Міністерство освіти і науки України

Харківський національний університет радіоелектроніки

Кафедра комп'ютерно-інтегрованих технологій, автоматизації, робототехніки та безпекової інженерії

I Всеукраїнська конференція «Інтелектуальні технології цивільної безпеки та робототехнічні системи аварійно-рятувальних робіт»

I All-Ukrainian Conference "Intelligent Civil Safety Technologies and Robotic Systems for Emergency and Rescue Operations"

ICSTRO

2026

I All-Ukrainian Conference

February 12 - 13, 2026

Kharkiv

УДК: 005:004.896:62-65:338.3

Інтелектуальні технології цивільної безпеки та робототехнічні системи аварійно-рятувальних робіт 2026: матеріали I-ої Всеукраїнська конференція, Харків, 12-13 лютого 2026 р.: тези доповідей / [редкол. І.Ш. Невлюдов (відповідальний редактор)].-Харків: [електронний друк], 2026. – 192 с.

У збірник включені тези доповідей, які присвячені сучасним тенденціям розвитку технологій та засобів моделювання, прогнозування та управління ризиками у сфері цивільної безпеки; техногенна та виробнича безпека: технічні засоби, оцінка ризиків, експертиза; інтелектуальні та робототехнічні системи аварійно-рятувальних робіт; кіберфізичні системи, інформаційна безпека та цифровий захист виробництв; інформаційно-комунікаційні технології в системах управління та моніторингу надзвичайних ситуацій; сталий розвиток, екологічна безпека та соціальна відповідальність у сфері цивільної безпеки; інтелектуальні системи прийняття рішень у сфері цивільного захисту.

Intelligent Civil Safety Technologies and Robotic Systems for Emergency and Rescue Operations 2026: Proceedings of I st All-Ukrainian Conference, Kharkiv, February 12 - 13, 2026: Thesises of Reports / [Ed. I.Sh. Nevlyudov (chief editor).] .- Kharkiv .: [electronic version], 2026. - 192 p.

The collection includes the thesises of reports on devoted to current trends in the development of technologies and tools for modeling, forecasting, and risk management in the field of civil safety; industrial and technological safety, including technical means, risk assessment, and expert evaluation; intelligent and robotic systems for emergency and rescue operations; cyber-physical systems, information security, and digital protection of industrial facilities; information and communication technologies in emergency management and monitoring systems; sustainable development, environmental safety, and social responsibility in the field of civil safety; and intelligent decision-support systems in civil protection.

Харківський національний університет радіоелектроніки
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Національний університет «Запорізька політехніка»
Національний університет «Львівська політехніка»
Державне підприємство «Південний державний проектно-конструкторський та науково-дослідний інститут авіаційної промисловості»
Головне управління ДСНС України у Харківській області

Всеукраїнська конференція «Інтелектуальні технології цивільної безпеки та робототехнічні системи аварійно-рятувальних робіт» (ICSTRO-2026)

All-Ukrainian Conference “Intelligent Civil Safety Technologies and Robotic Systems for Emergency and Rescue Operations” (ICSTRO-2026)

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DIGITAL TWIN: A VIRTUAL COPY OF A PHYSICAL OBJECT, PROCESS, OR SYSTEM. APPLICATIONS IN INDUSTRY, CONSTRUCTION, AND CITIES

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***Annotation*:** The paper considers the concept of a digital twin as a virtual copy of a physical object, process or system that operates on the basis of data obtained from a real object in real time or offline. The principles of construction and operation of digital twins, their structure and classification are analyzed. The role of digital twins in the concept of Industry 4.0 is shown, in particular in interaction with the technologies of the Industrial Internet of Things and product lifecycle management. Special attention is paid to the application of digital twins at different stages of the product lifecycle, as well as the use of this technology in industry, construction and "smart cities" in order to increase efficiency, reliability and optimization of processes.

Key words: digital twin, Industry 4.0, Industrial Internet of Things, PLM, Smart Factory.

ЦИФРОВИЙ ДВІЙНИК: ВІРТУАЛЬНА КОПІЯ ФІЗИЧНОГО ОБ'ЄКТА, ПРОЦЕСУ ЧИ СИСТЕМИ. ЗАСТОСУВАННЯ В ПРОМИСЛОВОСТІ, БУДІВНИЦТВІ ТА МІСТАХ

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***Анотація*:** У роботі розглянуто поняття цифрового двійника як віртуальної копії фізичного об’єкта, процесу або системи, що функціонує на основі даних, отриманих від реального об’єкта в режимі реального часу або офлайн. Проаналізовано принципи побудови та роботи цифрових двійників, їх структуру та класифікацію. Показано роль цифрових двійників у концепції Індустрії 4.0, зокрема у взаємодії з технологіями промислового Інтернету речей та управління життєвим циклом виробу. Окрему увагу приділено застосуванню цифрових двійників на різних етапах життєвого циклу виробу, а також використанню цієї технології в промисловості, будівництві та «розумних містах» з метою підвищення ефективності, надійності та оптимізації процесів.

***Ключові слова*:** цифровий двійник, Індустрія 4.0, Промисловий Інтернет речей, управління життєвим циклом виробу, розумна фабрика.

In the current conditions of digital transformation of industry, construction, and urban management, there is a growing need for accurate modeling of complex technical systems and processes [1-8]. Traditional approaches to designing and operating facilities require significant material costs, lengthy testing times, and do not always enable the timely detection of hidden defects and risks.

Digital Twin technology is a relevant response to these challenges, as it enables the creation of a virtual copy of a physical object, process, or system, with the possibility of continuous updating based on data from real sensors. This allows for repeated virtual testing, fault prediction, optimization of operating modes, and reduction of the number of physical experiments. Digital twins are particularly relevant in the context of the Industry 4.0 concept, where they are an integral part of «smart factories», product lifecycle management (PLM) systems, and the Industrial Internet of Things (IIoT) [9-11].

In construction and «smart cities», digital twins help improve energy efficiency, safety, and the quality of infrastructure management. Thus, the research and implementation of digital twins are a relevant area of development in modern information and engineering technologies, which have important practical significance for various sectors of the economy.

A digital twin is one of the key technologies of modern digital transformation. According to the research and consulting company Gartner, a digital twin is a digital representation of a real object or system. This definition emphasizes the main idea of the concept – the existence of a virtual copy of a physical object. In a broader sense, a digital twin is a software counterpart of a physical device that models its internal processes, technical characteristics, and behavior under real operational conditions. Unlike ordinary computer models, a digital twin can reflect dynamic changes in the object's state and respond to external influences.

A key feature of a digital twin is the constant exchange of data with the real object. Information from sensors of the physical device, which operates in parallel with the virtual model, is used to generate input influences. A digital twin can function both in real-time (online) mode and in offline (autonomous) mode, allowing numerous experiments to be conducted without risk to the real object. Comparing data from real and virtual sensors enables the detection of anomalies, prediction of malfunctions, and identification of the causes of deviations, which is particularly important for complex technical systems.

The implementation of digital twins is closely linked to the use of Industrial Internet of Things (IIoT) technologies. IIoT enables the collection of large volumes of data from sensors, controllers, and measurement systems. Without digital twins, full implementation of Product Lifecycle Management (PLM) – managing the product lifecycle – is impossible. IIoT and PLM are integral components of a Smart Factory, within which a digital model is created not only for individual products but for the entire production system. These technologies are part of the Industry 4.0 concept, which focuses on minimizing physical testing and maximizing the use of virtual modeling.

A digital twin of a product is a complex, multi-level model and includes:
- the geometric and structural model of the object;
- calculation data of parts, assemblies, and the product as a whole;
- mathematical models of physical processes;
- information about manufacturing and assembly processes;
- a product lifecycle management system.

The combination of these elements allows for the analysis of an object's performance even before its physical production and throughout its entire service life.

At the conceptual design stage, the digital twin is used to create and evaluate different design options. At the detailed design stage, the model is refined, operating modes and environmental impacts are taken into account, which allows for optimization of the interaction between components. During the manufacturing stage, the digital twin helps determine tolerances, quality parameters, and quickly identify the causes of malfunctions during testing. In the operational stage, the model is used for diagnostics, failure prediction, efficiency improvement, and feedback for enhancing future products.

Digital twin prototypes (DTP) contain the information necessary for designing and creating physical products and are relatively stable models. Digital twin instances (DTI) describe a specific product and change according to the conditions of its operation. Aggregated twins (DTA) are used to manage groups of products and analyze their performance collectively.

In addition to individual products, digital twins are created for: the entire production system; a specific production line; a particular asset within the line.

Such twins allow for the optimization of material flows, planning, and production management.

Table 1 shows the areas of application of digital twins.

Digital Twin technology has demonstrated measurable impact across multiple industries, though the extent of improvements varies depending on the sector and implementation approach. To illustrate the comparative effectiveness of Digital Twin adoption, let's examine key performance improvements observed across five major industries: Manufacturing, Automotive, Energy, Construction, and Smart Cities.

Table 1 – Areas of application of digital twins

Area of use	Digital twin object	Which processes are being modeled	Practical purpose	Expected effect
Industry	Machines, units, production lines	Operating modes, wear, failures	Production optimization, diagnostics	Reducing downtime, increasing reliability
Mechanical engineering	Product, assembly, part	Physical processes, loads	Design and virtual testing	Shortening development time
Energy sector	Turbines, substations, networks	Energy flows, thermal regimes	Failure prediction, optimization	Improving energy efficiency
Construction	Buildings, structures	Design and engineering systems	Design and operation	Reducing errors and costs
Building Maintenance	Engineering networks	Resource consumption	Monitoring and control	Saving energy
Transport	Cars, railway systems	Motion dynamics, wear	Maintenance	Increasing safety
Logistics	Warehouses, supply chains	Material flows	Route optimization	Reducing delivery time
Smart cities	City infrastructure	Traffic, energy consumption	Resource management	Improving quality of life
Environmental protection	Ecosystems, urban environment	Pollution, climate data	Analysis and forecasting	Reducing environmental risks
Education and Science	Educational and research facilities	Experiments, scenarios	Training and research	Safe testing

The diagram (Fig. 1) presents a visual comparison of performance enhancements achieved through Digital Twin implementation in these sectors, helping to identify which industries have benefited most significantly from this technology and where the greatest potential for optimization exists.

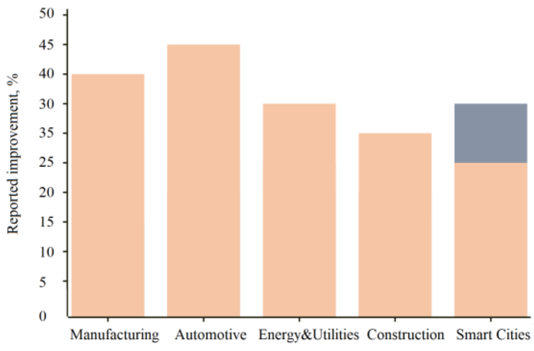

Figure 1 – Range of improvements with Digital Twin technology

Digital Twin technology delivers industry-specific benefits: manufacturing and automotive see 20-30 % less downtime through predictive maintenance; energy and utilities achieve 15-20 % cost savings via asset optimization; construction reduces rework by 10-15 %, improving safety and schedules; while smart cities gain 20-30 % efficiency in specific services like waste management, though overall city-wide impact remains complex to measure. Digital twin technology is a promising and relevant area of development in modern information and engineering technologies, with wide practical applications in industry, construction, and smart cities. It provides a deeper understanding of the behavior of complex systems, allows for predicting their condition, optimizing operational processes, and contributes to improving management efficiency and the quality of decision-making.

This research provides a comprehensive analysis of Digital Twin technology applications across key economic sectors, offering evidence-based insights into realistic performance improvements rather than inflated marketing claims. The work establishes a practical framework for understanding where and how Digital Twin implementations deliver measurable value, enabling organizations to set appropriate expectations and make informed investment decisions. By comparing adoption patterns and outcomes across manufacturing, automotive, energy, construction, and smart cities, this study identifies critical success factors including the necessity of deep integration with existing management systems, the importance of predictive maintenance capabilities, and the distinction between concentrated versus distributed impact patterns. The findings demonstrate that Digital Twin technology is not a universal solution delivering uniform results, but rather a sophisticated tool whose effectiveness depends heavily on industry maturity, implementation approach, and alignment with specific operational challenges. This understanding is essential for moving beyond theoretical potential toward practical, cost-effective deployment strategies that maximize return on investment while avoiding common pitfalls of over-expectation and inadequate system integration.

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