Developing a mixed-reality based application for bridge inspection and maintenance

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ABSTRACT: Bridge inspection, which collects data for assessment and decision-making processes, plays an important role in the maintenance job of bridge structures. However, all of the inspection jobs, including general inspection, principal inspection and special inspection, generate large and unstructured data resulting in ineffective maintenance. Besides, traditional inspection generates only 2D-based and less visionary information. For a more reliable assessment of structures, it is necessary to improve the current inspection technology and process. In recent years, mixed reality (MR) technology has been proved to be effective in improving interaction, communication and collaboration among stakeholders for evaluating the database. MR and holographic technology blend 3D models with physical assets and support users to engage in the models and interact with the project data more intuitively in the real-time simulation. This paper presents an application of MR-based system called HoloBridge to enhance and facilitate bridge inspection and maintenance. The application consists of modules of inspection, evaluation, and damage mapping. The HoloBridge application is being deployed to Microsoft Hololens for tracking and assessing conditions of bridges. The application has been developed by building information modelling (BIM)-based system linked and integrated into a cross-platform game engine to evaluate bridge damage information. The application is piloted with a highway bridge in South Korea and has shown the benefits not only in the digitalized inspection processes, but also in systematic managing bridge performance.

KEYWORDS: Mixed reality, building information modelling, bridge inspection and maintenance.

1. Introduction

In the construction 4.0 revolution, promising technologies such as building information modelling (BIM), virtual reality (VR), augmented reality (AR), mixed reality (MR) that promote digitization and automation in information management and visualization. MR technology shows the reality-virtuality continuum, which is the process of blending the 3D project model in real-world representation based on computing techniques. MR system is an innovation for project information interaction and collaboration among stakeholders (Dunston & Wang, 2005). It enables to enhance data accessibility for decision making in project management such as design check, construction simulation and monitoring, especially for operation and maintenance. MR goes beyond the AR-VR technology by combining the features of both VR and AR. VR environment provides a computer-generated reality wherein the user can completely immerse and interact with model objects using a VR headset. Rather than fully immersive in a virtual environment, AR enhances model interaction between the virtual and the real worlds via smartphones, tablets and AR glasses. According to Rokhsaritalemi (2020), three main characters of MR are immersion, interaction and information. Immersion refers to the act of user completely immersing oneself into the virtual-reality world by real-time interaction. In the MR environment, the user interacts with the object to access information by natural communication modes such as gestures, voice, and gaze. However, the development of MR technology faces two significant challenges: display technology and tracking. An MR application needs to display the output model with high resolution and contrast. The interaction between virtual models with the user's command requires precise and fast methods. For MR-based application development, the Microsoft Hololens has been introduced as the most prominent MR device. Microsoft Hololens is the first self-contained, holographic computer that allows users to engage with 3D digital content and interact with holograms in a hybrid reality. With the Hololens, users can bring the 3D project model to the real-world to collaborate with others by hands and voices. Since BIM adoption becomes popular in the construction sector, the BIM-based system has been proven as an

effective solution for project information management based on a 3D model working environment (Demian & Walters, 2014). Hence, combining an MR system and BIM can create a powerful application for project information management and visualization.

In recent years, the MR-based application for BIM system using Microsoft Hololens has been implemented in the field of Architecture, Engineering and Construction (AEC). An AEC project contains huge amount of information that requires be accessed from various parties such as contractor, owner and consultancy. By using Hololens, the BIM model in holographic environments is able to share construction-related information among different stakeholders that improve collaboration, coordination and understanding project documents (Hamzeh et al., 2019). In addition, using MR application for assembly instruction also reduces the installation errors and improve productivity in the construction site (Huang et al., 2019). In modern infrastructure development, bridges are the most expensive, complex structure. Therefore, the transportation agency needs to have a smart application for managing inspection and maintenance tasks. Bridge inspection is the process of determining the physical and functional condition of bridge structures. It is the main component of bridge monitoring and maintaining work, which provides the safety assessment and condition document for the bridge management system. During the bridge operation phase, the inspection work consists of the general inspection, principal inspection, and special inspection by various inspection methods and technologies. A huge amount of inspection data has been generated. The inefficient information system leads to incorrect safety assessment for maintenance works. Moreover, the limitation of monitoring the deterioration process is the lack of digitalized damage records to compare the current inspection results with the previous inspection. It requires a single-source data model, which can systematically manage the inspection database and ability to interact with the dataset.

Therefore, to solve this problem, the paper presents the development of HoloBridge application for Microsoft Hololens to improve the inspection and maintenance tasks based on the advance of BIM-based system and MR technology. The pilot implementation shows the result of BrIM inspection model in the MR environment. The application can support better decision-making by the function of information sharing, visualization, integration and real-time interaction among project stakeholders.

2. Literature review

Bridge information model (BrIM) is an integrated model, which includes a three-dimensional (3D) model and a bridge database. BrIM enables stakeholders to collaborate and manage works throughout the project lifecycle, from planning to maintenance (Shim et al., 2012). Recently, this BIM-based system has been widely adopted to improve bridge inspection and maintenance (McGuire et al., 2016; Shim et al., 2017). The process of integration of the inspection and maintenance information to a BrIM can improve the decision-making process and lead to more quality decisions. The most advanced feature of BIM is the facilitation of data exchange, integration and interoperability in digital formats during the project lifecycle (Eastman et al., 2011). For inspection work, the defect information is extracted and modelled to overlap with BIM element model (Hüthwohl et al., 2018; Sacks et al., 2018). The prototypical implementation proves the possibility of integrating inspection data with a 3D model to create a BIM-based inspection model. Moreover, the BrIM inspection model also can minimize the error from the inspector's personal evaluation and reduce the time by using 3D model visualization for better understanding bridge structure (Al-shalabi et al., 2015).

Literature shows that BIM has been utilized for developing VR, AR, MR applications. For project operation and maintenance, Omer (2019) developed a VR application to bring bridge inspection in the office. The application uses 3D models developed from the 3D scanned data, and the user can walk in this virtual environment to check the condition of the bridge structures. The inspection work using VR technology overcomes the limitation of the conventional method. AR technology also has been investigated and applied in bridge inspection work (Salamak & Januszka, 2018). Although VR, AR technology have been successfully applied in bridge inspection work as a new approach to improve the quality of damage visualization and detection, the application of MR has many limitations, particularly for the Hololens application. Hololens is a wearable device that can be used to inspect bridges in the field and office. Previous researches have focused on developing the Hololens application for onsite bridge inspection (Karaaslan et al., 2019; Moreu et al., 2017). By using Hololens, users can automatically detect some types of defects such as crack, spalling with dimension information in real-time. However, there is a lack of research on using Hololens application for remote bridge inspection in the office. It is necessary to develop a framework to build a Hololens application for bridge inspection from a BIM-based system and onsite inspection database.

3. Methodology

This research aims to highlight the capability of inspection data visualization and interaction in MR space and the systematic database management based on BrIM model to develop a smart MR-based application for enhancing and facilitating bridge inspection and maintenance. The critical review of the literature is conducted to realize the limitation and challenge of the current AR, MR application in terms of BIM model for inspection, data visualization, integration, and analysis for monitoring the structural condition. To achieve the research aim, a new framework, a BrIM model for inspection and maintenance, and a development workflow are proposed. To develop the application, a framework is created from the concept of a BIM-based system for inspection and the feature of MR-based application. The BrIM model for inspection is built based on the parametric modeling and systematic integration of inspection databases. Finally, the application has been implemented for a case study bridge to evaluate the effectiveness of inspection and maintenance works.

3.1 General MR application framework

This framework has four major parts: (I) Data acquisition, (II) Data processing, (III) BIM-based system, and (IV) Application development (see Figure 1). This paper mainly focuses on the BIM-based system for bridge inspection and application development process. Part I and II are the data preparation process to establish a BIM-based system. Ultimately, the application has been developed through a cross-game engine platform and a BIM system.

Data acquisition is the process of gathering bridge information from different inspection levels such as general, principal and special inspection by modern bridge inspection technologies. For visual inspection, a drone is used to simplify complex inspection tasks with high quality of photos and videos. The drone data provides a database to generate a 3D bridge scan model by photogrammetry technique. The scan model provides geometric data with defects visualization. Besides, ground-penetrating radar (GPR) is used to capture the subsurface of the concrete and pavement for detecting the damages such as delamination, voids. In the data processing, the inspection documentation is generated with the detail damage properties from the damage detection, classification and measurement process. The BIM-base system consists of two major components, which are the 3D bridge information authoring and the database from the data processing part. The 3D bridge structure model is created with the corresponding inventory system. Each bridge element model contains model attribute, archive data and a link to the inspection database. Finally, the HoloBridge application can be developed from a cross-platform game engine and BIM models. The application brings the 3D bridge model to the real-world and allows the user to query the inspection database to check and monitor the structural condition. By the damage mapping algorithm, the user can evaluate the damage development progress over time and make a more reliable decision for maintenance works.
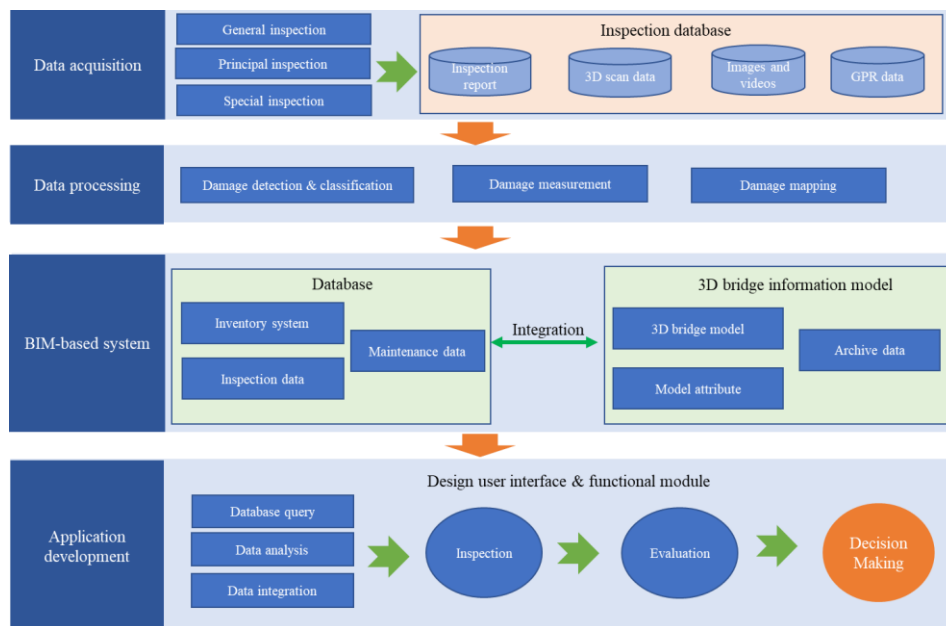

Fig. 1: Application framework

3.2 Case study bridge

The case study bridge is a PSC girder bridge built in 2001, 120-meter length with four spans (Picture in Figure 2). General, principal and special inspection jobs for the bridge have been conducted with modern technologies using a drone, laser scanning, and ground-penetrating radar (GPR). The most common damages are cracks and spalling on the piers, girders and bottom slab surfaces. The inspection data have been stored under 2D-based forms such as AutoCAD damage drawings, inspection photos and reports. The bridge was selected because the current management system has many limitations in terms of data interoperability and integration of the metadata. These data are discrete and not be linked between the current result and the previous result to monitor the damage development, especially for crack propagation. In order to systematically manage the inspection records, the bridge information model has been defined. This is a single-source data model, in which the inspection data of bridge structures have been integrated with 3D information element models.

The following sections describe the overview and the systematic process of BIM-based system for inspection and maintenance, explain the information exchange and relationship of the data model in the database system, and present the workflow of application development with the functional module. The conclusion section discusses the novel aspects of the application from BrIM model in MR environment working, and the extension for future works.

Fig. 2: Case study bridge

4. Bridge information model for inspection and maintenance

4.1 Bridge inventory system

The structural components are categorized and put into an inventory system based on their roles in the bridge system. Generally, the inventory includes the superstructures (e.g., slabs, girders, cross beams, barriers, bearings, expansion joints) and the substructures (e.g., bridge piers, abutments). The category system enables the identification of structural elements by using specific identifications (hereafter, ID) and create a systematic database. According to the ID definition, the 3D information model of bridge structures is generated by object-oriented modeling. The entire bridge model will be assembled by all elements' ID with coordinate and constraint data from bridge alignment. Figure 3 presents the inventory system with a detailed hierarchical category and ID naming convention.
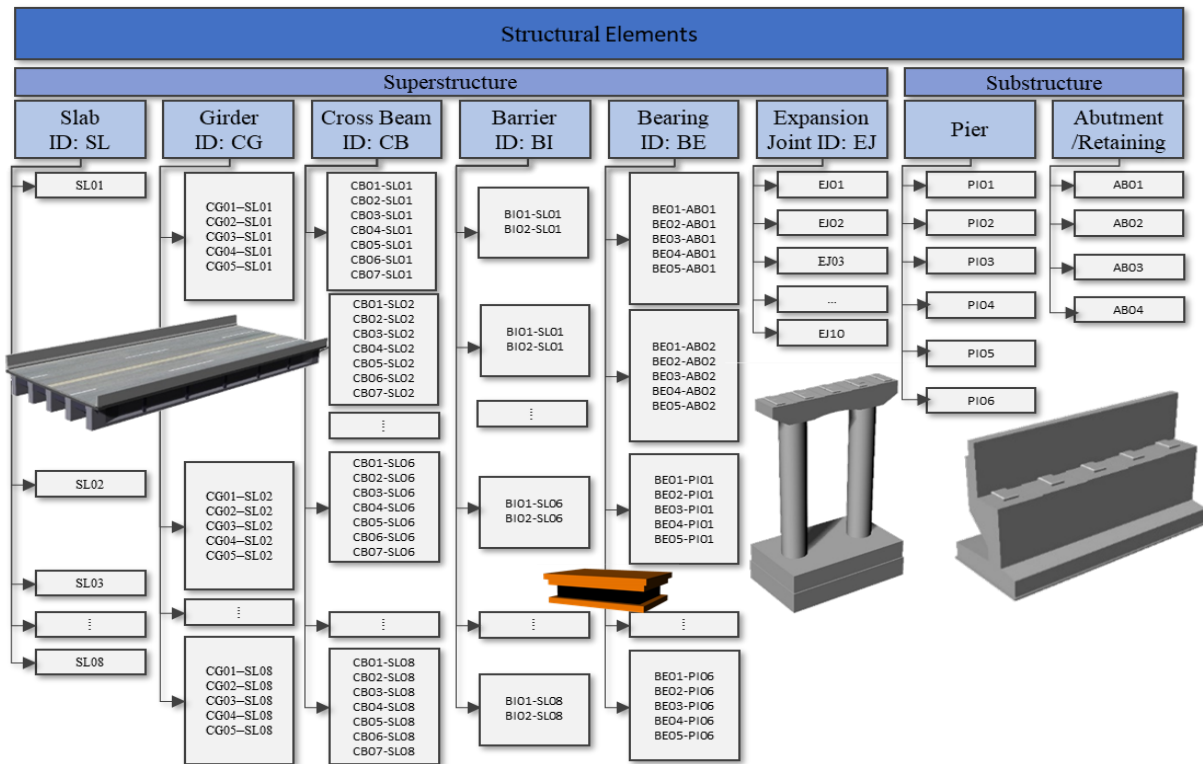
Fig. 3: Inventory system and ID definition

4.2 Model authoring

The creation of the BrIM model is an essential task in the BIM-based system establishment. According to the inspection and maintenance purpose, the BrIM model has been developed from 2D cad drawings in the level of development (LOD) 300. The model has three significant characteristics: structure recognition, relationship modelling and object-based parametric modelling. Structure recognition has a function to label the queried bridge components followed by the inventory system and ID definition. Relationship modelling establishes the topological relationship of bridge components. The object-based parametric modelling aims to generate a 3D digital representation of bridge components by the geometric parameters and modelling algorithms. Modelling algorithm is a mathematical calculation between geometric constraints and dimensions that allows automatically changing the shape of the model when the dimension value is modified. The advance of the parametric modelling method is flexible, fast and accurate because of using parametric features. Figure 4 explains a flowchart of bridge modelling authoring. There are four steps to make a parametric bridge model. First, the bridge element model needs to be defined from the inventory system with ID convention. Second, this step requires identifying the geometric and alignment parameter of each element. For instance, a bridge pier model comprises foundation, column and pier cap with the main geometric parameters such as length, width, height, radius and the position, orientation and constrain of the alignment parameter. Third, the object model is built based on the geometric and alignment algorithm. The geometric algorithm is the process of creating the geometric of an element model from the primitive shape such as curve, surface, solid in the Euclidean three-dimensional space. From the whole model structure and constrain of element objects, the alignment algorithm is created from the coordinate system and orientation vector. Similarly, the other elements can be modelled, such as abutment, girder, slab, and barrier. Finally, bridge substructures and superstructures models are placed in accordance with the 3D alignment-based parametric of the entire bridge model.
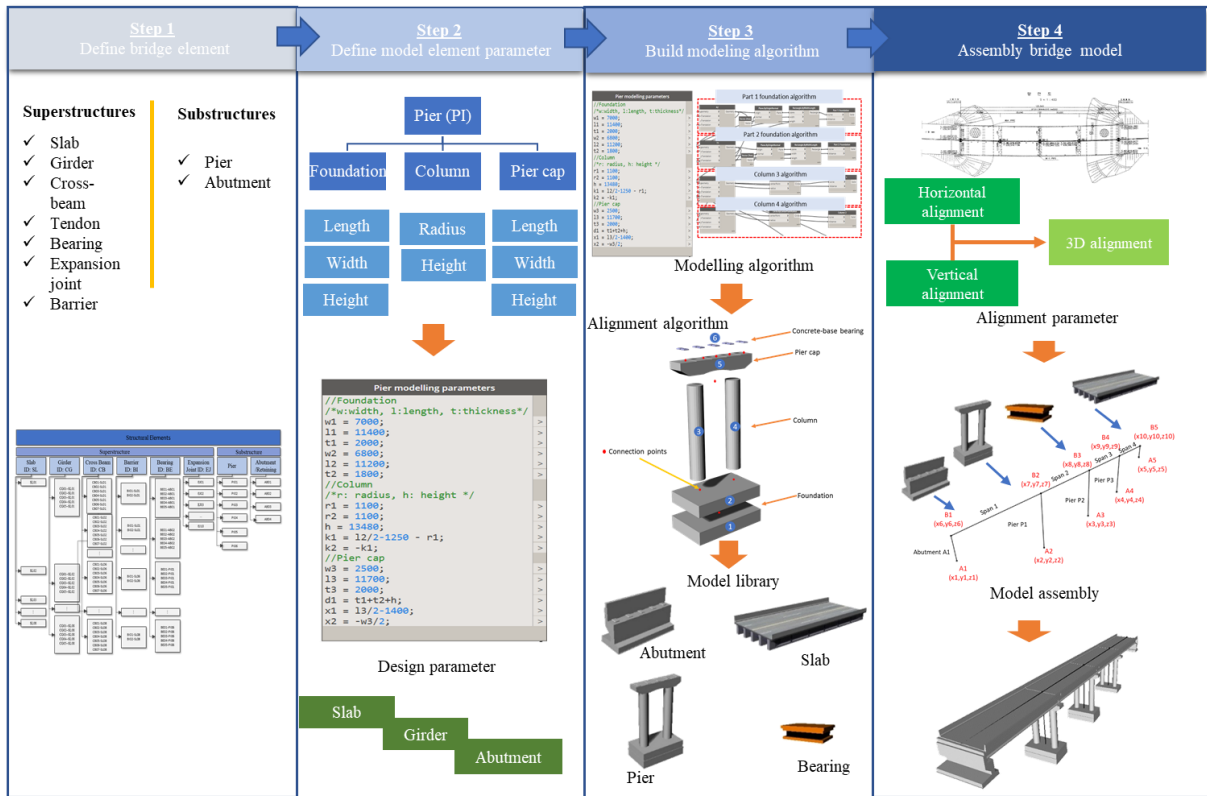
Fig. 4: Model authoring process

Figure 5 explains the process of converting the 3D foundation model from BIM platform to HoloBridge application. In this research, the bridge model from Dynamo is exported to Revit to finalize BIM models with the attribute and as-built information. From Revit, the bridge model is converted to the exchangeable 3D format, such as industry foundation classes (IFC) and FBX. In Unity 2019.3, a cross-platform game engine, the application has been developed with the programming of functional modules for inspection works. After the bridge model has been established, the application database is constructed with the systematic structure and data integration architecture.
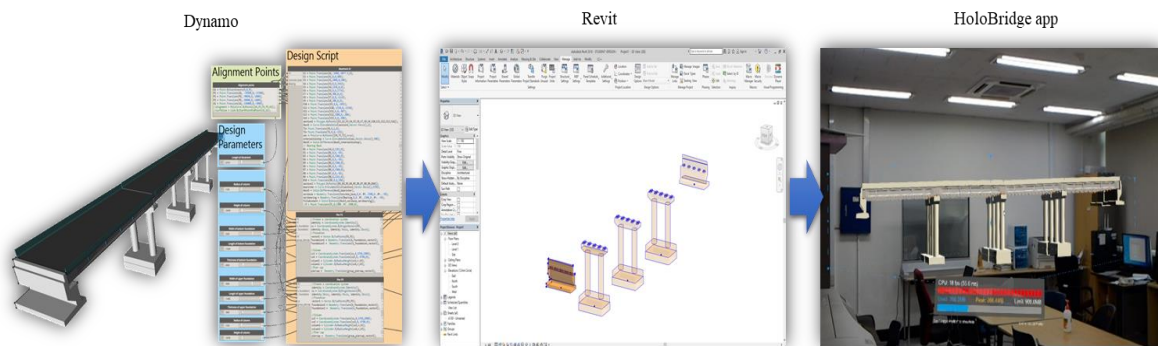

Fig. 5: Importing model to application

4.3 Database system

The application database has three main parts: inspection and maintenance data storage, 3D BIM foundation model, and data integration architecture. The inspection and maintenance data are commonly managed by various reports. The data accumulation and curation can be efficiently organized by BIM model-based and mixed-reality platform features. The bridge BIM-based database is built by integrating the corresponding data into the specific 3D structure model based on systematic classification from the inventory system. In the database management system, a structure element data has three main parts: 3D model, model attribute, and model archive. In the working of the master 3D bridge, the user can easily interact with the structure element because of object-oriented modelling and ID identification. Therefore, the 3D model inventory can be systematically accessed to extract and integrate data.

Figure 6 illustrates an example of the schematic information system of the bridge slab that can be standardized for information management of other structure's elements. The model attribute part contains general information in terms of the physical properties such as geometric, material properties, ID and location. It is the original data and extension part of the 3D model for network-level maintenance works. In addition, each element has its archive data list, which consists of all information for bridge inspection and maintenance requirements such as as-built information, inspection sheet, damage properties, repair manual and history. During the operation of the bridge, the data is accumulated in the archive data by the defined code system, which is described in the following section.
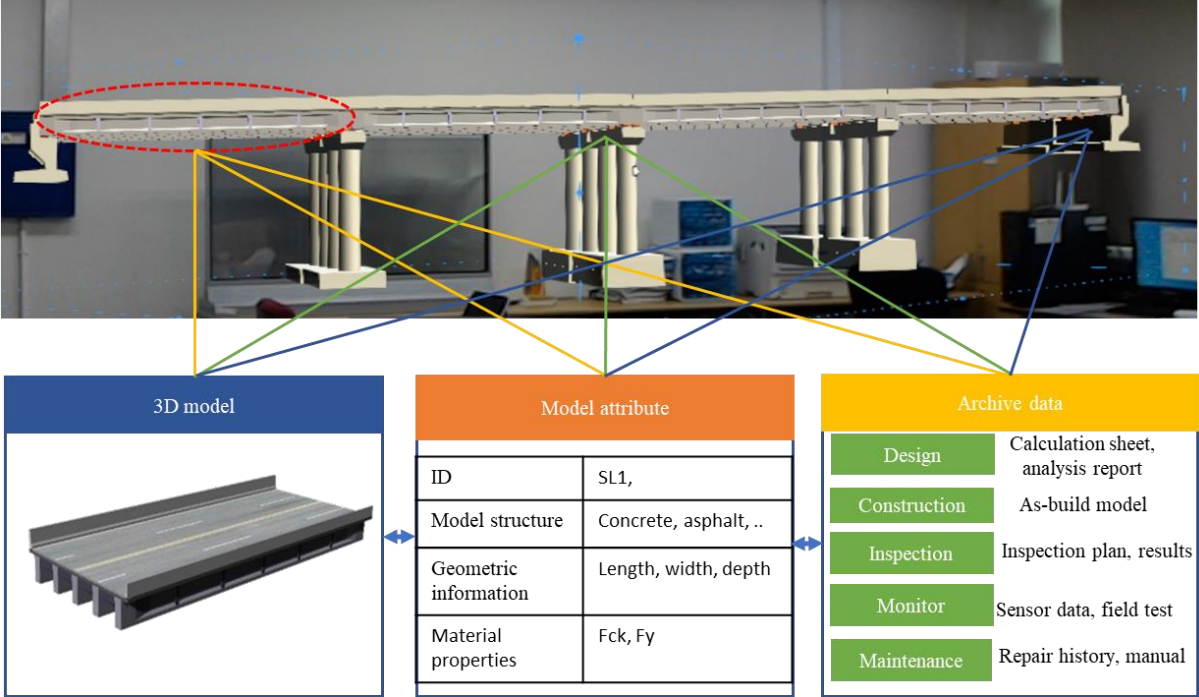

Fig. 6: The schematic information system

4.4 Documentation and damage code system

According to the guideline of bridge inspection and maintenance practices, the vast amount of inspected data from many sources has been accumulated during the service life. Nonetheless, the unclassified document is not available for inspectors who want to develop a deterioration model and monitor damage development based on the field inspection. In order to solve this problem, the document and damage code system was proposed, as shown in Figure 7 (Shim et al., 2019). For the document identification, class 01 is bridge name ID, and class 02 comply with the inventory system. Class 03 and 04 are the type and number of documents, respectively. From document to damage identification, class 05 and 06 are added to define damage and date of inspection. In the inspection documentation, the inspector uses the naming convention to quickly identify the damages with the history that is essential requirements for the maintenance task. Subsequently, the document of archive data can be linked to the model attribute document through the proposed code system and element ID. When this data system is used for whole bridges in a country, digital twin models for bridge members to express damage history can be built and utilized for future performance prediction.
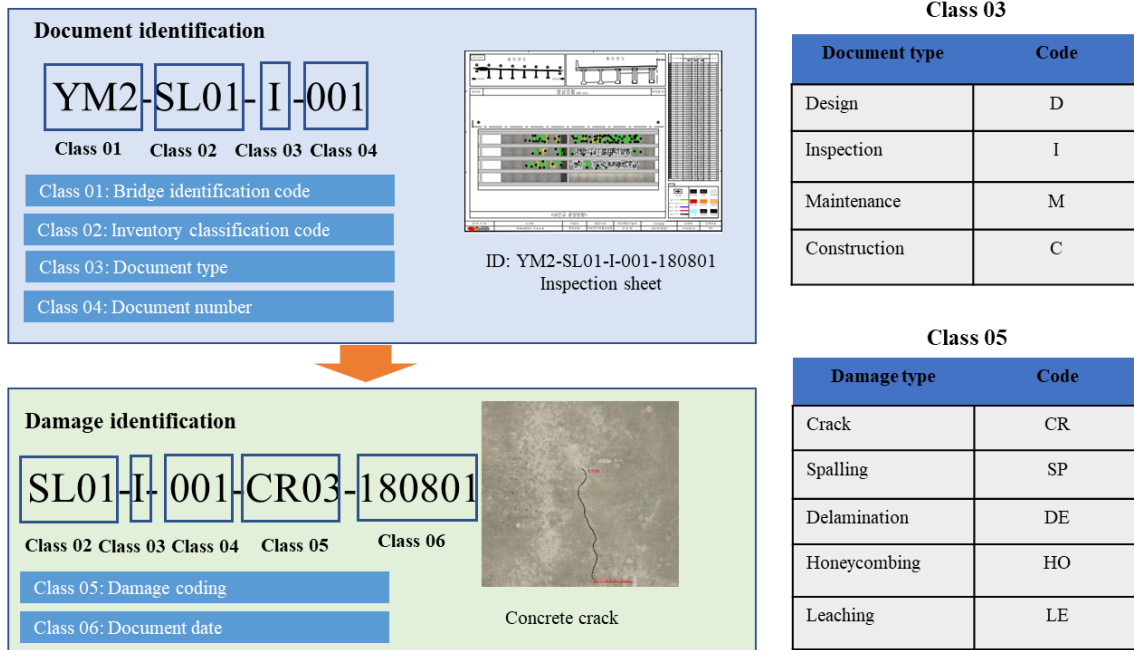
Document identification

YM2-SL01-I-001

Class 01 · Class 02 · Class 03 · Class 04

Class 01: Bridge identification code
Class 02: Inventory classification code
Class 03: Document type
Class 04: Document number

ID: YM2-SL01-I-001-180801
Inspection sheet

Class 03

Document type	Code
Design	D
Inspection	I
Maintenance	M
Construction	C

Damage identification

SL01-I-001-CR03-180801

Class 02 · Class 03 · Class 04 · Class 05 · Class 06

Class 05: Damage coding
Class 06: Document date

Concrete crack

Class 05

Damage type	Code
Crack	CR
Spalling	SP
Delamination	DE
Honeycombing	HO
Leaching	LE

Fig. 7: Document and damge coding definition

5. Development of Holobridge application

5.1 Application development workflow

Figure 8 presents the development workflow of the Holobridge application. The workflow has three primary layers: BIM modelling development, application development and application compilation. The first layer is the development process of the 3D model of the asset using Revit and Dynamo from bridge geometric information. The model was then exported to an exchangeable 3D format such as IFC, FBX. After importing the 3D bridge model and database, the second layer is the design of the user interface and the development of functional modules uses C# programming language in Unity 2019.3. It contains modules of inspection, evaluation, cloud-based document and damage mapping. Inspection modules have several useful functions to visualize the inspection report and damage location along with damage profiles. The monitoring function has an algorithm to overlap damage data in the element model over time. The cloud-based platform allows the user to access documents from cloud storage. Evaluation module emphases to highlight the rating system from the color scheme. Consequently, maintenance actions can be planned. The last layer is application complier, where the application is being deployed to Hololens by Microsoft Visual Studio.
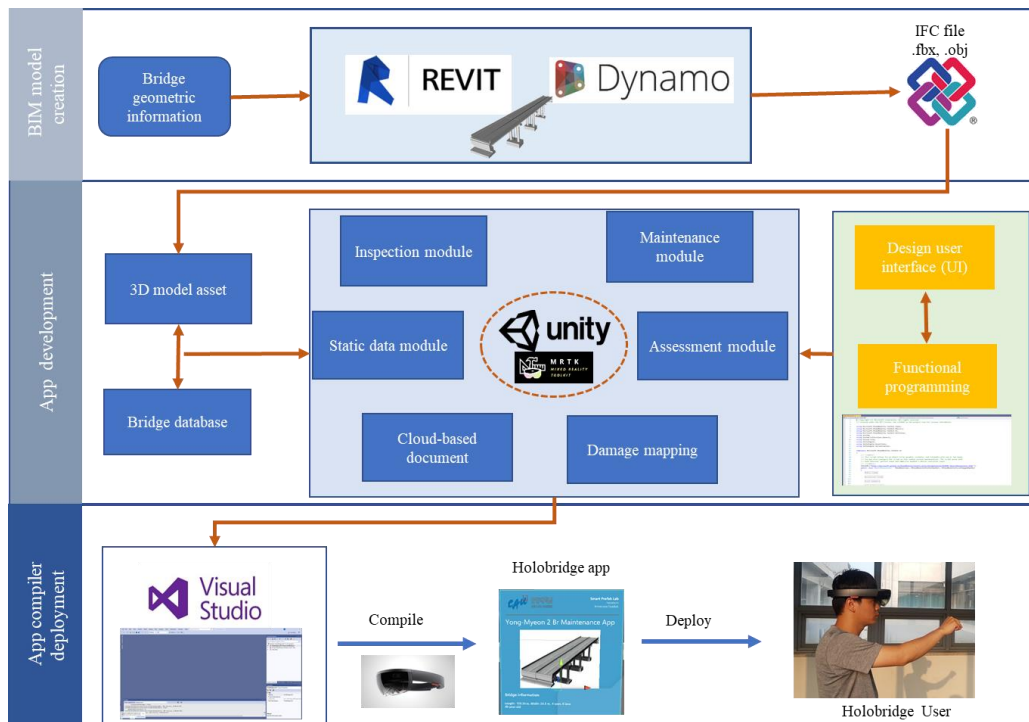
Fig. 8: The workflow of Holobridge application development

5.2 Bridge inspection module

Enhancing interpretation, analysis, evaluation and decision making are the main aims for visualizing damage records in MR space. The damage is visualized with the properties as location, dimension, history and causes. The bridge management agency categorizes the damage based on bridge structures itself, such as the damages of slab, abutment, pier and girder. The common types of bridge defects are crack, spalling, scaling, corrosion, leaching and delamination. Some defects can be detected by visual inspection (e.g. cracks, spalling, scaling), while others require an additional tool such as ground penetrating radar (GPR). The defect is extracted from the inspection report with properties and embedded into the BIM model. The federated model is a bridge inspection BIM Model with a defect database attached and located on bridge element surfaces. In the MR environment, the essential function of the Holobridge application to enhance and facilitate the bridge inspection work is the advance of the capability of integration damage data in the bridge BIM model. The application enables users to walk around the bridge and intuitively interact inspection database at defect locations.

On 3D model element surfaces, the damage can be managed by location-based algorithm. Each damage position is developed a function for observing and managing the damage propagation. The damage management process has two main steps, which are damage inspection and monitoring. Damage inspection is generally extraction of all relevant information for describing defects in terms of type, shape, dimension, and position from inspection reports. Besides, damage monitoring is the process of define condition state, cause and influence factors of damage propagation. Overall, six parameters are required for effectively managing one instance of damage: three to describe damage properties and three to assess and monitor the development of the damage. Figure 9 shows an example of crack visualization in the application.

The crack information contains ID, type, crack metric with width and length, condition state, cause, influence factors and crack history. Crack is one of the most common defects in concrete bridge structures. Crack is typically classified by cause and orientation as longitudinal, traverser crack. The crack width is categorized into hairline-minor, narrow-moderate and medium-severe, corresponding to condition state 1 to 3. During the operation phase, the factors affect crack formation and propagation caused by environmental conditions, design parameters, and maintenance works.
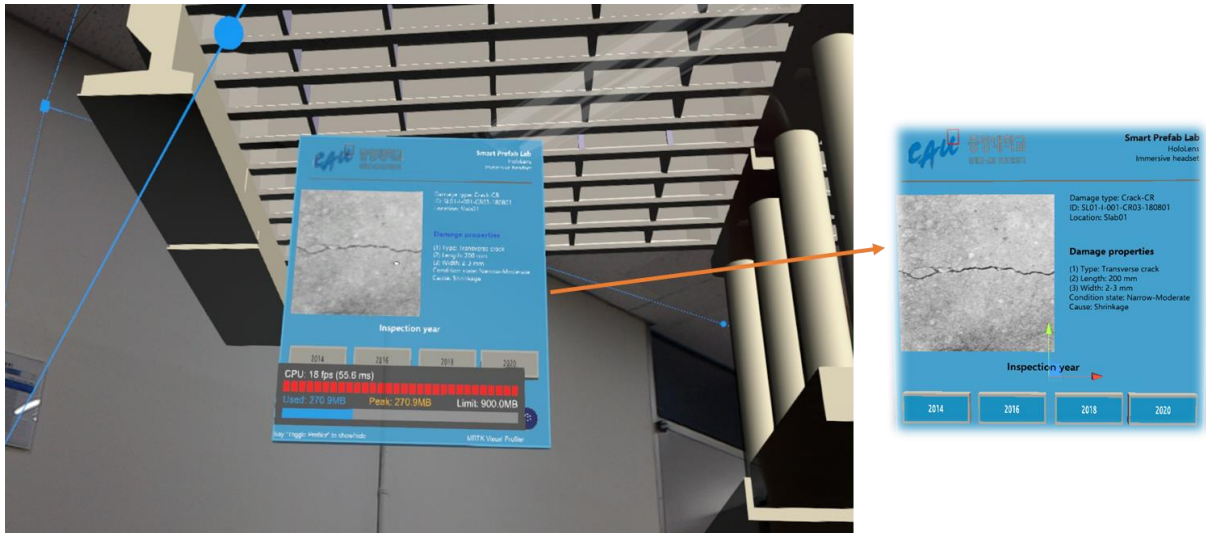
Fig. 9: Crack visualization

5.3 Damage mapping

The application develops the mapping function module for overlapping inspection photos with the 3D element model to provide the picture of an existing condition. The mapped model is a federated model to enrich information for inspection works. The element model is divided into observable surfaces, including top, lateral and bottom surface to map information. In the MR environment working, the inspector can check the damages information on the surface texture of the bridge elements model. Importantly, the inspection data can be stored in the element model during the operation phase. It is single-source information for monitoring damage development and developing a deterioration model for maintenance works. Figure 10 presents an example of mapping GPR data on the top surface of the slab to evaluate slab thickness, measurement of the thickness of the concrete cover, locating rebar. With this integration of GPR data for upper surface and damage records of the lower surface of the bridge slab, more reliable assessment can be supported.
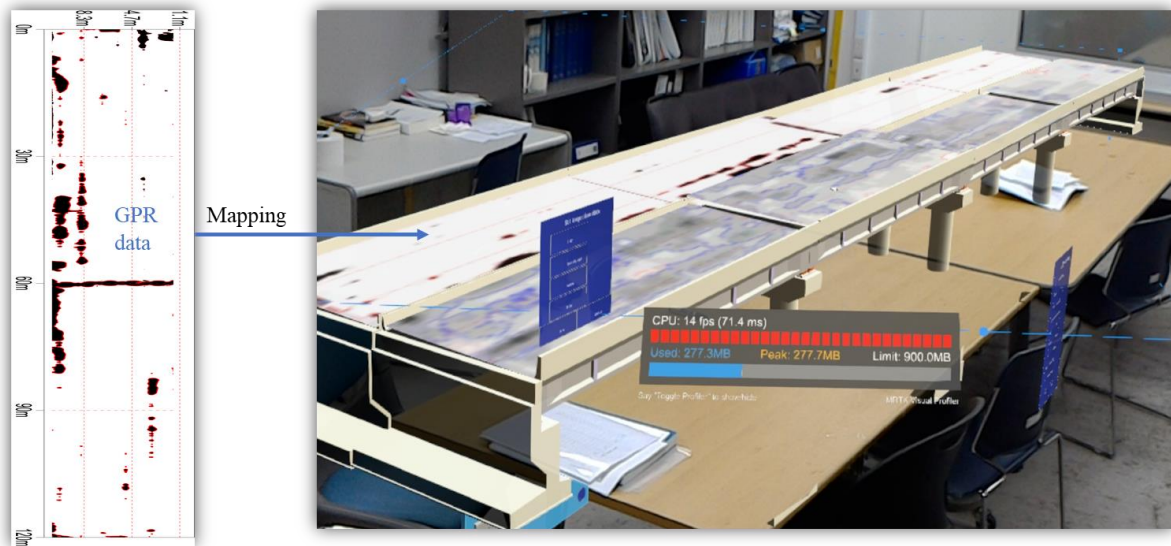

Fig. 10: GPR image mapping

Along with the BIM model and 2D-based inspection data, the 3D bridge scan model can be visualized in the application. With laser scanning and drone, the inspector can accurately and quickly capture the detailed geometric surface of bridge structures with damage information. 3D scan model is readily applicable to overlap with bridge BIM model to create a geometric digital twin model. The texture of the surface model can be used to measure the damage dimension. Figure 11 shows the result of visualizing a 3D bridge scan model in MR space. The overlapping between BIM and scan model enables the inspector to identify the defect location base on the reference BIM model.

Furthermore, the geometric digital twin model can be used for making a maintenance plan by the integration of the current condition of the 3D scan layer with the design information of the BIM model.
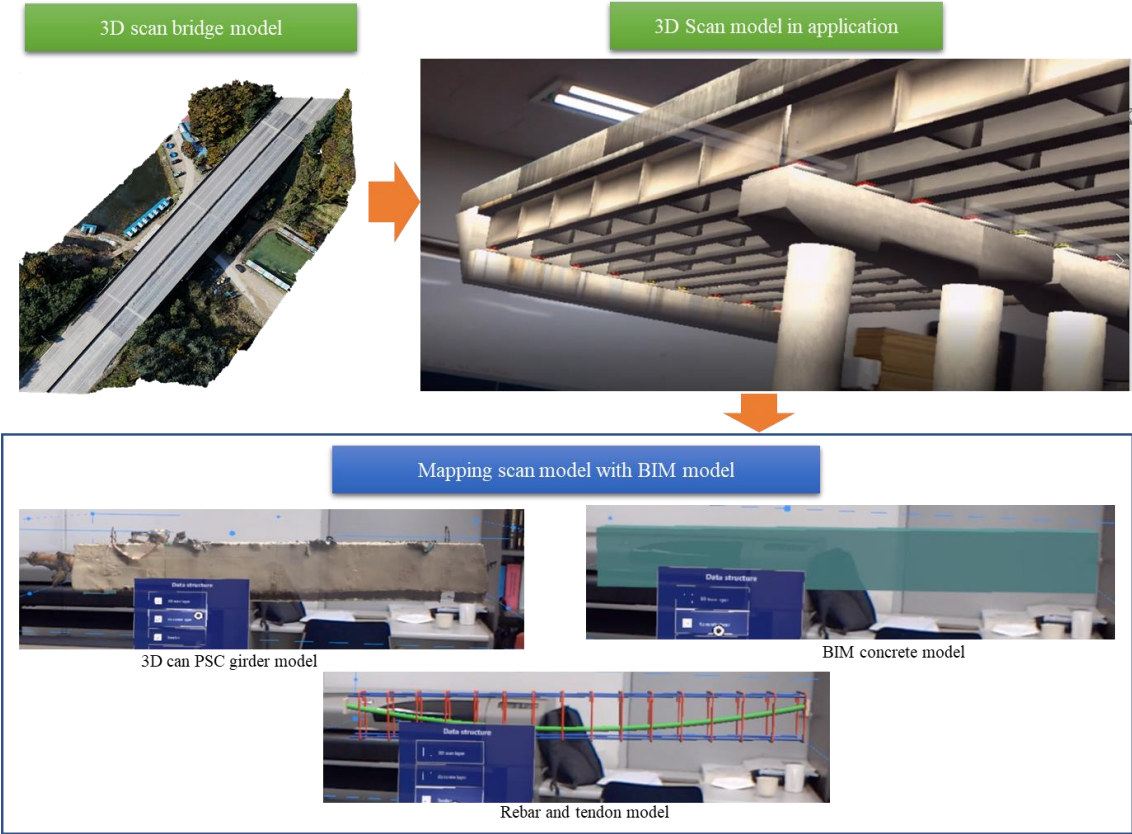

Fig. 11: Mapping scan module

5.4 Bridge evaluation and maintenance

Based on the results of the damage evaluation, bridge structures have been classified into groups of critical and non-critical. The condition rating of each element is defined by the deterioration model, including the field inspection result and the quantities analysis of damages history. The rating system has four condition states: good, fair, poor, severe, corresponding to blue, green, yellow and red color codes. In order to highlight the dangerous structures, the color condition rating module is developed. As shown in Figure 12, the bridge element model displays different colors. The pier column in yellow color shows the poor condition, and it needs to be repaired. The green structures are in good condition, and the red girder in severe condition requires to replace. As a result, the inspector can identify the structure currently in the dangerous condition to perform maintenance actions.
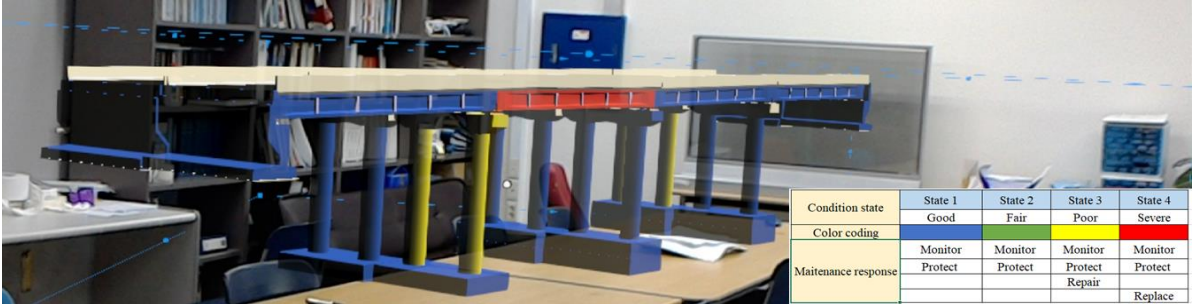

Condition state	State 1	State 2	State 3	State 4
	Good	Fair	Poor	Severe
Color coding				
Maitenance response	Monitor	Monitor	Monitor	Monitor
	Protect	Protect	Protect	Protect
			Repair	
				Replace

Fig. 12: Evaluation module

6. Conclusions

In this paper, a new approach for acquiring and compiling information on an MR-based application has been proposed. The concept of bridge inspection BIM model and geometric digital twin model is developed as the

theory-based for application development. The development process has two main parts: creating the database and programming of the functional module. The application database has three essential components: a well-organized foundation BIM model, inspection and maintenance information and data integration architecture. The functional module contains inspection, evaluation and damage mapping module. The conclusions from the pilot implementation are the following:

1. The inspection database can be systematically managed by using the 3D BIM model with attached data, and the proposed code system enables to monitor damage development and create a deterioration model efficiently.

2. In the MR space, the application improves information communication, visualization and collaboration in inspection and maintenance work because the data is more intuitively interactive in real-time simulation.

3. The inspection and maintenance tasks were significantly enhanced and facilitated by using a federated information model wherein the damage is mapped with a 3D foundation model during the whole life cycle of a bridge.

In future work, the research will be extended to develop a module for automatic damage detection, measurement and tracking. Through the system, digital twin models for bridge members can be developed.

7. Acknowledgments

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