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Concept of a Geospatial Digital Twin for Crisis Management and Military Applications: Information Scope and Data Modelling

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Abstract:

The increasing availability of geospatial data and the rapid development of digital technologies have significantly transformed the way spatial information is collected, processed, and used in decision-making processes. One of the most promising concepts emerging from this transformation is the Digital Twin (DT), defined as a dynamic, virtual representation of a physical object, system, or process that is continuously updated using real-time or near-real-time data. While Digital Twin technology has been widely adopted in industry, energy, and smart city applications, its implementation in geospatial contexts—particularly in crisis management and military operations—remains insufficiently explored and requires further conceptualization. The concept of a Digital Twin originates from earlier approaches to modelling physical systems, including CAD-based simulations and physical replicas used in engineering and space missions. The modern understanding of Digital Twin has evolved with the development of enabling technologies such as the Internet of Things (IoT), Big Data, cloud computing, and artificial intelligence. These technologies allow for continuous data exchange between the physical and digital worlds, enabling not only monitoring but also simulation and prediction of system behaviour. In the geospatial domain, this concept extends traditional cartographic representations by incorporating temporal dynamics, semantic relationships, and real-time data integration. From a cartographic perspective, the idea of representing reality in a model form has existed for centuries, with maps serving as early analogue "twins" of geographic space. However, traditional maps and even modern GIS datasets are inherently static, as their validity depends on the time of data acquisition and update cycles that are often measured in months or years. This limitation is particularly critical in applications such as crisis management and military operations, where decisions must be based on the most current and accurate information available. A geospatial Digital Twin addresses this limitation by enabling continuous updates and dynamic representation of spatial phenomena.

A geospatial Digital Twin can be characterized by several key properties. It provides accurate geometric representation in two, three, or even four dimensions, ensuring precise positioning of objects in a defined spatial reference system. It integrates heterogeneous data sources, including GIS datasets, BIM models, LiDAR point clouds, remote sensing data, and sensor-based observations. It maintains semantic information and relationships between objects, allowing for meaningful interpretation of spatial structures and processes. Furthermore, it enables real-time or near-real-time updates, supports advanced spatial analyses and simulations, and offers interactive visualization tailored to different user groups. Scalability and multi-resolution representation are also essential, allowing the system to operate across different levels of detail depending on the application context. The importance of such a system becomes particularly evident in the domain of crisis management, which encompasses activities related to prevention, preparedness, response, and recovery. All these phases have a strong spatial component, involving specific locations, infrastructure elements, and the movement of resources. Effective crisis management requires access to high-quality geospatial data that accurately reflects current conditions. Any discrepancy between the digital representation and real-world conditions may lead to incorrect decisions, potentially resulting in significant losses. Similar requirements apply to military operations, where situational awareness and timely access to reliable spatial information are critical. This study aims to address the following research question: what information scope should a geospatial Digital Twin include to effectively support crisis management and military operations? To answer this question, a conceptual framework for defining the required data structure and content of such a system is proposed. The approach is based on the identification of key thematic categories describing the geospatial environment, including terrain, infrastructure, hydrology, land cover, and environmental conditions. Particular attention is given to dynamic phenomena, such as weather conditions and seasonal variability, which significantly influence operational capabilities. The proposed framework also incorporates a multi-resolution data model, in which different levels of detail are associated with specific spatial scales. These range from ultra-detailed representations, suitable for engineering and tactical applications, to generalized representations used at regional or strategic levels. For each level, appropriate data sources are identified, including national geospatial datasets, open data platforms such as

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OpenStreetMap, remote sensing products, and sensor networks. The integration of these diverse data sources enables the creation of a coherent and scalable Digital Twin model.

Figure 1. Structure of proposed digital twin

A case study based on the territory of Poland is used to evaluate the availability and applicability of existing geospatial data for building such a system. The analysis demonstrates that a significant portion of the required data can be derived from national geodetic and cartographic resources, as well as open data sources. However, certain types of data, particularly those related to high-resolution representations and real-time updates, are not readily available and require dedicated acquisition processes. The study also presents an example of modelling selected spatial objects, such as buildings, across different levels of detail, taking into account geometry, semantics, and temporal variability. The results highlight both the potential and the challenges associated with the development of geospatial Digital Twins. Key challenges include the integration of heterogeneous data into a unified system, the management of large and continuously evolving datasets, the representation of temporal changes in both geometry and attributes, and the need for interoperability based on open standards. Additional difficulties arise from the limited availability of certain types of data and the high costs associated with their acquisition and maintenance.

In conclusion, a geospatial Digital Twin represents an advanced form of spatial modelling that integrates geometry, semantics, temporal dynamics, and system behaviour into a single, coherent framework. Such a system has the potential to significantly enhance decision-making processes in crisis management and military operations by providing accurate, up-to-date, and analytically rich representations of reality. However, its successful implementation requires careful definition of the information scope, appropriate data modelling strategies, and the development of robust data infrastructures.

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