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Remote Sensing System Enhancement for Digital Twinning of the Built Infrastructure to Support Critical Infrastructure Protection Research

FINAL REPORT
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Submitted by:

Jie Gong,

Associate Professor, Ph.D.

Rutgers University

Center for Advanced Infrastructure and Transportation
Rutgers, the State University of New Jersey
100 Brett Rd, Piscataway Township, NJ 08854

External Project Manager
Brad Mason, Director of Capital Resilience and Continuity
New Jersey Transit

In cooperation with

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And
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16. Abstract

The purpose of this project is to acquire a laser scanner and explore its utilities for creating digital twins of infrastructure systems to support infrastructure management. In joint with an ongoing project with NJ Transit OEM on developing an early flood warning system, the project focused on applying the laser scanning and building modeling technologies to support digital twinning of infrastructure systems. We conducted 3D mapping activities throughout the Hoboken Terminal to create a rich semantic building model for the station. Based on the building model, we have already created a preliminary digital twin which consists of digital models of the station itself, a hazard system simulating the compounding of storm surge and rainfall events, and a decision simulator to allow for the investigation of what-if scenarios under various storm events. Infrastructure stakeholders have experimented with the Hoboken digital twin for various flood mitigation analysis. The project ended with delivering a critical digital twin based early flood warning system for infrastructure stakeholders.

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INTRODUCTION

Description of the Problem

The concept of digital twins is an enabler to address today's infrastructure life-cycle management challenges, especially in this challenging era with the growing threats of pandemics, natural disasters, funding shortfalls, and social unrests. Digital twins support cost-effective ways of exploring what-if scenarios from which the most effective interventions can be identified. The resilience research group at Rutgers Center for Advanced Infrastructure and Transportation (CAIT) has been conducting pioneering research studies in the last decade along the dimensions of leveraging Geomatics Engineering technologies such as laser scanning to create high fidelity digital twins to support critical infrastructure protection. Some of our signature projects include, but are not limited to, use of Light Detection and Ranging (LIDAR) technologies to support the redesign of Port Authority Bus Terminal in Manhattan (the busiest bus terminal in the entire world), use of LiDAR and digital twins to evaluate UVC disinfection efficiency for transportation assets (in collaboration with CAIT transit research team), use of LiDAR to support bridge condition assessment (Arlington Memorial Bridge and other LTBP related bridges), and use of remote sensing technologies to support natural gas pipeline integrity assessments. In this project, we propose to acquire a new terrestrial laser scanner - Faro Focus S350 to further support and strengthen this line of research projects. The terrestrial laser scanner that is currently used in this line of research is 10-year old with significant wear and tear, and it has reached its end of life. The addition of this proposed scanner will enable new research studies in digital twining of the built infrastructure to support mitigation of flood threats to critical transit stations and evaluation of disinfection methods for transportation facilities.

Relevance to Strategic Goals

The focus of this project is particularly relevant to several USDOT strategic goals, which are also the primary focus of this consortium. The first and foremost strategic goal that this project contributes to is infrastructure resilience. The second goal supported by this project is state of good repair because the project helps the reduction of damage caused by flood. Lastly, by providing tools and data that can be used by infrastructure stakeholders to prioritize their investments on addressing infrastructure vulnerabilities to coastal flooding, the project can help prolong the life of infrastructure.

Research Goals and Objectives

The proposed project will forge a critical research capability at CAIT to address the security of the public transportation infrastructure and the enormous amount of public assets. The acquisition of this scanner and its related activities in integrating this instrument into our current Geomatics Engineering strength and our artificial intelligence assisted data analytics program will propel Rutgers CAIT into a leadership position both regionally and nationally in creating digital twins, using digital twins to solve emerging challenges facing transportation stakeholders. These challenges include ensuring continued operation of critical transportation links during extreme weather events, restoring trust in public transportation, enhancing mobility for disadvantaged social groups such as seniors and disabled users.

Overview of the Report

This report documents the research approach, methodology, findings, conclusions and recommendations of this collaborative research project. The following sections outline the approach and methodology. The next section presents the findings, followed by sections documenting the conclusions and making recommendations for future work and application in Life-Cycle Management of Transportation Infrastructure Projects

APPROACH

The research envisioned in this project is centered around acquisition of a new terrestrial laser scanner and building new research capabilities in digital twining. The study will involve system acquisition and integration, system evaluation, pilot studies centered around creating digital twins of selected infrastructure facilities, and joint evaluation sessions with infrastructure stakeholders. We plan to evaluate how the new system can be integrated into various platforms we currently have such that unique capabilities in infrastructure mapping can be developed for traditionally challenging use cases. For example, we will investigate whether this scanner can be integrated onto state of the art robotic platforms such as Boston Dynamic Spot dog to support the automated mapping of indoor environment or hazardous environment which are not safe for human operators. Once the system integration is completed, we will deploy the system in several facilities, jointly selected with project partners, to test its efficiency in collecting the baseline data - 3D point cloud and panoramic imagery to support digital twinning. We will also evaluate how accurate these digital twins can be based on the data collected.

Throughout the project, the research team will rely on hand-on experiments, prototype development, and technology demonstration with project customers and potential implementers as the primary means to forge a digital twinning tool for infrastructure stakeholders to make better decisions during challenging scenarios.

METHODOLOGY

The following research tasks are planned in this project.

Task 1: Laser Scanner Acquisition

Task 2: Laser Scanner Integration with Current Platforms and Research Capabilities

Task 3: Pilot Studies in Selected Transportation Facilities

Task 4: Joint Evaluation with Infrastructure Stakeholders

Task 5. Final Report, Conclusion, and Recommendation

FINDINGS

Our findings are organized around the research tasks.

Task 1: Laser Scanner Acquisition

LiDAR (a portmanteau of "light" and "radar.") is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. Among other applications, LiDAR is useful for detailed mapping of infrastructures, facilities, and asset management at several levels. The data products derived from LiDAR data can be used to assist facility owners to improve the efficiency of operations and maintenance. The field is rapidly maturing in capabilities, applications, and utility. In this task, we acquired a Faro Focus X350 scanner. The scanner is capable of scanning structures with a maximum range of 350 meters. The scan data can be used as a baseline data set to support the development of digital twins, especially the static building structures. The model developed based on scan data can generate benefits such as:

(1) The accurate geometric conditions of the structural elements in a transportation facility provide baseline data for monitoring structural hazards such as slab/beam deflections caused by repetitive loading, material deterioration, and extreme weather and man-made events.

(2) An up-to-date BIM model provides a 3D simulation environment for investigating retrofitting options, evaluating construction sequences, and exploring design optimization.
(3) A building information model not only describes the geometric conditions of the facility, but also captures the interrelationship of building spaces, building elements, and building systems. Therefore, it can be used to support the detection of and reasoning about possible cascading failures caused by individual disruptions.
(4) A building information model provides a virtual environment for simulating various operational decisions as well as for virtually conducting and visualizing high-level planning exercises.

Task 2: Laser Scanner Integration with Current Platforms and Research Capabilities

While the Faro scanner can be used out of box for static mapping, there are also opportunities to integrate with other mobile platforms to drastically reduce the time of mapping large-scale facilities. One of the things we investigated is converting the Faro scanner into an indoor mobile scanning system. This is accomplished by mounting the scanner on a mobile platform which can be pushed through indoor environment. The mobile platform itself has indoor localization capabilities offered by a line scanner system. We conducted the testing of the system in a campus building environment. We found that the system can cover large indoor areas in a short amount of time. The data coming out of the scanner can also be automatically processed into a common coordinate system such that the scans taken at different positions are aligned with good accuracy.

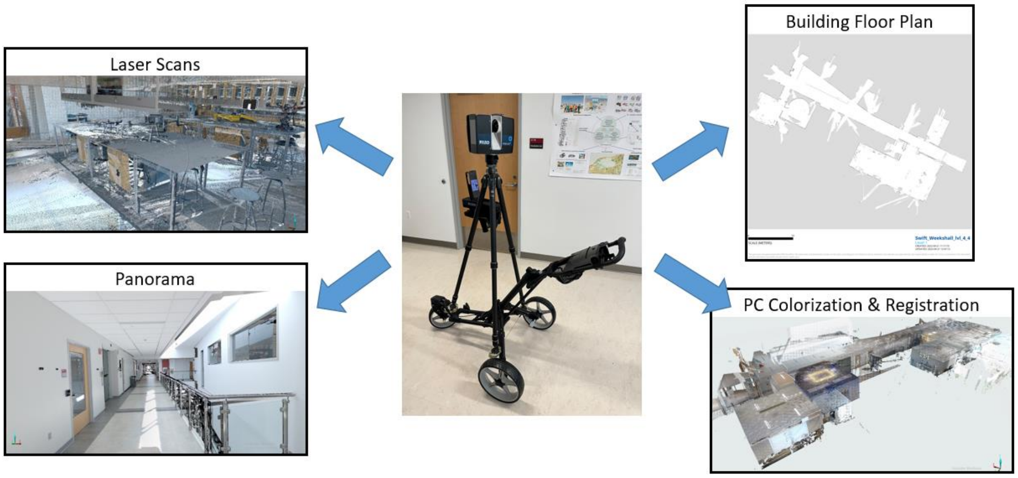


Figure 1 Scanner integration for indoor mobile scan

Task 3: Pilot Studies in Selected Transportation Facilities

In this task, we deployed the system to map Hoboken Terminal - a transportation facility, and developed a workflow specific to digital twining of the built infrastructure with a focus on flood mitigation. New Jersey is the second most vulnerable state in the country. Extreme precipitation causes frequent flooding in the state; Superstorm Sandy refreshed our perspectives of the storm surge risks in the coastal areas; and sea-level rise is posing a grave challenge of regular coastal flooding. Superstorm Sandy in October 2012 flooded the rail operations center of by 8 feet (2.4 m) of water [1] and damaged the North Jersey Coast Line and Atlantic City Rail Line, several rail stations including Hoboken Terminal, and Morgan Drawbridge on the North Jersey Coast Line [2]. As climate change and sea-level rise proceeds, the Rutgers team expects more flooding disruption in New Jersey -- a recent report showed that "flood height return periods that were ∼500 y during the preindustrial era have fallen to ∼25 y at present and are projected to fall to ∼5 y within the next three decades" in the New York/New Jersey area [3].

More specifically, in this task, we conducted LiDAR surveys of Hoboken NJ TRANSIT terminal and its surrounding streets and develop a digital twin for the facility. We used a combination of static and mobile LiDAR systems to conduct these surveys.

Figure 2 Phased Scanning of the different areas in Hoboken NJ TRANSIT

The scanning task was divided into five subtasks. Each subtask involves scanning and modeling of particular area of the Hoboken Terminal (as detailed in Figure 2). Each scanning day was planned out to include both scanners operated by two independent teams to maximize the efficiency of the process. Scanning began in the employees parking lot, and moved into the Ferry Terminal. From there the Northern and Eastern perimeter of the Terminal was covered.

Subsequently, both teams were deployed to cover the Southern perimeter, stretching from the back of the Ferry slip to conductors' waiting room, and Platform 12, approaching the area from the opposite ends. The next stage covered was the Waiting Room, and the second floor of the Ferry Terminal. Both were completed simultaneously. Before moving to scan the platforms, the teams covered both the Light Rail perimeter and tracks, as well as the Northern perimeter around the Bus Terminal, including the bus parking lot.

A detailed plan was developed before beginning to scan the Platforms due to the inherent difficulty associated with that area. Firstly, when scanning the platforms it was required to be escorted by the Flag Man at all times. Secondly, the constantly moving trains blocked the visible area further interfering with the scanning activities. Whereas the rest of the Terminal was scanned using a long scan duration, using a high quality and resolution settings, when scanning Platforms those had to be adjusted to decrease the scanning duration. When covering the platforms area, the average scan duration was 1.5 minutes as opposed to 6.5 minutes everywhere else. To assure that the accuracy remained the same, and to guarantee the successful registration process, the scan density was increased for the platform area.

Last covered area using the static scanner was the train yard (where possible). Terminal's roof including Northern, Southern, Eastern and Western perimeters. While performing the scanning activities, a number of GPS control points were collected throughout the project site to position the design correctly. The processed scan data was exported in the Recap format and imported into the Revit BIM software, where the model was Georeferenced and further, detailed model design performed. The result of these activities is the creation of the Digital Twin of the entire Hoboken Terminal with surrounding streets, and parking lots. The train yard had much larger scanning areas and obstacles than the terminal. Moreover, the scanning crew could not enter the train yard due to safety issues such as moving trains and high-voltage catenary towers.

In the end, nearly 300 scans were collected throughout the terminal to capture all the details (Figure 3). The LiDAR survey produced point cloud data georeferenced to the New Jersey State Plane and NAVD-88 vertical datum (Figure 4). Furthermore, the LiDAR data were converted into a 3D model with rich semantic information using the Autodesk Revit program.). The model was integrated into a web-based portal for visualization (Figure 5).

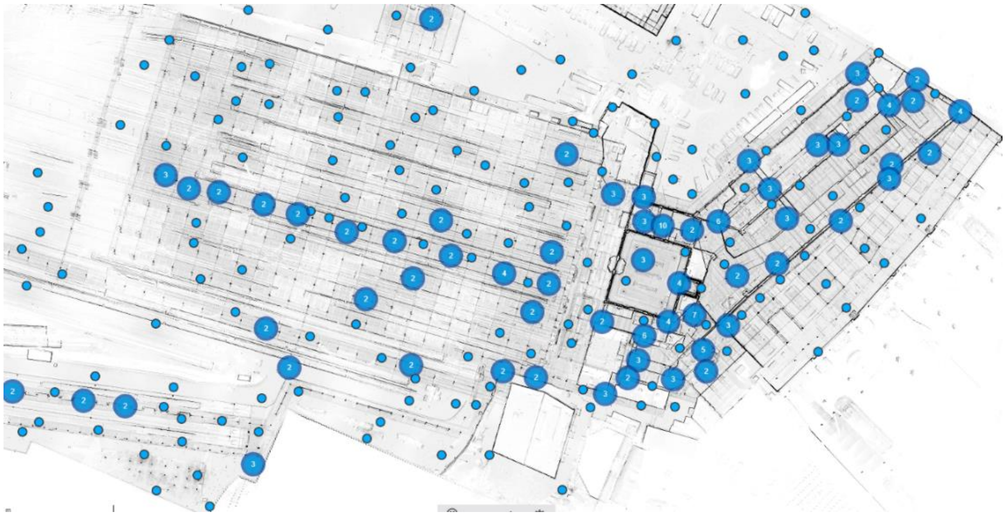


Figure 3 Scan distributions in the station

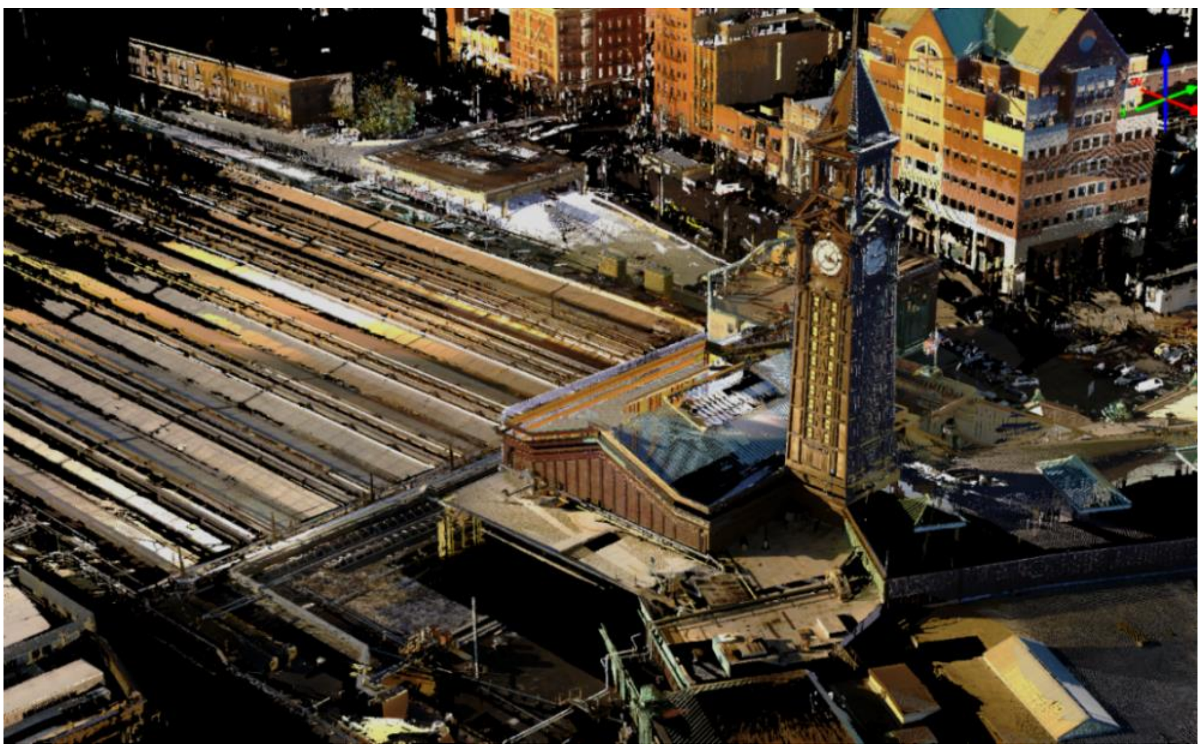


Figure 4 Example scan data

Figure 5 Digital twins of the Hoboken terminal

One of the applications of the digital twin model is a dash board for flood information. More specifically, a web-based dashboard application has been developed to serve as the user interface to the flood forecasting system. The dashboard integrates the building model with flood simulation to provide a multi-modal visualization that can support operational decisions during a flooding event.

The core of the dashboard is a 3-D Map module that visualizes the Hoboken terminal and its surrounding area. The module uses Mapbox's developer API to render the base map. On top of the base map, we used Mapbox's custom layer rendering interface to integrate other 3-D visualizations into the module. The following visualizations have been integrated:

1) A BIM model of the terminal facility is created from the scan data. The model is georeferenced and its rendering aligns with the base map.
2) A flood model mesh is constructed using the same computational mesh from task 2. Using the water elevation time series from the outputs of the flood model in task 2, the module renders an animated flood that allows the user to visualize the flooding scenario.
3) An asset layer tileset is constructed on Mapbox Studio using the critical asset information provided by NJ TRANSIT. An individual asset is rendered as an extrusion from the base

map where its height corresponds to the Z-Impact elevation of the asset, which indicates when the asset is considered inundated.

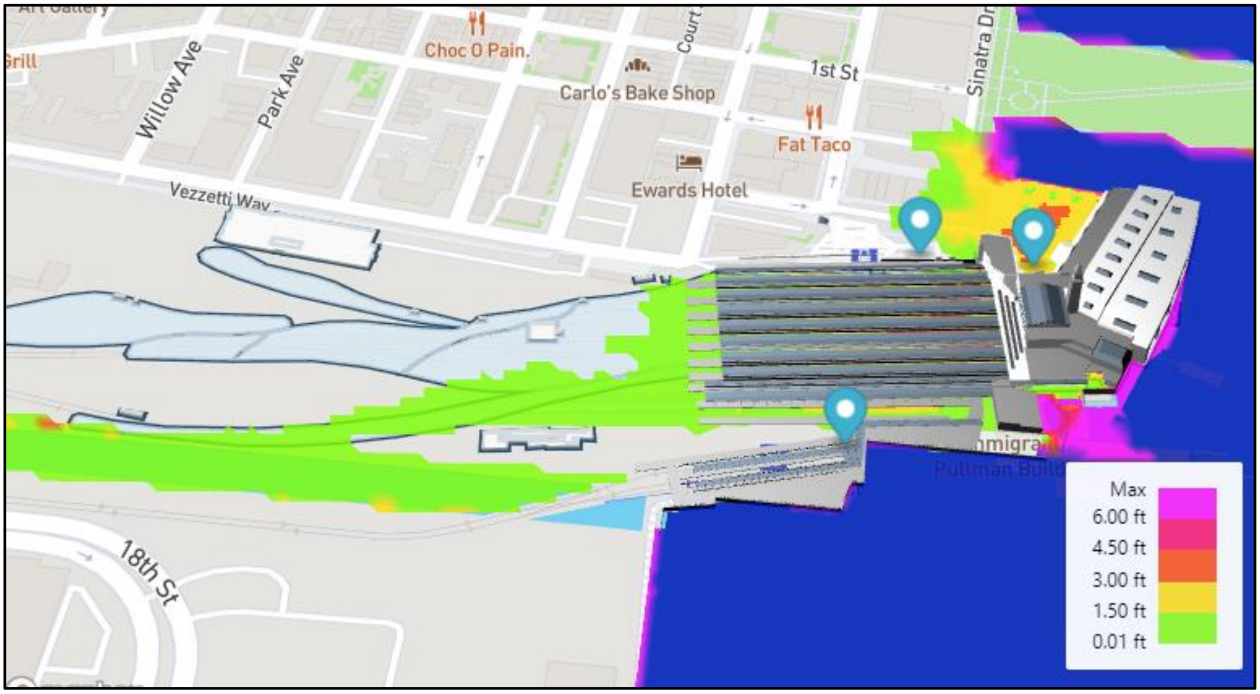


Figure 6 The 3-D Map module showing a top-down view of 1) the base map, 2) the Hoboken Terminal Facility, 3) a frame of animated flood scenario, and 4) the asset extrusions.

The flood visualization is configurable through several options that alter its appearance to the user. In addition to visual enhancements, we introduced a Safety Factor parameter that allows the user to visualize the flood scenario at elevated water elevations. For example, a safety factor of +1.0 feet will elevate the flooded areas in the scene by 1.0 feet. Then we use a simple bathtub model to simulate water flow to areas that were previously not inundated. This simulation is only performed in a smaller area around the Hoboken terminal. The area is highlighted and emphasized to the user that the Safety Factor parameter is active.

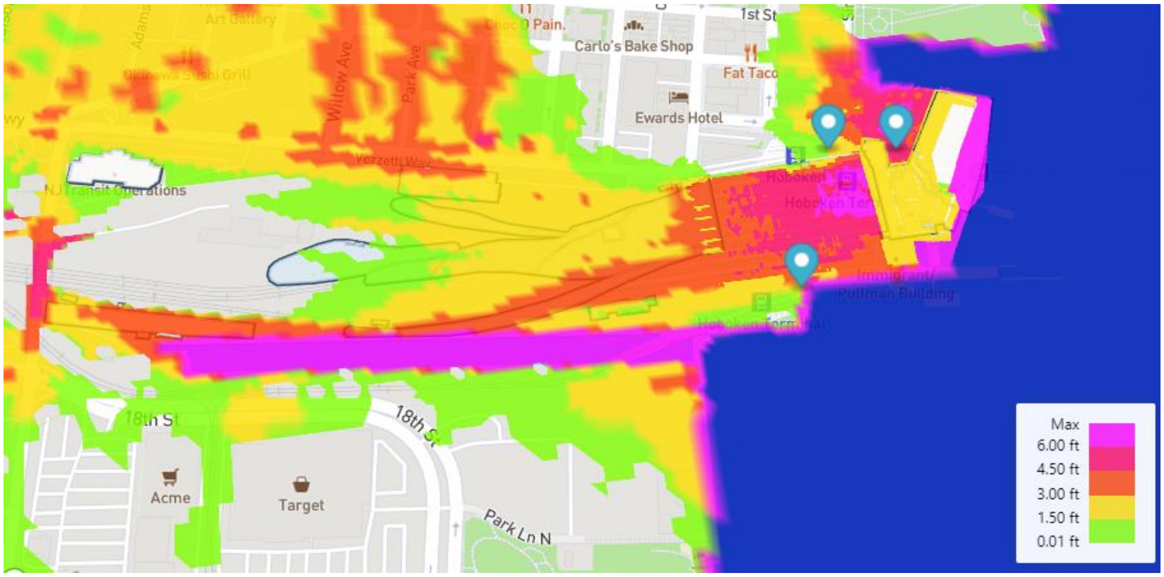


Figure 7 No Safety Factor applied

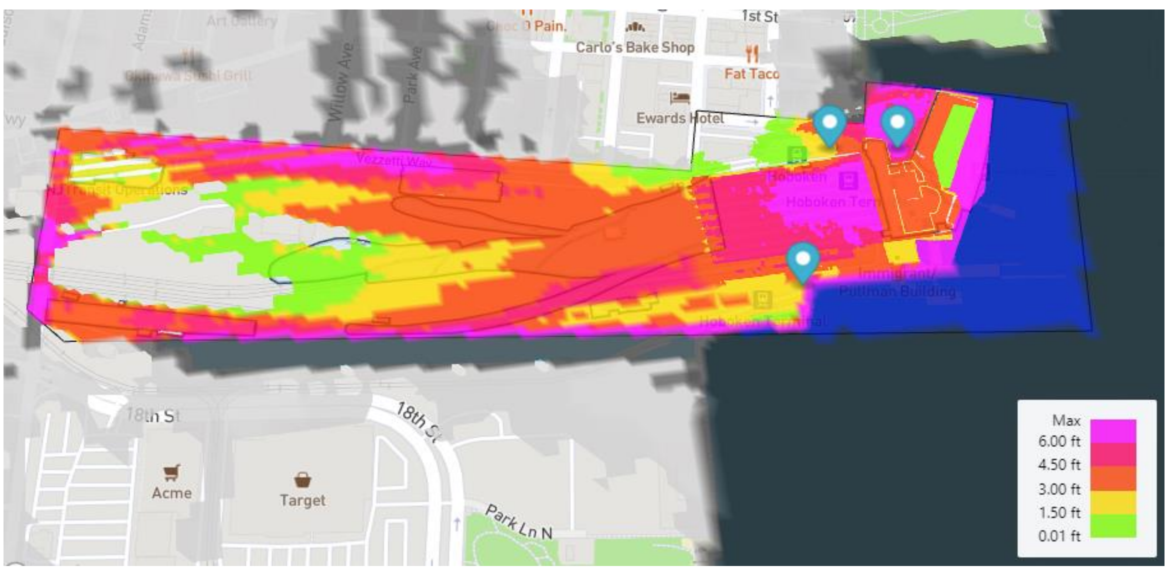


Figure 8 Safety Factor + 1.0 feet

Users can interact with the BIM model through the IFC Explorer module. The BIM model is loaded using the IFC.js API, which provides a 3-D mesh model of the BIM model. The API also provides an interface for manipulation and extraction of information from the IFC file. The module displays the extracted hierarchical structural information in a file tree format. Users can toggle the visibility of individual structural groups or structural elements, as well as highlighting them.

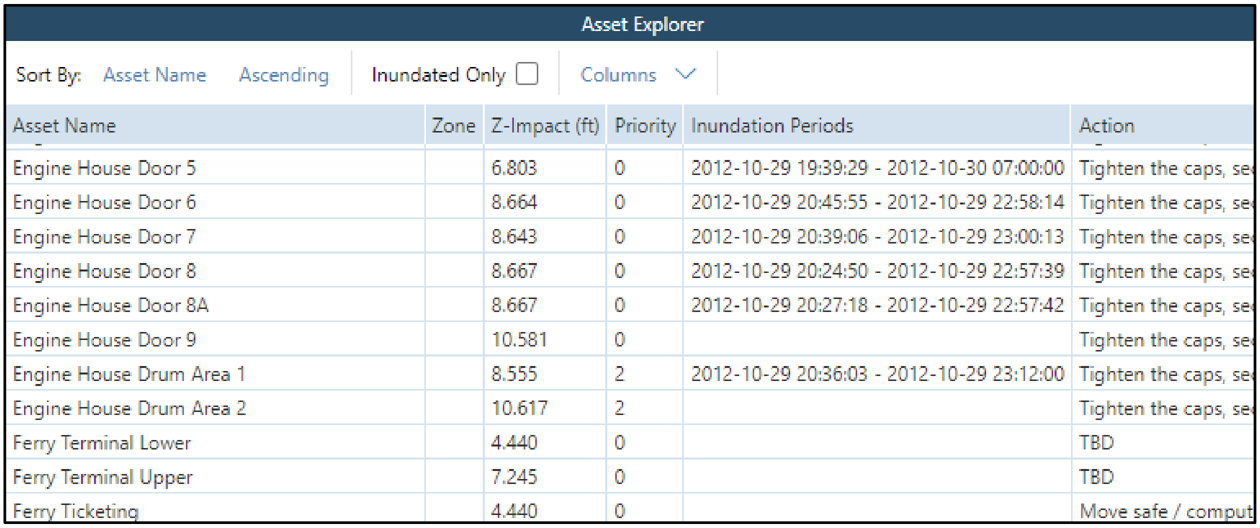
IFC Explorer

	Type	Name
−	IFCPROJECT	Project Number
−	IFCSITE	Default
−	IFCBUILDING	
+	IFCBUILDINGSTOREY	Subway floor
+	IFCBUILDINGSTOREY	subway ceiling
+	IFCBUILDINGSTOREY	Ferry Terminal Floor
+	IFCBUILDINGSTOREY	Platform Floor level
+	IFCBUILDINGSTOREY	Level 1
+	IFCBUILDINGSTOREY	Ferry Terminal Dock
+	IFCBUILDINGSTOREY	Light Rail Platform
+	IFCBUILDINGSTOREY	Bus termial Floor
+	IFCBUILDINGSTOREY	Platform Roof level
+	IFCBUILDINGSTOREY	Light Rail Roof

Figure 9 IFC Explorer module

The Asset Explorer displays a table of assets that corresponds to the rendered asset extrusions in the 3-D Map module. Each row represents an asset and columns represent asset attributes. The table is interactive and allows the user to navigate the rendered assets on the 3-D map from the module. In addition to the asset attributes given by NJ TRANSIT, the dashboard also computes and aggregates new asset attributes that would support decision making using other information from our data pipeline:

1) An asset's zone is not given natively but can be computed using the given zones in the facility and the asset's geographical location.
2) In the case where flooding is present, each asset's inundation period will be computed and displayed on the table.



Asset Explorer

Sort By: Asset Name Ascending | Inundated Only ☐ | Columns

Asset Name	Zone	Z-Impact (ft)	Priority	Inundation Periods	Action
Engine House Door 5		6.803	0	2012-10-29 19:39:29 - 2012-10-30 07:00:00	Tighten the caps, se
Engine House Door 6		8.664	0	2012-10-29 20:45:55 - 2012-10-29 22:58:14	Tighten the caps, se
Engine House Door 7		8.643	0	2012-10-29 20:39:06 - 2012-10-29 23:00:13	Tighten the caps, se
Engine House Door 8		8.667	0	2012-10-29 20:24:50 - 2012-10-29 22:57:39	Tighten the caps, se
Engine House Door 8A		8.667	0	2012-10-29 20:27:18 - 2012-10-29 22:57:42	Tighten the caps, se
Engine House Door 9		10.581	0		Tighten the caps, se
Engine House Drum Area 1		8.555	2	2012-10-29 20:36:03 - 2012-10-29 23:12:00	Tighten the caps, se
Engine House Drum Area 2		10.617	2		Tighten the caps, se
Ferry Terminal Lower		4.440	0		TBD
Ferry Terminal Upper		7.245	0		TBD
Ferry Ticketing		4.440	0		Move safe / comput

Figure 10 Asset Explorer module

The Hydrograph module displays water elevation time series information for a particular asset.

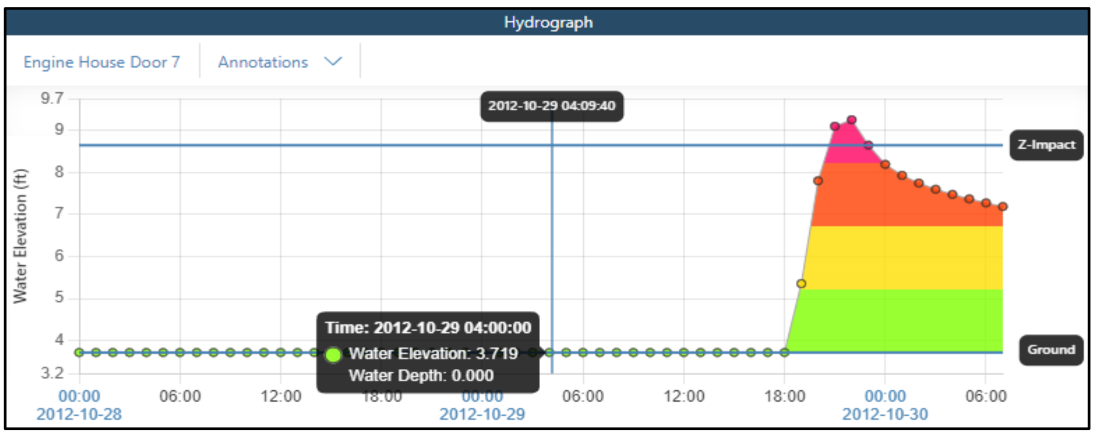


Figure 11 Hydrograph module

For some designated locations, the dashboard provides a street view version of the flooding scenario in the Panorama module. The street view is visualized using a panoramic image and point cloud captured at that location. Using the depth information from the point cloud, we were able to realistically overlay the flood rendering on top of the panoramic view to create an animated flood on top of the street view.

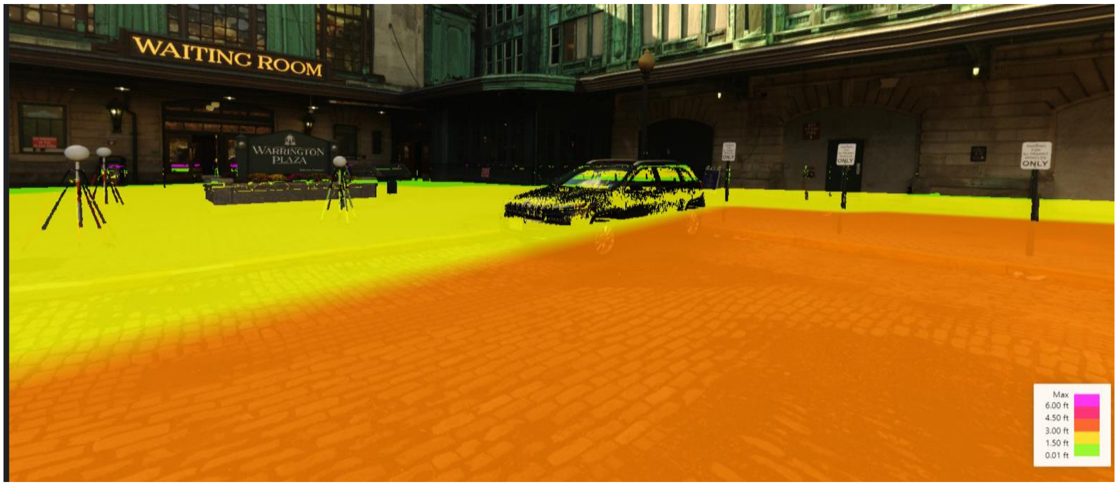


Figure 12 Street view with overlaid flood scenario

Users can export a report that summarizes the loaded flood scenario using the Export module of the dashboard. The report includes meta and aggregated information about the flood scenario, a screenshot of the flood scenario at peak elevation, and a table detailing the asset conditions and corresponding actions to take during a flood scenario.

Task 4: Joint Evaluation with Infrastructure Stakeholders

During the course of the project, we have conducted meetings and demos for various infrastructure stakeholders, in particular New Jersey Transit. We have invited stakeholders and practitioners to the visualization lab or via virtual conferences to demonstrate various digital twinning products. The purpose is to understand whether these data and digital twins can be used to support decision makings related to critical infrastructure protection such as flood mitigation. We also conducted several trainings at New Jersey Transit Emergency Operation Center for New Jersey Transit personnel. The digital twin product received overwhelming positive reviews. The digital twin based flood information system is currently an active flood forecasting system used by New Jersey Transit.

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this project is to acquire a laser scanner and explore its utilities for creating digital twins of infrastructure systems to support infrastructure management. In joint with an ongoing project with NJ Transit OEM on developing an early flood warning system, the project focused on applying the laser scanning and building modeling technologies to support digital twinning of infrastructure systems. We conducted 3D mapping activities throughout the Hoboken Terminal to create a rich semantic building model for the station. Based on the building model, we have already created a preliminary digital twin which consists of digital models of the station itself, a hazard system simulating the compounding of storm surge and rainfall events, and a decision simulator to allow for the investigation of what-if scenarios under various storm events. Infrastructure stakeholders have experimented with the Hoboken digital twin for various flood mitigation analysis. The project ended with delivering a critical digital twin based early flood warning system for infrastructure stakeholders. We believe the data afforded by the laser scanning and building modeling technology can further contribute to building an enhanced dynamic digital twin of the Hoboken Terminal of New Jersey Transit (NJT) and its surrounding environments (which include the static and dynamic content - buildings, roads, crowds, trains and buses) to address a much broader set of security challenges for surface transit than in the current project.

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