Recenzje spełnia wymogi formalne
Przewodniczący Rady Dyscypliny
Inżynieria Lądowa, Geodezja i Transport

Assessment of doctoral dissertation thesis

Author:	Msc. Eng. Muhammad FAWAD
Title:	BIM-based Framework of Bridge Health Monitoring Supported by Immersive and 3D Reconstruction Techniques for Analytical and Asset Model Updates
Reviewer:	Associate Professor Ing. Petr Konečný, Ph.D.

A. Formal assignment and object of the review

The review is conducted based on the request of Associate Professor Marcin Staniek (Przewodniczacy Rady Dyscypliny Inzynieria Ladowa, Geodezja i Transport, Wydzial Budownictwa Politechniki Slaskiej) from July 5, 2024.

The subject of the review is the doctoral thesis „BIM-based Framework of Bridge Health Monitoring Supported by Immersive and 3D Reconstruction Techniques for Analytical and Asset Model Updates“ prepared by M.Sc. Eng. Muhammad FAWAD. The student prepared the thesis under the guidance of two supervisors Prof. Marek Salamak in Poland and Prof. Kálmán Koris in Hungary. The reason for two supervisors is preparation of thesis in joint program (so called double degree form) at two universities Silesian University of Technology at Gliwice and Budapest University of Technology and Economics.

B. Topic of the thesis

I consider the choice of the dissertation topic and its execution as very timely because the civil engineering is least automated industry. Therefore, the contributions to automation of bridge health monitoring systems, considering the specifics of bridges, and their practical adaptation in the civil engineering industry is addressing the needs of industry. Moreover, the visualization of structural defects indicators in real time on-site and with reference to the sensor location has currently limited capabilities.

The thesis introduced and evaluated the cutting end technology either on full scale pilot projects where possible or in lab conditions. Moreover, the thesis made very good impression because of utilization of Building Information Modeling (BIM), Mixed Reality (MR), Finite Element Analysis (FEA), Structural Health Monitoring (SHM), Internet of Things (IoT) as well as Digital Twins, in order to help to made the selection of most suitable bridge design as well as help to have access to SHM on site with MR, and overall overview of the SHM data in the form of digital twin web interface.

Therefore, this thesis showed the fruitful connection between academia and practical need of the industry and pave the way to the future with respect to digitization and automation of our industry.

C. Layout of the thesis and its parts

The submitted work has all the expected parts of the dissertation thesis: Introduction, Definition of goals and scope, Chapter 2 and Chapters 3-5 that discuss topics related to thesis objectives including general overview, methodology and presented results. Thesis also contains concluding chapter as well as references and appendix. The work is reasonable structured and al parts are connected to each other. The details of each subsequent chapters are listed below:

Chapter 2 is aimed at the issues of bridge management system (BMS) and its applications in the SHM of bridges. It discusses conventional methods like visual inspections as well as the role of IoT technology in SHM, focusing on smart wireless sensors and their development components. It also highlights the benefits of SHM integration with BMS with focusing on addressing the shortcomings of traditional inspection methods.

Chapter 3 explores the use of BIM and digital technologies in bridge engineering, including emerging technologies like visual programming, Artificial Intelligence (AI), 3D reconstruction methods, and Virtual/Augmented/Mixed Reality (VR/AR/MR) for bridge health assessment and monitoring. It also introduces the concept of Digital Twin, highlighting its benefits and applications in sustainable development of bridges. Finally, in Section 3.5, it discusses the practical implementation of VR/MR technologies using the Trimble Hololens headset or a smartphone extended with Trimble Site vision augmented reality capabilities on the case of bridge designed in city of Sanok in Poland.

Chapter 4 explores bridge modeling techniques, focusing on analytical modeling and BIM. It uses Finite Element Method (FEM) analysis for bridge damage assessment. Moreover, it proposes a robust SHM system. Two case studies demonstrate the practical application of analytical modeling and bridge load testing methods. One bridge discussed in section 4.3 was located in Eastern Hungary and the other one given in section 4.4. was located in Kurow, Poland. It is worth mentioning, that the section 4.4 with Kurow bridge also discuss the load test and practical implementation of SHM and its integration with BIM via IoT. It highlights the use of IoT for real-time bridge health monitoring. Moreover, the development of cost-effective wireless sensors, and the integration of IoT systems with MR through 3D game engine Unity is presented on this pilot study.

Chapter 5: discusses the case study of an arch bridge Panewnicka where 3D reconstruction techniques, focusing on developing 3D models, are used. Finite Element Analysis (FEA) is used to simulate the bridge damage state and to propose a bridge SHM system, which is installed to monitor bridge heath parameters. Moreover, this chapter is synthesizing the gained skills, and tools for the development of a novel approach for infrastructure asset management, focusing on the development of an Immersive Bridget Digital Twin Platform (IBDTP). The platform is intended to automate the bridge SHM system and uses MR devices for immersive decision-making. The practical applications that is potentially scalable for different bridge types and critical infrastructure is presented and discussed.

Chapter 6 is concluding consisting of Discussion of results to achieve research objectives, Final Conclusions, New scientific achievements, Practical applications of the research work,

Note: Since there is more investigated bridges and it was hard to navigate between particular methods, applied procedures and bridges, following labels will be used in the review: Newly designed bridge in city of Sanok in Poland that is discussed in section 3.5 - ***Sanok,*** analytical modeling of bridge in Eastern Hungary discussed in section 4.3 - ***Hungary,*** *model updating and SHM calibration using field load testing of bridge that was located in Kurow, Poland that is discussed in section 4.4. -* ***Kurow,*** *analytical modeling of and Immersive Bridget Digital Twin Platform (IBDTP) preparation for Panewnicka bridge in Poland that is discussed in section 5 –* ***Panewnicka bridge.***

D. Goal of the thesis

The thesis main goal is contribution to the development of an Immersive automated bridge Structural Health Monitoring (SHM) system by utilizing the applications of BIM methodology, 3D-reconstruction techniques, Internet of Things (IoT) approach, and Mixed Realities (MR) technologies, and including concept of Digital Twins.

The main goal is divided to following partial goals:

1. Development of bridge asset management framework using analytical and BIM modeling tools.
2. Proposal of advanced SHM system and its validation.
3. Integration of SHM, BIM, and IoT technology for smart infrastructural health monitoring.
4. Development of Immersive Bridge Digital Twin Platform (IBDTP) using Mixed Reality technology.

The goals of the thesis were achieved.

E. Applied methods and procedures

The above mentioned goals were reached via several partial application described in the thesis that allowed to demonstration of investigated and tested approach.

3.5 Sanok: Exploration of the basic applications of VR/MR tools for visualizing bridge concepts during design phases, and the assessment of bridge design concepts through immersive technologies in case of newly designed bridge in Sanok. The onsite visualization of two designs at a scale were made. Common Data Environment (CDE) with MR extension, BIM model of the bridge, Visualization tools (Headset and mobile phone extension) were used in order to test its the possibilities and limitations.

4.3 Hungary: Use of BIM in bridge asset management, with a focus on using BIM tools for the development of automated SHM systems, and the BIM-based Finite Element (FE) modeling of bridges in Eastern Hungary. Two modeling approaches were used. First linear static response based model in AXIS VM and second nonlinear model prepared in Athena software were used. The utilization of non linear model allowed for more precise evaluation of the effect of cracking. The numerical results were compared with experimental data that were not referenced. Moreover, as the authorities were not interested in installing the SHM system, so, another case study was considered for further research.

4.4 Kurow: However, the possibility of SHM was not available in Hungary. Therefore, the other bridge **Kurow,** Poland was selected for modelling and validation with field test in order to calibrate SHM Investigation of the integration of IoT technology with SHM systems for real-time monitoring and periodic maintenance of bridges, by developing low-cost wireless sensors. Since, the preparation of the model was enhanced by implementation of Virtual Programming language (VPL) using Dynamo. VPL allowed to generate and update the model based on the SHM resulting in the effective preparation of FEA model via CADIMP protocol. The bridge SHM system utilizes IoT technology to create a virtual sensory model, enabling real time communication with real sensors. This integrated system integrates SHM measuring the structural data, IoT collecting diverse data sources, and BIM integrating SHM and IoT data to provide a holistic view of infrastructure performance. However, the test of the system was conducted in the lab scale and no data were provided about lab scale or virtual model providing the actual SHM data.

5 Panewnicka bridge: Another bridge and its model served as a object of testing in case of developing an online web platform for bridge SHM that incorporating IoT sensors and integrating MR using the BrIM models. Therefore, creating Immersive Bridge Digital Twin Platform (IBDTP). For this purpose, the IoT-based web platform is linked with the BrIM reality model of the bridge to prepare the corner stones for the development of IBDTP. The bridge digital twin platform was developed in the UNITY game engine, embeds virtual sensors of the bridge SHM system in the BrIM reality model, enabling real-time communication between the virtual and real systems, resulting in the automatic functionality of the bridge SHM system.

Moreover, evaluation of the efficiency, accuracy, and scalability of the IBDTP as compared to traditional SHM approaches, was conducted by qualified engineering judgement.

F. Results and discussions

Note: The following remarks are numbered based on the page that they are related to: e.g. 22.1 means first remark related to page 22. General remarks are numbered as G section of the review and number in the order remarks at a particular page.

3.5 Sanok: The onsite visualization of two bridges in Sanok were conducted and helped authorities to made immersive experience based selection. Based on the conducted tests it was assume that the HL device does not work well in open areas with longer-span structures. Such an open area without any characteristic objects with flat surfaces does not allow for full visualization of a larger model and its precise display.

32.1, Fig. 3-6: Full structural details are presented on the figure according to its caption. However, connections of hangers to structures and railings are missing. The definition of full detailness is not clear. LOD or similar definition might be used for such definition to avoid misunderstanding.

33.1: In chapters 3-5, there is mixed theoretical information with own work of the student which was unexpected. Another approach would be to start with state of the art first and proceed with own research contribution in following chapters. However, that particular type of layout does not reduce the overall quality of the work. The reader has a Content helping with navigation and own contribution is stated clearly in section 6.3 New scientific achievements.

4.3 Hungary: The practical application of these techniques is demonstrated through a case study of an RC bridge. The case study employs an analytical modeling approach, utilizing static and 3D nonlinear analysis for the damage assessment of the bridge which is found to have extensive cracking. Subsequently, a sophisticated SHM system is proposed for effective monitoring of bridge damage.

46.1: Author used a term "displacement damage". Generally displacement is a reversible process and a serviceability issue in case of static linear response is considered in a similar way to case discussed in section 4.3.2. Therefore, the loading induced displacement is not expected to remain when the structure is unloaded in case of linear response. Therefore, what damage is author mentioning in case of displacement?

47.1: Does AXIS VM allow for scripting or batch mode in order for the parametric processing of input data?

47.2, Fig 4-2: Deflection look unsymmetrical. What has caused the asymmetry of the deflection. What combination of load cases?

48.1: Non-linear analysis with ATENA contains modulus of elasticity, Poisson ration. However, those were not mentioned in application with AXIS – VM software. Were those the same? Moreover, constitutional model for concrete non-linear behavior is not provided. The respective parameters are also not given (Fracture energy and other necessary parameters of used constitutive model).

48:3: PhD Candidate states: "Maximum deflection is calculated to be 20 mm, while the minimum deflection is 5.4 mm." without specification of a location. Minimum deflection near the support is close to zero. Therefore, location is missing (e.g. mid span).

49.1: Yielding of steel is mentioned. What is f_y, E and stress-strain diagram of applied steel?

49.2: Are creep and shrinkage included in the calculation with ATENA?

50.1: In-situ measurements are mentioned but no value or reference to the measured data report is provided in actual text of the thesis.

50.2, 53.1: Serviceability criterion is related to crack width. What may cracks and damage of concrete cover cause to steel reinforcement? Is corrosion related only on cover thickness?

52.1: Can be rotation angle derived from Liquid leveling system measurements? If so, how?

52.2: Can proposed IoT system allow for connected with the camera in order to record the vehicle if the loading value threshold violated?

4.4. Kurow: The second case study explores an extradosed bridge in Poland, where the BrIM model is developed to generate an accurate parametric FE model using the VPL algorithm in dynamo. The numerical model was calibrated with SHM results.

However, permission to physically access the bridge SHM system was not granted, so, a lab-scale bridge model was used to practically demonstrate the developed IoT-enhanced SHM system. A lab-scale simulation integrated the IoT-based sensor system with the BrIM model of the bridge, successfully implementing real-time SHM of the bridge.

55.1, Fig 4-9 and Tab 4-1 show E_{cm} and $E_{cm(t)}$ based most likely on Eq. 5.1. Is there a reference test to compare with numerical prediction?

57.1: What FEA software that can read parametric input language CADINP is used herein?

57.3: It is mentioned that direct method for analytical model from the BIM model is not recommended. Just a note, direct method for the generation of structural model from BIM with preparation of elements that are not explicit in the real structure, e.g. hard links, supports and load cases is possible e.g. in ArchiCAD with export to open *SAF file format ready to be used in structural analysis software.

57.4: Author states that "The topology of the span requires divisions into sections of parametric density defined in the open VPL code." Why sections with variable density? Is not the change of stiffness and either the modulus of elasticity or cross-section the parameter to be changed if cracking occurs?

61.1: Tab. 4-2: Shows what is computed and measured. However, it is unclear what is measured and computed. In case of S2. N1 and N2 $U_t=U_e+U_d$. Even though, it is not the case of S1 (A1 and B1). Therefore, it seems that U_t is calculated and U_d is measured even though in text is given that U_t is measured and U_d is theoretically calculated (based on FEM analysis). Clarification is appreciated.

65.1: Is the design of SHM given in tab 4-3 work of the PhD candidate?

70.1: The author stated: "The initial plan of this research included the field installation of the developed sensors on the Kurow bridge and data measurement in the field condition, but unfortunately, permission to physically access the bridge SHM system was not granted, so, a lab-scale bridge model was used over which the developed IoT sensors were installed and simulation of the bridge SHM system with the developed wireless sensors was performed at the lab scale." It is confusing rainsing two questions:

70.1.a: So, what SHM data were accessible for calibration?

70.1.b: On what labscale model were SHM data obtained? The technical drawings picture from tests or any other more specific information about virtual sensory model were not found in the thesis. More details would be helpful.

G.F.2 Description of the lab-scale model for testing of the IoT-enhanced SHM system was missing. The description of the lab-scale model would be appreciated.

G.F.3. The integrating the SHM data from IoT sensors is indisputable very good achievement. However, the statement: "The predictive maintenance can thus be performed by such systems in real time with clear visualization of damages in graphical formats, improving the safety, reliability, and efficiency of infrastructure while optimizing maintenance efforts and resource utilization for smart infrastructural health monitoring". The optimization is most likely meant with respect to reducing the labor costs. What would be necessary to optimize the maintenance effort besides the data itself.

5 Panewnicka bridge: The thesis discusses the development of Immersive bridge digital twin platform that integrates the proposed SHM system with BIM, IoT, and MR technologies to develop an Immersive Bridge Digital Twin Platform (IBDTP). After the successful development of the wireless sensors and connected IoT-based web platform, the system was tested at a lab scale for the case study of the bridge SHM system discussed in section 4.6. In this study, BIM methodology offered a bridging role between the SHM system of the bridge and developed IoT-based wireless sensors.

72.1: What are the licensing issues or costs associated with Unity 3D engine utilization (if any)?

72.2: It is worth mentioning that there is Wearecho tool intended for architectural design in 3D https://wearrecho.space/. The software is developed in Czech Republic and the company is cooperating with universities. Maybe there is possibility of extending a software for such interactive applications that needs connection via URL and prepare similar application as prepared in Unity game engine.

74.1: Table 4-7 states that the tradition SHM have only off-site monitoring option. It seems like misunderstanding. If the notebook is hooked to data logger that is on-site the results are available on-site. So, what is meant by off site option only.

82.1: FEA model parameters that are given in section 5.4 are only brief. Hanger material description is missing.

G.F.4: The author used Unity game engine to transfer the BrIM model to MR environment. What was the exchange file format (e.g. *.Ifc?) and what were the challenges?

G. other Remarks, comments suggestions for discussion

The following remarks numbered based on the page that they are related to: e.g. 22.1 means first remark related to page 22.

22.1: Authors mentions: "This high resolution point cloud can then analyze different structural elements, detect their deformations and damages, and identify signs of deterioration such as cracks and corrosion. Additionally, it can be used to create accurate models that are compatible with BIM tools and can be used as a part of a bridge management system.". However, the human involvement is still necessary in the process of turning the cloud of points into 3D model and structural members. What PhD candidate thinks about possible automated processing of point cloud?

23.F: Following statement seems to be contradictory or not understood well: "However, the point cloud can be used to generate polygonal meshes that can reproduce the scanned or photographed surface of the object. ..Polygons can be additionally imaged (rendered) using smoothing and shading algorithms, which is impossible in point clouds". So clarification what is possible to be generated with point clouds and what cannot be done with point clouds is appreciated.

24.1: It is unclear what is meant by: "the main difference being the starting point," in the sentence: "A comprehensive bridge model, combining BIM and FEM properties, closely resembles a digital twin, with the main difference being the starting point, largely due to computer-aided design tool evolution.".

27.1: Fig 3-3: Figures of staircase and corridors (without a person with helmet and Hololens) look like visualization and the actual reality is not visible. So, it looks like virtual reality and not mixed reality. Comment is appreciated.

42.1: Authors wrote: "Numerous deficiencies of existing Reinforced Concrete (RC) bridges are due to the absence of detailed durability rules in the original design, which can be verified by carrying out static and 3D nonlinear structural analysis.". Can be PhD candidate more specific about how static and 3D nonlinear structural analysis can overcome deficiencies in durability design because of absence of detailed durability rules in the original design?

93.1: Author states: "Whereas the other parameters like deflection of bridge, bending, and shear capacity in the Ultimate Limit State (ULS) and stresses in the Serviceability Limit State (SLS), are satisfying...Is the limit of deflection criterion for ULS or SLS? However, since the structural assessment is not the main goal of the thesis, this does not affect the presented achievements.

99.1: Within scientific achievements authors states that he developed FEA model with the help of VPL. This is related to section 4.4 (Kurow bridge). Were the other BIM and/or FEA models also prepared by author of thesis or someone else?

100.1: The further development of the already presented achievements such as IBDTP can be conducted with incorporating the LCA or sustainable and multi parametric criterion.

H. Significance for practice and development of the research field

The thesis represents significant achievement in the field of combination MR, SHM, IoT and Bridge assets management and modeling even though there were not given all the information necessary for the structural analysis repeatability. However, this drawback does not jeopardize the achievement of the main goals.

Therefore, considering the advantages of VR technology, this PhD research successfully executed VR-based field experiment in collaboration with a municipality partner, as a case study to demonstrate the design concepts of a future bridge helping the clients in the selection of the final design for the construction of the bridge.

The utilization of VPL in preparation of analytical model based on the SHM update is paving the way to more automated preparation of structural models. Therefore, leading to ad another step in automation of the work of structural engineers. Moreover, the integration of BIM with SHM and IoT data creates a significant step in providing a tool for a holistic view of infrastructure health that would made performing the predictive maintenance of such systems in real-time with clear visualization of damages in tabulated and graphical formats. Therefore, it allows managers to automate the SHM of bridges and engage them in immersive decision-making processes using MR.

Practical outcomes are also identification of the limitations of Hololens MR equipment when the BrIM model supplemented with virtual sensors uploaded to HL where the virtual sensors (with the embedded URL of the SHM platform) were not functional in the MR environment. The problem was addressed witch was reviewed by PhD candidate that prposed and solution to this problem was tackled using UNITY 3D engine.

I. Formal aspects of the thesis and references

Thesis consists of an extensive review of existing literature on the evolution of bridge management (BMS), SHM for bridges, and the adoption of advanced technologies in bridge monitoring and management. The Reference section contain 243 cited works including 3 publications of the Ph.D. student (three articles and one conference paper).

The thesis is well written and easy to read without significant flaws. However, some minor issues that does not affect overall quality of the thesis were found. The number of the respective paragraph represent the page.

4.1 Empty page that seems to be a intentional end of a chapter.

7.1 Multiple references were not divided by comma (e.g. [11][14]). The expected form of referencing would be [11],[14].

8.1 "The sub-continent" word "Indian" is missing ("The indian sub-continent").

10.1 Fig. 2-2: "damage typification" does seem awkward. What about "damage classification"?

22.1-2: The definition of UAV was doubled as cited next: "UAV (*Unmanned Aerial Vehicle*) means *unmanned aerial vehicle* (UAV)". Moreover, word *attitude* was also double on the same page: "the *attitude* and *attitude* of the aircraft".

77.1-78.1: Two concrete arches are mentioned in case of Panewnicka bridge. Moreover, caption of Fig. 5-1 contains description "Concrete arch bridge". This is generally description even though the concrete structure most likely contains reinforcement and girder is prestressed.

G.I.1: The hardcopy of thesis contains randomly placed envelope with CD-ROM without any label and any note in the Content. Therefore, creating doubts what is inside it.

G.I.2: Moreover, the thesis contains several cases of bridges and lab test, and it is little bit confusing what type of modeling and testing was performed on each of the cases. Table with overview of the bridges and availability of performed analysis, models, presence of SHM interface would be helpful to make the orientation easier.

J. Concluding summary and evaluation

Considering the evaluation of the dissertation, I believe that it represents an original solution to a scientific problem and demonstrates the doctoral candidate's general theoretical knowledge in the scientific discipline of civil engineering, geodesy and transport. It also confirms the ability to conduct scientific work and thus fulfills the requirements of the following legislative requirements of the Republic of Poland: „Ustawa z dnia 20 lipca 2018 roku Prawo o szkolnictwie wyższym i nauce (Dz. U. 2018 r. Poz. 1668, z późniejszymi zmianami)" and I propose that it be accepted and admitted to public defense.

September 10, 2024

Recenzję podpisał
Petr Konečný

K