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Articles

Study on the Influence of Converters on Current in Mine Electrical Network: A Case Study of a Mine in Vietnam

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Abstract

Inverters, soft starts, and power converters are all common in Vietnam's mining industry today. The usage of these devices in the mine electrical network produces other current components with frequencies other than 50Hz, which have undesired repercussions during operation. The results for the leakage current of the electrical network show that at the time of leakage before the inverter, the leakage current of the electrical network increases with a pulse coefficient k_{xk} = 2.2 times and the current after the inverter fluctuates strongly and takes about 0.2s to return to zero, which leads to the mistaken operation of the leakage protection relay in the mine electrical network.

The research results provide the basis for calculating and selecting appropriate electrical equipment to improve safety in underground mining.

Keywords: current, inverter, mine electrical network.

1. Introduction

Currently, in mining, many power electronic devices, including frequency converters, are used to improve the working efficiency of machines. In addition, according to the results in research (Kim, 2018; de Paula et al., 2015), it is shown that in the future, when the mine capacity increases and the mining depth increases to ensure and improve the efficiency of power supply, mining enterprises will use more and more of these types of devices. The conversion equipment is usually a rectifier to convert AC into DC, an inverter to convert DC into AC, or both to provide reasonable voltage for the loads in the electrical network (Do, 2018).

Using converters has many benefits such as: increasing power quality, reducing harmonics, reducing voltage flicker during switching, reducing cable costs, reducing motor and cable heating. In addition, converters can also provide DC power to DC motor load devices. Using single inverters or external inverter stations causes harmonic problems, increases equipment losses, etc. and also causes many other factors that lead to the mistaken impact of leakage protection devices in the electrical network, causing unsafe mining operations (Zhao et al., 2016).

Many research projects have shown the influence of frequency converters on leakage currents in industrial electrical networks in general and underground mine electrical networks in particular.

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In the study (Wymann et al., 2015; Nguyen et al., 2007; Beleiu et al., 2020) studied the effect of high frequency current in the range of 50 Hz to 150 kHz on the operation of Residual Current Devices (RCDs), the results of the study showed that type A and AC RCDs have increased fundamental tripping current (50 Hz) in the presence of HF components, which poses a potential safety hazard. In the study (Ngo, Do., 2022; Do, Ngo, 2021; Marek, 2017; Pontt et al., 2009) studied the effect of high-order harmonics on electrical equipment in mining, the results of the study showed that high-order harmonics negatively affect the operation of mine electrical equipment.

Through the above analysis, it can be seen that the use of power electronic devices generates harmonics, increases losses on equipment, causes errors in measuring devices, etc. and also causes many other factors that lead to the confusing effects of leakage protection devices. The content of the article analyzes the impact of converters on current in the mine electrical network. The research results are the basis for calculating the selection of suitable electrical equipment to improve safety in underground mining in Vietnam. The research method is shown on the basis of theory and simulation, the research results will provide recommendations to improve leakage protection in the mine electrical network to ensure safety in mining.

2. Discussion and results

Mine power network model containing conversion equipment

The underground mine electrical network model containing converters to supply power to AC and DC loads is shown in Figure 1 (Kim, 2018).

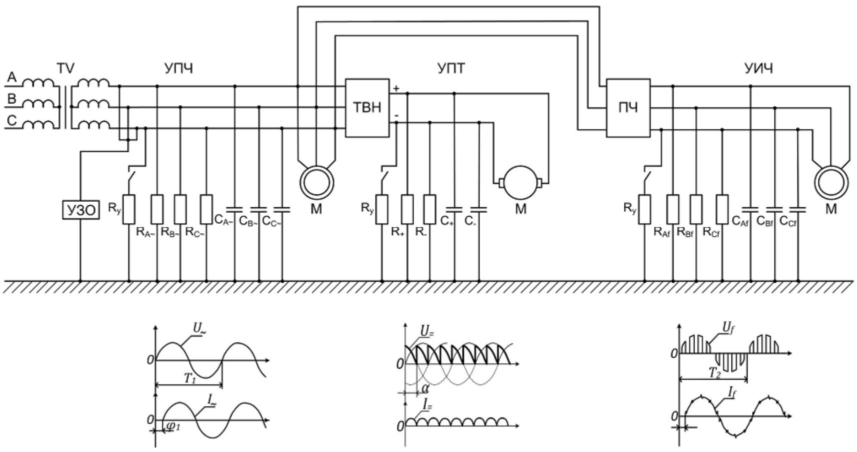

Fig. 1. Mine electrical network containing conversion equipment

Figure 1 shows that in a mine electrical network containing converters, the electrical network will include three types of current components: 50Hz alternating current component before the inverter (BI), direct current component (DC) and alternating current component with a frequency other than 50Hz after the inverter (AI). The general replacement diagram for an underground mine electrical network containing converters is shown in Figure 2 (Nguyen et al., 2023).

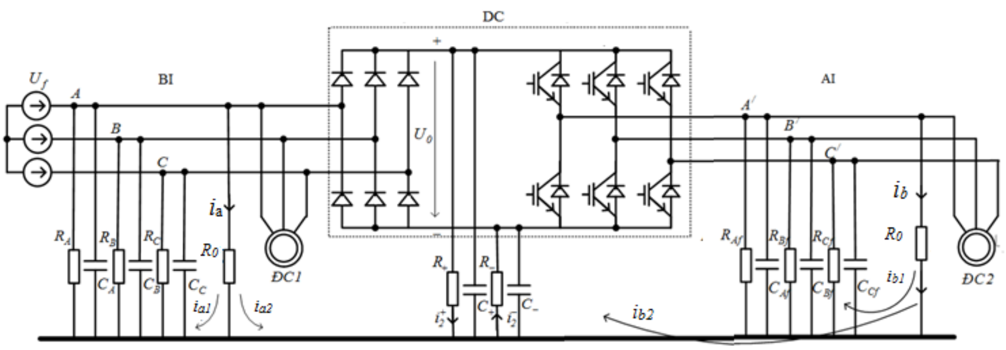

Fig. 2. Schematic diagram of the mine electrical network replacement containing conversion equipment

In the diagram, symbols R_A, R_B, R_C, C_A, C_B, C_C are the insulation resistance and phase capacitance relative to ground of the network part before the inverter (BI); R_{Af}, R_{Bf}, R_{Cf}, C_{Af}, C_{Bf}, C_{Cf} are the insulation resistance and phase capacitance relative to ground of the network part after the inverter (AI); R_+, R_-, C_+, C_- are the insulation resistance and capacitance between the positive (+) and negative (-) poles relative to ground of the direct current (DC) network part; U_f is the secondary phase voltage of the area transformer; U_0 is the average value of the three-phase bridge rectifier voltage.

The simulation model for general research is suitable for the underground mine electrical network in Vietnam using inverter on Matlab-simulink software as shown in Figure 4, AC network insulation resistance R=150k Ω/phase, AC voltage frequency 50Hz, network voltage U=1140V, in Figure 3.

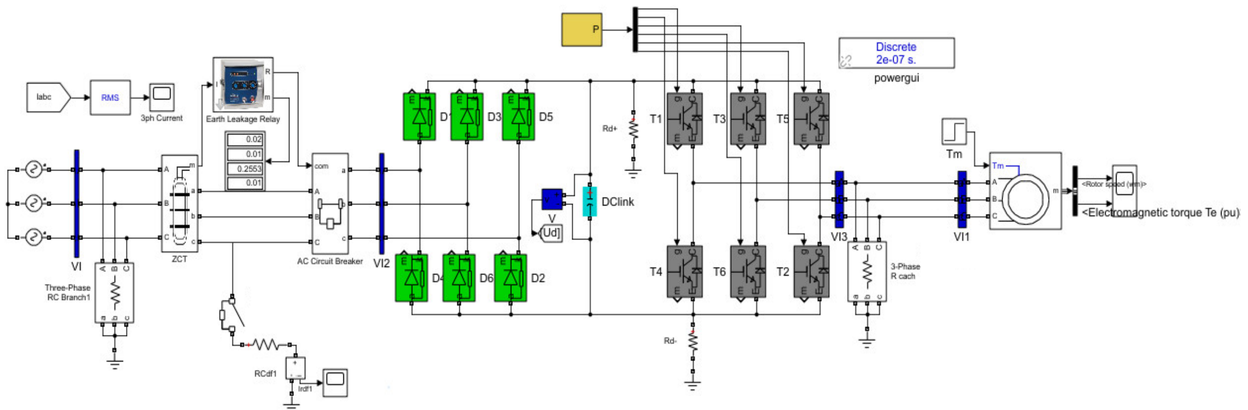

Fig. 3. Simulation model of mine power network using inverter

Based on the research model in Figure 3, the influence of the converter on the current in the mine electrical network is studied. During the research process, the leakage current in the electrical network when leakage occurs before the inverter with a 300k leakage resistor Ωat 0.8s is also studied. The survey results on voltage, current and leakage current before and after the inverter are shown in Figures 4 to 8.

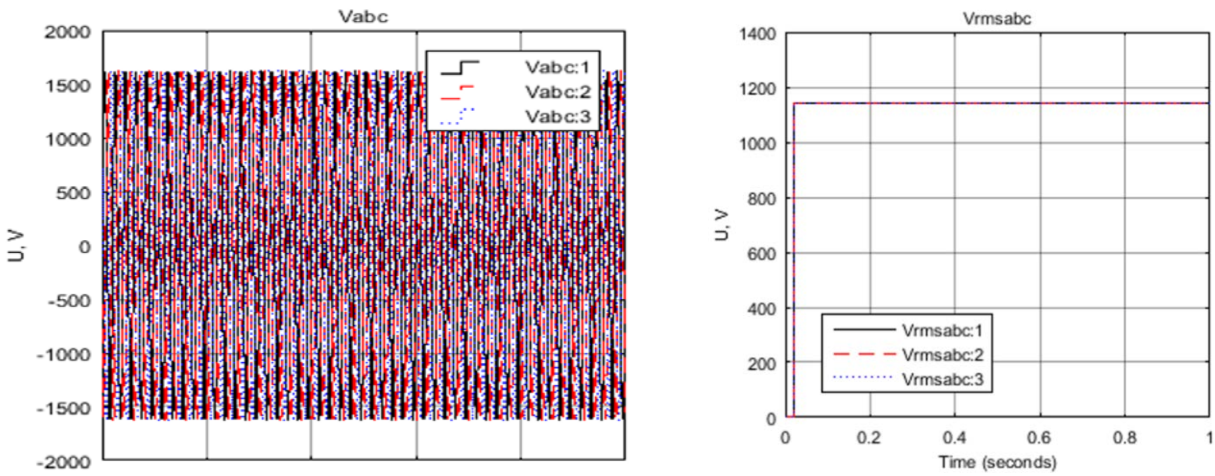

Fig. 4. Voltage before inverter

Results in Figure 4 and Figure 5 show that the supply voltage and the electrical network have a sinusoidal shape with an amplitude of 1140V. However, with the participation of the inverter in the mine electrical network, the current in the electrical network is no longer sinusoidal, in addition to the 50Hz frequency current, there are many other current components of 50Hz. When an electric leakage occurs at 0.8s, the current amplitude before the inverter does not change much.

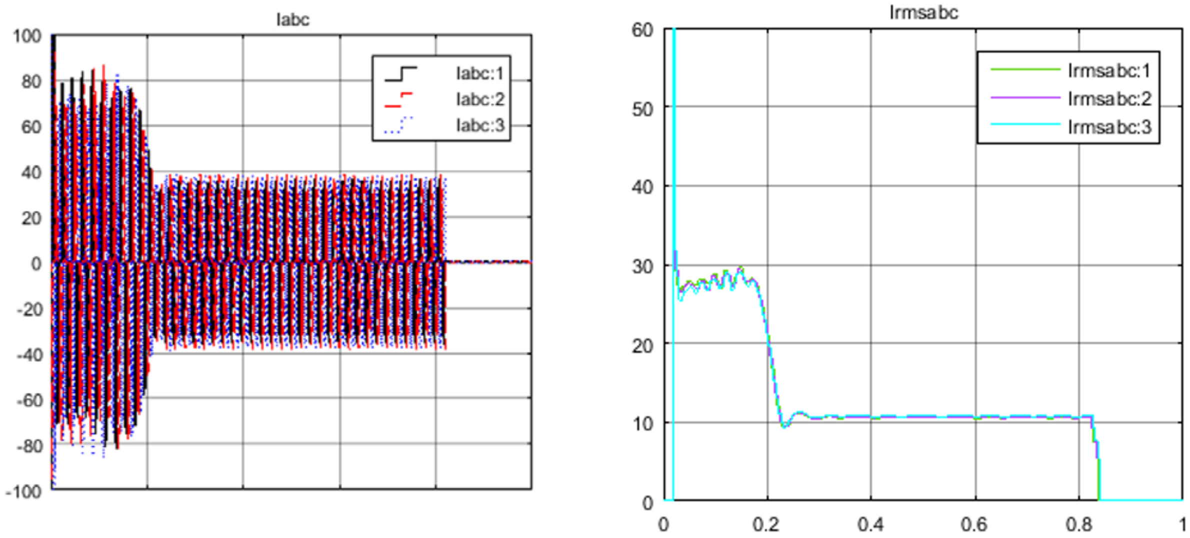

Fig. 5. Current before the inverter

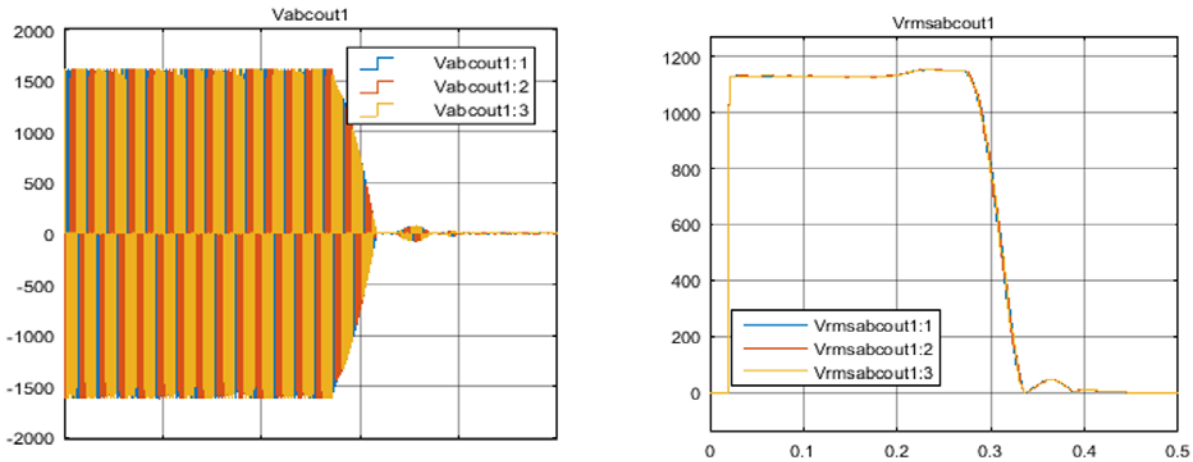

Fig. 6. Inverter output voltage

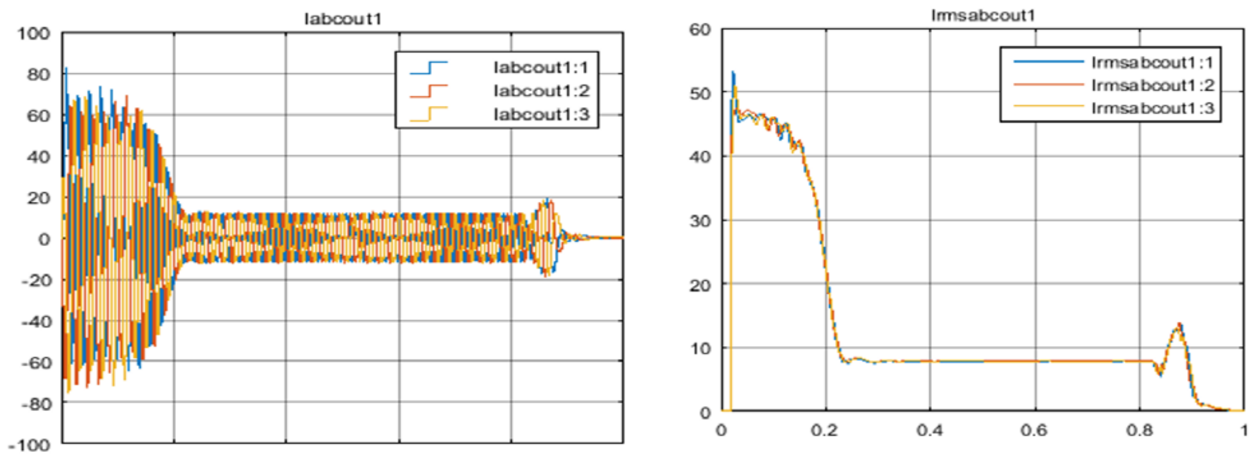

Fig. 7. Output current from the inverter

The research results in Figure 6 and Figure 7 show that after the inversion process to convert into AC voltage, the current amplitude after rectification suddenly increases with a peak amplitude of up to 52A after a period of 0.2s, the current stabilizes at an amplitude of 9A. After the electric leakage occurs at 0.8s, the current after the inverter fluctuates strongly and takes about 0.2s to return to zero.

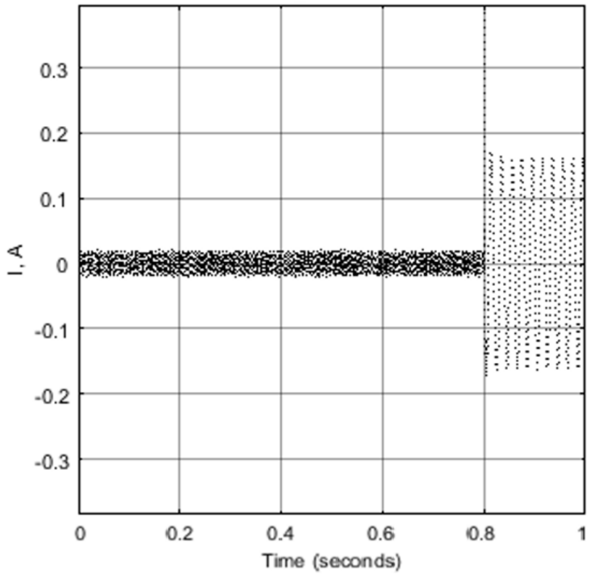

Fig. 8. Leakage current of the power network

The results for the leakage current of the electrical network in Figure 8 show that when a leakage occurs, the amplitude of the leakage current increases suddenly with a pulse current value of up to 0.4A and then stabilizes at an amplitude of 0.18A. Thus, it can be seen that at the time of leakage before the inverter, the leakage current of the electrical network increases with a pulse coefficient k_{xk} = 2.2 times the normal leakage current amplitude, which leads to the mistaken operation of the leakage protection relay in the mine electrical network.

3. Conclusion

Converters such as inverters, soft starters, and power converters are commonly used in mining in Vietnam today. In the future, when mining capacity increases and mining depth increases to improve power supply efficiency, mining enterprises can switch to using inverter stations. The use of these devices in the mine electrical network, in addition to the 50Hz alternating current component, also includes current components with frequencies other than 50Hz. These current components can cause confusion with the leakage protection relay. To improve operational efficiency in mining, it is necessary to have measures to limit the impact of this current component caused by power electronic devices.

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Spatial Knowledge Models

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Abstract

The article explores the field of computer science and geoinformatics, which apply and process spatial information. Spatial information serves as the basis for obtaining spatial knowledge models. A general knowledge model is an ontology. When using spatial information, a spatial ontology serves as a knowledge model. Spatial ontologies, which are models of spatial knowledge, are considered. Spatial ontologies are created using spatial knowledge models. The taxonomy of ontologies is shown. A dictionary ontology is described as a basic ontology, which is used in the construction of complex ontologies. The concept of ontological information units is introduced. The content of descriptive logic is revealed. The significance of an information field as a unifying information model is shown. Examples of a spatial descriptor are given. A mechanism for obtaining spatial ontologies based on spatial conceptual blending is considered. Conceptual blending in geoinformatics is a transfer of the ideas of conceptual blending from psychology. The significance of spatial relations for the formation of spatial ontologies is shown. An example of a spatial ontology might be the result of conceptual blending or an electronic map. Generally, these models may or may not be ontologies. The conditions for transforming spatial models into ontologies are given. It is shown that a spatial model is an ontology if it contains knowledge. A formal description of spatial composition and cartographic composition is provided.

Keywords: spatial knowledge model, ontology, spatial ontology, spatial conceptual blending, cartographic composition, spatial composition, ontological modeling.

1. Introduction

Information sciences, particularly computer science and geoinformatics, use different types of information models. The most important model in computer science and geoinformatics is the knowledge model. A knowledge model has many forms of representation. The traditional form of knowledge description is ontology (Chen et al., 2025). Ontology has a multi-level representation. The lowest level of an ontology is a dictionary. A dictionary can be viewed as a set of thematically related information units. If dictionary information systems form a single, consistent terminological system, then such a dictionary is an ontology. The vocabulary units of ontology vocabularies are ontological units. Complex ontologies are created based on dictionaries, or systems of ontological information units. A dictionary-level ontology is called descriptive. This ontology is constructed using descriptive logic. The term "descriptive logic" comes from the word descriptor (Latin descriptor "describing"). Descriptive logic is interpreted as "describing and consistent" logic. A descriptor, in one sense, is a phrase used to describe the semantic content of a term or model. Another meaning of a descriptor is a dictionary. In linguistics, a descriptor, as a

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phrase, represents a linguistic information unit. In the field of knowledge, a descriptor is a linguistic ontological unit. This information (geoinformation) unit is the basis for constructing linguistic information constructs in an information field. A linguistic construct can describe knowledge. In this case, the descriptor is an element of knowledge and ontology. The key to dictionary ontology is that it provides a consistent foundation for constructing composite knowledge models. The large amount of spatial information used to solve practical problems has led to the need to use it for cognition and management. This situation has led to the need to construct spatial ontologies (Strader et al., 2024; Bateman and Farrar, 2004). Spatial ontologies are a tool for cognition and knowledge acquisition in geoinformatics. A distinctive feature of knowledge in geoinformatics is the use of not only spatial ontologies but also geoinformation ontologies (Rosenberg, 2016). Spatial knowledge includes geoknowledge, spatial relations, and spatial ontologies. Spatial knowledge is often represented visually: digital images, electronic maps, and visual models. This article builds on the work of (Tsvetkov, Kurdyukov, 2024), which focused on spatial ontologies.

2. Discussion and results

Basic Knowledge Models

Basic knowledge models are lower-level ontologies. Alexander's taxonomy (Alexander et al., 1986) distinguishes three types of ontologies: static, epistemic, and dynamic. A static ontology is interpreted as a dictionary ontology. It uses description logic. This logic is also called terminological logic of concepts. It represents domain knowledge in a formalized form that eliminates ambiguity. To link models into a single system, either a rule system or a unifying model is used. Unifying models in computer science, geoinformatics, and the Earth sciences are the information field (Tsvetkov, 2014) and the information space.

In an information field, a descriptor defines the semantic meaning of a model or group of models within the terminological system of the knowledge domain being studied. In geoinformatics, one example of a descriptor is conventional cartographic symbols. The formal approach defines a descriptor as a description of a frame. Frames are also used to describe knowledge. Description logic (Baader et al., 2008) uses the concepts of "concept" and "role," which further links it to ontology and mathematical logic.

At the level of cognitive modeling, concepts are used to describe either categories or classes, for example: "text models," "point models," "linear models," and "areal models." A role is a description of the relationship between pairs of objects. For example, in urban settings, there is a binary relation "City (A) is the parent of Street (B)" or a binary relation "Owner (X) owns House (Y)," where X and Y can be substituted by arbitrary objects. Description logic formulates general statements such as "every owner is a subject," "every real estate is owned," "every city is located in a country".

The basic knowledge model is the information unit – the descriptor. A descriptor is associated with a word or sentence (phrase). By analogy with linguistic units, the concept of an ontological unit can be introduced. A related set of information units creates a more complex construct. For example, a set of related words creates a sentence. If such a sentence is free of contradiction, it is an ontological unit. Ontological units can be combined or mixed. This mechanism creates a new ontology if the resulting mixture is free of contradictions and united by a single theme. An example is an electronic map, which "mixes symbols of three types, inscriptions, and additional designations, all meeting the requirements of cartographic composition". An electronic map may or may not be an ontology. Everything depends on the new knowledge it contains. The basic knowledge model is an ontological information unit.

Mechanisms for constructing knowledge models.

Many geoinformation models have a visual representation. This visual representation has morphology and semantics (Tsvetkov, 2025). This property of geoinformation models enables the application of morphological and semantic modeling. Morphology can contain knowledge. Morphological modeling can create a new type of knowledge, that is, an ontology.

Conceptual blending (CB) is an example of a mechanism for constructing spatial ontologies. Conceptual blending can be interpreted as the blending of concepts. Concepts are a component of ontologies. This mechanism was originally unrelated to ontologies and arose in psychology as a cognitive technology. CB moved into the field of cognitive semantics, then into information modeling. Conceptual blending was developed by J. Fauconnier and M. Turner (2008). The theory of conceptual blending (Gregorcic, Haglund, 2021; Yoon, 2024) states that the relationships between cognitive situations are "blended" in the overall cognitive process of cognition. They view concepts as a factor of cognition.

The theory of conceptual blending in ontology theory asserts that the blending of ontological concepts creates a new ontology. In the modern understanding (Shahrokhi, 2024), this mechanism creates new knowledge. In geoinformatics, this mechanism creates morphological and semantic transformations. Conceptual blending uses the composition of morphologies. Cartographic composition is an analog of such a composition. The process of creating maps can be viewed as conceptual blending. It follows that a map constructed in this way is a spatial ontology.

A distinctive feature of morphological modeling is the presence of two approaches: onomasiological and semasiological. An electronic map is created using onomasiological modeling. In this approach, knowledge elements (information units) create a common complex knowledge model. Another approach is to first blend and then extract knowledge elements. This is semasiological modeling.

The description of spatial situations uses morphological representation as a set of images depicting real objects.

Conceptual blending theory is associated with cognition, and therefore it is associated with ontologies as tools for cognition.

Spatial ontologies are a broader concept than geoinformation ontologies. These ontologies are developed exclusively in geoinformatics. Spatial ontologies can be developed in geodesy, photogrammetry, cartography, remote sensing, image processing, geology, cadastral surveys, and so on. Such ontologies are used in transportation management (Levin et al., 2018) and real estate management (Gurgov, Kurdyukov, 2024). Spatial ontology is a type of information ontology (Tsvetkov, Kurdyukov, 2025). Transportation ontology (Kudzh, Kurdyukov, 2024) can be considered a type of spatial ontology.

Spatial Knowledge Models.

Spatial knowledge models have two main construction methods: informational and ontological. A spatial knowledge model (SKM) can be viewed as a new information model or as the result of ontological modeling and a special case of ontologies. A SKM in geoinformatics can be considered a special geoinformation model. Both types of models belong to the information field (Tsvetkov, 2014). A SKM in geoinformatics becomes an ontology if it contains knowledge.

An information ontology is an information model that contains knowledge and meets the requirements for constructing ontology. Accordingly, a spatial ontology is a geoinformation model that contains spatial knowledge. Spatial information models contain spatial relations (Savinykh, 2017).

Spatial relations are the basis for ontological modeling and the construction of spatial ontologies. Thus, a spatial ontology is interpreted as a geoinformation model that contains knowledge. There may be several geoinformation and spatial ontologies. The simplest geoinformation ontology is a terminological system of cartographic symbols.

Spatial ontology and geoinformation ontology can be epistemic, dynamic, or combined. When describing stationary objects such as maps, epistemic technologies, including vocabulary ontologies, are used. An epistemic ontology describes spatial situations. When studying dynamic processes such as traffic flows, dynamic ontologies or transport ontologies are used. Both ontologies are varieties of information ontology or ontology in the information field. A spatial knowledge model is often an epistemic ontology.

Conceptual blending as a procedure and spatial ontology.

Conceptual blending can be compared to classification since it has two meanings. The result of classification is a classification model. CB and classification as a technology describe certain processes. CB and classification as a result denote constructed models. CB as a result describes a spatial model, which is always an ontology.

Conceptual spatial blending exploits morphological similarities and differences. Conceptual spatial blending is feasible in the presence of figurative models. An important condition for conceptual blending is the presence of spatial relationships between the objects being blended. Spatial relationships are defined by a unified coordinate system.

In general, the process of conceptual mixing of figurative models (fm) can be represented in the form of a formal expression (1).

$$SR\wedge [fm1(x1, y1)\ STR\ fm2(x2, y2)\ STR\ fmn(xn, yn)] \rightarrow CB(x, y) \quad (1)$$

In expression (1) (x1, y1) is the set of points belonging to the spatial image fm1; SR is the spatial relations; fm is the spatial images, the number of which is equal to n; STR is a set-theoretical or logical operation; x, y is the set of points belonging to the result of conceptual mixing CB. The set of spatial images fmn(x, y) in combination with STR and with the relations SR forms the composition CB. Figure 1 shows examples of input spatial images fm1, fm2.

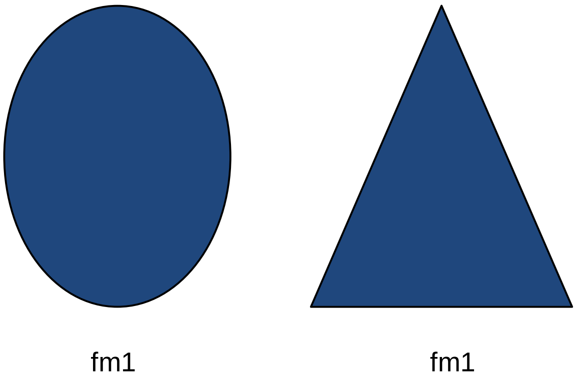

Fig. 1. Example of spatial images of concentrically related figures.

Figure 1 does not show coordinate systems because the geometric centers are connected. This spatial connection precludes the use of coordinate systems.

Figure 2 shows examples of conceptual blending during various blending operations.

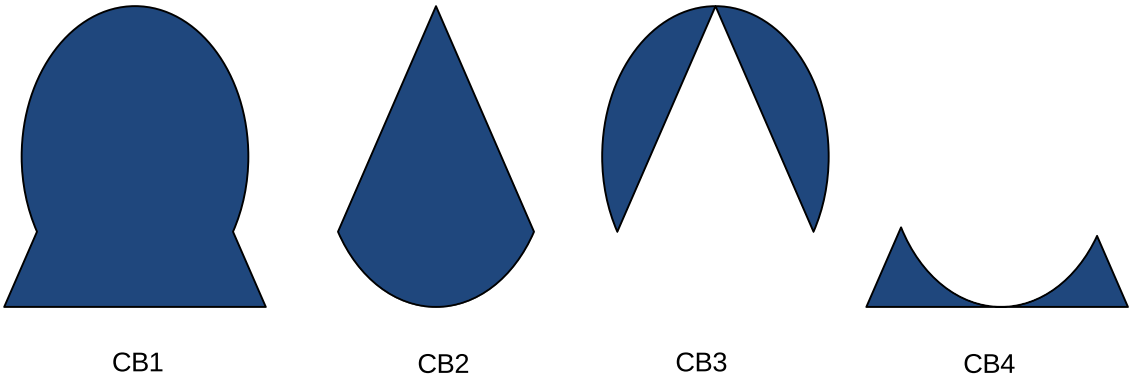

Fig. 2. An example of conceptual blending across different operations

The following operations were applied to Figure 2:

$$CB1=fm1 \cup fm2 \quad (2)$$
$$CB2=fm1 \cap fm2 \quad (3)$$
$$CB3=fm1 - fm2 \quad (4)$$
$$CB4=fm2 - fm1 \quad (5)$$

Expression (2) describes the union of the images fm1 and fm2 and the resulting conceptual blending result CB1. Expression (3) describes CB2 as the intersection of the images fm1 and fm2. Expression (4) describes CB3 as the difference between the images fm1 and fm2. Expression (5) describes the conceptual blending CB4 as the difference between the images fm2 and fm1.

In the given example, the spatial coordinates are defined such that the centers of the figures coincide. In this case, there is no need to introduce coordinate systems. The general conclusion is that conceptual blending creates a spatial composition as a new knowledge model.

Electronic map as a knowledge model.

An electronic map can be either a knowledge model or a spatial model. For example, a photograph is a spatial model and is not a knowledge model. It is a reflection of reality, like a mirror. A knowledge model is something that contains something new, and this newness is definitely knowledge.

Conceptual spatial blending (CB) as a spatial morphological procedure and conceptual blending in digital map construction as a spatially stratified procedure differ. All the conditions of spatial conceptual blending are preserved during digital map construction. In geoinformatics, conceptual blending can be implemented through overlay (Overlay Spatial Analysis) (Kumar, Akkinepally, 2024). This mechanism is used in the construction of digital maps in geographic information systems. The general scheme for digital map construction is more complex. It can also be interpreted as a process of conceptual blending of figurative basic cartographic models (fm).

$$A \wedge SR \wedge [fm1(x1, y1)\ STR\ fm2(x2, y2)\ STR\ fmn(xn, yn)] \rightarrow EM(x, y) \quad (6)$$

Expression (6) shows that the electronic map is realized with an additional parameter, order A, and the same conditions as conceptual blending. The set of spatial models fmn(xn, yn) forms a composition as the electronic map EM(x, y), which is a more complex version of conceptual blending. The electronic map EM and conceptual spatial blending CB have similar construction mechanisms but are qualitatively different. Additional conditions for constructing EM include four components: the presence of order (A) between the original spatial images; the presence of proportionality (Bolbakov, 2022) between spatial information images (this is not necessary for conceptual blending); the presence of a system of spatial information units; and the presence of a single coordinate system for all images.

In conceptual blending, the coordinate system can be replaced by non-fixed spatial relationships, such as the relationship between the centers of figures.

To emphasize the difference between EM and CB, we introduce the concept of a cartographic composition, which corresponds to expression (6). For conceptual blending, we introduce the concept of spatial composition, which is described by expression (1).

The order between spatial images affects the hierarchy of their spatial arrangement during conceptual blending. Many geographic information models are stratified and consist of layers. For a knowledge model, such as an electronic map, the bottom layer typically contains the "world ocean" layer. Next comes the "continents" layer, which represents areal objects. Next comes the layer for state boundaries, which is a linear feature. Lakes and rivers are then added, and so on. If the world ocean were superimposed on top, it would cover all objects, and the model would be uninformative. This suggests that spatial blending is not commutative, and it requires defining an order using cognitive modeling.

The presence of proportionality between information images suggests that geometrically proportionate objects, such as land parcels, cadastral plans, and so on, should be used in constructing electronic maps. Proportionality is interpreted as equal scale. That is, objects of equal scale should be blended. The state and a single plot of land or building cannot be confused. Proportionality is achieved by creating maps of a specific scale.

The presence of a system of spatial information units implies the presence of a basic vocabulary ontology in the form of a thesaurus or cartographic classifier. The spatial ontology created by conceptual blending is a complex object to perceive. A cartographic composition is an example. Reading it requires libraries of cartographic symbols and map design rules.

3. Conclusion

It has been shown that spatial relationships can be defined either through a coordinate system or through tie points of geometric images, such as geometric centers. It can be concluded that spatial blending offers an alternative to the coordinate system in the form of tie point assignment. The spatial composition of a single conceptual blend is implemented according to the principle of "figure-figure blending by tie points or by a common coordinate system." Cartographic composition is implemented according to the principle of "{coordinate system-figure}; {coordinate system-figure}; equal scales; {blending in a single coordinate system}." A prerequisite for creating a cartographic composition is the presence of a stratified hierarchy between the spatial images used to create the electronic map.

This study examines two types of knowledge models: conceptual blending (CB) and electronic map (EM). These spatial models are spatial ontologies. Conceptual blending technology is used in both models, but with varying degrees of detail and under different conditions. Conceptual blending technology can be defined as an ontological modeling technology. An electronic map, as a knowledge model, uses a system of vocabulary ontologies. A photograph, like an image in a mirror, is not an ontology because it does not have a vocabulary ontology.

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Uncertainty of Information and Cyber-Physical Space

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Abstract

The article explores the uncertainty of information space and cyber-physical space. The content of information space and cyberspace is revealed. A new point of view on information space is given. The difference between parametric information spaces and physical information spaces is described. The importance of spatial information in modern society and business is noted. Four types of different information spaces are identified. Virtual space is considered as one of the types of information space. The coordinate system is considered as one of the types of information space. The main purposes of information space are revealed. The analysis of information space shows the objective existence of information uncertainty in it. The reasons for the emergence of uncertainty in information space are shown. The relationship between the information field and information space is noted. The difference between these entities is shown. The importance of spatial relations as a prerequisite and as a factor of uncertainty in information space is noted. The relationship between information space and cyber-physical space is substantiated. The main function of information space is semantics or content. The main function of cyberspace is communication and management. The content of several types of cyberspace is revealed. Social cyberspace is highlighted. The article introduces the concept of partial information uncertainty. Particular information uncertainty characterizes an object, a process, and a situation. The existence of cognitive uncertainty is noted. The content of morphological uncertainty and semantic uncertainty is revealed. The article introduces the concept of spatial uncertainty. The concept of field uncertainty is introduced as a mass uncertainty characteristic of all objects in a given part of the information field or part of the information space. A taxonomy of factors influencing the emergence of uncertainty is provided.

Keywords: information space, cyberspace, types of information spaces, information uncertainty, information field, partial uncertainty, spatial uncertainty, field uncertainty.

1. Introduction

The current state of societal development is characterized by the growth of informatization (Bearman et al., 2023) and the expansion of digitalization. These general trends are well known. However, the fact that spatial information is acquiring increasing importance in modern society is rarely noted. The development of business and production is accompanied by the development of various information spaces and the development of cyberspaces. Information spaces exist in two types: parametric, in the abstract domain, and physical, associated with real space. Physical spatial information is used in construction, transportation (Tsvetkov., Oznamets, 2020), regional economics, and spatial economics (Curry, 2020, Tsvetkov, 2013). All areas encounter information

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uncertainty. Parametric spatial information is used in virtual models and virtual spaces. Cyber-physical spatial information is used in both virtual spaces and physical spaces. It follows that cyber-physical space connects abstract and physical spaces. This property is widely used in digital twin technologies.

Society's development is characterized by the growth of information volumes, including spatial information. The growth of information volumes creates the problem of big data (Himeur et al., 2023, Levin, Tsvetkov, 2017). The growth of information volumes, for example, in transportation is due to the increase in speeds (Connolly, Costa, 2020). Increasing speeds create a vast control space. The growth in information volumes is driven by the use of new data collection technologies, including mobile laser scanning (Gospodinov et al., 2024, Markov, Mitev, 2024) and digital railways (Tsvetkov et al., 2019). This growth in information volumes is driven by the increasing complexity of control situations (Connolly, Costa, 2020).

This growth in information volumes is driven by the use of cyber-physical systems (El-Kady et al., 2023) and information flows obtained through the Internet of Things (Soori et al., 2023). Cloud technologies (Marinescu, 2022) also generate and utilize large volumes of data. All of this increases the relevance of technologies that process and utilize large volumes of spatial information. The growth in information volumes and the increasing complexity of information in physical and parametric spaces entails increased information uncertainty.

2. Discussion and results

Implementation

Content of information spaces.

Information space is interpreted in various ways, and sometimes these interpretations are contradictory. The simplest model of information space is a coordinate system in real space. This model characterizes the information space as a shell for the objects it contains. This model describes a physical information space. No one disputes this model. A complement to the model of such a space is the model of the information field. The information field is analogous to physical fields and abstract fields. Physical information space exists alongside the information field.

Information space is defined as a global sphere in which information is created, transmitted, and consumed. This model is organizational and technological. Such an information space is not so much informational as organizational. It includes physical and non-physical components. Physical components include technical resources, physical infrastructure, physical networks, physical devices, and physical data. Non-physical components of organizational information space include information resources, software, algorithms, and interaction rules. Information space is defined as a virtual space in which virtual models and processes that do not exist in the real world are created. Virtual information space allows for arbitrary scales to be defined for a model of physical space. It allows for events to be slowed down or sped up, and for viewpoints to be selected that are difficult or impossible to select in ordinary space. Virtual information space allows for the flow of time to be set forward or backward. Closely related to virtual information space is immersive space, used in simulators and computer games.

There is a rare definition of information space as a coordinate system in abstract space (mathematics) or as a phased abstract space. This information space is abstract and parametric. Another definition of information space is the space in which mass media operate. This information space can be called mass information space.

The key is that there are different types of information spaces. Each type of space has its own spatial relationships. There is no single definition that describes all the different information spaces. The dogma of one-dimensionality does not apply here. Large volumes of information and the imprecision of measurements and descriptions create information uncertainty.

Analysis of cyberspace.

Cyberspace can be viewed as a modernization of information space. The emergence of the "Internet of Things" led to the coining of the term "Internet of Things space" (Jiao et al., 2021). It is this space that served as the foundation of cyberspace. The term "cyberspace" is polysemic and can refer to various entities.

The concept of "cyberspace" has become polysemic. Cyberspace, as an information space, denotes various entities. Therefore, it is necessary to clarify the specific cyberspace being discussed.

A comparison of information space and cyberspace reveals that cyberspace is a specialized type of information space.

Formally, the term "cyberspace" was introduced by William Gibson in 1982 (Clute, 1984). This term, coined in William Gibson's science fiction, describes cyberspace as a real digital environment and a concept of virtual reality in which people interact with technology and with each other. This generalized concept encompassed various entities.

The term "cyberspace" was officially adopted to denote the World Wide Web or Internet in the 1990s (Lippert, Cloutier, 2021). This meant that cyberspace is an information space whose core is a communications network. This interpretation of cyberspace was linked to its primary function: communication. This type of cyberspace is transborder. Let's designate this cyberspace as "cyberspace 1" or communication cyberspace.

The key aspects of this space are virtual reality and the information aspect. Virtuality is expressed in phenomena similar to the real world, but with new capabilities. The information aspect is expressed in the presence of information flows and data circulating in digital form.

In addition to communication in an open environment, the problem of information security has arisen (Tariq et al., 2023). To ensure information security, a cyberspace has been created that acts as a shell for another space or for a secure object. The key aspect of this space is ensuring information security. Let's designate this cyberspace as "cyberspace 2" or security space. It complements cyberspace 1.

The emergence of the Internet of Things has led to the inclusion of information collection and control functions in cyberspace. A key aspect of this space is real-time control. We will designate this cyberspace as "cyberspace 3" or management cyberspace.

The widespread influence of mass media, especially in interactive mode, has led to the emergence of "social cyberspace." One could continue analyzing the types of cyberspace, but it's easier to refer to the work (Tsvetkov, 2025a), which identifies seven types of cyberspace, excluding social cyberspace.

General conclusion: Information uncertainty is more present in cyberspace than in information space.

Specific information uncertainty.

Information uncertainty is typically attributed to individual objects or processes. This uncertainty is isolated or specific. It is simply defined as a state. An object's state of uncertainty is characterized by contradictory, incomplete, or imprecise information. A situation's state of uncertainty is characterized by the unpredictability of the situation's dynamics and the lack of complete knowledge about the situation. Uncertainty of a situation and an object can be caused by an excess of data that is difficult to analyze. Big data causes this uncertainty. These types of uncertainty are object-specific or isolated. This category includes cognitive uncertainty, caused by a low level of intelligence that precludes the subject's ability to analyze or make decisions. This is subjective uncertainty.

The concept of a "state of uncertainty" should be accepted. However, the concept of an "uncertainty factor" should be added to this characteristic. A state is a generalized concept. It states the presence or absence of uncertainty. An uncertainty factor allows one to find a cause-and-effect relationship between the uncertainty of a state and its causes. There are two other types of informational ambiguity that are little discussed: morphological ambiguity and semantic ambiguity (Tsvetkov, 2025b). Morphological ambiguity is independent of semantic ambiguity. Semantic ambiguity and morphological ambiguity depend on situational ambiguity, that is, on the situation in which the object finds itself.

Morphological figurative ambiguity arises when the object model is a visual image and there is a lack of information in its clear description or interpretation. For example, an object may have the shape of a circle or an ellipse. There is morphological ambiguity of reciprocity or spatial relationships. It is expressed in the fact that the intersection area of objects, due to their morphological ambiguity, may have different shapes and different sizes. An example of morphological figurative ambiguity is topological ambiguity. A topological model expresses the main properties from a topological perspective and excludes secondary properties. The main properties are structural relatedness and the possibility of topological transformation. Topology excludes properties such as metric dimensions and area. Topology precludes coordinate referencing of figures. Topological models contain metric and coordinate uncertainty. This determines the content of topological uncertainty.

Semantic uncertainty exists in semantic modeling and appears in processes that use semantics. One approach to assessing it is the Dempster-Shafer theory [3csf] or DST. It is called "Mathematical Theory of Proofs," but is actually a theory of assumptions and reasoning. It is permissible within certain conditions that allow the application of this theory.

Spatial or Field Uncerta

Uncertainty in information space differs from individual uncertainty. It has a number of additional factors. One cause of information uncertainty in cyberspace and information space is the problem of polysemy and terminological relationships. In cyberspace and information space, an additional cause of uncertainty arises in the form of uncertainty in the relationships between spatial objects. Spatial relationships can determine the uncertainty factor. For example, a train is a clearly defined object. A railroad track is a clearly defined object. A station is a clearly defined object. However, the train's arrival at the station may not be precisely determined due to stochastic factors during travel.

Closely related to uncertainty in information space is field uncertainty. Field uncertainty is a mass uncertainty characteristic of all objects in a given part of a field or part of space. Field uncertainty, which translates into uncertainty in information space, can be caused by interactions in the field that cause uncertainty in space.

An example is the Heisenberg Uncertainty Principle. This is a fundamental law of quantum mechanics, stating that it is impossible to simultaneously measure certain pairs of quantities, such as the position and momentum of a particle, with absolute precision: the more precisely one is known, the less precisely the other. This is not a limitation of our instruments, but a property of the very nature of quantum objects (their wave-particle duality). The uncertainty principle mathematically describes the lower limit for the product of the uncertainties of these quantities.

For information space and the information field, for cyberspace, there is spatial uncertainty that complements object or situational uncertainty. This uncertainty is determined by spatial relationships and spatial interactions. This uncertainty is determined by the fundamental properties of matter, such as the Heisenberg Uncertainty Principle or the "Law of Chiral Purity." The "law of chiral purity" is a fundamental observation in biology that life preferentially utilizes one of the mirror isomers (enantiomers): all amino acids in proteins are "left-handed" (L-amino acids), while sugars in DNA/RNA are "right-handed" (D-sugars). This property, called homochirality or chiral purity, is critically important for the functioning of biomolecules (proteins, DNA), but its origin and mechanism of occurrence in early life remain a mystery. Recently, this law has been studied in cybernetics and computer science for the possibility of cloning or the "purity" of cloning.

An example of spatial certainty and uncertainty is shown in Figures 1 and 2.

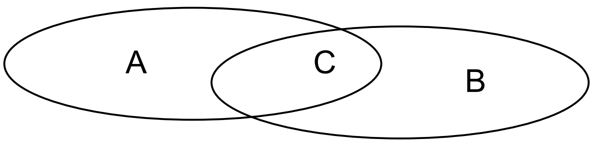


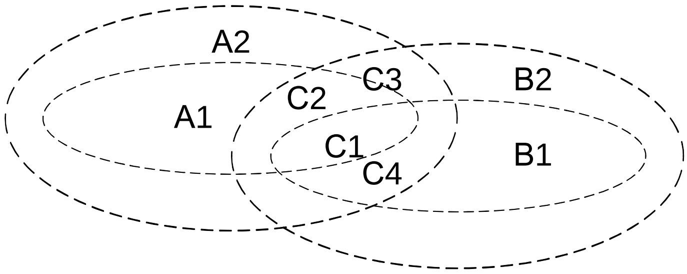
Fig. 1. Spatial Definition

Figure 1 shows three defined sets related by the relation

$$C=A \cap B \quad (1)$$

The definiteness of sets is shown by solid lines. Set C is uniquely defined as the intersection of distinct sets A and B.

Figure 2 shows a spatial situation with uncertainty. The uncertainty of sets is shown by the dashed boundaries of the sets.



The definiteness of sets is shown by solid lines. Set C is uniquely defined as the intersection of distinct sets A and B.

Figure 2 shows a spatial situation with uncertainty. The uncertainty of sets is shown by the dashed boundaries of the sets.

$$A \to A1, A2 \quad (2)$$

$$B \to B1, B2 \quad (3)$$

$$C \to C1, C2, C3, C4 \quad (4)$$

The resulting uncertainty is expressed through the set C. The intersection set is not uniquely defined and is estimated using the formulas.

$$C1 = A1 \cap B1 \quad (5)$$

$$C2 = A2 \cap B2 \quad (6)$$

$$C3 = A1 \cap B2 \quad (7)$$

$$C4 = A2 \cap B1 \quad (8)$$

Spatial uncertainty creates ambiguity in the description and representation of a portion of space. Spatial uncertainty can be represented as a discrete set of dimensions. Depending on the context, each of the expressions (5-8) has a most probable meaning. This uncertainty is resolved through additional contextual analysis.

3. Conclusion

There is no single definition that describes different information spaces. Analysis shows that four types of information spaces must be distinguished: physical, organizational, virtual, and mass. These types of spaces have different dominant spatial relationships and different primary processes. Cyberspace, as an information space, denotes different entities. It is necessary to clarify in each case which cyberspace is being discussed.

Information uncertainty is usually attributed to individual objects, situations, or processes. It is simply defined as a state. This uncertainty is called individual and can be: object uncertainty, procedural uncertainty, and situational uncertainty. The state of individual uncertainty is characterized by contradictory, incomplete, and inaccurate information. Uncertainty in information space and cyberspace differs from individual uncertainty. Uncertainty in the physical field and information field differs from the individual uncertainty of objects.

Spatial relationships in information space or cyberspace can cause uncertainty. Interactions in information space or cyberspace can cause uncertainty. Cognitive relationships in information space or cyberspace can cause uncertainty.

Uncertainty research has not yet led to a standardized concept of morphological uncertainty. Figurative morphological uncertainty visually reveals confidence intervals and uncertainty zones. Spatial uncertainty creates ambiguity in the description and representation of a part of space. Spatial uncertainty allows for the application of morphological assessment methods. Spatial uncertainty is related to field uncertainty. Field uncertainty allows for quantitative and functional assessments. Spatial uncertainty can be represented as a discrete set of sets.

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Analysis of Data Visualization Tools Application

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Abstract

The article studies the application of analytical data visualization tools to support management decisions in the company based on the literary analysis and expert survey. A comparative analysis of visualization tools is carried out according to the criteria of convenience for analysts and management, the possibilities of interactive analysis and adaptation to specific tasks of business informatics. It has been demonstrated that the use of modern data visualization tools in business analytics allows organizations to enhance the transparency of business processes, optimize the decision-making cycle, and improve the efficiency of information resource use. Taken together, this is seen as an important factor in strengthening a company's competitive position and increasing the effectiveness of its digital transformation strategy.

Keywords: data visualization, business analytics, BI systems, data-driven management, management decisions.

1. Введение

Современный бизнес сталкивается с необходимостью принимать решения в условиях высокой неопределённости, возрастающих объёмов данных и жёсткой конкуренции, что усиливает роль бизнес-аналитики как ключевого инструмента управления на основе данных. В этой связи традиционные методы отчётности, основанные на статичных таблицах и разрозненных источниках информации, перестают обеспечивать требуемую скорость, наглядность и глубину анализа для менеджмента разных уровней. Это обусловливает переход к применению современных аналитических инструментов визуализации данных и BI-систем, интегрированных с корпоративными информационными системами (CRM, ERP, системы учёта и маркетинговой аналитики), что позволяет формировать целостное представление о деятельности компании, оперативно выявлять отклонения и оценивать влияние управленческих решений. Актуальность такого подхода подтверждается исследованиями в области бизнес-аналитики, цифровой трансформации и управления эффективностью, где подчёркивается значимость визуальных дашбордов и интерактивных отчётов для мониторинга ключевых показателей, анализа поведения клиентов и оценки рентабельности бизнес-инициатив (Рязапов, 2025).

2. Обсуждение

Определено, что основные проблемы классического подхода к аналитике связаны с высокой трудоёмкостью подготовки отчётности, рисками ошибок при ручной обработке данных, запаздывающей информацией и низкой доступностью аналитики для

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непрофессиональных пользователей (Сорокина, Федоряк, 2022). Отдельной задачей является недостаточная визуальная интерпретируемость сложных показателей (например, связки финансовых и операционных KPI), что затрудняет выявление скрытых закономерностей и коммуникацию результатов анализа между ИТ-специалистами, аналитиками и бизнес-подразделениями. В качестве решения обозначенных проблем обосновывается целесообразность внедрения аналитических инструментов визуализации данных и BI-платформ, обеспечивающих автоматизированную интеграцию данных, построение интерактивных дашбордов, поддержку многомерного анализа и адаптацию представлений под потребности различных ролей в системе управления, что рассматривается как важный элемент построения ИТ-архитектуры предприятия (Ильяшенко и др., 2017).

В работах по бизнес-аналитике отмечается, что опора исключительно на традиционные методы отчётности в виде статичных таблиц и разрозненных Excel-файлов приводит к запаздывающей реакции на изменения внешней и внутренней среды, информационной перегрузке менеджеров и повышенному риску ошибок при интерпретации данных (Старых, 2023). Это ограничивает возможности оперативной реализации управленческих решений и снижает эффективность использования накопленной корпоративной информации. В то же время развитие BI-платформ и специализированных инструментов визуализации данных позволяет перейти от фрагментарной аналитики к целостному, интегрированному представлению о деятельности компании, поддерживая сценарии интерактивного анализа, мониторинга KPI и моделирования вариантов развития (Тенденции развития..., 2025).

Для сопоставления традиционного подхода к аналитике и подхода, основанного на использовании современных инструментов визуализации, рассмотрим ключевые показатели, влияющие на качество и скорость принятия управленческих решений в сфере бизнес-аналитики (Таблица 1; Гудзь, Цуканова, 2019).

Таблица 1. Сравнительная характеристика традиционного подхода и использования инструментов визуализации данных

Показатель	Традиционный подход	Подход с визуализацией
Скорость получения управленческой информации	Низкая: длительная ручная подготовка отчётов	Высокая: оперативные дашборды в режиме близком к реальному времени
Наглядность и интерпретируемость данных	Низкая: перегруженные таблицы, сложность восприятия	Высокая: графики, диаграммы, интерактивные панели
Риск ошибок при обработке данных	Повышенный из-за ручных операций	Сниженный за счёт автоматизации загрузки и обновления данных
Доступность аналитики для менеджмента	Ограниченная, требует участия аналитика-«переводчика»	Расширенная: самообслуживание, интерактивная фильтрация
Глубина анализа и выявление закономерностей	Ограниченная, фокус на описательной статистике	Расширенная: сценарный, многомерный и визуальный анализ
Скорость реакции на изменения показателей	Запаздывающая	Оперативная за счёт мониторинга KPI в дашбордах
Поддержка культуры управления на основе данных	Слабая, аналитика воспринимается как вспомогательная функция	Сильная, аналитика интегрируется в ежедневные управленческие практики

Таким образом, проблема фрагментарной и запаздывающей аналитики в организациях требует комплексного решения, основанного на внедрении современных инструментов визуализации данных и интегрированных BI-платформ, позволяющих обеспечить целостное и наглядное представление о ключевых показателях деятельности и ускорить цикл принятия управленческих решений. На основе анализа публикаций в области бизнес-аналитики и цифровой трансформации предложена характеристика основных тенденций внедрения визуально-аналитических решений в корпоративную практику (Таблица 2; Чаплыгина, Котовенко, 2024).

Таблица 2. Ключевые тенденции развития инструментов визуализации данных и их преимущества для бизнес-аналитики

Тенденция	Преимущества использования
Интеграция платформ аналитики с корпоративными системами (системы планирования ресурсов, управления взаимоотношениями с клиентами, системы учёта и маркетинговой аналитики)	Консолидация данных из разрозненных источников в единую аналитическую среду, формирование целостной картины деятельности компании и снижение трудоёмкости подготовки управленческих отчётов
Развитие интерактивных информационных панелей и панелей мониторинга	Сокращение времени на получение актуальной информации, повышение доступности аналитики для менеджмента без участия специалистов по информационным технологиям, поддержка самообслуживания и интерактивной фильтрации данных
Применение многомерного анализа и углубленной детализации	Углубление анализа за счёт детализации показателей до уровня продуктов, клиентов и каналов, выявление скрытых закономерностей и факторов, влияющих на ключевые показатели
Использование визуализации для коммуникации результатов анализа	Повышение наглядности сложных метрик, упрощение обсуждения аналитических выводов между аналитиками и подразделениями компании, снижение риска неверной интерпретации данных руководством
Внедрение автоматизированных систем мониторинга ключевых показателей	Оперативное выявление отклонений, поддержка регулярного контроля целевых показателей, усиление культуры управления на основе данных на всех уровнях организации
Развитие облачных платформ аналитики и сервисов по требованию	Снижение затрат на инфраструктуру и поддержку, быстрое масштабирование аналитических решений, обеспечение доступа к информационным панелям для распределённых и удалённых команд
Интеграция визуализации с предиктивной аналитикой и моделями машинного обучения	Автоматизированное выявление трендов и аномалий, визуальное представление прогнозов и сценариев, повышение обоснованности стратегических и тактических управленческих решений

На основе анализа литературы по бизнес-аналитике и управлению на основе данных установлено, что современные инструменты визуализации информации выступают ключевым элементом повышения эффективности управленческих решений в компаниях.

Визуальный формат представления показателей позволяет не только упростить восприятие сложных массивов данных, но и обеспечить их оперативную интерпретацию руководителями и специалистами без углублённой подготовки в области аналитики.

Опираясь на принципы системного анализа и комплексной оценки факторов, влияющих на деятельность организации (динамика продаж, эффективность маркетинговых мероприятий, поведение клиентов, структура затрат), аналитические панели и отчёты наглядно демонстрируют взаимосвязи между ключевыми показателями и сценариями развития ситуации (Ильяшенко и др., 2017). Интеграция визуальных инструментов с корпоративными информационными системами позволяет автоматизировать обновление данных и запуск алгоритмов пересчёта показателей, что сокращает временные затраты на подготовку отчётности и снижает риск ошибок ручной обработки (Сунгатуллин, 2025).

Такой подход обеспечивает реализацию концепции гибкого управления, когда руководители получают возможность своевременно реагировать на отклонения значений показателей, оценивать последствия принимаемых решений и корректировать планы на основе фактической информации, представленной в наглядной форме. Визуальные дашборды, отражающие структуру выручки, динамику спроса, загрузку ресурсов и достижение целевых ориентиров, способствуют более полному использованию потенциала накопленных данных и формированию устойчивой практики управления на основе доказательной аналитики.

3. Результаты

В рамках исследования проведен опрос среди 34 компаний, в результате чего получены следующие данные. В большинстве организаций при подготовке отчетов по-прежнему используют Excel – 48 % респондентов выбрали этот вариант. Тем не менее, современные BI-платформы уже используют 34 %, а комбинированный подход – 18 %. Получение управленческой информации часто остаётся медленным: 44 % отметили низкую скорость, только 30 % достигли высокого уровня оперативности. Более половины участников (54 %) хотя бы частично используют интерактивные дашборды для мониторинга KPI, но всё ещё много тех, кто их не использует вовсе – 46 %. Наиболее популярные инструменты визуализации – Tableau и Power BI (42 %), однако 28% компаний визуализацию не применяют совсем. Обновление данных в аналитических системах происходит в режиме реального времени только у 30 % организаций, чаще всего (42%) данные обновляются ежедневно. Большинство сотрудников имеют средний уровень подготовки к работе с инструментами визуализации (48 %), а продвинутый уровень у 32 %. Полную интеграцию аналитики с корпоративными системами реализовали 46 % компаний, у 36 % интегрировано несколько систем, а у 18 % только одна. Самый высокий показатель внедрения передовых технологий – использование многомерного анализа и методов машинного обучения – 56 %. В то же время 18 % компаний не используют такие подходы вовсе. Основная преграда для развития – сопротивление организационным изменениям (50 %), далее идут недостаток бюджета (26 %) и компетенций (24 %). Лидирующее число (54 %) отметили сильную трансформацию корпоративной культуры в сторону управления на основе данных.

4. Заключение

Таким образом, применение современных инструментов визуализации данных в сфере бизнес-аналитики позволяет организациям повысить прозрачность бизнес-процессов, оптимизировать цикл принятия решений и увеличить результативность использования информационных ресурсов. В совокупности это рассматривается как важный фактор укрепления конкурентных позиций компании и повышения эффективности реализации стратегии цифровой трансформации.

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Анализ применения инструментов визуализации данных

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Аннотация. В статье изучается применение аналитических инструментов визуализации данных для поддержки управленческих решений в компании на основе литературного анализа и экспертного опроса. Проведен сравнительный анализ инструментов визуализации по критериям удобства для аналитиков и менеджмента, возможностям интерактивного анализа и адаптации под специфические задачи бизнес-информатики. Показано, что применение современных инструментов визуализации данных в сфере бизнес аналитики позволяет организациям повысить прозрачность бизнес процессов, оптимизировать цикл принятия решений и увеличить результативность использования информационных ресурсов. В совокупности это рассматривается как важный фактор укрепления конкурентных позиций компании и повышения эффективности реализации стратегии цифровой трансформации.

Ключевые слова: визуализация данных, бизнес-аналитика, BI-системы, управление на основе данных, управленческие решения.

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Development of Dynamic Geoinformatics

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Abstract

The article explores a new direction in geoinformatics – dynamic geoinformatics. The diversity of spatial data and temporal problems motivates the differentiation of applied geoinformatics. Dynamic geoinformatics is a development of applied geoinformatics and studies a special area of dynamic processes and dynamic states. The article shows the place of dynamic geoinformatics in the system of sciences. The structure of dynamic geoinformatics is studied. The significance of two types of monitoring in dynamic geoinformatics is shown. Dynamic geoinformatics uses a system of models and a system of technologies. The main theory of dynamic geoinformatics is spatial and temporal analysis. It includes the study of information uncertainty. An important technology of dynamic geoinformatics is geoinformation monitoring. It includes state monitoring and process monitoring. These types of monitoring allow the formation of models in three-dimensional and analytical form. Models facilitate decision-making and compress information in conditions of large volumes. The main theoretical direction of research in dynamic geoinformatics is associated with the study of spatio-temporal processes and the identification of functional dependencies in a spatial environment. The information field and information space are used as auxiliary models in dynamic geoinformatics. The primary goal of dynamic geoinformatics is to generate new knowledge. Dynamic geoinformatics is applied in high-speed and intelligent transport. It is essential for unmanned transport systems.

Keywords: dynamic geoinformatics, applied geoinformatics, spatial monitoring, temporal data.

1. Introduction

The development of dynamic photogrammetry (Blume et al., 2020) contributed to the emergence of dynamic geoinformatics (Raev, 2022). Dynamic geoinformatics is a development of applied geoinformatics (Elbshbeshi et al., 2023). The main research focus in dynamic geoinformatics is the study of spatio-temporal processes and patterns in the environment. The information field and information space are auxiliary models used in dynamic geoinformatics. Dynamic geoinformatics is constantly evolving, driven by the needs of society, science, and technology. The development of dynamic geoinformatics depends on the areas of its application. These areas include transportation, Earth exploration from space, and artificial intelligence. Dynamic geoinformatics, like classical geoinformatics, is a spatial science (Gospodinov, 2022). The object of study is processes and states in space. Dynamic geoinformatics is primarily the science of dynamic spatial processes. Research in the field of intelligent UAVs falls within the field of dynamic geoinformatics (Tsvetkov, Oznamets, 2020).

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2. Results and discussion

The place of dynamic geoinformatics in the system of sciences.

Dynamic Geoinformatics is a development of applied Geoinformatics. It is related and interacts with transport Geoinformatics, ballistics, logistics Geoinformatics, space Geoinformatics, Earth exploration from space, cadastre, ecology, land use, and military operations. The place of Dynamic Geoinformatics (DG) among other sciences is shown in Figure 1. Logistics Geoinformatics (Ndayishimiye, 2023) occupies an intermediate position between applied Geoinformatics and dynamic Geoinformatics. Transport Geoinformatics is most closely related to DG. Transport poses special challenges for Dynamic Geoinformatics. Dynamic Geoinformatics in the field of transport studies fast and slow processes. Fast processes include the movement of vehicles. Slow processes include changes in the state of the transport infrastructure.

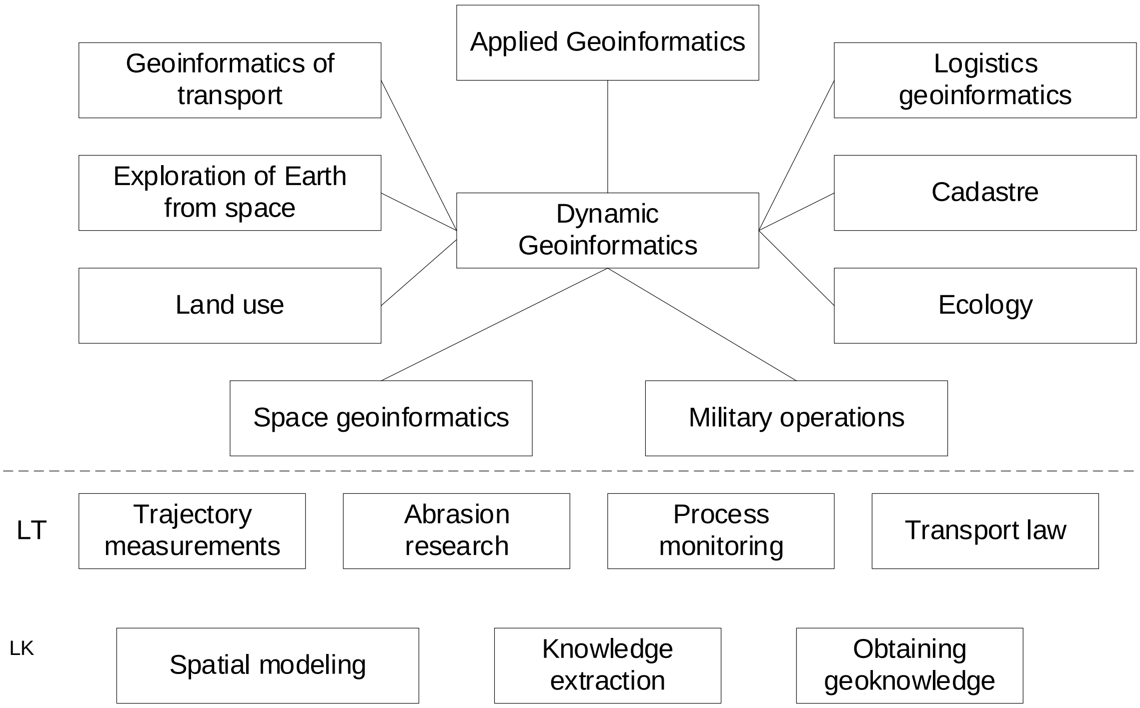

Fig. 1. The place of dynamic geoinformatics among other sciences.

Modern transportation includes intelligent transport (Gong et al., 2023), cyber-physical transport systems (Levin, Tsvetkov, 2018), and unmanned vehicles, transport robots, digital transport (Tsvetkov et al., 2019), and digital twins (Attaran, Celik, 2023). All modes of transport are studied using dynamic geoinformatics.

Dynamic geoinformatics is applied in Earth exploration from space. It is used to monitor the dynamics of the Earth's surface based on remote sensing data. DG, as part of space monitoring, is used for global control of vehicles, primarily maritime transport.

Dynamic geoinformatics is used in land use, cadastral surveys, and ecology. In these areas, it is used to monitor the state of the environment and the Earth's surface. Dynamic geoinformatics is used in conjunction with space geoinformatics to study the motion of celestial bodies. DG is used in combat operations to monitor the position of enemy forces and identify hidden changes in the situation of their armed forces. Dynamic geoinformatics has two levels of implementation: the technology level (LT) and the knowledge level (LK).

The technology level includes specific or frequently used technologies. The knowledge level contains research results in the form of process models or knowledge models. Examples at the technology level include technologies for trajectory measurements of ballistic and tactical missiles; coastal abrasion monitoring; monitoring of transport processes; and transport law. Transport law is considered in connection with the development of digital transport and digital law. At the DG knowledge level, spatial modeling, knowledge extraction in the form of ontology models, and spatial knowledge extraction in the form of spatial ontologies are noted. Dynamic geoinformatics is aimed at obtaining spatial knowledge (Lin et al., 2020) and geoknowledge.

Modern dynamic geoinformatics uses spatial dynamic models (Rosenberg, Tsvetkov, 2010). Dynamic geoinformatics develops spatial monitoring (Shahzaman et al., 2010), which supports the management of dynamic infrastructure. Spatial monitoring in dynamic geoinformatics is based on geoinformation monitoring and uses temporal data. Dynamic geoinformatics uses two types of monitoring: state monitoring and process monitoring. Geoinformation monitoring of states uses temporal labels and time series. Geoinformational process monitoring reveals temporal functions.

Characteristics of dynamic geoinformatics

Geoinformatics applies five basic classes of models: data models, object models, process models, spatial situation models, and knowledge models. Dynamic geoinformatics applies the same classes of models, but the main classes of DG are the class of process models and the class of situation models. Dynamic geoinformatics applies spatial logic (Dolgy et al., 2021) to the study of complex situations involving the movement of unmanned vehicles. Modern dynamic geoinformatics applies spatial analysis and logic to the study of the movement of transport modes: digital railways, cyber-physical transport systems (Pundir et al., 2022), unmanned vehicles (Dolgy et al., 2021), high-speed transport, and transport robots.

Qualitative analysis in dynamic geoinformatics revealed the presence of dynamic geoinformatics categories. Categories in dynamic geoinformatics can be considered the most general concepts that divide the DG research area into subdomains. The boundaries of categories are fuzzy and overlap. This situation necessitates the use of fuzzy set theory. Categories in dynamic geoinformatics are a means of knowledge generalization. A common category in dynamic geoinformatics is the "information field." Studying these categories reveals the state and development trends of dynamic geoinformatics. Categories in dynamic geoinformatics help explore its structure. Figure 2 shows the categorical structure of dynamic geoinformatics.

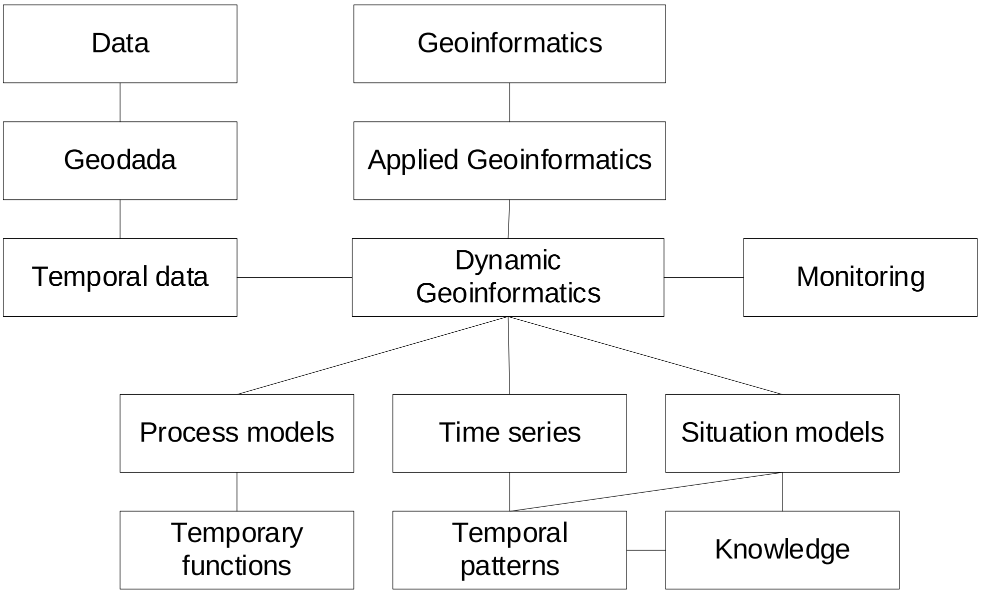

Fig. 2. Structure of dynamic geoinformatics

Modern dynamic geoinformatics uses automated measurement systems to collect data. Initial spatial data is transformed into geodata. The time factor is important for dynamic geoinformatics. This is reflected in the use of temporal data, which is not used as extensively in other types of geoinformatics. In modern dynamic geoinformatics, information is collected using a variety of sensor systems.

Dynamic geoinformatics is based on the integration of dynamic process research, applied geoinformatics methods, dynamic photogrammetry methods, spatial monitoring methods, spatial management methods, and informatics.

Informatics is the methodological basis for information processing. Currently, a large amount of information is received visually. This creates the need for intelligent processing of sensory data. The cognitive factor is taken into account through the use of information reception technologies.

Monitoring is an important component of dynamic geoinformatics. In monitoring, the primary object of observation is a spatial complex, including objects, situations, processes, process patterns, and interaction models. Based on observations and monitoring, time series, process models, and situation models are created. Monitoring results are stored in spatial databases or geodatabases. Monitoring in dynamic geoinformatics is used to study the condition of right-of-way.

Models of information situations are also important for dynamic geoinformatics. The dynamics of object movement are assessed relative to spatial information situations. In dynamic geoinformatics, two types of information situations are qualitatively distinguished: moving (dynamic) and external (stationary). A moving information situation represents the immediate surroundings of an object. It moves along with the object. For a transport object, this includes a railway track and objects adjacent to the route: crossings, trees, other vehicles, and animals. For an aircraft or an incoming missile, this is the potential impact zone around the object.

Dynamic geoinformatics uses spatial logic to study complex spatial situations. Dynamic geoinformatics observes and analyzes the movement of vehicles. The main object of study in dynamic geoinformatics is a complex model that includes a moving object and a dynamic situation. Space-based dynamic geoinformatics is used to monitor the Earth's surface and space objects.

The volume of data in space-based dynamic geoinformatics is significantly larger than in stationary geoinformatics systems. This is due to the large flow of counter-information along the path of a moving object. This counter-information includes not only the visible or immediate area but also information hidden several kilometers away that can affect the object's movement. For this reason, a number of moving objects (unmanned vehicles, cyber-physical transport systems) have built-in onboard computers.

The large volumes of data that onboard computers must process are processed using artificial intelligence methods. This is the only option for controlling high-speed objects. This also creates a connection between dynamic geoinformatics and artificial intelligence. This connection leads to control theory being included in dynamic geoinformatics to a greater extent than in applied geoinformatics.

A contemporary feature of dynamic geoinformatics is its consideration of the digital transformation of society and mobile objects.

Since the scale of information situations studied in dynamic geoinformatics is very large, it is necessary to use models to support situation analysis. The main support models are various spaces: Such support models for dynamic geoinformatics include information space (Hughes et al., 1997), cyberspace (McCarthy, 2018), information field (Tsvetkov, 2014), and transport cyberspace.

DG uses various types of modeling. Geoinformation modeling (Samoilenko et al., 2021) and information modeling are the most important types of modeling. Newer types include onomasiological modeling and semasiological modeling. Information interactions are also important for dynamic geoinformation systems due to the highly dynamic nature of situations. Types of information interactions in dynamic geoinformation systems are divided into object-based, subject-based, and situational. Monitoring moving objects in dynamic geoinformation systems primarily examines the dynamics of movement and, secondarily, the dynamics of state. This is an operational task. The tactical task consists of identifying patterns in the object's movement. Overall, dynamic geoinformation systems examines a spatial complex, including objects, situations, processes, interactions, as well as the connections and relationships between them. All of this together forms the basis for developing a spatial ontology.

The construction of spatial models utilizes a semiotic approach. This involves using information units as a vocabulary ontology. For moving objects, the semantics of the object are considered first and foremost, followed by its morphology. The processing results in the creation of digital maps and digital models.

Dynamic geoinformatics utilizes complex spatial and temporal analysis. Complex analysis includes qualitative analysis, comparative analysis, system analysis, situational analysis, logical analysis, correlative analysis, semantic analysis, and cause-and-effect analysis. Complex analysis in dynamic geoinformatics utilizes spatial and environmental information. The results of the analysis are stored in databases. The analysis identifies latent variables, reveals tacit knowledge, and makes predictions. The overall result of the analysis is the acquisition of new knowledge about movement patterns.

A prerequisite for the functioning of dynamic geoinformatics is the use of a unified global coordinate system. Many types of applied geoinformatics make do with local coordinate systems. In these cases, research is conducted in a single local spatial zone. The global coordinate system of dynamic geoinformatics allows for the comparison of observation results obtained in different spatial zones. The primary information system in dynamic geoinformatics is a geographic information system (GIS). Technically, a GIS simplifies the interaction of attributes with spatial data. GIS reduces the user's workload when analyzing situations and traffic patterns.

Dynamic geoinformatics is used to assess the dynamics of the impact of harmful pollutants. Environmental assessments are performed in three ways. The first relates to the impact of transport on environmental pollution. The second relates to the impact of industrial pollutants on the environment. The third relates to the placement of housing and green spaces. Therefore, dynamic geoinformatics addresses placement issues.

3. Conclusion

Dynamic geoinformatics emerged from applied geoinformatics as a unified group of methods and tasks for studying spatial dynamic processes. The results of such research are temporal functions or time series. Dynamic geoinformatics enables retrospective analysis and forecasting of future processes. Dynamic geoinformatics primarily studies processes and, secondarily, the state of observed objects. Dynamic geoinformatics of transport networks studies the state and deformation of networks. It primarily studies the geometry and, secondarily, the topology of networks. Dynamic geoinformatics of transport studies the movement of various objects: conventional trains, digital railways, cyber-physical transport systems, unmanned systems, and transport robots. From space, dynamic geoinformatics studies the dynamics of the Earth's surface state and processes on the Earth's surface. In this area, it is closely related to space geoinformatics.

DG is the primary tool for analyzing the state and development of processes in geosystems. The use of dynamic geoinformatics is an essential component of transport management.

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Letters to the Editorial Board

Improvement of the Process of Monitoring the Condition of Technological Equipment

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Abstract

In the context of industrial digital modernization, upgrading approaches to monitoring the condition of technical units becomes crucial for enhancing the resilience and efficiency of industrial enterprises. The use of intelligent analytical systems and industrial internet of things technologies is particularly relevant, where the timeliness and completeness of information directly determine the possibilities for preventing emergencies and rational allocation of maintenance resources. The implementation of innovative monitoring tools allows for the restructuring of maintenance processes, reduction of labor costs, and minimization of the likelihood of unplanned shutdowns. This paper analyzes the main benefits of modernizing monitoring systems, including increased productivity, extended intervals between repairs, and improved stability of production operations. Special attention is paid to the difficulties faced by domestic enterprises in implementing such projects: significant initial investments, the need for personnel retraining, compatibility issues with existing control systems, and threats in the field of information security. Based on the study of Russian experience and research data, practical recommendations are formulated for the successful updating of monitoring processes. The material is of interest to specialists in production asset management, IT experts, and managers interested in strengthening the operational resilience of industrial facilities.

Keywords: equipment condition monitoring, predictive analytics, industrial internet of things, production assets, scheduled maintenance, digital model, operational availability, information security.

1. Введение

В современный период модернизация методов контроля технического состояния производственных активов выделяется как один из определяющих векторов развития отечественных промышленных организаций. Данная тенденция обусловлена требованиями к повышению отказоустойчивости, возрастающей ценой простоев и усилением роли профилактических стратегий в обслуживании. Переход к прогнозным моделям особенно важен для наукоемких отраслей, где исправность активов напрямую коррелирует с показателями безопасности и экономической результативности (Кибербезопасность…, 2025).

2. Обсуждение

Согласно аналитическим оценкам, свыше 40 % крупных отечественных промышленных организаций уже применяют или рассматривают возможность применения интеллектуальных систем контроля на базе технологий IIoT. Это связано с тем, что современные методы наблюдения обеспечивают не только регистрацию актуальных параметров, но и прогнозирование остаточного эксплуатационного потенциала, что существенно улучшает управление жизненным циклом активов, уменьшает непредвиденные расходы и способствует развитию производственной культуры (Исследование дефицита..., 2025).

Однако реализация проектов по внедрению усовершенствованных систем контроля сопряжена с комплексом трудностей, которые требуют учета для результативной технологической трансформации. В представленной работе исследуются как потенциальные выгоды, так и вероятные риски, а также предлагаются практические меры для отечественных организаций (Влияние цифровой..., 2025).

К числу важнейших преимуществ современных решений относится существенное повышение детализации и регулярности сбора диагностической информации. К примеру, постоянное наблюдение за вибрационными характеристиками, термическими режимами, уровнями давления с применением беспроводных сенсорных сетей обеспечивает получение актуальных данных в режиме реального времени. Применение подобных систем на отечественных производствах позволяет обнаруживать отклонения на 60–80 % раньше по сравнению с традиционными методами плановых проверок, что способствует недопущению серьезных поломок (Интеграция систем..., 2025).

3. Результаты

Модернизация контроля минимизирует субъективное влияние человеческого фактора на диагностические процедуры, что имеет особое значение для сложных технологических комплексов. Так, системы прогнозной аналитики способны автономно исследовать спектральные характеристики вибрации, идентифицировать зарождающиеся дефекты в подшипниковых узлах или дисбаланс роторных систем и формировать прогнозные заключения без субъективной трактовки оператора. Это снижает риск пропуска дефектных состояний и повышает обоснованность принимаемых решений (Таблица 1; Эффективность внедрения..., 2025).

Таблица 1. Сопоставление методик контроля до и после внедрения систем прогнозного мониторинга (Интеграция систем..., 2025)

Контролируемый параметр	Традиционная методика (периодический/ ручной сбор)	Современная методика (постоянный/ прогнозный анализ)	Эффект улучшения, %
Регулярность сбора вибродиагностических данных	1 раз в 1–3 месяца	Постоянно, в реальном времени	Более 1000 %
Срок обнаружения развивающегося дефекта (на примере подшипника качения)	30–60 суток до отказа	90–180 суток до отказа	Упреждающий период увеличен в 2–3 раза
Трудозатраты на сбор информации (на агрегат в год)	40 человеко-часов	5 человеко-часов	Уменьшение на 88 %
Вероятность необнаружения критической неисправности	15–25 %	2–5 %	Снижение на 75–85 %

Современные технологические платформы дают возможность реализовать концепцию обслуживания по фактическим показателям состояния, что заметно повышает рациональность использования ресурса агрегатов. Например, платформы, использующие цифровые модели, анализируют операционные показатели, архив отказов и нагрузочные режимы, что позволяет точно определять оптимальные моменты для замены компонентов.

Организации, внедрившие подобные системы, фиксируют рост продолжительности работы между капитальными ремонтами на 20–40 % (Кибербезопасность..., 2025).

Кроме того, соединение систем контроля с корпоративными системами планирования ресурсов предприятия и управления основными фондами позволяет автоматизировать процедуры составления ремонтных графиков, заказа комплектующих и формирования нарядов. Автоматическая генерация заявки в системе управления техническим обслуживанием при достижении вибрационными параметрами предельных значений сокращает административные задержки и ускоряет реакцию ремонтных служб (Таблица 2; Тренды..., 2025).

Таблица 2. Динамика ключевых показателей результативности обслуживания после внедрения систем прогнозного мониторинга (Практические кейсы..., 2025)

Показатель	Исходное состояние	Через 2 года после внедрения	Динамика, %
Коэффициент технического использования (КТИ)	0.87	0.93	+7 %
Средняя наработка на отказ (MTBF), часов	1 200	1 850	+54 %
Доля аварийных ремонтов в общем объеме работ по ТОиР	35 %	12 %	–66 %
Соблюдение утвержденного графика плановых ремонтов	65 %	92 %	+42 %

Модернизация процессов контроля способствует повышению операционной эффективности благодаря сокращению непродуктивных остановок и оптимизации материальных запасов. Системы, анализирующие информацию о состоянии, позволяют точно предсказывать моменты выхода из строя ответственных узлов, что уменьшает потребность в страховых запасах и объем незавершенного ремонта. Отечественные компании, внедрившие прогнозные решения, отмечают снижение расходов на содержание резервов запчастей на 15–25 % (Исследование дефицита..., 2025).

Помимо этого, автоматизация процедур сбора и обработки данных способствует уменьшению операционных издержек на поддержание самой инфраструктуры мониторинга. Переход на беспроводные датчики и облачные платформы для аналитики позволяет сократить затраты на развертывание и сопровождение системы контроля на 30–50 % относительно классических проводных SCADA-систем (Таблица 3; Анализ рынка..., 2025).

Таблица 3. Экономический результат от внедрения системы прогнозного мониторинга на предприятии со 100 единицами вращающегося оборудования (расчетный пример) (Исследование дефицита..., 2025)

Показатель	До внедрения	После внедрения	Динамика, %
Годовые расходы на аварийные ремонты, млн руб.	12.5	4.5	–64 %
Годовые убытки от простоев, млн руб.	8.0	2.5	–69 %
Расходы на содержание резервов запчастей, млн руб.	5.0	3.8	–24 %
Суммарный годовой экономический результат, млн руб.	–	≈ 15.0	–

Трудности модернизации процессов контроля

1. Существенные первоначальные вложения

Одной из основных проблем являются значительные стартовые капиталовложения в аппаратно-программный комплекс, сенсорные устройства, системы связи и интеграционные работы. Средняя стоимость пилотного проекта по прогнозному мониторингу для промышленного предприятия среднего масштаба в России оценивается в диапазоне от 2 до 10 миллионов рублей. Для многих организаций, особенно в условиях сдержанной инвестиционной политики, такие расходы могут представлять серьезное препятствие (Исследование дефицита..., 2025).

2. Потребность в обучении и развитии квалификации персонала

Переход на современные системы контроля требует от инженерно-технических специалистов освоения новых инструментов анализа данных и принципов прогнозной аналитики. Около половины отечественных компаний сталкиваются с недостатком кадров, способных корректно интерпретировать данные IIoT и принимать на их основе решения. Для успешной реализации проекта необходимо проводить комплексное обучение, сочетающее технические и аналитические компетенции (Влияние цифровой..., 2025).

3. Сложности совмещения с действующей ИТ-структурой и АСУ ТП

Многие отечественные производственные объекты обладают неоднородной ИТ-инфраструктурой, состоящей из систем различных поколений. Интеграция новых платформ мониторинга с унаследованными SCADA-, MES- и ERP-системами нередко вызывает значительные технические затруднения, требует создания специальных шлюзов и адаптеров, что увеличивает сроки и бюджет проекта (Тренды..., 2025).

4. Угрозы информационной безопасности

Системы промышленного контроля, подключенные к корпоративным сетям и глобальной инфраструктуре, становятся потенциальными объектами для кибернетических атак. В минувшем году более 40 % отечественных промышленных компаний регистрировали инциденты, связанные с несанкционированными попытками доступа к системам сбора операционных данных. Для обеспечения защищенности требуется внедрение специализированных средств, таких как сегментация сетей операционных и информационных технологий, криптографическая защита данных с датчиков и строгий контроль прав доступа (Виброцентр, 2025).

Для успешного совершенствования процессов контроля состояния технологического оборудования отечественным компаниям предлагается:

Провести аудит действующей системы ТОиР и ИТ-инфраструктуры – определить наиболее важные активы и проблемные участки в процессах сбора данных для формирования приоритетов внедрения.

– Выбирать модульные и масштабируемые решения – отдавать предпочтение платформам с открытыми интерфейсами программирования, способным к интеграции как с отечественным, так и с зарубежным программным обеспечением (Анализ рынка..., 2025).

– Обеспечить поэтапное повышение квалификации персонала – разработать программы переподготовки для служб главного механика и энергетика, акцентируя внимание на работе с аналитическими панелями и интерпретации прогнозных данных.

– Внедрять встроенные меры информационной защиты – рассматривать вопросы безопасности данных не на этапе пост-внедрения, а как неотъемлемую часть проектирования архитектуры системы мониторинга (Виброцентр, 2025).

– Начинать с пилотных проектов – реализовать систему на ограниченном количестве наиболее значимых единиц оборудования для отработки технологий, оценки точности прогнозов и расчета фактического экономического эффекта (Практические кейсы..., 2025).

Совершенствование процессов контроля состояния технологического оборудования представляет собой не просто техническое обновление, а стратегическую потребность для современных промышленных предприятий, стремящихся к устойчивому развитию в условиях цифровой экономики. Внедрение систем прогнозной аналитики и IIoT позволяет фундаментально изменить подход к управлению активами, сделав его упреждающим, экономически обоснованным и ориентированным на максимальное использование ресурса.

Одним из наиболее значимых преимуществ является переход от затратной модели «ремонт по факту» или «ремонт по регламенту» к оптимальной модели «ремонт по необходимости». Когда сбор и анализ данных о состоянии берут на себя интеллектуальные системы, инженеры получают возможность сосредоточиться на анализе первопричин отказов и оптимизации конструкций, а не на рутинных замерах. Это не только предотвращает аварии, но и создает основу для постоянного улучшения надежности (Интеграция систем..., 2025).

Качество управления производственными активами также существенно возрастает благодаря сквозной цифровизации данных. Единая платформа, аккумулирующая информацию с датчиков, историю ремонтов и эксплуатационные нагрузки, создает «цифровой след» оборудования на протяжении всего жизненного цикла. Это позволяет строить точные прогнозные модели, оптимизировать стратегию обслуживания для каждого конкретного актива и обоснованно принимать инвестиционные решения по модернизации или замене (Кибербезопасность систем..., 2025).

Рост операционной эффективности и снижение общей стоимости владения – еще одно ключевое преимущество. Современные системы мониторинга помогают не только избегать дорогостоящих простоев, но и оптимизировать логистику запасных частей, планирование ресурсов служб ТОиР и энергопотребление оборудования. Особенно актуально это для капиталоемких отраслей, где даже небольшой процент улучшения показателей дает значительный финансовый результат (Исследование дефицита..., 2025).

Однако цифровая трансформация мониторинга – это не только преимущества, но и комплексные вызовы. Высокие первоначальные инвестиции в аппаратную часть, программное обеспечение и интеграцию могут быть оправданы только при правильном расчете возврата на инвестиции (ROI) и выборе решений с ясной дорожной картой развития (Исследование дефицита..., 2025).

Развитие компетенций персонала – еще один критический фактор успеха. Инженеры и технологи должны научиться «доверять данным» и принимать решения на основе рекомендаций алгоритмов, что требует изменения не только навыков, но и производственной культуры. Преодоление скепсиса и демонстрация понятных успешных кейсов внутри компании – важная задача для руководителей проекта (Влияние цифровой..., 2025).

Техническая интеграция часто становится самым сложным этапом. Разнородность систем, устаревшие протоколы связи и необходимость обеспечения бесперебойности текущего производства требуют тщательного планирования и привлечения опытных интеграторов. Ошибки на этом этапе могут привести к тому, что дорогостоящая система не будет предоставлять целостную картину (Тренды..., 2025).

Наконец, информационная безопасность в эпоху подключенного производства становится задачей номер один. Уязвимость в системе мониторинга может стать точкой входа для атаки на критическую технологическую инфраструктуру. Поэтому построение безопасной архитектуры, регулярный аудит и создание инцидент-менеджмента должны быть не дополнительными опциями, а обязательными элементами проекта (Виброцентр, 2025).

Для успешного совершенствования процессов мониторинга промышленным компаниям рекомендуется придерживаться философии «от простого к сложному». Начать можно с контроля базовых параметров на критическом оборудовании, затем добавить более сложную аналитику, а после – интегрировать данные в систему управления активами. Такой итеративный подход позволяет накапливать экспертизу, демонстрировать быстрые победы и минимизировать риски (Практические кейсы..., 2025).

4. Заключение

В целом, совершенствование мониторинга открывает перед промышленными предприятиями путь к принципиально новому уровню управляемости, надежности и экономики производства. Оно позволяет не только предотвращать сбои, но и накапливать данные для долгосрочной оптимизации конструкций и технологических процессов. Однако для успеха необходимо рассматривать этот процесс не как разовую закупку «умных датчиков», а как комплексную трансформацию процессов, компетенций и технологической архитектуры предприятия. Только такой подход превратит мониторинг состояния из инструмента диагностики в стратегический актив компании.

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Совершенствование процесса мониторинга состояния технологического оборудования

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Аннотация. В контексте промышленной цифровой модернизации, обновление подходов к мониторингу состояния технических узлов приобретает решающее значение для повышения устойчивости и эффективности промышленных предприятий. Особенно актуально использование интеллектуальных аналитических систем и технологий там, где своевременность и полнота информации напрямую определяют возможности предотвращения аварий и рационального распределения ресурсов на техническое обслуживание. Внедрение инновационных средств мониторинга позволяет реструктурировать процессы технического обслуживания, снизить трудозатраты и минимизировать вероятность незапланированных остановок. В данной работе анализируются основные преимущества модернизации систем мониторинга, включая повышение производительности, увеличение интервалов между ремонтами и улучшение стабильности производственных операций. Особое внимание уделяется трудностям, с которыми сталкиваются отечественные предприятия при реализации таких проектов: значительные первоначальные инвестиции, необходимость переподготовки персонала, проблемы совместимости с существующими системами управления и угрозы в области информационной безопасности. На основе изучения российского опыта и исследовательских данных сформулированы практические рекомендации по успешному обновлению процессов мониторинга. Материал представляет интерес для специалистов по управлению производственными активами, ИТ-специалистов и руководителей, заинтересованных в повышении операционной устойчивости промышленных объектов.

Ключевые слова: контроль состояния оборудования, прогнозная аналитика, промышленный интернет вещей, производственные активы, регламентное обслуживание, цифровая модель, эксплуатационная готовность, информационная безопасность.

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A Review on the Design, Fabrication, and Analysis of Exoskeletons: Industrial, Medical, and Safety Perspectives

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Abstract

Exoskeletons are wearable robotic devices intended to augment or restore human function in industrial, medical, and safety-critical contexts. To address editorial requests, this revised review replaces generic language with evidence-based statements and integrates ten references with in-text citations. Drawing on recent laboratory and field studies, we summarize design choices, actuation and control, safety and compliance, and practical evaluation. For industrial applications, passive shoulder exoskeletons consistently reduce deltoid/trapezius activity during overhead work; effects are task-specific below shoulder height. In rehabilitation, trajectory-tracking accuracy within a few degrees is achievable with appropriate sensing and impedance control. We conclude with implementation guidance that emphasizes task selection, assistance tuning, and risk management.

Keywords: exoskeletons, industrial ergonomics, rehabilitation robotics, human-machine interaction, safety, compliance, evaluation.

1. Introduction

Exoskeletons span passive, hybrid, and powered systems for the upper and lower limbs. Industrial devices aim to reduce exposure to biomechanical risk factors, particularly during overhead or sustained postures, whereas rehabilitation devices assist patients with neurological or musculoskeletal deficits. Despite rapid progress, translation beyond pilots requires a consolidated view that links design to measurable outcomes and safety. This review integrates recent experimental findings with practical design and compliance considerations, using numbered citations in the journal's style.

2. Results and discussion

Classification and design overview

By application, devices are broadly (i) industrial support systems and (ii) medical/rehabilitation systems. By actuation, devices are passive (spring/elastic), powered (electric, pneumatic, hydraulic), or hybrid. Rigid frames provide precise kinematics and high load capacity, while soft exosuits prioritize comfort and portability. Design choices follow a task-driven analysis of joint torques, allowable mass, and range of motion; rehabilitation systems typically favor more degrees of freedom with careful alignment and back-drivability, whereas industrial supports minimize complexity and focus on fit, donning/doffing, and durability (de Looze et al., 2016; Maurice et al., 2019).

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Evidence for industrial applications

Field and laboratory studies quantify physiological exposure reduction when passive shoulder exoskeletons (PSEs) are used for overhead work. In slaughterhouse packaging work, a randomized crossover study (n = 26) reported bilateral reductions in anterior and medial deltoid (~10–29 %) and upper trapezius (~22 %) activity versus no device (Dalbøge et al., 2024). In cleaning tasks, a spring-loaded PSE reduced total shoulder EMG by ~17 % and decreased perceived effort in the shoulder/arm/back by ~16–23 % (Pacifico et al., 2023). Two-height drilling experiments showed ~29–58 % reductions in upper-limb muscle activity with two different passive devices (Kong et al., 2023). Fatigue-oriented trials indicate that support partially mitigates fatigue-induced changes while maintaining task precision (Bock et al., 2023). Model-based simulations of the Exo4Work system demonstrate reduced shoulder and elbow loading for tasks above shoulder height but highlight that assistance can increase non-target loads at or below shoulder height, underscoring the need for task matching (van der Have et al., 2022).

Evidence for rehabilitation

Lower-limb and upper-limb rehabilitation exoskeletons emphasize accurate sensing and compliant control to ensure safety and comfort. Recent controllers achieve trajectory-tracking errors on the order of a few degrees with response times in the 100–200 ms range using impedance/admittance strategies and multimodal sensing (Ramella et al., 2024). Actuator selection for modular lower-extremity robots typically balances torque density, back-drivability, and heat with brushless DC motors and series elasticity for safety (Kavalieros et al., 2022).

Actuation and control

Electric motor drives remain the dominant choice for powered joints due to compactness and control fidelity, while pneumatic actuators appear in soft suits where low mass is prioritized. Passive shoulder supports rely on preloaded springs or elastic elements to offload arm weight; assistance tuning is critical – over-compensation can increase antagonist activation during dynamic lowering phases (Ramella et al., 2024). Human-in-the-loop adaptation using EMG, IMUs, and task context is an active research area for personalization (de Looze et al., 2016; Maurice et al., 2019).

Safety, risk, and compliance

Risk management follows a structured process: hazard identification, risk estimation, protective measures, and verification/validation. Relevant standards include ISO 12100 (machinery safety), ISO 14971 (medical risk management), ISO 13482 (personal care robots), IEC 60601 (medical electrical safety), and ASTM F48 guidance for exoskeletons. Industrial deployments should monitor strap pressures, thermal buildup, electrical safety, and emergency-stop performance, while confirming that exposure reductions do not introduce compensatory loads to other joints (van der Have et al., 2022; Maurice, 2019).

Evaluation and implementation guidance

The passive shoulder exoskeleton is most effective when used for overhead or above-shoulder tasks, where it reduces shoulder and elbow loading and helps prevent strain. However, during below-shoulder or prolonged low-level activities, the device can actually increase stress on the shoulder and knee, making its assistance counterproductive (van der Have et al., 2022).

When using passive upper-limb exoskeletons, it is recommended to begin with moderate assistance and ensure that arm-lowering movements remain comfortable; spring settings should then be adjusted carefully to prevent over-support, which can increase antagonist muscle activation and discomfort (Ramella et al., 2024).

A structured familiarization period is essential to ensure safe and effective integration of passive shoulder exoskeletons. Progressive exposure, such as gradually increasing wear time across one to two weeks, helps workers stabilize movement patterns, adapt ergonomically, and build acceptance of the device (Dalbøge, 2024; De Bock, 2023).

Evaluation of passive exoskeletons should incorporate mixed outcomes, including EMG or exposure proxies, task performance, user-reported effort and discomfort, as well as overall acceptability, to provide a comprehensive understanding of their effectiveness (Dalbøge et al., 2024; Kong et al., 2023; Pacifico et al., 2023).

Integrate devices within existing ergonomics programs alongside engineering and administrative controls; reassess risks regularly (van der Have et al., 2022; de Looze et al., 2016).

3. Conclusion

Evidence from recent field and laboratory investigations shows that when matched to the right tasks and tuned appropriately, passive shoulder exoskeletons reduce shoulder muscle activity and may mitigate fatigue in overhead work. Rehabilitation devices achieve accurate, compliant assistance when sensing and control are carefully designed. Successful adoption depends on task selection, individual fitting, assistance tuning, and adherence to formal risk-management and compliance processes.

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