Theoretical Aspects of Transdisciplinarity in Telerehabilitation

Kyrylo S. Malakhov[1], Sergii V. Kotlyk[2], Mykola G. Petrenko[3]

[1] MSc (Computer Sciences), Researcher, Microprocessor Technology Lab, V.M. Glushkov Institute of Cybernetics of the National Academy of Sciences of Ukraine

[2] PhD (Computer Sciences), Associate Professor, Educational and Scientific Institute of Computer Engineering, Automation, Robotics and Programming named after P.M. Platonova, Odesa National University of Technology, Ukraine

[3] DSc (Computer Sciences), PhD (Computer Sciences), Senior Researcher, Microprocessor Technology Lab, V.M. Glushkov Institute of Cybernetics of the National Academy of Sciences of Ukraine

Abstract

This article explores the theoretical aspects of transdisciplinary research, with a specific focus on its application to telerehabilitation. The integration of multiple disciplines – ranging from medicine, digital health, and informatics to engineering and the social sciences – is increasingly necessary to address the complex challenges of delivering effective remote rehabilitation services. The article begins by outlining the conceptual framework, distinguishing between disciplinary, interdisciplinary, multidisciplinary, and transdisciplinary approaches, and highlighting the importance of transcending traditional disciplinary boundaries.

The theoretical foundations discussed provide a basis for understanding how the convergence of diverse fields can lead to innovative solutions in telerehabilitation. The integration of disciplines is examined in detail, illustrating how collaborative efforts across medicine, technology, and behavioral sciences can enhance patient outcomes, improve accessibility, and foster the development of personalized rehabilitation plans. The article also covers the practical implications for clinical practice, emphasizing the need for a more collaborative model of care delivery and the potential for cost-effective, scalable solutions.

Looking toward the future, the article identifies key areas for research, including the development of advanced technologies, exploration of new therapeutic modalities, and consideration of ethical and social impacts. The need for standardization and interoperability in telerehabilitation systems is also underscored, as these will be critical to ensuring the seamless integration of various technologies and platforms.

Keywords: *Interdisciplinarity, Multidisciplinarity, Telerehabilitation, Transdisciplinarity, Vernadsky's Noospheric Theory*

In the modern scientific picture of the world (SPW), grounded in the principles of general evolution, self-organization, co-evolution, and nonlinearity, it is assumed that the subject – understood as society – enters the system it seeks to understand as an active component of this process-system. This perspective highlights the dynamic and participatory role of society in shaping and being shaped by the systems it studies (Palagin, 2021; Shyrokov, 2017).

A well-known philosophical concept that has emerged in this context is transhumanism, which explores the possibilities and consequences of scientific and technological advancements, weighing the potential dangers and benefits of their application. In contrast, the ideas of posthumanism propose a central thesis that emphasizes the interdependent evolution of *Man*, *Society*, and *Nature* as three interconnected systems (Bostrom, 2005).

Techno-science has become a transformative force, fundamentally altering human nature and life itself. This shift necessitated an expansion of the scientific worldview, requiring a more profound and intensive penetration into the essence of the laws governing nature and society – beyond what was achievable through disciplinary or even interdisciplinary approaches. Jean Piaget famously suggested that "after the stage of interdisciplinary research, one should expect a higher stage – transdisciplinary research, which will not be limited to interdisciplinary relations but will place these relations within a global system, without strict boundaries among disciplines. Transdisciplinarity should be considered a new field of knowledge, distinct from multidisciplinarity and interdisciplinarity" (Piaget, 1974). The historical development of transdisciplinary research has been explored in various works (Jantsch, 1972; Palagin, 2013; Palagin, Petrenko, et al., 2023; Palagin & Petrenko, 2018).

The purpose of this study is to explore the theoretical aspects of transdisciplinary research, with a focus on its application to telerehabilitation. By discussing the theoretical underpinnings and practical implications of transdisciplinary approaches, this survey aims to contribute to the ongoing evolution of telerehabilitation as an integrated and holistic field of study.

Conceptual Framework

In the classification of scientific approaches, a useful criterion is the degree of completeness of knowledge regarding the surrounding world. Based on this criterion, scientific approaches can be categorized into four main types: disciplinary, interdisciplinary (ID), multidisciplinary, and transdisciplinary (TD) approaches.

In this note, these terms are understood in relation to the "distribution" of concepts and scientific disciplines across different ontological levels of hierarchy, which implies varying patterns of interaction. This distribution is important when considering the methodology of TD interaction, the systematic integration of knowledge from subject disciplines, and the formation of "convergence clusters" (Palagin, 2013; Palagin et al., 2017) in the implementation of transdisciplinary projects, including their information and technological support.

Key concepts such as *Noosphere, Object, Process, System, Information, Nature, Society, Man, Knowledge Domain, Science, Scientific Activity, Scientific Picture of the World, Engineering,* and *Technology* belong to the category level. Concepts such as *Philosophy, Physics, Mathematics, Biology, Chemistry, Medicine, Humanities and Social Sciences, Informatics,* and *Nanotechnologies* correspond to the level of scientific discipline domains. Many sub-disciplines and specializations within these domains fall under the level of scientific disciplines.

The scheme of the categorial and domain levels of knowledge in the SPW is illustrated in Figure 1, while the concepts related to the levels of domains and disciplines are depicted in Figure 2. A full description of all elements is beyond the scope of this study and is detailed by Palagin and Petrenko (2018).

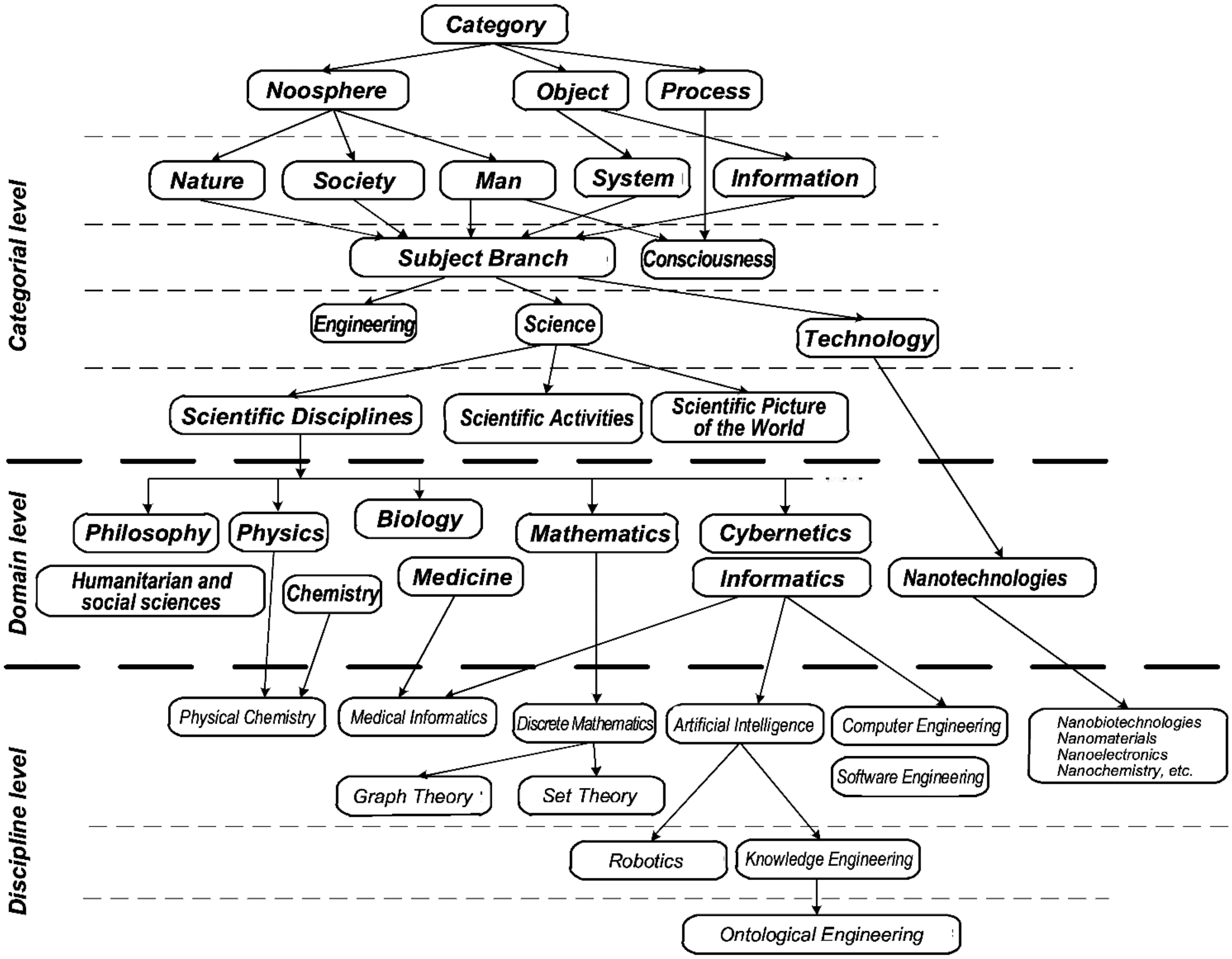
Disciplinary approaches allow science to progress within specific subject areas, dividing the world into distinct domains. However, when a problem extends beyond the scope of a single discipline, it is often considered to be at the intersection of scientific disciplines. As the disciplinary approach evolves, a natural tension arises: on one hand, it fosters the accumulation of disciplinary knowledge, while on the other, it reaches a natural limit in fully understanding the surrounding world. This situation suggests that when it becomes impossible to move beyond a disciplinary direction, the scope of disciplinary methodology can be extended (Jantsch, 1972). This extension has led to the emergence of ID and multidisciplinary scientific approaches, which form subsequent levels in the classification of scientific approaches. The development of these approaches has transformed the metaphor of "the junction of disciplines" into established ID and multidisciplinary directions, each with its unique methods of addressing research problems (Jantsch, 1972).

Interdisciplinarity involves the integration of multiple scientific disciplines, with one discipline often playing a leading role. The results of interdisciplinary research are typically interpreted within the framework of the leading discipline. A key feature of the ID approach is its facilitation of direct transfer of research methods from one discipline to another, driven by the discovery of similarities between subject areas. The ID approach primarily aims to address specific disciplinary problems, especially when conceptual and methodological difficulties arise within a particular discipline.

The synergetic paradigm, as a branch of the ID approach within the hierarchy of knowledge, occupies a special place. On one hand, it appeals to holistic representation, systematically determining the effects of interactions between objects, processes, and subjects. On the other hand, it focuses on nonlinearities, instabilities, and the emergence of attractors, which ultimately alter multilevel organization and system behavior. This paradigm is expressed through formal models of self-organization and plays a key role in reproducing the SPW, particularly during the transition to a TD approach and the implementation of the paradigm of global evolutionism. The SPW can be represented as a TD ontology (Palagin, Petrenko, et al., 2023), incorporating not only the ontologies of individual disciplines but also their methods, including cross-disciplinary influences. TD approaches enable the creating of a unified TD methodology for analysis and synthesis, integrating it into the general SPW. The challenges and potential of synergy are discussed in (Palagin, 2013; Palagin, Petrenko, et al., 2023).

Figure 1

The Categorial and Domain Levels of Knowledge in the Scientific Picture of the World



In a multidisciplinary approach, researchers develop a generalized picture of the research subject, with all disciplinary perspectives being equally valid. The accumulation of multidisciplinary research results in similar areas of disciplinary knowledge leading to the emergence of new multidisciplinary disciplines, such as physico-chemical biology and ecology. The multidisciplinary approach has found practical application, particularly in the work of expert groups.

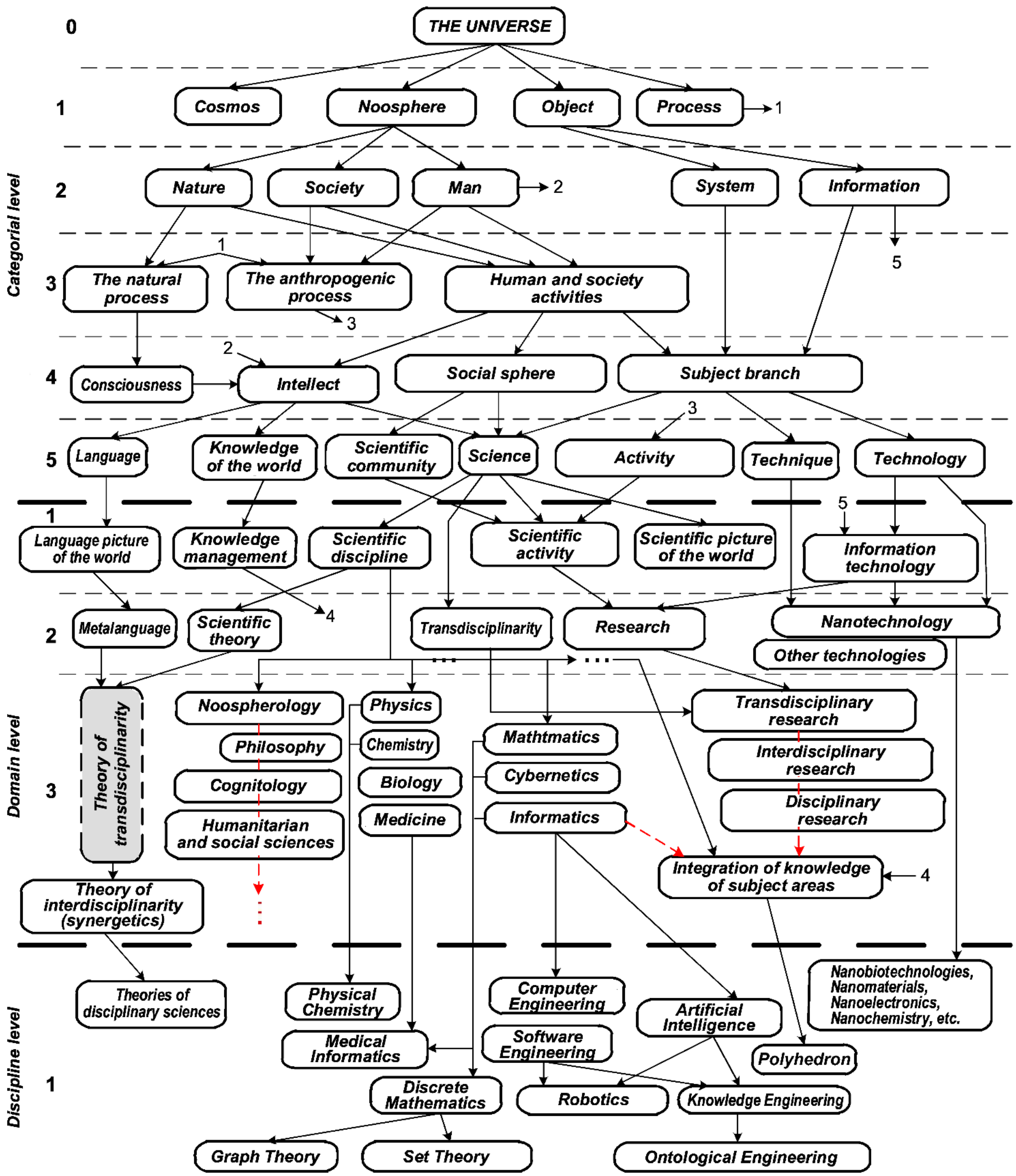
Multidisciplinarity does not involve the transfer of research methods between disciplines; instead, each discipline retains its subject focus.

The TD system approach utilizes knowledge generated and accumulated by disciplinary, interdisciplinary, and multidisciplinary approaches. TD aims to ensure the coordination and integration of disciplinary knowledge based on a unified axiomatic approach (the TD general systems). This vision of TD was initially conceptualized by J. Piaget and E. Jantsch (Jantsch, 1972; Piaget, 1974).

Transdisciplinarity represents a research strategy that transcends disciplinary boundaries, fostering a holistic view (i.e., prioritizing the whole over its parts). In a narrow sense, TD involves the integration of various forms and methods of research, including specialized techniques of scientific inquiry, to solve complex scientific problems. In a broader sense, TD signifies the unity of knowledge beyond specific disciplines.

Figure 2

Concepts Related to the Levels of Domains and Disciplines



The transformation of science's structure due to the shift from disciplinary to TD research is marked by several signs of the post-nonclassical stage: changes in the nature of scientific activity due to advances in knowledge acquisition and storage (e.g., computerization of science, the fusion of science with industrial production), increased importance of economic and socio-political factors and goals, and changes in the object of study itself – open, self-developing systems (e.g., biotechnology objects, ecological systems, the biosphere).

TD studies, by capturing the border zones (demarcation areas) of scientific disciplines, integrate their essential foundations, forming "convergence clusters" (Palagin, 2013; Palagin, Petrenko, et al., 2023). These clusters facilitate powerful synergistic interactions due to the interpenetration of paradigms and specific current results from each discipline involved. This interaction reflects the real world's integrity, serving as both an incentive and a guarantee of success for TD research and related practical projects, whose non-triviality and significance are underscored by their results.

Theoretical Foundations

The unity and systemic complexity of the world as an object of scientific research suggest that, alongside the process of differentiation, it is equally important to consider the integration of scientific disciplines and relevant technologies. This integrative process is aligned with the fundamental paradigm of the evolutionary theory proposed by Academician Vernadsky (Vernadsky, 1945). While the integration of scientific disciplines began somewhat spontaneously and intuitively, it has now become a more conscious and deliberate endeavor. This process is increasingly guided by evolutionary theory, aiming to create a unified body of *General Knowledge* (GK) (Palagin, Petrenko, et al., 2024). The essence of this endeavor is to construct a general SPW based on a transdisciplinary concept of scientific development.

The initial stage of this integration process can be described as the clustering stage. Even a cursory analysis of the clustering phenomenon reveals that it is rooted in the deep interaction of methods, tools, and capabilities of the cluster components. The synthesis of these components generates synergistic effects through the integration of their functional properties, thereby opening up broad prospects for the creation of previously unknown scientific theories, new equipment, and technologies. The ongoing integration process raises numerous questions, the answers to which will help outline new, promising paths for the evolution of knowledge and science in general, in line with *Vernadsky's Noospheric Theory* (Palagin et al., 2017; Vernadsky, 1945).

One of the tasks in this evolutionary path is to analyze the structure of knowledge at the conceptual level. GK, along with each of its disciplines, can be represented as a comprehensive set of concepts-terms that constitute the ontological basis for describing knowledge, whether formal or informal. Each term within this framework has its generally accepted definition, which is explained using lower-level terms or concepts. A technological multilevel ontological description has been developed for both GK and its individual disciplines, sections, theories, etc., thereby enabling the formal representation of knowledge using a unified ontological engineering toolkit (Malakhov et al., 2023; Palagin et al., 2014; Petrenko et al., 2023). This toolkit opens up broad prospects for the development of cognitive technologies and their productive application.

Currently, there is a growing trend toward intensifying scientific research both at the intersection of different subject disciplines (ID research) and within convergence clusters (TD research). To support these studies, several key factors are decisive, including the construction of knowledge-oriented information systems, the improvement of research organization processes, the enhancement of methods and tools for ontological analysis of natural language objects using generative language models (Palagin, Kaverinskiy, et al., 2024; Ramesh, 2023) to extract knowledge, and the applied use of ontologies, meta-ontologies, and knowledge integration systems (Palagin, 2016) in transdisciplinary convergence clusters.

The rapid development of convergent technologies has the potential to significantly enhance both human activity and national economies. Notable examples of such advancements include increased efficiency in work and learning, enhanced sensory and cognitive capabilities, fundamentally new manufacturing processes, revolutionary changes in healthcare, improved individual and group effectiveness, advanced communication methods (including brain-to-brain interaction), improved human-machine interfaces (Kurgaev & Palagin, 2021) (such as neuromorphic engineering for industrial and personal use), enhanced human capabilities for defense purposes, and the achievement of sustainable development with the help of NBIC (N – Nano, B – Bio, I – Info, C – Cogno) tools (Roco, 2016). Additionally, these technologies hold promise for addressing the physical and cognitive decline associated with aging.

The NBIC-convergence cluster (Roco, 2016) serves as a vivid example of technoscience, where informatics contributes both system-forming and computer-technological components. The main breakthrough directions within these clusters include blurring the lines between living and non-living systems, advancements in nanorobotics with numerous applications, and the development of global supercomputer agglomerations with advanced artificial intelligence (AI) capabilities. To these, one can add the unified distributed TD knowledge system, envisioned as a globally communicative version of a general SPW and representing the next stage in the evolution of the existing Internet and the Semantic Web.

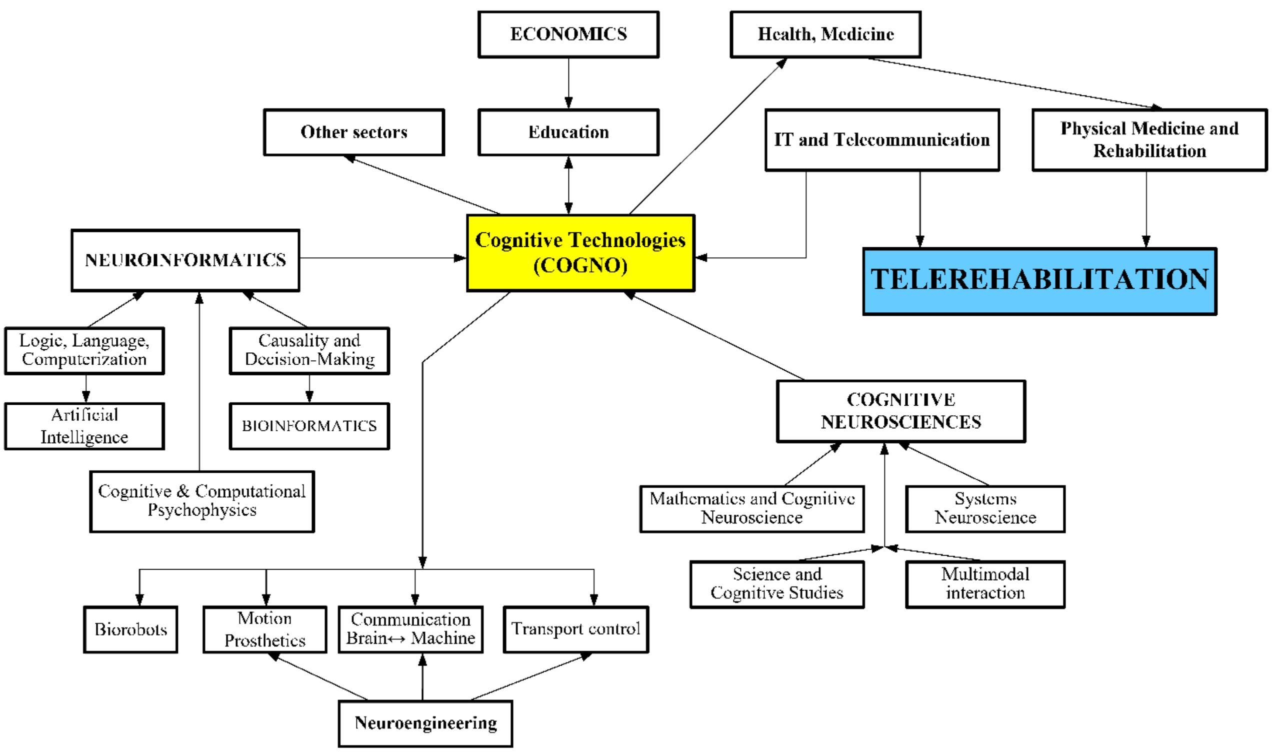
A possible scheme for forecasting and intentionally forming promising convergence clusters, along with their synergistic interactions and the resulting aggregate efficiency for humanity, requires further exploration in separate study.

Application of These Theories to Telerehabilitation

The principles of transdisciplinary research, particularly those related to the integration and convergence of knowledge across disciplines, have significant implications for the field of telerehabilitation. Telerehabilitation inherently operates at the intersection of multiple domains, including medicine, physical therapy, digital health, informatics, and engineering. The Figure 3 illustrates a diagram of the connections between cognitive technologies, various fields of science and telerehabilitation.

Figure 3

The Connections between Cognitive Technologies, Various Fields of Science and Telerehabilitation



The application of transdisciplinary theories in this context enables the development of holistic rehabilitation programs that are more personalized, adaptive, and responsive to the unique needs of patients.

- *Clustering of disciplines and technologies*. In telerehabilitation, the clustering stage involves the integration of medical knowledge, physical therapy techniques, and digital technologies such as telecommunication platforms, wearable sensors, and AI. This synthesis creates new opportunities for delivering remote rehabilitation services that are both efficient and effective. For instance, the integration of AI-driven analytics with real-time patient data (Malakhov, 2024) can provide tailored rehabilitation exercises and adjust therapy protocols dynamically based on patient progress.

- *Synergistic effects and innovation.* The synergy generated through the integration of these diverse disciplines can lead to innovations in rehabilitation practices. For example, combining insights from neurobiology with advanced robotics and machine learning could result in the development of intelligent prosthetics (Nasr et al., 2021; Sanchez et al., 2023) that not only enhance mobility but also adapt to the neurological signals of the user, thereby improving outcomes in telerehabilitation settings.
- *Ontological engineering in telerehabilitation*. The application of technological multilevel ontological descriptions in telerehabilitation (Kaverinsky & Malakhov, 2023; Palagin, Kaverinskiy, et al., 2023; Palagin, Kaverinsky, et al., 2023) allows for the formal representation of patient data (*Conceptual Models for Clinical Data Repository Implementation*, 2022), treatment protocols, and rehabilitation outcomes. This structured knowledge can be leveraged to create comprehensive, interoperable information systems (Palagin, Petrenko, et al., 2024) that facilitate communication and data exchange between different healthcare providers, enhancing the continuity of care for patients undergoing telerehabilitation.
- *Convergence clusters in practice.* The NBIC-convergence cluster, when applied to telerehabilitation, fosters the development of integrated systems where nanotechnology, biotechnology, information technology, and cognitive science converge to create advanced rehabilitation tools. For example, brain-computer interfaces (BCIs) (Kurgaev & Palagin, 2021) could be used in telerehabilitation to assist patients with severe mobility impairments, allowing them to control prosthetic limbs or communicate via thought, thus greatly enhancing their quality of life.
- *Challenges and future directions* While the application of these transdisciplinary theories to telerehabilitation holds great promise, it also presents challenges that need to be addressed. These include the need for standardized protocols for data integration (Ramesh, 2024), ensuring patient privacy and data security (using modern technologies such as multilevel face recognition (Opanasenko, Fazilov, Mirzaev, et al., 2024; Opanasenko, Fazilov, Radjabov, et al., 2024)), and developing scalable models that can be applied across different healthcare settings. Future research should focus on addressing these challenges while continuing to explore new frontiers in the integration of technologies and disciplines within telerehabilitation.

The TD research represents a qualitatively new stage in the integration of science and society. To fully realize its potential, especially in fields like telerehabilitation, the scientific community still needs to design and develop several key components:

- A general SPW that includes subject disciplines and a corresponding global network of TD knowledge.
- A metatheory and metalanguage (Kurgaev, 2020; Kurgaev & Grigoriev, 2016) for TD.
- A systemology of TD interaction, including figurative conceptual apparatus and models, capable of encompassing all factors that form and affect complex problems, as well as identifying and accounting for the mechanisms through which these effects occur.
- A method (or set of methods) for system research that provides access to and analysis of all disciplinary information, understandable and accessible to specialists from any scientific discipline.
- Prospective and self-sufficient convergence clusters that will form the core of the sixth technological order.
- Experimental methods that allow for the study of multifactorial effects on objects of knowledge and the evaluation of their results. This includes various information technology tools designed to increase efficiency and accelerate results.
- Approaches to posing and solving complex multifactorial problems in science, engineering, and technology.

These developments will be core in advancing the integration of knowledge and in achieving the goals of transdisciplinary research in the future, particularly in the evolving and impactful field of telerehabilitation.

Integration of Disciplines in Telerehabilitation

Telerehabilitation is a field that inherently requires the integration of multiple disciplines to deliver effective, patient-centered care remotely. As healthcare continues to evolve with technological advancements, the integration of disciplines within telerehabilitation becomes increasingly essential. This section explores the primary disciplines involved in telerehabilitation and how their intersection and integration contribute to the development and implementation of transdisciplinary approaches in this domain.

Key Disciplines Involved in Telerehabilitation

Medicine and Physical Rehabilitation. At its core, telerehabilitation is deeply rooted in the principles of medicine and physical rehabilitation. Physicians, physiatrists, and physical therapists are responsible for diagnosing, designing, and implementing rehabilitation protocols tailored to individual patient needs. These healthcare professionals must ensure that the therapeutic interventions delivered remotely are as effective as in-person care, taking into consideration the nuances of each patient's condition.

Digital Health and Health Informatics. The advent of digital health has revolutionized telerehabilitation, enabling the remote delivery of care through telecommunication technologies (Busti et al., 2021; *Remote Patient Monitoring Playbook*, 2022; *Telehealth Implementation Playbook*, 2022). Health informatics plays a major role in managing patient data, facilitating teleconsultations, and ensuring the seamless integration of electronic health records (EHR) with rehabilitation protocols. These technologies support continuous monitoring, patient engagement, and the efficient management of large volumes of data, which are critical for the success of telerehabilitation programs.

Computer Sciences and Engineering. The development and application of digital platforms, mobile health applications, and wearable technologies are driven by advancements in computer sciences and engineering. These disciplines contribute to the creation of user-friendly interfaces, secure data transmission protocols, and the integration of AI and machine learning algorithms into telerehabilitation systems. Engineers and computer scientists work closely with healthcare providers and vendors to ensure that these technologies are not only functional but also enhance the quality of care delivered remotely.

Cognitive and Behavioral Sciences. Cognitive and behavioral sciences are integral to understanding patient behavior, motivation, and adherence to rehabilitation protocols. These disciplines inform the design of interventions that are psychologically supportive and encourage sustained patient engagement. By applying principles of cognitive-behavioral therapy (CBT) and other psychological frameworks, telerehabilitation programs can be tailored to address the mental and emotional aspects of recovery, which are often critical to successful rehabilitation outcomes.

Humanities and Social Sciences. The humanities and social sciences offer valuable insights into the social determinants of health, cultural considerations, and ethical implications of telerehabilitation (Stucki et al., 2017). These disciplines ensure that telerehabilitation programs are inclusive, culturally sensitive, and ethically sound. They also address the broader societal impacts of remote rehabilitation, including access to care, equity, and the digital divide, which can significantly influence the effectiveness of telerehabilitation services.

Interdisciplinary and Transdisciplinary Integration

The integration of these disciplines within telerehabilitation occurs at both ID and TD levels:

- *ID integration.*

  In telerehabilitation, ID integration involves the collaboration of various disciplines where each discipline maintains its specific methodologies and perspectives. For instance, a rehabilitation program may involve a physical therapist working with an engineer to develop a wearable device that tracks patient movements (Internet of Medical Things). The data collected by the device is then analyzed by health informaticians to adjust the rehabilitation protocol, and cognitive scientists might assess the patient’s psychological response to the treatment. Each discipline contributes its expertise, but the focus remains on solving a particular aspect of the rehabilitation process.
- *TD integration*.

  TD integration goes a step further by transcending traditional disciplinary boundaries to create a unified framework for telerehabilitation. In this approach, the distinctions between disciplines become less pronounced, and there is a concerted effort to integrate knowledge, theories, and methods to address complex rehabilitation challenges holistically. For example, developing a comprehensive telerehabilitation program that incorporates AI-driven adaptive therapies requires the seamless integration of medical knowledge, digital health platforms, AI algorithms, and an understanding of patient behavior. This holistic approach enables the creation of personalized rehabilitation plans that are continuously optimized based on real-time data and patient feedback (Kurgaev & Palagin, 2021).

Practical Implications and Challenges

The integration of multiple disciplines in telerehabilitation offers numerous practical benefits, including more personalized care, improved patient outcomes, and increased accessibility to rehabilitation services. However, this integration also presents challenges that need to be addressed.

Collaboration and Communication. Effective ID and TD collaboration requires clear communication and mutual understanding among professionals from diverse backgrounds. Overcoming differences in terminology, methodologies, and objectives is essential for successful integration.

Data Management and Privacy. The integration of digital health technologies necessitates robust data management systems that ensure patient privacy and security. As more disciplines contribute to the collection and analysis of EHR, there must be stringent protocols in place to protect sensitive information.

Standardization and Interoperability. Ensuring that different technologies and systems used in telerehabilitation are compatible and can seamlessly share data is critical. Standardization of protocols, data formats, and interfaces is necessary to facilitate interoperability between various platforms and devices.

Equity and Access. While telerehabilitation has the potential to reach underserved populations, disparities in access to digital technologies and the internet can limit its effectiveness. Addressing the digital divide and ensuring equitable access to telerehabilitation services is a significant challenge that requires a coordinated effort across disciplines.

The integration of disciplines in telerehabilitation is not just a theoretical exercise but a practical necessity for advancing the field. By bringing together expertise from medicine, digital health, computer sciences, cognitive and behavioral sciences, and the humanities, telerehabilitation can offer comprehensive and effective care that addresses the multifaceted needs of patients. As the field continues to evolve, embracing both ID and TD approaches will be essential in overcoming the challenges and fully realizing the potential of telerehabilitation to transform healthcare delivery.

Implications for Practice and Future Research

The integration of TD approaches in telerehabilitation not only enhances the effectiveness of rehabilitation programs but also has profound implications for clinical practice and future research.

Implications for Clinical Practice

Personalized rehabilitation plans.

The application of transdisciplinary research in telerehabilitation enables the development of personalized rehabilitation plans that are tailored to the specific needs and conditions of each patient. By integrating insights from medicine, digital health, cognitive sciences, and engineering, healthcare providers can create adaptive therapies that respond to real-time data, ensuring that interventions are both effective and patient-centered. This approach enhances patient engagement and adherence to rehabilitation programs, which are critical factors in achieving successful outcomes.

Enhanced accessibility and reach.

Telerehabilitation, supported by TD integration, has the potential to reach a broader population, including individuals in remote or underserved areas. The ability to deliver high-quality rehabilitation services via digital platforms overcomes geographical barriers and reduces the need for physical visits to healthcare facilities. This increased accessibility can lead to earlier interventions, more consistent follow-up, and ultimately, better long-term outcomes for patients.

ID collaboration in care delivery.

The implementation of ID and TD approaches in telerehabilitation necessitates a shift in how care is delivered. It promotes a more collaborative model where professionals from various disciplines work together seamlessly. This model encourages shared decision-making, where insights from different fields are integrated into a cohesive treatment plan. The collaboration also extends to the use of technology, where engineers, data scientists, and healthcare providers jointly develop and refine the tools used in patient care.

Efficiency and cost-effectiveness.

By using digital health technologies and integrating them into a unified system, telerehabilitation can significantly reduce the costs associated with traditional rehabilitation services. Automated monitoring, AI-driven analytics, and remote consultations can decrease the need for in-person visits, reducing travel costs and time for both patients and healthcare providers. Additionally, the use of data-driven insights allows for more efficient allocation of resources, ensuring that patients receive the most appropriate care based on their needs and progress.

Implications for Future Research

Exploration of new therapeutic modalities.

The integration of various disciplines opens the door to exploring new therapeutic modalities that can be delivered remotely. For example, the combination of virtual/augmented reality with CBT could provide immersive rehabilitation experiences that enhance patient engagement and outcomes. Additionally, the use of neuromodulation techniques in conjunction with telerehabilitation platforms could offer new ways to manage pain and promote neuroplasticity in patients with neurological conditions.

Ethical and social considerations.

As telerehabilitation becomes more widespread, future research must address the ethical and social implications of these advancements. This includes ensuring that the benefits of telerehabilitation are accessible to all patients, regardless of socioeconomic status. Research should also explore the impact of remote rehabilitation on the patient-provider relationship and how to preserve the human aspects of care in a digital environment.

Longitudinal studies on outcomes.

To fully understand the impact of TD approaches in telerehabilitation, there is a need for longitudinal studies that track patient outcomes over extended periods. These studies can provide valuable insights into the long-term effectiveness of remote rehabilitation programs, identify factors that contribute to sustained improvements, and highlight areas where further refinement is needed. Such research will be essential in establishing evidence-based best practices for telerehabilitation.

Impact of emerging technologies.

The rapid evolution of technologies such as 5G networks, blockchain (Ramesh, 2018), and advanced data analytics offers new opportunities for telerehabilitation. Future research should explore how these emerging technologies can be harnessed to further enhance the delivery and effectiveness of remote rehabilitation services. For example, the increased bandwidth and lower latency of 5G networks could support more robust and real-time interactions between patients and providers, while blockchain could offer secure and transparent ways to manage patient data (Ramesh, 2018).

The integration of TD approaches in telerehabilitation has the potential to transform both clinical practice and research. By embracing the convergence of multiple disciplines, telerehabilitation can provide more personalized, accessible, and efficient care, while also driving innovation in rehabilitation technologies and methodologies. However, realizing this potential will require ongoing research into the development of advanced technologies, the exploration of new therapeutic modalities, and the careful consideration of ethical and social implications. As the field continues to evolve, it will be essential for researchers and practitioners to collaborate closely, ensuring that telerehabilitation remains at the forefront of healthcare innovation and continues to deliver meaningful benefits to patients worldwide.

Conclusions

This article has explored the theoretical aspects of TD research with a focus on its application to telerehabilitation. The evolving landscape of scientific inquiry, driven by the need for integration across multiple disciplines, is well-suited to the challenges and opportunities presented by telerehabilitation. As a field that inherently operates at the intersection of medicine, digital health, informatics, engineering, and the social sciences, telerehabilitation stands to benefit immensely from a transdisciplinary approach.

We began by establishing the conceptual framework, identifying how disciplinary, ID, multidisciplinary, and TD approaches differ in their methodology and scope. The theoretical foundations underscored the importance of integrating diverse disciplines to address the complex, multifaceted challenges of modern healthcare. This integration is not just an academic exercise but a practical necessity, particularly in fields like telerehabilitation, where patient outcomes depend on the seamless collaboration of various specialties and technologies.

The integration of disciplines within telerehabilitation, as discussed, reveals how each field contributes unique insights and tools to enhance patient care. Medicine and physical rehabilitation provide the clinical foundation, while digital health and informatics offer the technological platforms necessary for remote care. Computer sciences and engineering drive innovation in wearable devices and AI applications, and cognitive sciences ensure that patient engagement and adherence are prioritized. The humanities and social sciences bring essential perspectives on ethics, access, and the broader societal impacts of telerehabilitation.

Furthermore, the implications for practice and future research are significant. In clinical practice, TD approaches enable the creation of personalized, adaptive rehabilitation plans that are accessible to a wider population, including those in remote or underserved areas. The efficiency and cost-effectiveness of telerehabilitation are enhanced by these integrated approaches, offering a sustainable model for the future of healthcare delivery.

For future research, there is a clear need to continue developing advanced technologies, exploring new therapeutic modalities, and addressing the ethical and social considerations associated with telerehabilitation. Longitudinal studies will be vital in establishing the long-term efficacy of these approaches, while efforts to standardize protocols and ensure interoperability will support the broader adoption of telerehabilitation services.

In conclusion, TD research represents a critical advancement in the way we approach complex healthcare challenges. Telerehabilitation, as a rapidly growing field, exemplifies the potential of this approach to improve patient outcomes, enhance accessibility, and drive innovation. As we move forward, continued collaboration across disciplines will be essential in realizing the full potential of telerehabilitation and ensuring that it remains at the forefront of modern healthcare practice.

Corresponding Author

Kyrylo S. Malakhov https://orcid.org/0000-0003-3223-9844

MSc in Computer Science & IT, Bachelor of Philology – English and foreign literature, Researcher, Backend developer, DevOps engineer, Microprocessor Technology Lab, V.M. Glushkov Institute of Cybernetics of the National Academy of Sciences of Ukraine. Graduate of Luhansk Taras Shevchenko National University.

Since 2023, a member of the *Interdepartmental Working Group on the Development of Telemedicine Implementation in Ukraine.*

Since 2024, a member of the *Coordination Scientific Council of the National Academy of Sciences of Ukraine on Artificial Intelligence*.

References

Bostrom, N. (2005). A History of transhumanist thought. *Journal of Evolution and Technology*, *14*(1), 1–25. http://jetpress.org/volume14/freitas.html

Busti, C., Gamboni, A., Calabrò, G., Zampolini, M., Zedde, M., Caso, V., & Corea, F. (2021). Telestroke: Barriers to the transition. *Frontiers in Neurology*, *12*. https://doi.org/10.3389/fneur.2021.689191

Conceptual Models for Clinical Data Repository Implementation. (2022). https://www.youtube.com/watch?v=uw0a4HAX7mc

Jantsch, E. (1972). *Technological Planning and Social Futures*. Littlehampton Book Services Ltd. https://archive.org/details/technologicalpla0000jant

Kaverinsky, V. V., & Malakhov, K. S. (2023). Natural language-driven dialogue systems for support in physical medicine and rehabilitation. *South African Computer Journal*, *35*(2), 119–126. https://doi.org/10.18489/sacj.v35i2.17444

Kurgaev, O. P. (2020). Extension of the Metalanguage of normal forms of knowledge. *Cybernetics and Systems Analysis*, *56*(6), 1021–1028. https://doi.org/10.1007/s10559-020-00322-w

Kurgaev, O. P., & Grigoriev, S. N. (2016). Metalanguage of normal forms of knowledge. *Cybernetics and Systems Analysis*, *52*(6), 839–848. https://doi.org/10.1007/s10559-016-9885-3

Kurgaev, O. P., & Palagin, O. V. (2021). Rehabilitation According to the Biological Feedback. *2021 11th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS)*, 1170–1175. https://doi.org/10.1109/IDAACS53288.2021.9660953

Malakhov, K. S. (2024). Innovative hybrid cloud solutions for physical medicine and telerehabilitation research. *International Journal of Telerehabilitation*, *16*(1), Article 1. https://doi.org/10.5195/ijt.2024.6635

Malakhov, K. S., Petrenko, M. G., & Cohn, E. (2023). Developing an ontology-based system for semantic processing of scientific digital libraries. *South African Computer Journal*, *35*(1), 19–36. https://doi.org/10.18489/sacj.v35i1.1219

Nasr, A., Laschowski, B., & McPhee, J. (2021). Myoelectric control of robotic leg prostheses and exoskeletons: A review. *Volume 8A: 45th Mechanisms and Robotics Conference (MR)*, V08AT08A043. https://doi.org/10.1115/DETC2021-69203

Opanasenko, V. M., Fazilov, S. K., Mirzaev, O. N., & Kakharov, S. S. ugli. (2024). An ensemble approach to face recognition in access control systems. *Journal of Mobile Multimedia*, 749–768. https://doi.org/10.13052/jmm1550-4646.20310

Opanasenko, V. M., Fazilov, Sh. Kh., Radjabov, S. S., & Kakharov, Sh. S. (2024). Multilevel face recognition system. *Cybernetics and Systems Analysis*, *60*(1), 146–151. https://doi.org/10.1007/s10559-024-00655-w

Palagin, O. V. (2013). Transdisciplinarity problems and the role of informatics. *Cybernetics and Systems Analysis*, *49*(5), 643–651. https://doi.org/10.1007/s10559-013-9551-y

Palagin, O. V. (2016). An ontological conception of informatization of scientific investigations. *Cybernetics and Systems Analysis*, *52*(1), 1–7. https://doi.org/10.1007/s10559-016-9793-6

Palagin, O. V. (2021). Information technology tools for controlled evolution. *Problems of Control and Informatics*, *66*(5), 104–123. https://doi.org/10.34229/1028-0979-2021-5-9

Palagin, O. V., Kaverinskiy, V. V., Litvin, A., & Malakhov, K. S. (2023). OntoChatGPT information system: Ontology-driven structured prompts for ChatGPT meta-learning. *International Journal of Computing*, *22*(2), 170–183. https://doi.org/10.47839/ijc.22.2.3086

Palagin, O. V., Kaverinskiy, V. V., Malakhov, K. S., & Petrenko, M. G. (2024). Fundamentals of the integrated use of neural network and ontolinguistic paradigms: A comprehensive approach. *Cybernetics and Systems Analysis*, *60*(1), 111–123. https://doi.org/10.1007/s10559-024-00652-z

Palagin, O. V., Kaverinsky, V. V., Petrenko, M. G., & Malakhov, K. S. (2023). Digital health systems: Ontology-based universal dialog service for hybrid e-rehabilitation activities support. *2023 IEEE 12th International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS)*, *1*, 84–89. https://doi.org/10.1109/IDAACS58523.2023.10348639

Palagin, O. V., Kurgaev, O. P., & Shevchenko, A. I. (2017). The noosphere paradigm of the development of science and artificial intelligence. *Cybernetics and Systems Analysis*, *53*(4), 503–511. https://doi.org/10.1007/s10559-017-9952-4

Palagin, O. V., & Petrenko, M. G. (2018). Methodological foundations for development, formation and IT-support of transdisciplinary research. *Journal of Automation and Information Sciences*, *50*(10), 1–17. https://doi.org/10.1615/JAutomatInfScien.v50.i10.10

Palagin, O. V., Petrenko, M. G., Kryvyi, S., Boyko, M., & Malakhov, K. S. (2023). *Ontology-Driven Processing of Transdisciplinary Domain Knowledge*. Iowa State University Digital Press. https://doi.org/10.31274/isudp.2023.140

Palagin, O. V., Petrenko, M. G., & Malakhov, K. S. (2024). Challenges and role of ontology engineering in creating the knowledge industry: A research-related design perspective. *Cybernetics and Systems Analysis*, *60*(4), 633–645. https://doi.org/10.1007/s10559-024-00702-6

Palagin, O. V., Petrenko, M. G., Velychko, V. Yu., & Malakhov, K. S. (2014). Development of formal models, algorithms, procedures, engineering and functioning of the software system “Instrumental complex for ontological engineering purpose.” *CEUR Workshop Proceedings*, *1843*, 221–232. http://ceur-ws.org/Vol-1843/221-232.pdf

Petrenko, M. G., Cohn, E., Shchurov, O., & Malakhov, K. S. (2023). Ontology-driven computer systems: Elementary senses in domain knowledge processing. *South African Computer Journal*, *35*(2), 127–144. https://doi.org/10.18489/sacj.v35i2.17445

Piaget, J. (1974). L’Epistémologie des Relations Interdisciplinaires. In R. Schwarz (Ed.), *Wissenschaft als interdisziplinäres Problem, Teil 1* (pp. 154–172). De Gruyter. https://doi.org/10.1515/9783112415504-006

Ramesh, S. (2018, May 26). Introducing MedBlocks—Storing Medical Records Securely on the Interplanetary File System using Blockchain technology. *MedBlocks*. https://medium.com/medblocks/introducing-medblocks-storing-medical-records-securely-on-the-interplanetary-file-system-using-20f4e88c9bda

Ramesh, S. (2023, October 18). *Will LLMs make Structured Healthcare Data Obsolete?* https://www.youtube.com/watch?v=KCKYdR7Otq4

Ramesh, S. (2024, June 10). *Generative AI, Structured Data & openEHR*. https://www.youtube.com/watch?v=XUp99f8C5us

Remote Patient Monitoring Playbook. (2022). American Medical Association. https://www.ama-assn.org/system/files/ama-remote-patient-monitoring-playbook.pdf

Roco, M. C. (2016). NBIC. In W. S. Bainbridge & M. C. Roco (Eds.), *Handbook of Science and Technology Convergence* (pp. 209–226). Springer International Publishing. https://doi.org/10.1007/978-3-319-07052-0_16

Sanchez, A., Rossos, T., Mihailidis, A., & Laschowski, B. (2023). Preliminary development of a robotic hip-knee exoskeleton with 3D-printed backdrivable actuators. *Volume 8: 47th Mechanisms and Robotics Conference (MR)*, V008T08A072. https://doi.org/10.1115/DETC2023-116406

Shyrokov, V. (2017). Evolution as universal natural law (prolegomena to the future general evolution theory). *Bionics of Intelligence*, *88*(1), 3–14. http://openarchive.nure.ua/handle/document/4868

Stucki, G., Zampolini, M., Juocevicius, A., Negrini, S., & Christodoulou, N. (2017). Practice, science and governance in interaction: European effort for the system-wide implementation of the International Classification of Functioning, Disability and Health (ICF) in Physical and

Rehabilitation Medicine. *European Journal of Physical and Rehabilitation Medicine*, *53*(2), 299–307. https://doi.org/10.23736/S1973-9087.16.04436-1

Telehealth Implementation Playbook. (2022). American Medical Association. https://www.ama-assn.org/system/files/ama-telehealth-playbook.pdf

Vernadsky, V. I. (1945). The biosphere and the noosphere. *American Scientist*, *33*(1), 1–12. https://monoskop.org/images/5/59/Vernadsky_WI_1945_The_Biosphere_and_the_Noosphere.pdf