A Perspective Review on Digital Twins for Roads, Bridges, and Civil Infrastructures*

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***Abstract*—A digital model that is the counterpart — or twin — of a physical asset is considered a digital twin. Digital twins are becoming one of the most important technology trends for transportation infrastructure because of their potential to increase asset reliability and performance. As they offer current information about the status of the road infrastructure and the risks connected to it, digital twins can be seen as the foundation of infrastructure decision-making. Digital twins provide civil engineers with the ability to visualise assets across their entire life cycle to track changes and to perform analysis that optimises asset performance. The aim of this paper is to present a novel perspective for designing, prototyping and testing digital twins of bridges and road infrastructure. The methodology used takes into account the potential for developing a digital twin for the road infrastructure, taking into account stratigraphic analysis, surface condition monitoring, and bridges structural analysis. We seek to stimulate global efforts towards the achievement of efficient maintenance and management of infrastructures and facilities.**

***Index Terms*—digital twin, road infrastructure, robotics**

I. INTRODUCTION

The road infrastructure is fundamental for the existence of societies, representing both the largest built structures and the largest capital investment for most nations. Operation, maintenance, and development are key activities to persistent growth of economy. The importance of these activities is emphasised in the United Nations (UN) Sustainability Development Goal (UN-SDG) no 11, target 2: “Provide access to safe, affordable, accessible and sustainable transport system for all, improving road safety, ...”. However, construction of new roads can be negative to the environment, caused by both the impound areas, the emissions to soil, water and earth, and the consumption of building materials. E.g., the consumption of natural sand ores and crushed rock in Norway is estimated to more than 15 tons per capita per year [1]. Caretaking of the road infrastructure is mandatory to nurture both the capital investment and the societal need for transportation - and to accommodate the UN-SDG target 12.2 “Sustainable management and efficient use of natural resources”. Still, this is an overwhelming challenge to both restricted budgets and the practical issue of staffing. In the recent Norwegian “State of the Nation report” [2], the backlog of maintenance of the road infrastructure is estimated to more than 240 billion US dollars – in a country with only 5.3 million inhabitants. UN-SDG might pinpoint the necessary trajectory to follow in target 12.2 “Achieve higher levels of economic productivity through diversification, technological upgrading and innovation”. The use of new technology opens for innovations to monitor and maintaining the road infrastructure. This includes use of digital twins. The concept of digital twins was first publicly introduced in [3]. Digital twins represent connections between the physical world and the information world, providing upgrading of the information flow and allowing for efficiency through automated monitoring. Digital twins enable the use of artificial intelligence (AI) to analyse big data and select when to implement actions to prevent hazardous situations.

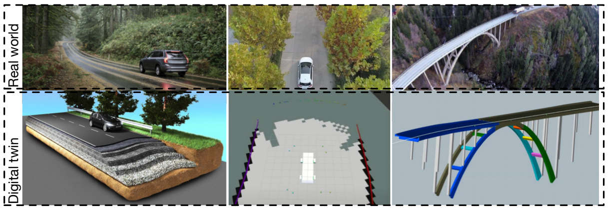

Fig. 1. The underlying idea of creating a digital twin for the road infrastructure, including stratigraphic analysis, surface condition monitoring and bridges structural analysis. Elements of this figure are courtesy of [4], [5].

The use of digital twins is well known from various other societal sectors, like monitoring the conditions of production fa-

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cilities for manufacturing industry [6], hydropower plants [7], ships [8], and offshore installations [9]. When considering road infrastructure, few examples have shown that adopting digital twin solutions are economical and efficient, i.e., for the reconstruction of Genoa bridge in Italy. In [10], workflows for modelling the reality of a major bridge infrastructure in Morocco with digital twins is presented. However, there is still a gap in the implementation of digital twins. This work aims at providing an up-to-date perspective on the challenges and possibilities for designing, prototyping, and testing digital twins of bridges and road infrastructure for the purpose of efficient operation, management, and development of the road infrastructure. As shown in Fig. 1, the underlying idea considers the possibility of creating a digital twin for the road infrastructure, including stratigraphic analysis, surface condition monitoring and bridges structural analysis.

This paper is organised as it follows. The need for a unified framework to achieve digital twinning of the road infrastructure is described in Section II. A perspective related to the currently available sensing technology is provided in Section III. An overview of the technology to achieve efficient maintenance and management of infrastructures and facilities is presented in Sections IV. Finally, concluding remarks, guidelines and future outlook are presented in Section V.

II. NEED FOR A UNIFIED FRAMEWORK

A digital twin is a probabilistic multi-physical, multi-scale simulation of a system that uses the best available physical models, to replicate the life of its corresponding twin [11]. To enable digital twinning for road infrastructure, different sensors, robots, unmanned aerial vehicles (UAVs), and different technologies, the physical entities, activities, behaviours, and interactions are required to be connected to a digital model for a more realistic data platform [12]. The integration of the digital twin as a 3D representation of the road infrastructure and associated information can be used for the assessment of the performance by using a data management system. Blockchain techniques for secure storage of data in cloud environments can be adopted [13]. The involvement of many automated devices, such as multiple mobile robots, mobile sensors, and fixed sensors, significantly increases the complexity [14]. Existing software frameworks are not mature enough to support the integration of this necessary paradigm. When considering the possibility of designing a framework architecture to enable digital twinning for the road infrastructure, a unified design approach is still missing to the best of our knowledge. To contribute towards this direction, a universal framework architecture is proposed in this section. When contemplating the design guidelines for the proposed framework, the following criteria are taken into account: a) flexibility, the framework must allow for the execution of various research activities; b) integrability, the framework must be able to integrate real sensors/robots as well as simulated devices in the future; c) reliability, as a research tool, the system must be simple to maintain, update, and extend by adding new components and features.

Fig. 2 depicts the proposed framework. A hierarchically organised structure is suggested. With a bottom-up method, the following abstraction levels are defined and listed:

- Physical/virtual layer. The framework must be designed to support the physical road infrastructure and interact with the real world scenario. In this layer, the physical road infrastructure and the virtual road infrastructure are interconnected;
- Sensors embedded on the infrastructure. These sensors are installed on the road network either before/during the construction process or successively. These devices, e.g., accelerometers and vibrometers, are permanently fixed and used to constantly collect data. Obviously, the more sensors are deployed to the physical asset, the more accurate the view we get [15];
- Carrier layer. Important data could also be gathered through mobile sensors on board of different carriers, such as wheeled robots, legged robots, limbless robots and UAVs. These carriers can be sent on a specific mission, allowing for more precise measurements;
- Add-on layer. This layer makes it possible to add extra sensors on board of the selected carriers. These additional mobile sensors can be used for performing different research activities;
- Data acquisition layer. This layer is responsible for gathering and acquiring all the raw data generated by both fixed sensors embedded on the road infrastructure as well as mobile sensors transported by carriers. The sensors continuously collect data and deliver it across the network to edge or cloud servers in real time [15];
- Annotation layer. This layer makes it possible to manually adding information, e.g., reports from janitors and shared information from road users (e.g., waze [16]). These data represent an important sources for information on condition, damages and traffic status. Moreover, this layer enables the collection of historical information, e.g., when a damage is discovered, analysed, reported and repaired;
- Application layer (data interpretation). When the data arrives at its destination, it is analysed, synthesised, and finally presented to the users in an appropriate format. This layer enables the possibility of implementing decision support systems to backing determinations, judgements, and courses of action related to the road infrastructure.

The proposed framework could be implemented based on the Robot Operating System (ROS) [17] paired with the *Gazebo* simulator [18]. The RViz (ROS visualisation) visualisation tool could be used in addition to ROS and Gazebo to visualise and monitor sensor data obtained in real-time from the simulated environment. These choices are based on our previous research experience [19]–[21].

Regarding the carrier layer, there is a range of unmanned vehicle (UV) that can be employed to transport and deploy sensors into the road infrastructure, as shown in Fig. 2. An UV is a mobile system not having or needing a person, a crew, or staff operator on board [22]. UV systems can either be remote-controlled or remote-guided vehicles, or they can be autonomous vehicles that can sense their surroundings and navigate on their own. Different varieties of UVs are employed in other domains. Our research group recently developed an aquatic surface robot [23] to build a digital twin map of underwater landscapes and to collect bathymetry data in lakes, rivers, and coastal ecosystems. UV systems that can be used as carriers for digital twinning of road infrastructures may include the following systems [24]: unmanned ground vehicles (UGVs; e.g., autonomous cars, legged robots, limbless robots); unmanned aerial vehicle (UAVs; e.g., unmanned aircraft generally known as "drones"). UGVs have been used, for example, for non-destructive testing of fiber-reinforced polymer bridge decks [25]. UAVs have been adopted to monitor civil infrastructure [26], industrial facilities [27], and power plants [28] during development and operation. Their operational simplicity along with time-and-cost-related benefits have already rendered them attractive for structural surveying [29].

III. SENSING TECHNOLOGY

A digital twin requires the actual measurement from the real world to be included in the digital model of the system such that it is in synchronous and close to the physical system. It is very desirable to measure the parameters that define the structural integrity accurately, precisely and continuously. Structural damage can occur due to fatigue, mechanical or thermal stress, impact with objects (and their impact is not visually observable), degradation (e.g., corrosion of metals, freeze-thaw spalling of concrete, loss of elasticity in synthetic cushing materials for bearings due to UV-light, etc.). Structural health monitoring (SHM) refers to the continuous monitoring of the key parameters of the structure during its operation using integrated sensors or sensor systems [32], [33]. SHM has several implications such as (a) increased safety by determining the fatigue at early stage while estimating the time between failure, (b) facilitate modelling of the physical process and digital twin accurately and (c) enable predictive and prescriptive maintenance.

Methods exist that allow for monitoring of structures. Methods based on ultrasound, acoustic emission, piezoelectric, fibre optic and laser-based sensors have been implemented for structural monitoring of bridges [34]. The methods for SHM can be classified based on different criteria, e.g., (a) whether the sensor is contact or non-contact (b) works in electrical or optical domain and (c) measure a point or a region.

A. Acoustic emissions (AE)

Ultrasound waves are acoustic waves having frequency higher than 20 kHz. They are characteristic of the surface that undergo fatigue. These waves are usually generated by the impact of the different objects hitting the structure. This aspect, makes these waves suited candidates for SHM of civil engineering infrastructure, such as bridge, roads and tunnels [35]. This exploits the principle that - fatigue, impact loading, strain in the structure generate ultrasonic waves. These waves propagate through the medium with an elastic behaviour and can be detected by electrical/optical means. Thus, detection of ultrasound from structures contain important information about the integrity of the material it self.

Approaches based on phased array are commonly used to detect ultrasounds and characterise faults in the structure [36]. These techniques are used for the non-contact displacement due to the waves capability to propagate to fairly longer distance in the transmission medium (i.e., air, liquid or rigid structure). Generally, a phased array of a micro electro-mechanical system (MEMS) or a piezoelectric material is used to detect the ultrasound waves. However, the detector device needs to be placed in contact with the structure to be monitored. This causes loading effects, i.e., it interferes with the measurement. These detectors are prone to other electrical interference. They are suitable for point measurements.

Another way to detect the acoustic waves is to use optical methods [37]. In this approach, a laser is pointed at the region of interest. The perturbation caused due to its propagation modulates the laser emission and this modulation is detected by the photodiode. By utilising signal processing techniques the related parameters of the acoustic wave, such as amplitude and frequency, can be calculated [38]. The methods based on lasers have added advantages as - they are non-contact. Because of the non-contact nature, these procedures do not interfere with the measurement and do not cause loading effect. In addition, they can be placed far apart from the source. Further, they have better resolution, thanks to the shorter wavelength. However, they are limited to point measurements.

B. Strain measurements

To overcome the issues of the point based measurement techniques, fibre optic based SHM is adopted. Fibre Bragg Grating (FBG) together with fibre optic is also used widely in SHM [39]. It consists of grating that is tuned to reflect a particular frequency, called Bragg wavelength. The pulse from a laser is allowed to propagate through the fibre embedding FBG. Without any disturbance, the grating is made such that it reflects a particular frequency. However, in the presence of disturbance due to thermal or strain variations, the grating structure changes, causing the shift in reflected frequency. From the shift of frequency, the quantity of strain can be computed. In [39], the strain in the structure was measured based on differential relative phase, by using fibre Bragg grating [40]. In [41], FBG was used for SHM of arc bridges. In [42], the strain on concrete railway bridges was measured. In [43], the measurement of the real-time strain for bridge weigh in motion in reinforced concrete bridge structures through the use of optical fiber sensor systems was performed. While distributed fibre-based sensing allows for measurements of disturbances at several locations, the sensors must be connected to the structure, making it a contact-based measurement.

C. Vibrations measurements

Another parameter that is useful for SHM is represented by vibrations. For example, when a fast moving vehicle moves over the infrastructure, it exerts force and causes the structure

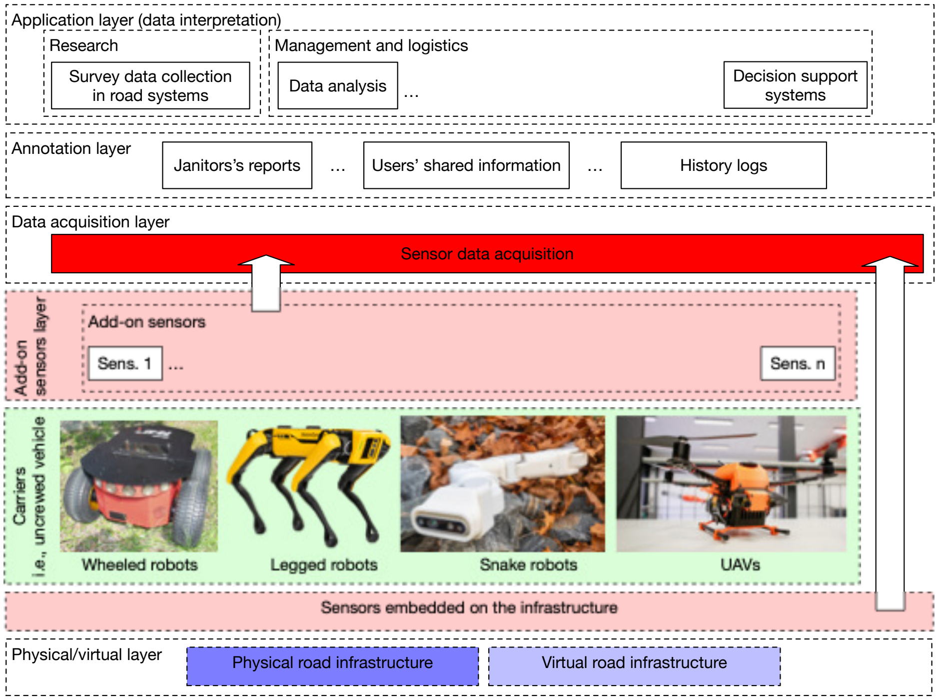

Fig. 2. The framework for creating a digital twin for the road infrastructure. Elements of this figure are courtesy of [30], [31].

to displace and vibrate. Over time, the continuous use, causes fatigue that in turn alters the displacement or vibration patterns and thus they can be detected at early stages by just tracking the changes in displacement or vibrations. Typically piezoelectric, capacitive, null-balance, strain gage, acclerometer are used to detect the vibrations [44]. However they suffer from electrical interference, are contact based and cause loading effect, and cannot be placed at the desired location. In [45], [46], non-contact methods based on radars were used to calculate the vibration patterns in a railway bridge. Similarly, FBG was used in [44] to measure the vibration patterns of a suspension bridge. In this last work, FBG was used as point measurement to measure the vibration and strain at specific points of interest. The point measurement technique employing laser for vibration measurements has also been demonstrated in [47], [48]. This approach can be incorporated into SHM to measure the critical points or the region of interest.

Depending upon the parameters to be monitored, one or more methods can be used together and or independently. For example, when the joint or a particular point of interest is important for structural engineers to monitor, point and non-contact (in this case laser or radar) can be used. Further, if the resolution and accuracy is crucial, laser can be the best option (because of the shorter wavelength). On the contrary, if instead of a point, the entire structure is to be monitored, then fibre together with Bragg grating can be used. The surveyed methods and associated parameters are summarised in Table I.

IV. EFFICIENT MAINTENANCE AND MANAGEMENT OF INFRASTRUCTURES AND FACILITIES

In civil engineering, digital twins are playing an increasingly important role in efficient asset monitoring, operation and maintenance of infrastructures and facilities [49], [50]. Although the term "digital twin" has not been applied until recently, numerical modelling or numerical simulation has been extensively used in various sub-disciplines. With the abundance of computational resources, numerical methods, like the finite element (FE) method, have been considered as a useful means for design analysis and structural dynamics study. For any numerical models, there exist uncertainties [51] in geometries, material properties, boundary conditions, and loading conditions. Simplifications and assumptions are common in the modelling process. It is recognised that the design document-based FE models of a structure, e.g., a bridge or a road, may deviate significantly from the in-service physical entity. To improve such numerical models, operational information of the physical bridge must be collected. In recent decades, SHM [32], [33] technology has been developed to measure the loading environment and responses of long-

TABLE I
CLASSIFICATION OF DIFFERENT METHODOLOGIES FOR SHM.

Method	Param.	Contact	Non-contact	Electrical	Optical	Point	Distributed
Piezoelectric	AE, vibration	x	x	x	-	x	-
Fibre	strain, AE	x	-	-	-	-	x
Laser	vibration, AE	-	x	-	x	x	-
FBG	strain, vibration	x	-	-	x	x	x
Radar	displacement, vibration	-	x	x	-	x	-

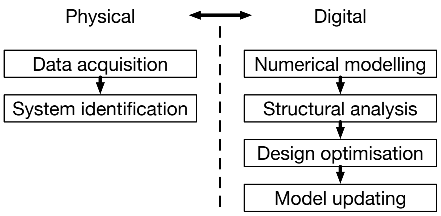

Fig. 3. Flowchart for building a digital twin for a bridge.

span bridges such that symptoms of operational incidents and potential damages can be detected at an early stage. Nowadays, many modern bridges are equipped with advanced SHM systems and the real-time measurement data from sensors, e.g., accelerometers and vibrometers. The data collected from SHM systems can be used to update the numerical model that approximates a true digital twin.

Fig. 3 shows the procedures for building a digital twin of a physical bridge based on SHM data [52]. In the physical world, measurement data are used to identify the modal parameters of the bridge system by applying operational modal analysis techniques like the enhanced frequency domain decomposition (EFDD) method [53] and the covariance-driven stochastic subspace identification (SSI-COV) method [54]. In the digital world, an initial FE model of a certain fidelity level is first created, and dynamic properties (e.g., mode shapes and natural periods) can be identified by structural analysis methods including modal analysis, static analysis, or dynamic analysis. To match dynamic properties of the digital twin with those of the physical model, updating of parameters of the numerical model is key. These parameters include mass, stiffness, damping or geometrical thickness of components. The FE model can involve multiple scales [52] and the parameter space is large. To address this challenge, response surface methods, e.g., polynomial surfaces [55], Kriging models [56] and artificial neural networks (ANNs) [57], and efficient optimisation algorithms, e.g., gradient-based methods [52] are involved. Linear model updating is most widely applied. For certain scenarios such as seismic collapse of bridges, structural deformation is nonlinear and a nonlinear model updating produces a more accurate digital twin, as shown by Lin et al. [58]. The development of model updating techniques facilitates the applications of digital twins in performance assessments of civil structures like bridges and offshore structures.

V. CONCLUDING REMARKS

We surveyed challenges and possibilities with designing digital twins of bridges and road infrastructure. The field of digital twins can be characterised as heterogeneous when it comes to its maturity to be brought into the modelling of bridges and road infrastructure. We can conclude – in alignment with other works(e.g., [34], [51], [59], [60]) – that approaches are still exploratory. This work is a viewpoint study rather than a systematic literature review. This choice was deliberate, as we want to stimulate research in the specific domain of road infrastructure. The need for maturing the digital twin concept for civil engineering in combination with the technological opportunities (i.e., sensors and robots) allows for an outlook. A research and implementation agenda is proposed in the form of a unified framework, which include different logical layers, i.e., physical/virtual layer, carrier layer, add-on layer, data acquisition layer, and application layer. The goal of this article is to boost global efforts to realise the wide range of possibilities afforded by digital twins for bridges and road infrastructure, as well as to present a perspective as a stepping stone for new research in this domain.

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