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Research on the development and application of digital twin for the full life cycle of bridge engineering

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Abstract. Bridges play an important role in modern society, whereas many bridges are in poor condition and are characterized by complexity, randomness, and risk no matter what phase the bridges are in. Meanwhile, with advanced technologies such as IoT and Big Data, Digital Twin has been developed in different industries, such as aerospace. With multiple superiorities of real-time data detection, big data processing, full life-cycle management, etc., it is appropriate for bridge engineering. The paper aims to present a state-of-the-art literature review on the full life cycle of the application of Digital Twin in Bridge Engineering. The article discusses the relationship between Digital Twin and Building Information Model (BIM) and constructs a comprehensive framework for Digital Twin in Bridge Engineering. The review is classified into three main parts – design and construction phase, operation and maintenance phase, and demolition phase based on different stages of the full life cycle. The results show the application's high potential and feasibility, and show that most of the current research focuses on the operation and maintenance phases. However, intensive research is still necessary to improve the accuracy, quality, efficiency, timeliness, and versatility of the Digital Twin in Bridge Engineering.

Keywords: Digital Twin, bridge engineering, BIM, full life cycle

1. Introduction

Bridges play a critical role in transportation infrastructure to offer adequate transport capacity. However, during the full life cycle of a bridge, firstly, it is hard to construct bridges, especially in some areas with rugged terrain and horrible environments. Moreover, many bridges become deteriorative and destroyed throughout use due to aging and excessive load [1, 2]. Also, Greenhouse Gas (GHG) will be released without control during the construction and maintenance [3]. Even at the end of the bridge's life, there is a high potential safety hazard when demolishing the bridge [4]. Thus, it is crucial to monitor the full life cycle of the bridge to ensure its safety, reliability, environmental friendliness, etc. The development of computational engineering has led to the industrial revolution, i.e., Industry 4.0, and Digital Twin is a crucial technique in the process. Compared with other sectors, such as aerospace, it is still in the primary stage of Digital Twins. It is insufficient in the architecture, engineering, construction, and facility management (AEC/FM) sectors [5]. Hence, there is still plenty of scope for this approach to develop.

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The literature review will focus on developing and applying digital twins for bridge construction and is divided into two parts. The first part will talk about the development, definition, and model of digital twins. The second part will be divided into three phases of the full life cycle in which digital twin is applied: the design and construction phase, the operation and maintenance phase, and the demolition phase. The conclusion and recommendation will be presented in the last section. The report aims to analyze the current situation in the field and give some suggestions and inspiration for future research.

2. Digital twin in Bridge engineering

2.1. The development of digital twin

The idea of "twin" emerged from NASA in the 1960s when the explosive of the oxygen tank in Apollo 13 was modeled and simulated for further analysis [6]. David Gelernter described a mirror world as an information sea consisting of various data flows in his book – Mirror Worlds, published in 1991[7]. Then, in the Winter Simulation Conference, the Digital Twin concept was redefined as "Simulation," aiming at predicting future behavior in multiple areas [8]. The technical definition of Digital Twin was first introduced by Michael Grieves, the father of Digital Twin, in a presentation about Product Lifecycle Management (PLM) in 2002, and not until 2011 the terminology of "Digital Twin" born in 2011 proposed by Grieves [9]. Digital Twin has developed rapidly in the past decade, especially with the development of Internet of Things (IoT), big data, et cetera. In 2012, Airframe Digital Twin was modeled to improve the full life cycle management of aircraft in the American Air Force [6]. The United States Air Force also applies a Digital Thread/Twin to aid analysis and decision-making [10]. Digital Twin is utilized in the industry in the manufacturing process by GE, Siemens, and Dassault [6].

2.2. Digital Twin in Bridge Engineering

2.2.1. Definition. Though several definitions of Digital Twin have been proposed, the basic description has not changed much. In 2002, Digital Twin was defined as a digital mirror model of the physical system with the characteristic of real-time information interaction, as shown in Figure 1. Also, in 2017, Grieves and Vickers defined the Digital Twin as a set of digital information of a physical entity based on which the physical entity can be fully and accurately described and forecast in real-time [11]. The application of Digital Twin in bridge engineering is still in the preliminary stage; thus, there is no universally approved definition. Considering that the aerospace and manufacturing industry takes the lead in Digital Twin, the framework and description can be used for reference in bridge engineering. Thus, referring to the official definition in the manufacturing industry [12], the Digital Twin in bridge engineering can be divided into four fundamental components. The first is the physical "twin," i.e., the bridge in reality. The second is the virtual "twin," where the virtual and digital images fully mirror the physical entity in real-time. The second is the connection between "twins" where the system collects perception data from the "virtual twin" and then returns the simulation data to the "physical twin". The fourth is data integration and service: managing, analyzing, and utilizing data for assistance. Also, the application of Digital Twin includes the following basic steps: bridge modeling - modeling correction - real-time information interaction and correction – Digital Twin service. Also, it is worth noting that there are some extra characteristics for bridge engineering, such as a heavier workload and a longer full-life cycle, which make the Digital Twin system much more complex.

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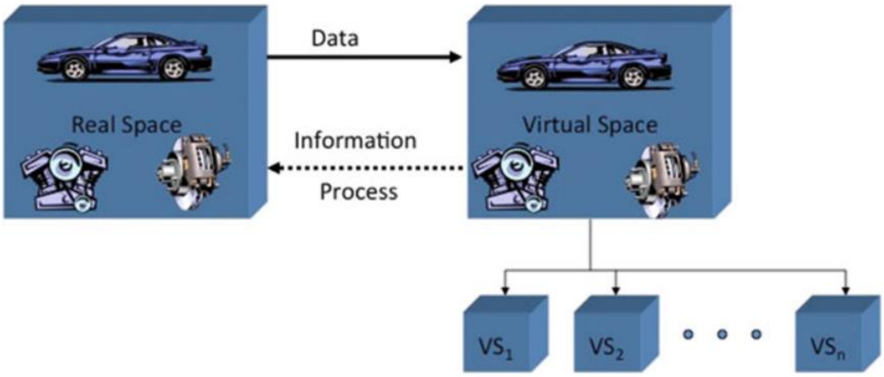

Figure 1. Conceptual Ideal for PLM [11]

2.2.2. Framework. Referring to IoT framework for digital twins in manufacturing in ISO-23247-1, the standard for Digital Twin in manufacturing engineering [12], as well as the applications in Civil Engineering [13-16], a comprehensive framework for Digital Twin in bridge engineering is shown as Figure 2. Three main layers are shown: the data collection and check layer, the data process layer, and the full life-cycle network interface layer. Moreover, data transport can refer to the data transport layer, which assists with 5G, optical fiber ring networks, etc.

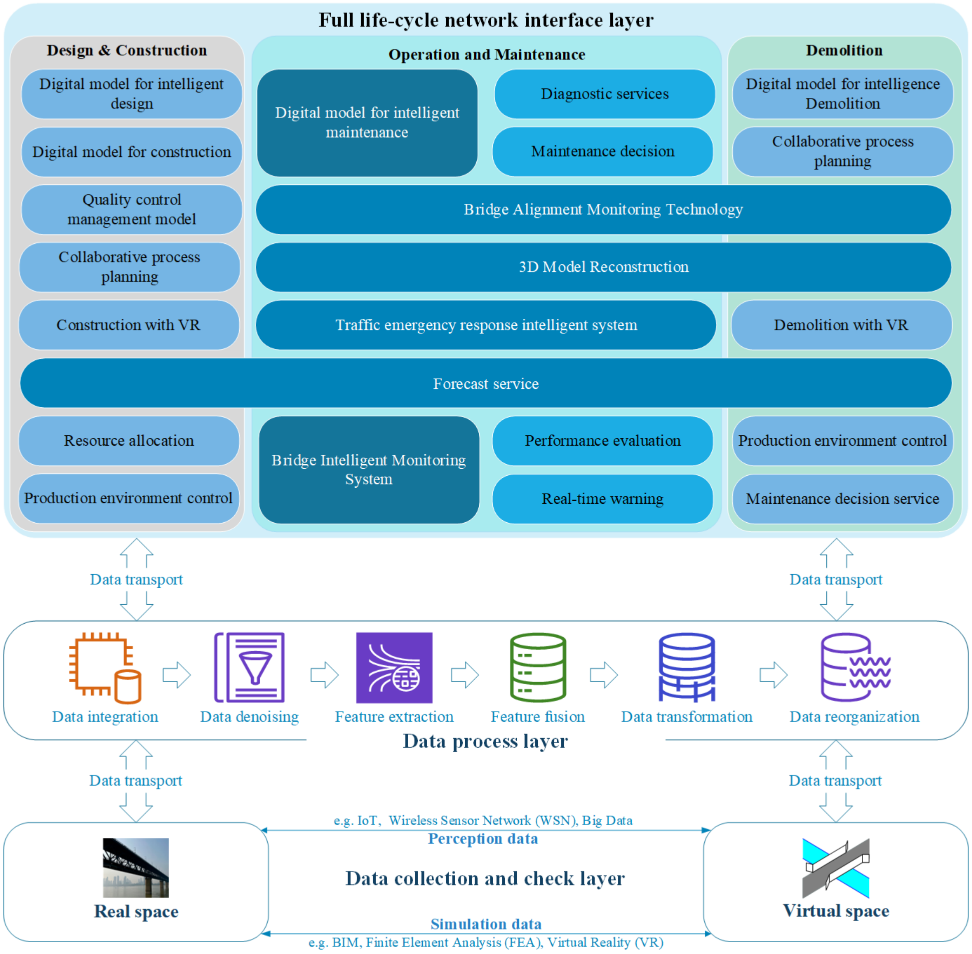

Figure 2. Framework of Digital Twin in Bridge Engineering

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2.2.3. BIM to Digital Twin. There is a universal misunderstanding between the Building Information Model (BIM) and the Digital Twin (DT). For BIM, it is commonly used during the design and construction phase. Even though it developed from 3D BIM to 10D BIM[17], it is still limited to this phase. However, Digital Twin is a full life-cycle system for building, including design, construction, operation, maintenance, and demolition, containing the function of connecting with some up-to-date technologies, which BIM does not have.

It is more of a development from BIM to Digital Twin. Some scholars believe there are five extra elements to developing BIM to Digital Twin–simulation, current-state scanning, AI, IoT, and BIM-based MR/AR/VR [18]. That is, $\text{Digital Twin} = \text{Simulation} + \text{Scanning} + \text{AI} + \text{IoT} + \text{BIM based MR/ AR/VR}$.

3. Full life cycle bridge engineering

This section will focus on the existing research and application of Digital Twin in full life cycle bridge engineering, including design and construction, operation and maintenance, and demolition phases. In general, most research focuses on the operation and maintenance phase, which is also the main part of this section.

3.1. Design and Construction Phase

There is little research in the bridge design and construction phase, considering that BIM can control most processes of this part. However, for some areas, with the characteristics of up-to-date technologies and mass and multiple data in this phase, which BIM cannot replace, there is plenty that Digital Twin still does well.

Wu et al. introduced an innovative holographic projection technology to the bridge construction process, applying a new algorithm to improve the efficiency and quality of visualization of real-time bridge construction scenes [19]. It provided effective approaches to visualization tasks. Alizadehsalehi and Yitmen developed an automated system to monitor the construction progress, where the core technology is Digital Twin. The system has the function of managing, monitoring, and simulating the construction process and making some predictions. It has great prospects in construction to improve the construction process's efficiency and quality [20]. Sun and Liu introduced the novel DT-BIM algorithm for Intelligent Dispatching System Management based on the two technologies. It turns out that hybrid technology performs better in integrating and analyzing resources, decision-making, resource allocation, and transportation [21]. Also, contraposing bridge construction in a complex mountain area, Shi set up a virtual platform with a construction scene consisting of complex surrounding environments and the digital bridge to simulate the whole construction process, including wind field and bridge construction.

3.2. Operation and Maintenance Phase

Compared with other phases, Digital Twin is widely used in the operation and maintenance phase of bridge engineering. Meanwhile, it is much more essential for the application because of the unique characteristics of bridges, e.g., massive and complex traffic flow rate, long span, hostile environments, high possibility of damage, and high demand of service cycle. After reviewing essays in these areas, applications can be classified into five kinds.

3.2.1. Bridge Modelling. Modeling is a fundamental process of Digital Twin in bridge engineering, considering that either the existing model is outdated or lacks a bridge model. Also, there is a high demand for fast and accurate modeling techniques to improve the efficiency of Digital Twin. Hu et al. utilize terrestrial laser scanning techniques to produce high-quality and fast gDT bridge models with point cloud, which performs well by testing [22]. Also, Hu et al. set up a semi-automated method to generate bridges without point clouds. It is done by a translation strategy to replenish the unknown, which performs well [23]. Moreover, Mohammadi proposed a methodology combining comprehensive judging criteria to evaluate the accuracy of Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicles (UAV). It is capable and applicable to assessing and has better performance in modeling [2].

3.2.2. Bridge Health Monitoring and Maintenance System. Digital Twin is widely used to set up a health monitoring and maintenance system. Kang, Chung, and Hong constructed a multimedia knowledge-based bridge health monitoring system that integrates information based on simulation and database. With real-time updating parameters by machine learning, the system functioned well in decision-making on maintenance plans [24]. Naraniecki et al. applied Digital Twin in Filstal bridges, which will operate in 2023. With real-time data collection, the system has the function of safety verification and maintenance decisions and can be displayed to consumers directly and visually [25]. In addition, Arcones attempted to apply the Bayesian framework with perception data to overcome the problems of ever-changing structural characteristics. Through assessment and verification, it is promising for Digital Twin, based on the Bayesian framework, to provide timely and accurate data [26].

In detail, fatigue detection and prediction are crucial to monitoring and maintenance. Considering the uncertainty of the propagation of cracks, Ding et al. applied random parameters to Paris' law and utilized Markov chain Monte Carlo (MCMC) to make Bayesian inferences. It detected real-time crack propagation and accurately predicted fatigue life [27]. Moreover, Nhamage et al. set up a system combining Digital Twin with BIM and Fatigue Analysis System (FAS). With the verification of the vibration test, the system works well, especially in timely damage evaluation and color-scale-based information visualization [28].

Apart from these basic applications, the functions, such as economic and responsibility management, are also considered with the collaboration of stakeholders in the system. Also, many cases combine Digital Twin with BIM to reach the highest benefit. Tita et al. constructed a digital twin system of an existing bridge based on BIM with multiple functions. With functions such as finite element analysis (FEA), real-time traffic flow detection, and effective collaboration among stakeholders, it performed well in bridge management, decision-making, asset management, et cetera [29]. Kaewunruen et al. also apply functions of cooperation of stakeholders into the Digital Twin – BIM model. Moreover, the emission of greenhouse gas (GHG) can also be monitored in the system, greatly reducing the cost and carbon emissions [3]. Shim et al. also set up a stakeholder-oriented Digital Twin – BIM platform with the characteristics of long-term data collection, flexible analysis model, and information interoperability [1].

3.2.3. Real-time Traffic Flow Monitoring. Traffic flow is the main part of the bridge service, and it changes from moment to moment. Thus, there is a high demand for timely traffic flow monitoring for emergency management and fatigue monitoring, which may also contribute to monitoring and maintenance systems. Xu et al. constructed a digital twin framework based on multiple monitoring systems and theories, such as the Monte Carlo method, and the result shows that it has the function of accurate traffic flow monitoring, structure condition evaluation, and full life-cycle bridge health assessment [30]. Based on the Digital Twin, Yu estimated the model of the stochastic process of traffic load and evaluated the bridge fatigue under ever-changing traffic flow and temperature [31]. Zhao et al. developed the Digital Twins using response function and distribution factors in a physical-based way and directly collected data on random flow rate from field measurements [32]. Also, there is another approach to data collection. Adibfar and Costin tried to construct a mock-up bridge based on Digital Twin by integrating the information from Wight-in-Motion (WIM) systems and found the high potential of such a trial [33].

3.2.4. Risk-Based Maintenance. Except for those maintenance systems based on the normal circumstances mentioned above, some research focuses on monitoring and maintaining some extreme cases, such as seism. A digital twin-based collapse fragility assessment method was established by Lin et al. to assess the safety of long-span cable-stayed bridges after the strong seism. The technique has great potential because of its accuracy and feasibility [34]. Yoon et al. used unmanned aerial vehicles (UAV) for bridge characteristics detection after the earthquake. Based on the updated data, the Digital Twin system could do well in seismic fragility analysis of bridges. Apart from seism, Kaewunruen

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established a Digital Twin – BIM platform to detect risks and reduce stakeholders' possible exposure to extreme conditions [35].

3.3. Demolition Phase

Similar to the construction phase, little research has been done on the demolition phase. It was probably because it is a better repair choice than demolition, and few bridges serve far beyond their durable years. Besides, few digital technologies have been utilized in this process, and only a few protection methods and devices have been designed. However, as mentioned, there is a high possibility of failure in demolishing bridges [4]. Thus, applying Digital Twin in bridge demolition is urgently required. Liu et al. carded five possible applications - refined simulation analysis, bridge condition assessment before demolition, construction monitoring, safety control strategy, and reuse of component resources [15]. Moreover, in other cases of concrete structure demolition, except bridges, intelligence demolition is favorable to green development and sustainable development. Thus, these could be the future direction of development of Digital Twin in bridge demolition, especially as more bridges age.

4. Conclusion

Digital Twin has high potential to be applied to bridge engineering with the characteristics of aging, long-service-life requirements, multiple and massive parameters, etc., where Digital Twin can be well applicable. The report introduces the development of Digital Twin, discusses the definition of Digital Twin in bridge engineering, and sets up the framework for the full life-cycle bridge Digital Twin Model. Also, the report discusses the relationship between Digital Twin and BIM. Based on the literature review of the existing research, methods, and applications in the area, the conclusions are as follows.

Firstly, a significant technological disparity exists between Digital Twin and BIM. Digital Twin, especially in the Architecture, Engineering, and Construction (AEC) industries, is the superstructure of the BIM, which consists of not only BIM but also other advanced technologies, such as IoT, Big Data, and 5G. Also, it has a full life cycle characteristic, whereas BIM is mostly in the design phase. Secondly, the development of Digital Twin in bridge engineering is still in the primary stage; thus, intensive study remains to be continued in the field. Most existing research focuses on the applications in the operation and maintenance phases instead of the design, construction, and demolition phases, which may be caused by supply and demand. Thus, with the change in demand relations, it could be inferred that there is a higher possibility of developing Digital Twin in the demolition phase. Thirdly, Digital Twin has three main research orientations in the operation and maintenance phase – bridge modeling, bridge monitoring and maintenance system, and real-time traffic flow monitoring. The maintenance of bridges in extreme environments is also an innovative line of research in bridge monitoring and maintenance systems. Various functions are applied in the system, e.g., safety verification, decision-making, emergency management, stakeholder connection, and GHG controlling. However, more research needs to be done for accuracy, data handling capacity, timeliness, etc.

Finally, real-time data feedback, giant and complex databases, and full-lifecycle operation are some fundamental and indispensable characteristics of Digital Twin. However, these are also the hardest parts of achieving the accuracy and realizability of Digital Twin. Although multiple methods, such as the Bayesian framework and Monte Carlo method, are proposed to achieve high quality of these characteristics, the related methods remain to be further discussed and researched.

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