Opportunities and Challenges of Digital Twins in Structural Health Monitoring

Minh Quang Tran, Hélder S. Sousa, Nhung Thi Cam Nguyen, Quyet Huu Nguyen, and José Campos e Matos

Abstract Digital twin (*DT*) is one of the most modern and promising technologies in realizing smart manufacturing and implementing Industry 4.0. DT offers opportunity to integrate the physical world with digital world with a seamless data source. Civil engineering industry, in general, is facing many challenges in the process of digital transformation to improve efficiency and technology to meet the current growth rate of the economy. *DT* technology has the potential to transform and improve the exploitation and management of infrastructure in civil engineering, especially in the service phase. Based on *DT* model, managers and maintenance operators can test different scenarios, improve efficiency, and make accurate decisions in maintenance of the structure, leading to reduction of management and other regular monitoring costs, as well as accurate prediction of risks during the lifespan of the infrastructure. This study presents advances in digital twin implementations in structural health monitoring. This presents the opportunities and challenges of the digital twin in structural health monitoring with current technologies and future directions.

Keywords Digital twin · Structural health monitoring · Opportunities and challenges of DT

1 Introduction

Early warnings, regular maintenance, inspection, and emergency response plans are essential to ensure safety throughout the lifecycle of critical infrastructure. Stemming from the above requirements, structural health monitoring (*SHM*) systems have been widely deployed and received much attention from researchers in the field of civil engineering around the world. Through the data collected during the operation of the

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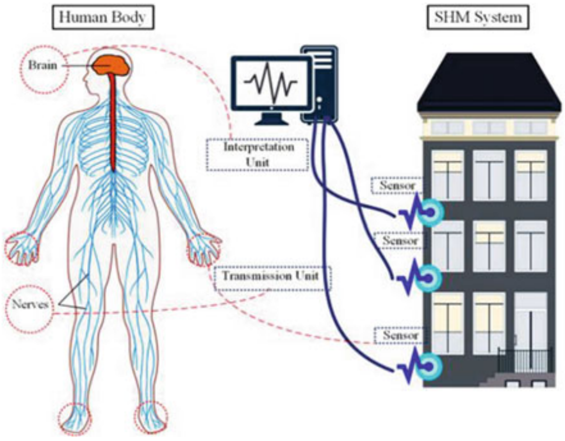

Fig. 1 Comparison between the human body and the *SHM* system [9]

infrastructure by sensors, the change in the properties of the constructions will serve as the basis for diagnosing the structural health [1–4].

In the past, when sensor technology was not yet developed, *SHM* was often performed based on geodetic engineering and machinery [5–8]. *SHM* is based on the characteristics of geometrical factors such as settlement, deformation, and displacement, among others of structures.

Monitoring the response of structures and detecting possible failures to improve their performance and reduce maintenance costs are considered to be a main goal in *SHM*. From the modern point of view, the foundation of *SHM* includes existing techniques for damage identification, diagnosis, and prediction of possible risks to the structure using advanced automated techniques, smart sensors, and artificial intelligence. Speckmann and Henrich suggested that *SHM* could be described through an analogy with the human nervous system (Fig. 1) [9].

SHM is an inverse problem in which damage is identified through data collected from sensors (Fig. 2). *SHM* is a technology to automate the inspection process in order to assess and evaluate the health condition of structures in real-time or at specified time intervals. There are four different sequential levels: detection, identification, quantification, and prediction. The higher levels of *SHM* are, the more complicated *SHM* technology. The levels of SHM have been studied and classified as follows:

- Level 1: Identification: determine the existence of damage on the whole structure.
- Level 2: Locate: find out the damaged part and location.
- Level 3: Evaluation: determine the damage level of various components
- Level 4: Assess the life and durability of the structure on the basis of detected damage.

Currently, research often focuses on goals at levels 1–3. Yan et al. [4] propose a wavelet-based method of the free vibrational responses of structures to accurately determine the location of the damage. The digital twin with many advantages being

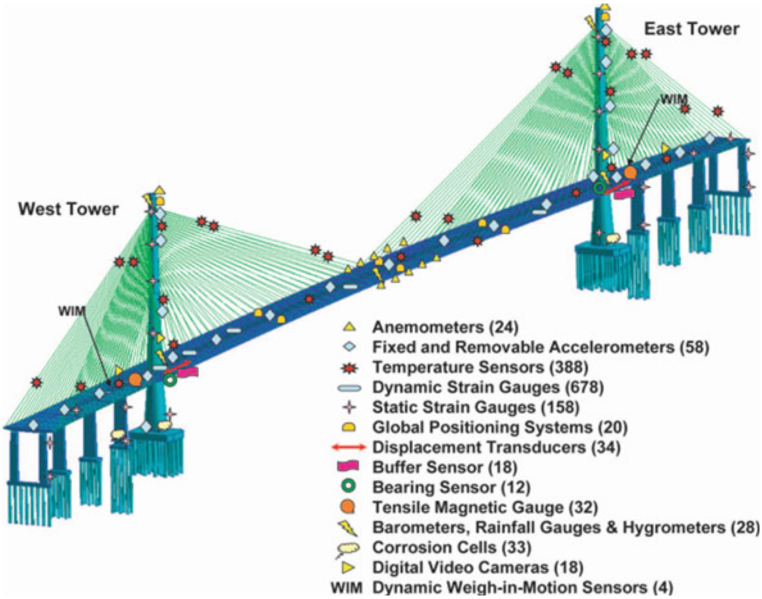

Fig. 2 *SHM* monitoring system in Stonecutters Bridge [10]

able to integrate the physical world with the virtual world is one of the potential techniques for development, covering all levels of *SHM*. The *DT* is capable of accurately reflecting the behavior of the real object and continuously updating throughout its lifecycle. As a result, the digital twin has great potential in the field of *SHM*.

2 Digital Twins

2.1 Digital Twin Concept

DT insight was first introduced in 2003 by Michael Grieves as a concept for Product Lifecycle Management [11]. However, at that time, *DT* only consisted of a physical object, virtual counterpart, and connection, with no specific description and exploration. The importance of DT is increasingly recognized by both academia and industry. According to Gartner [12], digital twins is the leading strategic technology trend in the Hype Cycle for Emerging Technologies (Fig. 3).

The digital twin must have a physical system with a digital representation or virtual model of that system, and the digital model reflects the physical system. Reflection and interoperability can only be achieved through data exchange, which requires sensors to be installed on the physical system to collect and transmit these

The high-fidelity digital twin model contains a lot of complex information. Some must be stored intact; some are just a small part of the process. The data is very large. Therefore, data construction and management technology are quite important in *DT.* Nowadays, in data storage frameworks a large amount of data can be sorted and used correctly (such as *MySQL* database, *HBase* database, and *NoSQL*, among others). In *MySQL*, data are stored as a table. Many rows and columns form a form, and several forms create a database. *HBase* employs the Hadoop Distributed File System (HDFS) as its file storage system, and Hadoop *MapReduce* provides *HBase* with high-performance computing power.

Virtual modeling technologies allow users to visualize specific objects in the *DT*, while helping to manage information about geometry and texture response. Currently, there are many Computer-Aided Design (*CAD*) software that can display the geometric information of a physical object, such as *UG*, *AutoCAD*, *SolidWorks*, and *Creo*. Many physics-based theories/models have been established to reveal the mapping relationship between input and behavior, such as computational fluid dynamics models (*CFD*), finite element modeling (*FEM*) [13].

The available data transmission methods include wired transmission and wireless transmission. Currently, transmission methods using coax cables are being widely used. However, wireless transmission methods including Zig-Bee, Bluetooth, Wi-Fi, ultra-wideband are gradually replacing and becoming more modern. A series of application program interfaces (*APIs*) are commonly used to exchange data between different software to perform data transfer at the software level. Recently, 5G technology can be applied to meet the demand for high data rates, high reliability, high coverage, and low latency.

3.2 Challenges of Digital Twins in Structural Health Monitoring

Currently, building the *DT* framework for structural health monitoring (*SHM*) is incomplete: Although the digital models have been accurate and minimize the difference to the real structure by updating the model based on real data, this model is only a reflection of the actual structure at a moment of the object (similar to a picture in a movie clip). The update over time has not been thoroughly implemented due to the lack of transmission and storage methods. In fact, all things and phenomena in real life are subjected to change over time. These objects are uncertain, constantly changing in physical space. Building digital models in virtual space to reflect realities with high fidelity is a fundamental problem. When there is no consistency between virtual models and real objects, how to define and update them appropriately is very difficult.

The connections between the virtual model (virtual part) and the real part have not been made. Because of the lack of connectivity, the implementation of tasks such as real-time-based control, continuous updating is still difficult. The virtual structural model uses real-time data of physical entities, and the analysis results are used to guide physical entities in real time. Due to a large amount of data, network latency, and model analysis time, it is difficult for *DT* in structural health monitoring to achieve real-time, bidirectional connectivity.

There have yet to be any standards to assess the reliability of digital twins. Therefore, research directions are scattered. This poses a challenge to a unified standards framework. Although Artificial Intelligence technologies have been integrated (through machine learning algorithms), this is not enough to create breakthroughs in the self-updating of the system. Deploying too many sensors on the structure leads to very expensive. More optimization is needed in data generation and prediction. The data transmission is also one of the problems to be solved in structural health monitoring. Data transmission methods also have a delay. Solutions for deep learning, direct data processing need to be developed. The storage space of *DT* in structural health monitoring is currently not interesting. Most of the raw data collected from real textures after a while become huge and get erased. Solutions for data optimization and noise filtering need to be developed. In *DT* in general, the data seem to be very large, multidimensional, multisource, and heterogeneous. In structural health monitoring, although the data source has been reduced, this is still a challenge for research and application of *DT* in structural health monitoring. The actual data source is too large to be collected on a daily basis. It requires an optimized method, and the raw data need to be converted to filter noise and processed quickly. To ensure reliable and real-time simulation analysis results, we need to develop some fast data analysis methods with high accuracy.

4 Conclusions

This paper presents the opportunities and challenges of digital twins in structural health monitoring. With the explosion of information technology, modern sensor technologies, 5G techniques, and digital transformation, the development potential of digital twins in structural health monitoring is huge. However, there are also many challenges posed in developing a comprehensive digital twin. Integrating and applying new technologies to the digital twin in structural health monitoring will bring many benefits to managers, help sustainable development, and reduce maintenance costs. At the same time, it helps to make accurate decisions based on the scenarios predicted by the digital twin.

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