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16. Abstract This project explores the design and implementation of digital twin models for the continuous monitoring and performance prediction of precast concrete (PC) bridges. Leveraging NVIDIA Omniverse, a cutting-edge 3D modeling platform, the research establishes a streamlined methodology for rapidly prototyping digital twin models using engineering drawings, inspection data, and real-world bridge configurations. The study includes case studies of two bridges in Illinois, showcasing the digital twin's ability to integrate bridge metadata, environmental and condition monitoring data, and inspection imagery into a cohesive digital representation. Additionally, the project extends the digital twin application to precast concrete beam testing, incorporating finite element analysis and crack segmentation into the simulation for enhanced structural assessment and visualization.		
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Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Design and Implementation of Digital Twin Models for Continuous Monitoring and Performance Prediction of Precast Concrete Bridges
UI-23-RP-03

FINAL REPORT

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Executive Summary

This project explores the design and implementation of digital twin models for the continuous monitoring and performance prediction of precast concrete (PC) bridges. Leveraging NVIDIA Omniverse, a cutting-edge 3D modeling platform, the research establishes a streamlined methodology for rapidly prototyping digital twin models using engineering drawings, inspection data, and real-world bridge configurations. The study includes case studies of two bridges in Illinois, showcasing the digital twin's ability to integrate bridge metadata, environmental and condition monitoring data, and inspection imagery into a cohesive digital representation. Additionally, the project extends the digital twin application to precast concrete beam testing, incorporating finite element analysis and crack segmentation into the simulation for enhanced structural assessment and visualization.

Table of Contents

TRANS-IPIC Final Report

Research Plan - Statement of Problem

This research project aimed to design and validate a digital twin model of a precast concrete bridge structure, subsequently integrating this model with sensor data derived from a real-world bridge. This integration was envisioned to serve as the foundation for driving the simulation and analysis of the bridge model. The digital twin model was to be constructed utilizing NVIDIA Omniverse, an innovative platform that facilitates the creation of collaborative and immersive 3D objects, equipped with real-time simulation capabilities.

Research Plan - Summary of Project Activities (Tasks)

Task 1: Digital Model Development: We explore how to use technical drawings and the design and inspection data that may exist for the bridge itself or the precast parts used in its construction in order to rapidly implement a digital twin model. The outcome of this task is a methodology for rapidly prototyping a 3D model of a PC bridge based on the above-mentioned sources of initial information.

Task 2: Digital Model Implementation: We study how NVIDIA Omniverse platform for digital twins operates and how to build new models within the platform's capabilities, including linking it with external data sources. The outcome of this task is a PC bridge twin model implemented in NVIDIA Omniverse environment.

Task 3: Bridge Simulation using Real-Time Data: Our goal is to enable ingesting real-time data from a specific PC bridge to be incorporated with the digital twin model as well as any readily available environmental data, such as weather, traffic, any imagery. Such data will be used to model the bridge performance and predict its response to different usage conditions. The outcome of this task will be a data-driven digital twin model of a PC bridge updated each time new data about the bridge is available.

Research Plan - Outcomes

Initial exploration

Since PC bridges are constructed from precast concrete blocks, we investigated how to build a digital library of such precast concrete blocks using engineering drawings such as shown in Figure 1, and the ridge beams that were evaluated for stress in the lab, Figure 2. Specifically, we built models of an 838mm x 914mm PPC deck girder and a precast bridge in Blender before exporting to NVIDIA Omniverse. The exact dimensions of the models were extracted from the plans given in ISO drawing format. These basic components of bridges can be assembled either manually or programmatically in the Omniverse to build the model of the bridge, as shown in Figure 3.

Furthermore, versions of the beams with cracks built into the 3D model were also made to test how effective the cracks would translate to Omniverse. Lastly, the components of the beams were exported separately to multiple USD files along with the fully assembled beams. These components comprised of physical sections of the beam such as end and middle spans, as well as abstract components such as voids within the beam which made 3D models to better represent them in NVIDIA Omniverse.

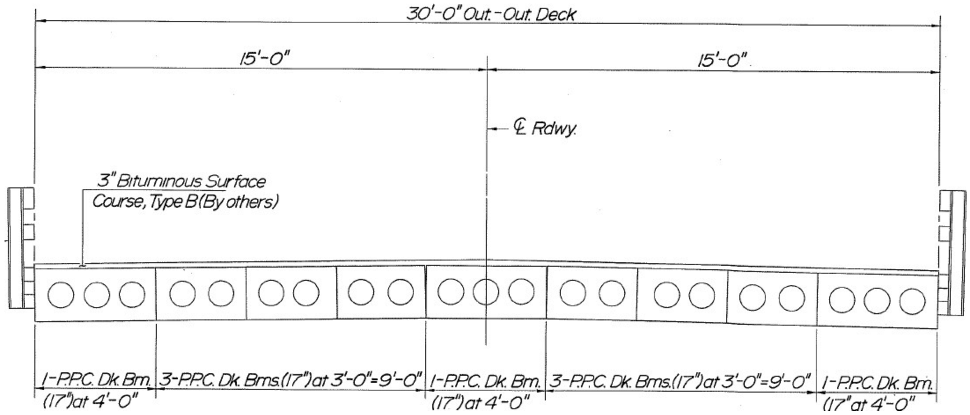

Figure 1. Cross-section of a multi-box girder bridge.

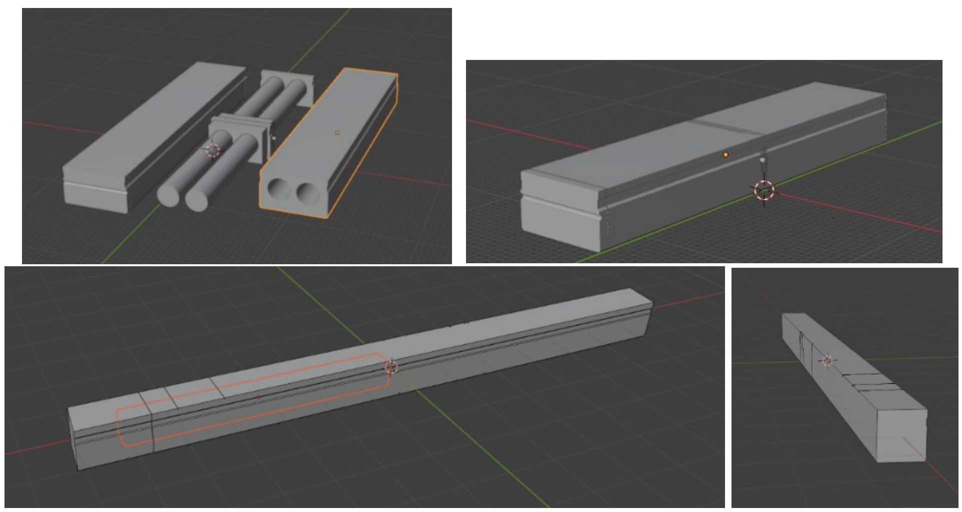

Figure 2. Precast parts.

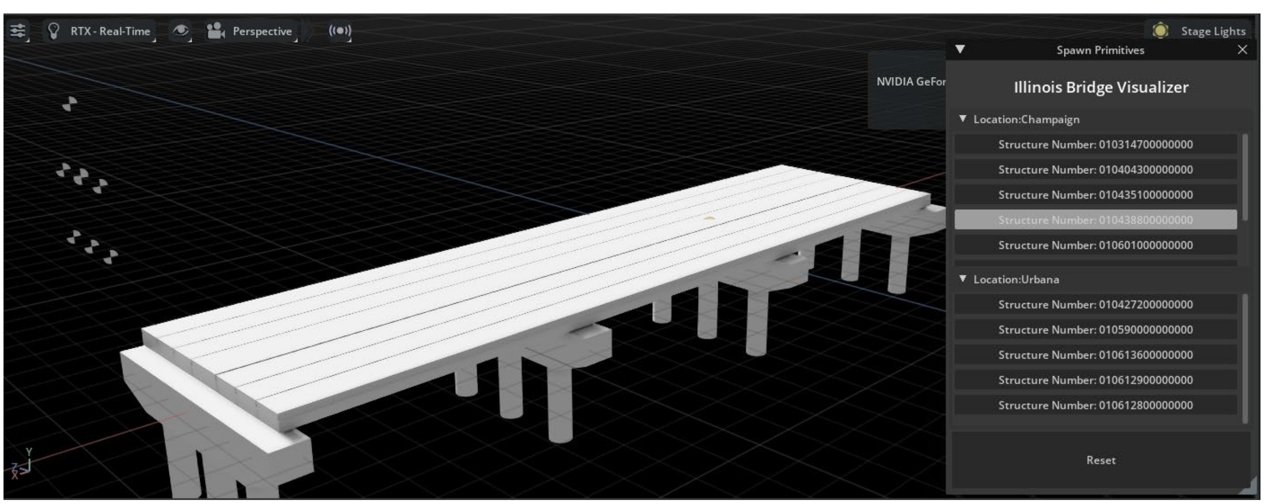

Figure 3. Precast parts assembled into a bridge structure.

A multi-box girder bridge (alt. PPC deck girder bridge) from Jersey County, IL was chosen as the first example to explore the capabilities and ease of implementation in the NVIDIA Omniverse Platform. The bridge cross-section contained six 17x33 and three 17x48 PPC deck girder beams to form a 30’ roadway. Figure 4 shows a snapshot of the two-span bridge model in the Omniverse platform with added texture and pother environmental elements.

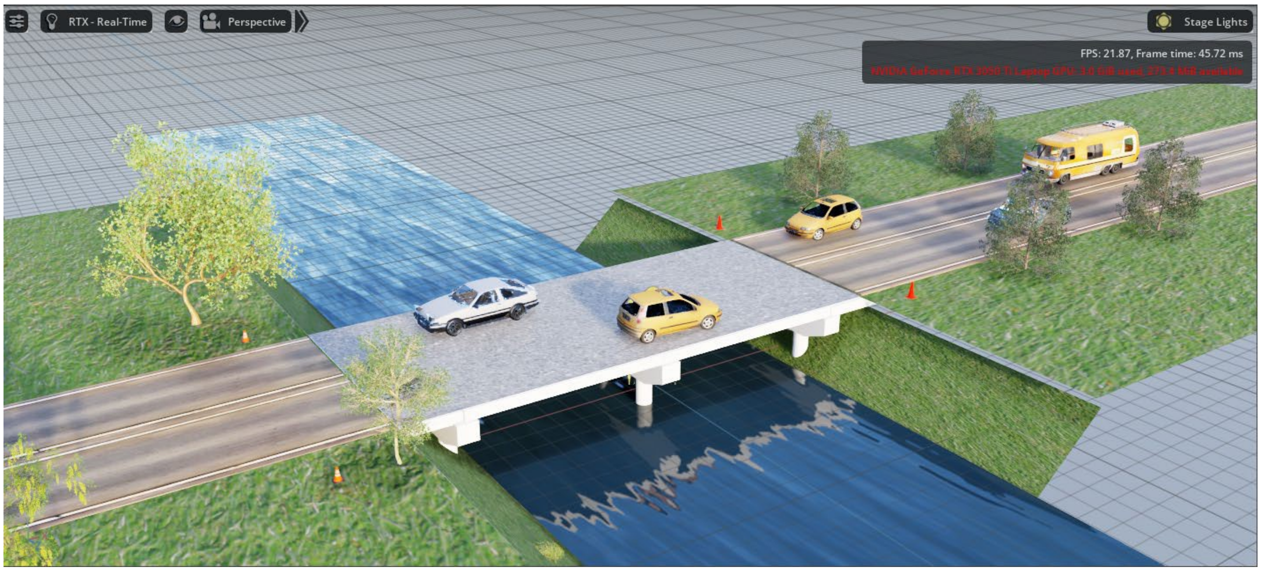

Figure 4. Two-span bridge model in the Omniverse platform.

We also experimented with the physics extensions available on the Omniverse platform to conduct simulations of beams subjected to loads. This functionality enables us to visually represent the process of cracking and eventual failure under external pressures. This simulation is executed by incorporating fracture material data, wherein we define the breaking point. Force is applied to the beam at the initiation of the simulation within the Omniverse environment. A screenshot of this simulation is shown in Figure 5.

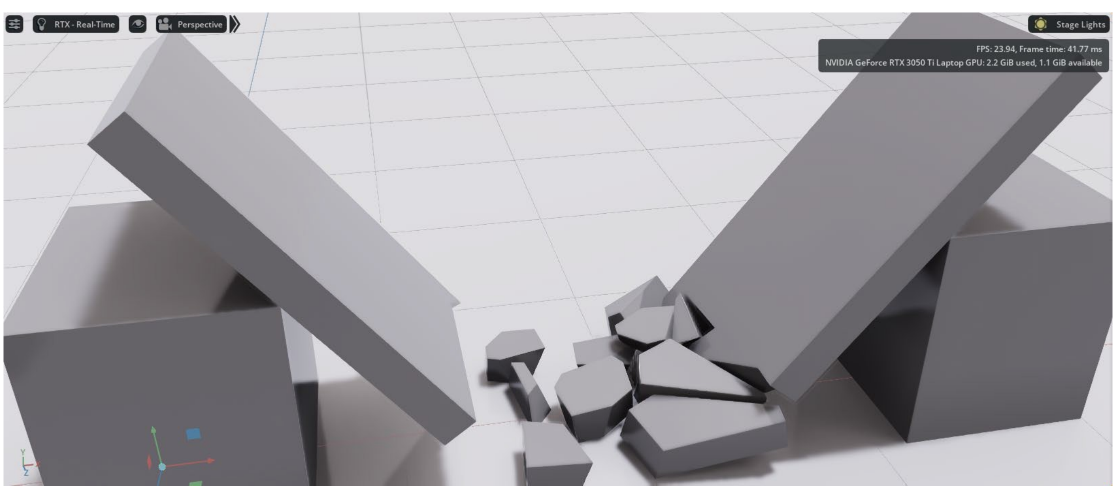

Figure 5. Applying physics extensions in Omniverse.

Digital Twin System Architecture

The 3D geometry of all bridge components, including various beams, columns, and supports, was modeled in Revit. These fundamental elements were created based on bridge sketches and insights gained from multiple on-site inspections. Once completed, these components are assembled within the NVIDIA Omniverse Platform.

The Omniverse Platform offers the capability to develop customized extensions that enhance specific digital twin functionalities. We have developed several extensions to integrate external databases and link inspection data seamlessly. Our Digital Twin system architecture based on Omniverse is illustrated in Figure 6.

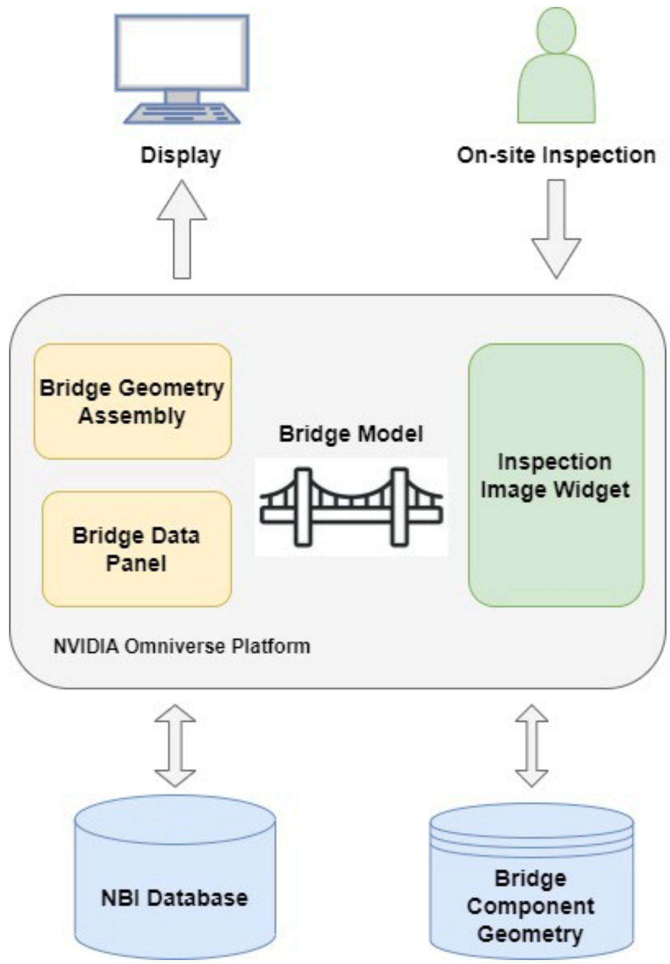

Figure 6. System Architecture for Digital Twin Bridge Model

The bridge data originates from the National Bridge Inventory database, which provides comprehensive information about bridges across the United States, including metadata, annual condition reports, and environmental data. Additionally, we created a simple mobile app that allows engineers to capture inspection images and connect them directly to our digital twin model in the Omniverse.

The Bridge Assembly extension enables detailed configuration of bridges by assembling their geometries directly within the Omniverse environment.

The Bridge Data Panel extension facilitates the visual representation of bridges in the Omniverse, integrating real-world data. This extension allows users to display detailed specifications and monitor condition changes for the selected bridge, providing engineers with an opportunity to review critical information in real-time.

The Inspection Image Widget is linked to specific bridge components, which are visually highlighted within the Omniverse. This widget connects to the inspection image database, enabling engineers to perform on-site inspections and automatically update images in the digital twin model in real-time. We also support the feature that when users click on the button on the widget, the camera flies to the viewpoint from which the current selected image was taken.

The general workflow of the digital system is illustrated in Figure 7. Users begin by selecting a bridge to view within the Omniverse, which is linked to a unique bridge key. Based on this key, the system generates the corresponding geometry and retrieves relevant data, displaying it in both the Omniverse viewport and the bridge data panel. Once the bridge is visualized in the Omniverse, users can highlight specific components with inspection data for further review. If a component lacks inspection data, the widget will automatically be hidden. Additionally, a dedicated button allows users to adjust the viewport camera to focus on the corresponding inspection view.

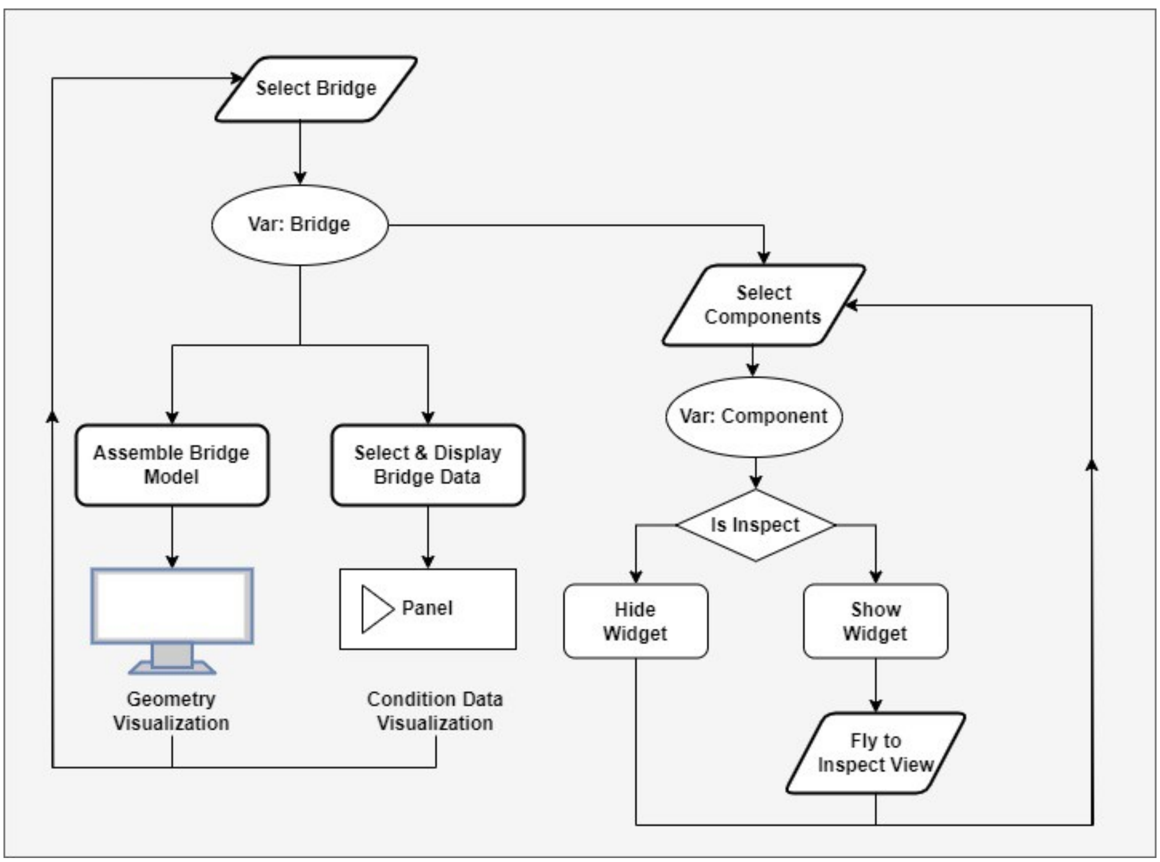

Figure 7. System workflow

Final Results

After learning how to develop models in Omniverse and about various tool capabilities, our main focus shifted to the integration of the research and development results from each task and a demonstration of the developed methodology and tools for a rapid prototyping of digital twin models. Specifically, we have developed two new virtual bridge models in Omniverse, situated near Champaign-Urbana. These bridges have clearly defined configurations, allowing for parameter inference from the National Bridge Inventory database. One bridge spans a creek at 2259 S Staley Rd, Champaign (Figure 7), while the other crosses I-74 highway at 879 N Cottonwood Rd, Urbana (Figure 8). We conducted site visits and visual inspections of these bridges and utilized the configuration data from the National Bridge Inventory to inform their implementation in Omniverse.

Street view Side view

Figure 7. Bridge at 2259 S Staley Rd, Champaign

Figure 8. Bridge at 879 N Cottonwood Rd, Urbana

The screenshots below demonstrate the Omniverse implementation of these two bridges. We create models for the beams, supports, and columns using the main span structure and building materials, then extract detailed geometry from inspection images and Google Map street view. These elements are eventually integrated into the Omniverse Platform.

Figure 9. Omniverse model of the 2259 S Staley Rd, Champaign bridge.

Figure 10. Omniverse model of the 879 N Cottonwood Rd, Urbana bridge.

We also connected the Omniverse model with the data available for the implemented bridge models. The connectors and plugins that were previously developed to ingest data from external sources into an Omniverse model link the two virtual bridges to these external data sources. One such data source is the images obtained from bridge inspections. Figure 11 is an example of an Omniverse extension that allows users to display images by clicking on the specific part of the bridge for which an image is available. An additional feature was developed to exhibit the historical numerical data associated with that bridge. This information is sourced from the NBI database, encompassing metadata of the bridge, historical condition records, and traffic data. A screenshot illustrating this functionality is provided in Figure 12 and Figure 13. In addition, we also support the feature that the camera of Omniverse can go to the similar viewpoint as the selected inspection image, an example is shown as Figure 14.

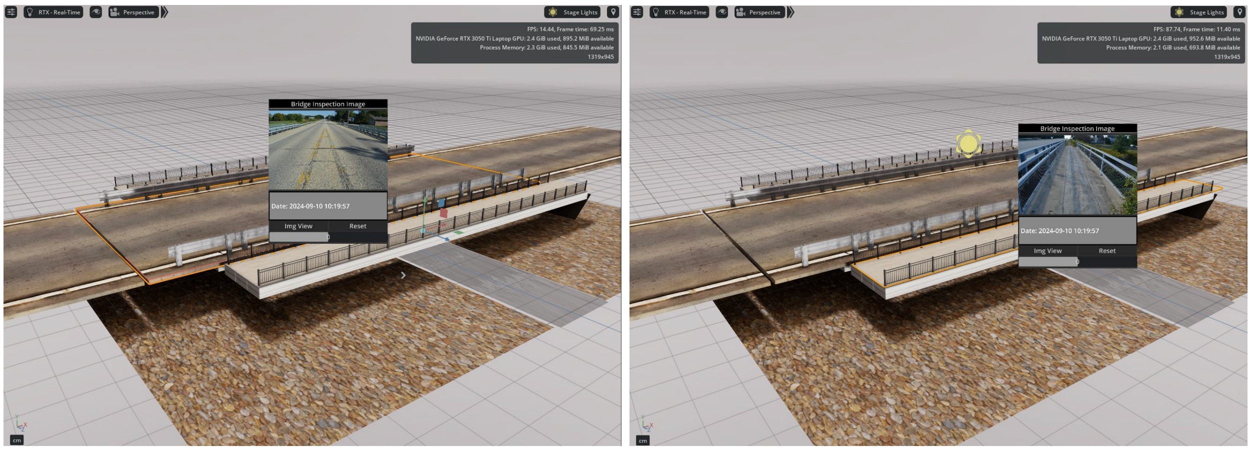

Figure 11. Inspection images can be shown in Omniverse.

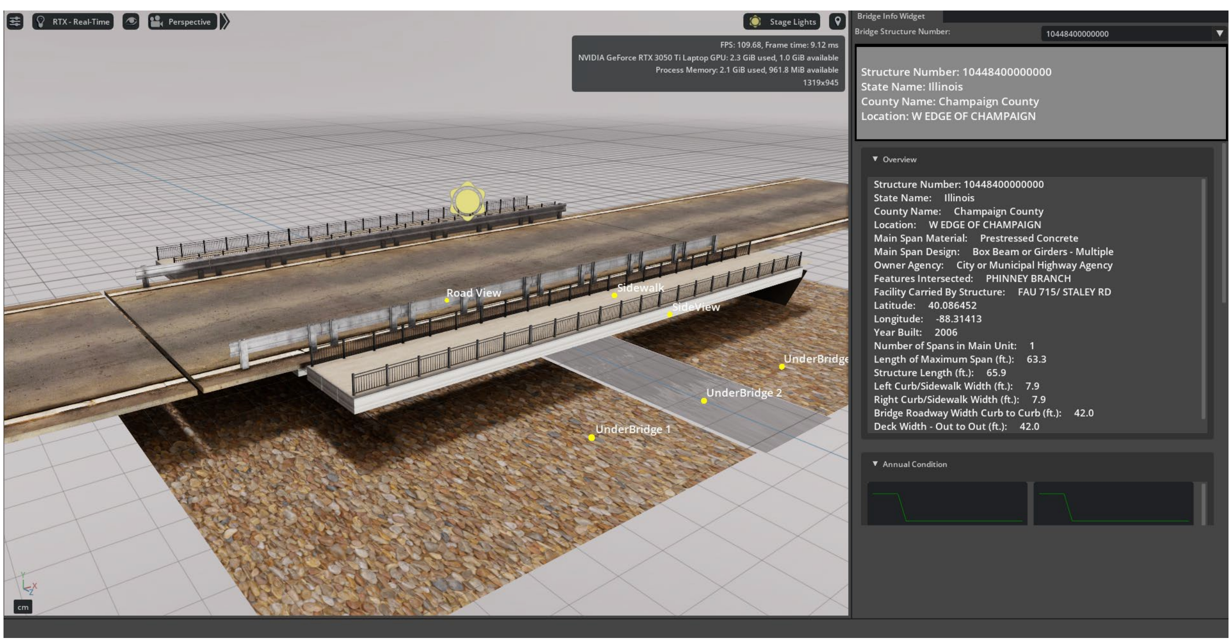

Figure 12. Bridge metadata directly queried from the NBI database.

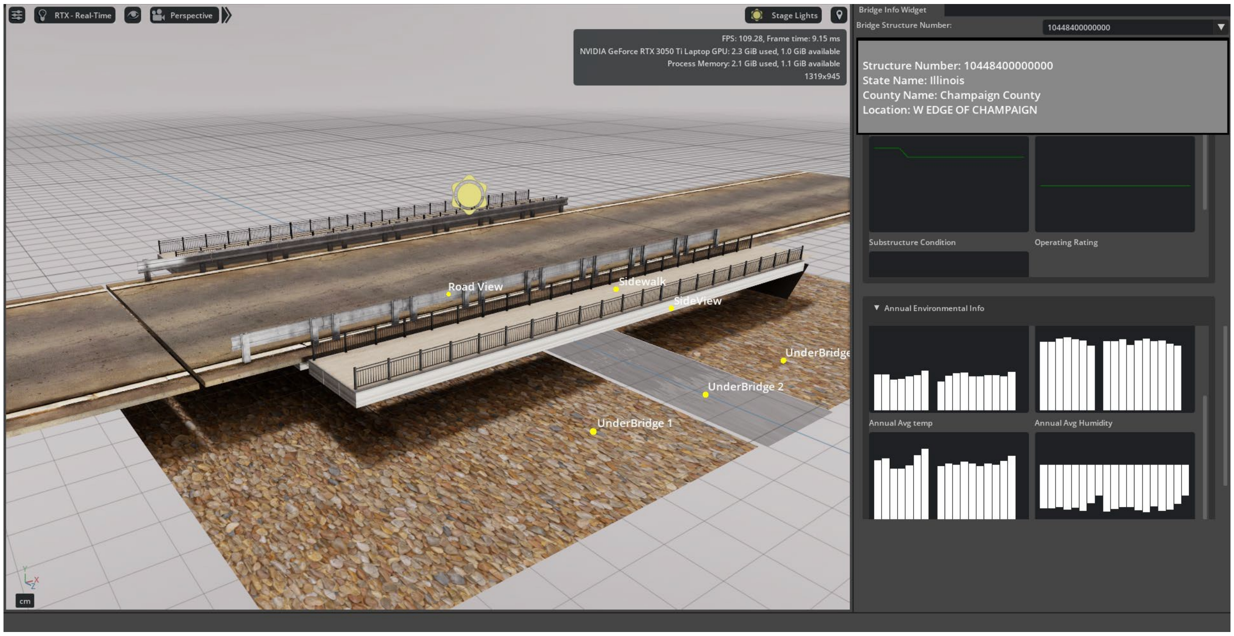

Figure 13. Bridge annual condition and environment information from the NBI database

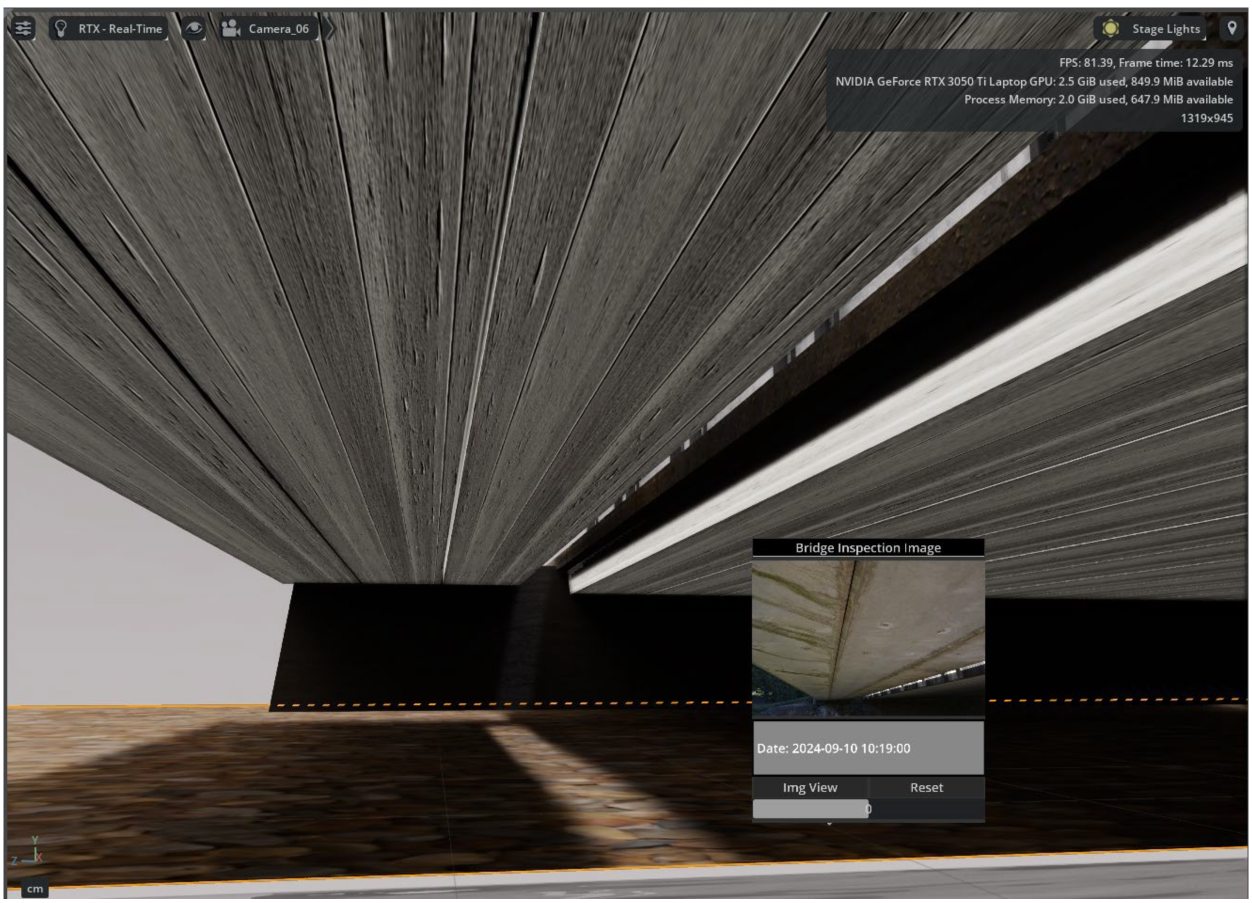

Figure 14. Inspection view corresponding to the image

Additional Investigations

One of the goals of our work was to enable ingesting real-time data from a specific PC bridge to be incorporated with the digital twin model in addition to any readily available environmental data. Such data would be used to model the bridge performance and predict its response to different usage conditions. Since access to any real-time data was not readily available, we used lab environment to simulate the availability of such data using an on-going experiment on a new test beam and develop and demonstrate the Omniverse tools and technologies needed to ingest and visualize such data in real-time.

We implemented a virtual laboratory environment in Omniverse that resembles the actual physical settings at the Newmark Structural Engineering Laboratory, Figure 15. We use this virtual laboratory Omniverse environment to reproduce the experiment on a new test beam (a 533mm x914 mm IDOT PPC deck girder beam with a span of 15.24m span length) under four-point bending test carried out by Prof. Andrawes' team. Our developed extension facilitates the visualization of the beam under test and displays the strain and crack data during the experiment.

Figure 15. Virtual laboratory and playback of the experiment.

We implemented an Omniverse extension to replay the experiment in the Omniverse Platform. This extension includes a slider that represents the experiment's timeline. Users can interact with this slider, moving it left or right, to retrospectively examine the experiment data, images, and bending of the beam within Omniverse. This feature provides engineers with a convenient method to conduct a post-analysis of the entire beam testing process.

We have developed an extension in Omniverse that shows bridge cracks in detail, see Figure 16. Users can select a specific crack of interest, and the extension will display information about that crack and any nearby strain gauges in a dedicated panel. Additionally, by manipulating the slider bar, users can visualize the formation and progression of cracks throughout the experiment, offering a dynamic view of the structural behavior.

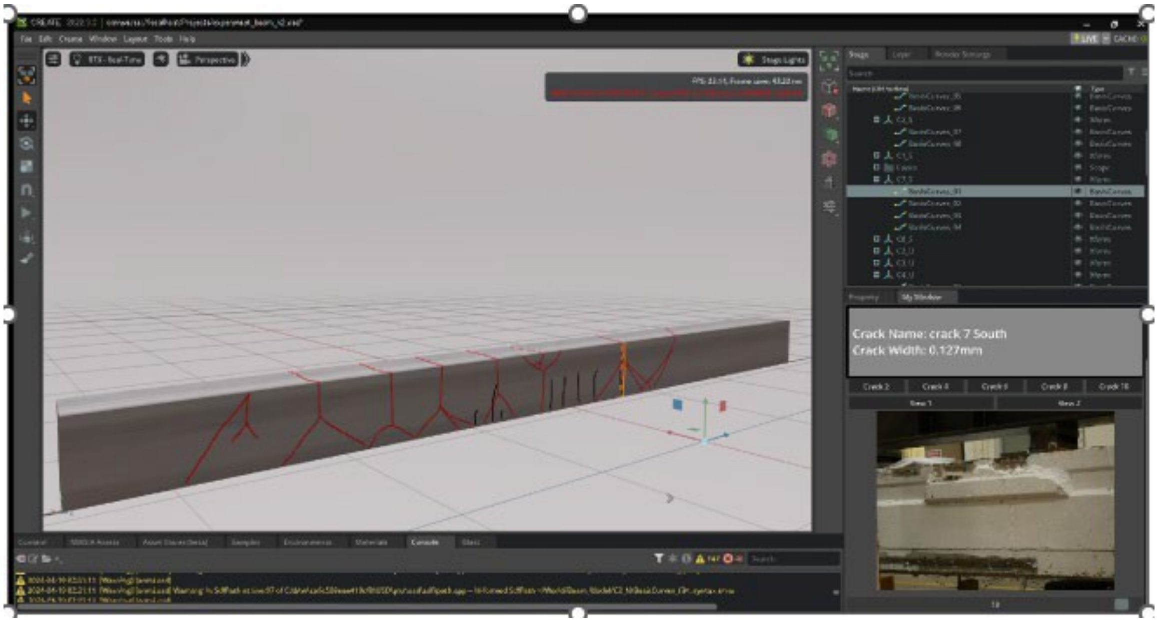

Figure 16. Crack visualization and analysis interface.

In addition to connecting Omniverse with the data from an actual lab experiment in the lab, we investigated how to connect the data produced through the Finite Element Analysis (FEA) modeling and simulation tools. In particular, we have implemented a beam in FEA tool Abaqus, and the geometry and simulation results are exported to ParaView software. This software provides an extension for Omniverse Platform to export and collaborate on simulation geometry. Through that, we could build a more detailed digital model of the beam. We expect this to lead to a more accurate bending model visualization in Omniverse.

The results of these additional investigations allowed us to build and test various tools and techniques in Omniverse for working with more complex data that would come from a detailed inspection of PC bridges.

Workforce Development Activities

The project supported several graduate and undergraduate students who have contributed to the development of various aspects of the project. This work also inspired a summer project as part of the NCSA REU program in which two students from underrepresented in science and engineering communities worked on the development of a machine learning model for crack segmentation using publicly available datasets.

Presentations and Posters of TRANS-IPIC Funded Research

The team presented at the 2024 TRANS-IPIC Annual Workshop and at the NCSA Annual Student Research Conference:

Wentao Yao, Dachina Gunasekaran, Tasho Madondo, Hyunwoo Kwon, Arslan Khan, Volodymyr Kindratenko, Bassem Andrawes, *Design and Implementation of Digital Twin Models for Continuous Monitoring and Performance Prediction of Precast Concrete Bridges*, 2024 TRANS-IPIC Annual Workshop, Chicago, IL, April 2024.

Wentao Yao, Dachina Gunasekaran, Tasho Madondo, Hyunwoo Kwon, Arslan Khan, Volodymyr Kindratenko, Bassem Andrawes, *Design and Implementation of Digital Twin Models for Continuous Monitoring and Performance Prediction of Precast Concrete Bridges*, 2024 NCSA Annual Student Research Conference, Urbana, IL, April 2024.

Other Outcomes

The software and 3D models developed as part of this project are available in GitHub (https://github.com/Wentaoy-19/Digital-Twin-Bridge).

New item published by NCSA's Center for AI Innovation about team's presentation at the 1st Annual Workshop at the Big Ten Conference Center in Rosemont, IL. https://ai.ncsa.illinois.edu/news-events/2024/04/caiis-wentao-yao-presents-at-trans-ipic-workshop/