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Digital Twin Visualization System for Urban Bridge Maintenance

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Abstract. Addressing fragmented information and delayed defect warnings in traditional urban bridge maintenance, this paper formulates a web-based digital twin visualization system. The proposed architecture incorporates lightweighting, semantic mapping, and dynamic early warning as its core innovations. Firstly, geometric redundancy removal and mesh simplification techniques enable lightweight web rendering of Building Information Modelling (BIM) models. Secondly, a semantic mapping mechanism based on universally unique identifiers (UUIDs) establishes spatio-temporal links between Internet of Things (IoT) monitoring data and 3D virtual components. Finally, the system executes a data-driven early warning algorithm based on safety margins, adhering to international bridge assessment standards such as Eurocode 3. Validation using the Lanzhou Zhongshan Bridge verifies a model compression ratio exceeding 97%, with initial web load times reduced to under 4 seconds. The system maintains a stable rendering frame rate above 45 frames per second (FPS) during navigation and controls warning response times within 500 milliseconds. This research significantly lowers hardware deployment thresholds, yielding an efficient, low-cost decision-support tool for transitioning urban bridges from reactive repair to proactive predictive maintenance.

Keywords: Digital twin, Bridge maintenance, Lightweight model, Semantic mapping, Dynamic early warning.

1. Introduction

Bridge is a kind of important hub in the urban transportation network, its operation safety concerns social-economic stability and safety of people's lives and properties. With extended service life of urban bridge, they will face some problems like material aging, structural fatigue, environmental corrosion. Therefore, it is very practical to do a good job with the maintenance of bridges.

Traditionally, bridge maintenance is done through manual periodic inspection and two dimensional drawings which are on paper. And it has some obvious shortcomings. 2D drawings cannot easily give people a clear picture of how stress works for complicated bridges that exist in 3D. More over its manual inspection time is too much and cant be updated on time. Therefore, managers will inevitably be compelled to do remedial work after the fact once problems arise, and this goes against preventative maintenance [1].

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Digital twin technology is progressing rapidly, which gives some brand new technical ways out of these troubles. Furthermore, Tao points out that if precise replicas of all real-world objects in the surrounding environment are constructed and linked to information collected by IoT monitoring devices, digital twins could establish a highly accurate one-to-one mapping relationship between the two [2]: This paper aims to develop a user-friendly digital twin visualisation system and provide a lightweight version of it, thereby reducing the information fragmentation and alert latency issues mentioned in current maintenance strategies. The study looks into how to get past the problem of smooth 3D model loading for web platforms, and makes out a way to connect different types of watching information with virtual parts. And ultimately it would be a nice intuitive decision making model for day to day management of urban bridges.

2. Review of related research

In recent years, it is becoming more and more common to combine BIM with Geographic Information Systems (GIS) and the IoT in order to create a sort of digital twin management of infrastructure. Gao's group also worked to make such a bridge digital twin framework using GIS plus BIM which results that, it will increase how much visual and macro level of geographical data can be utilized on actual bridge during time, as well as for maintenance [3]. At the same time, according to Structural Health Monitoring (SHM) recently reviewed by Sun et al [4]., they also think it is changing how to traditionally monitor the civil structure; by making them more integrated and connected with a larger amount of points.

However, existing bridge visualization system still have some difficulties to be used in reality. The vast majority are still just at the level of model display and data popping up. According to Mousavi et.al, the direction of present work done about digital twin framework for bridge management is going to be irreversible from early passive 3D model show to actively intelligent analyze and make decision [5].

Additionally it can be stated that according to Van Dinter et al., the utilization of Digital Twin technology with algorithms for predictive maintenance is becoming a main bottleneck for Operations & Maintenance [6]. The authors of this paper state that there are mainly three shortcoming existing systems have. Firstly, big BIM model is very heavy for hardware to calculate and prevent people from using the Internet; Secondly, the serious situation exists between physical sensor time-series data and 3D spatial component. It is difficult to integrate them in real time. Thirdly, the use of data is still low. No one does a thorough risk evaluation by combining mechanical laws and relevant regulations. Through solving these troubles, the current article will distinguish it from other works that talked about systems. Unlike those displays which relies upon desktop software. This will be something with its own architecture, algorithms and all can connect via web without needing the desktop itself. Light weight but data connected. It then reduces the hardware barrier. And it will have a method for using it as dynamic early warning based on safety margin and that is good news to smarter bridge.

3. Design and implementation of a digital twin system for urban bridge maintenance

And on the basis of B/S structure, a kind of a sort of Digital Twin Visualization System is proposed in order to overcome operations difficulty and hardware dependency. To realize this major element of the present system, one needs three aspects.

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3.1. Construction of a web-oriented lightweight twin model

The operation basis of a digital twin system is that it must be a very accurate 3D model. But it is also not possible to import the raw BIM models with all the detailed constructions front-end render. According to Gao et al. [3] , transforming the model like IFC, and then converting it to the glTF format and integrating this into a web engine will be able to realize effective lightweight rendering of bridge models. So this process has employed strict geometric optimization methods when doing the modeling.

First remove the geometric redundancy. For the minor metal components like internal reinforcing bar and secondary connecting bolts which have negligible effect on the whole situation, it could be just removed those by hand. It kept just the main load-bearing parts like the major beams and piers. The second change is to simplify the mesh topology of the remaining surface elements, greatly reduced the number of polygons. Lastly it was exported in the glTF format which is made solely for transferring on the web. And this workflow can compress the files without losing the accuracy on spatial topological relationships between the bridges so it will make sure the web rendering is smooth.

3.2. Multi-source data fusion and unique identifier mapping

For the sake of digital twins, physical entities should be linked to their virtual models. In order to solve the problem that it is difficult for the low-cost IoT sensor data and the 3D digital twin model of railway or urban bridge to be matched accurately, a specific mapping method is proposed according to the special ID [7].

In terms of the model processing part, a completely unique identification code is gave out for each key thing left after that. At the same time. a Mapping Table is created in the back end's Database so that each Physical Sensors' device number can correspond to its own Model Component ID. The system is being executed and the front end program parses the model components' id and then gets the corresponding real time sensor data stream sent from back end. And by using such an index it displays the physical bridge's status info on their right spot in the virtual 3D space.

3.3. Data-driven dynamic early warning based on safety margin

System contains the values on which decision was made and these have some value of data analysis and safety margin assessment logic so that they can get more from this element. Convert the hidden behind the scenes information into visible signs saying whether something is safe, not just numbers. Back-end system: Load bearing limits have been set in advance for different important parts. These Safety Margin Thresholds are strictly in line with the British Code for Assessing Road Bridges and Structures (DMRB-CS 454) [8] as well as the European Code for the design of steel structures: Eurocode 3:EN-1993-2) [9]: Just like on the stress limits and ultimate limit state(U LS)evaluations on the steel trusses' component values which are calibrated from structural safety evaluations stated in Reference Codes.

After getting the most recent monitored information, it would compute the percentage that represents the present amount concerning the code limitation boundary. The front-end visualization engine causes it to have dynamic colors render according to this percentage. When the value is lower than 50% the component is green meaning that it is OK. Between 50%-80% it is yellow which means it is a warning. When it goes over 80% the part gets shown up as red, giving off a big

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warning. And then there would be this constantly, kind of a worldwide safety evaluation system, dealing with what is often a big problem about people only getting old machines fixed really slowly.

4. Case study application and analysis

To verify the feasibility of the above system design in actual complex structures, this study selected the Zhongshan Bridge in Lanzhou City, Gansu Province as a case study for theoretical simulation and application testing. The Zhongshan Bridge was built in 1909 and spans the Yellow River. It is a typical old steel truss bridge. Its complex steel structure network poses significant challenges to daily inspections.

4.1. Quantitative comparison before and after model optimization

Before applying lightweighting techniques, the original BIM model file for the Zhongshan Bridge was approximately 500 MB in size. Directly import it to the browser and this will cause the browser to lag heavily and crash. The following geometric redundancies have been removed, after glTF conversion as mentioned in this paper, the model size was around 15MB which is more than 97% compressed. In a normal office network environment, the system's first-page load time increased from over 30 seconds to under 4 seconds. During 3D scene panoramic navigation, the rendering frame rate remained stable between 45 and 60 FPS, completely resolving the system's stuttering bottleneck.

4.2. Validation of core functional scenarios

The next part is going to talk about 2 main function scenarios for the lightweight model. The first one is about the spatial archiving retrieval and intuitive browsing. When admin clicks on some virtual entity like south pier inside here, 3d interactive environment then it should be the usage of ID indexing. It will also show the historical settlement records, anti-corrosion coating information for this spot on the side bar automatically. It can break data silos, enhance the speed of spatial information search, this scene proves it.

The second scenario is about Structural Defect Visual Localization. After injected some abnormal data, which signified that the stress on the lower chord in the main span was more than limits and simulated its injection into model, then the Safety Margin algorithm calculated very quickly that it has exceeded by 85%. The warning's response time was no longer than half a second. The virtual scenario, at that same place on the steel trusses it went from gray to red and there was an alert box that appeared. The verification result is that it can help employees find out what parts of the complex steel structure may have safety hazards very fast and accurately.

4.3. Analysis of potential engineering obstacles in actual deployment

Though good enough at theoretical simulation, there will probably be some hurdles to jump over when put into practical use inside actual bridges. As for first one, unstable 4G / 5G signal under extreme weather or in remote places might break the sending process of IoT monitor information flow, this would make warning's timeliness be affected. Secondly, long-term environmental erosion may distort sensor readings, triggering false alarms due to time drift and physical failures in hardware sensors. To address these potential engineering obstacles, future implementations must integrate an edge computing caching mechanism at the data access layer. This should be combined

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with sensor self-calibration and multi-channel data cross-validation algorithms to further improve the system's robustness.

5. Discussion and future prospects

Now it mainly adopts the way of passive early warning with fixed threshold for the use of data. In order to improve not only the system's academic level but also its engineering practical value, it is necessary to integrate digital twin visualization framework and artificial intelligence technology deeply in the future [5]. To be specific, there will be more work on these 3 core things.

5.1. Anticipating the remaining service life of bridges

Bridge component's material aging and fatigue damage is a kind of long time and nonlinear process. In the future this system back ends will most likely use deep learning algorithms like Long Short-Term Memory (LSTM) networks that are really good with time series data. So that the algorithms can constantly learn from all kinds of past observations, it becomes possible for this kind of digital twins to make predictions. It will show not just the present condition, but it will also give dynamic prediction on how much time is left for important parts. Integrate the life decay curve and economic evaluation model, it will automatically present when is the best time for the next maintenance and present to manager. This predictive method is going to totally change how to do the current cycle maintenance, which can be either too much or too little [6].

5.2. Precise spatial localization of predicted failures

The traditional discrete sensor monitoring is hard to tell ahead of time which part will break down. In the future Graph Neural Networks (GNNs) will be introduced, to do condition assessment of bridges topological structure [10]. Because the three dimensional structures of bridges have the node connectivity characteristics of graphs, GNN algorithms can analyze how stress anomaly would spread around from a certain point. Therefore, in the Digital twin model, it would be able to forecast the particular 3D location on where most of the failures are going to happen. To highlight the place first of all on a web interface so that there would be no exact spatial locations to danger.

5.3. Post-disaster mapping of surface defects using UAV vision

Digital twins can also utilize external visual technologies in addition to built-in sensors. Drawing on the graphics-based digital twin framework proposed by Wang et al. [11] , future systems could introduce Unmanned Aerial Vehicles (UAVs) equipped with high-definition cameras for automated inspections. After identifying cracks on the concrete surface using Convolutional Neural Networks (CNNs), the system can apply coordinate transformation algorithms to precisely project the defects from the two-dimensional images onto the surface of the three-dimensional digital twin model. This extension applies to routine defect marking and holds significant potential for rapid damage assessment following extreme disasters.

6. Conclusion

To tackle the problems with getting delayed info and not very clear visual stuff from traditional urban bridge maintenance, this paper made and put together a lighter kind of internet-based digital twin visualization thingy. It's about the 3 main conclusion.

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The first step was to solve the problem of lightweight rendering of 3D models on the web. The repetitive geometries and simplification of the mesh topology have been done prior to this therefore the Initial BIM model is only 97% more than volume That would get rid of any regular browser playing with a messy bridge model, no new hardware.

Secondly, the right matches are made between all types of monitoring info sources & virtual parts. An association method based on the global unique id has been developed using a semantic association; the databases under the hood and the front end visualization engine get along well. And can do the current location and casting of the changing sensor information into the relevant sections of this virtual world.

Third, this paper has realized the implementation of data driven dynamic early warning systems according to the international regulations. The system will do more than just giving out ordinary date chart presentation, it uses algorithmic evaluation models according to the load bearing percents in both British and European standard. With color gradation and pop up windows showing how much room is left on each bridge component, it's easy to see which part isn't safe anymore, so it can fix problems really quickly.

To sum up, the lightweight visualization system put forward by this article will play an important role in improving the level of information technology in bridges. It can give useful technical help to promote the digital change and intelligent prediction maintenance of urban transport infrastructure.

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