Development of an immersive digital twin framework to support infrastructure management: a case study of bridge asset health monitoring.

Muhammad Fawad[1,2], Marek Salamak[1], Qian Chen[3] and Kalman Koris[2]

[1] Department of Mechanics and Bridges, Faculty of Civil Engineering, Silesian University of Technology, Poland,
[2] Department of Structural Engineering, Budapest University of Technology and Economics, Hungary,
[3] Faculty of Applied Sciences, University of British Columbia, Canada.

muhammad.fawad@posl.pl, marek.salamak@polsl.pl, qian.chen@ubc.ca, kalman.koris@emk.bme.hu

Abstract –

Digital Twin (DT) has been widely adopted in construction and infrastructure projects to focus on the management and control of physical systems and assets responsively to meet the users' requirements. When integrating immersion functions with the digital and wireless transformation models, the DT applications can further allow users to interact with and experience the model information in a more engaging and intuitive way. To add new perspectives to DT applications, this research gave reality functions to develop an immersive DT framework and presented a case study of VR- and AR-based bridge health monitoring and twining systems to demonstrate the functionalities. The case study was focused on the Structural Health Monitoring (SHM) processes for a newly constructed extradosed bridge, facilitated by the integration of Building Information Modeling (BIM), Virtual Reality (VR), Augmented Reality, 3D game engines, and Internet of Things (IoT) technologies. The bridge's geometric and property information was modeled in BIM parametric design software as a basis for VR model development and was used to develop the BIM-based sensory model in the 3D game engine according to the on-site conditions of the physically installed system. The integrated virtual model was further deployed to the AR device via a VR-to-AR workflow and was presented through the immersive DT dashboard. Project stakeholders can perform bridge damage detection using the information available from the dashboard. In this dashboard the IoT tools were used for the multi-source data integration process by storing, processing, and transforming the monitoring data, lending opportunities for predictive simulations of bridge condition states.

Keywords –

Augmented Reality (AR), Structural Health Monitoring (SHM), Virtual Reality (VR), Digital Twin (DT), data fusion.

1 Introduction

Technological advancement has continuously challenged the way of managing, monitoring, and maintaining the infrastructure assets' structural health [1]. The application of "digital twin" systems has been a game-changer that substantially revamped the processes of bridge health monitoring and management [2][3]. DT applications assist stakeholders in making reliable and quick decisions by automatically diagnosing the faults which leads to improved bridge performance and enhanced service life, which in turn reduces the maintenance and operation costs of the infrastructure [3][4].

Developing a DT prototype requires a complex and comprehensive approach to address the problem of inadequate resources at the network level while appropriately taking a bridge's health data into account [5]. A DT of a bridge comprises a connectivity module that enables synchronization of the physical and virtual assets along the asset's life cycle stages [6], as well as a virtual duplication of an actual bridge [7]. To deal with this complexity, this research proposes the Immersive DT framework ('Figure 1'). A structural twin can be built using the Finite Element (FE) model [8], whereas the bridge's 3D geometry and properties can be produced using the BIM technique [9]. Though the FE model is not perfectly interoperable with BIM data schema, data regarding environmental conditions, loads, and the structure's response to those loads can be obtained from sensors installed during a SHM procedure and be semi-automatically integrated with BIM designs [10]. The virtual assets produced as a result of the BIM model, can be used as a replica of the physical system and simulate

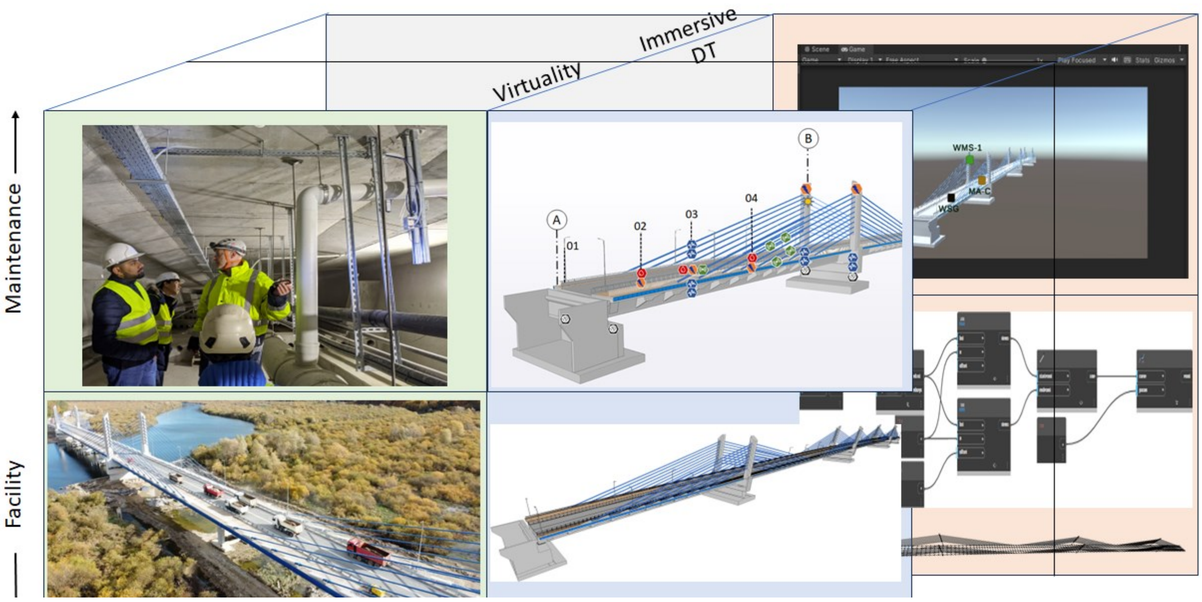

Figure 1 – The proposed immersive DT framework focusing on information flows between virtual and reality models.

the actual bridge's condition electronically which can be remotely visualized by the applications of AR [1][11]. This integration facilitates the remote and on-site monitoring of bridge health by visualizing and interpreting the data under both "normal" and "damaged" conditions. This data is then used to train AI data-driven models, which can instantly identify damages [12]. By using the information produced, the bridge management team and other interested parties can maximize the resources at their disposal for predictive decision-making [13].

The proposed immersive DT based on AR/VR technology not only visualizes the bridge health data but also helps to manage and process this data for predictive decision-making [14]. This way the wireless link between the digital and physical SHM system can be developed which controls the interface for the physical model including AR capability and represents real-time data fusion on the digital model (3D) of the bridge [15].

Considering these benefits, this study aims to develop an Integrated Bridge Digital Twin immersed in the AR environment to assist the infrastructure management and monitoring. This immersive DT explains the conception, development, and implementation of an Integrated Bridge Digital Twin, and how predictive analytics can be performed for intervention planning. This research explores the many facets of the implementation of the proposed framework, from the designing, initial data collection, and visualization of bridge SHM data using the applications of 3D game engines and simulation approaches. It also emphasizes how this digital twin supports predictive decision-making, allowing authorities to anticipate possible structural problems, maximize maintenance plans, and schedule interventions ahead of time.

2 Description of the bridge project case study and bridge SHM modeling

To test the usefulness of the proposed DT framework, the case study of a newly constructed bridge on Poland's National Highway 75 was chosen. This bridge has a continuous, four-span (100.0, 200.0, 200.0, and 100.0 m) extradosed structure with a C60/75 concrete box girder superstructure. The Load Model (LM1) according to Eurocode (EC)-1 standard [16], was utilized in the bridge's design, with adaptation coefficients of $\alpha = 1.00$. For class A, the Polish Norms (PN) 85/S standard [17] was followed. The span cross-section ('Figure 2') measures 17.68 m in width, while the intermediate supports are 23.0 m wide. The bridge is traversed by a dual carriageway road that is 8.60 m wide (between curbs) and has a 4.0 m wide pedestrian and bicycle lane.

To identify the possible damages and the expected location of monitoring devices, the Finite Element Analysis of the bridge was carried out. Based on that the bridge monitoring system that reflects the real-time condition states of the bridge assets was designed [18]. The FEA parameters of investigation include internal forces and span displacement. The possible cracking of the bridge surfaces was observed from this analysis but no prominent abnormalities were found. The bridge was verified for ULS and SLS as required by EC, and it was

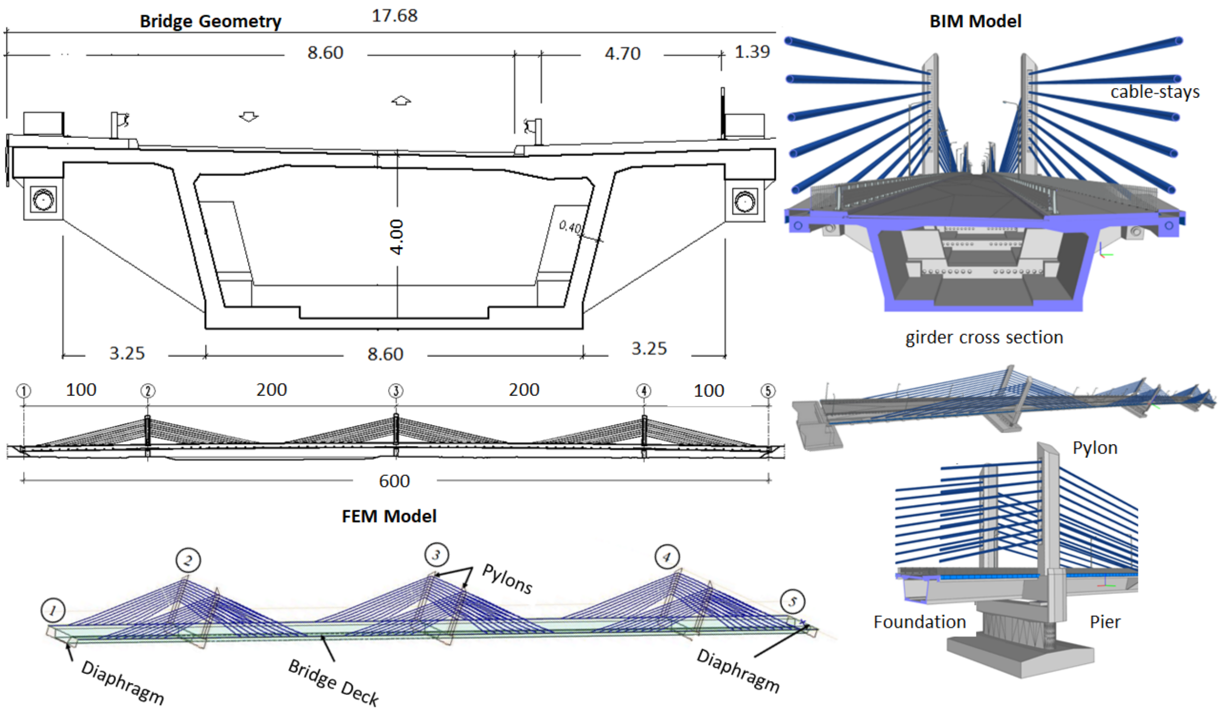

Figure 2 – The BIM design of the bridge case study

found to be satisfactory. The deflected shape of the cables was considered to evaluate their deformations for the identification of monitoring points. For numerical analysis, only the parameters that have a direct impact on the bridge health and whose monitoring is critical were modeled including the stresses, strains, internal forces, crack widths, temperature, and humidity variations. Based on the FEA parameters, we proposed an integrated SHM system equipped with various IoT sensors, including Wired Strain Gauges (WSG), Liquid Levelling Sensors (LLS), MEMS accelerometers, and a Weather Monitoring Station (WMS) to monitor concrete deformations, vertical displacements, structural vibrations, and weather conditions. As a basis of the Digital Twin of the SHM model, the BIM design of the bridge was developed to include geometry and properties information ('Figure 2'). All the families of structural elements were developed by importing actual details of materials and accessory elements.

The developed BIM model is further used in the 3D game engine to develop the DT model which can perform automated bridge health monitoring.

3 Case study demonstration of the immersive DT

Using the bridge case study, the immersive DT was demonstrated on the bridge health monitoring processes by automatically identifying the damages. The whole process of digital twinning involves three different states, Physical State (PS) (reality state), Virtual State (VS), and Hybrid State (HS) for simulations.

The physical or reality state involves the physical model of the bridge, where the real sensors are installed on the bridge along with the network of monitoring systems. The PS defines the base of the DT framework where the SHM system collects the data and sends it to web servers or web platforms which then communicate with the VS. The VS involves the development of the BIM design and DT dashboard which replicates the physical model and SHM system in the virtual environment and each element of the bridge and SHM system is designed as an individual entity to communicate with the PS. The HS of DT involves the data streaming from the physically installed sensors to the virtual system to provide accurate information about bridge health. The DT dashboard was developed based on the integration of the gamification approach of the 3D game engine (UNITY 3D). All the parameters are automated by the relevant C# codes to formulate a data-centric mode of bridge SHM system. The novelty of this research provides the framework of the bridge SHM system, its integration with AR devices, and automated data-processing workflows which help the authorities in predictive decision-making.

The first step of DT generation involves the development of the BIM model using any of the BIM software (e.g. Autodesk Revit). This model is then imported to the 3D game engine using the Revit plugin directly. It can also be done by using the Industry Foundation Class (IFC) file format but importing models with all the native properties makes them heavy and inefficient thus requiring some extra manual work to import all the design data. Therefore, direct import is preferred and recommended in such cases.

After importing the BIM model, the virtual replicas of all the sensors are developed at their exact installation locations in the, where they are installed in the PS. All these replicas virtually represent the actual sensors giving birth to the sensory model of the bridge in the VS.

The next workflow lies under the DT where each sensor is provided with several functions. For embedding any function in the DT dashboard, canvases are used to mesh the virtual model which develops the regenerative algorithms and links them with the sensory model. These meshes control the automation of the generated virtual elements and directly call the web platform connected to the sensory model. To automate the connection between the sensory model and the canvas, a proprietary C# script is developed in the visual studio and then embedded in the canvas. This automatically starts the communication between the PS and VS of the SHM system. Inside the canvas, a special button is generated which can give clickable features. This button is then embedded into the virtual replicas of the sensors, enabling communication with the actual sensors.

The data processing is automatically done using the AI tools on the web platform of the provided SHM system. As the SHM system is provided, installed, and developed by our industrial partners under a Non-Disclosure Agreement, detailed decision information about the smart sensors, and their Internet of Things (IoT)-based web platform are not discussed in this research. The dashboard of the DT model and the different states of the process are shown in 'Figure 3'.

4 VR-to-AR flow of bridge SHM data using Immersive DT

To demonstrate the VR-to-AR workflows for the case study, the VS of the model is transformed from VR to AR using the proprietary AR application. The development of this application is supported by the Mixed Reality Tool Kit (MRKT) and Universal Window Platform (UWP) in the UNITY game engine. These computing platforms help to develop applications that can run on the Windows system and AR platforms. DT model is used as the base 3D model for this application and transformed to immersive DT by importing all assets to this application. The real-time functionality of the application is developed using the virtual buttons as a connection between the PS and VS. To import the reality, an AR

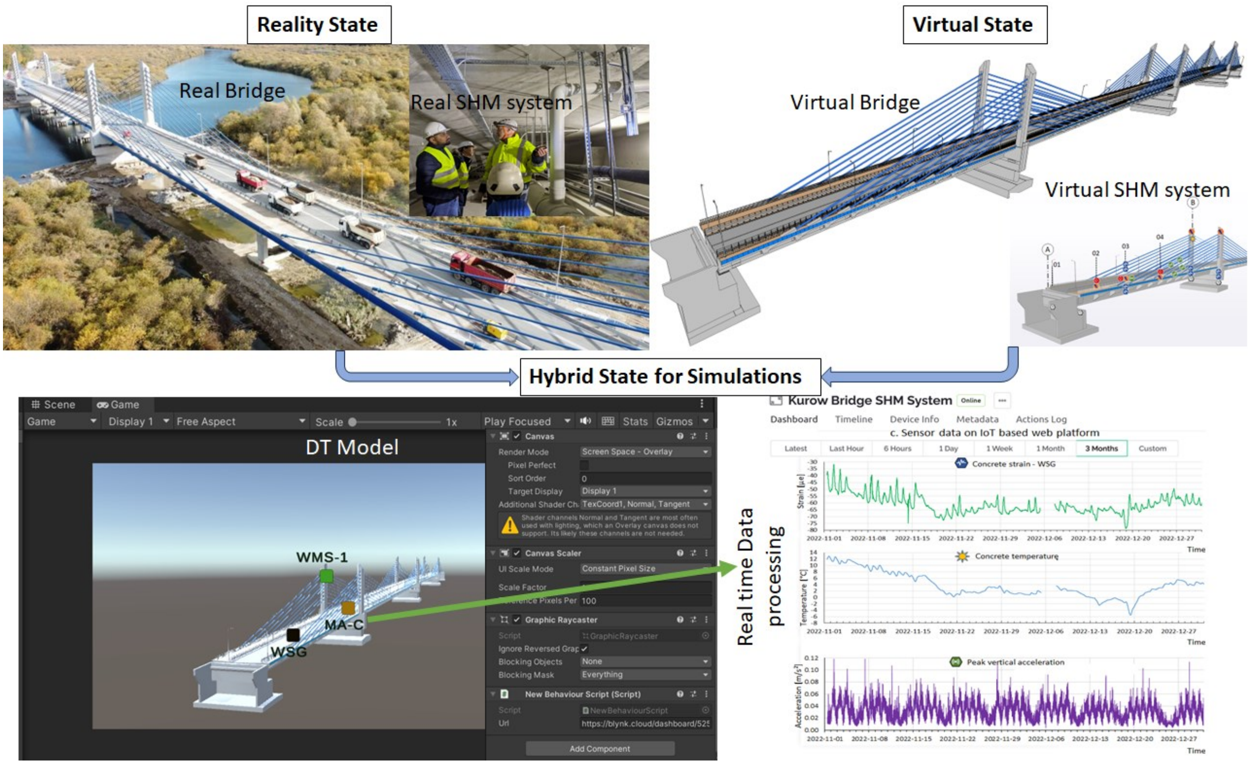

Figure 3 – Defining the three states in the proposed immersive DT framework.

development plugin is used (Vuforia) [19][20]. This plugin enables its own camera to convert the static DT model into an immersive DT model. So, when the game mode of UNITY is turned on, the VR system connects to the AR system in real time. Thus, the DT model can be used as an immersive AR application in the gaming environment as shown in 'Figure 4'. After this, the application is deployed to an AR headset (Microsoft HoloLens (HL)) using Visual Studio (ViS). Debugging is initiated in ViS, and the DT model is visualized in the HL app menu, allowing the immersive DT to function in an AR environment.

The successful testing of the deployed DT involved data integration and onsite bridge damage detection in the AR environment. Data integration in the developed DT application uses the IoT platform to gather, consolidate, and transform data from the installed IoT sensors, and systems into the web platform. The data on the web platform is available in graphical and tabulated formats so it can be transferred from the system to the users even when working on AR devices. As the data from different sensors is collected with different frequencies, data fusion methodology is adopted to integrate multiple sensor's data and produce a more consistent, accurate, and useful dataset for meaningful analysis. The outcomes of the measured data are then compared with the outcomes of numerical analysis (Finite Element Analysis) and the damages are identified in the system.

Figure 4 – VR to AR workflow for the proposed immersive DT framework

5 Conclusions

The use of Digital Twin applications for bridge monitoring processes has become a growing trend in construction and infrastructure projects. This research implemented the DT concept on the bridge health monitoring system by designing an immersive DT framework, which took the major step to tackle the research challenges in the integration of the DT model with VR/AR technologies to provide a holistic technologically available framework.

The proposed immersive DT model was demonstrated using the existing bridge project in Poland. As a basis of the DT model, the Physical State (PS), the Virtual State, and the Hybrid State of the bridge assets were defined for the SHM processes. The Virtual State (VS) is in the form of a BIM model and virtual replica of installed sensors and involves the data streaming from the physical system to the virtual system to provide accurate information about bridge health. Using such state definitions, the DT model of the bridge was developed in the UNITY game engine and deployed to the AR device (Microsoft HoloLens). The developed DT model is then successfully tested in its immersive nature and successful integration of measured data is observed in the AR environment. The case study shows that the AR-enhanced DT of bridge SHM systems not only helps the real-time monitoring of bridge health but also performs predictive decision-making regarding bridge health. This integrated system has turned the conceptual designs into a matured BIM framework that is taking the BIM implementation to a new dimension.

6 Practical implications

The developed framework is practical in nature as it achieved the integration of the conceptual designs of BIM workflows in the AR/VR domain to digitize the physically installed SHM system. Therefore, the application of the developed methodology on this bridge is already planned. The authors have already contacted the authorities to practically implement the research results so in case of the approval, the research findings will be practically implemented on the subject bridge, which could also involve the professional training of the working staff. Also, once the research is implemented in the real life, it could be possible to calculate the cost details and the comparison of installation and maintenance costs.

Moreover, the core information extracted from the framework can help to define the future development of bridge immersive DT applications to aid the monitoring strategies of infrastructure assets. This way a detailed comparison of the performance of the immersive DT of SHM system with the use of traditional methods can be performed.

Further, this paper reinforces the understanding of immersive digital twins and contributes to their practical adaptability, showcasing the DT applications as an extension of BIM tools integrated with monitoring technologies for the management and monitoring of infrastructural assets.

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