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REDESIGNING THE KNOWLEDGE OF ROBOTIC SYSTEM ENGINEERS THROUGH THE MODEL-PARAMETRIC SPACE OF INFORMATION TECHNOLOGY

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ABSTRACT

The relevance of the topic is driven by the rapid development of digital technologies and the growing complexity of designing robotic systems, which requires new approaches to the representation, structuring, and verification of knowledge. The need to integrate heterogeneous models and parameters into a single information environment determines the importance of the study for industrial and scientific applications. The purpose of the study is to investigate methods of representing the knowledge of robotic system designers based on the model-parameter space and to describe the possibilities of their practical use. The object of research is the process of formalizing knowledge and integrating models in the design of complex technical systems. The methodological basis of the study is a systematic approach, semantic modeling methods, interval analysis, and theoretical set operations on knowledge neighborhoods. As a result of the work, the concept of building a model-parameter space (<M,P>) was formed, a classification of basic concepts and categories in the field of design was developed, and formal measures of compatibility, integrity, and completeness of knowledge were proposed. Algorithms for constructing knowledge neighborhoods and integrating models into holistic methodologies with automated consistency checking have been developed. The structure of the tool and software complex to support the processes of model analysis and synthesis in robotic systems is presented. The practical significance of the results lies in the possibility of using the proposed approaches in the development of digital engineering platforms, reducing the risk of design errors, increasing the adaptability of design solutions, and reducing the development time of complex technical systems.

Keywords: *Model, Parameter, System, Analysis, Design, Research, Complex Object, Knowledge Base, Consistency, Heterogeneous Models, Information Technology*

1. INTRODUCTION

Modern industrial production and automated technological processes cannot be imagined without the introduction of robotic systems. The development of Industry 4.0, digital twins, and cloud platforms significantly complicates the structure of knowledge used by designers in developing technical solutions. The growing number of parameters, relationships, and models requires a systematic organization and a formalized approach to presenting information. The problem is not only the accumulation of knowledge, but also its structuring, verification, and integration into a single information environment. Given the constant dynamics of technological development, the search for tools that would maintain data consistency, flexibly update information models, and ensure adaptability to new production requirements is particularly relevant. The global scientific community pays great attention to the organization of knowledge in the field of robotic design. The works by Choi and Kim [1], Yao et al. [2], and Xu et al. [3] analyze the role of digital twins and machine learning in improving model accuracy and optimizing production processes. The studies by Guo et al. [4] and Shen et al. [5] demonstrate the benefits of semantic networks and ontological approaches for visualizing complex relationships between parameters. Liu and Xu [6], Yu et al. [7] emphasize the prospects of cloud production and decentralized knowledge storage systems, and Zhou [8] describes theoretical approaches to assessing the reliability of information under uncertainty. However, despite the

diversity of scientific approaches, the issue of building a holistic model-parameter space with formal measures of compatibility and consistency remains underdeveloped.

Much of the research focuses on specific aspects: individual elements of intelligent design, simulation, or optimization. Instead, there are no generalized methods that allow integrating disparate models and parameters into a single information environment with the ability to automatically check their consistency. The issues of creating tool and software systems for visualizing and controlling the integrity of knowledge, convenient for use in industrial environments, remain poorly developed. Especially relevant is the lack of approaches that would combine theoretical rigor with practical adaptability in multi-agent and cloud environments.

The purpose of this paper is to investigate approaches to organizing the knowledge of robotic system designers based on the model-parameter space, describe existing tools and approaches, identify weaknesses in the theoretical and practical basis of this topic, and characterize our own approach to building a toolkit to support the processes of model analysis and synthesis. The main objectives of the study were to (a) analyze the structure and main elements of the <M, P> space in modern scientific sources, (b) find out the possibilities of its integration in decision support systems and (c) propose requirements for further development and application in industrial design environment.

2. LITERATURE REVIEW

The recent research work in the field of information technology for representation of the knowledge of the robotic system designer is based on digital twins, ontological modeling and model parameter spaces. In particular, Choi and Kim [1] show that integration of digital twins in the optimization and simulation systems enhance accuracy and speed in the engineering decision making. Yao et al. [2] also mention how the concept of meta-universe of industrial production ought to be introduced and how to build adaptive digital models of production processes. In complex systems, control of model compatibility and consistency is paid considerable attention to, and in systems where centralized control coordinates activities at multiple sites. Valkman's et. al. [9] fundamental study proposes a methodology for creating a model-parameter space (<M,P>-space) of the design knowledge space in the design process so as to reduce the possibility of contradictions between model and parameter. Guo et al. [4] also consider a similar approach, however, in this case, they concentrate on the implementation of semantic networks and visual control for automated manufacturing. Rykhalskyy [10] discusses specific implementation details.

Currently, the problem of integrating heterogeneous data and models is actively developed. For instance, Xu et al. [3] apply machine learning for automated model adjustment in production processes in order to make them able to respond to changes in their conditions. Sinha and Lee [11] consider a similar problem of engineering in industrial industrial systems, but specifically the problems with the data reliability and consistency in the introduction of artificial intelligence. It is still a hot topic, the formalization of knowledge and building of unified databases. Using a digitalization mechanism and small and medium enterprises engineering knowledge management as a research topic, Chen et al. [12] analyze the extent to which digitalization affects engineering knowledge management. Shen et al. [5] propose the role for artificial intelligence and optimization for intelligent production planning which is the growing role of artificial intelligence and optimization algorithms.

Moreover, research is actively considering development of tool and software systems for knowledge support. Specifically, Lee et al. [13] focus on cyber physical systems in industrial production, and their architecture to integrate modelling, simulation and production process. Moreover, Kaur and Dhindsa [14] take knowledge indexing methods into consideration that are vital for an automated search for the relevant information in large databases. The synergy defined between digital twins, semantic modeling and artificial intelligence in knowledge representation for the robotic systems design is demonstrated by modern research. Such efficiency and reliability engineering solutions is enabled by the use of model parameter spaces and algorithmic analysis of model compatibility [9, 10, 1, 3, 11].

In addition, Zhou [8] made a significant contribution to the development of the methodology of formalized representation of knowledge by looking into what functions can be performed by beliefs over such systems of lattices of the distribution types used to estimate the reliability of information in a complex multifactorial system. In their comparative analysis, Liu and Xu [6] argue that both Industry 4.0 and cloud manufacturing are characterized by many characteristics including

scalability and decentralized knowledge management of digital manufacturing platforms. In their proposed blockchain architecture for cloud based manufacturing [7] for securely distributed model and parameter data in the distributed environment. Based on the fact that it is important to build dynamic updated Model in <M,P>-space, approaches for automatic generation of controllers for robotic systems from dependencies of multisensor variables have been considered by Kobayashi et al. [15].

Moreover, it is key to mention the study of Sydorov et al. [16], about developing an approach on how styles may be applied in software engineering. The relevance of this study is for the automated generation of templates and techniques when building knowledge bases towards synthesis of integral systems of models and parameters. Use of the formalized styles makes the structure of knowledge consistent and allows to increase the quality of the integration of heterogeneous information components.

Sequeira and Gervasio [17] are also worthy, as they investigate the explainability of agents in reinforcement learning that can contribute to the creation of self learning design models. Malus et al. [18] proposed a real time method of tasks dispatching to a fleet of autonomous mobile robots with practical value for multi agent approach. Çapunaman and Gürsoy [19] present computational approaches in robotic manufacturing using machine vision that aims to improve the modelling accuracy of complex object. The research of Chu et al. [20] is related to consensus theory in multi agent systems with delays and is relevant for formalizing asynchronous interaction in large projects. In addition, Roehr et al. [21] and Stojanovski et al. [22] emphasize the importance of automated research on robot behaviour and new approaches to computer-aided architectural design, respectively, which expands the application of knowledge formalization methods. Kusiak [23] emphasizes that digital manufacturing should fully integrate big data analysis, which correlates with the idea of using distributed databases and intelligent interfaces.

Thus, current research focuses on combining the model-parametric approach with digital twins, artificial intelligence, blockchain technologies, and multi-agent systems [8, 6, 7, 15]. At the same time, there are still problems with scaling built solutions for industrial cloud platforms and insufficient integration of tools for automated adaptation to dynamic changes in project tasks.

3. METHODS

The study was conducted through a systematic analysis of modern scientific sources and publications on the design of robotic systems and intelligent information technologies. The methodological basis was semantic modelling methods for formalizing the relationships between models and parameters, a set-theoretic approach for defining operations on knowledge neighborhoods, and interval analysis for estimating the ranges of parameter values and controlling their reliability. The model-parameter space was structured using graph models and matrix descriptions. The algorithms were built and tested by developing experimental examples based on typical design tasks for industrial robotic systems and autonomous mobile platforms. The practical study was conducted using publicly available databases of technical specifications and simulation results, as well as materials from scientific conferences and international research in the field of digital engineering.

4. RESULTS AND DISCUSSION

Knowledge representation is highly justified in the modern robotic engineering, as it enables an effective design process. The development and inclination of the intellectualization of development and modelling of complex technical objects in the context of rapid development of digital technologies proves to be the predomination of formalization of knowledge and database areas. There are essentially three knowledge representation methods like declarative, procedural, and hybrid.

1. Methods of declarative description of the parameters and structural characteristics of systems include the use of frames, semantic networks and ontologies. Because it is a structured representation of information, it is effective to the experiential level, the design case, for providing structured representations of information and for automated model analysis [1].

2. Procedural methods follow the algorithmic methods and are used when the knowledge has to be represented in the form of some sequences of actions. For a specific example, that is, the product rules for the automatic selection of technical solutions [11].

3. Examples of uses of hybrid methods include the use of fuzzy logic or neural networks with classical knowledge bases in order to enhance

the adaptability and accuracy in predicting the parameters of robotic systems [3].

As application areas, model parameter space [9]. The design parameters are represented by an architecture that allows them to be effectively organized together with relationships between different models used in the design process, and an automated analysis of parameter consistency is provided. The integration of the artificial intelligence, digital twins, and knowledge management technologies are the basis for modern toolkits for computer aided design of robotic systems.

1. The digital twin of the physical system allows creating virtual copies, offering the opportunity to test and optimize the parameters at the design stage [2]. The reduction in development time and reliability of the structure is this factor very vital.

2. Knowledge management systems (KMS) are used in the design process in order to store, analyse and reconfigure information used in the design process. These kind of systems enable engineers to interact effectively with databases or artificial intelligence in order to obtain… optimal solutions [12].

3. Interaction between the modeling, simulation and production stages is provided by Integrated CAD/CAE/CAM systems (Siemens NX, CATIA, SolidWorks, etc.). Such systems help to automate the decision making process and elevates the work efficiency to a great extent [13].

Knowledge representation in a modern design of a robotic system is actively developed by integrating ontological, digital twins, and AI technologies. The process of model analysis and synthesis can be automated using model(parametric) space and tool and software systems and as a result ensures quality of the design and reduces time of its realization.

To systematize knowledge and enhance effective information technology development, in the field of robotic systems design, there are a lot of concepts and categories that have to be offered in clear ways. This enables formalization of the subject area, a unification of knowledge base, and guarantees of integrity of design decisions [5]. The main categories and concepts for the subject area of robotic system design is further expanded in the following table (Table 1).

Table 1. Key categories and basic concepts of the subject area of robotic system design

Category	Basic concept	Description and features
Design object	Robotic system	A set of hardware and software components designed to automate production or service processes [4]
Parameter	Characterization of the system	A formalized description of a property or state of an element or system as a whole, used in models [9]
Model	Formalized relationship	A representation of the relationships between system parameters to describe, predict, or optimize the system [1]
Methodology	System of models	An ordered, consistent system of models that enables the calculation and estimation of target parameters [3]
Context	Conditions of interpretation	A formalized description of the range of acceptable parameter values and conditions for applying models [13]
The neighbourhood of knowledge	System group of models	Linked models and parameters grouped around a central element for local analysis [2]
Compatibility	Interaction of models	The degree of agreement between models that allows them to be used together in integrated calculations [11]
Integrity of knowledge	Completeness of model coverage	Reflecting the ability to cover all the necessary aspects of the study without contradictions [12]

Source: created by the author based on [4, 9, 1, 3, 13, 2, 11, 12]

In conclusion, the formalization of the important concepts and categories permits the creation of unified knowledge bases, and helps in the development of integrated information technologies to facilitate the development of robotic systems. It was on this basis that the further construction of

model schema spaces taking effect integration and verification of models were made.

In order to design effectively complex robotic systems, these systems must take advantage of modern knowledge bases and databases that will enable the integration of disparate models and parameters as a single information environment. Creation of such databases allows to have a consistent interpretation of existing research objects, formalization of synthesis and analysis methods, and allows to have a multi-level verification of information integrity [14, 9, 10]. Knowledge management and the management of information base should serve not only for accumulation of data but also searching and integration of the knowledge from multiple sources considering their heterogeneity and diversity [2]. Table 2 shows the main methods used to build such systems.

Table 2: Methods of creating and using knowledge and data bases to support the analysis and synthesis of robotic system models

Method	Description and features of application
Ontological modeling	Creating semantic structures that describe the relationships between objects, parameters, and processes [5]
Using semantic networks	Visualization of complex relationships between models and parameters to facilitate analysis and search for dependencies [4]
Interval analysis	Estimating the reliability of parameters and determining the ranges of possible values to improve the reliability of calculations [3]
Model-parametric approach	Building knowledge neighborhoods and forming universal databases and knowledge using formal apparatuses [9, 10]
Integration of digital twins	Combining knowledge bases with simulation models to predict the behavior of systems in different scenarios [2]
Methods of knowledge indexing	Automated organization and classification of information for quick search and selection of relevant models [14]
Building a verification system	Implementation of mechanisms for checking the consistency and consistency of knowledge stored in databases [11]
Automated formation of methods	The use of templates and algorithms to generate complete systems of models and parameters based on input data [12].

Source: created by the author based on [5, 4, 3, 9, 2, 14, 11, 12]

Overall, we can summarize that the establishment of such effective knowledge bases for the support of robotic system's analysis and synthesis based on the combination of interval estimates approach, ontological approach, semantic networks, and the model parametric structure provides. This allows the automation of engineering decision making, the improvement of modeling quality and the development of a flexible information environment for the development of complex systems.

One of an important task in design of the robotic systems, is to formalize the representation of the knowledge in the <M,P>-space (model parameter space). It provides for structuring models, parameters, and interrelationships, and organizing information for system analysis and synthesis of new models [9].

The model parameter space has the following main components:

- parameters that describe the properties of an object or process;
- models that reflect the relationship between parameters;
- methodologies, which are ordered systems of models;
- knowledge neighbourhoods that would help localizing fragments of knowledge around certain models or parameters.

A diagram (Figure 1) shall be proposed to visualize the structure of the <M, P>-space.

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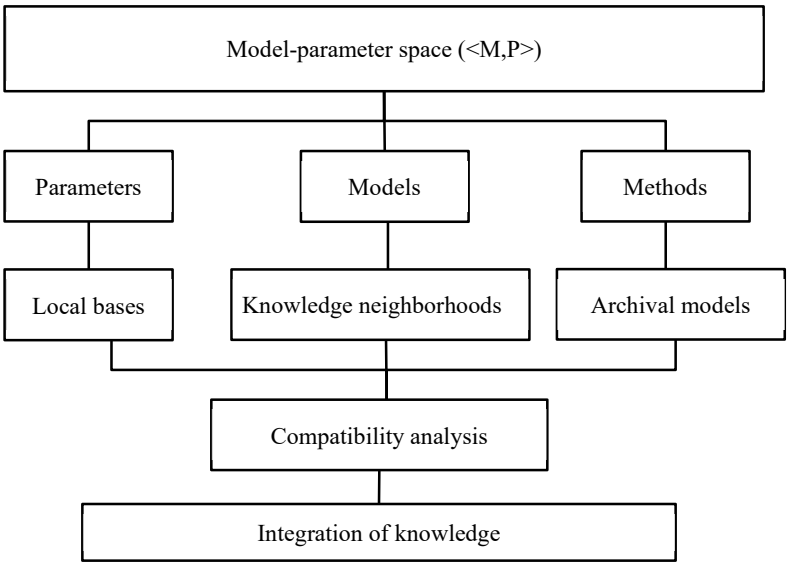

Figure 1: Structure of the model-parameter space for designing robotic systems
Source: developed by the author

In this space, algorithms construct knowledge neighbourhood sets of models and parameters connected to the central element to navigate this space. The first, second, and subsequent neighbour orders in are determined [9]. Calculating distance between models in <M,P>-space involves the searching of the minimum number of steps in element of dependency graph. The distance is used as a measure of semantic proximity also for compatibility testing and in the context of incorporating models into one unified methodologies. This work proposes a unified approach to organizing design of robotic systems in the space of model parameter using structure of model parameter space. The work on the construction of knowledge neighbourhoods and calculation of model distance leads into effective model consistency and able to work model integration based on which high quality design solutions are accomplished.

For designing complex robotic systems, knowledge from different sources must be integrated, particularly in different formats, and in different structural approaches. For this, they require formalized operations of working with model parameter neighbourhoods, that are local groups of interconnected model and parameter tuples [9]. The basis for integration is two key set theoretic operations of knowledge neighbourhood union and intersection. Their application allows to reconcile knowledge, identify duplications, contradictions, and form a more complete picture of the subject area [2]. Below is an extended description of the operations with their interpretation for practical use (see Table 3).

Table 3: Theoretical set operations on model-parametric neighbourhoods and their practical application

Operation	Formal definition	Practical significance
Intersection of neighbourhoods	A set of elements that simultaneously belong to each of the neighbourhoods: $O_1 \cap O_2$	It is used to identify common knowledge and parameters, useful for checking the compatibility of different approaches.
Merge neighbourhoods	A set of elements that belong to at least one of the neighbourhoods: $O_1 \cup O_2$	It allows combining knowledge from different sources and get a more complete picture of an object or process.
Difference of neighbourhoods	A set of elements that belong to one neighbourhood but do not belong to another: $O_1 \setminus O_2$	It is used to identify unique knowledge and to identify specialized features of models.

Symmetric difference	A set of elements that belong to one of the neighbourhoods, but not both at the same time: $O_1 \triangle O_2$	It is used to analyse the differences between knowledge sets and assess conflict zones.

Source: created by the author based on [9, 4, 3, 11, 2]

Theoretical and set-theoretic operations of combining, intersecting, and differing knowledge neighbourhoods are important tools for integrating heterogeneous models and parameters into a single information environment. Their use helps to identify contradictions, form consistent methodologies, and improve the quality of design decisions in the development of robotic systems. Designing complex robotic systems involves the use of many models created by different researchers or departments. To ensure the correct operation of such systems, it is necessary to formally assess the degree of compatibility and consistency of models, as well as determine the level of integrity, completeness, and consistency of the model-parameter space [9].

Formal measures of model compatibility. The compatibility of two models in <M,P>-space can be estimated using the compatibility vector:

$$LV = (LVT; LVK; LVTK; LVKT) \quad (1)$$

where:

- LVT — the normalized level of compatibility of the textual parts of the models (common parameters in the model texts);
- LVK — normalized level of context compatibility (intersections of application conditions);
- $LVTK$ — consistency of textual and contextual connections;
- $LVKT$ — consistency of contextual and textual relations [9].

For a comprehensive assessment of the <M,P>-space, the following indicators of integrity, completeness, and consistency are used (see Table 4):

Table 4: Quality indicators of the model-parameter space

Indicator	Formalized definition	Practical significance
Integrity (I)	The ratio of the number of integrated models to the total number of models in the space	It allows to assess how the models are interconnected and form a single information environment [4]
Completeness (C)	Ratio of the number of covered parameters to the total number of relevant parameters	Reflects the degree of coverage of all aspects of the subject area in the design [3]
Non-contradiction (NC)	Share of models for which no conflicts in texts and contexts were detected	The indicator is important for the correct integration of knowledge and the formation of safe technical solutions [11]

Source: created by the author based on [9, 4, 3, 11]

The constructed formal measures of model compatibility and consistency allow us to quantify the quality of the model-parameter space. Indicators of integrity, completeness, and consistency serve as a tool for diagnosing and optimizing the knowledge system, ensuring increased reliability of design decisions in the field of robotic systems. Let us consider the development of principles for the implementation of problem-based information technology to support the design of robotic systems and the creation of a software and information toolkit for managing databases and knowledge. Problem-based information technology in the field of robotic system design should support all stages of the life cycle of creating complex technical objects: from formulating requirements and building models to integration, compatibility testing, and knowledge verification [9, 10].

Implementing Problem Based Information technology can be described by the basic principles as follows:

1. *Multimodel* – simultaneous support for several forms of knowledge representation (mathematical models, logical connections, graphical visualizations) [5].
2. *Integrative* – is the ability to combine disparate data sources and synchronize them into a single environment [4].
3. *Hierarchicality* – building a knowledge structure with different levels of detail: from global

systemic connections to local parametric descriptions [3].

4. *Contextual adaptability* is the dynamic adjustment of algorithms and data processing mechanisms to the conditions and objectives of a particular project [11].
5. *Automated verification* is the availability of mechanisms to control the consistency and compatibility of models and parameters in the process of their integration [9, 10].

The structure of the instrumental software and information complex is shown in Figure 2. Before creating the diagram, it should be noted that the above structure shows the main components of a database and knowledge management system for designing robotic systems.

The proposed principles for implementing problem-based information technology allow creating a universal environment for the accumulation, structuring, and integration of knowledge in the design of robotic systems. The instrumental software and information complex provides support for design decision-making, automated compatibility control, and the formation of an integral model-parameter space, which significantly increases the efficiency and quality of engineering developments.

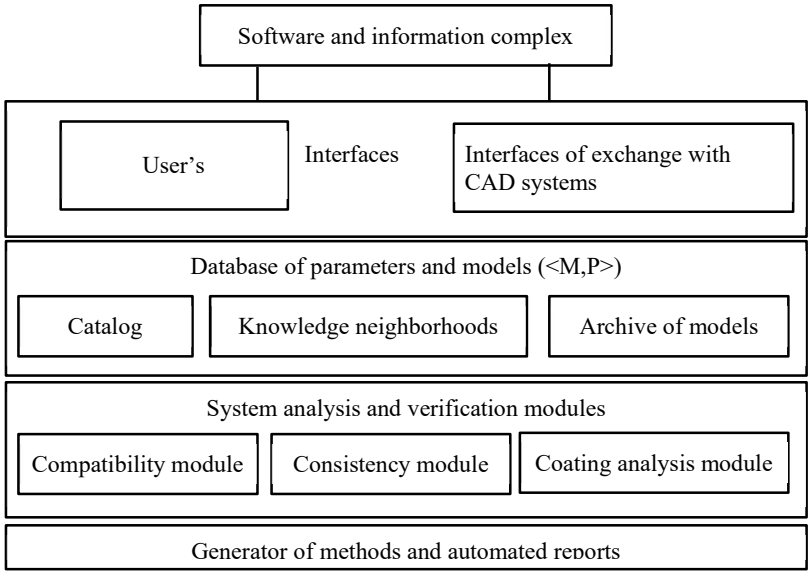

Figure 2: Structure of a software and information complex to support the design of robotic systems
Source: created by the author on the basis of [9, 5, 4, 3, 11]

The purpose of this study was to substantiate and build an information technology for representing the knowledge of robotic system designers based on the model-parameter space, as well as to create appropriate tools to support design decisions. The results confirm the hypothesis that the use of a model-parametric approach can increase the integrity and consistency of the knowledge required to design complex technical systems. This is in line with the findings of Valkman et al. [9], who substantiated the effectiveness of using <M,P>-space in building complex information models.

At the same time, there are different views in the literature on the extent to which integration of heterogeneous models is feasible and to what extent automated systems can control the consistency of such knowledge. For example, Choi and Kim [1] point out the high risk of errors when combining models built using different description languages and at different stages of the life cycle. However, our research position is that these problems can be reduced by using clear formal interoperability measures and specialized verification modules in software and information systems, which was implemented in this study. This approach is also supported by Xu et al. [3], who emphasize the importance of creating algorithms for controlling inconsistencies in industrial design environments.

The study by Yao et al. [2] emphasizes that excessive formalization of models can limit the flexibility of engineering thinking and adaptation to new requirements. We can partially agree with this opinion, but it is worth emphasizing that the use of the concept of knowledge neighborhoods allows localizing knowledge fragments for flexible adaptive analysis without compromising the integrity of the overall system. Thus, the proposed approach combines a formalized structure with the possibility of local expansion and refinement of information. Compared to Guo et al. [4], who consider knowledge integration in the field of automated manufacturing with an emphasis on visual interpretation, our study goes beyond visualization and focuses on formal logical relationships and an analytical framework that allows quantifying the compatibility and completeness of the model.

The results are consistent with the hypothesis, but there are certain limitations of the study. First, the built metrics and integration principles were tested on a limited number of test tasks and cases, which does not exclude the need for further research to scale them up. Secondly, the issue of adapting this technology to real industrial CAD systems remains open and requires additional experimental work in production conditions. The practical application of the research results is seen in the implementation of knowledge support tool modules in industrial software and information systems for the design of automated and robotic systems. This will not only reduce design time but also reduce the number of design errors and increase the reliability of technical solutions.

In general, the results obtained are consistent with some of the existing scientific approaches, while demonstrating the need to develop the concept of model-parameter space in the direction of adaptability and integration into industrial digital environments. Further research should be directed to the development of methods for scaling computational procedures and testing the technology in the conditions of real manufacturing enterprises.

5. CONCLUSION

The results obtained show that the use of the model-parameter space in combination with formal measures of model compatibility and consistency makes it possible to improve the quality of design solutions for complex robotic systems. The proposed concept of knowledge neighborhoods has demonstrated the ability to localize and adaptively integrate fragments of information from different sources without compromising the overall integrity of knowledge. Unlike classical approaches, where visualization tools and informal integration methods dominate, the developed approach is based on rigorous mathematical models and quantifies completeness and consistency, which is innovative for practical project tasks. At the same time, the study showed that scaling such solutions for large industrial systems requires significant optimization of computational algorithms and flexibility of interfaces for users with different levels of competence. It is important to note that the proposed approaches work most effectively in systems with a clearly structured subject area, while in dynamic environments with frequent changes in parameters and tasks, further expansion of automatic self-adaptation mechanisms is required. It is recommended to focus further research on the development of cloud versions of such software and information systems, which will allow processing large amounts of data in real time and integrating with industrial digital platforms. Another promising area is the combination of the model-parametric approach with artificial intelligence methods to automatically generate new models and design scenarios based on the experience and data from previous projects.

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