of AGIS-CH and its website [46]. It should be noted that this Public register is an official “extract” from the Permanent record of the CH. In particular, it is designed to perform a protective function. Literally, any user must understand that Ph&Pr of the Public register are protected by a state (or organization managing the territory) and violation of that protection may result in sanctions.
6. Electronic Atlases of the territory. Here it is proposed to start AGIS-LT building by creation a dynamic, constantly updated electronic Atlas of the territory. This Atlas should be extended to AGIS-LT even in the first stage.

7. Applications1. In the 1st stage of the 1st phase this element can be geoinformation packages such as QGIS, MapInfo Pro, ArcGIS Pro.

The 2nd stage of the first phase consists of those shown in Fig. 4 items (bottom-up):

8. "Territorial systems and data (claim for Ph&Pr)". The layer is an informative reflection of the Ph&Pr field. In other words, this is still the same as "Object systems and data (claim for Ph&Pr)" with the substitution of entity/object for field/layer.

9. Provision of administrative services. Accepts different values depending on the domain/context. The responsible organization, for example, protects the "entities of the domain of inquiry" from the so-called "stalkers" in the case of the reserve or the protection of the entities of cultural heritage in the case of the organization of cultural protection. If a responsible organization exists, we can now determine the list of administrative services provided by the organization. In the future, this will include admin services related to the new vision of the territory management process, for example, scientific research from other institutions (both national and international) in the territory.

10. Atlases of the territory (paper and electronic). In the 2nd stage of the 1st phase, this element should be extended with both paper atlases and AtIS.

11. Applications 2. In the 2nd stage of the first phase, a set of applications should be implemented that realizes the basic functionality of the AGIS-LT for the Application echelon. In particular, these should be both functional and cartographic transformations of Infrastructure echelon data for use on the Operational echelon.

12. Target register. Considering the processes in Ukraine, this register should be attributed to the 2nd phase and further, as it is likely not to be created soon. First of all, we have in mind the Draft Law on National SDI, which was adopted as a basis in the first reading in 2019-Dec-04/05 [47]. A criticism of this Law is contained in [48], according to which the Law will not work for so-called protected areas (in INSPIRE terminology).

The Introduction lists all five properties of modern GIS that are called Critical (CP1–CP5) — those that, in the case of absence in resulting system, will be among the main reasons for the failure of a GIS project. At the same time [1] on the example of GIS previously created by abductive inferences, we proved the criticality of CP1-CP4 for the success of their implementation. In this article, we justify the Critical property five (CP5):

- In order to solve the problems of managing large territories in modern conditions it is necessary to create not GISn, but GISb and, in particular, AGIS.

To prove the criticality of CP5, deductive and / or inductive inferences based on theoretical constructs of Relational cartography are used [2]. In addition, the criticality of CP1-CP4 for AGIS and, thus, for modern GIS is further proved. Deductive and/or inductive reasoning is also used for proof. In general, AGIS is a modern vision of GIS that we define, describe conception (notion), and give an example of subject. Again, this vision is limited to such domain of inquiry: spatial phenomena and processes of "large" territory.

CRITICAL PROPERTY 1 (CP1) IN AGIS: EDUCATION-SCIENTIFIC, PRODUCTION AND MANAGEMENT COMPONENTS

The conceptual diagram of the AGIS-LT creation process is shown in Fig. 5. It corresponds to the general scheme shown in Fig. 1. Compared with Fig. 4, in the right part Fig. 5 shows the Atlas geoinformation model AGIM-LT, which consists of the GeoSF (GeoSolutions Framework), the AtlasSF (Atlas Solutions Framework) and Electronic atlases created with AtlasSF that can be used in AGIS-LT. For example: updated site/atlas of the Nature Reserve Fund (NRF1+ site, here is an example site for the Kyiv region), updating ElNAU to AtS of the classic dynamic type (ElNAU1.0+) etc. It should be noted that AGIM-LT on the one hand is a method of AtSn (or AGIS) CoFr, on the other — is a tool that is currently implemented as the so-called Atlas Extender (AtEx). Since some elements of AGIS-LT may already exist (for example, a topographic map of the territory), the creation of AGIS-LT can be called an extension of several "ordinary" Atlas and Geoinformation systems to GISb of special type — to AGIS-LT. AGIM-LT elements must be created BEFORE creating the appropriate AGIS-LT elements. In this sense, AGIM-LT is the education-scientific component of the AGIS-LT full version. This education-scientific component is not always shown in the diagrams, but it must always exist.

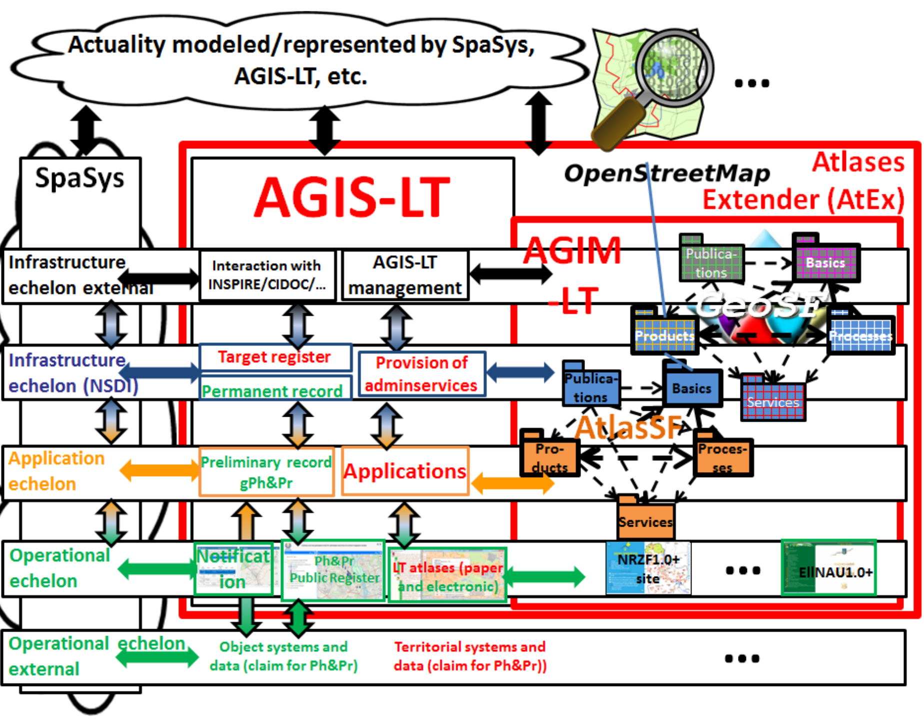

Fig. 5. Conceptual scheme of AGIS-LT creation

Production and management components are parts of AGIS-LT. Conditionally speaking, at the first phase the production component is the left-hand column of elements that implement the main process of recording and monitoring of the Ph&Pr state. It starts with the element "Notification" and ends with the "Target Register" element. The Target register should interact with the National Spatial Data Infrastructure (NSDI) and adapt the relevant European project materials. The management component is the right-hand column of elements that implement two management processes.

The first management process is the Ph&Pr protecting. It should be implemented first of all in the project of creation of an AGIS type system. The second process is called "AGIS-LT management", which is shown as a separate element in *Fig. 4* and *Fig. 5*. This process consists of many elements. They should be implemented at the second phase of the AGIS creation project, after implementation of at least permanent recording of Ph&Pr. The "AGIS-LT management" process is also covered in the next section.

CRITICAL PROPERTIES 2 (CP2 - ATLAS) AND 3 (CP3 - PORTAL) IN AGIS

Critical property 2 (CP2): Availability of an atlas solution (or Atlas system — AtS), relatively independent of other elements of the large territory GIS, which could work offline. The name of CP2 is not very good because it allows for several interpretations. In the form the "relative independence" of the atlas solution means that it must be able to work separately from the full AGIS. This means, in particular, that the atlas solution must work offline when the Internet connection is disconnected (or lost). When connected to the Internet, synchronization with the full AGIS must take place and the atlas solution should work online. In essence, "relative independence" has several meanings related to the essence of AGIS. Consider the options.

The answer, perhaps, to the main question is — why the ATLAS GIS. This adjective is included in the GIS class name due to the following chain of conclusions. The first is the claim that National Atlases (NA) are the simplest, most complete, well-known, and at the same time, sufficiently developed models of a country. The datalogical similarity of Ukraine and Switzerland NA was proved in [49]. Thus, there are similarities also between the NA of Ukraine versions, created at different times (for example, between ElNAU2000 and ElNAU2007). There is also a similarity between the NA of Ukraine and the model of sustainable development of Ukraine, which is determined by the Decree of the President of Ukraine №722/2019 “On the sustainable development Goals of Ukraine for the period up to 2030” [50]. This statement follows from the proof of the similarity between the NA of Ukraine and the balanced model of sustainable development of Ukraine [30], since the Decree №722/2019 model corresponds to the model of sustainable development in [41]. It follows that the maps of Ukraine's NA, such as the model of sustainable development, can correspond (model) to the indicators of sustainable development from [41].

Thanks to such transformations, the NA of Ukraine has the opportunity to "weigh" each "indicator", since it may correspond to some "indicator" map. We can get a numerical rating of each indicator map and this estimate will be uniform for all atlas maps. For a "zero" approximation of the estimate, it is possible to first "weigh" each map by one number. From individual map estimates we can get a numerical estimate of the atlas as a whole. This assessment will be an assessment of the level of sustainable development of the country at the time the atlas was created. Thus, a relatively independent atlas solution in AGIS is required in order to be able to obtain an estimate of the level of sustainable development at this point in time.

An atlas solution of the AGIS Operational stratum is not enough for normal operation. In order to be able to analyze both structural and thematic indicators of the AtIS of the Operational stratum, it is necessary to have an AtIS of the Application stratum, which will be dynamic for the AtIS of the Operational stratum. In Fig. 4 $AtIS^2$=AtISxAtIS was used to designate the AtIS Application stratum. This means that we can change all the components of the AtIS of Operational stratum while remaining, however, in the same class of AtIS. For example, we can change the structure of an AtIS contents tree and move a map from one section to another if the map theme belongs to a new section. We may, for example, change the method of classifying a choropleth map if the new method allows us to better model the field of a spatial phenomenon or process from reality. Spatial information systems of Conceptual stratum are also needed, among them GIP is important (Fig. 4).

In choosing the best option for prioritizing AGIS over blocks of sustainable development, two fairly obvious theses were used, which in mathematics are called theses "from the opposite":

1. All 17 sustainable development goals cannot be simultaneously achieved [41], although their achievement should improve the economic, social and environmental aspects of Ukraine as part of humanity and our planet. Moreover, it is not possible to reach at the same time about 300 indicators [41], which measure the progress of the 17 target areas.

2. Most of these indicators in [41] are in one way or another related to economic aspects. Given the real economic situation of Ukraine, these indicators cannot be prioritized.

However, if you follow these two theses, then what? We will analyze several options to optimize [41] for Ukraine. The remaining options are shown in *Fig. 6*.

Each of the selected options should be a multigoal-oriented system according to [25]. We will not build here a generalization of AGIS using the G. Klir apparatus. However, with the application of generalization, it is possible to create a whole-directional AGIS, which will consist of three elements: generating, seeking and implementing of the goal. The goal seeking element can be formed by the culture indicators. For this purpose, [41] proposed to extend by the indicators of culture [30]. The number of these indicators will be relatively small, but they will determine the characteristics and limitations of achieving the goal. All other indicators will form a goal implementation element. AGIS will be applied and developed iteratively, most likely in years. During each iteration, the main steps of the empirical study, which are shown on Fig. 7.

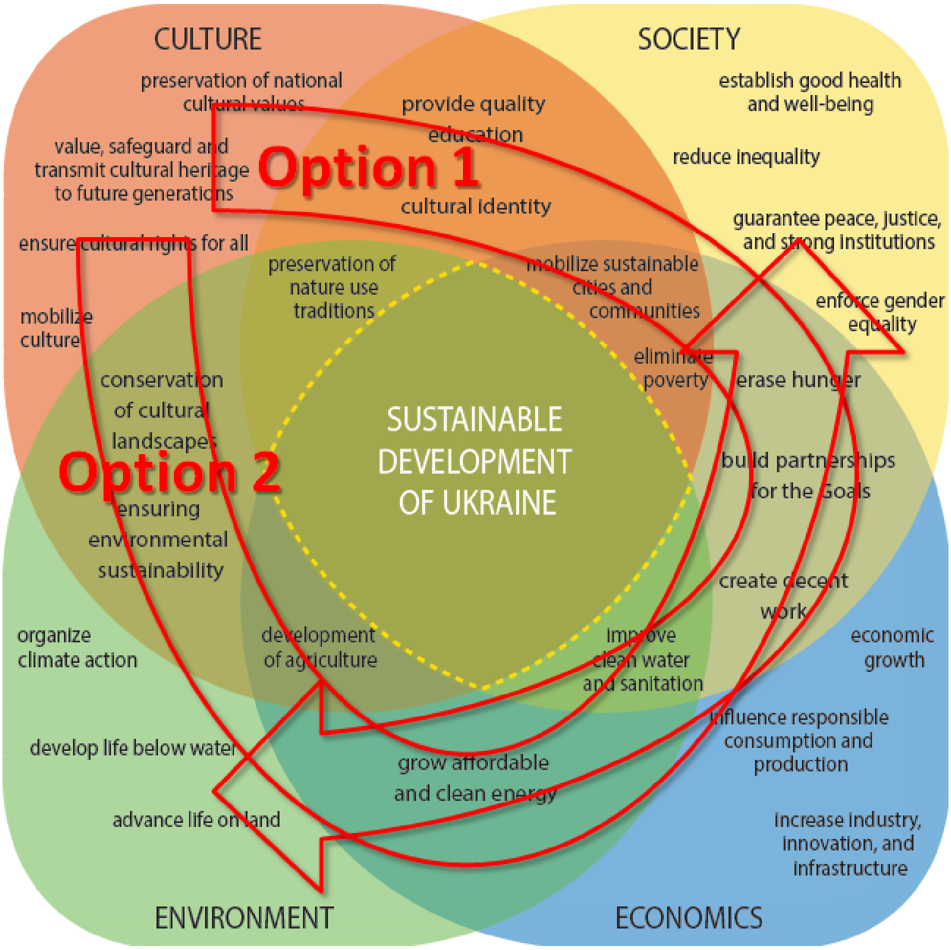

Fig. 6. Two main options for optimal achievement of goals [41] in Ukraine

It should be said that the approach described above is not so unique. We use works [51], [52], [53] and others for arguments of this statement. We cannot focus on the differences between the two approaches. If we consider the similarities of approaches, then we should point to Fig. 8. There are quite obvious analogies between Inventory Fig. 8 and elements of Inventory echelon Fig. 4, between the Spatial analysis Fig. 8 and the elements of the Application echelon Fig. 4. The analogy between Decision making is a little less obvious and the elements of the Operational echelon Fig. 4, Management Fig. 8 and the elements of the AGIS-LT management.

In conclusion CP2 analysis we make three important notes:

1. At the beginning of the CP2 analysis we have described in fact the main steps of empirical research with the help of the AtIS Operational and then the Application strata, and so it is possible to continue further with the elements of the Conceptual stratum.

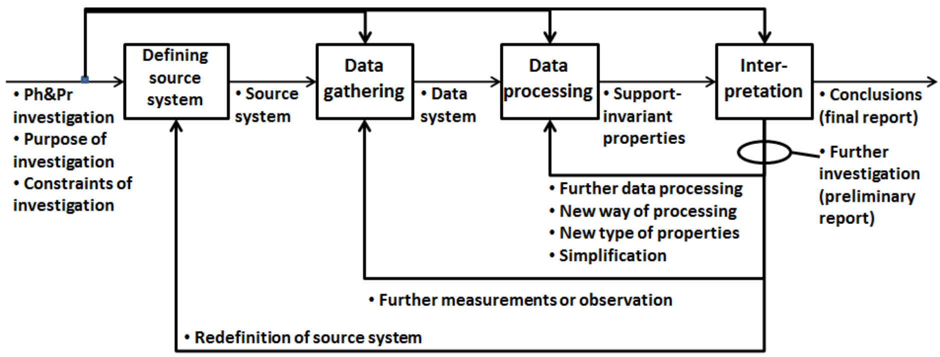

Fig. 7. Main stages of empirical research on Ph&Pr using AGIS [25]

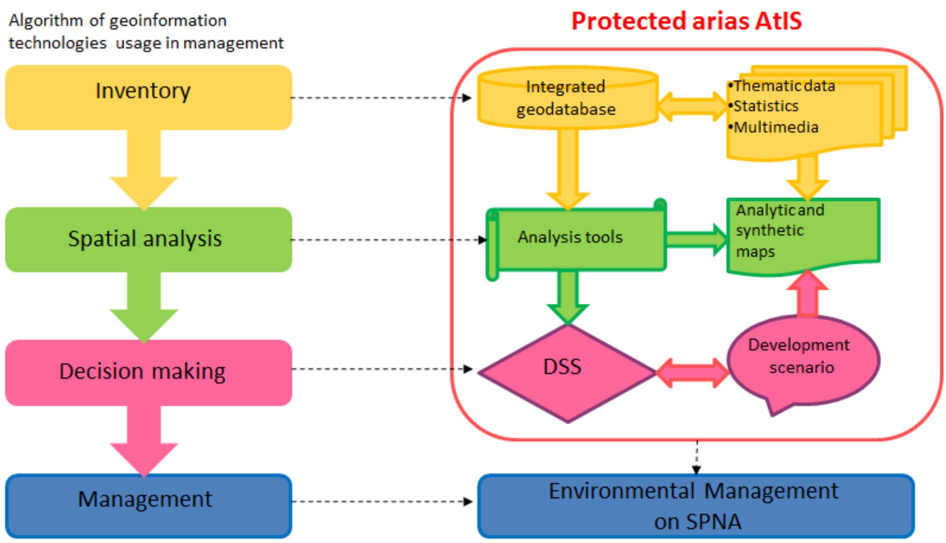

Fig. 8. Conceptual diagram of the sustainable development AtIS in [53; Fig. 9]. DSS — Decision Support System

2. The process of managing the sustainable development of a large territory that is a country is described. This is obviously the case for the unification of countries, which is the Russian Federation. This is also true of any other large territory. This is because no one will argue that the territory of Ukraine, the protected area or the territory of the community must be constantly developed. Perhaps, in this case, only the AGIS-LT model will be simpler than the model [41].

3. We consider the criticality of the atlas solution to be proven for any modern GIS of large territory management.

Critical property 3 (CP3): Portal as a means of building GIS in some broader sense (GISb) with GIS in the narrow sense (GISn) and other elements, as well as to provide on-line teamwork with all elements-systems. At the end of the first — at the beginning of the second decade, a project was underway in the Netherlands, which is appropriate to call the "National Atlas of the Netherlands as a metaphor for the National SDI". This name derives from the title of the thesis [54]. To explain the term "metaphor" in the context used [54] indicates that designers have long used metaphorical references in user interfaces to facilitate the understanding and use of content by the latter. Moreover, familiarity and understandability of the original content are critical when choosing a new metaphor. And users in many countries are familiar with atlases because they are most likely to use them in high school.

The following substantiates the idea [55; p. 29] that the map is a metaphor in its own right, because with the help of the map the cartographers suggest that the reader believes that points, lines and polygons located on paper (or on the screen) are equivalent to a multidimensional world in space and time. However, to fully understand this view, readers should refer directly to the reflected real world. Following the dissertation [54], several articles [55], [56] etc. were published. They focused on the identified phenomenon — ElNAN as a metaphor for the Netherlands NSDI. What is important to us is the argument that the authors of this phenomenon used to prove the need to use National atlases in conjunction with NSDI.

In the context of this article, perhaps the first article on the subject should not be forgotten [57], which states that in some countries the use of portals to search for geospatial data sets was the result of the implementation of Spatial Geodata Infrastructures (SGI). The authors of the article cited highlighted two disadvantages of existing portals: inappropriate navigation tools and a lack of supports for users' understanding. Therefore, the article proposes a new approach to developing portals using atlases as metaphors. It allows you to use the atlas not only to access a set of thematic maps, but also to find sets of data.

«Within the atlas, an information structure plays an important role in organizing the content. Metadata published by providers are incorporated into this structure as metadata summaries. Based upon the topical relevancy of the data, each metadata summary is linked to a specific map within a particular topic. These summaries can be represented as symbols to support discovery tasks, either loosely or strictly defined. Browsing can be used to deal with the first via navigations and map interfaces. Searching can be used to deal with the second via explorer and search presentation interfaces…».

In the previous citation the usage of the portals (geoportals), in particular for SDI, was taken for granted. However, it should be noted that the issue of geoportals was discussed in detail, a year or two before. For example, the first issue of Computers, Environment and Urban Systems in 2005 was devoted to the issue of geoportals. The articles of the issue described both the causes and the main features of geoportals.

Among the reasons for the emergence of geoportals were the following: 1) “maturing” of GIS — the transition from GIS of individual groups to corporate, 2) implementation of National SDI, 3) the need to use geoinformatics in electronic governance, 4) the development of information technologies.

Among the main features of geoportals were: 1) organization of content and services such as directories, search tools, community information, support resources, access to data and applications, 2) direct access to application services and metadata records from regular on-line GIS applications, 3) development of elements of service-oriented software architectures.

Thus, the appearance of CP3 in the created by us GIS of large territories, is hardly to say a coincidence. Full confirmation of the criticality of CP3 is provided in the sources cited above.

CRITICAL PROPERTIES 4 (CP4 – SOLUTIONS FRAMEWORK) AND 5 (CP5 – CONCEPTUAL FRAMEWORK) IN AGIS

In this section, we first present the conceptual structure of AGIS class system (Fig. 9), which summarizes all that has been said before, and also includes the CP4 — Solutions Framework (SoFr). Two SoFr — AtlasSF and GeoSF — are shown in Fig. 5. The more correct entries are αAGIM (AtlasSF, …) and βAGIM (GeoSF, …), since both αAGIM and βAGIM consist of a much larger number of application and conceptual SoFr, respectively. We have only shown SoFr that have already been created and used in any version. These SoFr may be enough for beginning the realization of some AGIS. In addition, there are also operational and general SoFr. At the same time, Fig. 5 shows us that each SoFr "works" between the elements of two adjacent strata, with the main triad of SoFr being Products-Processes-Basics(Products, Processes), and the usage of SoFr is always performed from the elements of the epistemically higher to the lower strata.

GeoSF SoFr is derived from ProSF (Project Solutions Framework) SoFr. ProSF was used in [1] to formulate CP4. It describes the use of ProSF SoFr for three projects of the so-called French-German Chornobyl Initiative (FGI). At the beginning of the first decade of the 21st century, we found that the activities of geoinformation enterprises (geo-enterprises) could be divided into project and everyday activities. In order to put NSDI into practice in Ukrainian geo-enterprises, we have adapted ProSF to GeoSF. GeoSF SoFr (standard version — GeoSF0) was implemented as a portal intended for introduction into business processes of the geo-enterprise.

Let's explain the abbreviations of the "2-dim AGISb" elements on Fig. 9:

- The letters D, I, U from above indicate the levels: D — Datalogics, I — Infologics, U — Usagelogics. The letters G, C, A, O on the right indicate the strata: G — General, C — Conceptual, A — Application, O — Operational.
- XYM, where X = D, I, U; Y = G, C, A, O; stands for XY M(odel). For example, DCM stands for Datalogical (D) Conceptual (C) Model (M).
- The structure of "2-dim AGISb" corresponds to the structure of the Conceptual Framework (CoFr) of Relational cartography [2].
- There are two meanings of M: AGIS and AGIM. Between AGIS and AGIM there exists relation χ (conformsTo).

Unfortunately, Fig. 9 is very ambiguous, but we haven't prepared better yet. The ambiguities (not all) are:

- If we replace the value M=AGIS with M=AGIM, then we will have the same conceptual structure, but for the AGIM model.
- The entry AGISχ▶AGIM means that this relation is valid also between the corresponding elements of both structures. That is, an AtCχ▶AtlasSF record is valid. This entry corresponds to the general scheme of Fig. 1. Moreover, AtS can be created using AtlasSF.
- Atlas general systems on the right reflect the results of [58] usage. These results, in particular, argue that, in addition to modeling Object stratum models, the success of an AtIS or GIS creation project must necessarily metamodel and create metamodels. These metaprocesses and metaproducts are elements of the aforementioned higher metasystem of metaAtIS or metaGIS and, at the same time, Metastratum.

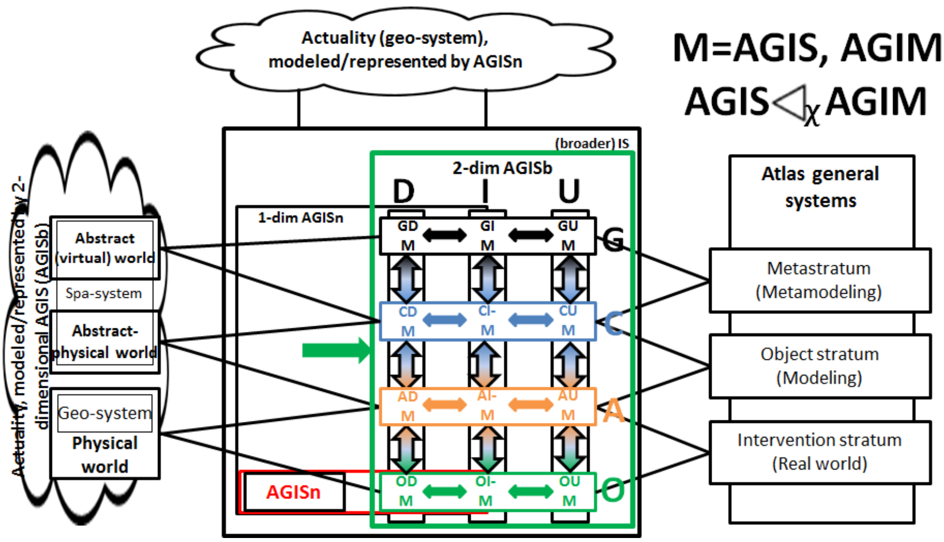

Fig. 9. Conceptual structure of AGIS class systems

- Writing AGISn in a red rectangle and a green arrow from one-dimensional to two-dimensional IS means that the former can be converted to the second.

Better to describe CP4 and CP5 we are not able due to the limited size of the article. Additional evidence for the validity of SoFr and CoFr for a large range of spatial systems is contained in a monograph [2]. This range of systems includes AGIS, as these systems are considered in the monograph as AtS (AtSb) class .

CONCLUSIONS

Above, in addition to the abductive reasoning of the [1], inductive and/or deductive reasoning about the validity of the Critical properties (CP) of CP1–CP4 in modern GIS of large territories are given. The validity of CP5 is also given. In the absence of one of the CP1–CP5 properties, we can speak about the corresponding critical disadvantage of the project of creating GIS over a large territory. The criticality is that in the absence of a suitable property, the GIS project is likely to be a failure.

Due to the formulation and proof of CP1–CP5, we believe that: 1) the term “Atlas geoinformation system” (AGIS) is defined as a GIS of large new-generation territories, 2) the conception of AGIS is described, 3) an example of AGIS of a certain class is given. We believe that practitioners will use the results of this article to create GIS of large territories. Theorists will also gain a better understanding of the next generation of geoinformatics research that would meet the demands of today. With this understanding it will be possible to create a geoinformation theory that will correspond to a "rigid" view of it in [21, p. 58].

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КРИТИЧНО ВАЖЛИВІ ВЛАСТИВОСТІ СУЧАСНИХ ГЕОІНФОРМАЦІЙНИХ СИСТЕМ ДЛЯ КЕРУВАННЯ ТЕРИТОРІЯМИ

Вступ. Питання дефініції «геоінформаційної системи» (ГІС) є важливим як для теорії, так і для практики створення сучасних ГІС великих територій. Аналіз останніх досліджень показав, що більшість загальнодоступних наразі означень ГІС не відповідають потребам сучасних територіальних ГІС.

Метою статті є доведення твердження, що для керування територіями у сучасних умовах мають використовуватися не ГІС у «вузькому» розумінні, а ГІС деякого нового покоління, зокрема, ГІС у «розширеному» розумінні, наприклад, Атласні геоінформаційні системі (АГІС), які відповідають певній наперед визначеній структурі — Концептуальному каркасу Реляційної картографії.

Результати. Визначено термін «Атласна геоінформаційна система» як ГІС великих територій нового покоління. Описано концепцію Атласної геоінформаційної системи (АГІС). Наведено приклад АГІС визначеного класу. Вважаємо, що практики будуть використовувати результати цієї статті у створенні ГІС великих територій. Теоретики отримають краще розуміння галузі досліджень геоінформатики нового покоління, яке задовольнятиме вимоги сучасності.

Висновки. Наведено індуктивні та/або дедуктивні умовиводи щодо справедливості основних визначених критичних властивостей в сучасних ГІС великих територій. За відсутністю однієї з таких властивостей можемо говорити про відповідний критичний недолік проекту створення ГІС великої території. Критичність полягає в тому, що у разі відсутності відповідної властивості проєкт створення такої ГІС найімовірніше буде провальним.

Ключові слова: *геоінформаційна система, керування територіями, Концептуальний каркас, Каркаси рішень, критична властивість.*

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CONTROL OF A NONSQUARE MULTIVARIABLE SYSTEM USING PSEUDOINVERSE MODEL-BASED STATIC OUTPUT FEEDBACK

Introduction. *The paper deals with nonzero set-point regulating the first-order linear discrete-time multivariable system. The case where the number of outputs exceeds the number of control inputs is considered. It is assumed that arbitrary but bounded unmeasurable disturbances are present. The assumption that the elements of the matricies arising in the system equation are unknown. However, their bounds are assumed to be known a priori. From practical point of view, it is important to design a simple controller similar to reduced-order or static output feedback (SOF) controllers. A difficulty associated with this problem is in establishing the existence of SOF control to be able to cope with a given system. The three different problems concerning the optimality, ultimate boundedness and robustness features are stated and solved.*

The purpose *of the paper is to answer the question: is there the SOF control based on the pseudoinverse concept to stabilize some first-order multivariable system with nonsquare gain matrix?*

Methods. *The methods based on the theory of matricies are utilized.*

Results. *The pseudoinverse model-based control leading to static output feedback is proposed to reject unmeasured disturbances. The optimality and robustness properties of such controller are established. Numerical examples and simulation results are presented to support theoretical study.*

Conclusion. *The paper shed some light on the existence of the pseudoinverse static output feedback controllers which can either be optimal (in the absence of any uncertainty) or be robust stable against parameter uncertainties dealing with the linear multivariable first-order discrete-time system in a hard case when its gain matrix is nonsquare (in contrast to the known results).*

Keywords: *discrete time, feedback control methods, pseudoinversion, multivariable control systems, robustness.*

INTRODUCTION

A problem of an efficient control of multivariable systems in the presence of unmeasurable disturbances stated three decades ago in [1] remains a topic of meticulous attention of many researches until recently. Their results have been reported in numerous papers and generalized in several books [2–5] et al.

To reject arbitrary bounded disturbances, the so-called inverse model concept has been proposed by several authors. Since the beginning of the 21st century, a significant progress has been achieved utilizing this concept [6, 7] and other works. Most these works except [7] dealt with continuous-time multivariable systems. However, this approach is quite unacceptable if the systems to be controlled are either ill-conditioned or nonsquare. Some researches observed that the inverse-based controller may be also not feasible for designing some process control systems containing ill-conditioned plants since they may become (almost) noninvertible in the presence of uncertainties [8]. Also, there exist certain difficulties in order to achieve a perfect control performance in the case where the number of the plant outputs exceeds the number of its control inputs. Similar problem falling into this category is the development of the automatic control system for an artificial heart having three outputs and two control inputs [9].

It turned out that the so-called Moore-Penrose inverse (pseudoinverse) model-based approach can be exploited to cope with the noninvertibility of singular square and any nonsquare systems. This approach has theoretically been substantiated in the papers [10–12] which dealt with problems of rejecting any bounded disturbances for a wide class of discrete-time multivariable noninvertible memoryless systems.

From practical point of view, it is important to design a simple controller similar to reduced-order or static output feedback (SOF) controllers. A difficulty associated with this problem is in establishing the existence of SOF control to be able to cope with a given plant [13–15]. Nevertheless, it turns out that in the case of the first-order multivariable system, the pseudoinverse model-based approach leads straight to SOF control.

In last years, various constructive approaches applicable to linear continuous-time and discrete-time systems with possible uncertainties have been advanced for establishing conditions under which SOF controllers can exist. Also, different numerical algorithms for designing these controllers have been proposed in [16–22] et al. Among them, the authors of [16] have obtained some attractive SOF solvability conditions derived from structural properties of the open-loop discrete-time systems. Within the framework of these conditions, they studied the case where there were more outputs than control inputs. Now, the question that we need to answer is as follows: is there the SOF control based on the pseudoinverse concept to stabilize some first-order multivariable system with nonsquare gain matrix?

The paper extends the ideas of [10–12] to nonzero set-point regulating non-square discrete-time first-order system in which the number of outputs exceeds the number of its control inputs. The main effort is focused on deriving conditions under which the optimality, ultimate boundedness and also robustness properties of resulting closed-loop control system can be achieved.

The purpose of the paper is to answer the question: is there the SOF control based on the pseudoinverse concept to stabilize some first-order multivariable system with nonsquare gain matrix?

PROBLEM FORMULATION

Consider a linear first-order multivariable discrete-time time-invariant system described by the autoregressive moving average exogenous (ARMAX) model of the simplest form

$$y_{n+1} = Ay_n + Bu_n + v_{n+1}, \tag{1}$$

where $y_n \in \mathbf{R}^m, u_n \in \mathbf{R}^r$ and $v_n \in \mathbf{R}^m$ represent the measured output, control input and the unmeasurable disturbance vectors, respectively. $A \in \mathbf{R}^{m\times m}$ and $B \in \mathbf{R}^{m\times r}$ are the fixed square and nonsquare matrices, respectively, given as

$$A = \begin{pmatrix} a^{(11)} & \dots & a^{(1m)} \\ \cdot & \cdot & \cdot \\ a^{(m1)} & \dots & a^{(mm)} \end{pmatrix} \text{ and } B = \begin{pmatrix} b^{(11)} & \dots & b^{(1r)} \\ \cdot & \cdot & \cdot \\ b^{(m1)} & \dots & b^{(mr)} \end{pmatrix}. \tag{2}$$

Let

$$r < m \tag{3}$$

mean that the number of control inputs is less than the number of system outputs.

The following assumptions are made.

A1. The elements $a^{(ij)}$ and $b^{(ij)}$ of A and B having the form (2) may be unknown. However, the bounds

$$a_{\min}^{(ij)} \le a^{(ij)} \le a_{\max}^{(ij)}, \quad (i=1,\dots,m,\ j=1,\dots,m), \tag{4}$$

$$b_{\min}^{(ij)} \le b^{(ij)} \le b_{\max}^{(ij)}, \quad (i=1,\dots,m,\ j=1,\dots,r) \tag{5}$$

on these elements are known *a priori*.

A2. The each component of v_n is an arbitrary, but bounded in modulus variable satisfying

$$\| v_n \| \le \| v \|_\infty < \infty \qquad \forall n = 1, 2, \dots, \tag{6}$$

where the well-known definition $\| z \|_\infty := \sup_{0 \le n < \infty} \| z_n \|$ of the so-called ℓ_1-norm of any bounded sequence $\{z_n\}$ denoted as $\| z \|_\infty$ is used.

A3. $\{y_n^0\}$ is a bounded nonzero set-point vector sequence such that the desired y_{n+1}^0 is always known at each nth time instant implying $\| y_n^0 \| \neq 0 \quad (n = 1, 2, \ldots)$ and $\| y^0 \|_\infty < \infty$. Without loss of generality, it is supposed that each component of y_n^0 may remain constant over a time (finite or infinite).

Defining the output error vector

$$e_n = y_n^0 - y_n, \tag{7}$$

introduce the local control performance index

$$J_n = \sup_{v_n :\ \| v_n \|_2 \le \varepsilon} \| e_n \|_2, \tag{8}$$

where $\| z \|_2$ denotes the Euclidean norm (2-norm) of a vector z. This criterion evaluates the capability of a controller to rejecting the bounded disturbances at the nth time instant in the worst case.

The following three problems are stated and solved.

Problem 1. Suppose matrices A and B are known. Noting that J_n of the form (8) depends only on one past u_{n-1} (due to (7) together with (1)), devise the optimal control which minimizes J_{n+1} with respect to all possible bounded u_ns at the nth time instant producing

$$J_{n+1} \to \inf_{u_n \in \mathbf{R}^r}. \tag{9}$$

Problem 2. Setting A and B be known, establish conditions guaranteeing the ultimate boundedness of outputs and control inputs in the form

$$\limsup_{n \to \infty} \| y_n \| < \infty, \quad \limsup_{n \to \infty} \| u_n \| < \infty. \tag{10}$$

Problem 3. Subject to Assumptions A1–A3, devise the control law under which the requirements (10) will be satisfied for any A and B with the elements given by the interval constraints (4) and (5), respectively, i.e., the robustness of controller will be achieved.

A PRELIMINARY

Consider the system (1) with no uncertainties with respect to the matrices A and B. Moreover, let (for the time being) B be a nonsingular $r \times r$ matrix implying that $r = m$ (instead of (3)). Choose the control law

$$u_n = B^{-1} y_{n+1}^0 - B^{-1} A y_n \tag{11}$$

in which B^{-1} denotes the inverse of B, to produce $e_{n+1} = -v_{n+1}$ $(\| e_{n+1} \| = \| v_{n+1} \|)$. This causes

$$\| e_{n+1} \| \leq \| v \|_{\infty}, \quad n = 0, 1, 2, \dots \tag{12}$$

It can simply be shown that the controller defined in (11), which may be called the inverse model-based controller, is optimal (in the sense of (9)). Actually, any other control law may give $\| e_{n+1} \|_2 > \| v \|_{\infty}$ (instead of (12)) if certain v_n satisfying (6) is present at $(n+1)$th time instant.

At first sight, it seems that if B is noninvertible then B^{-1} might be replaced by the Moore-Penrose inverse matrix B^{+} defined by the formula in [23, Theorem 3.4]

$$B^{+} = \lim_{\delta \to 0} (B^{\mathrm{T}} B + \delta^2 I_r)^{-1} B^{\mathrm{T}} \tag{13}$$

to design the control law

$$u_n = B^{+} y_{n+1}^{0} - B^{+} A y_n. \tag{14}$$

Nevertheless, such a possibility remains without strict substantiations for the time being since both the optimality of (14) and the stability of the closed-loop control system (1) exploiting (14) are not guaranteed as yet. Next section sheds some light on this possibility.

OPTIMAL STABLE CONTROL DESIGN

In this section, Problems 1 and 2 are solved. Namely, the optimality and the stability (the ultimate boundedness) of the closed-loop control system containing the plant (1) and the controller (14) are established in the following theorem.

Theorem 1. Subject to (3), and Assumptions (A2) and (A3), if the control law (14) is applied to the system (1), then:

a) the optimality properties of the closed-loop control system (1), (14) defined in (9) is ensured with

$$J_{n+1} \leq \| (I_m - BB^{+})(y_{n+1}^{0} - Ay_n) \|_2 + \varepsilon, \tag{15}$$

where

$$\varepsilon := \sup \| v_n \|_2 \tag{16}$$

and I_N denotes the $N \times N$ identity matrix;

b) the ultimate boundedness of $\{\| y_n \|\}$ caused by (14) is guaranteed if

$$q < 1 \tag{17}$$

with

$$q = \| (I_m - BB^{+}) A \|, \tag{18}$$

where $\| P \|$ denotes any norm of some matrix P;

c) under conditions (17) together with (18), the sequence $\{\| u_n \|\}$ remains bounded.

Proof. a) Using (1) together with (7), one has $e_{n+1} = y^0_{n+1} - Ay_n - Bu_n - v_{n+1}$ which causes

$$\| e_{n+1} \|_2 \le \| y^0_{n+1} - Ay_n - Bu_n \|_2 + \| v_{n+1} \|_2 \ . \tag{19}$$

Since the sequence $\{v_n\}$ does not depend on $\{y_n\}$, due to (6), (8) and (16), the inequality (19) yields

$$J_{n+1} \le \| y^0_{n+1} - Ay_n - Bu_n \|_2 + \varepsilon ,$$

giving

$$\inf_{u_n \in \mathbf{R}^r} J_{n+1} \le \inf_{u_n \in \mathbf{R}^r} \| [y^0_{n+1} - Ay_n] - Bu_n \|_2 + \varepsilon. \tag{20}$$

Further, utilizing Theorem 3.4 of [23], it can be concluded that there exists a vector u_n satisfying

$$\| [y^0_{n+1} - Ay_n] - Bu_n \|_2 = \inf_{\chi:\, \mathbf{R}^m \times \mathbf{R}^m \to \mathbf{R}^r} \| [y^0_{n+1} - Ay_n] - B\chi(y^0, y_n) \|_2 \tag{21}$$

with any vector-valued operator χ. By virtue of (21), this vector is determined as $u_n = B^+[y^0_{n+1} - Ay_n]$ leading directly to the pseudoinverse control of the form (14). Comparing (21) with (20), one can argue that such control is optimal since it minimizes the upper bound on J_{n+1} among all possible $\chi(\cdot\,,\cdot)$ mapping the pair (y^0, y_n) onto u_n. Substituting (14) into the right-hand side of (20) gives this upper bound in the explicit form represented by (15). This establishes statement a).

b) Substituting (14) into (1), one gets

$$y_{n+1} = BB^+ y^0_{n+1} + (I_m - BB^+)Ay_n + v_{n+1}.$$

By virtue of (6), this equation produces

$$\| y_{n+1} \| \le \| BB^+ \| \| y^0 \|_\infty + \| (I_m - BB^+)A \| \| y_n \| + \| v \|_\infty , \tag{22}$$

where the well-known properties $\| P_1 P_2 z \| \le \| P_1 P_2 \| \| z \|$ and $\| z_1 + z_2 \| \le \| z_1 \| + \ + \| z_2 \|$ of the norm of any matrices P_1, P_2 and of any vectors z, z_1, z_2 have been utilized.

Using (18), we may rewrite (22) as follows:

$$\| y_n \| \le \| BB^+ y^0 \| + q \| y_{n-1} \| + \| v \|_\infty \ . \tag{23}$$

Iterating (23), we obtain

$$\begin{aligned}\| y_{n+1} \| &\le \| BB^{+} \| \; \| y^0 \|_\infty + q \| y_n \| + \| v \|_\infty \\ &\le (1+q) \; \| BB^{+} \| \; \| y^0 \|_\infty + q^2 \| y_{n-1} \| + (1+q) \| v \|_\infty \le \ldots \\ &\le (1+q+q^2+\ldots+q^{n-1}) \, (\| BB^{+} \| \; \| y^0 \|_\infty + \| v \|_\infty) + q^n \| y_0 \| .\end{aligned}$$

These inequalities give that if (17) is satisfied, then

$$\limsup_{n\to\infty} \| y_n \| \le \frac{1}{1-q} (\| BB^{+} \| \| y^0 \|_\infty + \| v \|_\infty) < \infty.$$

This fact proves statement b).

c) Since $\{\| y_n \|\}$ is shown to be bounded, from (14), the validity of this statement follows immediately. □

Corollary. Let

$$\| A \|_2 < 1, \tag{24}$$

where $\| A \|_2$ denotes the spectral norm of A given by

$$\| A \|_2 = \max_{i=1,\ldots,m} \lambda_i (A^{\mathrm{T}} A),$$

and where $\lambda_i(\cdot)$ represents the ith eigen-value of $A^{\mathrm{T}} A$. Then, with the requirement (17), the boundedness properties given in statements b) and c) of Theorem 1 are guaranteed.

Proof. According to [23, Exercise 3.7.6], it can be established that $\| I_m - BB^{+} \|_2 = 1$. This yields

$$q = \| (I_m - BB^{+}) A \|_2 \le \| I_m - BB^{+} \|_2 \| A \|_2 \le \| A \|_2 \, . \tag{25}$$

Due to (24), the last inequality of (25) leads to the condition (17) of Theorem 1 proving the result. □

Remark 1. Note that, the condition

$$\operatorname{rank} B = r, \tag{26}$$

implying that B has the full rank, is not necessary.

Remark 2. If $\operatorname{rank} B$ satisfies (26), then instead of (13), the simple formula $B^{+} = (B^{\mathrm{T}} B)^{-1} B^{\mathrm{T}}$ taken, e.g., from [23, Exercise 3.5.3] may be used to calculate B^{+}.

Remark 3. The condition (24) means that the open-loop control system (1) is asymptotically stable since

$$\max_{i=1,\ldots,m} | \lambda_i(A) | \le \| A \|_2$$

holds producing

$$\max_{i=1,\ldots,m} | \lambda_i (A) | < 1.$$

In this case, A is said to be the Schur stable matrix. □

AN OBSERVATION

It turns out that the asymptotic stability of (1) is not necessary to ensure $q<1$.

To illustrate this fact that is not obvious, the following numerical example will be considered.

Example 1. Let

$$A=\begin{pmatrix}-0.35 & -0.35 & -0.35\\ -0.20 & -1.00 & -0.30\\ -0.20 & -0.20 & -0.50\end{pmatrix},\quad B=\begin{pmatrix}1.2 & 0.1\\ -0.6 & 0.9\\ 0.6 & 2.1\end{pmatrix}.$$

In this case, $\operatorname{rank} B=2$, and $\max_{i=1,\dots,m}|\lambda_i(A)|\approx 1.24>1$ whereas $\|A\|_1:=\max_{j\in[1,\,r]}\sum_{i=1}^{m}|a^{(ij)}|=1.55$, where $\|P\|_1$ denotes the column norm of P. This implies that equation (1) describes the unstable system. Nevertheless, the calculation of q by (18) gives $q=\|(I_m-BB^+)A\|_1\approx 0.9<1$. Hence, the requirement (17) may be satisfied while the plant is actually unstable.

ROBUSTNESS ANALYSIS

In the case of parameter uncertainty given by (4) and (5), we propose replacing the control law (14) by

$$u_n=B_0^+y_{n+1}^0-B_0^+A_0y_n \tag{27}$$

with some fixed matrices $A_0=(a_0^{(ij)})_{m\times m}$ and $B_0=(b_0^{(ij)})_{m\times r}$. Their elements are chosen as $a_0^{(ij)}\in[a_{\min}^{(ij)},a_{\max}^{(ij)}]$ and $b_0^{(ij)}\in[b_{\min}^{(ij)},b_{\max}^{(ij)}]$, respectively, to obtain $\operatorname{rank} B_0=r$.

The following robustness result is given in the theorem below.

Theorem 2. Let Assumptions A1 to A3 be valid. Then the controller defined in (27) will be robust (in the sense that the boundedness of $\{\|y_n\|\}$ and $\{\|u_n\|\}$ is guaranteed for any matrices A and B having the elements which satisfy (4) and (5), respectively), if (17) is satisfied with

$$q=\max_{\substack{\hat{A}\in\Xi_A\\ \hat{B}\in\Xi_B}}\|\hat{A}-\hat{B}B_0^+A_0\|. \tag{28}$$

In this expression, Ξ_A and Ξ_B are the bounded sets of all matrices $\hat{A}=(\hat{a}^{(ij)})$ and $\hat{B}=(\hat{b}^{(ij)})$ having the elements $\hat{a}^{(ij)}\in[a_{\min}^{(ij)},a_{\max}^{(ij)}]$ and $\hat{b}^{(ij)}\in[b_{\min}^{(ij)},b_{\max}^{(ij)}]$, and $\|\cdot\|$ is any matrix norm (as in (18)).

Proof. Follows immediately from Theorem 1. □

The result given in Theorem 2 may be reformulated in terms of the linear programming problems similar to that in [11] as follows.

Define the variables

$$\hat{d}^{(ij)} = \hat{a}^{(ij)} - \sum_{k=1}^{r} h_0^{(kj)} \hat{b}^{(ik)}, \quad i, j = 1, \ldots, m, \tag{29}$$

where $h_0^{(ij)}$ denotes the corresponding element of the fixed matrix $H_0 = B_0^+ A_0$. Further, $\hat{d}^{(ij)}$ is the element of $\hat{D} = \hat{A} - \hat{B}H_0$, and find

$$\max \hat{d}^{(ij)} \quad \text{and} \quad \min \hat{d}^{(ij)} \tag{30}$$

subject to the constraints

$$a_{\min}^{(ij)} \le \hat{a}^{(ij)} \le a_{\max}^{(ij)}, \qquad b_{\min}^{(ij)} \le \hat{b}^{(ij)} \le b_{\max}^{(ij)} \tag{31}$$

for each $1 \le i \le m$, $1 \le j \le m$.

Since (29) describes the functions depending linearly on the variables $\hat{a}^{(ij)}$ and $\hat{b}^{(i1)}, \ldots, \hat{b}^{(ir)}$ that are the elements of the ith row of $\hat{B}$, and (31) represent the simple linear constraints, the problems given by (30), (31) are the simplest linear programming problems. They are solved independently for each pair (i, j) taking into account that each element of the jth column of $\hat{D}$ depends only on the elements of each ith row of $\hat{A}$ and $\hat{B}$ but not on the elements of other their rows with numbers $k = 1, \ldots, m$, $k \ne i$. Then the following results can be shown to be valid.

Theorem 3. Subject to Assumptions A1 to A3, if

$$\sum_{i=1}^{m} \max\{|\min \hat{d}^{(ij)}|, |\max \hat{d}^{(ij)}|\} < 1 \quad \forall j = 1, \ldots, m$$

with $\min \hat{d}^{(ij)}$ and $\max \hat{d}^{(ij)}$ giving the solutions to the linear programming problem (30), (31), then the controller (27) applied to the system (1) guarantees that the boundedness properties (10) will be achieved in the presence of interval uncertainties defined by (4), (5).

Proof. Follows the lines of the proof of Corollary to Theorem 2 given in [11]. Due to space limitation, the details are omitted. □

Thus, Theorem 3 specifies the sufficient conditions under which the pseudoinverse model-based controller (27) employed to regulating the uncertain system (1), (4), (5) will be robustly stable. It gives an effective solution to Problem 3 using a simple computation technique.

Example 2. Let the system to be controlled be described by

$$A = \begin{pmatrix} -0.20 & -0.15 & -0.15 \\ -0.10 & -0.25 & -0.10 \\ -0.15 & -0.15 & -0.16 \end{pmatrix}, \quad \text{and} \quad B = \begin{pmatrix} 1.2 & 0.1 \\ -0.6 & 0.9 \\ 0.6 & 2.1 \end{pmatrix}.$$

Assuming that the parameter uncertainty is given as $a^{(11)} \in [-0.28, 0]$, $a^{(12)} \in [-0.2, \ -0.1]$, $a^{(13)} \in [-0.12, 0]$, $a^{(21)} \in [-0.12, 0]$, $a^{(22)} \in [-0.28, 0]$, $a^{(23)} \in [-0.2, \ -0]$, $a^{(31)} \in [-0.2, 0]$, $a^{(32)} \in [-0.2, \ -0.1]$, $a^{(33)} \in [-0.2, \ -0]$, $b^{(11)} \in [0.6, 1.2]$, $b^{(12)} \in [0, 0.2]$, $b^{(21)} \in [-0.7, 0]$, $b^{(22)} \in [0.8, 1.1]$, $b^{(31)} \in [0.5, 1.2]$, $b^{(32)} \in [1.9, 2.2]$,
the matrices

$$A_0 = \begin{pmatrix} -0.25 & -0.10 & -0.10 \\ -0.15 & -0.10 & -0.17 \\ -0.10 & -0.15 & -0.19 \end{pmatrix} \quad \text{and} \quad B_0 = \begin{pmatrix} 0.8 & 0.2 \\ -0.5 & 1.0 \\ 1.0 & 2.0 \end{pmatrix}$$

yielding (by the formula $B^+ = (B^{\mathrm{T}} B)^{-1} B^{\mathrm{T}}$ given in Remark 2)

$$B_0^+ = \frac{1}{677} \begin{pmatrix} 370 & -418 & 172 \\ -95 & 272 & 212 \end{pmatrix}$$

may be chosen to satisfy $A_0 \in \Xi_A$ and $B_0 \in \Xi_B$. Utilizing now Theorem 3 one can conclude that the value of q determined by (28) via solving the linear-programming problem is equal to 0.87. This shows that the requirement (17) is satisfied.

SIMULATION

To support the theoretic study, three simulation experiments were conducted. In first simulation experiment, the unstable open-loop control system with A and B given in Example 1 was studied. Its behavior is illustrated in Fig. 1, where $u_n^{(1)} \equiv 0.1$, and $u_n^{(2)} \equiv 0.1$ were chosen.

The second simulation of the optimal closed-loop control system containing the plant (1) and the controller (14) in the presence of the i.i.d. pseudorandom $v_n^{(i)} \in [-1, 1]$ was conducted. The simulation results for different y^0s with the components determined as $y^{0(1)} = 7$, $y^{0(2)} = 3$, $y^{0(3)} = 15$ at $1 \le n \le 40$; $y^{0(1)} = 2$, $y^{0(2)} = 7$, $y^{0(3)} = 3$ at $41 \le n \le 60$; $y^{0(1)} = 3$, $y^{0(2)} = 7$, $y^{0(3)} = 9$ at $61 \le n \le 100$ are presented in Fig. 2.

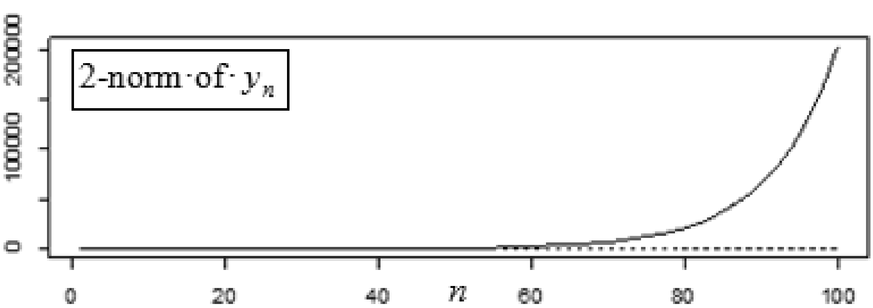

Fig. 1. 2-norm of output vector of the open-loop control system releted to Example 1

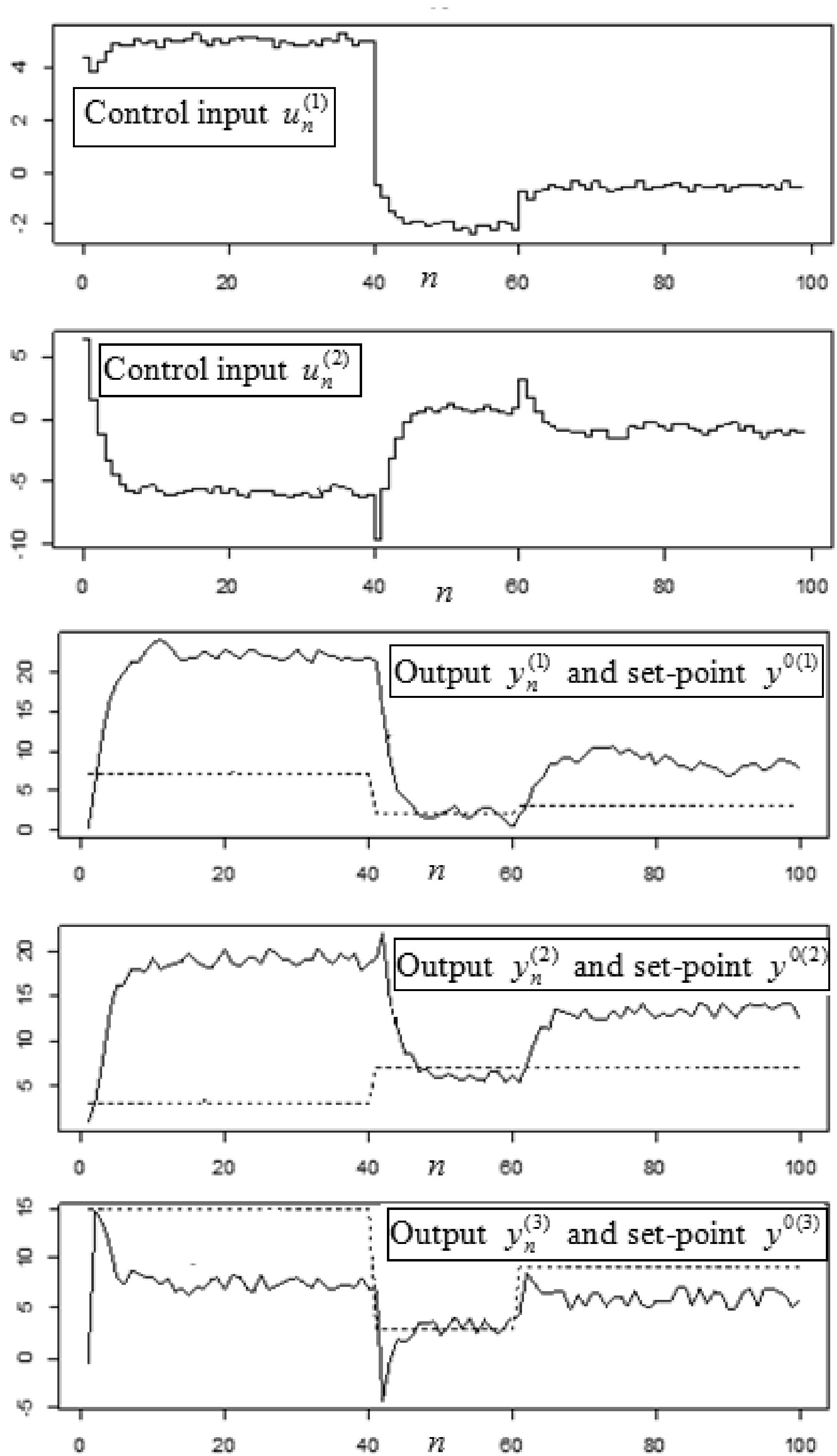

Fig. 2. Control inputs and outputs (solid lines), and set-points (dashed lines) of the closed-loop control system in the conditions of Example 1

In the third simulation experiment, the robust closed-loop control system with the uncertainties and with the feedback described in Example 2 subject to the same disturbances and $y^{0(1)} = 3$, $y^{0(2)} = 7$, $y^{0(3)} = 9$ was simulated. Fig. 3 depicts its results. They show that the closed-loop control system (1), (14) is stable and its performance is satisfactory enough.

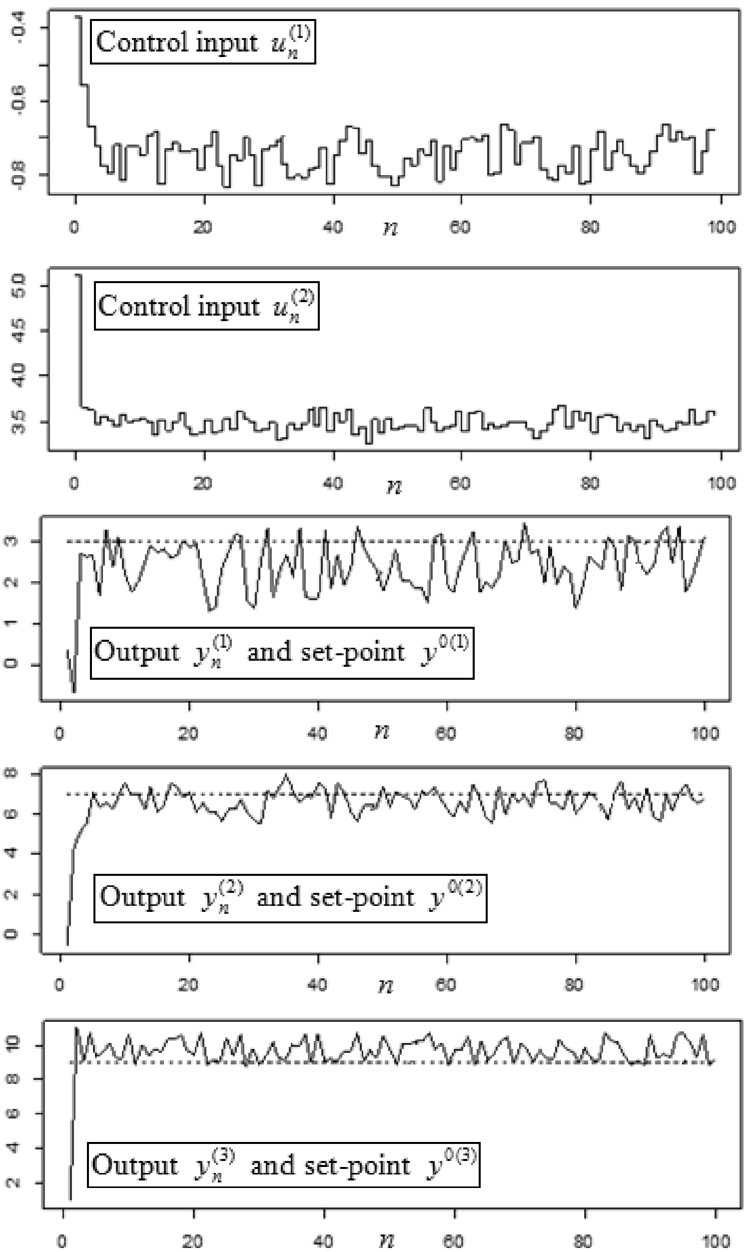

Fig. 3. Control inputs and outputs (solid lines), and set-points (dashed lines) of the closed-loop control system in the conditions of Example 2

A DISCUSSION

To compare the pseudoinverse model-based approach proposed above with existing ones related to the SOF concept, rewrite first the control law (14) as

$$u_n = L_{\mathrm{FF}} y_{n+1}^0 - L_{\mathrm{FB}} y_n, \tag{32}$$

selecting the feedforward and feedback terms with gain matrices $L_{\mathrm{FF}} = B^+$ and $L_{\mathrm{FB}} = B^+ A.$

Now, consider the open-loop discrete-time system described by the standard state-space model

$$\begin{cases} x_{n+1} = Ax_n + Bu_n + \Gamma v_{n+1}, \\ y_n \quad = Cx_n, \end{cases} \tag{33}$$

where $u_n \in \mathbf{R}^r, y_n \in \mathbf{R}^m, v_n \in \mathbf{R}^m$ (as before), and $x_n \in \mathbf{R}^p$ is the state vector. $A \in \mathbf{R}^{p\times p}$, $B \in \mathbf{R}^{p\times r}$, $\Gamma \in \mathbf{R}^{p\times m}$ and $C \in \mathbf{R}^{m\times p}$ are constant matrices. It is not hard to see that this system reduces to (1) by setting $C = I_m, \Gamma = I_m \ (p = m)$.

$$\det (GCA^{-1}B) \neq 0. \tag{34}$$

Furthermore, it follows from Theorem 5 of [16] that if (34) together with some other assumptions hold, and A is nonsingular then the SOF control

$$u_n = -L_{\mathrm{FB}} y_n \tag{35}$$

with

$$L_{\mathrm{FB}} = (GCA^{-1}B)^{-1} G \tag{36}$$

stabilizes the system (33) at $y_n^0 = [\underbrace{0, \ldots, 0}_{m}]^T$ and minimizes the quadratic criterion

$$J = \sum_{n=0}^{\infty} y_n^{\mathrm{T}} (A^{-1})^{\mathrm{T}} G^{\mathrm{T}} G A^{-1} y_n, \tag{37}$$

but not the criterion (8). On the other hand, it can easily be shown that if $\det A \neq 0$ and (26) holds $(C = I_m)$ then G may be chosen as $G = \beta B^+ A$ with an arbitrary $\beta > 0$ to satisfy the requirement (34). According to (36) such a choice of G yielding directly $L_{\mathrm{FB}} = B^+ A$ gives that in this case, the SOF control (35) becomes finally the pseudoinverse stabilization control having the form (32) in which $\| y_n^0 \| \equiv 0$.

It is interesting to note that, contrary to [16], the pseoduinverse control (32) may be used to minimize the criterion (8) when A is singular and B has nonfull rank (Example 1). Nevertheless, the condition $\| (I_m - BB^+)A \| < 1$ guaranteeing the ultimate boundedness of $\{\| y_n \|\}$ and $\{\| u_n \|\}$ is assumed to be satisfied (in accordance with Theorem 1 given in [16]). Of course, this condition may not be satisfied if A is not the Schur stable.

In order to cope with the instability of (1), at least, the two ways may be proposed. First, if $\operatorname{rank} B = r,$ then some r outputs $y_n^{(i_1)}, \dots, y_n^{(i_r)}$ might be included in the feedback loop to control the system (1) via an inverse model-based controller similar to (11) with the square submatrix $B[i_1, \dots, i_r \,|\, 1, \dots, r]$ (instead of B). It can be clarified that remaining outputs will become bounded if and only if all the $m - r$ diagonal elements of A defined as $a^{(i_k i_k)}$ with $i_k \neq i_1, \dots, i_r$ satisfy $|\, a^{(i_k i_k)} \,| < 1.$ Again, this way does not minimize the criterion (8). Second, we may attempt to design the SOF controller based on the ideas of [16, 19] et al. However, such way leads to minimization of the criterion similar to (37) but not to (8) whereas one seems to be more suitable for practical applications dealing with the problems of the nonzero set-point regulation.

Since most the process control systems remaining stable in their nature and can be described by model similar to (1) [8], we conclude that the approach proposed here has advantage in comparison with existing ones if the multivariable systems to be controlled are nonsquare and stable.

CONCLUSIONS

The paper shed some light on the existence of the pseudoinverse static output feedback controllers which can either be optimal (in the absence of any uncertainty) or be robust stable against parameter uncertainties dealing with the linear multivariable first-order discrete-time system in a hard case when its gain matrix is nonsquare (in contrast to the known results).

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КЕРУВАННЯ БАГАТОВИМІРНИМИ СИСТЕМАМИ З ПРЯМОКУТНИМИ МАТРИЦЯМИ КОЕФІЦІЄНТІВ ПІДСИЛЕННЯ НА ОСНОВІ ПСЕВДООБЕРНЕНОГО СТАТИЧНОГО ЗВОРОТНОГО ЗВ'ЯЗКУ

Вступ. Стаття стосується регулювання на ненульовому заданому рівні лінійної дискретної багатовимірної системи першого порядку. Розглядається випадок, коли кількість вихідних змінних перевищує кількість каналів передачі керувальних дій. Припускається, що наявними є довільні, але обмежені невимірювані збурення. Вважається, що елементи матриць, які фігурують у рівнянні системи, невідомі, однак апріорі відомими є їхні межі. З практичної точки зору важливо розробити простий регулятор, подібний до регулятора типу SOF (static output feedback). Труднощі, пов'язані з цим завданням, полягають у встановленні умов існування регулятора типу SOF, здатного справитися з такою системою. Поставлено та розв'язано три різні завдання, а саме: забезпечення оптимальності, граничної обмеженості та робастності замкненої системи керування.

Мета роботи — дати відповідь на запитання: чи існує регулятор типу SOF, в основу якого покладено концепцію псевдообернення, аби стабілізувати деяку багатовимірну систему першого порядку з прямокутною матрицею коефіцієнтів підсилення?

Методи. Використовуються методи, основані на теорії матриць.

Результати. Аби придушити невимірювальні збурення, запропоновано керування, яке базується на методі псевдооберненої моделі. Цей метод формально приводить до реалізації статичного зворотного зв'язку. Встановлено умови оптимальності та робастності такого регулятора. Для підтвердження теоретичного дослідження наведено числові приклади та результати моделювання.

Висновок. Стаття проливає деяке світло на існування псевдообернених регуляторів, що реалізують статичний зворотний зв'язок, які можуть бути або оптимальними (за відсутності будь-якої невизначеності), або робастно стійкими до невизначеності відносно параметрів лінійної багатовимірної дискретної системи першого порядку у випадку, коли її матриця коефіцієнтів підсилення є прямокутною (на відміну від відомих результатів).

Ключові слова: *дискретний час, методи керування зі зворотним зв'язком, псевдообернення, багатовимірні системи керування, робастність.*

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КОМПЛЕКС МОДЕЛЮВАННЯ ДИНАМІЧНИХ КОНФЛІКТНИХ СИТУАЦІЙ ПОВІТРЯНИХ КОРАБЛІВ У МАСШТАБІ РЕАЛЬНОГО ЧАСУ

Вступ. *Моделювання польотів повітряних кораблів (ПК) має багато вирішених та відкритих завдань. Розвиток сучасної авіації неможливий без якісних засобів моделювання, а кожна нова розробка, яку пропонують використовувати, повинна бути ретельно протестована. Завдання попередження конфліктів ПК в реальному часі є одним з ключових серед проблем авіації, отже потребує методів розв'язання та засобів для моделювання і тестування.*

Мета статті *—проаналізувати методи визначення та розв'язання конфліктних ситуацій ПК, розробити програмний комплекс для моделювання динамічних конфліктних ситуацій у масштабі реального часу.*

Методи. *Програмне розроблення комплексу базується на методах статистичного і імітаційного комп'ютерного моделювання, обчислювальної геометрії та математичного аналізу. Для визначення та розв'язання конфліктних ситуацій використано методи теорії автоматичного керування, навігації та інтелектуального керування.*

Результати. *Розроблений комплекс моделювання дає змогу оцінити кількісні показники симуляції повітряних кораблів у згенерованому просторі та досліджувати особливості вирішення конфліктних ситуацій. Проведено моделювання переміщення, взаємодії та маневрування ПК. У розв'язанні конфліктних ситуацій запропонована експериментальна система була ефективнішою за чинну систему TCAS II.*

Тестування розробленого комплексу моделювання та використаних алгоритмів визначення і розв'язання конфліктних ситуацій було проведено з використанням типових дослідних сценаріїв, починаючи від простих конфліктів між двома ПК до гранично складних, за участі в одному конфлікті значної кількості ПК. Основними показниками оптимальності розв'язання конфліктів прийнято кількість та довжину маневрів уникнення конфліктної ситуації за умови різної завантаженості повітряного простору, за різних типів конфліктних ситуацій, пов'язаних з порушеннями норм ешелонування.

Висновки. *Отриманий комплекс може застосовуватися для дослідження взаємодії багатьох ПК в динамічному середовищі, розроблення та тестування методів розв'язання конфліктних ситуацій. Модульність комплексу також дає змогу виконувати моделювання інших елементів, таких як системи передачі даних.*

Ключові слова: *інформаційна технологія, авіація, комп'ютерне моделювання, конфліктна ситуація, повітряний корабель, система.*

ВСТУП

Кількість авіаперельотів щороку зростає зі швидкою динамікою. Згідно зі статистикою організації EUROCONTROL, у 2012 році кількість перельотів у європейському повітряному просторі становила 9,5 мільйонів на рік, а у 2018 році — 11 мільйонів. У червні 2019 року було зареєстровано рекордну кількість перельотів на день — більше 37 тисяч, а загальне зростання кількості у першій половині року склало 1,7 % відносно аналогічного тогорічного періоду часу.

Забезпечення безпеки польотів повітряних кораблів (ПК) є основним завданням кожної організації, причетної до обслуговування, організації, виконання чи моніторингу повітряного руху. Координація взаємодії ПК у повітряному та наземному просторах забезпечується автоматизованою роботою багатьох програмних і апаратних систем, а також операціями людського персоналу. За рішенням Міжнародної організації цивільної авіації (ІКАО) для польотів ПК з масою більшою за 5700 кг або сертифікованих для перевезення 19 і більше пасажирів, обов'язковим є наявність системи попередження зіткнення TCAS (Traffic Alert and Collision Avoidance System) [1]. Однак система має достатню кількість недоліків, серед яких високовартістність та необхідність наявності передавачів на кожному ПК для коректної роботи та обмеженість розв'язання конфліктів лише з використанням вертикального ешелонування. Окрім цього, органи керування повітряним рухом (КПР) можуть автоматично отримувати інформацію про рекомендації з вирішення ситуації зіткнення, випущених TCAS, тільки коли повітряне судно знаходиться у зоні дії режиму опитування Mode-S авіаційного радіолокаційного відповідача або мережі автоматичного спостереження ADS-B (Automatic Dependent Survillance — Broadcast). В інших випадках диспетчери можуть не знати про рекомендації вирішення таких ситуацій на основі TCAS або навіть надавати суперечливі інструкції (якщо тільки члени КПР явно непоінформовані членами екіпажу про рекомендації, які надано TCAS у ситуації високого навантаження), що може призвести до додаткового збільшення робочого навантаження пілота.

Розроблення та впровадження нових методів попередження зіткнень ПК потребує застосування програмних комплексів для моделювання польотів, які мають змогу конфігурувати параметри ПК, бортові системи та особливості траєкторій та навколишнього середовища.

СИСТЕМА ПОПЕРЕДЖЕННЯ ЗІТКНЕНЬ TCAS

Згідно з правилом ІКАО, кожен ПК має бути обладнаним системою попередження зіткнень. Відповідно до рішення Європейської Агенції Авіаційної Безпеки від 2012 року, обов'язковим є використання TCAS II версії 7.1 [2].

Версія TCAS I є першим поколінням системи, що використовувалася до 1989 року і за деяких обставин може бути використана зараз. Вона виконує основні завдання, такі як моніторинг повітряного простору у радіусі 65 км та надання інформації щодо пеленгу і висоти інших ПК у такому радіусі. Також система повідомляє про можливість зіткнення у вигляді «Рекомендації щодо трафіку» (Traffic Advisory, TA). TA попереджають пілота про знаходження ПК в небезпечному радіусі, але не пропонують засобів розв'язання конфлікту. Пілот самостійно або за сприяння наземних диспетчерів вирішує, які дії виконувати. Коли загроза минула, система оповіщає повідомленням «Немає конфлікту».

Оновлена версія TCAS II використовує усі функції TCAS I та, окрім них, має низку вдосконалень. Система пропонує пілотові чіткі голосові інструкції для уникнення небезпеки — «Консультації щодо вирішення» (Resolution Advisory, RA). Запропонована дія може бути коригувальною або превентивною. Коригувальна інструкція передбачає зміну вертикальної швидкості. Використовують повідомлення «Спуск, спуск», «Підйом, підйом» або «Регулювання вертикальної швидкості». Превентивні інструкції попереджають пілотів про необхідність відхилитися від їх поточної вертикальної швидкості, оголошуючи «Відслідковувати вертикальну швидкість» або «Підтримувати вертикальну швидкість, Підтримувати». Перед подачею команд пілотам відбувається синхронізація рекомендацій між системами TCAS II кожного літака-учасника конфліктної ситуації. Отже, якщо одному літаку дають настанову спуститися, іншому зазвичай вказують піднятися, що максимально збільшить відстань між двома літаками. TCAS II одночасно може відстежувати до 30-ти повітряних кораблів і для трьох одночасно видавати команди з розв'язання конфліктної ситуації.

TCAS може взаємодіяти лише з ПК, на яких встановлено активний радіолокаційний відповідач режиму C або S. Кожному ПК, що має радіолокаційний відповідач режиму S, присвоюється унікальний 24-бітний ідентифікатор. Під час взаємодії з літаками система генерує тривимірну мапу у повітряному просторі заданого радіусу. Кожний ПК на мапі характеризується трьома основними показниками: відстанню, висотою та пеленгом. Відстань отримується з затримки часу передачі запиту і відповіді; висоту визначають згідно з повідомленням опитуваного літака; пеленг визначається напрямком находження антени. Система визначає, чи є потенційна загроза зіткнення, використовуючи методи екстраполяції цих характеристик на очікуванні майбутні значення.

Під час побудови мапи та обчисленні можливих загроз системи попередження зіткнення враховують об'єм повітряного простору навколо власного ПК. Розмір такого простору залежить від висоти, швидкості і курсу літака, який бере участь в зіткненні. На рисунку 1 надано приклад типового захищеного простору для літака, обладнаного системою TCAS II?.

Принцип роботи TCAS II (рис. 1) засновано на визначенні часу польоту до точки найбільшого зближення CPA (Closest Point of Approach) залежно від діапазонів висот (рівень чутливості). У режимі 1-секундного циклу TCAS II відстежує інші повітряні кораблі, запитуючи їхні прийомо-передавачі, а коли перевірка дальності та перевірка висоти дають позитивний результат, TCAS видає попередження про небезпечне зближення TA (Traffic Advisory) а якщо літаки продовжують зближуватися, то екіпаж отримує повідомлення TCAS про необхідність розв'язання конфліктної ситуації RA (Resolution Advisory) і команду на виконання маневру зниження («Зниження», «Descend») або набору висоти («Набір висоти», «Climb»). Якщо системами TCAS II версії 7.1 оснащено обидва літаки, то вони обмінюються інформацією для запобігання однакових маневрів розходження (рис. 2).

Основною особливістю другої версії TCAS є використання вертикального ешелонування. Це одночасно є і перевагою, і недоліком, оскільки окрім вертикального ешелонування виділяють повздовжнє та бічне. З середини 1990-х років розроблялися концепти третьої та четвертої версій системи TCAS, які б враховували інші методи ешелонування, проте їхнє розроблення було заморожено. Останні розробки в галузі передачі даних поставили під сумнів доцільність використання окремих каналів зв'язку для попередження конфліктів. Технологія ADS-B (Automatic Dependent Surveillance — Broadcast, Автоматичне залежне спостереження — радіомовне) дає змогу визначати положення ПК за допомогою систем супутникової навігації та передавати його через бортові відповідачі [3].

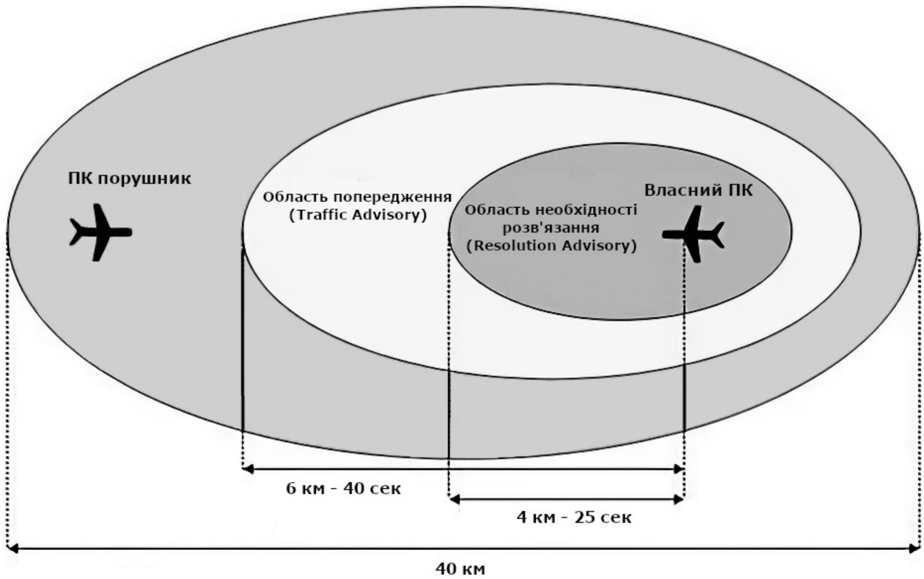


Рис. 1. Приклад захищеного простору для ПК

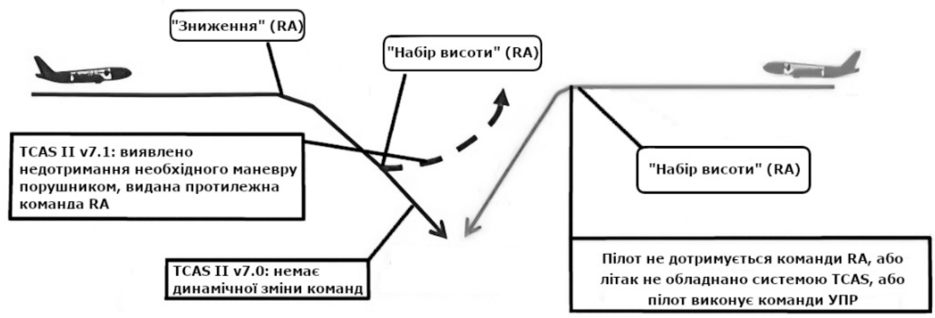


Рис. 2. Схематичне зображення роботи системи TCAS у разі конфлікту двох ПК

НОРМИ ЕШЕЛОНУВАННЯ ЗГІДНО З ІКАО

Норми ешелонування було введено ІКАО для розподілу ПК у повітряному просторі на встановлені інтервали заданої величини з метою попередження конфліктних ситуацій. Вони поширюються на всі ПК, які мають національні знаки та реєстраційні знаки держав-членів ІКАО. В Україні норми ешелонування було затверджено наказом «Про затвердження Правил ешелонування під час обслуговування повітряного руху» Міністерства транспорту та зв'язку України від 29.09.2010 [4].

Вертикальним ешелонуванням називають розосередження повітряних суден на різних рівнях (ешелонах) за висотою. Рівні вертикального ешелонування позначаються абревіатурою FL (Flight Level), за якою зазначається номер ешелону, що визначається висотою у сотнях футів. Наприклад, FL20 — це рівень на висоті 2000 футів (600 метрів).

Вертикальне ешелонування зазвичай здійснюється у напівкруглій системі ешелонування: для польотів з істинними шляховими кутами від 0 до 179° вибирається непарний десятковий ешелон (10, 30, 50, …, 490); для польотів з істинними шляховими кутами від 180 до 359° вибирається парний десятковий ешелон (20, 40, … 500). Мінімум вертикального ешелонування повинен становити:

1) номінально 300 м (1000 футів) — для ешелонів, нижчих за FL290 та номінально 600 м (2000 футів) — для ешелону FL290 та вище, крім наступної умови;

2) 300 м (1000 футів) між ешелонами FL290 та FL410 включно, за умов використання скороченого мінімуму вертикального ешелонування (RVSM, reduce vertical separation minima), та номінально 600 м (2000 футів) вище ешелону FL410.

Бічне ешелонування полягає в розподіленні запланованих маршрутів так, щоб відстань між їхніми ділянками ніколи не була меншою за деякі визначені дистанцію і розмір встановленого буфера. Відстань між повітряними трасами повинна бути не меншою за 50 км. У разі польоту поза трасою бічна відстань між ПК, які летять в одному або протилежному напрямках, не повинна бути меншою за 10 км. Мінімальна дистанція бічного ешелонування у разі розходження в умовах безперервного радіолокаційного контролю згідно з правилами польотів за приладами становить не менше за 20 км.

Точками бічного ешелонування називають точки входу у район з бічною відстанню, меншою за необхідний мінімум, та виходу з нього для треків, які перетинаються. Площина, обмежена точками бічного ешелонування, називається районом конфлікту. Точки бічного ешелонування обчислюють за формулою

$$l = \frac{S_y}{\sin(u)},$$

де l — відстань від перехрестя до точки бічного ешелонування; S_y — бічна відстань між лініями шляху, що дорівнює мінімуму бічного ешелонування; u — кут між лініями шляху. Схему розрахункових точок бічного ешелонування і зони конфлікту зображено на рис. 3.

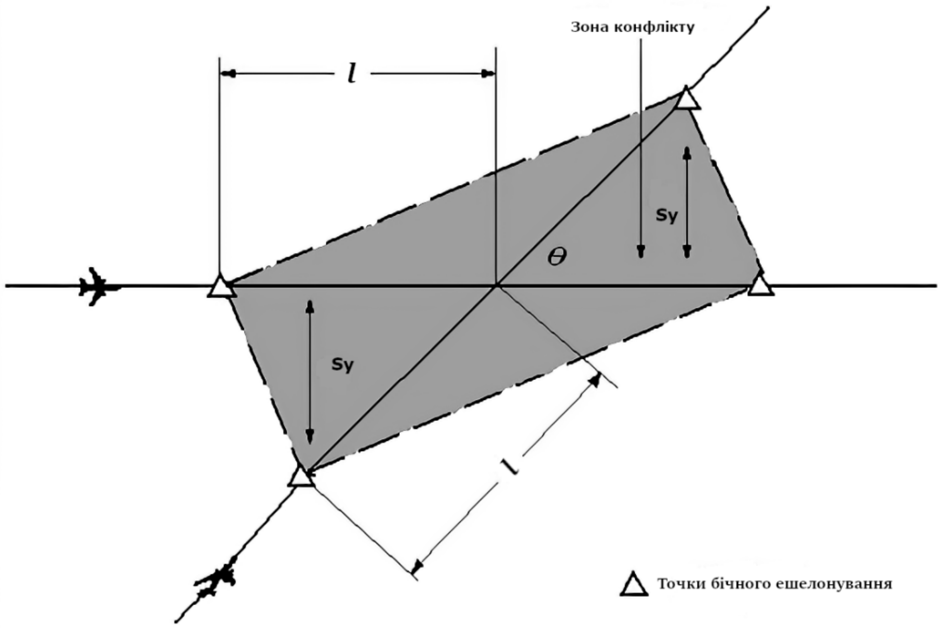


Рис. 3. Точки бічного ешелонування і зони конфлікту

У разі ***повздовжнього ешелонування*** інтервал між розташуваннями повітряних кораблів ніколи не повинен бути меншим за встановлений мінімум. Повздовжнє ешелонування між ПК, які прямують за попутними або протилежними треками, може бути витримано шляхом застосування керування швидкістю, включаючи використання методу числа Маха. Мінімуми повздовжнього ешелонування можуть базуватися:

- на часі;
- на часі – з використанням методу числа Маха;
- на відстані – з використанням всебічно направлених далекомірних радіомаяків та/або GNSS;
- на відстані – з використанням зональної навігації, з використанням методу числа Маха;
- на відстані – з використанням зональної навігації, у місцях, де встановлені потрібні навігаційні характеристики.

СТРУКТУРА КОМПЛЕКСУ МОДЕЛЮВАННЯ ПК

Систему для симуляції польотів ПК реалізовано з використанням чотирьох програмних модулів (рис. 4). Більшість модулів є незалежними один від одного та можуть комбінуватися для виконання окремих етапів симуляції.

Модуль генерації задіяно на початковому етапі роботи комплексу моделювання. Він створює базову 3D мапу з ландшафтом, секторами і наземними об’єктами та моделями повітряних кораблів, які розташовуються у створеній мапі. Повітряний простір подано у вигляді графа. Вершинами графа є наземні об’єкти, ребрами — оптимальні траєкторії. Мапа розділяється на сектори чотирьох типів: нейтральна зона; зона, де ПК може взаємодіяти з наземними об'єктами; зона підвищеної небезпеки та заборонена для польотів зона. Створення мапи є можливим у ручному, частково автоматичному та повністю автоматичному режимах. Генерація моделей ПК відбувається згідно з встановленою кількістію та заданими характеристиками із бази даних.

Початкова генерація траєкторій ПК відбувається за допомогою модуля планування польотів. Також цей модуль є пов'язаним з графом повітряного простору, за допомогою якого вибирає оптимальну початкову траєкторію, базуючись на критеріях відстані, ефективності, часу та інших.

Модуль переміщення виконує основну симуляцію усієї системи, що здійснюється потактово із синхронізацією взаємодії всіх ПК та їхніх окремих елементів. Так, наприклад, обмін повідомленнями між системами TCAS двох ПК займає 1 такт, а взаємодія з наземним диспетчерським центром займає принаймні 10 тактів, оскільки враховується час реакції людського персоналу та обміну голосовою інформацією. Координація взаємодії переміщення виконується за допомогою модулів планування та обчислення. Додатково виконуються обчислення траєкторій руху та за необхідності їх оптимізація.

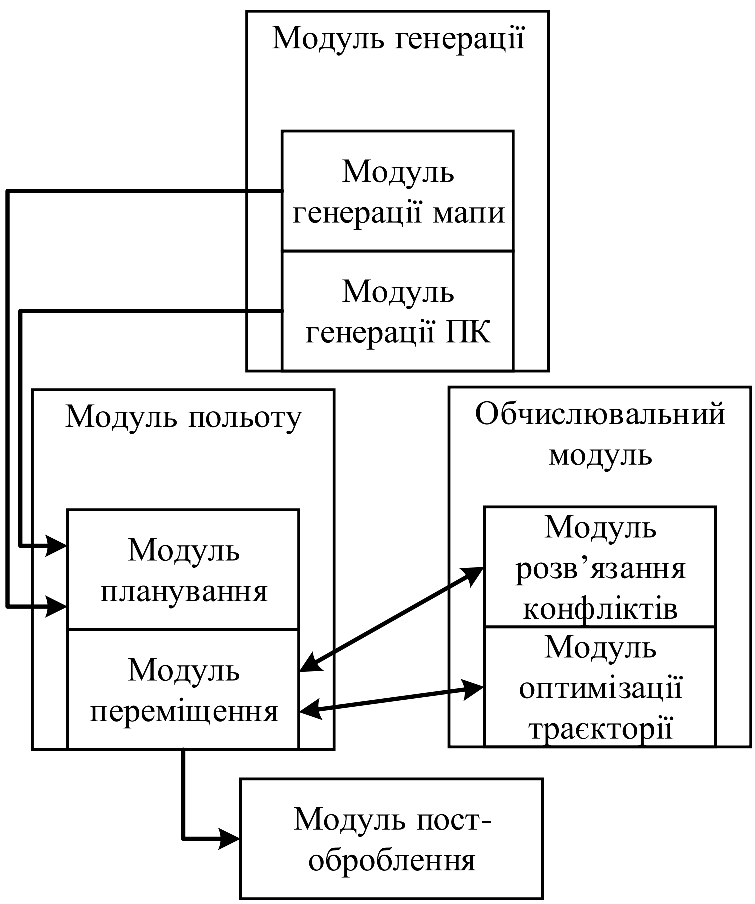


Рис. 4. Організація комплексу моделювання динамічних конфліктів ПК

Для надання користувачу системи інформації про процес та результати роботи використовується графічний інтерфейс. У модуль пост-оброблення постійно надходить необхідна інформація від усіх активних модулів та генерується зображення. За рахунок використання зовнішніх розширень для модуля є можливим адаптувати системи до веб-інтерфейсів, до командного рядка чи до мобільних додатків.

МОДУЛЬ ГЕНЕРАЦІЇ

Початковим етапом виконання симуляції є створення тривимірного простору. Основна увага приділяється двомірній площині XY, яка містить основні необхідні елементи. У третьому вимірі Z (висота) генеруються лише елементи ландшафту, такі як гірські масиви, та виконується розподіл висот на ешелони до FL920 включно.

Генерація площини XY розпочинається зі створення координат наземних об'єктів: населених пунктів, аеродромів, наземних станцій зв'язку, центрів зон заборонених для польотів та інших. Координати точок генеруються за правилом розподілу Бокса-Мюллера [6]:

$$z_1 = x * \sqrt{\frac{-2 * \ln(R)}{R}} \qquad z_2 = y * \sqrt{\frac{-2 * \ln(R)}{R}},$$

де $R = x^2 + y^2$, x та y — незалежні випадкові величини з відрізку [-1, 1].

На основі просторового розподілу виконується агрегація та розподіл згенерованих точок за встановленими правилами. Так, наприклад, точки аеродромів не можуть розташовуватися дуже близько одна до одної, не може бути більше двох аеродромів у одному місті, заборонені для польотів зони з більшою вірогідністю розташовуються на відстані від населених пунктів. Залежно від розміру генерованої площини, виконуються декілька циклів розподілу точок для відповідності встановленим правилам та наближенню до закону нормального розподілу.

Для розбиття площини на сектори використовується декомпозиція Вороного з алгоритмом Форчуна [7]. Цей підхід дає змогу отримати сектори, межі яких є рівновіддаленими від вершин графа повітряного простору. Додатково після декомпозиції виконується перевірка на відповідність правилам розбиття секторів.

Моделі ПК створюються відповідно до заданої кількості чи випадковим чином. Під час генерації вони розміщуються в аеропортах чи у повітряному просторі. Для технічних характеристик взято за основу інформацію з відкритих баз даних про 50 найпопулярніших пасажирських та транспортних літаків. Дані зберігаються у форматі CSV (рис. 5). Фізичні показники ПК, які змінюються в польоті, задаються рівняннями відповідних розділів фізики та авіації.

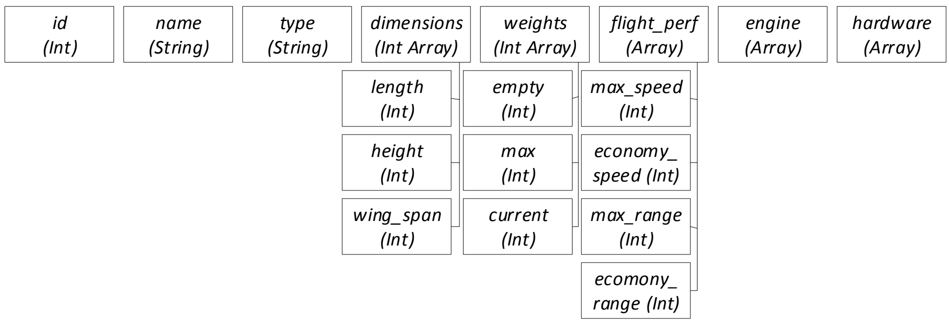


Рис. 5. Надання характеристик ПК в програмному комплексі

МОДУЛЬ ОБЧИСЛЕННЯ

Модуль обчислення виконує дві основні функції – розв’язання конфліктів ПК та оптимізацію траєкторії для уникнення конфліктів. У якості основного пристрою для виявлення та розв’язання конфліктів ПК використовується система TCAS II. Альтернативно було реалізовано експериментальну систему гарантованого розв’язання динамічних конфліктів повітряних кораблів у масштабі реального часу [8, 9].

Розглянемо принцип роботи модуля обчислення ЕС згідно з алгоритмом, який зображено на рис. 6. Модуль працює циклічно, безперервно отримуючи дані з багатьох джерел свого літака та всіх інших ПК, що знаходяться в певній заданій обмеженій частині простору, передаючи результати обчислень до інших ПК, систем свого ПК і наземних служб та систем. Дані постійно приймаються та обробляються, частина з них за необхідності може зберігатися для використання в наступних інтервалах часу.

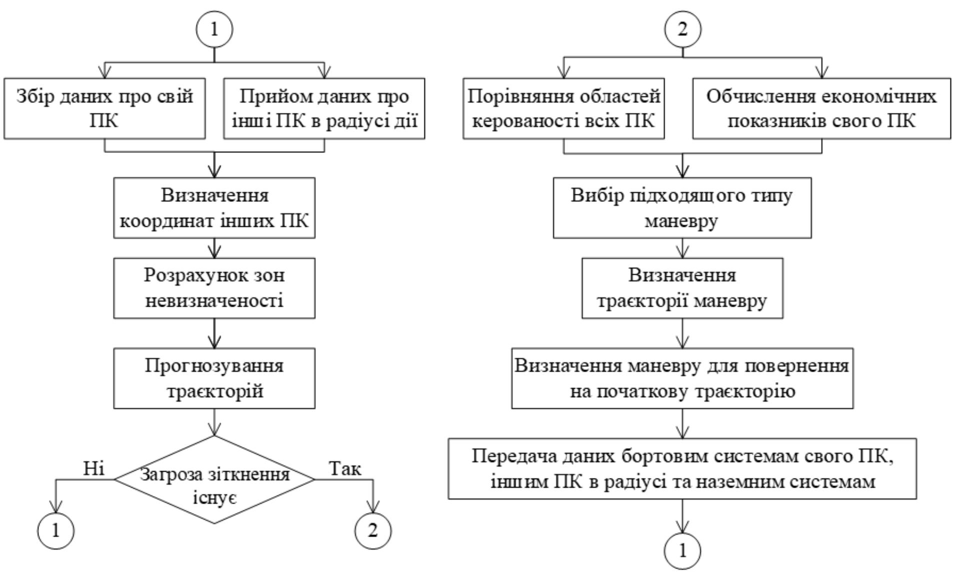


Рис. 6. Алгоритм роботи модуля обчислень

Після прийому та оброблення даних відбувається аналіз загрози зіткнення на основі прогнозів траєкторій руху ПК в заданій зоні, які базуються на координатах, швидкості, прискоренні, курсі та можливих додаткових параметрах математичних моделей руху ПК. Додатково, для визначення координат усіх ПК на просторово-часовій координатній сітці враховується інформація про так звані «зони невизначеності». На основі отриманих даних та прогнозованих траєкторій ПК проводиться аналіз та моделювання для визначення ймовірності загрози зіткнення ПК у заданій області простору. Якщо загроза зіткнення відсутня, підсистема повертається до початкового стану і циклічно продовжує аналіз.

За наявності загрози зіткнення розпочинається розрахунок параметрів маневрування, основним завданням якого є визначення оптимальної траєкторії маневру для уникнення зіткнення. Сукупна інформація про прогнозовані траєкторії використовується для визначення областей керованості ПК в зоні конфліктної ситуації у кожен момент часу. Додатково враховуються економічні показники власного ПК, а саме зміна маршруту маневру за відстанню та часом, економія палива, зручність перевезення пасажирів і багажу тощо. Ці показники та критерії надалі враховуються в обчисленнях для визначення траєкторій відхилення. На основі інформації, отриманої на попередніх етапах обчислень, вибирається відповідний тип маневру, який найбільше підходить для розв'язання заданої конфліктної ситуації, розраховується траєкторія маневру ухилення та кроки для повернення на початкову траєкторію після ухилення. Кожен з отриманих результатів є вихідною інформацією модуля, яка передається до інших пов'язаних модулів.

Для формування керувальних команд та циклічної роботи цього модуля інформація зберігається у внутрішніх системах свого ПК. За допомогою систем зв'язку та передачі даних модуль передає інформацію про власні маневри та траєкторії іншим ПК у заданій частині простору, а також, за можливості, до наземних систем, таких як диспетчерські пункти, радіолокаційні системи та пілотажно-навігаційні комплекси.

ТЕСТУВАННЯ КОМПЛЕКСУ МОДЕЛЮВАННЯ ТА ОЦІНЮВАННЯ РЕЗУЛЬТАТІВ

Процес моделювання зв'язків та властивостей авіаційних систем, елементів та процесів дає змогу оцінити їхній стан, зробити прогноз, прийняти обґрунтоване рішення, перевірити точність і правильність моделі тощо. Статичними складниками моделі виступають ПК, кожен зі своїми сталими фізичними характеристиками та вектором запланованого руху. Динамічним складником моделі є процес функціонування і розвитку статичних елементів, тобто характеристики та показники польоту, траєкторій, що змінюються у часі. Початковими даними для роботи комплексу є:

- кількість ПК, які знаходяться у деякій частині простору;
- кількість наземних об'єктів, які знаходяться у деякій частині простору;
- початкові координати ПК та наземних станцій;
- незмінювані фізичні показники кожного ПК (розміри, вага, пріоритет тощо);
- змінювані фізичні показники кожного ПК (швидкість, висота, запас палива тощо).

Процес моделювання здійснюється з дискретизацією переміщення ПК з певним інтервалом часу за допомогою синхронізації годинника системи з годинниками ПК та наземних станцій. Згідно з початковими координатами та траєкторією руху ПК переміщуються в деякій визначеній тривимірній площині. Кожний ПК у реальному часі, згідно з реалізацією алгоритму передачі даних під час руху, обмінюється інформацією з іншими ПК та виконує прогнозування загрози зіткнення в деякій визначеній зоні. У разі виникнення конфліктної ситуації ПК виконують розрахунок параметрів маневрування та після маневру повертаються на попередню траєкторію.

Розроблений програмний застосунок виконує потактове моделювання за вказаними умовами та початковими параметрами. Основне вікно містить графічне подання мапи зони симуляції у трьох виглядах: Радар (рис. 7), Перегляд за висотою та Мапа. Область у правій частині вікна програми дає змогу переглядати системні повідомлення про виконані дії, маневри та ситуації. У фоновому режимі здійснюється збір даних про числові характеристики кожного об'єкту системи моделювання, які зберігаються у файл. Налаштування початкових умов для простору, ПК та траєкторій є можливим у ручному та автоматичному режимах (рис. 8 а, 8 б).

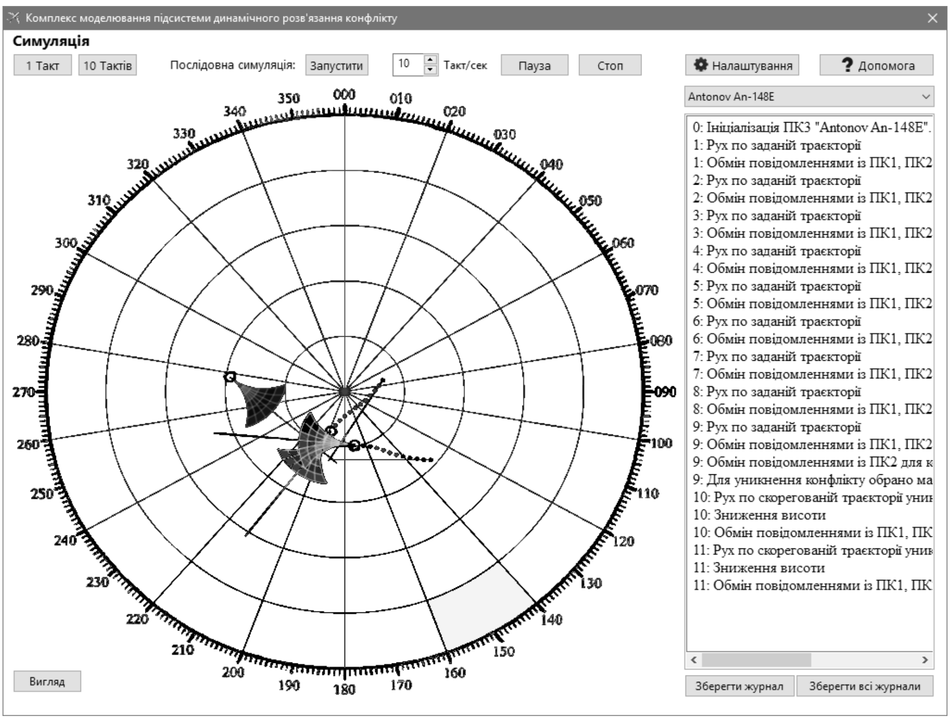
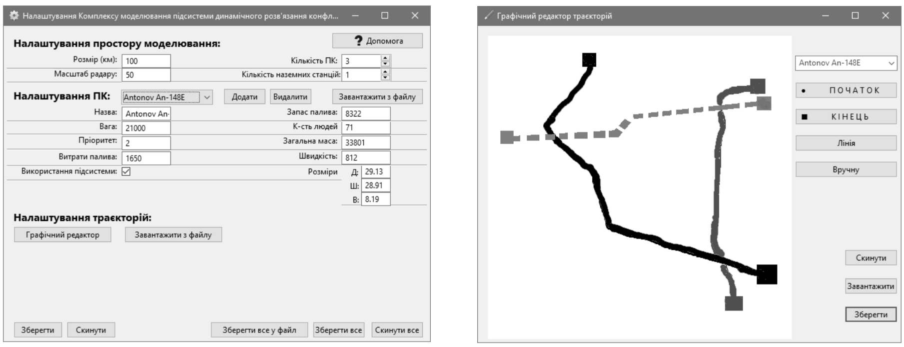


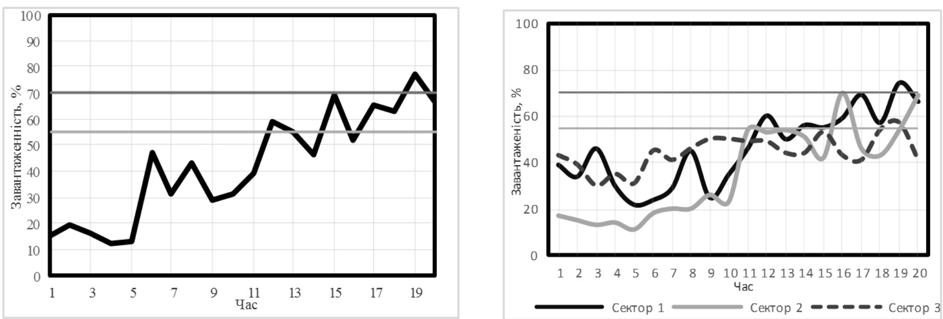
Рис. 7. Графічний інтерфейс розробленого комплекс моделювання

Тестування розробленого комплексу було проведено декількома серіями для виявлення показників загальної завантаженості повітряного простору (Рис. 9а) і його окремих секторів (рис. 9б). На рисунках показано середні значення для серії тестувань за п’яти різних початкових умов, заданих випадковим чином. Вертикальні лінії вказують на допустиме (55 %) та критичне (70 %) значення завантаженості простору. Окрім цього, виконано обчислення залежності кількості та довжини маневрів від завантаженості простору та кількості конфліктних ситуацій (рис. 9в та 9г). Зростання завантаженості простору спричиняє експоненційну залежність кількості та довжини маневрів.

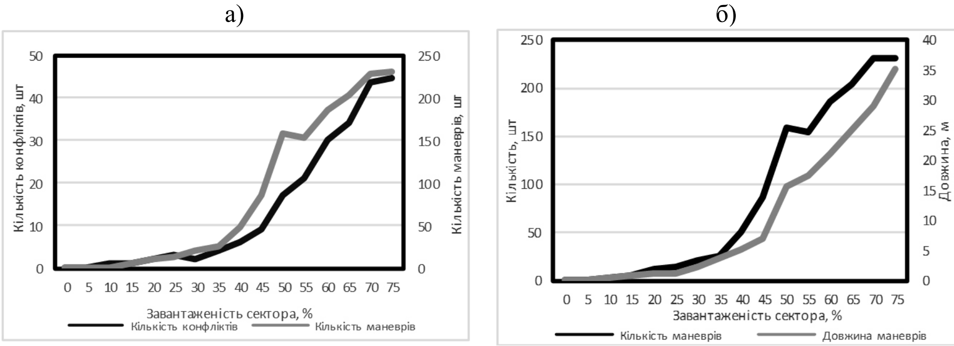


а) б)

Рис. 8. Графічне вікно налаштування генерації елементів (а) та редактора траєкторії (б)



а) б)



в) г)

Рис. 9. Результати моделювання конфліктних ситуацій ПК: а) загальна завантаженість простору; б) завантаженість секторів простору; в) кількість конфліктних ситуацій та виконаних маневрів залежно від завантаженості; г) кількість та довжина виконаних маневрів залежно від завантаженості

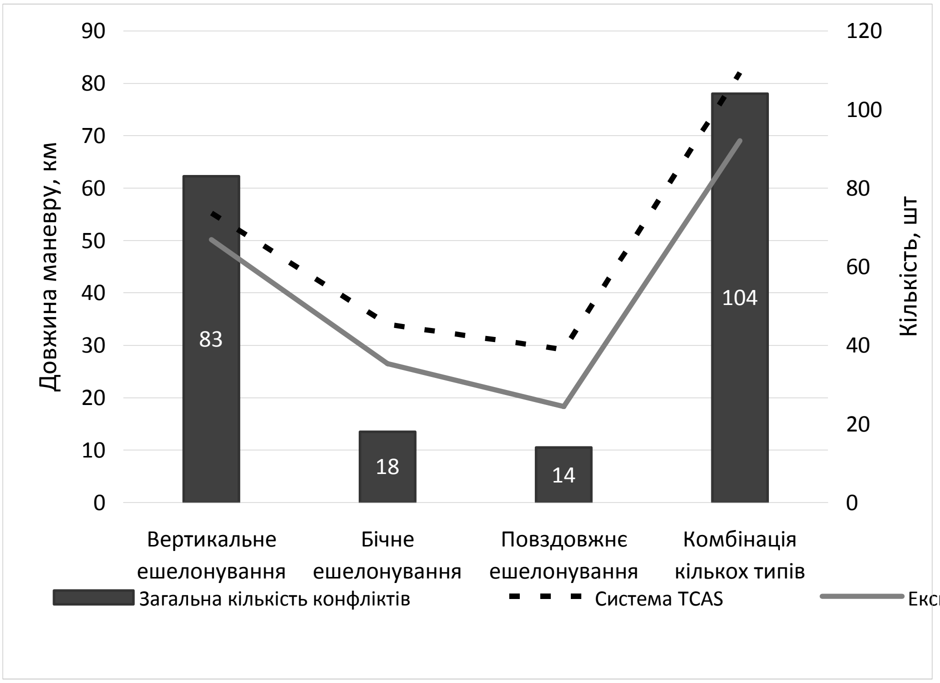


Рис. 10. Порівняльний графік моделювання з використанням експериментальної системи розв'язання конфліктних ситуацій та системи TCAS II

На основі отриманих результатів можна виконувати оцінювання згенерованої моделі та порівняння з іншими аналогічними моделями та з даними реальних польотів. Графіки завантаженості повітряного простору відповідають динаміці показників графіків уникнення конфліктних ситуацій. У разі зростання кількості ПК на одиницю площі виникає більше критичних ситуацій, що в свою чергу спричиняє збільшення обміну повідомленнями між усіма об'єктами в радіусі виникаючих конфліктів. За значної кількості ПК виникає перенавантаження систем розв'язання конфліктних ситуації та уникнення конфліктів спричиняє утворення нових конфліктів. На рис. 9г показано, що за великої завантаженості утворювалися конфліктні ситуації між багатьма (п'ять та більше) ПК та після виконання маневрів ухилення утворювалися нові конфлікти, які потребували більшої довжини траєкторій маневрування.

Для дослідження якості експериментальної системи (ЕС) гарантованого розв'язання динамічних конфліктів ПК у масштабі реального часу було виконано збір та аналіз даних щодо типів конфліктних ситуацій згідно порушень норм ешелонування та виконано порівняння із чинною системою розв'язання конфліктів TCAS II (рис. 10).

Близько 85 % конфліктів було отримано через порушення норм вертикального ешелонування чи в комбінації кількох типів. Відповідно довжина маневрів у таких конфліктах була значно більшою. Система TCAS гірше розв'язує конфлікти у разі порушення бічного та повздовжнього ешелонувань, оскільки вони вирішуються правилами вертикального ешелонування. Натомість ЕС розв'язання конфліктів краще впоралася з розв'язанням конфліктних ситуацій, а її ефективність вища на 18,2 %.

ВИСНОВКИ

Розвиток сучасної авіації є неможливим без якісних засобів моделювання, а кожна нова розробка, яку пропонується використовувати, повинна бути ретельно протестована. Завдання попередження конфліктів повітряних кораблів (ПК) в реальному часі є одним з ключових серед проблем авіації, а отже потребує розроблення методів розв'язання та засобів для моделювання та тестування. В роботі проаналізовано переваги та недоліки чинної системи попередження конфліктних ситуацій TCAS II та норми ешелонування ПК згідно з рекомендаціями ICAO.

Розроблений комплекс для моделювання динамічних конфліктних ситуацій ПК у масштабі реального часу дає змогу оцінити кількісні показники симуляції руху ПК у згенерованому просторі та розглядати особливості вирішення конфліктних ситуацій. Чинна система TCAS застосовується вже більше 20-ти років та має деякі суттєві недоліки. Результати модельних експериментів показують, що розроблений комплекс коректно моделює переміщення, взаємодію та маневрування ПК, а експериментальна система розв'язання динамічних конфліктів є ефективнішою за чинну систему TCAS II за рядом показників.

Оцінювання ефективності функціонування розробленого комплексу моделювання та використовуваних алгоритмів виявлення і вирішення конфліктних ситуацій проводилася з використанням типових дослідних сценаріїв, починаючи від простих конфліктів між двома ПК до гранично складних за участі в одному конфлікті значної кількості ПК. Основними показниками ефективності розв'язання конфліктів прийнято вважати кількість та довжину маневрів уникнення конфліктної ситуації за різної завантаженості повітряного простору, за різних типів конфліктних ситуацій, пов'язаних з порушеннями норм ешелонування.

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COMPLEX FOR MODELING AIRCRAFTS' DYNAMIC
CONFLICT SITUATIONS IN REAL-TIME

Introduction. Aircraft flight simulation has many solved and open tasks. The development of modern aviation is impossible without high-quality modeling tools, and every new proposed development must be thoroughly tested. Real-time aircraft conflict prevention is one of the key tasks in aviation, and therefore requires solutions and tools for modeling and testing.

The purpose of the paper is to provide brief information on identifying and resolving aircraft conflict situations methods, to develop a software package for modeling dynamic conflict situations in real-time.

Methods. Software development of complex is based on the statistical and simulation computer modeling, computational geometry and mathematical analysis methods. The theory of automatic control, navigation and intelligent control methods are used to identify and resolve conflict situations.

Results. The developed modeling complex allows evaluating the quantitative indicators of aircraft simulation in the generated space and examination the features of conflict situations resolution. Modeling of movement, interaction and maneuvering of the aircraft is carried out. In conflict resolution, the experimental system was more efficient than the current TCAS II system.

Testing the developed modeling complex, detecting and resolving conflict situations algorithms was performed using typical research scenarios, ranging from simple conflicts between two aircraft to extremely complex, involving a significant number of aircrafts in a single conflict. The main indicators for the optimal resolution of conflicts are the number and length of maneuvers to avoid a conflict situation with different airspace congestion, with different types of conflict situations associated with violations of the separation rules.

Conclusions. The proposed complex can be used to research the interaction of numerous aircrafts in a dynamic environment, the development and testing of conflict situations resolving methods. The modular structure of the complex allows performing simulations of other elements, such as data transmission systems.

Keywords*: information technology, aviation, computer simulation, conflict situation, aircraft, TCAS system.*

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HIERARCHICAL SIMULATION. ALGORITHM FOR PREDICTION OF GLYCEMIC PROFILE FOR DIABETES

Introduction. *Diabetes mellitus, a common chronic disease, requires lifelong treatment and, like any chronic disease, requires regular monitoring and self-control at home. Revolutionary changes in glycemic control in diabetic therapy have occurred thanks to the development of sensors for continuous glucose monitoring (CGM), which can, almost continuously, measure the concentration of glucose in the subcutaneous tissue. The most common barriers to CGM use are related to high device costs and lack of insurance coverage for their purchase, alleged sensor inaccuracy, anxiety, which is associated with* *dislike of wearing the device. Thus, sensors are good but expensive, not affordable for everybody and could be uncomfortable. Therefore, the constant search for alternative solutions remains an important challenge.*

The purpose *of the paper is to show the possibility of using hierarchical modeling technology to develop and study glycemic profile prediction algorithm as, to some extent, alternative to continuous monitoring sensors in a context of limited irregular measurements.*

Results. *The program-algorithmic structure for realization of the concept of hierarchical simulation is developed. The possibility of conducting research on models of varying complexity is shown. An algorithm for insulin-glucose tolerance test was synthesized. A procedure for predicting the daily glycemic profile by analytical formulas has been developed, which provides an opportunity to assess the trend of glycemic dynamics as an addition to the irregular glucose measurements with a glucometer. A simulation study, the result of which is the visualization of glycemic profile in a context of expected food intake schedule and compensating insulin doses obtained by the analytical algorithm, was conducted.*

Conclusions. *The proposed hierarchical modeling technology, based on the use of mathematical models of varying complexity, allows to conduct a complex of simulation studies to correct glycemia in diabetes at the preclinical and pre-ambulatory stages. During the simulation of forecasting procedure, configuration discrepancies of the glycemic profile obtained from different models were detected, but they are within the margin of error and reproduce the main trend in the dynamics of glycemia during meals and insulin injections. The calculated bolus doses of insulin are almost identical to those used by insulin-dependent patients. The simplicity of calculations using analytical formulas can be a prerequisite for the implementation of the algorithm in a special-purpose portable autonomous devices or in applications for Android OS.*

Keywords: *digital medicine, hierarchical simulation, glycemic control system, identification algorithms control, forecasting, simulation preclinical trials.*

INTRODUCTION

Diabetes mellitus (DM) is a chronic disease that manifests in a persistent elevation in blood glucose level caused by absolute or relative deficiency of insulin, a hormone that stimulates glucose transport from the blood stream into cells, providing the body with the main energy resource.

The problem of diabetes is becoming increasingly important due to the evergrowing number of patients in all countries and on every continent. To date, the number of patients on the planet is more than 180 million people, the current number of which, according to WHO estimates, will almost double by 2045 [1]. Currently, this disease is a global medico-social problem. This is not only because of progressive increase in the number of patients with diabetes, but also because of the extremely high risk of complications that lead to loss of working capacity, disability and mortality in this group of patients. Consequently, at present, the main focus of diabetic patient treatment is the development of methods and programs aimed at risk reduction of micro- and macrovascular complications of the disease [2].

Diabetes mellitus, as a chronic disease, requires lifelong treatment. The goal of treatment is "disease compensation", i.e. achievement of glycemic indicators that are close to normal values, since glycemic indicators that go beyond certain limits cause complications. This remains one of the main tasks to prevent their appearance and progression.

Diabetes, like any other chronic condition, requires regular monitoring and self-control at home. Unconditionally, it is very important to measure blood glucose level regularly — the main indicator that describes the state of carbohydrate metabolism and the diabetic status of an organism. To address this issue, the modern industry produces affordable glucometers, using of which the patient can take measurements, if necessary, few times a day, that contributes to a better quality of glycemic self-control.

Despite the various etiologies of the existing types of diabetes and the peculiarities of the course, their therapy pursues a common goal — the normalization of glycemia, the elimination of symptoms associated with high blood glucose level, the reduction of risks of hypoglycemia and the prevention of complications.

One of the methods of treatment for diabetes with endogenous insulin deficiency is intensive hormone therapy based on repeated daily injections, which include one or two long-acting hormone injections per day to create a basal concentration of glucose in the blood (fasting glucose level is an indicator for this) and additional fast-acting hormone injections before each meal in an amount that depends on glucose component.

To avoid complications, it is very important to choose an adequate insulin dose, consistent with the carbohydrate component in the food. Insufficient insulin dose can lead to hyperglycemia. And if this happens regularly, it could cause severe vascular complications such as retinopathy, nephropathy, neurological damage and diabetic foot syndrom. They are the cause of disability and increased mortality. On the other hand, an overdose of insulin can cause hypoglycemia which leads to loss of consciousness and if it is not compensated immediately, even to death. As a result, diabetics should monitor glucose concentration during the day and adjust insulin therapy accordingly.

An insulin pump is used to improve injection therapy in modern diabetic practice. This is medical device that injects fast-acting insulin into abdominal subcutaneous tissue during the day at a constant rate to ensure glucose levels in the permissible background range. Additional insulin doses are injected before meal to ensure its utilization. Many papers, for example [3], outline the effectiveness of insulin pump usage, which, compared with injection therapy, improves glycemic control.

But despite continuous improvement of insulin administration methods, all patients on insulin therapy should conduct self-control of blood glucose (SCBG), which is an integral part of effective therapy. For many patients, this will require testing 6–10 times a day. Glycemic control in diabetic therapy has been revolutionized by the development of sensors for continuous glucose monitoring (CGM), which can measure glucose concentration in the subcutaneous tissue almost continuously (eg. Every 5 minutes) [4, 5]. The results of studies on the use of these devices provided in a review paper [6]. The result of their use in combination with intensive insulin therapy regimens is a decrease in HbA1c levels and the frequency of hypoglycemic events [7, 8]. However, the CGM sensors usage remains limited for a large segment of the population with diabetes, mainly for patients with type 1 diabetes [9]. More recent data show that even in highly developed countries only 17 % – 25 % of patients use CGM [10, 11]. The use of CGM is even less widespread among patients with type 2 diabetes [12–14]. The most common barriers to CGM use were related to high device costs and lack of insurance coverage for their purchase [15, 16]. The most common reasons for stopping CGM use were cost, anxiety, alleged sensor inaccuracy, and dislike of wearing the devices. Thus, sensors are good but expensive, not affordable for everybody and could be uncomfortable. Therefore, the constant search for alternative solutions remains an important challenge for researchers.

Diabetes is a complex metabolic disease that requires involvement of specialists from many related disciplines: pathophysiologists, pharmacologists, technicians etc. In modern society, the technology of mathematical modeling is practically an essential component that accompanies almost all branches of activity. State-of-the-art information technologies that are based on mathematical modeling can be an effective auxiliary decision support tool in many segments of endocrinology at various stages of diagnostic processes and diabetes treatment. A person with diabetes has to perform many routine calculations forming a diet that is aligned with physical activity and therapeutic measures. Daily glycemic profile of the patient is an indicator of the adequacy of interactions of therapeutic measures and harmonization of dietary exposure and vigorous activity. There is a large segment of users who are not able regularly use continuous glycemic monitoring devices (CGM).

The purpose of the paper is to show the possibility of using hierarchical modeling technology to develop and study glycemic profile prediction algorithm in a context of limited irregular measurements.

EVOLUTION OF MODELLING

Currently, a large number of mathematical models are known. Information about them can be found in review publications [17–21], devoted to the study of various aspects of glycemic regulation, the dysfunction of which is the cause of diabetes mellitus.

In case of an advanced system of models, it is advisable to structure their set according to the principle of hierarchy, the basis of which is a different level of abstraction during the imitation of functional features of investigated system. In this paper, for the synthesis of the algorithm and evaluation of its effectiveness hierarchical modeling technology was used, which envisages the usage of models of varying complexity from the most complex systems of nonlinear differential equations, that with some degree of approximation try to recreate systematicity, complexity and functionality of real physiological regulation to the simplest minimal models used in autonomous technical devices [22].

The evolution of study of dynamic properties of the physiological system of glycemic regulation using mathematical modeling methods began with an analysis of the interaction of insulin-glucose bonds and has now moved on to a large-scale simulation studies *in silico*, which are reported [19–23] and which enable to conduct a number of different studies of the functioning of the system at the preclinical stage, including engineering tests of glycemic control devices by using closed-loop artificial pancreas.

Minimal models. Methodological analysis and examples of the use of minimal modeling approach conducted in [24, 25, 26]. The key requirements for minimal models are that they must have a minimum number of parameters that must be identified by a single dynamic response under a limited number of system measurements and at the same time satisfy the purpose for which it was created — to reproduce the basic intended functionality of the system regulation. Further developed class of this type of models is based on classic Bolie model, 1961 [27]. This is a system of differential equations that has 2 compartments and describes the linear nature of glucose-insulin interaction in the zero-order approximation. Various modifications and examples of its use are provided in papers [28–31]. The general view of this type of model can be written in the system of equations:

$$\frac{dx}{dt} = a_{11} F_1(x, y) + a_{12} F_2(x, y) + G_u$$

$$\frac{dy}{dt} = a_{21} F_3(x, y) + a_{22} F_4(x, y) + I_u ,$$

where x, y — blood glucose and insulin concentrations, $F_i(x, y)$ — delivery rate and utilization rate of glucose and insulin as a result of metabolic transformations resulting from homeostatic regulation, G_u, I_u — the rates of external influence of factors that increase or decrease the level of glycemia (it can be glucose in a food or injections / infusions of insulin).

There is a known methodology for constructing models based on the criterion of dynamic equilibrium of glucose and insulin flows in the body as in an open system [32–33]. A model of this type was developed by Russian scientists Novoseltsev V.N., Orkina E.L., Kuchkarov Z.A. etc. and described in [24].

An example of the most minimal model, that in its structure has only one glucose compartment, is a physiologically adequate mathematical model of glycemic regulation, developed by Ukrainian scientists, in the form of a first-order differential equation with a delayed argument, which makes it possible to reproduce the dynamics of the glycemic curve under various external influences quite accurately. The structure of the model has allowed the authors to conduct a series of studies taking into account the peculiarities of glucose absorption from the intestinal lumen, improve the detection of latent forms of diabetes mellitus and simulate the calculated optimal regimen of insulin therapy for an automated dispenser [34–35].

Maximal models. Mathematical modeling technology is constantly being improved by creation of new tools and methods available for biomedical modeling. Furthermore, the demand for theoretical simulation studies of various hypotheses verification of functioning of carbohydrate metabolism regulation system and also for quantitative assessment of elements interconnection in a complex biological systems is not decreasing. This led to the creation of computational structures that facilitate comprehensive analysis of theoretical ideas about holistic biological system functioning [36].

The basis of these computational complexes are mathematical models with advanced link architecture, that describe in more detail the set of physiological mechanisms of glicemia metabolic regulation. They represent the systems of high-dimensional differential equations with many nonlinearities and unknown parameters, which illustrate (even if only hypothetically) a wide range of possible interactions in a real physiological system. Such models enable the creation of various modeling scenarios with which it is possible to conduct analysis of the effectiveness of various treatment strategies without spending resources on real research.

It should be noted that the identification of such models is a complex issue, which is analyzed and discussed in [37, 19, 25]. The problem of identification of these models is reduced through the use of real functional dependencies obtained in a special physiological experimental studies that are included in a complex simulation model by separate modules [38]. Partially, the solution to the problem of identification and complex models was proposed by Novoseltsev V.N. back to 1991 [21]. This approach consists in the fact that a minimal parametric structure is allocated in a complex model, that permits an identification computational procedure according to the available data of specific measurements. The last part of the unknown parameters is verified based on fundamental functional dependencies known in physiology and a priori personal information about a particular patient. It should be noted that the problem of complicated identification of such models is also reflected in forecasting since these models reproduce the population tendency of the dynamic properties of a real physiological processes. However, the role of such mathematical objects, which have accumulated many years of knowledge about functioning of the regulatory system, encoded in mathematical structures and parameters, which are used in the educational process as textbooks is difficult to overestimate [39, 40].

Such models enable stimulation of different scenarios of occurrence, course and treatment of the disease, followed by assessment of treatment measures by using possibility, unprecedented in clinical practice, of repeatedly renewing clinical situations. Complex of models equipped with a specialized interface is a kind of “virtual clinic” which includes the subsystems “virtual diagnostics” and “virtual therapy”.

This entire arsenal of tools can be a clear illustration of the treatment process in teaching, can serve as a guide for classroom training on the one hand, on the other — allows medical students to be active participants in many stages of the treatment process, to offer and to check using virtual objects — models — their options of condition assessment, therapeutic effects, recommendations. Undoubtedly, the main form of accumulating practical experience is a clinical practice under the guidance of a teacher. However, the effectiveness of this form of training can be significantly improved with the involvement of new computer technologies.

Simulation studies on complex models are provided in publications [38–40]. They are used when it is difficult and risky to conduct studies of the effectiveness of therapeutic measures in a real conditions or they require valuable costs. In this case, simulation studies on complex models perform the function of preclinical trials. In foreign papers these studies are published under the term "*in silico*". In silico research has become especially relevant in the study of the effectiveness of not only feedback control algorithms directly, but also their technical implementation with all their problematic attributes related to the accuracy of measurements, testing the accuracy of algorithms to ensure infusion of insulin into the body etc.

For example, in paper [41], the model for such studies consists of 13 differential equations, has 35 parameters and is able to simulate the personal variability of the main metabolic parameters of the regulatory system, which is observed in type 1 diabetes, in virtual space. The feasibility of using this approach is confirmed by the fact that the FDA [45–47] has adopted simulation tests in silico with a global model as a necessary step in replacing preclinical animal trials before authorized permission for clinical trials directly on humans. Such large-scale studies are also reported in [48–54] publications.

ALGORITHM SYNTHESIS

The synthesis of the algorithm was performed directly on the model of minimum complexity MINIMODEL, which can be used to obtain analytical solutions of the problem. The model of greater complexity MIDIMODEL is used to compare numerical solutions with analytically obtained formulas and then these variants of algorithms are tested on a more complex model MAXIMODEL, which simulates a real object.

The main technological stages of using mathematical modeling to obtain information tools for visualization of glycemic profile and the possibilities for its correction:

1 stage — mathematical structure for problem solutions on analytical formulas;

2 stage — development of an insulin-glucose tolerance test for *identification* of parameters;

3 stage — obtaining analytical solutions of identification tasks, prediction and optimization of the compensating insulin dose within the limitations;

4 stage — formation of a common fundamental structure and software implementation of the algorithm simulation studies using hierarchical simulation technology.

Model for analytical solutions. A simple mathematical model is proposed, which provides the identification of unknown parameters by analytical formulas and with limited number of blood sugar measurements, which allow to estimate the dose of insulin for utilization of the amount of carbohydrates taken with food while preventing glycemia to exceed the specified range:

$$\frac{dI}{dt} = -k(y - y_n) - \lambda I + b_2 G(t), \quad y(0) = y_0$$

$$\frac{dI}{dt} = -b_1 I, \; I(0) = I_0, \tag{1}$$

$$G(t) = \begin{cases} G_0, \, 2\tau \le t < \vartheta \\ 0, \, t < \vartheta \end{cases}$$

where y – current blood glucose level (mg %), y_0 — initial glucose level, y_n — fasting glucose level, I_0 — insulin dose before meal, $I(t)$ — insulin, which is absorbed into the blood from the site of subcutaneous injection, G_0 — the rate of carbohydrate absorption from the gastrointestinal tract into the bloodstream, k, λ, b_1, b_2 — coefficients of dimension and proportionality, 2τ — the moment of the beginning of food intake, ϑ — duration of absorption of carbohydrates taken with food into the blood.

Identification. Insulin-glucose tolerance test. The identification of personal characteristics of the dynamics of glycemia is based on the data of insulin-glucose tolerance test. The detailed measurement of glucose on the background of injected insulin before meals, in which the amount of carbohydrate component is known, may serve as this test. The fasting blood sugar test is taken — y_n (0). For example, a patient is injected subcutaneously with insulin in the amount of Io units in the morning (for us it is $t = 0$). Before the first meal it is necessary to perform a second measurement y_1 (τ) through τ (min.) and at the time of eating a third measurement y_2 (2τ). The last measurement in the test a while after eating — y_3 (2τ + θ). It is desirable to choose the length of the interval θ so that the process of absorption of carbohydrates received with food almost ended. This is necessary in order to assess the magnitude of the maximum rise of glycemia level in the background of food intake. The carbohydrate content in the test breakfast should be regulated. The parameter b_1, which characterizes the type of insulin — its dynamic properties, is introduced. The rate of absorption of carbohydrates from the gastrointestinal tract — G_0 is defined by physiological data, this is an average of 1 g / kg / h, the amount of insulin injected subcutaneously before breakfast, I_0 — the amount of insulin before a meal, Dg — the amount of carbohydrates in the breakfast, τ — discreteness of measurements (min), value of 2 τ + θ — time of the maximum (min). The unknown parameters k , b_2 i λ that need to be found in the identification process characterize the user's individual sensitivity to the procedure. The structure of the test study is shown schematically in Fig. 1.

The procedure for calculating the unknown parameters is following.

Let's we write the solution of equation (1) on the background of insulin action:

$$y - y_n = \frac{\lambda b_1 I_0}{k - b_1}\left[\exp(-kt) - \exp(-b_1 t)\right]. \tag{2}$$

Substituting the values of glucose measurements at times τ and 2 τ: y_1 (τ) and y_2 (2τ) in this equation, the following system is obtained:

$$\begin{aligned} y_1 - y_n &= \frac{\lambda b_1 I_0}{k - b_1}\left[\exp(-k\tau) - \exp(-b_1\tau)\right] \\ y_2 - y_n &= \frac{\lambda b_1 I_0}{k - b_1}\left[\exp(-2k\tau) - \exp(-2b_1\tau)\right] \cdot \end{aligned} \tag{3}$$

Substituting the values of glucose measurements at times τ and 2 τ: y_1 (τ) and y_2 (2τ) in this equation, the following system is obtained:

$$k = -1/\tau * \ln\left[\frac{y_2 - y_n}{y_1 - y_n} - \exp(-b_1\tau)\right], \tag{4}$$

$$\lambda = \frac{(k - b_1)(y_2 - y_n)}{b_1 I_0\left[\exp(-2k\tau) - \exp(-2b_1\tau)\right]},. \tag{5}$$

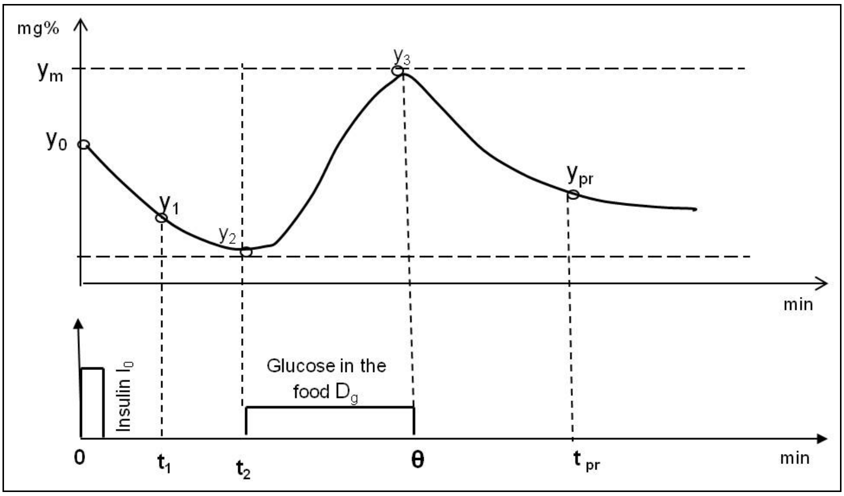


Fig. 1. The structure of the test study

Formulas for calculating unknown parameters k i λ are obtained by solving the above mentioned system.

To find the unknown parameter b_2 we use the solution of equation (2) on the background of absorption of carbohydrates from the gastrointestinal tract:

$$y - y_n = \frac{\lambda b_1 I_0}{k - b_1}\left[\exp(-kt) - \exp(-b_1 t)\right] + \frac{b_2 G_0}{k}\left[1 - \exp(-k(t - 2\tau))\right], \quad t > 2\,\tau. \tag{6}$$

Using the measurements of glucose at the point of the expected maximum– $y_3\,(2\tau + \theta)$, formula for calculating the coefficient b_2 is obtained:

$$b_2 = k * \left[y_3 - y_n - \frac{\lambda b_1 I_0}{k - b_1}\left[\exp\left(-k(2\tau + \vartheta\right) - \exp\left(-b_1\,(2\tau + \vartheta\right)\right]\right] / \\ G_0\left[1 - \exp(-k\vartheta)\right]. \tag{7}$$

These parameters are used in the calculation of the predicted glycemic curve at given glucose loads. It should be noted, that their identification can be carried out not in a special test study, but in the context of normal breakfast, in which the amount of carbohydrate component in food is known.

Control problem. In determining the control problem under the conditions of standard injectable insulin therapy, it is necessary to take into account that the main task is to choose insulin dose that would facilitate the absorption of food nesessary to compansate energy consumption, for adequate vital activity of a particular patient and which whould ensure glycemic variability in the acceptable limits. The entire control process is divided into as many cycles as number of meals and insulin injections expected. One cycle from the moment of the initial injection to the next one is divided into three intervals. The first interval $[0,\ \tau_i]$ — the period of time from the start of injection to the food intake, the second interval $[\tau_i,\ \theta_i\ ]$ — duration of assimilation of i-th food intake, the third interval — $[\theta_i, \tau_{i+1}]$ — the duration of time between assimilation of food intake and subsequent food intake, or by injection of insulin depending on the intended regulation.

The solution of equations at these three intervals has the form:

$$y - y_n = (y_0 - y_n)\exp(-kt) + \frac{\lambda b_1 I_0}{k - b_1}(\exp(-kt) - \exp(-b_1 t)),$$
$$0 \le t \le \tau_i, \tag{8}$$

$$y - y_n = (y_0 - y_n)\exp(-kt) + \frac{\lambda b_1 I_0}{k - b_1}(\exp(-kt) - \exp(-b_1 t)) +$$
$$\frac{b_2 G_0}{k}(1 - \exp(-k(t - \tau_i))), \quad \tau_i < t \le \vartheta_i, \tag{9}$$

$$y - y_n = (y_0 - y_n)\exp(-kt) + \frac{\lambda b_1 I_0}{k - b_1}(\exp(-kt) - \exp(-b_1 t)) -$$
$$\frac{b_2 G_0}{k}(\exp(-k(t - \tau_i)) - \exp(-k(t - \vartheta_i))), \quad \vartheta_i < t \le \tau_{i+1}. \tag{10}$$

To obtain the formula for calculating insulin dose I_0 in injection before meal, in order to prevent glycemia level from going beyound the acceptable limits on the background of food assimilation, the solution of an equation on the food assimilation interval (9) is used, according to which:

$$I_0 = \frac{k - b_1}{\gamma b_1} * \frac{A(y_0 - y_n) + B * b_2 G_0 / k - (y_m - y_n)}{C - A}, \tag{11}$$

where $A = \exp(-k(\tau + D / G_0));$ $B = 1 - \exp(-k * D / G_0);$ $C = \exp(-b_1(\tau + D / G_0));$ y_m — the upper limit of control range,

According to the described algorithm on the basis of the previous insulin-glucose testing, it is possible to obtain a daily prediction of the glycemic profile, taking into account the expected diet and insulin therapy. The input data is the fasting glucose concentration and glucose concentration before meal, its carbohydrate component, the upper limit of glucose level, the time interval over which after insulin injection it is necessary to take food. As a result, the predicted value and insulin dose are calculated.

It should be noted, that extremely complex processes that occur in the body with impaired carbohydrate regulation can not be accurately described by formal mathematical procedures, especially linear ones. The patient's sensitivity to insulin can vary over fairly short periods of time due to the influence of various external unforeseen factors that are difficult to take into account, such as quantitative and qualitative food composition, variety of physical activity, emotional component, other random disturbances that undoubtedly affect the glycemic variability, which couldn't be accurately considered using irregular measurements, even with the help of more detailed models. Actually, long-term forecasting for the whole day can reflect only a fundamental trend in the dynamics of glycemia on the background of planned treatment and food regimens. In the presence of a glucometer, the correction of bolus dose before meal according to the described algorithm can be carried out not based on predicted glycemia level, but using real measurements. However, the algorithm allows to take into account the carbohydrate component, the level of glucose before eating and the limitations of maximum rise on the background of food intake that cannot be exceeded.

At the same time, if glycemic value predicted by the algorithm lies within the margin of error of the received from glucometer usage, the correction does not occur. If the obtained value is out of the acceptable range, finding the solution to the task continues with the new obtained initial value. Therefore, it is advisable to provide additional correction of insulin doses before meals by attracting discrete feedback from glucose measurements using glucometer. In this case, it can be used to prevent hypoglycemia in calculation of the predicted glycemic value during insulin injection before the next meal, when the effect of the previous meal is already over, and the previous insulin still continues to fulfill its function.

Thus, the synthesis of program perturbation control is implemented when the carbohydrate component in the food is taken into account, with discrete feedback connection by including in the algorithm the predicted glycemia value by the model or measurements by glucometer. The tight control by which the compensating insulin dose is calculated on condition that raising of glycemia to the upper limit is limited, can be somewhat mitigated by a higher assignment of the upper acceptable limit, which occurs at a lower dose values.

SOFTWARE IMPLEMENTATION

The developed algorithm for identifying the parameters of model equations and calculating the insulin dose, that compensates the amount of carbohydrates in the food, is implemented programmatically in Matlab environment. The central role in the program is taken by the module which implements an algorithm for selecting doses of insulin injections before meals and calculating the daily dynamics of blood sugar levels. This algorithm is based on dividing the entire daily interval into a sequence of food intake cycles. Under the food intake cycle, within the framework of this formalism, is taken to be a set of processes proceeding from one insulin injection to another. The algorithm includes procedures for calculating the required insulin dose, calculating the insulin dynamics between the moment of insulin injection and the beginning of food intake, calculating the glycemia dynamics during the intake of carbohydrates from the gastrointestinal tract into the bloodstream, and calculating the glycemia dynamics after the end of glucose intake from the gastrointestinal tract, calculating the predicted value at the time of the next injection and continues as many times as number of meals expected.

Simulation study of the algorithm was performed on models of different complexity: 1) on the *model*, that has *analytical solutions* — one compartment — MINIMODEL, that imitates glucose dynamics, regimen of meals and control actions of insulin 2) on the *two-compartment model* — MIDIMODEL*,* that includes insulin-glucose interconnections, 3) on the *complex model* — MAXMODEL, which simulates a *virtual patient.* This is a model of the type [38], adapted for use in our conditions. In this model, the glucose balance in the body is realized through the insulin regulation subsystem and the counterinsular subsystem. It has seven differential equations, 15 nonlinear functional dependencies of sigmoidal type and more than 40 parameters. The structure of the model consists of insulin-dependent and non-insulin-dependent tissues, synthesis and secretion of insulin in the pancreas, insulin dynamics in the liver, in the intercellular fluid, dynamics of glucagon are simulated.

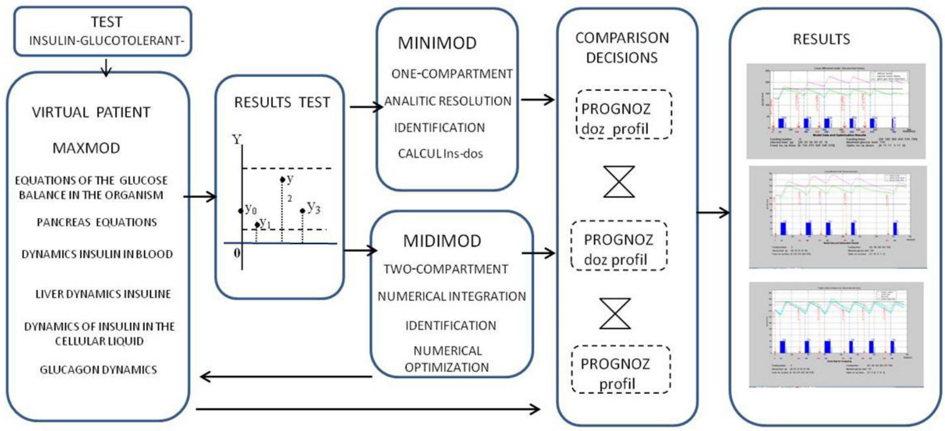


Fig. 2. The structure of the simulation study

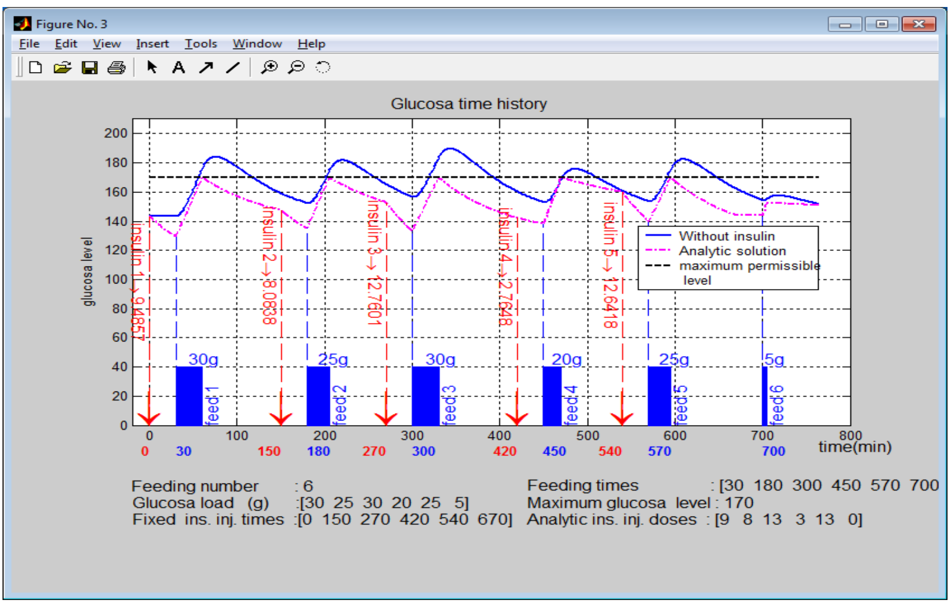


Fig. 3. Predicted glycemic profile obtained using the analytical solution of the control problem

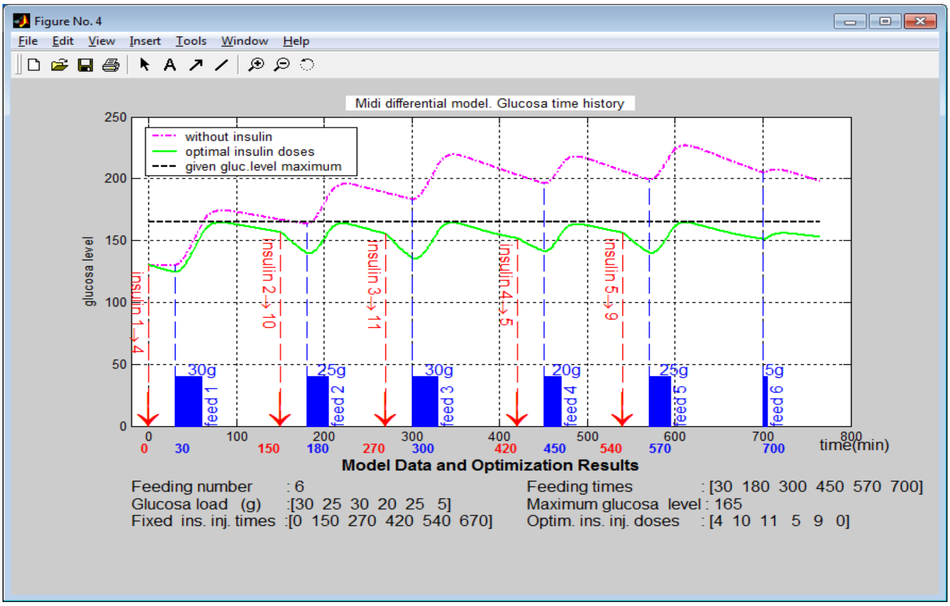


Fig. 4. Predicted glycemic profile (controlled / uncontrolled) obtained using a numerical algorithm for solving the control problem using two-compartment Midimodel

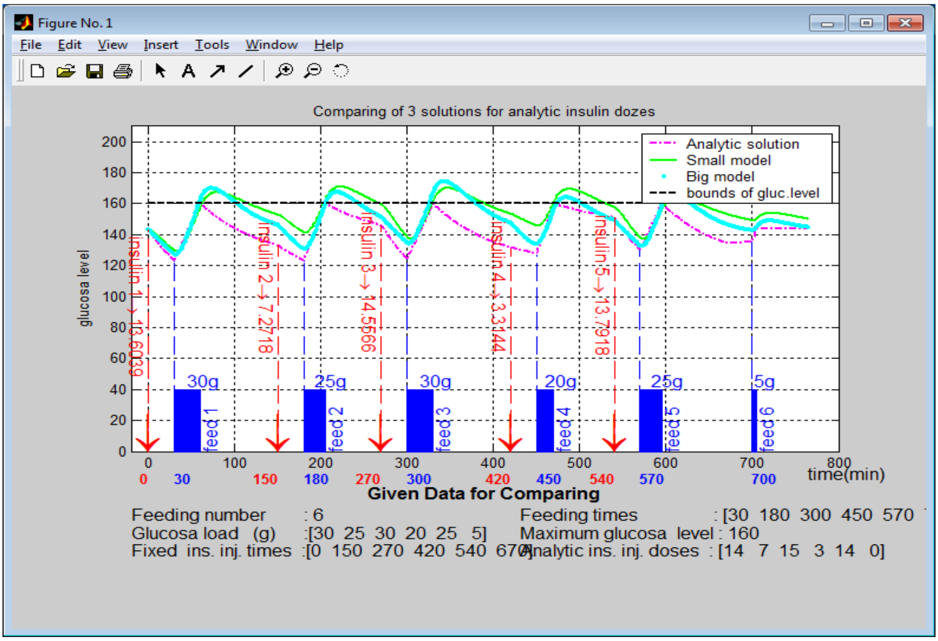
Software interface provides user-friendly navigation in terms of developed technology, in particular, model selection on which the appropriate stage of the work is currently being performed, analytical solution of the problem, numerical integration, identification, forecasting, graphic visualization.

The process of simulation research took place as follows. First, test insulin-glucose load was applied to the virtual patient model, key test points of measurement were applied to the MINIMOD and MIDIMOD models, by which their parameters were identified. Then their solutions with identical scheme of food intake per day were compared with compensating insulin doses calculated according to the appropriate algorithm on condition.

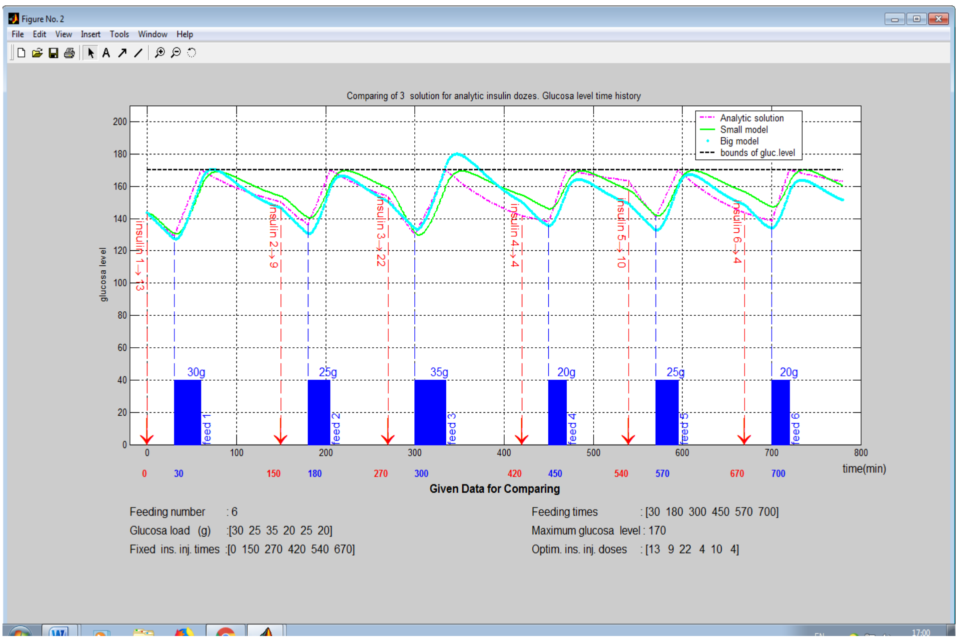
Figure 3 illustrates the glycemic profile forecast obtained by *analytical formulas*, in which six meals with compensating injections of insulin are planned.

Numerical algorithm. To simulate the process of glycemia correction in a model that takes into account glucose-insulin bonds, for which the analytical solution is problematic, the search for the optimal insulin dose was performed using a numerical algorithm by multiple integration of the corresponding equations. The optimal dose is the one at which the maximum level of glycemia reaches the upper permissible limit set by the user. The corresponding graphical illustration of the glycemia dynamics is shown (Fig. 4).

The simulation study of the algorithm obtained by the analytical solution was performed on models of different complexity. The optimal insulin doses obtained by this algorithm were applied to a model that simulates only glucose-insulin bonds and to a model that has a significant number of nonlinearities in its structure and simulates a real object — a virtual patient. The corresponding glycemic profile at different values of the upper permissible limit and various amount of carbohydrate components in the food are shown (Fig. 5 a,b), where



a)



b)

Fig. 5**, **a, b. Glycemic profiles obtained on models of varying complexity

solid curve — the solution using a complex model with a large number of nonlinearities Maxmod, dashed curve — a model that simulates only the glucose-insulin interaction — Midimod, dash-dotted curve — analytical solution of the problem — Minimod.

Small discrepancies in the solutions of the forecasting problem obtained on at MAXMOD (virtual patient) model and MIDIMOD, an approximation model reproducing glucose-insulin bonds, indicate that it reproduces dynamic properties, even in the zeroth approximation. The profile obtained by analytical formulas differs more significantly, especially on the decline of the glycemic curve. But, in the key points, highs and lows, these discrepancies are not significant and are within measurement errors. This expected result can be considered a disadvantage, but it is compensated by a fairly simple computational procedure for obtaining compensatory doses of insulin, which are virtually indistinguishable from those used by insulin-dependent patients.

CONCLUSIONS

The proposed hierarchical modeling technology, based on the use of mathematical models of varying complexity, allows to conduct a complex of simulation studies to correct glycemia in diabetes at the preclinical and pre-ambulatory stages. During the simulation of forecasting procedure, configuration discrepancies of the glycemic profile obtained from different models were detected, but they are within the margin of error and reproduce the main trend in the dynamics of glycemia during meals and insulin injections. The calculated bolus doses of insulin are almost identical to those used by insulin-dependent patients. The simplicity of calculations using analytical formulas can be a prerequisite for the implementation of the algorithm in special-purpose portable autonomous devices, or in applications for Android OS.

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ІЄРАРХІЧНЕ ІМІТАЦІЙНЕ МОДЕЛЮВАННЯ. АЛГОРИТМ ПРОГНОЗУВАННЯ ГЛІКЕМІЧНОГО ПРОФІЛЮ У РАЗІ ДІАБЕТУ

Вступ. Цукровий діабет (розповсюджене хронічне захворювання) потребує пожиттєвого лікування і як будь-яке хронічне захворювання вимагає регулярного контролю і самоконтролю у домашніх умовах. Революційні зрушення у контролюванні глікемії у діабетичній терапії відбулися завдяки розроблення давачів безперервного моніторингу глюкози крові (БМГК), які можуть майже безперервно вимірювати концентрацію глюкози у підшкірній клітковині. Найпоширеніші перешкоди на шляху використання БМГК є пов'язаними з високими витратами на пристрої і відсутністю страхового полісу на їх закупівлю, передбачувана неточність давача і втома пацієнта від тривоги, яка пов‘язана з неприязню до носіння пристроїв. Отже, давачі — це добре, але вони є дорогими, незручними і не всім доступними. Тож важливим завданням залишається постійний пошук альтернативних рішень.

Мета роботи — показати можливість використання технології ієрархічного моделювання для розроблення і дослідження алгоритму прогнозування глікемічного профілю як, певною мірою, альтернативи давачам неперервного контролю за умови обмежених нерегулярних вимірювань.

Результати. Розроблено програмно-алгоритмічну структуру для реалізації концепції ієрархічного моделювання. Показано можливість проведення досліджень на моделях різної складності. Синтезовано алгоритм інсуліно-глюкозо-толерантного тесту. Розроблено процедуру прогнозування добового глікемічного профілю за аналітичними формулами, яка надає можливість оцінити тенденцію динаміки глікемії як доповнення до нерегулярних вимірювань глюкози глюкометром. Проведено імітаційне дослідження, результатом якого є візуалізація глікемічного профілю на тлі передбачуваного регламенту прийому їжі і отриманих за аналітичним алгоритмом компенсувальних доз інсуліну.

Висновки. Запропонована технологія ієрархічного моделювання, яка базується на використанні різних за складністю математичних моделей, дає змогу проводити комплекс імітаційних досліджень корекції глікемії у разі діабету на доклінічному і доамбулаторному етапах. Внаслідок імітації процедури прогнозування виявлено розбіжності конфігурації глікемічного профілю, отриманого за різними моделями. Цей очікуваний результат компенсується за рахунок досить простої обчислювальної процедури отримання компенсувальних доз інсуліну, які практично не відрізняються від тих, що застосовують інсулінозалежні пацієнти. Простота обчислень за аналітичними формулами може бути передумовою для реалізації алгоритму в портативних автономних пристроях спеціального призначення або у смартзастосунках під ОС Андроїд.

Ключові слова: *цифрова медицина, ієрархічне моделювання, система регуляції глікемії, алгоритми ідентифікації, прогнозування, керування, імітаційні доклінічні випробування.*

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INFORMATION TECHNOLOGY FOR FORMING A PERSONAL MOVEMENT REHABILITATION PLAN AFTER A STROKE

Introduction. *Stroke ranks second in the list of major causes of death and is the leading cause of disability in Ukraine. Synthesis of innovative technologies that help to movement restoration after stroke is an urgent scientific and practical task.*

The purpose *of the paper is to synthesize the information technology for forming a personal movement rehabilitation plan after a stroke on the basis of quantitative assessment of movement deficit according to the evidence criteria.*

Results. *The technology for information support for forming a movement training personal plan to restore movements after a stroke has been developed. This technology is implemented by the specialized software module "MovementRehabStroke 1.0" for information and consulting support to the physician in determining the plan: movements, programs, movements training duration based on electromyostimulation and / or biofeedback.*

The structural and functional model of the operator (physician) and software module "MovementRehabStroke 1.0" interaction has been developed. This module consists of a graphical interface and basic information modules: Database, Module "MovementTestStroke 1.1" for quantitative assessment of movement deficit and Module for forming the personal movement training plan. The interface provides the interactive mode of work with information modules for operator.

An algorithm has been developed for the operation of specialized software module "MovementRehabStroke 1.0" in researching on the formation of a personal training plan for patient movements based on indicators of quantitative assessment of movement deficit, which is provided by the information module "MovementTestStroke 1.1" and information received from a personal electronic medical record (EMR) of the patient: indicators of neurological status, concomitant diseases etc.

Conclusions. *The obtained results will contribute to the creation of a new class of mobile means of digital medicine — mobile applications installed in the structure of the smartphones for movements assessment after a stroke, forming the personal rehabilitation plan, and assessment of rehabilitation results.*

Keywords: *information technology, digital medicine, software modules, stroke, movements, diagnostics, rehabilitation, personal plan, structural and functional model, algorithm, electrical stimulation, biofeedback.*

INTRODUCTION

Up to 150,000 strokes occur each year in Ukraine and more than 100,000 people die from cerebrovascular disease and stroke. This disease can cause disorders or loss of movements, vision, speech and mental functions. In addition, stroke dramatically increases the risk of dementia. Of particular concern the increase in stroke rates among people of working age: about a third of all strokes occur before the age of 60 and only a small proportion of stroke survivors return to work.

The World Health Organization (WHO) estimates that stroke events in EU countries are likely to increase by 30% between 2000 and 2025 [1]. In Europe the Stroke Action Plan 2018-2030 was approved.

The experience of many countries shows that quality care for stroke patients can significantly reduce the risk of premature death or acquired disability.

The relevance and social significance of scientific researches, which results are presented in the paper, are determined by the synthesis of innovative technologies, methods and means that contribute to the movements' rehabilitation after a stroke.

PROBLEM STATEMENT

The main purpose of the rehabilitation process is applying the methods and means that mobilize, launch and enhance patient's reserves, aimed at restoring the affected or lost functions adequately to their state at each rehabilitation stage taking into account the general patient's state, conco-mitant diseases etc. Stroke care should be a continuous sequence of individual treatment and rehabilitation measures up to the maximum restoration of affected or lost functions. Therefore, the movement deficit diagnostics after stroke at each rehabilitation stage, the use of methods and means for quantitative assessment of motor dysfunctions, which make it possible to perform an in-depth analysis, to identify the specifics and secondary prevention of motor dysfunctions as well as assessment of the effectiveness of rehabilitation, play an important role.

Quantitative assessment of movement deficit, which is built using modern intelligent information technologies (IIT) based on evidence criteria, plays an important role in digital medicine. This assessment supports the physician to reduce the error in assessing the course and effectiveness of rehabilitation process. And it is the basis for synthesis of the mobile means for information and consulting support the physician in formation and adjustment of personal plan for affected movements' restoration at each rehabilitation stage.

The quantitative assessment of hand movement deficit during purposeful find motor hand training to restore speech is of particular importance. It makes it possible to study and compare the restoration dynamics of affected fine motor hand movements with the restoration dynamics of speech in case of motor or motor-sensory aphasia after a stroke.

The clinical testing results of proposed new technique for quantitative assessment of movement deficit [2] in the study of their restoration dynamics by TRENAR® technology became the basis for a specialized digital medicine's software module "MovementTestStroke 1.0" for movements diagnosing [3]. This module is made in the software environment Visual Studio 2013, programming language — C#. It is installed in the PC structure [4].

The purpose of the paper is to synthesize the information technology for forming a personal movement rehabilitation plan after a stroke on the basis of quantitative assessment of movement deficit according to the evidence criteria.

INFORMATION SUPPORT FOR FORMING A PERSONAL MOVEMENT REHABILITATION PLAN AFTER A STROKE

Information support for forming the personal movements trainings plan with the purpose of their restoration is implemented by the specialized software module "MovementRehabStroke 1.0" for information and consulting support to the physician in forming such a plan: movements, programs and movements training duration, which is based on methods of electromyostimulation and / or biofeedback by “TRENAR”® technology. The basic factors in forming the personal movement training plan are informative indicators of quantitative assessment of movement deficit, muscle tone, which are determined by a specialized "MovementTestStroke 1.1" software module, as well as indicators of the patient's neurological status, information on concomitant diseases. These indicators determine the movements to be trained, their training duration, as well as the permission / limitation for training the forced muscle contractions by program electrical stimulation method or for training the voluntary contractions by biofeedback method.

The structural and functional model of interaction of the operator (physician) and specialized "MovementRehabStroke 1.0" software module for information and consulting support to the physician in forming the patient’s personal movements training plan after a stroke is presented (Fig. 1).

The software module "MovementRehabStroke 1.0" consists of the graphical interface and the software module objects — the basic information units: I – Database, II — Module for quantitative assessment of movement deficit "MovementTestStroke 1.1", III — Module for forming the personal movement training plan (Fig. 1).

These information modules are designed as separated units with complete functionality and are directly connected with the graphical interface. The interface provides the interactive mode of work with information modules for operator. The software implementation of "MovementRehabStroke 1.0" is the Microsoft Visual Studio 2013 environment, C # programming language. It is installed in the PC structure.

Information module I "***Database***" consists of two main components: "*Patients list*" and "*Patient’s account (personal electronic medical record)*". It is designed to store the information about each patient who has already passed or is passing the rehabilitation for the first time.

The "Patients list" component contains a tabular list, in which each patient is represented by express information record (hospitalization date, patient’s surname-initials-sex, medical record number, physician's surname).

The operator checks (1) on the interface the presence of the right patient in this list by the object-oriented programming (OOP) methods. In case of patient’s absence the operator adds to this list patient’s express information from the medical record according to standard — form 003/o "Medical card of the in-patient", and also inputs all information from this medical record (neurological status, concomitant diseases etc.) to ***Database***'s component "*Patient's account*".

The component "*Patient's account*" receives the specialized information:

- the prohibitions / limitations for movements training (e.g., acute period of illness, diabetes mellitus on decompensation, the artificial cardiac pacemaker presence, etc.), marked by the operator;

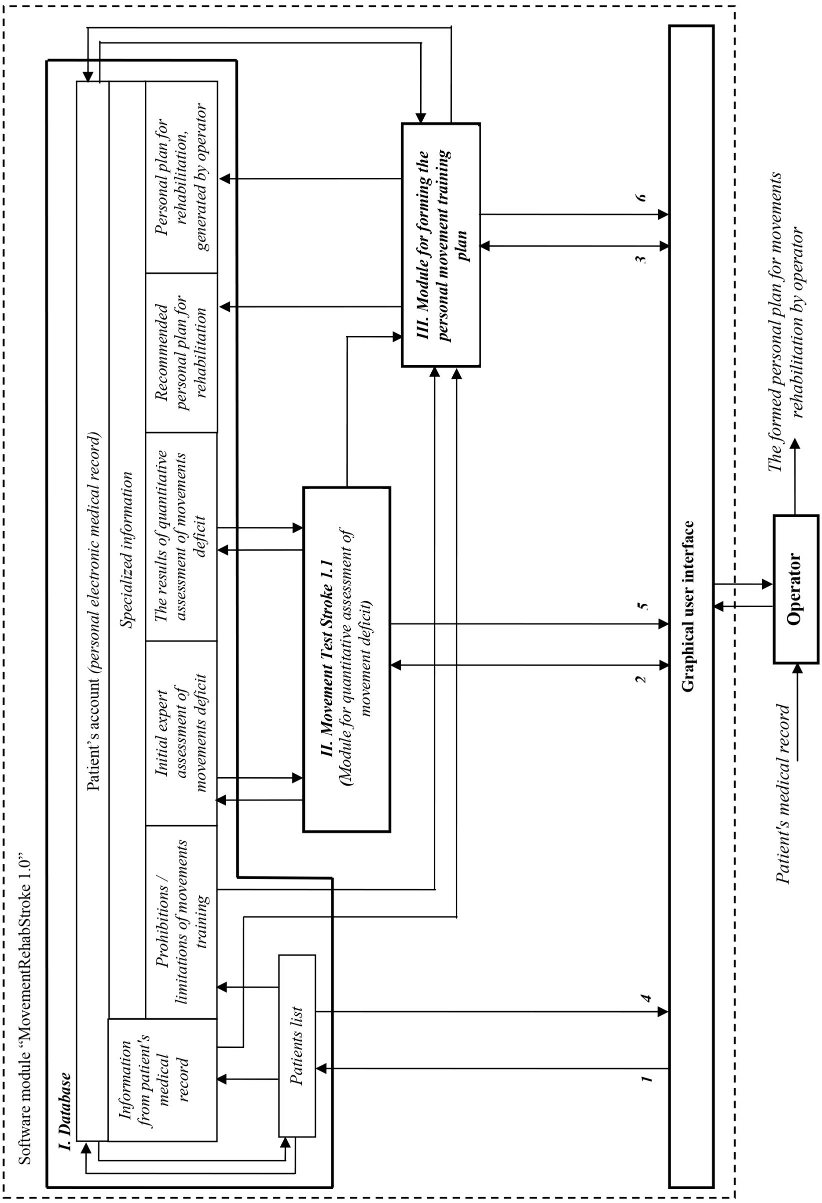

Fig. 1. Structural and functional model of interaction of the operator and software module "MovementRehabStroke 1.0". 1–6 markings are in the text

- initial expert assessment of movements deficit and results of quantitative assessment of movement deficit before and after rehabilitation from ***information module II*** (***Module for quantitative assessment of movement deficit***);

- the personal plans for movements rehabilitation (recommended and generated by the operator) from the ***information module III*** (***Module for forming the personal movement training plan***). This information is also stored in relevant clusters of the ***Database***'s patient's personal electronic medical record (EMR).

At the request of the operator (1), the interface displays (4) complete information from the patient's personal EMR — information from the medical card and specialized information.

Information module II — Module for quantitative assessment of movements deficit "***MovementTestStroke 1.1***" contains tables for expert assessment of movements deficit of upper and lower limbs at the individual joints level according to the main evidence criteria (muscle strength, movement's volume) [5]; for assessment by additional evidential criteria of fine motor hand (contrasting the thumb, flexing the hand's fingers in fist, the hand's main motor function (capturing), the hand's fingers extension) [3, 6] (Table 1) and walking (walking shape); as well as for assessment of muscle hyper- or hypotone [3, 5, 7] according to the Protocol for quantitative assessment of movements deficit of patient after a stroke [3].

The difference in fine motor hand assessment is in introduction of additional evidence criterion — the hand's fingers extension, which is important both for forming the personal plan of its training and to assess the fine motor hand restoration, associated with the speech restoration [8] according to the Table 1. These relevant changes are introduced in the previously developed Protocol [3]. It is this introduction of additional evidence criterion that differs the information module for quantitative assessment of movement deficit "***MovementTestStroke 1.1***" from the previously developed "***MovementTestStroke***" [3].

Expanding the criteria number for deficit assessment of affected hand supports the in-depth analysis of deficit. It is important for forming the personal fine motor hand training plan and for restoration of various aspects of its function, including speech restoration in case of motor or motor-sensory aphasia. Movement restoration of affected hand is of particular importance, after all most common deficit after a stroke is hemiparesis of contralateral upper limb, with more than 80 % of stroke patients experiencing this condition acutely and more than 40 % chronically [9].

The operator calls (2) on the interface the relevant expert assessment tables and performs with their application the initial expert assessment of patient's movement deficit according to the evidence criteria, expressed in points.

The operator receives (5) the results of quantitative assessment of patient's movement deficit (integrated quantitative assessment of the deficit, paresis degree, value and gradation of movement restoration efficiency) according to the OOP methods based on initial expert assessment from the ***information module II*** (***Module for quantitative assessment of movement deficit***).

The initial expert assessment and the results of quantitative assessment of movement deficit are stored EMR clusters ("*Initial expert assessment of movements deficit*" and "*The results of quantitative assessment of movements deficit*") in ***Database.***

Table 1. The fine motor hand assessment by criteria

Points / Criterion	Contrasting of the thumb	Flexion of the hand's fingers in fist	The hand's main motor function (grasping and holding objects)	The hand's fingers extension
5	Reaches the base of all fingers	Full fingers flexion in formed fist	The main function is saved completely	Full fingers extension
4	Reaches the base of all fingers (without holding the base)	Full fingers flexion in slightly opened fist	Grasping and holding of big objects are saved, grasping of small objects (with no hold function) is available	Significant fingers extension. The open fist volume is 75–90% of the norm.
3	Reaches the base of fourth finger	Limited fingers flexion in moderately opened fist	Grasping and holding of big objects is available, grasping of small objects is complicated	Moderate fingers extension. Hand is in the half-opened fist form.
2	Reaches the base of third finger	Moderate fingers flexion without fist formation	Grasping of big objects without their long and strong holding is available, grasping of small objects is impossible	Slight fingers extension. Hand is in the slight-opened fist form.
1	Reaches the base of second finger	Slight fingers flexion	Grasping and holding both big and small objects are impossible; the additional function of supporting and pressing the object is saved	Partial fingers extension. Hand is in the closed fist form.
0	Contrasting is impossible	No fingers flexion	Grasping and holding both big and small objects are impossible	Fingers extension is impossible. Hand is in the closed fist form.

Information module ***III*** "***Module for forming the personal movement training plan***" is designed for information and consulting support to the physician in forming the personal movements training plan, which is most effectively activates the additional reserves of the patient's organism to restore the movements.

This information module receives information on concomitant diseases, the emotional and volitional sphere state and prohibition / limitation factors of movements training from the relevant clusters of patient's EMR in ***Database***, the initial expert assessment of movements deficit and the patient's paresis degree from module for quantitative assessment of movements deficit "***MovementTestStroke 1.1***".

This module contains OOP methods, which determine the permission / limitation / prohibition for movements training based on certain factors, and permitted movements, methods, programs and movements training duration based on the initial expert assessment of patient's movement deficit; adjust these indicators based on concomitant diseases and the emotional and volitional sphere state; distribute methods, programs, movements and their training duration by priority according to the relevant decision rules.

Submitting the priority to method, training program comes from the principle of activating the additional reserves of organism for movement restoration at the current patient's rehabilitation stage. The priority for movement depends on motor disorders depth, but if patient has motor aphasia elements, then fine motor hand movements training gets a higher priority. The main factors of training duration are the patient's general condition, concomitant diseases, individual sensitivity to electrical stimulation, emotional and volitional sphere state etc.

The operator is issued (3) by notification and the patient's session ends in case of movements training complete prohibition factors are present in patient. In case of movements training limitations, the program continues to work with taking it into account.

The recommended personal rehabilitation plan according to priority of its components (methods, programs, movements and their training duration) is output for the operator on the interface (3) and also recorded in EMR cluster "*Recommended personal rehabilitation plan*" ***(Database)***.

The operator checks (3) the recommended personal plan and optionally calls up complete patient information, which is displayed (6) on the interface. Operator marks (3) in this plan concrete movements, programs and movement training duration, i.e. forms a personal plan for movements training at this rehabilitation stage. Using OOP methods, the personal plan is generated by the operator to the EMR cluster "*Personal plan for rehabilitation, generated by operator*" (***Database)*** and also is displayed as a text file on the interface (6).

The operator begins training the patient's movements at certain rehabilitation stage according to generated personal rehabilitation plan. After completing the movement training sessions, the operator diagnoses the patient's movements and determines the rehabilitation effectiveness.

ALGORITHM FOR FORMING A PERSONAL REHABILITATION PLAN

Algorithm for operation of specialized software module "MovementRehabStroke 1.0" for information and consulting support to the physician in researching for forming the patient's personal movements training plan based on expert and quantitative assessment of movements deficit, determined by specialized "MovementTestStroke 1.1" software module, with taking into account patient's neurological status, concomitant diseases, emotional and volitional sphere state etc. (Fig. 2).

According to the structural and functional model (Fig. 1), the module operation begins with loading the patients list, checking the presence of right patient in the list by the operator. If the list is not yet been created or no such patient exists, the operator inputs express information from that patient's medical record to create or update the patient list. At the same time, a personal electronic medical record (EMR) of the patient is created. After data input, the operator returns to the updated patients list.

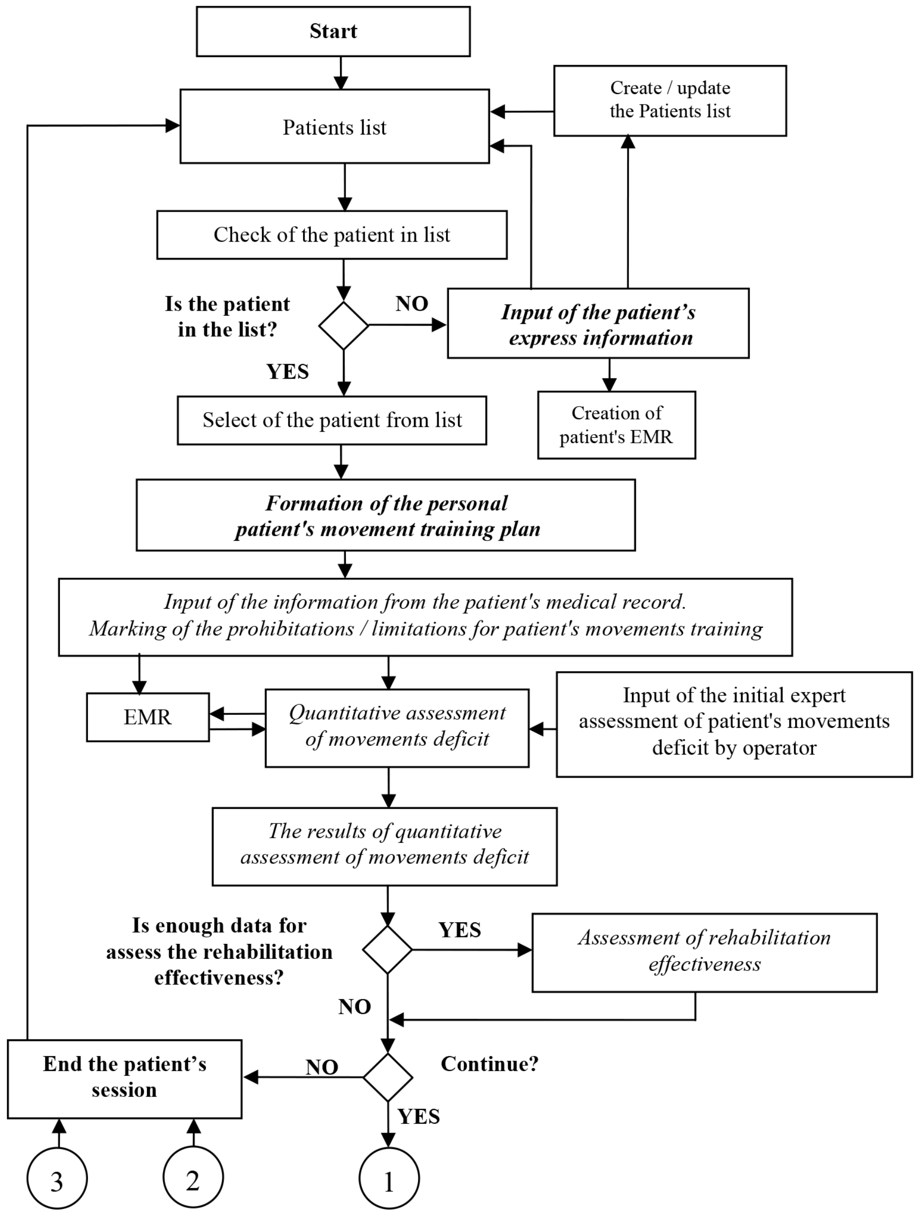

Fig. 2a. Algorithm for forming a personal movement rehabilitation plan: description of the patient's general state, assessment of movement deficit and rehabilitation effectiveness

Forming the patient's personal movements' rehabilitation plan begins with input of the information by the operator from the patient's medical record: neurological status, emotional state, concomitant diseases, as well as marking the prohibitation / limitation factors of movements training. The information is recorded in the patient's EMR.

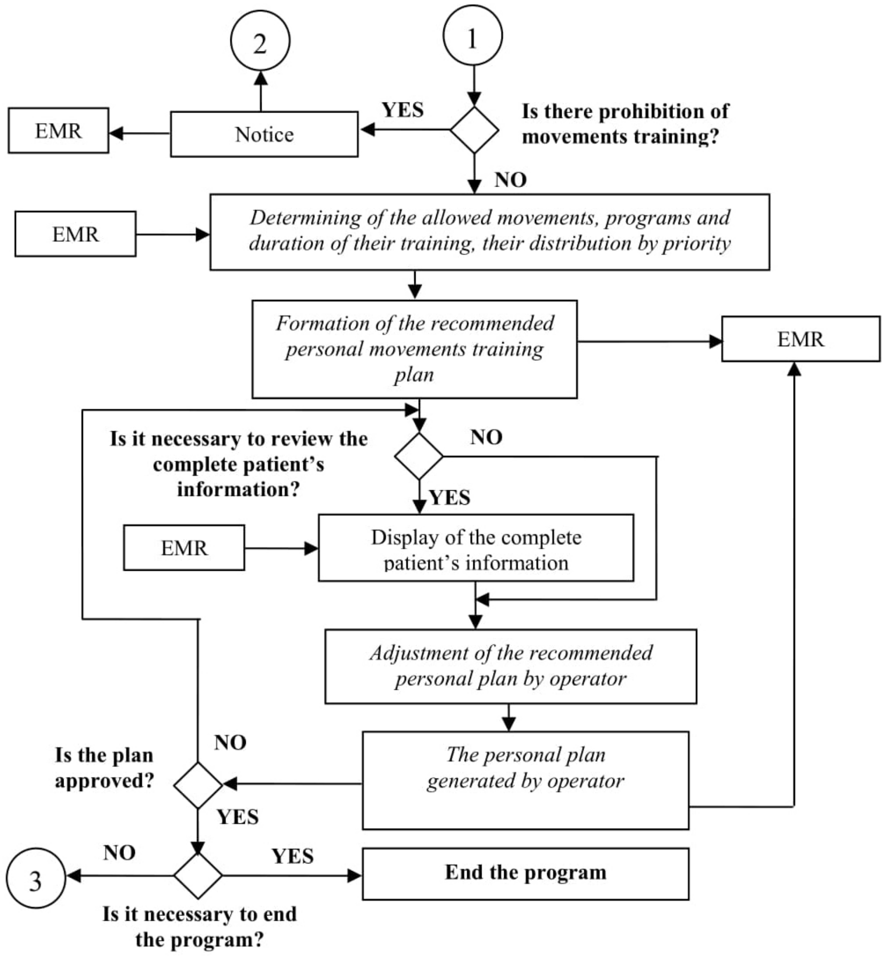

Fig. 2b. Algorithm for forming a personal movement rehabilitation plan: recommended and finally generated by operator plans

The next step is the movement deficit diagnostics. The operator inputs the initial expert assessment of movement deficit of patient's upper and lower limbs' selected departments at joints level, hand and walking. The program calculates and displays the results of quantitative assessment of movement deficit to the operator. The obtained information is recorded in the patient's EMR.

The rehabilitation effectiveness is quantitatively assessed at the end of patient's rehabilitation course. The operator is provided with quantitative and verbal characteristics of efficiency.

The patient session ends if only a quantitative assessment of movement deficit is required.

In case of forming the personal movements' rehabilitation plan there is a check of the permission / limitations / prohibition to perform the trainings based on prohibition / limitation factors of movements' trainings. If there is a movement training prohibition, the patient session ends, the operator is given the prohibition notice, which is recorded in the patient's EMR.

Forming the personal movements rehabilitation plan continues in case of training permission. The recommended personal movements' rehabilitation plan — permitted movements, methods, programs and movement training duration, which are distributed by priority, is output to the operator. This plan is recorded in the patient's EMR.

The operator after reviewing the plan adjusts it by marking the concrete movements, methods, programs and movement training duration. At the same time, operator's choice is based on complete information on the patient, which he can view optionally. The personal plan generated by the operator is also recorded in the patient's EMR and is displayed to the operator in the text file form. If the operator doesn't approve this plan, it is possible to correct it with rewriting in the patient's EMR. Finally the patient's personal movements training plan generated by the operator is that plan, according to which the movements are trained at this rehabilitation stage.

Then the operator either ends the session with the current patient or ends the program.

The patient's rehabilitation course ends with a diagnostics — the quantitative assessment of rehabilitated movements deficit with the rehabilitation effectiveness assessment.

It should be noted that the formed personal movements training plan at a certain rehabilitation stage needs to be updated at the following stages.

CONCLUSIONS

Theoretical and practical bases of synthesis of information technology for forming a personal movement rehabilitation plan for patients after a stroke have been developed. The information technology is implemented by the specialized tool of digital medicine — software module "MovementRehabStroke 1.0".

This module consists of a graphical interface and basic information modules: Database, Module "MovementTestStroke 1.1" for quantitative assessment of movement deficit and Module for forming the personal movement training plan. The software implementation of modules of both the "MovementRehabStroke 1.0" and "MovementTestStroke 1.1" is the Microsoft Visual Studio 2013 environment, C# programming language. They are installed in the PC structure.

The information module for quantitative assessment of movements deficit "MovementTestStroke 1.1" implements in an interactive mode a complete computational research algorithm of motor dysfunctions after a stroke. It provides the operator with distributed and integrated quantitative assessment of deficit of limb movements, their departments, fine motor hand, walking, muscle tone on the main and additional evidence criteria. The proposed approach in digital format provides an opportunity to perform the in-depth analysis, identify the disorders specificity for forming the personal rehabilitation plan, secondary prevention of disorders, rehabilitation effectiveness assessment.

The module operation is verified in clinical settings (23 patients after ischemic stroke). Expanding the range of additional evidence-based criteria for fine motor hand function assessing — the hand's fingers extension is important both for formation of the personal training plan and for assessing the recovery of fine motor hand, which is associated with speech restoration.

The recommended personal rehabilitation plan by priority of its components (methods, programs, movements and their training duration) provides the operator with information and consulting support in formation (determination) of the personal movement training plan, which most effectively activates additional reserves of the organism to restore the movements, affected by pathology, at a certain rehabilitation stage and doesn't harm the general patient's condition.

Storing the complete patient's information — information from the patient's medical record and specialized information (quantitative assessment of movements deficit, movements' restoration personal plans — recommended and generated by the operator) — in the personal electronic medical record provides an opportunity to assess the rehabilitation effectiveness and its in-depth analysis.

The movements training personal plan needs to be regularly updated at various rehabilitation stages for the purpose of maximum or full restoration of motor and speech functions. The speech restoration in case of motor or motor-sensory aphasia is dependent on training and restoration of affected fine motor hand.

The obtained results will contribute to the creation of a new class of mobile means of digital medicine, installed in the structure of the smartphones for movements' assessment after a stroke, forming the personal rehabilitation plan and assessment of rehabilitation results.

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ІНФОРМАЦІЙНА ТЕХНОЛОГІЯ ФОРМУВАННЯ ПЕРСОНАЛЬНОГО ПЛАНУ РЕАБІЛІТАЦІЇ РУХІВ ПІСЛЯ ІНСУЛЬТУ

Вступ. Інсульт посідає друге місце у переліку головних чинників смерті і є провідною причиною інвалідності в Україні. Синтез інноваційних технологій, які сприяють відновленню порушених або втрачених внаслідок інсульту рухів — актуальне науково-прикладне завдання.

Метою статті є синтезування інформаційної технології формування персонального плану реабілітації рухів після інсульту на базі кількісного оцінювання їх дефіциту за доказовими критеріями.

Результати. Розроблено технологію інформаційного супроводження формування персонального плану тренувань рухів з метою їх відновлення після інсульту, яку реалізує спеціалізований програмний модуль «MovementRehabStroke 1.0» інформаційно-консультаційної допомоги лікарю у визначенні плану: рухи, методи (електроміостимуляція та / або біологічний зворотний зв'язок), програми, тривалість тренування.

Розроблено структурно-функціональну модель взаємодії оператора (лікаря) з програмним модулем «MovementRehabStroke 1.0», який складається з графічного інтерфейсу та головних інформаційних модулів: Бази даних, Кількісного оцінювання дефіциту рухів «MovementTestStroke 1.1», Формування персонального плану тренування рухів. Інтерфейс забезпечує оператору діалоговий режим роботи з інформаційними модулями.

Розроблено алгоритм роботи спеціалізованого програмного модуля «MovementRehabStroke 1.0» у проведенні досліджень з формування персонального плану тренувань рухів пацієнта за показниками кількісного оцінювання дефіциту рухів, які надає інформаційний модуль «MovementTestStroke 1.1», та інформації, що надходить з персонального електронного медичного запису (ЕМЗ) пацієнта: показники неврологічного статусу, супутні захворювання тощо.

Висновки. Отримані результати сприятимуть створенню нового класу мобільних засобів цифрової медицини — мобільних застосунків у структурі сучасних смартфонів для діагностики рухів після інсульту, формування персонального плану реабілітації, оцінювання її ефективності.

Ключові слова: *інформаційна технологія, цифрова медицина, програмні модулі, інсульт, рухи, діагностика, реабілітація, персональний план, структурно-функціональна модель, алгоритм, електростимуляція, біологічний зворотний зв'язок.*

ДО УВАГИ АВТОРІВ!

У журналі надано результати досліджень у галузі 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:

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