Silesian University of Technology

DOCTORAL DISSERTATION

in the discipline: Civil Engineering, Geodesy, and Transport

Digital twins of bridges: establishing principles of virtualization with practical use cases

Abstract

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March 2023

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The ongoing digitization presents both challenges and opportunities. Industries are transforming at an unprecedented pace. Sustainable development goals, ecological aims, and a growing population motivate the introduction of modern and integrated techniques also in civil engineering. The need for digital transformation is expressed by the problems of aging infrastructure, the civil engineering productivity margin, and the expectations of engineers and managers of facilities. Bridges, as complex, unique structures of logistic and strategic importance, need a new strategy of management. Digital twins, announced as crucial components of Industry 4.0, have become an enabler of holistic digital transformation.

This dissertation proposes principles for creating and utilizing the digital twins of bridges. The proposed concept addresses the general multi-industrial digital twinning fundamentals (identified with the literature study), the specificity of bridges, and the demands of designers, engineers, and managers of civil engineering facilities. The proposed digital twin is a virtual counterpart of the bridge in its entire lifecycle characterized by actuality, intelligence and autonomy, interaction, interoperability, modularity, expansibility and scalability, accessibility and security, and uniqueness. From the technological perspective, it is an evolution of current practices, which have not yet been properly integrated. The proposed digital twin utilizes BIM (Building Information Modeling), SHM (Structural Health Monitoring), and AI (Artificial Intelligence). It states IFC (Industry Foundation Classes) as the base for the central model. It is also enhanced by other techniques (e.g., visual programming, point clouds). This approach enables the evolutionary process of adopting digital twins in civil engineering. Civil engineering digital twinning does not have to be perfect from the start. It should mature naturally, alluring designers, engineers, and managers of civil engineering facilities with its benefits.

To make this evolutionary development of digital twins possible, digital twinning must provide practical use cases giving clear benefits to engineers and managers of facilities. Therefore, this dissertation proposes two solutions created by the author, utilizing techniques identified as components of civil engineering digital twinning. The solutions regard various lifecycle phases and provide benefits on the design and operational phases of the objects' lifecycle.

The first proposed solution is the optimization using visual programming and genetic algorithm. Visual programming is used to link BIM modeling, FEM analysis, and optimization algorithm. The solution is a step towards utilizing digital twins' techniques in the design phase. The system is an effective geometrical optimization approach, assisting designers in their day-to-day tasks. Moreover, the integration of BIM and FEM models is crucial for creating a fully-functional digital twin of a bridge.

The second proposed technique is the generation of synthetic point clouds' datasets. Point clouds can be a base for modeling actual geometrical conditions in both operational and building phases. To automate the extraction of point clouds' information or even the generation of geometrical models, often machine learning algorithms are used. However, the available point clouds' datasets are not sufficient for the training of machine learning algorithms. The alternative is synthetic data. A scanning simulator created by the author allows for generating synthetic point clouds from BIM models. Acquiring the data is the first but indispensable step in developing machine learning solutions automating the utilization of point clouds, including systems to monitor geometrical changes in the digital twin models. The scheduled scanning of the physical object and then updating the model with trained algorithms will create a model-based history of geometrical changes. Monitoring, identifying, and comparing the geometrical changes can help identify structural malfunctions. As for bridges, monitoring the geometrical changes is crucial, especially for objects on the ground deformation areas (e.g., mining or post-seismic activities, tunneling). The model updating can therefore lead to expert systems alarming about hazards.

The proposed in this dissertation concept of a digital twin of a bridge is one of the first approaches to establish the foundations for these data-rich models of bridges. The literature study revealed that research on digital twins of bridges is still in its infancy. The ongoing digital transformation is undoubtedly a challenge – but also an opportunity. Given the increasingly complex interconnections of scientific and industrial activities of various sectors, digital twinning improves the effectiveness of civil engineering and enables interdisciplinary cooperation in the digital dimension. The here-proposed principles and solutions are a brick towards the infrastructure of the future: reaching the modern world's goals and delivering everyday value.