Digital Twin and Its Application in Transportation Infrastructure

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***Abstract*—A prevailing challenge lies in how to properly design, construct and maintain transportation infrastructure engineering. Due to the development of sensor technology and computing technology, the amount of equipment monitoring data has multiplied and it causes difficulties in real-time state assessment and prediction under the traditional modeling condition. The introduction of Digital Twin technology, which aims to reflect the performance of the real-world product by simulating a virtual space, can solve these problems effectively. This paper reviews recent applications of four types of transportation infrastructure: railways, highways, bridges, and tunnels. Also, the existing research gaps are identified.**

Keywords—digital twin, transportation infrastructure, data-driven, simulation models, physical entity

I. Introduction

The digital twin (DT) is a new concept, which includes creating a new virtual entity in cyberspace, imitating the original physical entities in most aspects, and finally monitoring, analyzing, testing, and optimizing the physical entities [2] [3]. The theoretical basis of DT comes from different disciplines, such as computer science, information science, data science, and production engineering[4]. At present, DT is becoming one of the most focused areas of all industries in the world.

Transportation infrastructure includes the construction of highways, railways, tunnels, bridges, stations, and other facilities to ensure the safe and normal operation of the transportation system. At present, transportation infrastructure faces many challenges in terms of basic theories and cutting-edge technologies. Among them, intelligence is an important development direction of industry innovation. To further promote the data and visual management of the whole life cycle of transportation infrastructure, DT is a perfect candidate technology at present.

The DT is a data-driven analytic system, which integrates physical models and historical data, and then reflects in a virtual space to simulate the performance of the real-world product [7]. It sets a link between physical models and simulation models to predict the product life-cycle and offers decent maintenance advice for decision-makers [8]. DT has a wide range of applications in transportation infrastructure.

This study summarizes the application of DT in transportation infrastructure and the characteristics of the time dynamic model. The methodology and physical models in DT are statistically analyzed. In this paper, the technology integration stages of DT of transportation infrastructures, such as simulation and modeling, design and verification methods, state inspection, and life prediction, are deeply analyzed. Finally, it summarizes the development trend and challenges of DT in the field of transportation infrastructure, which provides valuable research direction for the future.

The remainder of this study is organized as follows. Section II presents the modeling and methods of the DT in the usage of transportation infrastructure. Section III outlines the application and modeling method of the DT in transportation infrastructure. Section IV discusses the existing research gaps of DTs for future study. At last, in section V, the conclusions of this study are summarized.

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II. Current Development of DT in Transportation Infrastructure

We have used the following methodology to select the articles for this survey. We choose the following keywords for paper search, including "Digital twin", "Transportation infrastructure", "Railway", "Rail", "Highway", "Road", "Bridge", "Tunnel", etc. To obtain the state-of-the-art in this field, the search was limited in the publication of scientific journals, conferences, and dissertations in English for the last 5 years, which is from 2016 to 2021. Finally, the search engine we used include Google Scholar, Science Direct, IEEE, Elsevier, Springer, and we also search those cited references in search results. A total of 28 papers were identified.

We classified the literature of DT in transportation infrastructure into four areas, railway, highway, bridge, and tunnel: (1) In the area of railway, the DT has been explored in the fields of rail transit traction power supply system, railway hump station, overhead line equipment, and railway turnout system. (2) In the field of highway, to obtain high-quality predictions of the system's performance over its whole life cycle, the primary task is to model the real-world highway system as accurately as possible during its life cycle, and at the same time, integrate highways organically with other elements in the transportation system. (3) For bridges, the area of preventive maintenance is becoming a vital strategy in existing bridges for their whole lifecycle as the requirements of sustainability and intelligent structure. Much of the literature has focused on identifying and evaluating the proper maintenance plans with the aid of the DT model. (4) Concerning tunnels, previous applications of DT pay more attention to smart inspection and component life prediction.

The IT technologies, such as the Internet of things, BIM, and 3D GIS, can be observed in DT Modelling. To date, several cross-section studies have highlighted the application of this emerging technology in transportation infrastructure. Table 1 summarizes the existing studies of DTs in transportation infrastructure.

TABLE I. Existing Studies of Digital Twins Applied to Transportation Infrastructure

Area	Model Name	Category	Method
Railway	BIM life-cycle model for railway turnout system[5]	Railway turnout health management	6D BIM model
	A source-network-load-storage interaction model[6]	Railway power supply maintenance	MATLAB, Simulink
Highway	Spatiotemporal information model [7]	Road networks management	UML packages, PostgreSQL
	IDT-SDVN [22]	Road network construction	MEC, SUMO, python
Bridge	Bridge maintenance for the entire lifecycle [9] [10] [11] [12] [13] [14]	Preventive maintenance strategy	BIM model, FEM, Machine learning
	Prediction of the damage or the optimal maintenance time in a certain area [15] [16]	Bridge monitoring	SFEM, Machine learning
	Bridge structural monitoring under strong earthquake [17]	Bridge monitoring	Machine learning, FEM, MATLAB
Tunnel	Noise barrier tunnels (NBTs) maintenance for the entire lifecycle[8]	Tunnel Noise Prediction	BIM model, FEM
	Tunnel shell cracks identification autonomously[18]	Tunnel inspection	BIM model, Machine learning
	Tunnel incidents tracking and identification autonomously automatically[19]	Tunnel inspection	BIM model, Machine learning

III. Digital twin of Transportation Infrastructure

A. Application of Digital Twin in Transportation Infrastructure

a) Applications in Railway

DT of rail infrastructure is still in its infancy. Some researchers have worked on digital modeling of complex entities, life cycle management of specific railway facilities, and simulation of important workflows.

Creating digital models for DT by the manual method is generally time-consuming and laborious, such as modeling several kilometers of railway overhead line equipment. Researchers used more efficient and intelligent technologies such as using LiDAR data and machine learning algorithms to generate the virtual models automatically [20]. It is beneficial to integrate the high-dimension information of each stage of the railway infrastructure to make full use of DT. BIM can meet this demand and help collaboration and co-creation of policy and solutions among stakeholders from different technical backgrounds[5]. DT can also make a significant impact in aspects of the safety, energy conservation, emission reduction, and efficient operation of the real-world system. By combining data with the physical model, important production and operation processes can be simulated in advance, which can identify problems that cannot be easily detected in the complex system, and improve the practical efficiency and safety in time [6] [21] [28].

b) Applications in the highway system

With the development of the transportation industry, the smart highway system and the smart city network system have become the inevitable trend of upgrading and evolution in the next generation road system technology form.

The main function of the road system is to serve all elements of the traffic system, so the DT of the road system is mainly reflected in the combination with other elements. In the study of road systems with traffic, physical road systems and their DTs are monitoring and optimizing traffic flow in real-time. In this way, the basic service function of the smart road can be improved by combining the vehicle-road coupling development

[23]. In the field of self-driving vehicles, this advanced intelligence cannot be realized only through the infrastructure of traditional roads, because it relies heavily on the continuous data exchange with the surrounding environment, including the road itself. For the question of road durability, the DT system collects and provides real-time and accurate traffic data, location information of key driving actions, and state change information such as road damage or friction change [22]. With the support of GIS technology, the construction of the road transportation DT system is accelerated. Based on the geometric model of transportation infrastructure established by GIS, the DT data are calculated by using data fusion algorithms at different levels, and the simulation results which reflecting its physical and operational rules were obtained [24].

Also, creating a DT of roads can greatly help reduce crime and help authorities capture and track suspicious people and vehicles [1].

c) Applications in Bridge

Preventive maintenance is becoming a vital strategy in existing bridges for their whole lifecycle with the requirements of sustainability and intelligent structure. Much of the literature has focused on identifying and evaluating the proper maintenance plans with the aid of the DT model. Shim et al. carried out several studies in the bridge maintenance system. The study by [25] offers a virtual model which was simulated after recording the damage on the surface of bridges by 3D scanning. It also builds up an interface to link between the maintenance system and the monitoring system for visualization.

Thanks to computing science, a vast amount of information can be coped with. In particular, the feedback in virtual twin can perform 'what-if' scenarios and predict the bridge behaviors. Combined with the environmental conditions, A comprehensive analysis and discussion were presented by [16]. The BIM, Finite Element Modelling, and Statistical Modeling were used for bridge strain prediction. In 2021, Kaewunruen et al. proposed the " BIM +bridge risk inspection model " to decrease the risk of bridge inspection[17]. Also, they took the internal risk, natural risk, and human risk into consideration to get full-bridge risk prediction. As another example, [16] suggested a multimedia knowledge-based method to predict the appropriate maintenance time point under various situations. To name a few, one can further refer to [17] [26] [27].

d) Applications in tunnel

The smart inspection and the component life prediction in the tunnel make it possible for cost and labor reduction due to the application of DT. Some literature exist on the application and challenges of the DT in tunnel inspection. As [18] denoted, the cracks in tunnels, captured by the automatic cameras, can be detected and classified after training. Also, it compared 7 types of algorithms to get the highest accuracy and precision. Meanwhile, some special conditions, for instance, fire accidents in tunnels are increasingly paid more attention to. To rescue with less delay, Kim suggested a robot system to recognize and monitor the fire condition and location, using the result from a prototype of the DT [19]. Concerning life prediction, one study by Kim et al. investigated the perfricated components of the tunnel and estimated the displacement based on the fitted data [8]. According to the displacement, we could obtain the approximate lifespan to produce reasonable maintenance guidance.

B. Key Technologies for Digital Twin in Transportation Infrastructure

a) High-dimension transportation infrastructure model covering the whole life cycle

Digital models are a prerequisite for the development of DTs of transportation infrastructure. The prospective DT model aspires to cover the entire life cycle of planning, design, construction, operation, maintenance, and demolition of real infrastructures. Geometric information, schedule, engineering monitoring index, economic cost, energy consumption, and other different data will occupy the dominant position in different stages. To meet the needs of digital twinning, high-dimension, accurate systems models of infrastructures need to be built. The lightweight integration platform of GIS+BIM is becoming the mainstream solution to this problem. After the secondary development, the BIM platform can accommodate enough model information to effectively meet the needs of stakeholders in different stages.

b) Accurate and efficient monitoring and sensing technology

It is the basis for the DT model to play its role in the life cycle in that it can perceive the performance state of the physical entity in real-time, collect the surrounding environmental information and transmit it back to the virtual model system in time. This puts forward higher requirements for accurate detection and efficient transmission of various parameters. Through the deployment of miniaturization, IoT, and high-precision sensing devices, or the integration of necessary sensing and communication devices in the manufacturing stage, the current structure state and load changes, operational orders, and information of the service environment of the system can be continuously obtained and achieve the intelligent perception of the equipment.

IV. Existing Research Gaps

There is a huge gap between the bright prospect described by DT and the realistic technology level in the field of transportation infrastructure. Many basic technical requirements are still not met, which is reflected in the following aspects.

- How to obtain accurate data on the existing transportation infrastructure remains a challenge. Engineering construction and data modeling are highly related to the experience of experts in different industries and fields. In addition, the existing accumulated data is of poor quality and low value, which is difficult to match with the urgent demand of reality and the effect of the rapid application. Data sources have become the current and future constraints on data analysis and utilization, and even the basic bottleneck for the development of DT technology.
- Currently, the level of digital design in the industry is relatively low, and the basic mathematical model and simulation model which are needed to support the construction of the DT technology system is lacking. Especially the digital simulation ability of key work or

construction process is insufficient, which has become a major challenge restricting the development of DT technology.

- The level of software specialization in transportation infrastructure is low. Each sub-specialty of transportation infrastructure has different specialty characteristics and handles information in different ways. Therefore, it is difficult to construct the DT technology system and technology platform suitable for multi-domain generalization in the short term.
- Other key technologies involved in the DT technology system have certain gaps with the practical application. These technologies include sensor and sensor fusion technology, life prediction technology, support test, and verification technology, etc.
- Other challenges include the security aspect of the DT, especially when the data comes from internet of things devices. And there is a pressing need in developing methods to improve the confidence of integrated simulation models and their predictions.

V. Conclusion

DT technology seems to be of great interest in the future. This study reviews studies that apply DT in transportation infrastructure. The implementation of the DT in the whole life cycle of transportation infrastructure is anticipated to greatly improve the management level of planning, design, construction, operation, and safety.

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References

[1] O. E. Marai, T. Taleb, and J. Song, "Roads Infrastructure Digital Twin: A Step Toward Smarter Cities Realization," IEEE Netw., vol. 35, no. 2, pp. 136–143, Mar. 2021.

[2] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital Twin in Industry: State-of-the-Art," IEEE Trans. Ind. Inform., vol. 15, no. 4, pp. 2405–2415, Apr. 2019.

[3] A. Madni, C. Madni, and S. Lucero, "Leveraging Digital Twin Technology in Model-Based Systems Engineering," Systems, vol. 7, no. 1, p. 7, Jan. 2019.

[4] B. Schleich, N. Anwer, L. Mathieu, and S. Wartzack, "Shaping the digital twin for design and production engineering," CIRP Ann., vol. 66, no. 1, pp. 141–144, 2017.

[5] S. Kaewunruen and Q. Lian, "Digital twin aided sustainability-based lifecycle management for railway turnout systems," J. Clean. Prod., vol. 228, pp. 1537–1551, Aug. 2019.

[6] J. Guo, X. Wu, H. Liang, J. Hu, and B. Liu, "Digital-twin based Power Supply System Modeling and Analysis for Urban Rail Transportation," in 2020 IEEE International Conference on Energy Internet (ICEI), Sydney, NSW, Australia, Aug. 2020, pp. 74–79.

[7] T. Machl, A. Donaubauer, and T. H. Kolbe, Planning Agricultural Core Road Networks Based on a Digital Twin of the Cultivated Landscape. DE: Wichmann Verlag, 2019. Accessed: May 08, 2021.

[8] J. Kim and S.-A. Kim, "Lifespan Prediction Technique for Digital Twin-Based Noise Barrier Tunnels," Sustainability, vol. 12, no. 7, p. 2940, Apr. 2020.

[9] S. Kaewunruen, J. Sresakoolchai, W. Ma, and O. Phil-Ebosie, "Digital Twin Aided Vulnerability Assessment and Risk-Based Maintenance Planning of Bridge Infrastructures Exposed to Extreme Conditions," p. 18, 2021.

[10] S. Dang, H. Kang, S. Lon, and C. Shim, 3D DIGITAL TWIN MODELS FOR BRIDGE MAINTENANCE. 2018.

[11] N. Dang, C. Shim, and D. Nguyen, "Bridge assessment for PSC Girder Bridge using Digital Twins Model," p. 7.

[12] C. Shim, H. Kang, and N. Dang, "DIGITAL TWIN MODELS FOR MAINTENANCE OF CABLE-SUPPORTED BRIDGES," p. 7, 2019.

[13] H. Sofia, E. Anas, and O. Faiz, "Mobile Mapping, Machine Learning and Digital Twin for Road Infrastructure Monitoring and Maintenance: Case Study of Mohammed VI Bridge in Morocco," in 2020 IEEE International conference of Moroccan Geomatics (Morgeo), Casablanca, Morocco, May 2020, pp. 1–6.

[14] C. Ye et al., "A Digital Twin of Bridges for Structural Health Monitoring," 12th International Workshop on Structural Health Monitoring 2019, Sep. 12, 2019.

[15] E. Febrianto, L. Butler, M. Girolami, and F. Cirak, "A Self-Sensing Digital Twin of a Railway Bridge using the Statistical Finite Element Method," ArXiv210313729 Cs Math, Mar. 2021, Accessed: Apr. 28, 2021.

[16] J.-S. Kang, K. Chung, and E. J. Hong, "Multimedia knowledge-based bridge health monitoring using digital twin," Multimed. Tools Appl., p. 17.

[17] K. Lin, Y.-L. Xu, X. Lu, Z. Guan, and J. Li, "Digital twin-based collapse fragility assessment of a long-span cable-stayed bridge under strong earthquakes," Autom. Constr., vol. 123, p. 103547, Mar. 2021.

[18] F. Panella, Y. Loo, M. Devriendt, D. Gonzalez, A. Kaushik, and J. Boehm, "Smart Image Based Technology and Deep Learning for Tunnel Inspection and Asset Management," p. 12.

[19] Y.-D. Kim, G.-J. Son, H. Kim, C. Song, and J.-H. Lee, "Smart Disaster Response in Vehicular Tunnels: Technologies for Search and Rescue Applications," Sustainability, vol. 10, no. 7, p. 2509, Jul. 2018.

[20] M. R. M. F. Ariyachandra and I. Brilakis, "Digital Twinning of Railway Overhead Line Equipment from Airborne LiDAR Data," presented at the 37th International Symposium on Automation and Robotics in Construction, Kitakyushu, Japan, Oct. 2020.

[21] A. Kochan, "Digital Twin Concept of the ETCS application," p. 13.

[22] L. Zhao, G. Han, Z. Li, and L. Shu, "Intelligent Digital Twin-Based Software-Defined Vehicular Networks," IEEE Netw., vol. 34, no. 5, pp. 178–184, Sep. 2020.

[23] M. Kaliske, R. Behnke, and I. Wollny, "Vision on a Digital Twin of the Road-Tire-Vehicle System for Future Mobility," Tire Sci. Technol., vol. 49, no. 1, pp. 2–18, Jan. 2021.

[24] S. Wang, F. Zhang, and T. Qin, "Research on the Construction of Highway Traffic Digital Twin System Based on 3D GIS Technology," J. Phys. Conf. Ser., vol. 1802, no. 4, p. 042045, Mar. 2021.

[25] C. Shim, H. Kang, and N. Dang, "Digital Twin Models for Maintenance of Cable-Supported Bridges," in International Conference on Smart Infrastructure and Construction 2019 (ICSIC), Cambridge, UK, Jan. 2019, pp. 737–742.

[26] R. Lu and I. Brilakis, "Digital twinning of existing reinforced concrete bridges from labelled point clusters," Autom. Constr., vol. 105, p. 102837, Sep. 2019.

[27] F. Din-Houn Lau, L. J. Butler, N. M. Adams, M. Z. E. B. Elshafie, and M. A. Girolami, "Real-time statistical modelling of data generated from self-sensing bridges," Proc. Inst. Civ. Eng. - Smart Infrastruct. Constr., vol. 171, no. 1, pp. 3–13, Mar. 2018.

[28] A.N.Shabelnikov, I.A.Olgeyzer, "Technology and Mathematical Basis of Digital Twin Creation in Railway Infrastructure," in Proceedings of the Fourth International Scientific Conference "Intelligent Information Technologies for Industry" (IITI'19), vol1156, pp.688-695, 2020.