Framework for Bridge Management Systems (BMS) Using Digital Twins

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Abstract. Bridge structures have significantly long life spans; many medieval and historic bridges remain in operation in the world. The concept of bridge management contains the activities related to managing bridge inspections and condition assessment, which can be gathered into a Bridge Management System (BMS). Deterioration and failures have increased over the years in the already aging bridges; therefore, the importance of BMS to ensure safety of bridge operation and maximize investments in bridge maintenance has also increased. Digital Twin (DT) technology can be applied in the construction industry to achieve smart management through the entire life cycle of structures. Unlike the aerospace and manufacturing industries, the maturity of development of DT models in the construction industry still lags behind. In this study, a literature review was initially performed to gather knowledge on the origins of the digital twin concept and current best practice focused on bridge structures. A systematic approach for the literature review is presented in the methodology. Lastly, a framework for facility management of bridge structures using digital twins is proposed.

Keywords: Bridges · Digital twins · Bridge management systems · BMS · Facility management

1 Introduction

Facility management of bridge structures is usually handled by each country's road administration entity through Bridge Management Systems (BMS). The systems vary according to the specific needs and resources of each country, but the scope itself consists primarily of inspection, structural health monitoring (SHM) and rehabilitation [1]. In order to handle the amount of information required to achieve optimal management of infrastructure, managing agents are using increasingly sophisticated computerized management systems to support their decision making process [2].

In this study, a framework for smart bridge management using Digital Twins (DT) is proposed. The use of digital models, such as DT, adds automation, efficiency and accuracy to the system. The frameworks divides the DT approach into 5 steps: bridge inspection, BIM model, damage identification, data transmission, and facility management.

C. Pellegrino et al. (Eds.): EUROSTRUCT 2021, LNCE 200, pp. 687–694, 2022.
https://doi.org/10.1007/978-3-030-91877-4_78

A systematic state-of-the-art literature review was performed to identify the main challenges and respective solutions of the processes that compose the proposed framework. This review, along with this study, is part of a broader research on facility management of bridges using digital models.

2 Methodology

In order to develop a framework for facility management of bridges using DT, a state-of-the-art literature review was performed. The review consisted of three main steps: definition of the strings of research, research of the selected database, and assessment of the articles.

The strings of research were defined based on keywords identified in a preliminary exploratory literature review. The most recurring keywords were divided into five groups of subjects, and each group was given a set of strings as follows:

- BIM: ("BIM" OR "Building information modelling");
- Bridges: ("Bridge information modelling" OR "BrIM" OR "Bridge" OR "Bridges");
- Digital Twins: ("Digital twin" OR "Digital twins" OR "DTM");
- Management/inspection: ("Facilities management" OR "Facility management" OR "inspection" OR "monitoring");
- Maintenance: ("Maintenance" OR "assessment").

Different combinations of groups of strings were searched in Scopus, the selected database, limited from years 2010 to 2020 to be considered as state-of-the-art. The search was applied to title, keywords and abstract of each paper, and added up to 600 results in Scopus. Some of the papers were eliminated before assessment, because the article was a repeated result, written language other than English, conference review paper or unrelated area of research (medicine, psychology, etc.).

The selected articles were then evaluated using three different filters: Filter 1 for title, abstract and keywords; Filter 2 for introduction and conclusion; and Filter 3 for the entire paper. The main reason for rejection was low relevance of the subject to the scope of this study, lack of access or overall quality. The articles approved after the third filter were included in the review. An iterative process also occurred and references from selected papers were assessed and included to the study as well.

3 Literature Review

3.1 Bridge Inspection

Regular structural health assessment and interventions are essential to ensure that bridges continue to operate safely throughout their intended design life and beyond [3]. Routine inspections are periodical quality assessment procedures usually scheduled during the bridge's service life to evaluate their health [3, 4].

Current bridge inspection procedures are mostly based on intensive visual investigations and field measurements performed manually by bridge inspectors [5]. However, manual inspections are time-consuming and highly dependent on the inspector's knowledge of the structural behavior of the investigated system [3, 5]. Therefore, the idea of substituting human visual perception with an automated, systematic and quantitative 3D point cloud assessment is currently an intensively investigated topic [4]. The latest research tends to systematize imagery acquisition techniques with damage detection and feature extraction methods into an automated bridge inspection system [4]. Some of the different technologies employed in recent literature to automate bridge inspection and damage detection are presented in Table 1.

Table 1. Inspection and automated damage detection technologies and respective references.

Technology	References
Photogrammetry	10 references [3–12]
Laser scanning	9 references [4–8, 11, 13–15]
Ground Penetrating Radar (GPR)	5 references [12, 16–19]
Unmanned Aircraft Vehicle (UAV)	5 references [3, 13, 20, 23, 25]
Infrared (IR)	4 references [4, 8, 16, 18]
Fiber Optic Sensors (FOS)	3 references [20–22]
Computer vision algorithms	3 references [4, 10, 20]
Light Detection and Ranging (LiDAR)	1 reference [24]
Wireless sensor network (WSN)	1 reference [26]

3.2 Digital Models

Bridge Information Modeling, or BrIM, is a novel approach able to manage the entire life cycle of a bridge: fabrication, construction, operation, maintenance and inspection [11]. Data harvested from bridge inspections can be used to develop digital models using BIM [4, 7, 18, 20, 23, 27, 28], which in turn can be used for prediction of structural decay using FEM [17, 19, 29] and to anticipate the effects of such decay upon structural integrity [17]. This is essential in the context of a smart BMS, since accurate modeling of the as-is condition and prediction of future behavior are key elements in a digital twin model.

Autodesk Revit was the commercial BIM software endorsed by most authors in this review [11, 13–15], and described as one of the most advanced digital twinning software solutions [5]. The program also offers an inter-operable Industry Foundation Class (IFC) platform that allows for the exchange of data between nonnative file types [28]. The use of IFC as a BIM standard file format aims to solve the interoperability issues, since this is a neutral format for the exchange of digital building models [4]. Table 2 presents other solutions to this problem addressed by authors in this review.

Table 2. Technologies for data transmission and respective references.

Data transmission	References
IFC	5 references [4, 7, 30–32]
Machine learning	3 references [3, 10, 26]
MATLAB	2 references [6, 29]
Artificial intelligence algorithm	1 reference [25]
3G/4G/5G and WLAN	1 reference [33]

3.3 Digital Twins

Although much has been published on the topic, a general definition and an agreement over the digital twins' features and scopes has not been reached [34]. Kritzinger et al. (2018) [35] presented a definition which differentiates Digital Models, Digital Shadows and Digital Twins. According to the authors, a Digital Model is digital representation of an existing physical object that does not use any form of automated data exchange between the physical and the digital objects [35]. A Digital Shadow, on the other hand, has an automated one-way data flow between the state of an existing physical object and a digital object. Finally, in a Digital Twin the data flows between an existing physical object and a digital object are fully integrated in both directions [35].

Few studies that employ DT for bridges were encountered in the literature. Andersen & Rex (2019) [36] developed a SHM system backed up by a digital twin able to predict responses from possible critical scenarios during retrofit of the Henry Hudson Bridge in New York. Shim et al. (2019) [37] proposed a bridge maintenance system that applies the concept of digital twins through the creation of three models: a 3D geometry model, a model that contains the current status of the bridge, and a third model created between the first two. Lu & Brilakis (2019) [30] created a geometric digital twin of an existing bridge, which is as a digital twin with only geometry data. The authors also defend the use of a platform-neutral data format, i.e. IFC, to represent all the associated geometric and property information. Lastly, Ye et al. (2019) [38] proposed a DT framework combining BIM with bridge, FE and statistical monitoring, which was tested in a case study of railway sleepers instrumented with fibre optic sensor (FOS) systems.

4 Results and Discussion

Different steps have to be considered in order to develop a BMS. In the literature review section, first the importance of performing regular bridge inspections was established, as well as the main issues with current procedures and respective technologies to improve inspection and damage detection. The second subsection, digital models, approached mainly BIM, FE modelling and technologies to integrate data between different platforms. Lastly, the third subsection addressed digital twins, disclosing the lack of consensus as to the definition of the DT for the construction industry, and that the approach towards bridge management, although growing, is still incipient. Therefore, based on the best practice presented in the literature review section, the desired BMS should include:

- Inspection: automated process combining accurate and reliable technologies that enable the generation of digital models and automated damage identification, with little to no dependence on human eye and access to the site.
- BIM model: semantically rich and thorough model, generated mostly automatically from geometry data, containing the original geometry, current status updated with inspection data and visualization of monitoring points.
- Digital Twin: from the BIM model, the digital twin should be able to be automatically updated with monitoring data from the site and to have a connection with other layers, such as a FE model for prediction of future behavior. For the facility management aspect of the structure in its entire life cycle, the DT system should also:

  o Include analysis of optimal intervention strategies;
  o Predict improvements due to future interventions;
  o Handle costs for intervention, inspection, and peripheral costs such as traffic delay, accident and environmental;
  o Allow archive of basic construction information, inspection information, and intervention history;

The system should also have a user-friendly and include functions such as mindful alerts when certain parameters reach warning or critical levels. For each of these macro-aspects, the possible technologies identified in the literature were summarized in the framework presented in Fig. 1. From this framework, non-destructive testing (NDT) can be applied to identify inner geometry and material properties, and different solutions can be combined to achieve smart facility management of bridges.

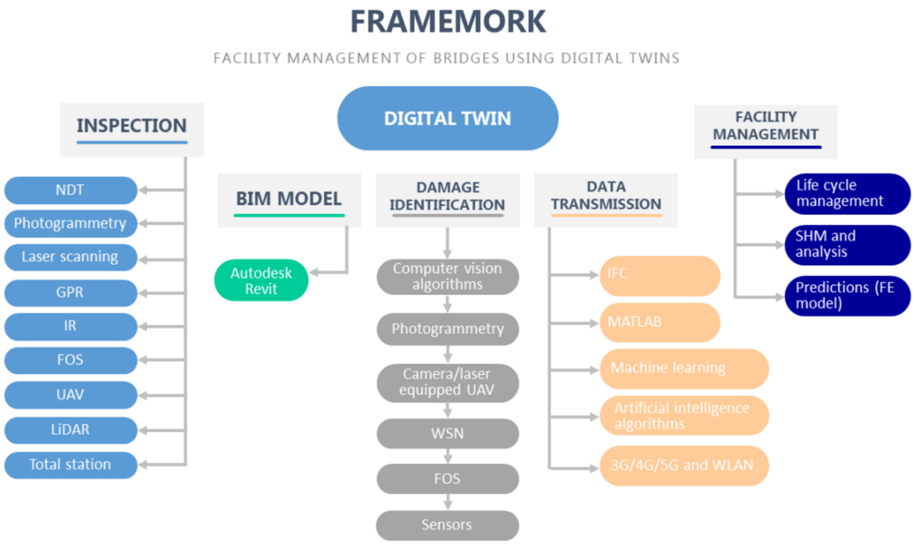

Fig. 1. Framework for facility management of bridges using digital twins.

5 Conclusion

This study aimed at developing a framework for a facility management system of bridge structures using digital twins. This is a highly complex process, mainly due to the integration of a large amount of data from different platforms. To approach this system, a brief literature review covered potential solutions to technological problems related to bridge inspection, digital models and digital twins. The solutions identified in the review were then organized into a framework, which divided the Digital Twin approach into 5 steps: bridge inspection, BIM model, damage identification, data transmission, and facility management.

The proposed framework indicated that, when breaking down the structure for smart bridge management, some aspects have been well addressed by current research. However, this does not apply for the full process, as seen in the literature review, which makes the integration of all the steps and data the main gap to be addressed. This study is part of a broader research, which aims at addressing this gap and constructing a BMS using DT. Future work will include applying this framework initially to a DT of concrete beams under laboratory tests, then to a case study of a bridge.

Acknowledgements. This work was carried out within the strategic innovation program InfraSweden2030, a joint venture by Vinnova, Formas and The Swedish Energy Agency, the work is also funded by SBUF (construction industry's organisation for research and development in Sweden) and Skanska Sweden.

References

1. Khan MA (2015) Recent developments in ABC concepts. In: Khan MA (ed) Accelerated bridge construction. Butterworth-Heinemann, Boston, pp 53–102. ISBN 978-0-12-407224-4
2. Mirzaei Z, Adey BT, Klatter L, Thompson P (2014) The IABMAS bridge management committee overview of existing bridge management systems (2014)
3. Morgenthal G et al (2019) Framework for automated UAS-based structural condition assessment of bridges. Autom Constr 97:77–95
4. Isailovic D, Stojanovic V, Trapp M, Richter R, Hajdin R, Döllner J (2020) Bridge damage: detection, IFC-based semantic enrichment and visualization. Autom Constr 112(103088)
5. Popescu C, Täljsten B, Blanksvärd T, Elfgren L (2019) 3D reconstruction of existing concrete bridges using optical methods. Struct Infrastruct Eng (2019). https://doi.org/10.1080/15732479.2019.1594315
6. Riveiro B, Jauregui DV, Arias P, Armesto J, Jiang R (2012) An innovative method for remote measurement of minimum vertical under clearance in routine bridge inspection. Autom Constr 25:34–40
7. Huthwohl P, Brilakis I, Borrmann A, Sacks R (2018) Integrating RC bridge defect information into BIM models. J Comput Civil Eng 32(3) (04018013):04018013–1–04018013–14
8. Ban F, Barazzetti L, Previtali M, Roncoroni F (2017) Historic BIM: a new repository for structural health monitoring. International archives of the photogrammetry, remote sensing and spatial information sciences - ISPRS archives, XLII-5/W1, pp 269–274
9. Cha G, Park S, Oh T (2019) A terrestrial LiDAR-based detection of shape deformation for maintenance of bridge structures. J Constr Eng Manag 145(12) (04019075):04019075–1–04019075–12

10. Borin P, Cavazzini F (2019) Condition assessment of RC bridges. Integrating machine learning, photogrammetry and BIM. International archives of the photogrammetry, remote sensing and spatial information sciences - ISPRS archives, XLII-2/W15, pp 201–208
11. Barazzetti L, Ban F, Brumana R, Previtali M, Roncoroni F (2016) BIM from laser scans... not just for buildings: NURBSbased parametric modeling of a medieval bridge. In: ISPRS annals of the photogrammetry, remote sensing and spatial information sciences, III-5, pp 51–56
12. Stavroulaki ME, Riveiro B, Drosopoulos GA, Solla M, Koutsianitis P, Stavroulakis GE (2016) Modelling and strength evaluation of masonry bridges using terrestrial photogrammetry and finite elements. Adv Eng Softw. https://doi.org/10.1016/j.advengsoft.2015.12.007
13. Popescu C, et al (2019) Optical methods and wireless sensors for monitoring of bridges. In: IABSE symposium, Guimaraes 2019: towards a resilient built environment risk and asset management
14. McKenna T, Minehane M, O'Keefe B, O'Sullivan G, Ruane K (2017) Bridge information modelling (BrIM) for a listed viaduct. In: Proceedings of the institution of civil engineers: bridge engineering (1600007)
15. León-Robles CA, Reinoso-Gordo JF, González-Quiñones JJ (2019) Heritage building information modeling (H-BIM) applied to a stone bridge. ISPRS Int J Geo-Inf 8(121)
16. Riveiro B, González-Jorge H, Varela M, Jauregui DV (2013) Validation of terrestrial laser scanning and photogrammetry techniques for the measurement of vertical under clearance and beam geometry in structural inspection of bridges. Measurement 46:784–794
17. Alani AM, Aboutalebi M, Kilic G (2014) Integrated health assessment strategy using NDT for reinforced concrete bridges. NDT E Int 61:80–94
18. Abu Dabous S, Yaghi S, Alkass S, Moselhi O (2015) Concrete bridge deck condition assessment using IR thermography and ground penetrating radar technologies. In: 5th international/11th construction specialty conference (262)
19. Conde B, Ramos LF, Oliveira DV, Riveiro B, Solla M (2017) Structural assessment of masonry arch bridges by combination of non-destructive testing techniques and three-dimensional numerical modelling: Application to Vilanova Bridge. Eng Struct 148:621–638
20. Xu Y, Turkan Y (2019) BrIM and UAS for bridge inspections and management. Eng Constr Archit Manag 27(3):785–807
21. Delgado JMD, Brilakis I, Middleton C (2016) Modelling, management, and visualization of structural performance monitoring data on BIM. In: Proceedings of the international conference on smart infrastructure and construction, ICSIC 2016, pp 543–549
22. Davila Delgado JM, Butler LJ, Gibbons N, Brilakis I, Elshae MZE, Middleton C (2017) Management of structural monitoring data of bridges using BIM. Bridge Eng 170(00):204–218
23. Sacks R et al (2018) SeeBridge as next generation bridge inspection: overview, information delivery manual and model view definition. Autom Constr 90:134–145
24. Omer M, Margetts L, Hadi Mosleh M, Hewitt S, Parwaiz M (2019) Use of gaming technology to bring bridge inspection to the office. Struct Infrastruct Eng 15(10):1292–1307
25. Zhao Z, et al (2019) Integrating BIM and IoT for smart bridge management. IOP Conf Ser Earth Environ Sci 371(022034) (2019)
26. Khajavi SH, Motlagh NH, Jaribion A, Werner LC, Holmstrom J (2019) Digital twin: vision, benefits, boundaries, and creation for buildings. IEEE Access 7(00):147406–147419
27. Abu Dabous S, Yaghi S, Alkass S, Moselhi O (2017) Concrete bridge deck condition assessment using IR thermography and ground penetrating radar technologies. Autom Constr 81:340–354
28. McGuire B, Atadero R, Clevenger C, Ozbek M (2016) Bridge information modeling for inspection and evaluation. J Bridge Eng 21(4), (04015076)

29. Boddupalli C, Sadhu A, Rezazadeh Azar E, Pattyson S (2019) Improved visualization of infrastructure monitoring data using building information modeling. Struct Infrastruct Eng 15(9):1247–1263
30. Lu R, Brilakis I (2019) Digital twinning of existing reinforced concrete bridges from labelled point clusters. Autom Constr 105(102837)
31. Wan C (2019) Development of a bridge management system based on the building information modeling technology. Sustainability 11(4583)
32. Zhu J, Tan Y, Wang X, Wu P (2020) BIM/GIS integration for web GIS-based bridge management. Ann GIS. https://doi.org/10.1080/19475683.2020.1743355
33. Lu Q, Xie X, Heaton J, Parlikad AK, Schooling J (2020) From BIM towards digital twin: strategy and future development for smart asset management. Stud Comput Intell 853:392–404
34. Cimino C, Negri E, Fumagalli L (2019) Review of digital twin applications in manufacturing. Comput Ind 113(103130)
35. Kritzinger W, Karner M, Traar G, Henjes J, Sihn W (2018) Digital twin in manufacturing: a categorical literature review and classification. IFAC Papers Online 51–11:1016–1022
36. Andersen JE, Rex S (2019) Concrete bridge deck condition assessment using IR thermography and ground penetrating radar technologies. In: 20th congress of IABSE, New York City 2019: the evolving metropolis
37. Shim C-S, Dang N-S, Lon S, Jeon C-H (2019) Development of a bridge maintenance system for prestressed concrete bridges using 3D digital twin model. Struct Infrastruct Eng 15(10):1319–1332
38. Ye C (2019) A digital twin of bridges for structural health monitoring. In: Proceedings of the 12th international workshop on structural health monitoring (2019)