FIRE AND CIVIL SAFETY

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DIGITAL TWINS AND CYBER-PHYSICAL SYSTEMS AS THE FOUNDATION FOR THE TRANSFORMATION OF CIVIL DEFENSE IN THE CONTEXT OF INDUSTRY 5.0

Abstract. This paper examines the use of digital twins and cyber-physical systems as the technological foundation for the transformation of civil protection in the context of Industry 5.0. A structural representation of a city digital twin is proposed to enable the integration of sensor data, infrastructure monitoring, emergency prediction, risk assessment, and real-time decision support. The proposed approach combines physical infrastructure, digital models, artificial intelligence, and cloud-edge computing technologies into a unified cyber-physical environment that enhances operational awareness, improves emergency response efficiency, strengthens the resilience of critical infrastructure, and increases the effectiveness of civil protection coordination.

Keywords: digital twin, cyber-physical system, civil protection, Industry 5.0, critical infrastructure, artificial intelligence, Internet of Things (IoT), Edge Computing, threat monitoring, decision support.

Contemporary challenges associated with the increasing number of natural, technological, military, and cyber threats necessitate the transformation of civil protection systems through the implementation of intelligent digital technologies capable of ensuring the timely acquisition, integration, and analysis of heterogeneous data to support operational decision-making [1,2]. The Industry 5.0 concept creates new opportunities for the development of digital twins and cyber-physical systems that provide continuous infrastructure monitoring, emergency prediction, risk assessment, and real-time simulation of potential response scenarios [3,4]. Therefore, research focused on the application of digital twins and cyber-physical systems as the foundation for the transformation of civil protection in the context of Industry 5.0 is highly relevant and of significant practical importance for improving public safety, enhancing the resilience of critical infrastructure, and increasing the effectiveness of civil protection management and emergency response operations.

A digital twin in cyber-physical systems for civil protection is a dynamic digital representation of a real-world object, process, or infrastructure component that is synchronized with its physical counterpart in real time through sensor data, communication technologies, and computing platforms to enable continuous monitoring, emergency prediction, and decision support [5]. The use of digital twins enables the simulation of various threat occurrence and development scenarios, assessment of their potential consequences, and selection of the most effective response strategies, thereby improving the responsiveness, reliability, and operational safety of cyber-physical systems for civil protection. Cyber-physical systems in civil protection serve as an integration framework that connects physical assets, sensors, communication networks, computing platforms, and intelligent algorithms to continuously monitor the condition of territories, critical infrastructure, and potential sources of hazards [6]. Their implementation enables timely threat detection, emergency forecasting, automated decision support, and real-time coordination of emergency response services. An example of a digital twin representation within cyber-physical systems for civil protection based on the Industry 5.0 concept is presented in Figure 1.

The main components of the digital twin within cyber-physical systems for civil protection based on the Industry 5.0 concept, presented in Figure 1, are described as follows. Physical City represents the real urban environment that serves as the physical domain of civil protection and includes buildings, transportation infrastructure, healthcare facilities, energy systems, communication networks, emergency response services, and the population, whose conditions are continuously monitored to provide up-to-date information on potential hazards [7].

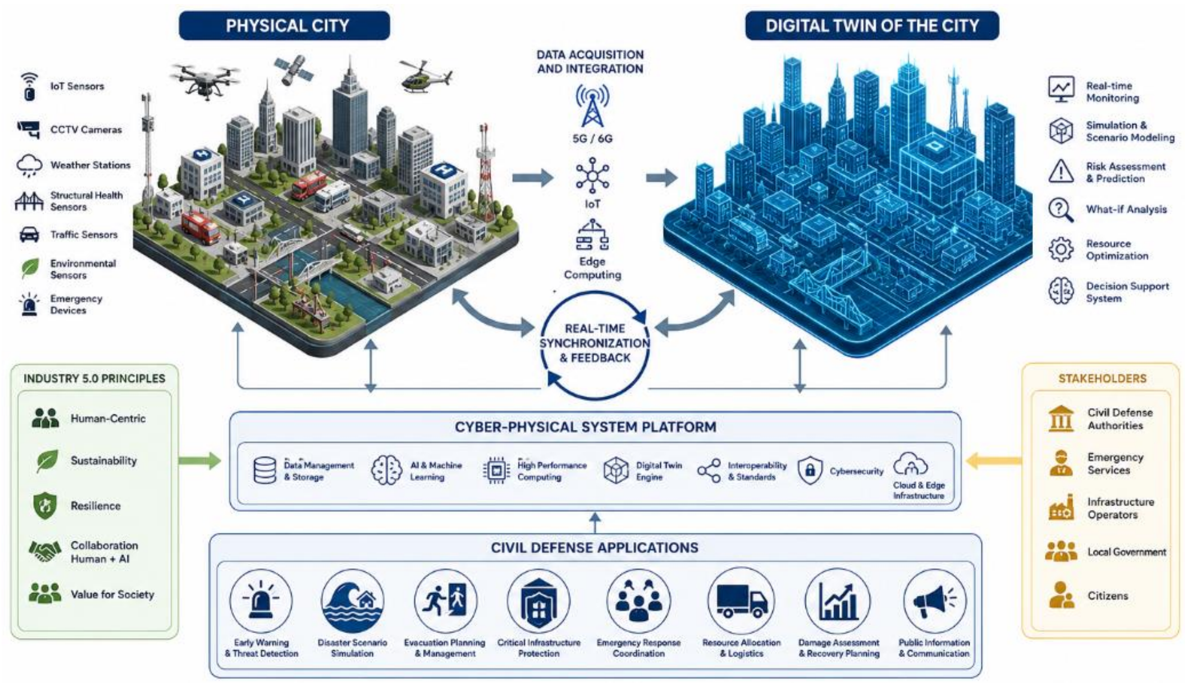

Figure 1. Representation of a Digital Twin in Cyber-Physical Systems for Civil Protection Based on the Industry 5.0 Concept

Digital Twin of the City is a virtual dynamic representation of the physical environment synchronized with its real counterpart in real time to simulate emergency scenarios, predict their consequences, and support managerial decision-making [8]. Data Acquisition and Integration is the subsystem responsible for collecting information from sensors, unmanned aerial platforms, surveillance cameras, IoT networks, 5G/6G communication technologies, and Edge Computing devices, followed by the integration of heterogeneous data streams into a unified information environment [9]. Real-Time Synchronization and Feedback is the synchronization and feedback module that enables continuous bidirectional information exchange between the physical city and its digital twin, ensuring that the digital model remains up to date and accurately reflects changes occurring in the physical environment. Cyber-Physical System Platform is the core platform that integrates data storage and processing technologies, artificial intelligence and machine learning algorithms, high-performance computing resources, the digital twin engine, interoperability mechanisms, cybersecurity solutions, and cloud-edge infrastructure to provide comprehensive management of civil protection processes [10]. Industry 5.0 Principles define the human-centric approach to civil protection systems by emphasizing resilience, sustainability, effective collaboration between humans and artificial intelligence, and the creation of societal value through advanced intelligent digital technologies [11]. Civil Defense Applications constitute the application layer that supports early threat detection, emergency scenario simulation, evacuation planning, critical infrastructure protection, coordination of emergency response teams, resource allocation optimization, damage assessment, and public information services based on the outputs generated by the digital twin [12]. Stakeholders include government authorities, emergency response organizations, critical infrastructure operators, local administrations, and citizens who utilize the information and recommendations provided by the digital twin to improve emergency response, enhance coordination, and increase the overall effectiveness of civil protection management [13,14].

Conclusion. The conducted research demonstrated that the integration of digital twins and cyber-physical systems in accordance with the Industry 5.0 concept provides a technological foundation for developing an intelligent civil protection system capable of continuous monitoring, emergency prediction, and real-time decision support. The proposed structural model integrates physical infrastructure, a digital twin, advanced data acquisition technologies, artificial intelligence, and high-performance computing into a unified information environment, thereby enhancing emergency response capabilities, improving the resilience of critical infrastructure, and increasing the effectiveness of civil protection coordination. The practical implementation of the proposed approach will facilitate the digital transformation of civil protection systems, improve public safety, and support the development of adaptive risk management mechanisms for addressing complex contemporary threats.

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