DOI: 10.32347/2412-9933.2023.53.45-51
УДК 004.942:681.5

Shaptala Stanislav
PhD Student, Department of Information Technologies of Electronic Devices, *https://orcid.org/0000-0002-2617-5904*
National University "Zaporizhzhia Polytechnic", Zaporizhzhia

Myronova Natalia
PhD (Eng.), Associate Professor, Department of Information Technologies of Electronic Devices[1], Guest Researcher[2]
https://orcid.org/0000-0001-7484-559X
[1]National University "Zaporizhzhia Polytechnic", Zaporizhzhia,
[2]Bonn-Rhein-Sieg University of Applied Sciences, Sankt Augustin, Germany

EMBEDDING DIGITAL TWIN TECHNOLOGY IN ROBOTICS

Abstract. *The relevance of introducing digital twin technology in robotics is substantiated, which allows testing and modelling the capabilities of robots, such as manipulation, grasping, etc., using virtual robot prototypes that are identical copies of physical robot prototypes. An overview of the key components of the digital twin framework for robotics, including the physical element, virtual element, middleware, service and transport components, is provided. A technology for designing a robot using digital twins is proposed, including the design of a computer model of a robot using a computer-aided design system or three-dimensional graphics packages, the use of robot simulation systems, data management, data analysis and human-machine interaction. The further development of the research is the implementation of digital twin technology for a rescue robot according to the proposed stages: building a computer model, programming robot behaviour in a simulation system, developing a mathematical and digital model of the robot, implementing human-machine interaction between a physical robot and its digital replica, which will allow testing the interaction of the main components of the digital twin, performing data exchange between the physical and digital replica, and building a digital data model to verify the main operations.*

Keywords: robotics; digital twin framework; digital data; digital model; artificial intelligence

Introduction

Today, the widespread use of digital twin (Digital Twin), robotics, and artificial intelligence technologies has found applications in all areas of human activity. One area where having a digital twin of robots is becoming more relevant is in practical scenarios, especially in post-war reconstruction efforts in Ukraine.

It is necessary to use rescue robots in situations where the risk to the life of the rescuer is too great. These situations include dealing with explosive hazards, detecting mines and metal in fields, and removing debris after earthquakes and bombings. However, it requires safe human-robot interaction and/or complex human-robot collaboration that prioritizes human safety and helps create a sustainable work environment (SG factor).

The use of Digital Twins technology in robotics enables the testing and simulation of robot capabilities such as handling, grasping, and more with virtual robot prototypes that are identical copies of physical robot prototypes. This simulation makes it possible to identify and eliminate all errors that occur in physical robot prototypes in a virtual environment. It can also save time and money by avoiding costly mistakes that could be made by experimenting with physical prototypes.

In addition, the use of data-driven models and machine learning algorithms in Digital Twins makes it possible to optimize robot performance and predict maintenance needs. This information can be used to improve the efficiency and effectiveness of robots in various applications.

Literature review

The digital twin concept has evolved over time to meet the increasing demands of various applications and technological advances. Initially, the widely accepted three-dimensional digital twin framework consisted of three major components[1]: the physical element, the virtual element, and the middleware and Internet transport component. The physical component includes hardware components such as sensors, actuators, microcontrollers, communication devices, power supplies, and mechanical components that make up the physical object or system. The virtual component is a probabilistic simulation model that analyzes and aggregates data to determine the state of the physical assets, enabling manufacturers and operators to predict system performance in different scenarios and identify potential problems before they occur. The middleware and transport Internet component includes databases and facilitates seamless connectivity and information exchange between the physical and virtual components, optimizing system performance and minimizing downtime.

Recent advances in digital twin technology and its application in various domains have led to the development of an extended framework known as the five-dimensional digital twin (5D digital twin) [2; 3]. This innovative framework extends the traditional three-dimensional digital twin by incorporating two additional components: digital data and services, which contribute to a more complete and efficient representation of the physical system.

Digital data includes related software, databases, and other relevant information sources that enhance the accuracy and completeness of data processing. Examples of digital data in the context of robotics include real-time monitoring of robot performance, integration of machine learning algorithms for predictive maintenance, and incorporation of sensor data to create an accurate representation of the physical environment. This enriched data processing capability enables better decision making and optimization of robotic systems, ultimately improving their overall performance and reliability.

Services represent the functionalities enabled by the digital twin that enhance its capabilities and overall utility. These services can include remote diagnostics, virtual training and decision support for robotic systems, as well as the ability to simulate different scenarios to predict and optimize system performance. By providing these services, digital twins can help streamline the development, deployment, and management of complex robotic systems, reducing costs and accelerating innovation.

The 5D Digital Twin model consists of five components: the physical object/entity, the digital model/entity, services, digital data, and connections between the components. In the context of a robotic assembly line, for example, the physical object might be an industrial robot, the digital model represents its virtual counterpart, the services enable seamless collaboration between multiple robots, the digital data ensures accurate analysis of operational data, and the connections facilitate communication between the digital and physical entities. This extended framework provides broader perspectives and higher efficiency compared to the original three-dimensional digital twin model.

As the adoption of digital twin technology in robotics continues to grow, the potential applications of the 5D digital twin framework are becoming more diverse. These include applications in autonomous vehicles, drones, collaborative robots (cobots), and even medical robots for surgery or rehabilitation. The development and implementation of the 5D Digital Twin framework allows for the integration of various data sources, services, and models, ultimately leading to a more accurate, efficient, and scalable representation of physical robotic systems (Figure 1).

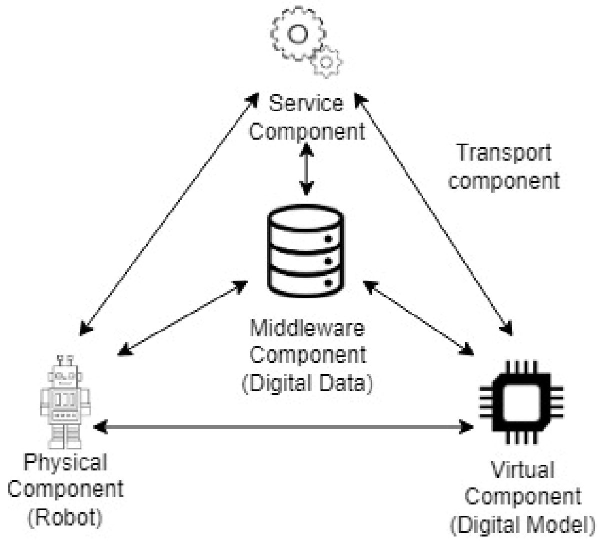

Figure 1 – 5D Digital Twin framework for Robotics

It is critical for organizations to invest time and effort in understanding and implementing these critical components to realize the full potential of digital twin technology in various applications, such as robotics. By adopting the 5D Digital Twin framework, engineers and researchers can harness the power of digital twins to optimize system performance, minimize downtime, and predict potential problems before they occur, ensuring the success and longevity of their robotic systems.

Objective of the paper

Description of the components of the 5D Digital Twin framework for Robotics. Development of technology for implementing a virtual and digital robot replica.

Overview of the physical component of Digital Twin

The effective functioning of a digital twin relies on a combination of physical components [4], each of which plays a critical role in the creation and operation of the system. This literature review provides an overview of the physical components involved in Digital Twin systems and their importance in achieving successful and effective digital twins tailored to the specific requirements of individual applications.

The physical component of Digital Twin technology includes a variety of elements such as sensors, actuators, microcontrollers, communication devices, power supplies, and mechanical components. Sensors collect data and provide feedback to the system, while actuators provide physical control and manipulation. Microcontrollers are responsible for monitoring and processing data from sensors, and communication devices facilitate the exchange of information between different components of the system. Power supplies provide energy to the system, and mechanical components build and support the physical structure of the system. The selection of specific physical components depends heavily on the needs and requirements of the particular application, and their combination determines the performance and reliability of the digital twin.

Recent research and advancements in Digital Twin technology highlight the importance of optimizing the physical components to achieve the desired performance in various robotic applications. For example, in an industrial robotic arm, high-precision sensors may be needed to ensure accurate position and force measurements, while robust actuators would be required for precise control and manipulation. In addition, the development of advanced communication protocols and efficient power supplies has improved the reliability and real-time capabilities of digital twins, enabling seamless interaction between physical and digital components.

By leveraging the synergistic interplay between physical and digital components, digital twins provide engineers with a powerful tool for optimizing system performance and anticipating potential problems before they occur. The ability to monitor, analyze, and simulate the behavior of the physical system in real time allows for continuous improvement and adaptation, ultimately resulting in increased efficiency and cost savings. This literature review highlights the critical role of the physical component in Digital Twin technology and provides valuable insights for researchers, engineers, and practitioners seeking to explore and implement Digital Twin systems in their robotic applications.

Overview of the Digital Twin transport component

The network infrastructure [5] consists of several components that play a critical role in communicating, sharing, and storing data in today's digital world. These components include network topology, network components, technologies, network protocols, and network security protocols.

Network topology refers to the arrangement of devices on a network, which can be classified into different types such as bus, star, ring, mesh, and hybrid topologies, depending on the requirements of the network.

Network components facilitate communication and data exchange between devices on a network and include switches, routers, hubs, bridges, gateways, and modems. Each component has its own functionality, and the choice of component depends on the requirements of the network.

The technologies used in the network allow devices to communicate with each other and exchange data over the Internet or LAN. These technologies include Ethernet, Wi-Fi, Bluetooth, and cellular networks. The choice of technology depends on the network requirements.

Network protocols are a set of rules and procedures used to communicate between devices on a network, such as TCP/IP, HTTP, FTP, SMTP, DNS, and MQTT, among others. The choice of protocol depends on the requirements of the network.

Network security protocols provide security and privacy for data exchanged between devices on the network. These protocols include Datagram Transport Layer Security (Digital TwinLS), Transport Layer Security (TLS), Mutual Transport Layer Security (MTLS), Secure Socket Layer (SSL), Secure Shell (SSH), and Internet Protocol Security (IPSec). Your choice of security protocol depends on your network security requirements.

Overview of the middleware (Digital Data) component of Digital Twin

The development of an effective and efficient digital twin system involves the use of several components, including middleware components such as data storage [6], data processing [7], and data modeling. Data storage is a critical aspect of digital twin technology because it involves how data is stored and retrieved. Organizations have several options for data storage, including relational databases, NoSQL databases, and data lakes.

Relational databases, which have been in use for many years, are still popular today because of their ease of use, security, and scalability. They are used to store structured data, which is data organized in tables with predefined columns and rows. Examples of popular relational databases include Oracle, MySQL, and Microsoft SQL Server. On the other hand, NoSQL databases are used to store unstructured or semi-structured data using document-oriented or key-value pair data structures. Examples of popular NoSQL databases include MongoDB, Cassandra, and Couchbase. Data lakes, on the other hand, are used to store large amounts of raw, unstructured data in distributed file systems such as Hadoop, often for big data analytics.

Data processing involves analyzing and interpreting data to gain insights and make decisions. Statistical analysis uses statistical methods to identify patterns and trends in data. Machine learning enables a system to learn and make predictions based on data using algorithms and statistical models, while deep learning uses artificial neural networks for complex pattern recognition tasks such as image and speech recognition and natural language processing.

Data modeling is the process of defining how data is structured and represented using techniques such as entity-relationship modeling, UML modeling, and dimensional modeling. Entity-relationship modeling is commonly used for relational databases, where entities and relationships are used to define the data structure. UML modeling, on the other hand, is a graphical language for modeling software systems, often used for object-oriented programming. Dimensional modeling, used for data warehousing, involves the use of fact and dimensional tables to define the data structure.

Data management software is a necessary component of the Digital Twin [7], as it manages and integrates the various data generated by the Digital Twin. The software is responsible for collecting, storing, and retrieving data from various sources such as sensors, CAD models, and simulation software. An example of data management software used in the Digital Twin is Apache Kafka. It is a high-throughput distributed messaging system that enables real-time data streaming and integration from multiple sources. This software can also handle large amounts of data with high throughput and low latency.

Data analysis and optimization software is an important tool for analyzing and optimizing the performance of physical assets or systems represented in the Digital Twin [8]. This software can process the data generated by the Digital Twin to identify patterns, trends, and anomalies. Some examples of data analysis and optimization software used in the Digital Twin include MATLAB, TensorFlow, and Apache Spark. These programs allow the use of various data analysis techniques such as statistical analysis, machine learning, and optimization algorithms.

Overview of the virtual (Digital Model) component of Digital Twin

A Digital Twin is a virtual representation of a physical asset or system that simulates its behavior and performance in real time. The development of a Digital Twin requires a combination of software components that can be divided into five categories: computer-aided design (CAD) software, simulation software, data management software, data analysis and optimization software, and human-machine interaction software.

CAD software is an essential tool for creating 3D models of the physical assets or systems to be represented in the Digital Twin. The software provides an intuitive interface for designing and modifying geometric shapes, surfaces, and volumes. Several CAD software programs are available, including SolidWorks, AutoCAD, Fusion 360, CATIA, NX, Creo, and Blender. These programs allow for the creation of complex 3D models with a high degree of accuracy that can be used as the basis for Digital Twin.

Another critical component of the Digital Twin is simulation software. Simulation software enables virtual testing of the physical assets or systems represented in the Digital Twin. This software can model the behavior of physical assets or systems in real time by replicating the physical laws that govern their operation. Some examples of simulation software include Gazebo, RoboDK, Webots, CoppeliaSim, OpenRave, Unity, UnrealEngine, NVIDIA Isaac, Drake, Simscape, and SimSpark. These programs can simulate various physical systems, from simple mechanical systems to complex robotic systems, with high accuracy and detail.

Human-machine interaction software is an essential component of the Digital Twin [9], enabling interaction between human operators and the virtual representation of physical assets or systems. This software provides an intuitive interface for controlling and monitoring the physical assets or systems represented in the Digital Twin. Some examples of human-machine interaction software include Unity, Unreal Engine, and MATLAB Simulink.

Augmented (mixed) reality technology allows us to represent digital content in a true 3D form and interact with it in the existing physical environment. On the other hand, virtual reality technology allows us to create entirely new environments for interacting with the digital twin with high immersion levels [10; 11]. These capabilities provide us with exciting 3D visualizations, realistic representations, natural gesture interactions, collaboration features, and fast navigation tools over a large area. As a result, users can easily focus on every component of the system, from the smallest device to the entire factory. We use virtual and augmented reality in several areas, including product or process design, facility planning, training, and remote collaboration [12].

In addition, the digital twin can serve as a tool for verifying a new factory configuration by defining a new design. However, the digital twin lacks realism when it comes to human-centered manufacturing process and workplace design. This is where virtual and augmented reality becomes a key tool, as it represents the system at scale and allows for intuitive and natural interactions [13; 14].

For example, engineers can design a new configuration using a digital twin that simulates the new configuration. By providing end users with realistic factory behavior, they can interact with it and provide feedback on the configuration. Because any necessary changes are made only in the digital world, the cost is significantly less than making changes in the physical system. After verifying the new configuration, new parameters and software can be deployed to the physical version of the system using the digital twin.

Overview of the service component of Digital Twin

Digital twin technology has been increasingly adopted across various industries, with the service component playing a pivotal role in enhancing the capabilities of robotic systems. The digital twin service component encompasses a range of applications, including remote diagnostics, virtual training, decision support, and scenario simulation, all of which contribute to optimizing system performance and reliability[15]. This technology's ability to provide real-time insights, facilitate informed decision-making, and predict potential issues has positioned it as a powerful tool for organizations seeking to maximize the value of their robotic systems.

Remote diagnostics is a key aspect of the digital twin service component, enabling operators to monitor the real-time performance and health of robotic systems, regardless of their location. By leveraging digital replicas of these systems, remote diagnostics can identify potential issues, predict maintenance requirements, and even perform troubleshooting, all without the need for physical intervention. This not only reduces downtime and maintenance costs but also ensures the ongoing reliability and efficiency of robotic systems. Furthermore, the integration of artificial intelligence and machine learning algorithms into remote diagnostics can enhance the accuracy of predictions and facilitate more effective maintenance strategies, further optimizing system performance.

Virtual training is another critical application of the digital twin service component, offering an immersive and risk-free environment for training personnel on the operation and maintenance of robotic systems. By creating a digital replica of the system, trainees can interact with the virtual model, gaining hands-on experience and familiarizing themselves with the equipment before working on the physical system. This approach to training not only accelerates the learning process but also significantly reduces the risk of errors and accidents during the training phase, leading to improved safety and efficiency in the workplace.

The digital twin service component also plays an important role in decision support for robotic systems. By analyzing real-time data from the digital replica, organizations can make informed decisions on system operation, maintenance, and optimization. This can include evaluating the impact of different operational strategies, scheduling maintenance activities to minimize disruptions, or identifying areas for system improvements. In addition, the ability to simulate various scenarios using the digital twin enables organizations to predict and optimize system performance under a wide range of conditions. This proactive approach to decision-making results in more efficient and resilient robotic systems, ultimately contributing to the overall success of the organization.

Technology of implementation a robot with a digital twin

Implementing a robot with a digital twin requires a multidisciplinary approach that combines knowledge from different fields such as robotics, computer-aided design (CAD), simulation, data management, and data analysis. The following steps can guide the implementation process [16], which are presented in Figure 2.

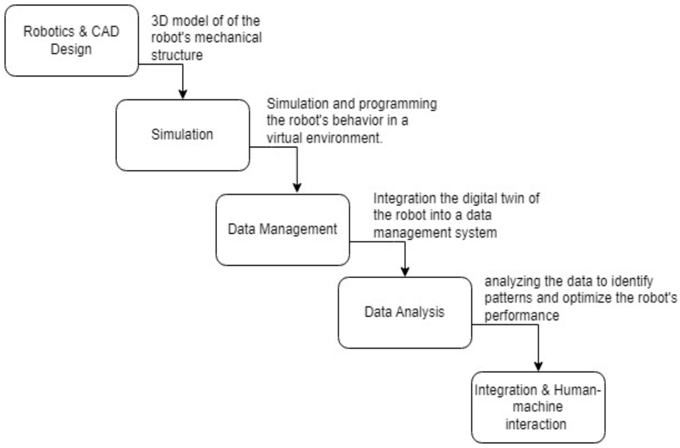

Figure 2 – Technology of implementation a robot with a digital twin

Step 1: Design the robot using CAD software such as SolidWorks, AutoCAD, Fusion 360, CATIA, NX, Creo, or Blender. This step involves creating a detailed 3D model of the robot's mechanical structure, including its joints, sensors, actuators, and other components.

Step 2: Use simulation software such as Gazebo, RoboDK, Webots, CoppeliaSim, OpenRave, Unity, UnrealEngine, NVIDIA Isaac, Drake, Simscape, or SimSpark to simulate the robot's behavior in a virtual environment. In this step, the robot's controllers are programmed and tested in a simulated environment to ensure that the robot behaves as expected.

Step 3: Integrate the digital twin of the robot into a data management system such as Apache Kafka, Siemens Teamcenter, Dassault Systèmes ENOVIA, TC Windchill, Oracle Agile PLM, and Aras Innovator. This step involves creating an interface between the robot's digital twin and the data management system to ensure that all data generated by the robot is captured and stored for analysis.

Step 4: Use data analysis and optimization software such as MATLAB, Python, R, TensorFlow, Keras, or PyTorch to analyze the data collected from the robot's digital twin. This step involves analyzing the data to identify patterns, anomalies, and other insights that can be used to optimize the robot's performance.

Step 5: Develop human-machine interaction software using programs such as Unity or Unreal Engine, to create a user-friendly interface for controlling and monitoring the robot. This step involves creating a user interface that allows the operator to interact with the robot in a natural and intuitive way.

Conclusion

In summary, the use of digital twin technology in robotics can greatly improve the efficiency and safety of human-robot interaction, especially in scenarios where there is a high risk to human life. By creating virtual replicas of physical robots, designers can identify and eliminate errors in a virtual environment, saving time and money. In addition, the use of data-driven models and machine learning algorithms can optimize robot performance and predict maintenance needs.

In this paper, we have provided an overview of the key components of a digital twin for robotics, including the physical element, the virtual element, and the middleware, the service and transport components. We have also outlined a five-step process for designing a robot using Digital Twin technology, which includes CAD design, simulation, data management, data analysis, and human-machine interaction.

By using Digital Twin technology, designers can not only create better performing robots, but also improve the overall sustainability of the work environment. Using of Digital Twin technology in robotics will continue to play an important role in various areas of human activity, including post-war reconstruction and disaster relief.

The further development of the research is the implementation of digital twin technology for a rescue robot according to the proposed stages: building a computer model, programming robot behaviour in a simulation system, developing a mathematical and digital model of the robot, implementing human-machine interaction between a physical robot and its digital replica, which will allow testing the interaction of the main components of the digital twin, performing data exchange between the physical and digital replica, and building a digital data model to verify the main operations.

References

1. Grieves, M. (2014). Digital twin: manufacturing excellence through virtual factory replication. *White paper*, 1–7.

2. Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., Wang, L. and Nee, A. (2021). Enabling technologies and tools for Digital Twin. Journal of Manufacturing Systems, 58, 3–21.

3. Hassan, M., Svadling, M., Björsell, N. (2022). Experience from implementing digital twins for maintenance in industrial processes.

4. Siciliano, B. & Khatib, O. (Eds.). (2016). Springer Handbook of Robotics. Springer International Publishing.

5. Stallings, W. (2007). DATA AND COMPUTER COMMUNICATIONS, 8th edition.

6. Schroeder, G. N., Steinmetz, C., Pereira, C. E., et al. (2016). Digital twin data modeling with automation and a communication methodology for data exchange. *IFACPapersOnLine*, 49 (30), 12–7.

7. Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. *Int. J. Adv. Manuf. Technol*., 94, 3563–3576.

8. Wang, T., Li, J., Kong, Z., Liu, X., Snoussi, H., Lv, H. (2021). Digital twin improved via visual question answering for vision-language interactive mode in human-machine collaboration. *J. Manuf. Syst*., 58, 261–269.

9. Ascone, C. & Vanderhaegen, F. (2022). Holistic framework for digital twins of human-machine systems. *IFAC-PapersOnLine*, 55(29), 67-72.

10. Delbrügger, T., Meißner, M., Wirtz, A., Biermann, D., Myrzik, J., Rossmann, J., Wiederkehr, P. (2019). Multi-level simulation concept for multidisciplinary analysis and optimization of production systems. *Int. J. Adv. Manuf. Technol*. 2019, 103, 3993–4012.

11. Wang, X., Liang, C.J., Menassa, C., Kamat, V. (2020). Real-Time Process-Level Digital Twin for Collaborative Human-Robot Construction Work. In Proceedings of the 37th International Symposium on Automation and Robotics in Construction (ISARC), Kitakyushu, Japan, 28 October 2020.

12. Bilberg, A., Malik, A. A. (2019). Digital twin driven human–robot collaborative assembly. *CIRP Ann.*, 68, 499–502.

13. Malik, A. A., Brem, A. (2021). Digital twins for collaborative robots: A case study in human-robot interaction. *Robot. Comput.-Integr. Manuf.*, 68, 102092.

14. Rosen, R., von Wichert, G., Lo, G., Bettenhausen, K. D. (2015). About the importance of autonomy and digital twins for the future of manufacturing. *IFAC-PapersOnLine*, 48 (3), 567–572.

15. Myronova, N. O., Shaptala, S. V. (2022). Study of the use of digital twins technology for the implementation of simulation of a rescuer. Modern problems and achievements in the field of radio engineering, telecommunications and information technology: XI International scientific and practical conference, 12-14 December 2022: abstracts / Edited by D. M. Pisa. Electronic data. Zaporizhzhia: National University of Zaporizhzhia Polytechnic, 2022. pp. 87–89. (in Ukrainian)

Стаття надійшла до редколегії 04.03.2023

Шаптала Станіслав Вікторович
Аспірант кафедри інформаційних технологій електронних засобів, *https://orcid.org/0000-0002-2617-5904*
Національний університет «Запорізька політехніка», Запоріжжя
Миронова Наталя Олексіївна
Кандидат технічних наук, доцент кафедри інформаційних технологій електронних засобів[1], гостьовий дослідник[2], *https://orcid.org/0000-0001-7484-559X*
Національний університет «Запорізька політехніка», Запоріжжя,
Університет прикладних наук Бонн-Рейн-Зіг, Санкт-Августин, Німеччина

ВПРОВАДЖЕННЯ ТЕХНОЛОГІЇ ЦИФРОВИХ ДВІЙНИКІВ ДЛЯ РОБОТОТЕХНІКИ

Анотація. *Обґрунтовано актуальність впровадження технології цифрових двійників у робототехніці, що дає змогу тестувати та моделювати можливості роботів, такі як маніпулювання, захоплення тощо, за допомогою віртуальних прототипів роботів, які є ідентичними копіями фізичних прототипів роботів. Виконано огляд ключових компонентів фреймворку цифрового двійника для робототехніки, включаючи фізичний елемент, віртуальний елемент, проміжне програмне забезпечення, сервісні та транспортні компоненти. Запропоновано технологію проєктування робота з використанням цифрових двійників, що включає проєктування комп'ютерної моделі робота за допомогою системи автоматизованого проєктування або пакетів побудови тривимірної графіки, використання систем симуляції роботів, управління даними, аналіз даних та людино-машинну взаємодію. Подальшим розвитком дослідження є реалізація технології цифрових двійників для робота-рятівника відповідно до запропонованих етапів: побудова комп'ютерної моделі, програмування поведінки робота в системі симуляції, розроблення математичної та цифрової моделі робота, реалізація людино-машинної взаємодії між фізичним роботом та його цифровою реплікою, що допоможе протестувати взаємодію основних компонентів цифрового двійника, виконати обмін даними між фізичною та цифровою копією та побудувати цифрову модель даних з метою веріфікації основних операцій робота-рятівника в реальному часі.*

Ключові слова: робототехніка; фреймворк цифрових двійників; цифрові дані; цифрова модель; штучний інтелект

Link to the publication

APA Shaptala, Stanislav & Myronova, Natalia. (2023). Embedding Digital Twin Technology in Robotics. *Management of Development of Complex Systems*, 53, 45–51, dx.doi.org\10.32347/2412-9933.2023.53.45-51.

ДСТУ Шаптала С. В., Миронова Н. О. Впровадження технології цифрових двійників для робототехніки. *Управління розвитком складних систем.* Київ, 2023. № 53. С. 45 – 51, dx.doi.org\10.32347/2412-9933.2023.53.45-51.