Designing Intelligent Systems with Integrated Spatially Referenced Data

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***Abstract*—The paper is devoted to the issues of representation, integration and processing of spatially referenced data in intelligent systems built on the principles of ostis-systems.**

***Keywords*—OSTIS, intelligent system with integrated spatially referenced data, semantic model, question language, design process automation**

I. Introduction

Large sets of spatially referenced data accumulated by mankind, their representation and storage through the created cartographic services [1]–[3], the development of remote sensing technologies [4] have contributed to the creation and development of applied geoinformation systems for various purposes.

Modern geographic information systems are computer systems that provide input, manipulation, analysis and output of spatially referenced data about the territory, social and natural phenomena in solving tasks related to inventory, analysis, modeling, forecasting and management of the environment and territorial organization of society

Since the above tasks are intelligent, such systems belong to the class of intelligent systems with integrated spatially referenced data (ISRD).

The currently offered ISRD development tools are not sufficiently interoperable due to the lack of unification of knowledge of subject areas for the benefit of which application systems are designed, ontologies of terrain objects and phenomena, and temporal components.

It is obvious that for a fixed territory the same spatially related data are used in different application areas: epidemiology, construction, environmental protection and nature management, land relations, creation of digital twins of enterprises, mobile robotics systems, etc., which determines that it is necessary to harmonize the ontologies of subject areas with the objects of terrain and phenomena inherent in a given territory, thus ensuring a vertical (subject-oriented) level of design. On the other hand, when designing ISRD for a new territory, the basic functional requirements are preserved and it is necessary to take into account not only the previous experience of system design, but also to use previously designed functional components, i. e. we are talking about the horizontal level of ISRD design when the territorial area is expanded and systems are designed for new territories.

The third aspect is the temporal component, relevant for retrospective analysis and modeling, thus ensuring the creation of dynamic ISRD that can deal with terrain objects and phenomena within a specific time period.

Therefore, the constant evolution of models and tools for ontological description of subject areas using spatial and temporal components, heterogeneity of spatial components and ambiguity of temporal components, poses new challenges in terms of interaction, integration and interoperability of different types of knowledge used in ISRD by integrating subject area ontologies (vertical level), extending systems at the horizontal level to new territories and time intervals, re-using

The necessity of solving the indicated problems determines the demand for intelligent systems with integrated spatially referenced data and indicates the existence of scientific and technical problem of intellectualization of systems with integrated spatially referenced data, and also becomes relevant to create the development tools themselves, which ultimately provides information support and automation of the activities of developers of application systems.

Within this article, fragments of structured texts in the SCn-code [5] will often be used, which are simultaneously fragments of the source texts of the knowledge base, understandable to both human and machine. This allows making the text more structured and formalized, while maintaining its readability. The symbol ":=" in such texts indicates alternative (synonymous) names of the described entity, revealing in more detail certain of its features.

II. Knowledge-based approach in the tasks of representation, integration and processing of spatially related data

The importance and necessity of analyzing data in space and time is primarily to discover hidden connections and patterns that may not be obvious at first glance. Representation of spatial data, correlating them with objects on the ground and time intervals provides opportunities to determine cause-and-effect relationships, to identify groups of similar data, and to predict future events.

On the one hand, the representation, integration and processing of spatially referenced data is the task of a corresponding class of systems called geographic information systems (GIS). On the other hand, the focus on using spatially referenced data to establish semantic links between spatially referenced data and the knowledge of the subject areas for which the GIS is being developed indicates the need to use artificial intelligence technologies and design intelligent systems.

It is noted in the work [6] that at the current level of development geographic information systems have become practically the main tool for modeling natural, economic, social processes and situations, tracing their relationships, interactions, predicting further development in space and time, and most importantly a means of providing (supporting) decision-making management. Modeling in geographic information systems is based on databases and knowledge bases. The former integrate digital cartographic, aerospace, statistical and other data reflecting the spatial position, state and attitude of objects, and the latter contain sets of logical rules, information, concepts necessary for modeling and decision-making. At the same time, GIS is a special technology based on computer complexes and software tools.

Consequently, from the very definition of GIS follows the need to implement intelligent tasks: analysis, modeling, forecasting and environmental management, because all these tasks are intelligent and require decision support in their implementation, and systems that use spatially referenced data belong to the class of intelligent systems with integrated spatially referenced data (ISRD).

In the past decade, remote sensing data have been the main source of new data about the Earth, which necessitates the creation of an information system with specialized services that allow scientists and specialists to perform thematic processing of remotely sensed data by changing the data processing parameters in a certain way and to analyse the obtained information independently [4]. At the same time, large crowdsourced geographic datasets have been generated about the Earth today as a result of the observed web phenomenon known as Volunteered Geographic Information (VGI) [7] through the development of spatial information systems and web mapping projects, the main ones being:

- Yandex search and information mapping service [2];
- a non-commercial web-mapping project to create a detailed free and free geographical map of the world OpenStreetMap (OSM) by the community of participants — Internet users [1];
- Google Maps is a set of applications built on top of the mapping service provided by Google [3].

The [8] argues that the growth of web services and applications for geographic information systems has made large archives of spatial data available over the Internet. Significant advances in GIS web service development technologies have resulted in several examples of mapping and graphics services that conform to web service standards and provide geospatial data and digital maps to enterprise developers. Thus, both government surveying and mapping services and private sector enterprises have recently experienced a surge in the development of web services and web-based applications for GIS, making large archives of spatial data available over the Internet.

In this regard, the role of the map as an image-sign geoinformation model of reality for quick and adequate perception of information is acquired. Creation of maps in electronic form, using GIS–technologies, is the most important task of modern society, because it is the map that becomes the tool with which a person can make a decision, from the simplest to the most complex, even in emergency situations. Accordingly, the society makes more and more demands to maps, the user, referring to the map, wants to receive reliable information and from a huge array of data to choose only the information that would be more suitable for making the right decision [9].

In addition, new and more sophisticated data collection technologies (knowledge bases based on wiki technologies, classifiers, natural language parsing, etc.) are now available. The large amount of accumulated geospatial data generated by Earth observation satellites as well as ground-based devices and sensors offers enormous potential to address global social issues related to natural disasters, health, transportation, energy and food security [10], [11]. Interoperability is particularly important as the level of cooperation between information sources at national, regional and local levels increases, requiring new methods to develop interoperable geographic systems [12]. Therefore, the use of terrain objects as integrating elements in information systems is essentially interdisciplinary in nature, as they integrate research in economics, ecology, climate forecasting, terrain development, formation of optimal routes, and more.

In the industry of geoinformation systems development nowadays there is a need in their intellectualization, i. e. in solving problems traditionally related to geoinformatics with the use of artificial intelligence methods. First of all, these are the tasks of intelligent search. Existing instrumental GIS, which are the means of development of applied GIS, do not solve the problems of intelligent search for a number of reasons, among which we will emphasize the following:

- practically all of them are based on internal (closed) formats of spatial data representation, and exchange open formats serve only as a means of map data exchange between different GIS tools;
- thematic data are mapped to specific spatial objects

and exclude the possibility of establishing links and relationships between such data;
- implementation of applied tasks of geoinformatics is carried out in internal programming languages, thus only simplifying access to spatial data, and the map serves as a means of visualization.

In the field of GIS development it is necessary to emphasize the problem of formation of cartographic images from information resources, for the solution of which the methods of dynamic representation of spatial data in GIS [13] are proposed, as well as the unsolved to date problem of information integration.

Thus, a group of international geographic and environmental scientists from government, industry, and academia brought together by the Vespucci Initiative for the Advancement of Geographic Information Science, and the Joint Research Centre of the European Commission [14], argue that despite significant progress, the ability to integrate geographic information from multiple sources is very limited and in order to facilitate such integration, an understanding of the statistical challenges of integration at different scales is needed, as well as the study of linguistic services

A mathematical model is proposed to facilitate the integration of spatial information and attribute data, which enabled the researcher to reduce the time to obtain data for management decision making in municipal services [15].

It should be noted that the need for information integration requires semantic geo-interoperability and harmonized understanding of the semantics of geodata [16]. Interoperability is an indicator of effective communication between systems [17]–[19].

On the other hand, known technologies of designing intelligent systems use cartographic materials, as a rule, in the form of raster images, i. e. there is no possibility to consider a map as a set of geographical objects with specified topological and subject-oriented (depending on the type of map) relations, while it is argued in the paper [9] that we need new maps, the content of which is supplemented with spatial knowledge, corresponding to the subject area for the preparation of spatial maps.

Besides, for a fixed territory the same objects of terrain and phenomena are used in different application areas: epidemiology, construction, environmental protection and nature management, land relations, etc., which determines the necessity to harmonize the ontology of subject areas with the objects of terrain and phenomena inherent in a given territory, thus providing a vertical (subject-oriented) level of GIS design.

Note that when designing a GIS for a new territory, the basic functional requirements are preserved and it is necessary to take into account not only the previous experience of GIS design, but also to use previously designed functional components, i. e. we are talking about the horizontal level of GIS design, when the territorial area is expanded and systems are designed for new territories.

The third aspect is the temporal component, relevant for retrospective analysis and modeling, thus providing a dynamic GIS that can deal with terrain objects and phenomena within a specific time period.

Currently proposed GIS tools have «weak» compatibility due to the lack of unification of subject knowledge with ontologies of terrain objects and phenomena, as well as with temporal components.

Known research on the integration of spatial data and domain knowledge to ensure semantic interoperability has been conducted for systems based on the Semantic Web technology stack RDF, RDFS, OWL and the Web Ontology Language OWL provides advanced capabilities for describing the subject areas of interacting systems and provides machine-interpretable definitions of fundamental concepts in the subject area and the relationships between such concepts in the ontology.

Recently, due to the development of Semantic Web technology, the key element of which is ontologies, it has become possible in GIS to emphasize the semantics of subject knowledge, to integrate and merge different datasets in related fields, to establish subject rules and their recording using RDF (Resource Description Framework) [20]–[22]. This capability certainly enhances the capabilities of GIS technologies. However, in order to do so, several important tasks must be solved. These are, first, justifying the use of tools to integrate spatial data and subject knowledge [23], and second, computing the similarity between geospatial objects that belong to different data sources [24]–[26].

For example, the paper [27] states that there are research problems related to the integration of different types of geographic information. The authors propose to base the GIS architecture on ontologies acting as a system integrator in order to ensure smooth and flexible integration of geographic information based on its semantic value. In this approach, the ontology system is a component, such as a database or knowledge base (in general case, an information component), interacting to achieve the goals of the geographic information system, and viewing the ontology, allows the user to obtain information about the existing (formalized) knowledge in the system. The use of several ontologies eventually allows to extract information at different stages of classification, i. e. for different types of information used for the purposes and in the interests of GIS. These ideas are developed in the works of [28]–[30].

The process of ontology development is called ontology engineering and according to the concept of ontology engineering, ontologies must be developed before they can be used in a GIS. Thus, a GIS is based on a subject area described initially by an ontology model, with ontologies acting as a tool for knowledge generation [31].

At present, scientific areas are developing so-called Smart-systems aimed at qualitative improvement of technical and economic indicators within the subject area. The application of geoinformation technologies for scientific research in the subject areas in conjunction with traditional tools, methods and models of artificial intelligence allow obtaining qualitatively new scientific results, as well as aimed at reducing the time of searching for acceptable solutions for the set tasks. At the same time, the authors pay special attention to the integration of terrain objects and data and knowledge in system research of a particular subject area.

Thus, Massel L. V. et al. proposed a methodical approach to the integration of remotely sensed earth observation data based on the methods of data and knowledge integration in energy system research [32], [33]. For this purpose, the authors developed a theoretical model of hybrid data based on the fractal stratified model (FS-model) of information space.

The hybrid data model is based on the development of a system of ontologies of the remote sensing information space, including a metaontology describing the layers of the FS model and ontologies of individual layers (subject areas).

As a result of ontological modeling, an ontological space including a set of ontologies is created, which should allow working not only with data, but also with knowledge, including descriptions of scenarios of various situations, models and software complexes, and integrate them into the IT infrastructure of interdisciplinary research.

The Open Geospatial Consortium (OGC) GeoSPARQL standard supports representing and querying geospatial data on the Semantic Web [34], [35]. GeoSPARQL defines a vocabulary for representing geospatial data in RDF, and it defines an extension to the SPARQL query language for processing geospatial data. In addition, GeoSPARQL is designed to accommodate systems based on qualitative spatial reasoning and systems based on quantitative spatial computations.

Thanks to Semantic Web technology and ontology engineering, as well as standardization processes for ontology development in the web ontology language, the problem of declarative knowledge representation has been solved, which contributes to the understanding of map objects and allows querying spatial data explicitly represented in spatial data storage formats [36], [37].

However, subject domain formalization and ontology engineering is only one step in intelligent systems design technology and by itself is not sufficient for knowledge-based inference, since ontology engineering allows for the description of declarative knowledge of subject domains, whereas procedural knowledge allows for the design of problem solvers and knowledge-based inference.

The above-mentioned possibilities of the technology based on the semantic web have certainly contributed to the development of geographic information systems with the ability to process colossal volumes of crowdsourced data. At the same time, decision making in problem domains of human activity requires obtaining an intelligent reference, i. e. actually solving a problem when the answer is not available in the datasets themselves or represented knowledge in the current version of the knowledge base or in the repository. A way of expressing such a need is the question [38]–[40]. In the process of communication there is always a context, which determines additional information that contributes to the correct understanding of the meaning of the message. Systems that are able to provide background information on the user's question belong to the class of intelligent help systems.

In intelligent reference systems, the problem is formulated in the form of a question, and the answer to the question requires specialized knowledge in science, technology, art, craft or other fields of activity, which is represented in knowledge bases. In other words, within the framework of the considered technologies it is necessary to first generate knowledge of the problem domain necessary for giving an answer. At the same time, the capabilities of knowledge bases of intelligent systems allow not only to represent and structure knowledge about the surrounding world, but also to quickly obtain and form this knowledge about it, thus satisfying the information need of the user [41].

One of the key features of an intelligent system is that the user has the ability to formulate his/her information need. The peculiarity of information representation in the knowledge bases of intelligent systems simplifies the formation of the user's information need, since the presented information in the knowledge bases is already structured and the relations defined on a certain concept, in respect of which the question-problem situation is solved, are known. In the work [42] it is shown that the question-problem situation cannot be solved within the framework of formal logic and the nature of the question can be understood in the system of subject-object relations. In connection with the fact that at formation of knowledge bases of intellectual systems the formation of subject-object relations within the given subject area takes place, thereby simplifying the expression of information need by the user by means of knowledge representation languages.

The proposed approaches to optimize information retrieval currently lie in the development of question-answer systems (QAS) in which user questions are matched with the required information. Such systems carry out a dialog between the user and the system in the form of the procedure "QUESTION-Answer" in the mode when the user asks a question and the system answers [43], [44]. A clear advantage of question-and-answer systems is the possibility of linguistic processing of user questions [40], [45]. At the same time, semantic classification of question-answer texts contributes to the isolation of specific types of relations, question types and answer classes [45]–[48]. The conceptual basis for formalizing questions in QAS is the question language and erotetic logic, which allows us to specify question-answer relations [39]. Currently known question-answer systems, which are capable of parsing a question and matching the answer with the help of a natural language analyzer, are Mulder [49], AllQuest (http://www.allquests.com) and AskNet Global Search (http://www.asknet.ru).

However, such systems are focused only on analyzing and detecting semantic relations between subject domain objects in indexed texts. This fact imposes the following limitations [50]:

- there is no possibility to strictly formally establish semantic relations between objects in the text;
- it is impossible to generate a response to the user when such a response does not exist in the indexed texts or in the current information state of the system;
- does not support questions to identify correspondences and analogies between objects and concepts.

The elimination of these limitations requires the creation of the next generation of question-and-answer systems — intelligent reference systems (IRS), or intelligent question-and-answer systems (IQAS). In such systems, the emphasis shifts from textual representation of information to the formation and use of knowledge spaces. The combination of work on the representation of knowledge in the IQAS knowledge base, the processing of this knowledge by special operations of the knowledge processing machine, and the interaction of the end user with the IQAS requires the coordination of all three stages of work. Thus, for the mass development of IQASs in various subject areas, a design technology for intelligent question-answering systems is needed in which, first, all design stages are coordinated, second, the languages of knowledge representation are compatible with the languages of knowledge processing and the languages of user communication with the IQAS

Despite the successes in the development of geoinformation services and their standardization, creation of ontologies of subject areas, knowledge about terrain objects and phenomena as integrating elements of subject areas, due attention has not been paid and not investigated semantic compatibility of GIS components and applied GIS, procedures for integration of spatial knowledge with knowledge of subject areas have not been established. In this regard, the actual task is:

- designing spatial ontologies and based on them solving the problem of integration of knowledge of subject areas and spatial relations, as well as solving the problem of metadata management and improving search, access and exchange in the conditions of growing volumes of spatial information and services provided by multiple sources of geoinformation;
- realizing knowledge inference using spatial and thematic information and meeting the information needs of users using question language;
- development of cartographic interface as a natural way for human to present information about terrain objects and phenomena, based on the formal description of the syntax of the map language, and providing both understanding of the semantics of terrain objects and phenomena immersed in knowledge bases, and providing changes in the state of knowledge bases.

Thus, the constant evolution of models and tools for ontological description of subject areas using spatial and temporal components, the heterogeneity of spatial components and the ambiguity of temporal components, poses new challenges in terms of interaction, integration and compatibility of different types of knowledge used in GIS by integrating subject area ontologies (vertical level), extending GIS subsystems at the horizontal level and utilizing new territories and time intervals

Analysis of human activities and works in the field of geoinformatics shows that further development in this area lies in the field of intellectualization of geographic information systems [51]–[58].

intelligence of systems with integrated spatially referenced data

⇒ *subdividing**:

{• *use of digital cartographic material and Earth remote sensing data in problem-oriented areas, creation of systems for pattern and image recognition from Earth remote sensing data [4], [59], [60]*

• *planning of actions in a dynamically changing situation under incomplete or fuzzy data using expert knowledge [61]–[63]*

• *Analysis of emergency situations and preparation of materials for decision-making on prevention or elimination of their consequences, creation of expert systems for forecasting the occurrence and development on the ground of man-made and natural situations: floods, earthquakes, extreme weather conditions (precipitation, temperature), epidemics, spread of radionuclides, chemical emissions, meteorological forecast, etc. [64]*

- *creation of decision support systems for applied geoinformation systems of territorial planning and management [65]–[68]*
- *development of diagnostic expert systems for geological exploration and underground hydrodynamics [69]–[71]*
- *control systems of transportation and transportation processes [72]–[74]*
- *logistic planning, creation of expert systems and software tools for enterprise and building management [75]–[77]*
- *creation of monitoring, control and navigation systems [78]*
- *creation of expert systems and software tools for geodata analysis [79]*
- *resolution of land disputes [80]*
- *medico-geographical assessment of environmental impact on human health [81]*
- *retrospective analysis of events and inventory of cultural heritage [82]–[86]*
- *creation of digital cartographic information banks with remote access to them, spatial information management based on spatial data portals, creation of information retrieval systems on Earth sciences and geoinformatics [87]–[90]*
- *development of support systems for pedagogical, educational and training activities, as well as training systems using spatial information [91]–[97]*

}

The intellectualisation of geographic information systems implies [51], [98]:

- the possibility of end-user communication with the system in the language of questions [99];
- the use of various interoperable problem solvers with the possibility of explaining the obtained solutions;
- use of cartographic interface for visualisation of initial data and results.

Realising the capabilities of intelligent reference geographic information systems can be done by:

- knowledge base management systems,
- intelligent search,
- interoperable problem solvers,
- intelligent map interfaces,
- expert systems in various fields of human activity,
- decision support systems,
- intelligent assistance systems

Full solution of the above tasks requires the use of open systems standards, the use of ontologies of terrain objects as integrating elements of different subject areas, communication of users with the system in the mode of question-and-answer system using the language of questions.

The technology that satisfies these requirements is the open complex technology for developing intelligent systems based on semantic networks [100] (OSTIS technology — Open Semantic Technology for Intelligent Systems), the main provisions and principles of which are described in the work [101], the principles of creation and unified design models in the works [102], [103].

OSTIS technology is based on the following principles [104]:

- orientation on semantic unambiguous representation of knowledge in the form of semantic networks having basic theoretical-multiple interpretation, which provides problems of diversity of forms of representation of the same meaning, and problems of ambiguity of semantic interpretation of information constructions;
- the use of associative graph-dynamic model of memory;
- application of agent-based model of knowledge processing;
- realisation of OSTIS technology in the form of intellectual Metasystem IMS [5], which itself is built on OSTIS technology and provides design support for computer systems developed on OSTIS technology;
- ensuring in the designed systems a high level of flexibility, stratification, reflexivity, hybridity, interoperability and, as a consequence, learnability.

Systems built on this technology are called ostis-systems, and the universal abstract language of semantic networks (SC-code) or semantic code is used as a language tool for knowledge representation. In this case, knowledge bases of ostis-systems have a semantic representation, and the knowledge and skills interpreter is a collection of agents that process the knowledge base and manage situations and events in this knowledge base [104].

At the same time, the systems developed using this technology do not have the disadvantages of systems based on generative models (systems like Chat-GPT [105]), because it is not the generation of new data, which are similar to the training data, but the relationship between the actual data and knowledge of the subject area is established, which ensures the reliability of conclusions based on knowledge.

In order to realise these possibilities, reduce the labour intensity of building and modifying intelligent systems with integrated spatially related data, it is proposed to build a semantic model of ISRD based on spatial ontologies, to ensure communication between users of ISRD in a formal language of questions and to develop means of automation and information support of the design process of this class of systems, including the formation of components of the core of intelligent systems with integrated spatially related data.

An important point that reduces the development time of intelligent systems with integrated spatially referenced data on the one hand, and increases their functionality on the other hand, is the availability of tools for designing such systems. At the same time, the technology of designing intelligent systems with integrated spatially referenced data should be oriented to multiple use of functional components of the system in order to reduce the design and development time of application systems. Thus, this study is about the creation of automation and information support for the design of intelligent systems with integrated spatially referenced data.

The structure of the study is presented in Figure 1. The first (upper) level corresponds to the data and knowledge level, where the integration of subject matter knowledge with spatial data and knowledge takes place; the second (middle) level is the system level, which corresponds to the principles underlying the proposed approach; the third (lower) level is the application level and corresponds to the application systems developed on the basis of the models and tools proposed in the paper.

The models, software tools and means of automation and information support of design proposed in this paper are proposed to be developed as a part of the open complex technology for the development of intelligent systems based on semantic networks OSTIS.

Using the notation adopted in the design of systems using OSTIS technology, let us clarify the concept of an intelligent system with integrated spatially referenced data (synonymous with intelligent geographic information system).

intelligent system with integrated spatially referenced data
:= [intelligent geographic information system]
:= [an information system designed to provide answers to a user's question, the main object of study of which is knowledge and data on terrain objects, acting as an integration basis for solving applied tasks in various subject areas]
⊃ *intelligent ostis-system with integrated spatially referenced data*
  ⊂ *ostis-system*
    := [an intelligent system with integrated spatially referenced data, developed according to the principles of OSTIS technology]
    ⇒ *subdividing**:
      {• *knowledge base of intelligent ostis-system with integrated spatially-referenced data*
      • *problem solver for intelligent ostis-system with integrated spatially referenced data*
      • *map interface of intelligent ostis-system with integrated spatially referenced data*
      }

III. Semantic model of an intelligent system with integrated spatially referenced data

This work is based on the method of knowledge representation in the form of a homogeneous semantic network with basic theoretical-multiple interpretation, which allows not only to describe declarative knowledge of subject areas, but also procedures of their processing, i. e. we are talking about procedural knowledge, the interpretation of which is carried out in a special component — semantic problem solver.

Therefore, in this paper, the concept of an interconnected system of coordinated semantic models of intelligent systems proposed in the works [102], [103], [106]–[109] is further developed in a more complete realisation of a special class of intelligent systems - intelligent systems with integrated spatially referenced data. For this purpose it is necessary to form the core ISRD, which is based on the semantic model of this class of systems. Thus, it is necessary to describe the semantic model of the knowledge base of an intelligent system with inegrated spatial data, which includes the construction of geontology and necessitates the development of a model of integration of subject areas with spatial components of geoinformation systems, the semantic model of the ISRD problem solver and the semantic model of the ISRD user interface [98], [110]. In this case, the user interface is not a viewer of cartographic (spatial) data, but a component interfaced with the knowledge base, i. e. knowledge about space understood by the system with simultaneous updating of knowledge both in the knowledge base of the system and in the knowledge base of the user interface.

In order to ensure semantic compatibility, an ontology of spatial objects has been developed, the task of which is to clearly and unambiguously define the semantics of terrain objects and phenomena.

The ontology of spatial objects consists of two sections. The first section includes directly the ontology of terrain objects and phenomena. The second section contains semantic characteristics of such objects — special elements specifying spatial and semantic characteristics of terrain objects and phenomena.

In the ontology of terrain objects and phenomena the objects of classification are terrain objects and phenomena to which map objects correspond, as well as features (characteristics) of these objects.

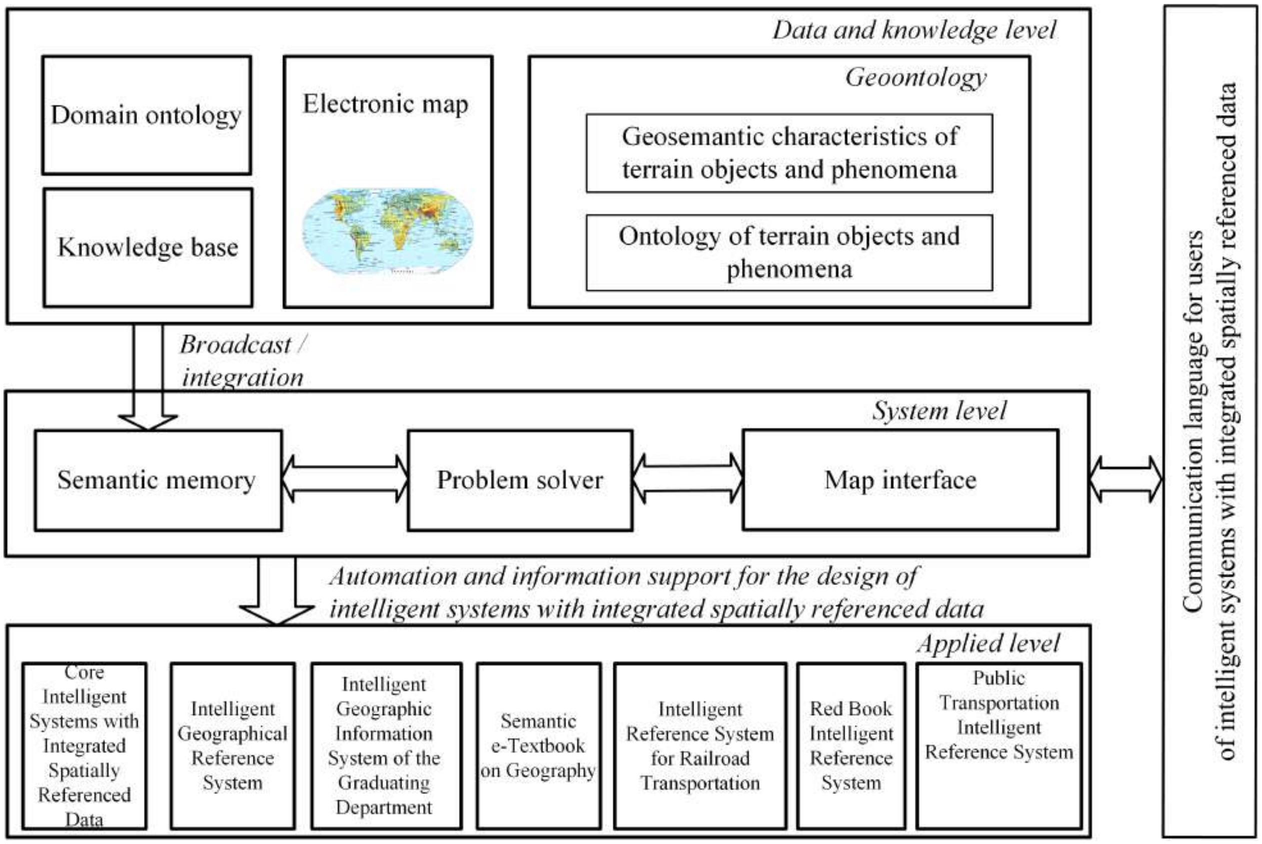

Figure 1. Structure of the study.

This section of the spatial object ontology presents classes of geospatial concepts of natural or artificial origin, natural phenomena that have common attributes (semantic attributes) characteristic of a certain *class of terrain objects* and describe the internal characteristics of the concept. Thus, *terrain objects* and *classes of terrain objects* are intended for different purposes. *Terrain objects* as physical elements themselves are formed in the knowledge base according to the specifications given in the ontology of terrain objects and phenomena. Accordingly, the knowledge base will store directly knowledge about a particular object, while in the terrain object ontology the terrain object is a concept and properties and relations defined on all objects of this type are established for it.

The characteristics of terrain objects are defined by the following types of relationships:

- *coordinate location of a terrain object* — geographic position, the location of a terrain object or phenomenon that is given in a geodetic coordinate system;
- *spatial relations* — a class of relations specifying the semantic properties of a terrain object in relation to other terrain objects and includes: *topological spatial relations*, *spatial ordering relation*, *relationship of principal directions of terrain objects*, *metric spatial relation*;
- *dynamics of the state of the terrain object* — a relation characterising the change of the state of the object in time.

spatial relations
⇒ *subdividing**:
{• *topological spatial relations*
• *spatial ordering relations*
• *metric spatial relation*
}

In order to determine the mutual spatial location of terrain objects depending on their type of localisation, basic *topological spatial relations* are established between instances of *terrain objects*:

- *inclusion**,
- *boundary**,
- *intersection**
- *adjacent**

Figure 2 shows schematically the possible variants of the *inclusion** relation with respect to area objects of the terrain.

To determine the spatial ordering of terrain objects,

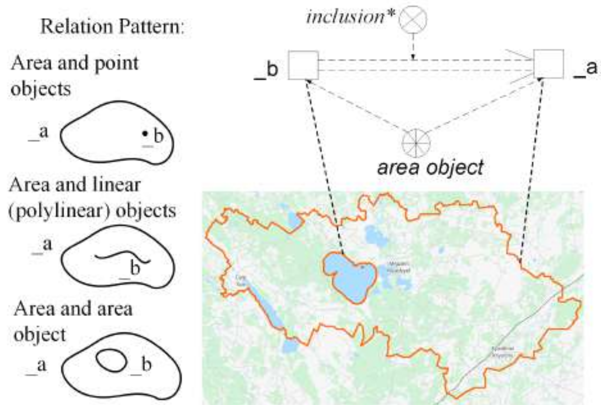

Figure 2. Establishing a topological relation “inclusion*”.

relationship of location of terrain objects and *relationship of main directions of terrain objects* are introduced, which allow to determine the mutual location of terrain objects, as well as to determine the geographical direction of one terrain object relative to another object.

In order to convey the dimensions of the distances between *terrain objects*, a *metric spatial relation* is introduced, which characterises the distance information between *terrain objects* and can be measured in units (kilometre, metre, etc.) or have a *scale metric spatial relation* (0-100 m., 100-500 m., etc.).

Terrain objects, instances of which are stored in the knowledge base, are an integration framework for different subject areas, allowing the same terrain objects to be used for different application tasks as shown in the figure 3.

In order to integrate knowledge of subject areas with spatial components of intelligent systems, a *stratified model of information space of terrain objects* is proposed, which is defined by a family of the following sets according to equation (1).

$$S^{\mu} = \{S_{\mathrm{SA}\mu}, S_{\mathrm{TO}}, E_{\mathrm{TO}}\}, \mu \in I, \qquad (1)$$

I – set of *subject areas*; $S_{\mathrm{SA}\mu}$ – ontology of the μ-th *subject area*; S_{TO} – ontology of *terrain objects*; E_{TO} – instances of *terrain objects*.

The layer of terrain object instances is an integrating layer with the knowledge of different subject areas in which the instantiated physical terrain objects and phenomena are already directly used. With this organisation of knowledge it is possible to repeatedly use the developed ontology of terrain objects and phenomena in different subject areas and, consequently, to solve different application problems.

The generalised structure of an intelligent system with integrated spatially referenced data is shown in Figure 4.

The problem solver is a collection of agents, which includes the following main agents: *computing geometric characteristics of terrain objects*; *determining the type of localisation of a terrain object*; *interfacing with various map systems and services, measurement systems and time intervals*; *establishing topological relations between terrain objects*; *verification of terrain objects knowledge base* for completeness of filling of knowledge bases with necessary terrain objects, correctness of values of semantic attributes of terrain objects entered into the knowledge base, correctness of characteristics of terrain objects entered or stored in the knowledge base.

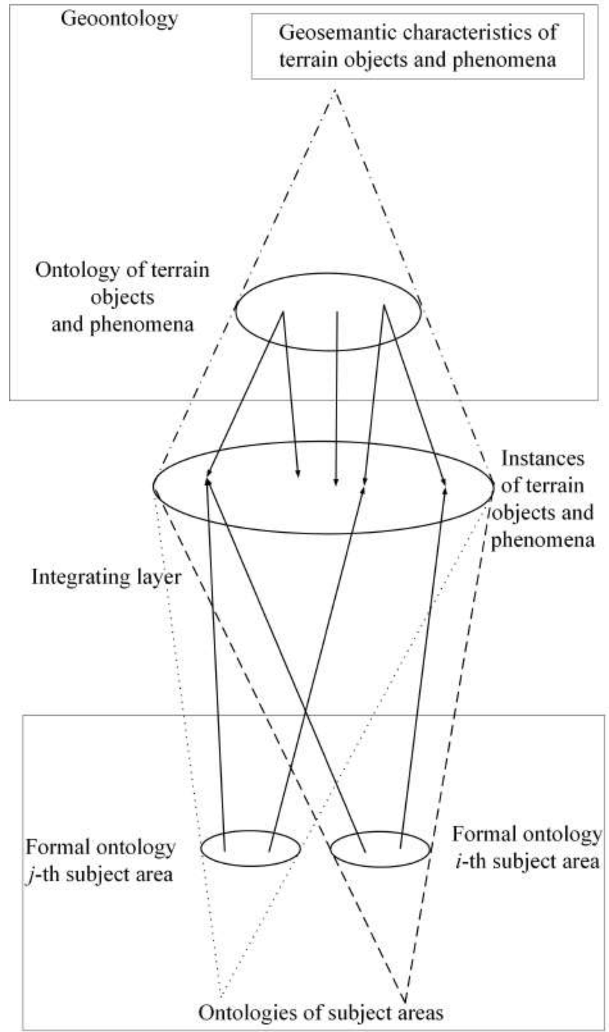

Figure 3. Integration of subject areas based on terrain objects.

The cartographic interface of an intelligent system with integrated spatially referenced data is considered as a particular type of user interface designed for visual display of terrain objects and phenomena in a formal map language. This language belongs to the family of semantic compatible languages and is intended for formal description of objects of terrain and phenomena, as well as relations between them in the systems of the intellectual system with integrated spatially related data.

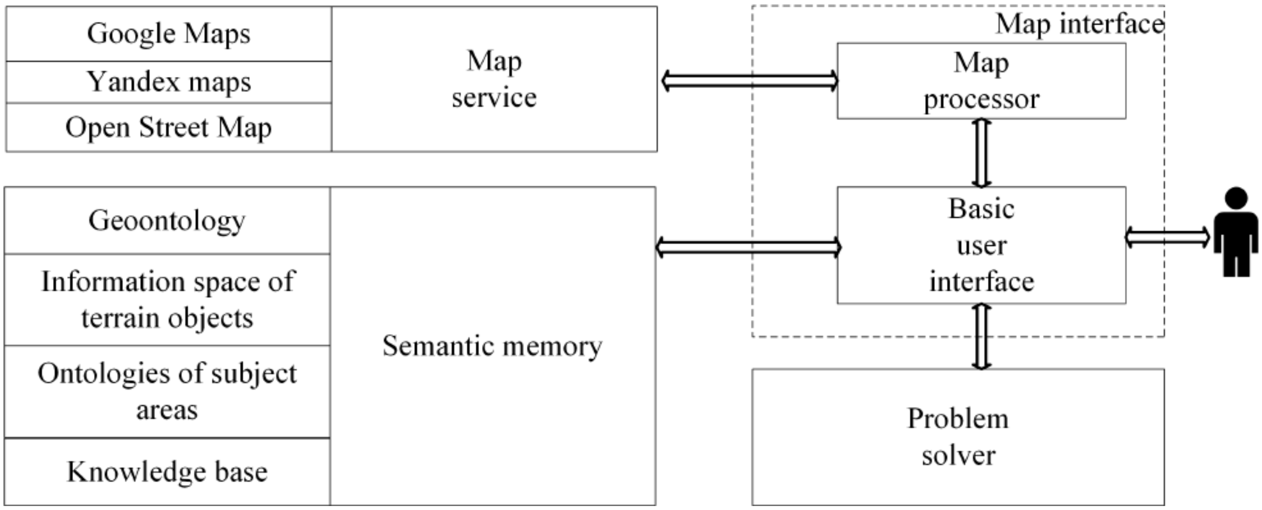

Figure 4. Structure of an intelligent system with integrated spatially referenced data.

It allows: to use minimum means for interpretation of given objects of terrain and phenomena on the map; to use the language of questions for intelligent systems; to reduce the search on the most part of given questions to the search of information in the current state of the knowledge base of the intelligent system with integrated spatially-referenced data.

IV. Language tools for communication between users of intelligent systems with integrated spatially referenced data

One of the key features of an intelligent system is that the user has the ability to articulate his or her information need. The way of expressing such a need is a question. The peculiarity of information representation in the knowledge bases of intelligent systems simplifies the formation of the user's information need, since the information presented in the knowledge bases is already structured and the relations defined on a certain concept, in relation to which the question-problem situation is resolved, are known. At formation of knowledge bases of intellectual systems the formation of subject-object relations within the given subject area takes place, thus simplifying the expression of information need by the user by means of semantic code [111].

The purpose of the question language and its subsequent development is to make it possible to understand the actions performed by the ISRD when forming an answer to a question. In the process of forming an answer to a question, the following options are possible:

1) the answer to the posed question exists in the knowledge base and a fragment of the knowledge base is localised in the context of the user's information need expressed by means of semantic code;
2) the answer is related to the resolution of some task situation, which is contained in the context of the question and the formation of the answer to the question is assigned to the problem solver.

In this regard, an intelligent system with integrated spatially referenced data is defined by the following set of systems according to equation (2).

$$S_{\text{IRSD}} = \{S_{\text{IIRS}}, S_{\text{AG}}\}, \tag{2}$$

S_{IRSD} – intelligent system with integrated spatially referenced data; S_{IIRS} – intelligent information retrieval system; S_{AG} – answer generation subsystem.

The intelligent information retrieval system is represented by a tuple of the following form (3).

$$S_{\text{IIRS}} : \{\{Q\}, \{A\}, \{F\}, \{UI\}\}, \tag{3}$$

S_{IIRS} – intelligent information retrieval system; $\{Q\}$ – set of questions; $\{A\}$ – the set of responses available in the current state of the system; $\{F\}$ – a set of operations of a problem solver that search for and generate answers to users' questions; $\{UI\}$ — a set of ways to visualise responses to the user.

The denotational semantics of a question language includes the classes of questions and the corresponding classes of answers needed to specify the wording of questions and their answers, as well as the classes of signs and relations that make up the structure of any question.

The following relations are introduced to systematise question types:

- *relationship within a given question* — a particular relationship between subject matter characters in the context of a question;
- *basic relation within a given question* — a class of relations uniting the relations in a given question, reflecting the same meaning and revealing a

certain feature of the signs of the subject area (state relation, action relation, composition relation, set-theoretic relation, temporal relation, spatial relation, quantitative relation, qualitative relation);
- *composition relation within a given question* — a stable combination of two action relations: *action directed to the question parameter* and *action directed to the answer to the question*.

Any question in the question language is a specification of an action to search for or synthesise knowledge that satisfies the information need of the user initiating the question. That is, a question is nothing but a task that expresses the user's need for some information, possibly stored or output in the knowledge base of an intelligent system. All the agents outputting answers to the question form a collective of agents and constitute a question language interpreter for intelligent reference systems with integrated spatially correlated data. Where each class of questions corresponds to certain agents realising the search or synthesis from the ISRD knowledge base of appropriate answers to the questions posed.

V. Design automation tools for intelligent systems with integrated spatially referenced data

We will refer to the means of automating the design of intelligent systems with integrated spatially referenced data as those that allow to improve the quality of designed systems and reduce the development time due to the repetition and compatibility of used components [112], [113]. In this case, we will consider as reusable components both fragments of knowledge bases, as well as problem solver agents and user interface components. The minimum set of components necessary for designing ISRD and based on them applied intelligent geoinformation reference systems will be called the ISRD core, which includes [114]:

1) Knowledge base components:
   - ontology of terrain objects and phenomena;
2) Problem solver components:
   - stack of mapping agents:
     - agents for calculating geometric features, localisation type agents,
     - agents for interfacing with different map systems and services, measurement systems and time intervals, topological linking agents;
   - search agents,
   - sophisticated search agents, Logical inference agents,
   - transaction calculation agents;
3) User interface components:
   - map interface:
     - work with point objects, linear and polylinear objects, area objects;
     - map viewer.

The formation of the knowledge base of the application ISDS is carried out in stages as shown in Figure 5.

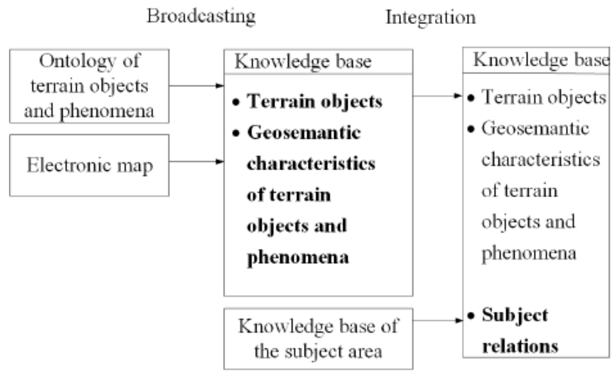

Figure 5. Formation of knowledge base of applied intelligent system with integrated spatially related data.

The first stage of formation of knowledge base of the applied intellectual system with integrated spatially related data is selection of data presented in the form of electronic map and translation into the knowledge base of terrain objects for a given territory. This stage is necessary for selection of terrain objects of a given territory in the interests of the application system. At this stage it is determined to which class the investigated terrain object belongs and, further, depending on the type of object, using the ontology of terrain objects and phenomena proposed in the paper, a fragment of the knowledge base corresponding to a particular physical terrain object in the semantic memory is formed. Thus, specific terrain objects are loaded into the knowledge base. At this stage, topological relationships between terrain objects are established in the knowledge base as illustrated in the example in Figure 2.

The second stage of knowledge base formation is integration with knowledge bases of subject areas. At this stage, knowledge of related subject areas is added, thus making it possible to set interdisciplinary links. At the same stage, homonymy in the names of geographical objects (toponymy) is removed, which makes it possible to avoid collisions in the knowledge base, when different localities belonging to the class of settlements correspond to the same sign in the knowledge base.

The means of automation and information support of ISRD design also include verification of knowledge bases of terrain objects and phenomena. Due to the specifics of development and operation of ISRD, it is necessary to ensure constant control of correctness and correctness of replenishment of the knowledge base with new terrain objects and updating of existing knowledge, i. e. it is necessary to ensure verification of completeness of filling the knowledge base with necessary terrain objects, correctness of values of semantic attributes of terrain objects entered into the knowledge base, as well as correctness of characteristics of terrain objects entered or stored in the knowledge base.

In order to develop ISRD for various application tasks, the design methodology of this class of systems is included in the means of automation and information support of design.

Stage 1: Deployment of basic software and information support for the design and operation of systems designed in accordance with the open integrated technology for the development of intelligent systems based on semantic networks.

Stage 2: Deployment of the components of the core of intellectual systems with integrated spatially correlated data. Installation of the developed components of the ontology of spatial objects, problem solver, including the main agents for processing spatially related data, question language interpreter, as well as software components of the mapping interface is carried out. The use of ISRD core components allows to create application systems with minimal functional purpose.

Stage 3: Formation of the subject area ontology. Formation of the ontology of the subject area in the interests of which the application system is being developed.

Stage 4: Broadcasting and loading of cartographic material into the knowledge base. Cartographic material is selected for a given area, translated and loaded into the knowledge base with the establishment of topological relations between the objects of the area using the ontology of spatial objects.

Stage 5: Formation of fragments of knowledge bases of the subject area. Filling of the knowledge base with knowledge of the subject area is carried out.

Stage 6: Integration of subject area knowledge bases with spatial knowledge. At this stage, the components of knowledge bases obtained at stages 4 and 5 are interlinked.

Stage 7: Development of problem solver components. If necessary, development of additional agents necessary for solving problems of the subject area is performed.

Stage 8. Verification of the developed components. At this stage the knowledge bases are verified by special verification agents.

Stage 9. Debugging of components. At this stage the components are debugged and errors are corrected.

At stages 3-9 of the design, the ISRD developer can decide to return to any previous stage, which corresponds to rapid prototyping technology, when a prototype of the system with minimal functionality is created and the functionality is subsequently increased. In this case, the prototype with minimal functionality is obtained after the 2nd design stage, i. e. after the deployment of the ISRD core components.

In accordance with the models and means of representation, integration and processing of spatially referenced data proposed in the work, means of automation of design of intelligent systems with integrated spatially referenced data, applied intelligent reference geoinformation systems on geography of the Republic of Belarus, graduating department, on public and railway transport, as well as semantic electronic textbook on geography have been developed.

The availability of developed application systems and analysis of the process of development of the mentioned intelligent reference geoinformation systems, software tools for their design, as well as means of design automation of the mentioned class of systems proposed in the work allow to unify and universalize to a high degree various components of intelligent systems with integrated spatially referenced data.

Thus, to develop a prototype of an intelligent reference geographic information system in the interests of a certain subject area, which allows simple navigation through the knowledge base, a ready-made ontology of terrain objects and phenomena, a set of information search agents and a stack of cartographic agents included in the corresponding libraries, as well as components of the cartographic interface - map viewer and map editor — can be used without any additions.

Based on the data presented in the studies [108], [109], time estimation for the development of the stack of map agents and map interface, and taking into account the number of used elements (fragments of knowledge bases, agents and ready-made user interface components) and time for their development the duration of application systems development is calculated by (4)

$$t_{pj} = \sum_{i=1}^{k} t_{fi} \cdot N_i + \sum_{i=1}^{l} t_{ai} \cdot P_i + \sum_{i=1}^{m} t_{ui} \cdot O_i, \quad (4)$$

t_{pj} - duration of development of the *j*th system (min); t_{fi} - duration of development of fragments of the *i*-type BR (min); t_{ai} - duration of development of *i*-type agents (min); t_{ui} - duration of development of the user interface of the *i*-type (min); *k* - number of types of database fragments included in the *j* system (pcs.); *l* - number of agent types included in the system *j* (pcs.); *m* - number of user interface types included in the system *j* (pcs.); N_i - number of fragments of the database of the *i*-type in the *j*-type system (pcs.); P_i - number of agents of the *i*th type in the *j*th system (pcs.); O_i - number of user interfaces of the *i*-type in the *j*-th system (pcs.).

Table I shows the indicators characterizing the stages of application systems development.

The average percentage of borrowing of knowledge base fragments, problem solver components and user mapping interface for existing systems without taking into account the complexity of development is calculated according to (5).

$$P_{\text{F}} = \frac{1}{k} \sum_{i=1}^{k} p_{\text{F}i}, \quad (5)$$

Table I
Indicators characterizing the stages of application systems development

Application system indicators	***System*** [a]	***System*** [b]	***System*** [c]	***System*** [d]	***System*** [e]	***System*** [f]	***System*** [g]
Time spent on formation of knowledge base fragments, min.	28224	56565	31896	42075	32391	42408	35991
Time spent on formation of borrowed fragments of knowledge bases, min.	0	28224	28224	28224	28224	28224	28224
Share of development time of borrowed knowledge base fragments to the total number of knowledge base fragments, %	0	50	88	67	87	67	78
Time spent on development of task solver agents, min.	11700	13500	13740	14160	11700	10260	12180
Time spent on development of borrowed task solver agents, min.	0	7860	10860	13500	10260	10140	10620
The proportion of development time of borrowed agents to the total number of problem solver agents, %	0	58	79	95	88	99	87
Time spent on the development of the map interface, min.	12600	12600	12600	12600	12600	12600	12600
Time spent on development of borrowed components of the map interface, min.	0	12600	12600	12600	12600	12600	12600
The proportion of development time for borrowed components of the mapping interface, %	0	100	100	100	100	100	100
Time spent on system development, min.	51924	82665	58236	68835	56691	65268	60771
Time spent on development of borrowed system components to total development time, min.	0	48084	51084	53724	50484	50364	50844
The proportion of the development time of borrowed components to the total system development time, %	0	58	88	78	89	77	84

[a] Core Intelligent Systems with Integrated Spatially Referenced Data.
[b] Intelligent Geographical Reference System.
[c] Intelligent Geographic Information System of the Graduating Department.
[d] Semantic e-Textbook on Geography.
[e] Intelligent Reference System for Railroad Transportation.
[f] Red Book Intelligent Reference System.
[g] Public Transportation Intelligent Reference System.

p_{Fi} – the share of development time of borrowed F-type components (knowledge base fragments, problem solver components, user map interface) to the total number of F-type fragments of the i-th application system (%); k – the number of application systems using borrowed components (pcs.).

Substituting into the formula (5) the obtained experimental data from the table I we obtain the average percentage of borrowing fragments of knowledge bases, problem solver agents and map interface for existing systems without taking into account the complexity of their development:

$$P_{\text{KB}} = \frac{1}{6}(50 + 88 + 67 + 87 + 67 + 78) = 72\ \%,$$
$$P_{\text{PS}} = \frac{1}{6}(58 + 79 + 95 + 88 + 99 + 87) = 84\ \%,$$
$$P_{\text{PS}} = \frac{1}{6}(100+100+100+100+100+100) = 100\ \%.$$

The obtained experimental data show that the development of each next system is significantly simplified due to the use of ready universal components. The number of components borrowed from the core of intelligent systems with integrated spatially referenced data shows that the current version of library filling allows to compose a significant part of the system components from ready-made components. In the future it is planned to actively replenish the libraries with new components.

As time passes and the production of intelligent systems with integrated spatially referenced data evolves, the number of such components will increase, consequently leading to an even higher borrowing rate.

A pessimistic approach was used to determine the reduction in time costs due to borrowing at this point in the library's development by estimating the least amount of borrowing in the systems in place today.

According to the results obtained, the availability of automation tools can reduce the duration of development of the class of systems in question by at least 58 % (min (58 %; 88 %; 78 %; 89 %; 77 %; 84 %)) due to the borrowing of previously developed components for developed application systems, which confirms the effectiveness of the methodology used. The average percentage of borrowing for existing systems without taking into account the complexity of the development of knowledge base fragments is 72 %, problem solver components — 84 %, user mapping interface – 100 %.

Conclusion

Let us list the main points of this paper:

- The problems solved by systems with integrated spatially referenced data have been analysed and the relevance of designing this class of systems has been substantiated. Based on the systematisation of tasks solved by ISRD, it is shown that one of the directions of increasing the efficiency of information-computing means use is the intellectualisation of systems with integrated spatially related data. It assumes: integration of knowledge of subject areas with spatial data and knowledge; possibility of communication of the end user with the system in the language of questions; use of various semantically compatible problem solvers with the possibility of explanation of the obtained solutions; use of cartographic interface for realisation of communication of the user with ISRD.

- Using ontological engineering the problem of semantic compatibility of knowledge of subject areas is solved and the model of integration of subject knowledge with objects of terrain and phenomena is proposed. Formal means have been developed to provide description of terrain objects and phenomena in knowledge bases of intelligent systems with integrated spatially related data taking into account semantics of links between terrain objects and phenomena, as well as knowledge of subject areas.
- The semantic model of ISRD including semantic memory, problem solver and cartographic interface is proposed, which unlike the known architectures of systems with integrated spatially related data allows integrating in the knowledge base the objects of terrain and phenomena of a given territory, translated into the internal language of the knowledge base, and the knowledge of different subject areas. Based on the formal description of the map language syntax, the cartographic interface provides a natural way for humans to represent information about terrain objects and phenomena and allows understanding the semantics of terrain objects and phenomena loaded into knowledge bases, as well as recording changes in the state of the ISRD knowledge base.
- A semantic model of user communication has been developed, in which interaction is carried out in the language of questions, semantically compatible with the languages of knowledge representation and processing, and designed to formally describe the search prescription in order to meet the user's information need. This allowed: to unify the form of questions and knowledge representation, with the help of which answers to the questions are constructed; to reduce the formation of answers to most of the given questions to the search of information in the current state of the knowledge base; to reduce the time to search for an answer in the knowledge base by the time required to parse the user's information request. Unlike existing approaches based on natural language processors, it does not require semantic parsing of the question sentence.
- The means of automation and information support of the process of design of ISRD are offered and their efficiency in the development of applied intelligent reference geoinformation systems is estimated. It is shown that the availability of automation tools can reduce the duration of the development of intelligent reference geographic information system by at least 58 % due to the borrowing of previously developed components, which confirms the effectiveness of the methodology used. The average percentage of borrowing for existing systems without taking into account the complexity of development of knowledge base fragments is 72 %, problem solver components – 84 %, user mapping interface – 100 %.

Acknowledgment

The author would like to thank the scientific teams of the Department of Intelligent Information Technologies of the Belarusian State University of Informatics and Radioelectronics for their help and valuable comments.

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ПРОЕКТИРОВАНИЕ ИНТЕЛЛЕКТУАЛЬНЫХ СИСТЕМ С ИНТЕГРИРОВАННЫМИ ПРОСТРАНСТВЕННО-СООТНЕСЕННЫМИ ДАННЫМИ

Самодумкин С. А.

Работа посвящена вопросам представления, интеграции и обработки пространственно соотнесенных данных в интеллектуальных системах и проектированию на основе предложенных моделей и средств прикладных интеллектуальных справочных геоинформационных систем, которые относятся к классу интеллектуальных систем с интегрированными пространственными данными (ИСПД). Основные положения данной работы:

- Проведен анализ задач, решаемых системами с интегрированными пространственно-соотнесенными данными, и обоснована актуальность проектирования данного класса систем. На основе систематизации задач, показано, что одним из направлений повышения эффективности использования информационно-вычислительных средств является интеллектуализация систем с интегрированными пространственно-соотнесенными данными, которая предполагает: интеграцию знаний предметных областей с пространственными данными и знаниями; возможность общения конечного пользователя с системой на языке вопросов; использование различных семантически совместимых решателей задач с возможностью объяснения полученных решений; использование картографического интерфейса для реализации общения пользователя с системой.
- С использованием онтологического инжиниринга решена проблема семантической совместимости знаний предметных областей и предложена модель интеграции предметных знаний с объектами местности и явлений. Разработаны формальные средства, обеспечивающие описание объектов местности и явлений в базах знаний ИСПД с учетом семантики связей между объектами местности и явлений, а также знаниями предметных областей.
- Предложена семантическая модель ИСПД, включающая семантическую память, решатель задач и картографический интерфейс, что в отличие от известных архитектур систем с интегрированными пространственно-соотнесенными данными позволяет интегрировать в базе знаний объекты местности и явления заданной территории, транслированные на внутренний язык базы знаний, и знания различных предметных областей. Основанный на формальном описании синтаксиса языка карт картографический интерфейс обеспечивает естественный для человека способ представления информации об объектах местности и явлениях и позволяет понимать семантику объектов местности и явлений, загруженных в базы знаний, а также фиксировать изменение состояния базы знаний ИСПД.
- Разработана семантическая модель общения пользователей ИСПД, в которой взаимодействие осуществляется на языке вопросов, семантически совместимом с языками представления и обработки знаний, и предназначенном для формального описания поискового предписания с целью удовлетворения информационной потребности пользователя, что позволило: унифицировать форму представления вопросов и знаний, с помощью которых строятся ответы на поставленные вопросы; свести формирование ответов на большую часть заданных вопросов к поиску информации в текущем состоянии базы знаний; сократить время на поиск ответа в базе знаний на время, необходимое для разбора информационного запроса пользователя, и в отличие от существующих подходов на основе естественно-языковых процессоров не требует семантического разбора вопросительного предложения.
- Предложены средства автоматизации и информационной поддержки процесса проектирования ИСПД и оценена их эффективность при разработке прикладных интеллектуальных справочных геоинформационных систем. Показано, что наличие средств автоматизации позволяет сократить продолжительность разработки интеллектуальной справочной геоинформационной системы как минимум на 58 % за счет заимствования разработанных ранее компонентов, что подтверждает эффективность применения использованной методики. Средний процент заимствования для существующих систем без учета сложности разработки фрагментов баз знаний составляет 72 %, компонентов решателя задач — 84 %, пользовательского картографического интерфейса — 100 %.

Received 01.03.2024