Research-related design systems*

Mykola Petrenko[1,*,†], Oleksandr Palagin[1,†], Mykola Boyko[1,†] and Kyrylo Malakhov[1,†]

[1] *Glushkov Institute of Cybernetics of the National Academy of Sciences of Ukraine, Ukraine*

Abstract

The integration of intelligent information systems into research projects has created the basis for the development of transdisciplinary ontology-oriented research-related design systems. These systems contribute to the creation of infrastructure and methodological support necessary for the convergence of knowledge from different fields to obtain new research results.

This study aims to investigate the creation and implementation of research design systems that include models and tools for ontological management, virtuality, and transdisciplinarity to support the design and development of high-tech objects of new technology.

The research employs intelligent information systems, including ontology-driven systems, data mining, and semantic text analysis, to support the iterative design process. A knowledge system framework is constructed, focusing on evolving research design processes and knowledge-based subsystems.

The study demonstrates the development of a new class of research-related design systems that support knowledge management, evolving in real time. The systems are shown to improve interdisciplinary collaboration, design efficiency, and integration of incomplete input information through semantic analysis and ontological frameworks.

Keywords

Ontological engineering, virtual paradigm, intelligent information systems for research-related design, personal knowledge base, smart systems

1. Introduction

The modern stage of development of science and its applications is clearly transdisciplinary in nature. This fact has necessitated the development of a rigorous methodology of transdisciplinary (TD) scientific research, the creation of TD-international centers and schools, and, finally, the determination of the place and role of informatics in the system-technological support of TD-research and the use of their results in solving global problems of modern civilization development. The TD-paradigm assumes the construction in the foreseeable future of a common scientific picture of the world or, what is the same, a unified TD-system of knowledge, providing formalized formulation and solution of specific tasks in the implementation of complex projects of high complexity, social significance, conflict and competitiveness.

2. Intelligent information systems for research-related design and their development

The development and application of intelligent information systems in various fields of human activity has led to the creation of a new class of intelligent information systems that combines the properties of transdisciplinarity, ontological management, united by the concepts of purposeful development and virtuality. This is the class of transdisciplinary ontology-driven research-related design systems. In addition to the tasks of infrastructural support for research, the tasks of their

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1* Corresponding author.

† These authors contributed equally.

petrng@ukr.net (M. Petrenko); palagin_a@ukr.net (O. Palagin); xeldag@ukr.net (M. Boyko); k.malakhov@outlook.com (K. Malakhov)

0000-0001-6440-0706 (M. Petrenko); 0000-0003-3223-1391 (O. Palagin); 0000-0003-1723-5765 (M. Boyko); 0000-0003-3223-9844 (K. Malakhov)

methodological support and ensuring the processes of integration, convergence, unified presentation of transdisciplinary knowledge, and operations on it come to the fore. A significant role is played by systematic training of skills and broadening the range of outlook of scientific researchers in order to ensure the quality of the concepts of deepening knowledge in a particular knowledge domain, on the one hand, and expanding the scope of the problem based on the reality of the unity of the world and the need to form a unified system of knowledge about the world, on the other (Palagin, 2013; Palagin, et al., 2024a, b).

One important type of scientific research is research design (R&D). A characteristic feature of R&D is that its main stages are associated with the process of describing the image of the designed object of new technology (ONT) in the absence of the object itself (Palagin, 2013). The design process itself is structured as a series of interactive procedures for attracting additional information and forming intermediate hypothetical options for a technical solution (TS), starting with the general concept (conceptual design stage), technical proposal and terms of reference (TP) (pre-design stage), and ending with the comparison of these options and the selection of the best one.

A technical solution is a systematic description of the projected object, the main components of which are the functional structure (or separately - functional and structural descriptions) and parametric characteristics.

Each iteration in the search for a technical solution is, in fact, a transformation of the descriptions of the design object with the involvement of additional information about the design object and the knowledge domain (KD) in general, as well as the knowledge and experience of the designer.

At the pre-design stage, there are two phases: conceptual and paradigmatic design (Palagin, 2016b). The first phase is about forming a set of initial concepts and judgments based on a conceptual model of the real world. The second phase is to generate a natural-language description of the designed product in the form of a technical specification. Its purpose is to form the primary image of the design object being created. In essence, this image is metaphorical, because its description is built by endowing a non-existent object with the properties that existing objects have. The formation of such images is carried out by building metaphorical models, on the basis of which the synthesis of the natural language description of the design object and the entire design process is performed. A metaphorical model is always the result of comparing an object with others based on their common features, using the knowledge and experience of the designer (subjective factor). The role of the latter, however, is less important, since its activity is based on a general conceptual model of the real world and the KD.

Based on the above, it is relevant to develop an information technology support system for the R&D process that inherits both the functions of research automation system and the functions of modern CAD. Such r research-related design systems (RDS) are characterized by a high degree of intellectualization at all levels:

– methodological;
– knowledge of the KD (with logical inference procedures);
– modeling and project description languages;
– the method of multi-criteria selection of alternatives;
– ensuring work with incompletely defined input information based on semantic analysis of texts.

The construction of an effective architecture of knowledge-based information systems for research design is seen as a way to constructively use such areas of modern computer science as:

– transdisciplinarity;
– knowledge processing;
– ontological concept;
– virtual paradigm and its applications (Palagin, 2013).

The generalized scheme of the functioning of an intelligent information computer system for research design can be expressed by the product chain: “input signal → knowledge system → reaction → decision”.

The basis of the subject activity of the RDS is the knowledge system, which is formed during the project implementation and determines technical solutions at all stages of design, and which can be represented as a subsystem of general knowledge of the KD that interacts with a set of knowledge subsystems corresponding to a particular project and a particular stage of design. Of interest is a new subclass of RDS that is just being formed – systems that have online self-development functions.

2.1. Evolving ontology-driven research-related design systems

As follows from the above, the peculiarity of the research design system, in particular, the evolving one (RDSE) is that the process of designing a given class of ONT using this system occurs simultaneously with the accompanying real-time development process of the R&D system itself and its functional subsystems, that is, the RDSE design process. Such systems are inherently two-process (P1, P2), in which the functions of the leading (P1) and the driven (P2) subsystems are interchanged (Palagin, 2016):

a) $P_1 = F(P_2)$; b) $P_2 = F(P_1)$, (1)

The function of knowledge-oriented development of RDSE based on a pre-formulated development strategy should be considered as the most intelligent in the class of systems of this type. In the simplest case, it can be reduced to increasing the existing knowledge (the well-known Brooks formula) (Palagin, 2006):

$$K(S) + \Delta I = K(S + \Delta S) \quad (2)$$

which is interpreted as follows. If a portion of information ΔI is added to the initial knowledge $K(S)$ of the information system under consideration, represented by some initial structure S, then the knowledge of the system will change:

$K(S) \rightarrow K(S + \Delta S)$. The case $\varphi(V) = \varphi_2(\varphi_1(V)) = ... = \varphi_1^* \varphi_2(V)$ means that the portion of information ΔI contains a portion of knowledge S that does not change the original structure , i.e., the system previously contained the knowledge represented in ΔI , perhaps only in a different form. The process described by expression (2) is based on the procedure of comparing the original structure of knowledge S with the structure explicitly or implicitly contained in ΔI . With regard to the ontological component of knowledge representation, this procedure ends with the addition of new elements to the sets X and R.

In general, the implementation of mapping $IS : \Delta I \rightarrow \Delta S$ is the main problem of knowledge discovery. It essentially boils down to the problem of managing the entire process of the RDSE functioning and is solved by applying the methods of semantic text analysis, data mining and ontology-driven systems. The latter are based on formal computer ontologies.

The main ontology-driven functions of the RDSE include (Palagin, 2016a):

– an effective compact representation of the knowledge system of a particular KD on the basis of modern information technologies (specification, conceptualization);

– reception and processing of signals from the outside world;

– search for information in the knowledge system of the KD (reference, training functions);

– search for necessary information on the Internet;

– formulation and solution of applied tasks in a given KD (scientific research, design of ONT and technologies, methods, techniques, and solution options);

– development of the system and obtaining new knowledge (or organizing existing knowledge, checking its consistency, correcting the category tree, etc.)

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It is relevant to note here that the ontological paradigm was formed and developed almost simultaneously with the paradigms of virtuality and transdisciplinarity. Today, concepts such as virtual world, virtual organization, virtual laboratory, virtual system, virtual addressing, etc. have become commonplace. A closer look at the virtual paradigm is nothing more than a type of the concept of evolving systems.

Virtual research environment is a set of networked tools, systems, and processes that support the research design process. It includes support tools for project administration, access to information resources, creation and use of databases and knowledge, support for the implementation of results and copyright protection, and collective online interaction of project participants. One example of promising virtual systems is the Virtual Research and Innovation Centers (VRIC), proposed in the 90s (Palagin, et al., 2003).

The main vector of the VRIC activities is aimed at implementing a new innovative strategy for R&D and research projects, which is based on the concept of "new product", clear formulation of scientific and practical problems, creation of organizational structures and determination of the type of management, combined with developed mechanisms to support the processes of formation and effective use of EI knowledge. A special place in the proposed innovation strategy is occupied by the regulation of the stages of the life cycle:

– innovation project management;

– commercialization of promising research works and projects;

– development of the infrastructure of science – production – education;

– effective interconnection of research and innovation principles.

Regarding the RDS, well-known method with the abbreviation of the name CESCF – the construction of an effective set of consumer features. The essence of the method is that, using the approaches of transformational and morphological synthesis, the process of finding technical solutions is performed as a sequence of procedures for finding clusters of ONT functions that are promising from the standpoint of improving the architecture of the designed object of market requirements, pricing, and promotion of a product (technology).

At one time, the method was tested when creating a class of computing equipment called "electronic harvesters."

The modern information and communication environment of the VRIC allows for the formation of structures with different functions and configurations based on the use of the virtual paradigm. A typical example of such structures is a virtual research laboratory (VRL), which is a combination of intellectual, material and documentary resources for research and design work in a single information space to obtain fast and high-quality results, their further use and commercialization of the results obtained. The current experience of the VRL will allow us to identify, among others, three main factors that testify to its advantages:

– ensuring effective interdisciplinary interaction;

– combining unique and expensive equipment in a virtual environment (Palagin, et al., 2003);

– creation of a distributed computer environment using modern Grid-networks.

2.2. Features of evolving information systems

Today, evolving (self-developing) information systems are at the forefront of computer science. Their main feature is that they have incorporated the properties of both complex natural, primarily biological systems and modern artificial intelligence systems. This process of mutual fertilization of these two systems is not accidental and obeys the general law of noosphere genesis, discovered a century ago by our great compatriot V.I. Vernadsky (Palagin, 2016a). All space, biological, social, anthropogenic and information systems are subject to this law and belong to the class of complex developing (evolving) systems. The development of such systems is associated with the acquisition and accumulation of new qualitative features and the emergence of new levels of organization in real time, which are the result of the interaction of the system with the external environment based on the feedback principle. The laws of such interaction, as a rule, go beyond the target causality and, due to situational uncertainty, the emergence of attractors, differentiation-integration processes, lead to a change in the main line of development, and sometimes an unpredictable loss of stability, which should be the subject of special attention of scientific researchers (Palagin, 2016a; Palagin, et al., 2018, 2023b; Petrenko, et al., 2024a, b; Malakhov, et al., 2024).

The synergistic paradigm occupies a special place in the knowledge of evolving systems in general and information systems in particular. On the one hand, it appeals to integrity and integral representation, systematically defining the effects of interaction between objects, processes and subjects, and on the other hand, it emphasizes nonlinearities, instability and the emergence of attractors that change the multilevel organization and behavior of the system as a result. In both cases, it is expressed by a set of formal models of self-organization and is aimed at reproducing the scientific picture of the world, which is especially important during the transition to a transdisciplinary approach in scientific research and the implementation of the global evolutionism paradigm. In this case, the scientific picture of the world can be presented as a transdisciplinary ontology that incorporates not only the ontology of individual disciplines, but also the methods of the latter, including options for their cross-influence. Transdisciplinarity, in addition to synergy, allows us to build a single transdisciplinary methodology of analysis and synthesis, including it in the general scientific picture of the world. From the perspective under consideration, all developing information systems can be divided into four interrelated classes:

– genetic;
– with virtual architecture and reconfiguration;
– knowledge-oriented;
– transdisciplinary.

In addition, they include two fundamentally different subclasses: autonomous and non-autonomous systems. The latter are designed for active human-machine interaction, or rather, natural and artificial intelligence (Palagin, 2016a).

2.3. Personal knowledge bases and ontological management

The central user of RDSE, both purely research and project RDS, is the researcher, represented by a researcher or engineer. Therefore, it is necessary to provide comfortable information technology and methodological support to this particular class of users. One of the main subsystems of a modern RDS is the personal knowledge base (PKB) of a researcher-designer. It can be divided into four types of information files (Palagin, 2016a; Palagin, et al., 2022; Malakhov, et al., 2023):

– documentation related to the class of new technology objects being designed;
–information about the KD (articles, monographs, patents and their integral description at the level of scientific theories);
– publications of the author (user);
– a repository of ideas, hypotheses, and sketches.

Each type corresponds to its own functional block of PKB, but they are served by a single mechanism of ontological management, content and semantic analysis, and ontological representation and markup of texts. This mechanism is realized by a set of information, software and methodological knowledge management tools, which operates on the basis of a transdisciplinary approach, ontological methods of information analysis and synthesis, and Internet resources. The content of the PKB is the personal property of the user, and access to its files in the network mode is regulated in accordance with the user's settings. The contents of the PKB can be used as the main corporate asset – the KB:

$$KB = \bigcup_i KB_i$$

where i is the ordinal index of a corporation employee or project participant managed by the subsystem of collective interaction organization (Palagin, 2016a).

The main functions of the PKB:

– user-friendly interface for interaction with the user;

– formulation of queries to the content of the PKB and to the external information space in accordance with the tasks of interest to the user, in particular, on the basis of pre-selected ontological clusters;

– preparation of materials for scientific publications, reports, patent research;

– forming a description of the knowledge domain;

– comparison of the author-user's research results with publications in a given knowledge domain, etc. (Palagin, 2016a).

The functioning of the PKD is based on the capabilities of the subsystem of syntactic and semantic text analysis, the current version of which is a system of the Polyhedron type (Malakhov at al., 2022). The main function of the Polyhedron is to integrate existing corporate information resources by processing natural language text documents with subsequent extraction of surface semantics and analysis of primary knowledge based on their ontological representation for decision-making purposes.

The PKD and Polyhedron subsystems are components of a higher-level system - a system of information and cognitive support for a generalist researcher, which, in turn, serves as the basis for research-related design systems that have the capabilities of personalization, i.e., functional orientation to a specific user, naturally with the function of authentication. An ontological approach to presenting the results of research design is extremely important for both PKD and RDS in general.

A variant of this representation is described in (Palagin, 2016b). It includes the following components:

– an ontological description of a functional fragment of knowledge in the form of an ontograph and a thesaurus of terms;

– the figurative component of the description (simple image, 3D graphics, multimedia video sequence);

– knowledge representation at the level of formal theory;

– a complete linguistic corpus representing a given KD or its fragment;

– a subsystem of services provided to the user.

If necessary, it is possible to display this information on a website or web portal for interaction with external users.

Thus, the RDS is built on the basis of the above concepts (noospheric paradigm, transdisciplinarity, evolutionism, virtuality, ontological management, and multi-level knowledge representation) and is a tool for designing complex objects of new equipment and technologies, primarily in the field of information hardware and software tools and technologies. On the other hand, its projection on the interests of scientific researchers and engineers can significantly expand the capabilities of the latter by providing intellectual support for their professional functions and skills, as well as an effective knowledge-oriented user interface. The ability to evolve the system over time, accumulate knowledge about the world around us, the KD, and the user himself opens up broad prospects for its use in scientific research and knowledge-intensive engineering developments, bringing to the fore the issues of problem orientation and replication.

3. Information technology and tools to support RD processes

3.1. Research-related design of smart systems

The level of development of intellectual information technologies has a significant impact on the efficiency of processes in the economic, scientific, technical, educational and other spheres of human society. The processes of global informatization of the world community are focused primarily on building a knowledge society and are becoming increasingly transdisciplinary. The undisputed leader here is knowledge engineering technologies, including its new direction - ontological engineering. These technologies implement Knowledge Management processes and success in this area is largely determined by the level of intellectualization and efficiency of computer systems (Palagin, 2017, Selskyy et al, 2018; Romaniv et al., 2022; Martseniuk et al., 2007, 2018, 2020, 2021, 2022; Mintser et al., 2020 & Vakulenko et al., 2015, 2017 - 2024; Vladymyrov, et al., 2024).

Currently, there is a tendency to intensify research at the intersection of different subject disciplines (interdisciplinary research) and in convergence clusters (transdisciplinary research). To support these studies, important factors include the construction of knowledge-based information systems, improvement of research design processes, development of methods and tools for ontological analysis of natural language objects to extract knowledge from them, applied aspects of ontology application, in particular in the development of e-learning courses (and other aspects of e-education), meta-ontologies, knowledge integration systems in transdisciplinary convergence clusters, etc.

Next, we consider the methodological foundations for building systems for the research design of new technology objects (as a type of Smart systems) using the ontological concept and Smart Research & Development technology, including models, information technology, and tools for cognitive information processing.

Smart systems

The process of intellectualization in the field of informatics and computing has reached a new large-scale level, expanding the scope and functionality of their applications in modern society, which was largely facilitated by the Horizon 2020 strategic framework program. It opened an era of intensive development of smart systems of various levels and purposes (Multi Annual Strategic Research and Innovation Agenda for ECSEL Joint Undertaking, 2017). This direction is supported by a joint technology initiative of a number of European international organizations. The multi-year strategic plan for the implementation of the research and innovation program in the field of electronic components, systems and technologies (MASRIA) ensures the development of the following main functional domains: smart society, smart mobility, smart energy, smart health, smart production. In essence, these are technologies that affect all aspects of modern society, such as real-time interaction between machines, people and objects in the world around us; ensuring the safety of individuals and society; efficient supply and distribution (water, food, etc.); logistics; smart administration and, in general, supporting the sustainable development of society. The entire set of these tasks and areas of activity is the subject of research and development of the MASRIA strategic plan. It should also be noted that the “Conception for the Development of E-Governance in Ukraine” and the digital economy envisage the use of modern innovative approaches, methodologies and technologies, including Internet of Things, cloud infrastructure, Blockchain, Big Data, etc. (Conception of e-Governance Development/Order of the Cabinet of Ministers of Ukraine, 2017). Figure 1 presents a classification of attributes that characterize smart systems and their brief description (Palagin, et al., 2018).

Attribute	Description
Adaptation, adaptation	The ability to change physical or behavioral characteristics in response to changes in the environment or to survive in it
Perception, reading, recognition, understanding	The ability to identify, recognize, understand and/or realize a phenomenon, event, object, impact, etc.
Logical inference	The ability to draw logical conclusions based on initial data, processed information, observations, evidence, assumptions, rules and logical reasoning
Learning, mastering	The ability to acquire new or change existing knowledge, experience, behavior to increase productivity, efficiency, skills, etc.
Anticipation (anticipation of events)	The ability to think or reason in order to anticipate future events or one's future actions
Self-organi-zation and restructuring (optimization)	The ability of a system to change its internal structure (components), self-heal and self-sustain in a purposeful (non-random) way under appropriate conditions, but without an external agent/entity

Figure 1: Table of classification of smart system attributes.

Figure 2 shows an ontographic representation of the concept of "Smart system".

The concept of "Smart system" in the ontological hierarchy is closely related at the top level to such concepts as cyber-physical systems and other sections of the Smart society. At the lower levels, there are various Smart devices that enable the implementation of user applications. The analysis of publications in foreign and domestic scientific professional journals allowed us to synthesize several upper levels of the ontology of the Smart System (Multi Annual Strategic Research and Innovation Agenda for ECSEL Joint Undertaking, 2017; Guinard, et al., 2016).

The following definitions of cyber-physical systems and Smart devices are known (Multi Annual Strategic Research and Innovation Agenda for ECSEL Joint Undertaking, 2017).

Cyber-physical systems are electronic systems, components, and software that closely interact with physical systems and their environment: embedded intelligence provides capabilities to track, monitor, analyze, and control physical devices, components, and processes in various applications. Their ability to connect and interact over all kinds of networks and protocols (including the Internet, wired, wireless) allows them to coordinate and optimize the functionality of physical systems.

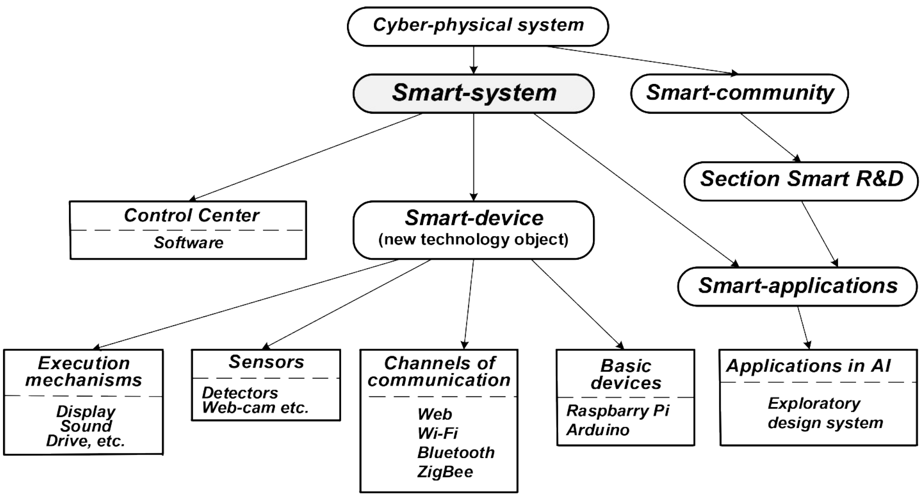

Figure 2: Ontographic representation of the concept of "Smart system".

Today, there is no generally accepted definition of a smart system. In our opinion, the following definition is correct.

Smart systems are systems that can function both autonomously and as part of more complex, cyber-physical systems, and are able to provide:

– mutual addressing and identification of each other;

– diagnosis, description and qualification of the environment;

– forecasting events, making decisions and their implementation;

– availability of more than one communication technology.

Smart device is a physical object that digitally interacts with one or more objects:

– sensors (temperature, light, motion, etc.)

– actuators (displays, sound, motors, etc.);

– controlled computing (can run programs and logic);

– communication interfaces.

The basic principles of an integrated approach to solving the problem of developing smart systems for the needs of modern society, formulated in (Palagin, 2017) in a specific implementation and taking into account Internet and Semantic Web technologies, are transformed into the following:

– (1) knowledge processing – when designing ONTs, it is necessary to have knowledge of several KDs formally described by one of the languages characteristics of the Semantic Web (e.g., RDF);

– (2) transdisciplinarity – systematic integration of knowledge of the KDs involved;

– (3) ontological concept – the structure of EFL knowledge is presented in the form of ontologies with a division into static and dynamic components;

– (4) definition of the problem situation and problem formulation;

– (5) virtualization, unification and standardization of technical solutions – communication of "Smart-systems" with each other and with users is carried out through the Web environment and/or the Cloud.

3.2. Toolkit for supporting R&D processes

The complexity of modern scientific research, including Smart R&D, puts forward increasingly high demands on the tools to support them, which should:

– operate with large amounts of textual information in order to obtain subject knowledge from them;

– form conceptual knowledge structures (ontologies) both at the intersection of subject disciplines and in convergence clusters;

– to systematically integrate the constructed ontologies in order to identify new knowledge, etc. This problem orientation corresponds to the ontological tool complex (OTC) proposed in (Palagin, et al., 2023).

OTC implements a number of components of the unified information technology:

– search in the Internet and/or other electronic collections of text documents relevant to a given POD, their indexing and storage in a database;

– automated processing of natural language texts (Palagin, et al., 2014);

– extraction from the set of TD knowledge relevant to a given KD, their system-ontological structuring and formal logical representation in one or more of the generally accepted ontology description languages (Knowledge Repression);

– creation, accumulation and use of large structures of ontological knowledge in the relevant libraries (Palagin, et al., 2023a; Malakhov, 2022, 2023a, 2023b, 2024c, 2024b, 2024a, 2025);

– systematic integration of ontological knowledge as one of the main components of the methodology of interdisciplinary and transdisciplinary scientific research.

OTC consists of three subsystems and is an integration of various information resources, software processing tools and user procedures, which, interacting with each other, implement a set of algorithms for automated iterative construction of conceptual structures of subject knowledge, their accumulation and/or system integration (Palagin, et al., 2023; Petrenko, et al., 2023).

In addition, it may contain FPGA technology for hardware support of the corresponding means (Kurgaev, et al., 1995; Petrenko, et al., 2003a, b).

4. Conclusion

The system of information and technological support for the research design process inherits both the functions of a research automation system and the functions of modern computer-aided design systems. Such research-related design systems are characterized by a high degree of intellectualization at all levels: methodological; knowledge of the KD (with logical inference procedures); modeling and project description languages; method of multi-criteria selection of alternatives; ensuring work with incompletely defined input information based on semantic analysis of texts.

The creation and implementation of ontology-driven information systems is one of the main trends in the development of the field of computer science.

A virtual research environment is a set of networked tools, systems, and processes that support the research design process.

The research-related design system, built on the basis of the concepts of the noospheric paradigm, transdisciplinarity, evolutionism, virtuality, ontological management, and multi-level representation of knowledge, is a tool for designing complex objects of new equipment and technologies, primarily in the field of information hardware and software. On the other hand, its projection on the interests of scientific researchers and engineers can significantly expand the capabilities of the latter by providing intellectual support for their professional functions and skills, as well as an effective knowledge-oriented user interface. The possibility of system evolution in time, accumulation of knowledge about the world around us, the KD and the user himself opens up broad prospects for its application in scientific research and knowledge-intensive engineering developments, bringing to the fore the issues of problem orientation and replication.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

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