C2SMART

CONNECTED CITIES WITH SMART TRANSPORTATION

A USDOT University Transportation Center

New York University

Rutgers University

University of Washington

The University of Texas at El Paso

City College of New York

Digital Twin Technologies Towards Understanding the Interactions Between Transportation and Other Civil Infrastructure Systems

December 2022

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Digital Twin Technologies Towards Understanding the Interactions Between Transportation and Other Civil Infrastructure Systems		5. Report Date December 2022 6. Performing Organization Code:
7. Author(s) Jeffrey Weidner, Adeeba Raheem, Ruey Long Cheu, Lauren Brown, Julio Gallegos, Jose Luis Lugo		8. Performing Organization Report No.
9. Performing Organization Name and Address Connected Cities for Smart Mobility towards Accessible and Resilient Transportation Center (C2SMART), 6 Metrotech Center, 4th Floor, NYU Tandon School of Engineering, Brooklyn, NY, 11201, United States		10. Work Unit No. 11. Contract or Grant No. 69A3551747119
12. Sponsoring Agency Name and Address Office of Research, Development, and Technology Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Final Report, 3/1/2021 - 12/31/2022 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Digital Twin (DT) technology is the next step in the gradual shift from physical to digital models in civil engineering. Computer-Aided Drafting (CAD) revolutionized the industry by reducing the time and costs associated with documenting design. Building Information Modeling (BIM) has eliminated the need for physical design descriptors (i.e., drawings or physical models). DT models build off CAD and BIM but are utilized over the operational life of the infrastructure as a management tool. A DT is a relevant abstraction of the physical asset; it is most frequently used to model, improve, and control manufacturing systems. Civil engineering applications using DTs have been emerging, but transportation infrastructure represents a challenging extension of DT technology because of its spatial scale, as well as its voluminous and time-varying data. However, DT is a powerful decision support tool for the design, maintenance, and management of transportation infrastructure, particularly for studying its interdependencies with other infrastructure systems, which is of relevance to smart cities. The primary objective of this research was to explore the effectiveness of DT technology as a tool to visualize and understand interactions between transportation and other related civil infrastructure systems.

17. Key Words Digital Twin, Civil Infrastructure		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 73	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page author

Digital Twin Technologies Towards Understanding the Interactions Between Transportation and Other Civil Infrastructure Systems

Jeffrey Weidner, Ph.D.
University of Texas at El Paso
0000-0003-0424-665X

Lauren Brown
University of Texas at El Paso
0000-0003-0677-3621

Adeeba Raheem, Ph.D.
University of Texas at El Paso
0000-0002-2226-5582

Julio Gallegos
University of Texas at El Paso
0000-0001-5614-1767

Ruey Long Cheu, Ph.D.
University of Texas at El Paso
0000-0002-0791-2972

Jose Luis Lugo
University of Texas at El Paso
0000-0002-9247-2069

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, by a grant from the U.S. Department of Transportation's University Transportation Centers Program. However, the U.S. Government assumes no liability for the contents or use thereof.

Acknowledgements

Executive Summary

Digital Twin (DT) technology is the next step in the gradual shift from physical to digital models in civil engineering. Computer-Aided Drafting (CAD) revolutionized the industry by reducing the time and costs associated with documenting design. Building Information Modeling (BIM) has eliminated the need for physical design descriptors (i.e., drawings or physical models). DT models build off CAD and BIM but are utilized over the operational life of the infrastructure as a management tool. A DT is a relevant abstraction of the physical asset; it is most frequently used to model, improve, and control manufacturing systems. Civil engineering applications using DTs have been emerging, but transportation infrastructure represents a challenging extension of DT technology because of its spatial scale, as well as its voluminous and time-varying data. However, DT is a powerful decision support tool for the design, maintenance, and management of transportation infrastructure, particularly for studying its interdependencies with other infrastructure systems, which is of relevance to smart cities.

The primary objective of this research was to explore the effectiveness of DT technology as a tool to visualize and understand interactions between transportation and other related civil infrastructure systems. We used The University of Texas at El Paso (UTEP) campus as a living lab by creating a DT model of part of the campus. While a substantial portion of the campus was included in the reality capture model, the model focused on a single building and the surrounding transportation network. The DT was approximated with a digital shadow model. We leveraged existing data sources on campus and supplemented them with synthetic data to simulate the DT. Specifically, the research focused on:

- Summarizing the existing literature around DT in transportation and providing an overview of the state of adoption;
- Creating a baseline digital shadow of a selected infrastructure at the UTEP campus;
- Studying the impact of construction-related activity on the surrounding transportation infrastructure;
- Developing a visualization of the impact analysis.

The team integrated the project with the Senior Design Capstone course at UTEP to expose civil engineering seniors to emerging technologies like LiDAR for reality capture, BIM modeling, Traffic Simulation, and DT. Given the limited time frame of the project, the team conducted a gap analysis based on our study and prepared a future roadmap to create a fully functional digital twin of campus, including identification of the physical and financial resources required to create a full DT model of a large-scale civil infrastructure system of systems like a campus. The project concluded with a stakeholder engagement workshop focused on the El Paso region.

Table of Contents

List of Figures

List of Tables

Introduction

Digital Twin (DT) technology is a cyber-physical system including a real system with some capacity for dynamic control, a real-time data stream from the real system, a digital model of that real system capable of ingesting data from and simulating behavior of the real system, some sort of decision-making intelligence, and a feedback loop to induce change in the real system. This project explores DT as a tool for management of civil infrastructure. More specifically, this project focuses on DT as a tool to manage transportation and construction. A conceptual schematic of a DT for the systems selected for this project, namely a partial campus transportation network and building under construction, is shown in Figure 1.

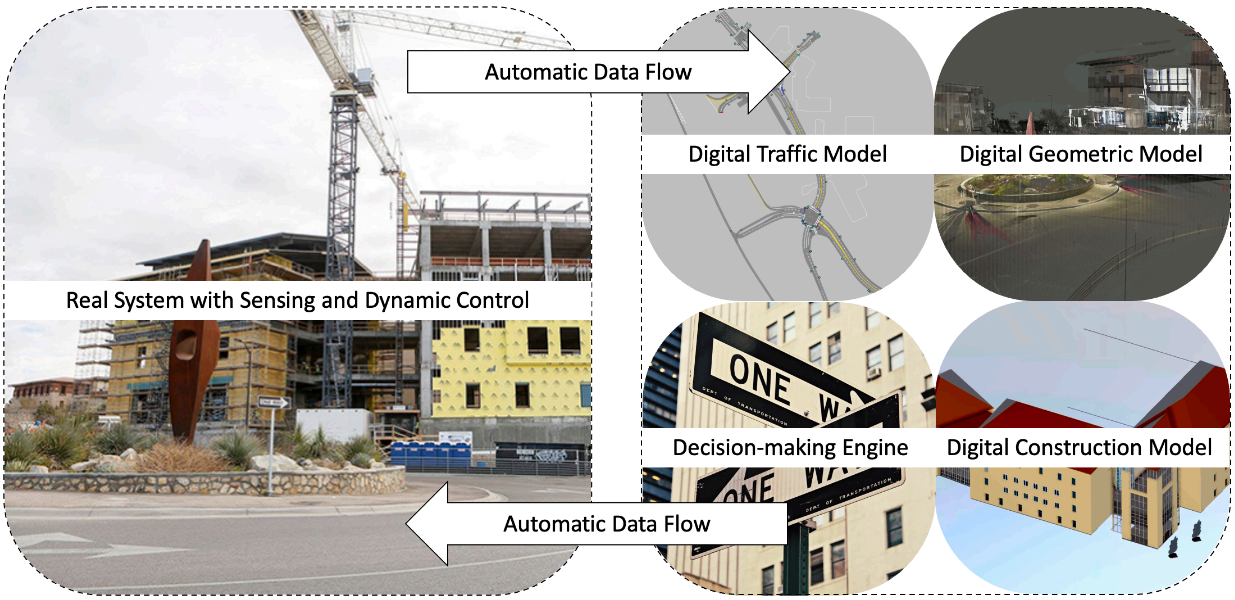


Figure 1. Diagram. Conceptual Project Digital Twin

The real system for this concept is a partial campus transportation network and adjacent infrastructure, inclusive in this case of a campus building under construction. This is depicted in the left-hand portion of Figure 1. The right-hand portion depicts the digital half of the DT. For this concept, the digital system includes a traffic model, a geometric model of the built environment, and a digital model of building construction, plus some decision-making intelligence. Data flow between the two systems is bi-directional. Achieving this level of DT technology is outside the scope of this project. This project serves as the foundation on which the type of DT depicted in Figure 1 will eventually be built.

The project was broken into four phases (P1 to P4) and a total of eight tasks. The Phase breakdown and some tasks and deliverables per phase are shown in Figure 2.

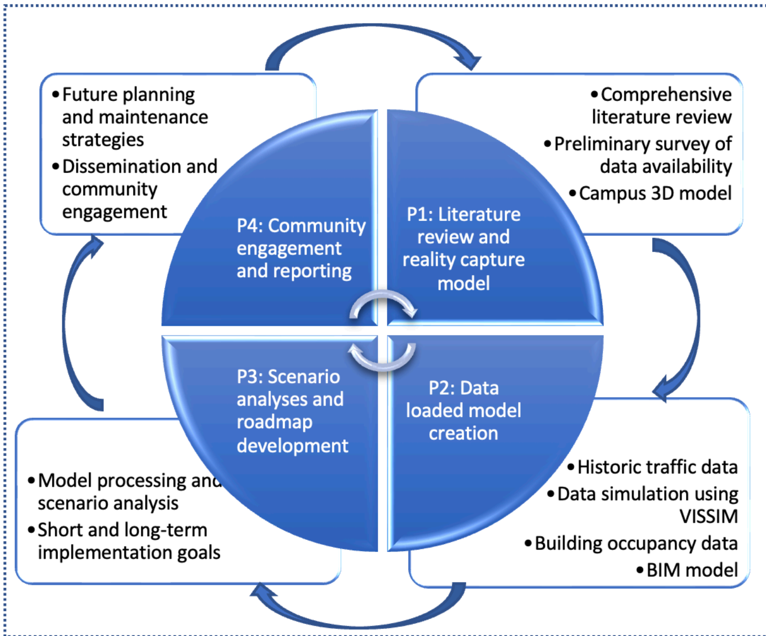


Figure 2. Diagram. Project structure by phase

Report Organization

This report is structured as follows:

- Introduction: Describes the structure of the report and provides an overview of the project, including challenges and assumptions
- Phase 1: Discusses Task 1 – Literature Review and Data Collection and Task 2 – Reality Capture of Existing Conditions
- Phase 2: Discusses Task 3 - Integrate Simulation and Information Models with Reality Capture and Task 4 – Develop a Digital Shadow Model of Campus
- Phase 3: Discusses Task 5 - Simulation of Campus Digital Twin and Visualization Demonstration and Task 6 - Gap analysis and Roadmap to Full Digital Twin Model
- Phase 4: Discusses Task 7 – Community Engagement Workshop and Task 8 – Reporting and Dissemination
- Conclusions: Summarizes the conclusions and future work

Project Overview

This project seeks to make incremental progress towards a true DT system for civil infrastructure. Notably, this means that the project team was not trying to create a full DT, which was beyond the scope of the project. The project team set out to achieve the following project-specific goals:

- Understand what a DT for Civil Infrastructure is, and how it is different that DT for other domains and use cases.
- Identify the key components of a DT designed to explore the interaction of a campus transportation network and an on-campus construction site.
- Identify data and data collection practices for reality capture of existing infrastructure.
- Create a Digital Shadow (DS) model of the selected civil infrastructure systems.
- Explore scenarios with real or synthetic data in the DS to understand how DT may affect operations of the selected civil infrastructure systems.
- Identify gaps and needs to facilitate a broader adoption of DT for a college campus, and to qualify the potential of DT.
- Disseminate the results and educate local public stakeholders about DT technology.

The case study for this effort was the campus of UTEP. In particular, the project team focused on the western edge of campus where the recently completed Interdisciplinary Research Building (IDRB) was located. Born out of anecdotal experience, the team elected to explore the interaction of the construction (of IDRB) and the neighboring transportation network. This area of campus, shown in Figure 3, tends to be congested at peak hours. This is particularly noticeable at the beginning of the semester when students and faculty are not yet in a travel routine and when there is any change or interruption to the network, such as lane closures for construction.

The area of interest is from the intersection of Sun Bowl Dr. and Schuster Ave. to the south, the ramps that connect University Ave. to/from the I-10 Freeway to the west, the entrance to the inner campus to the east, and the entrance to the Sun Bowl garage to the north, with the Mining Minds roundabout in the center of the area of interest. The IDRB is located on the southeastern corner of the Mining Minds roundabout. The northeast corner is the university bookstore, the northwest corner is barren land adjacent to a small surface parking lot, and the southwest corner is the Sun Bowl 2 surface parking lot.

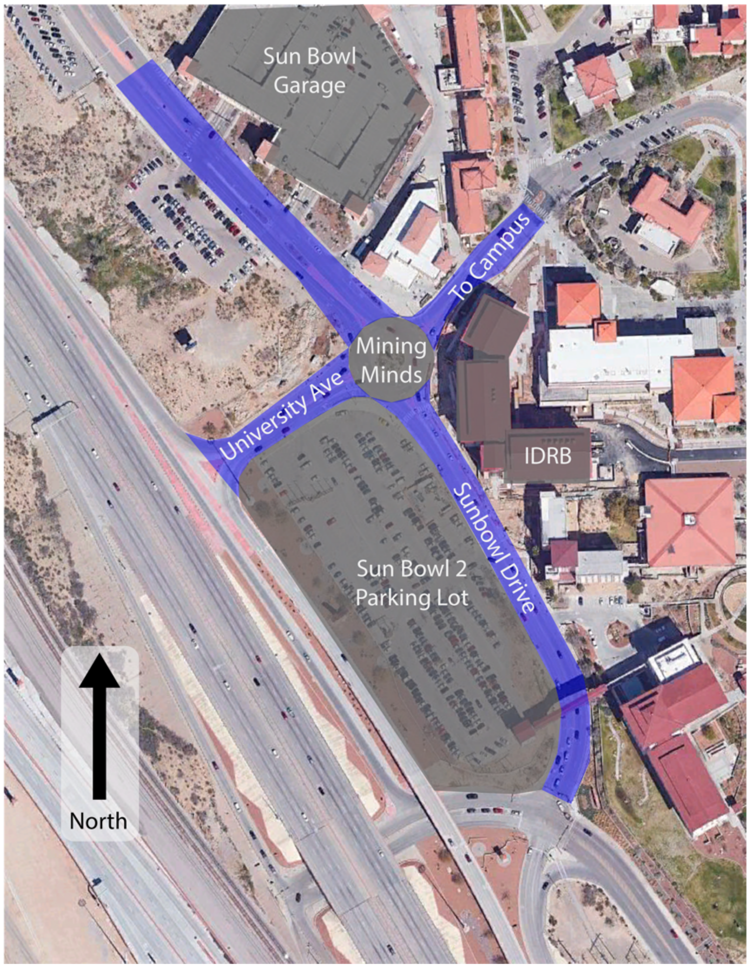


Figure 3. Map. Aerial View of Area of Interest on Campus

During construction of the IDRB, which occurred from 2016 to 2020, a portion of the Sun Bowl 2 parking lot was fenced off and dedicated for construction trailers and material staging. Two large tower cranes served the site, frequently picking materials from the Sun Bowl parking lot and transiting them over Sun Bowl Ave to the construction site. Whenever these moves were required, Sun Bowl Dr. was closed for safety of the traveling public. This was the primary idea behind the transportation and construction scenario that was developed as part of the project.

Ideally, the team would have had access to real-time monitored data from both the construction site and the local transportation network, the two of which comprise the “real system” components of a theoretical DT. The monitored data would feed into the “digital system” half of the DT where analysis would occur resulting in some adjustment or change to the real system to improve behavior or functionality.

As construction of IDRB was already completed, there was no current campus construction at the start of the project, and there were no readily available data streams from campus, immediately the team began exploring ways to recreate the scenario above using exclusively simulation models. More specifically, both components of the DT (real and digital) would have to be digital. This allowed the team to explore and understand the components and functionality of the DT without the burden of sensor procurement, installation, networking, maintenance, and troubleshooting.

The original intention was to utilize the contractor-built Building Information Model (BIM) of the IDRB which was a full 4D model inclusive of all construction staging and work zone traffic control. This would have allowed the research team to identify the scenarios experienced by campus stakeholders during the actual construction of IDRB with accurate semantic data and construction progress for visualization purposes. These snapshots in time would serve as inputs to the transportation network model, mimicking as the real system.

The transportation network was to be modeled using a traditional, industry standard traffic simulation tool. The project team considered SUMO, VISSIM, and AnyLogic, eventually settling on VISSIM because of the team's familiarity with the software, and the nuanced flexibility of the software to create detailed microsimulations. Based on the behavior of the perturbed transportation model (the real system), the research team could track a performance indicator (i.e., queue length) and use a duplicate of the transportation model as a digital system to development system interventions that may improve performance both acutely and over the full construction project. These interventions could then be implemented in the real system, completing the DT. At the outset, the intention was to utilize a third, as-of-yet unidentified software to combine, analyze, and visualize the DT.

All these models were to be augmented through reality capture of the existing conditions to create a visualization base layer on which the DT could be laid. The reality capture effort would include existing data sources and some new data collection.

As the project progressed, innovative solutions were improvised from the intended approach, by necessity, but the stated goals of the project were nonetheless achieved. Challenges to the project and required assumptions are listed below.

Challenges and Assumptions

The following challenges were faced and accounted for in this project:

- The COVID-19 Pandemic hampered the research team's ability to start the project in a timely fashion, recruit students, meet and collaborate regularly, engage with public stakeholders, and disseminate early results.

- The contractor for the IDRB was not willing to provide the full BIM model of the building to UTEP because the project was not yet closed out. Therefore, UTEP Campus Facilities and Services was unable to provide the BIM model to the project team.
- The selection of VISSIM limited the research team's ability to integrate the transportation model component with the construction component in any third-party software. VISSIM is a propriety software with little programmatic control flexibility. The software does have an Application Programming Interface (API) but the functionality is limited and the language required (COM) is unique.
- VISSIM did not have the capability (nor would most traffic simulation software) to exactly replicate the scenario desired.
- The network selected has limited options for interventions for the scenario created. There is no clear alternate route that could serve as a detour route.

The following assumptions were made to address challenges as required:

- The team assumed that replicating the scenario through which traffic was interrupted was more important than visualizing construction (i.e., incomplete building, tower cranes, etc), sacrificing the latter when it became clear that the 4D BIM model was unavailable.
- The team pivoted to VISSIM as the primary software platform for simulation, abandoning a third software to combine the VISSIM and the BIM. This was due to the challenges posed by a lack of interoperability of VISSIM.
- The team identified a single trigger and intervention, namely a reroute of traffic on Sun Bowl through the Sun Bowl 2 parking lot, as opposed to numerous options between which the DT may choose.

Phase 1

Phase 1 includes two preliminary tasks. They are Task 1: Literature Review and Data Collection and Task 2: Reality Capture of Existing Conditions. The results of each task are described below.

Task 1 – Literature Review and Data Collection

Task 1 contained two main subtasks. The subtask was the literature review as described in Task 1.1 – Literature Review. The second subtask was data collection via a survey as described in Task 1.2 – Data Collection.

Task 1.1 – Literature Review

This section presents a literature review of the existing practices on DT and related areas, with a focus on civil infrastructure systems. The reviewed materials are presented in five sub-sections: (1) DT definition and application in manufacturing purposes; (2) applications of DT technology and existing DT applications for the management of civil infrastructure; (3) available technologies for data collection and current simulation methods used in civil infrastructure systems; (4) comparison of modern techniques for modeling infrastructure systems such as BIM and Intelligent Transportation Systems (ITS); and (5) DT research gaps in manufacturing and infrastructure applications.

Task 1.1.1 - Review of Digital Twin application for Manufacturing

The fourth industrial revolution is known for the automation of data and noticeable advancements in manufacturing and other engineering technology. The Digital Twin in manufacturing was achieved thanks to the advances in artificial intelligence, cloud computing, and the Internet of Things (IoT). Initially, Grieves introduced the concept of a digital twin to follow an assembly process by using a virtual model to monitor the processes through information and data exchange (Dr. Grieves, 2015). The application of DT quickly expanded and improved on the idea of smart manufacturing (Lu et al., 2020). The DT concept was introduced for product life cycle management by using a virtual representation of the physical manufacturing process through the use of non-destructive sensors, gauges, lasers, and coordinate measuring equipment (Dr. Grieves, 2015). The DT was then expanded to predict behavior and operations of the equipment. A DT model for laboratory equipment was created to monitor equipment behavior, predict equipment failure, and improve laboratory operations by reducing the overall maintenance cost (Li et al., 2020).

A DT of the scheduling of a job-shop was developed to control the production of a small manufacturing assembly line process by using edge computing, virtual simulation, and data analysis to ultimately optimize the process (Xu & Xie, 2021). For a machining process, laser scanning was used to continuously monitor the geometric changes of a component and other processes occurring in the equipment, such as the speed of cutting and cutting the piece (S. Liu et al., 2020). Miller et al. investigated a model-based definition method to incorporate behavioral and product characteristic data via a plug-in directly into a 3D-CAD model (Miller et al., 2018). In addition, Miller et al. suggested that a behavioral model was not defined by the performance of a product but instead to the physical manifestations that occur in a specific part in response to external stimuli (Miller et al., 2018). Liu et al. explored the concept of biomimicry (perceive and simulate an environmental change) to simulate the geometric change response during the machining process of an air rudder into a DT model (S. Liu et al., 2020).

Task 1.1.2 - Review of Digital Twin application for Civil Infrastructure

DT for static processes in structures and transportation infrastructure present challenges for prolonged data exchange and connectivity when compared to manufacturing processes. To understand the real-time behavior of civil systems, sensors such as accelerometers, inclinometers, displacement transducers, pressure cells, and temperature sensors can be used to measure the infrastructure's global response (Angjeliu et al., 2020). A case study by researchers in Cambridge Centre for Smart Infrastructure and Construction (CSIC) and statisticians at Alan Turing Institute (ATI) proposed Digital Twin for bridge assets to study risks and predict its performance by focusing on four areas of research: real-time data management using Building Information Modeling (BIM), physics-based approach, data-driven approach, and data-centric engineering approach (Ye et al., 2019). The study explored a DT coupled with statistical data obtained from multiple strain gauge sensors to develop a complete analysis.

Dawkins et al. created a Digital Twin model of a building using BIM and light detection and ranging (LiDAR) data and leveraged cell phone Bluetooth detection to monitor near real-time occupancy activity (Dawkins et al., 2018). For example, the current infrastructure design method utilizes BIM models for design but does not provide continuous feedback on the infrastructure system's performance. DT technology was used to predict and reproduce damage observed in current and historic masonry structures by monitoring heavy structural loads, continuous changes in environmental conditions (winds, earthquakes), and material degradation over time (Angjeliu et al., 2020). A Digital Twin model of a lightweight concrete roof with hydronic piping was leveraged to improve productivity and overall building efficiency (Lydon et al., 2019). The geometry of complex roof design, a lightweight concrete system (including hydronic piping), and the operational data from the piping system were used to correlate embodied energy of the building to operational energy (Lydon et al., 2019). Modern infrastructure management strategies and advanced modeling methods steer the development of future infrastructure systems.

DT technology was used to predict and reproduce damage observed in current and historic masonry structures by monitoring heavy structural loads, continuous changes in environmental conditions (e.g., winds, earthquakes), and material degradation over time (Angjeliu et al., 2020). In a study conducted by Curl, a Digital Twin simulation model was developed for water utility management to allow for simulation of maximum flow case scenarios and to fully replicate the facility's hydraulics, controls, and process performance (Curl et al., 2019). The DT optimized disaster management strategies by providing leaders forecasts of the disaster's impact for proposed decisions through reliable and inexpensive simulations.

Smart cities DT for a disaster management model was used to enable intelligent investment decisions, preparation, and disaster event mitigation (Ford & Wolf, 2020). In the recovery phase of a disaster, a proposed guide for resource allocation strategies can be prepared beforehand in anticipation of the simulated event to aid with the decision-making process and benefit most communities in the response phase to emphasize the efficient first responder deployment (Ford & Wolf, 2020). Infrastructure management value is provided when there are complex interconnected systems or unique operational challenges that would benefit from the use of a Digital Twin (Curl et al., 2019). Risk management for infrastructure can be assessed using DT to systematically analyze the threats and vulnerabilities, determine the degree of damage, and propose corrective measures. For instance, active connectivity provided by Digital Twin promotes maintenance, event detection, prediction, state monitoring, and event preparation for an impending event.

Additional lab and field research found that Digital Twin applications in civil infrastructure extend to steel structures, bridges, and disaster management. Research conducted on safety risk assessment of pre-stressed steel structures shows Digital Twin technology can achieve real-time monitoring of pre-stressed steel structures currently in use and can provide timely predictions of the safety level (Z. Liu et al., 2020). The use of social and building infrastructure management makes leadership decisions more accurate, yet additional work is required to develop Digital Twin for community management of disrupting infrastructure systems and their interactions with them during a disaster (Ford & Wolf, 2020). To effectively apply DT, the use of multiple sensory automated data acquisition technologies is needed to increase the accuracy of data collected based on the complexity of each project and considering the limitations of technology (Moselhi et al., 2020).

Task 1.1.3 - Review of Available Technologies for Data Collection and Simulation Methods

DT modeling methods, such as Building Information Modeling (BIM) paired with automated data from remote sensing equipment, improves feedback to manage infrastructure systems, monitor performance, optimize maintenance, and anticipate potential risks. The virtual modeling is done through tools such as Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), or BIM, while the data acquisition is made through sensor and laser scanning using LiDAR or photogrammetry. This method is used for an accurate digital replica of the existing physical infrastructure. The application of DT technology for the management of infrastructure faces challenges with unpredictable environmental conditions and external stimuli. Therefore, there is a need to build a reliable and accurate application of the technology (Ford & Wolf, 2020). Data acquisition tools for Digital Twin models include LiDAR and photogrammetry coupled with sensors, artificial intelligence, and IoT to provide automation in real-time data of existing infrastructure (Angjeliu et al., 2020). LiDAR, a remote-sensing technology, is used to assist in mapping, monitoring, and assessing forest resources and can be used to create a large-scale virtual model of an infrastructure system by measuring the distance of a beam of light to determine the time of the reflected signal (Angjeliu et al., 2020). A study conducted by Lantz used LiDAR technology coupled with ArcGIS data and cost analysis to predict impacted areas due to flooding and estimate the cost of the building due to the damage(Lantz et al., 2020).

In Germany, a combination of both optical and radar data was used to determine building height, cost-effective mapping, and physical analysis of structures using public high spatial resolution data to determine the impact of vertical structures on the environment in urban areas (Frantz et al., 2021). In addition, building height, infrastructure covered area, and occupancy of the building can be leveraged from the analysis (Frantz et al., 2021).

Massive data collected from cell phones can be used to model daily activity in a city and analyze activity time, duration, and land use by using a geolocated timestamp to represent trip chains using a trip extraction method to reveal activity behavioral patterns in cell phone traces (Widhalm et al., 2015). Widhalm et al. used a Relational Markov Network to input collected cell data (arrival time and duration) and model dependencies such as activity type, trip scheduling, and land use (Widhalm et al., 2015). In contrast, the use of sensing technology also presents disadvantages for data acquisition of infrastructure applications due to the use of wide or narrow divergences causing changes in the precision of the data (Gatziolis & Andersen, 2008). For example, LiDAR use is not suggested for mountains or undulating terrain or in fog, rain, or winter conditions. Therefore, it is not a reliable source of continuous real-time data due to uncertainties in climate conditions (Gatziolis & Andersen, 2008). The complete list of automated data acquisition technologies was researched by Moselhi with full capabilities, data acquisition effort, processing time, affordability, data accuracy and reliability, scalability, limitations, and accuracy (Moselhi et al., 2020).

Task 1.1.4 - Digital Twin vs. BIM vs. ITS

The use of Digital Twin technology for infrastructure management is in its infancy. The accuracy of the technology and the design of models for each application are separated into separate fields in civil engineering. Chen et al. researched Intelligent Transportation Systems in the management and security of traffic flow detection for real-time data acquisition using a deep learning algorithm for vehicle detection of urban roads through captured videos and cloud data storage (Chen et al., 2020). The technology uses vehicle detection, vehicle counting, and a vehicle tracking algorithm with an average accuracy of 92% (Chen et al., 2020). The use of DT technology encountered challenges to accurately model the behavior response of an infrastructure system, and there is a need to link the modeled systems among other systems.

Kučera et al. improved city logistics and transportation planning with the use of PTV VISSIM software for traffic infrastructure planning in an area in the Czech Republic and studied the impact of rebuilding an intersection on traffic flow in city logistics using microscopic models to simulate congestion, reduce vehicle delays, and improve road safety based on traffic flow (Kučera & Chocholáč, 2021). A real traffic simulation management tool was used for logistic planning suitable for achieving the concept of sustainable city logistics, visualizing real city traffic, designing efficient traffic management strategies, and test different construction scenarios of all intersections (Kučera & Chocholáč, 2021). Additionally, Moselhi explored automated data acquisition using remote sensing technologies, including a focus on multi-sensor data fusion models by integrating radio-frequency identification (RFID), a wireless sensor network (WSN), BIM, and digital imaging to enhance site data acquisition (Moselhi et al., 2020).

Moselhi researched a construction management DT application to mitigate schedule delays, cost overruns, and safety on site (Moselhi et al., 2020). Kamari et al. evaluate design alternatives using virtual reality to understand cost and sustainability life cycle assessment using building information modeling (Kamari et al., 2021). A study conducted by Ma et al. provided visual architectural changes monitored during the construction phase using BIM and researched a sustained laser scanning application to a suspension bridge by using sensor data to accurately model the main frame of suspension bridge bending deformation and performance using a high precision total station for 5 hours(Ma, n.d.). Kamari et al. demonstrate an understanding of the preference of economy and sustainability using virtual reality (VR) experiences to enable improved design, decision making, and carbon footprint tracking using BIM (Kamari et al., 2021). The energy expenditure of the real-time monitoring system also requires a sustained amount of energy and additional resources.

Task 1.1.5 - Gaps in Digital Twin Research

During the review of research in manufacturing and infrastructure applications of Digital Twin, three main gaps in the literature were apparent. First, various lab and field studies have been conducted for individual civil infrastructural systems, but research on the impact of interactions between multiple systems is needed. A connection between systems can alleviate the outcome of disasters by forecasting an event and providing feedback on the impact of the actions taken. Secondly, studies recommended a DT model with a lower focus on geometric perfection by instead focusing on the representational accuracy of the model and on the systems' interactions to improve decision-making strategies. Thirdly, automated data acquisition methods, big data storage, efficient construction processes, and the benefits of a well-maintained system (or infrastructure) need to be investigated further.

At present, Digital Twin can only predict failures and their life cycles through internal operational data but cannot predict the failure caused by external physical effects (Li et al., 2020). The use of automated sensor scanning technology needs sustainable economic justification, in addition to the need for research on more extensive data acquisition methods and compatibility of automated data acquisition technologies

(Moselhi et al., 2020). DT sustainability benefits need to be established based on economic, social, and environmental impacts. DT technology aids in the efforts of sustainability goals by working with industry and academia to determine the efficacy of this modern technology for the life assessment of current infrastructure and assess the viability of DT for infrastructure management. Additionally, DT technology can align with United Nations sustainability goals for clean and affordable energy, promoting economic growth, clean water and sanitation, industry innovation and infrastructure, sustainable cities and communities, responsible consumption and production, climate action, and expand partnerships in the world.

Current infrastructure is maintained and inspected using methods that have not been updated in several decades; the adoption of Digital Twin technology presents a solution to improve infrastructure quality and current management practices. The United States 2021 ASCE Infrastructure Report Card obtained an overall rating of C minus (in terms of capacity, condition, funding, future need, operation and maintenance, public safety, resilience, and innovation) for the overall rating of the infrastructure (roads, bridges, transit, rail, etc.). DT presents an alternative to improve the current infrastructure rating by improving quality and safety conditions (DiLoreto et al., 2020). The use of this technology has encountered challenges in accurately modeling a specific system, but the capability of continuous data acquisition has the potential to improve the management and operational tasks of the infrastructure system.

DT modeling methods using data available from the construction of IDRB on the UTEP campus, LiDAR (aerial and ground sources), and existing transportation data (signage, bus stops, and traffic lights), a DT model will aid in the policy decision-making process for the creation of visualization models, simulated traffic interruption scenarios, and construction management improvements.

Task 1.2 – Data Collection

The goal of this subtask was to create and distribute a survey to campus stakeholders. The survey, as it was distributed via email, is shown below in Figure 4.

C2SMART: Survey Regarding Campus Data

I am writing to ask for a few minutes of your time to support a project on campus by completing a brief survey regarding the types of data that campus stakeholders collect and use on a regular basis.

Recently, Drs. Jeffrey Weidner, Adeeba Raheem, and Kelvin Cheu from the Department of Civil Engineering at UTEP were awarded a USDOT grant titled "Digital Twin Technologies Towards Understanding the Interactions between Transportation and other Civil Infrastructures." The goal of the project to begin to create a Digital Twin (DT) model for the UTEP campus. A DT model is a simulation model or models that replicate a real system which utilize data from sensors within the real system. DT models are frequently used in closed systems in manufacturing to help optimize and improve the process.

Our project aims to explore how this technology would apply to a complex system like a university campus. Our initial focus is on civil infrastructure systems on campus (broadly inclusive of transportation and buildings/construction at this time) but one of the tasks in this project is to explore the availability and applicability of existing data sources on campus that can be added to the DT model in the future. That is the purpose of this survey.

The subsequent questions are an informal survey about your department and the data that you use on a regular basis. The survey does not require IRB approval because it is not human subject research. There are no obligations to participate or otherwise commit any time outside of the survey. We are just trying to understand the complex campus system on campus and the data that drives it. We are hoping to generate future research ideas based on your input.

Survey

A key aspect of a Digital Twin model is data collection, analysis, and feedback to the simulation model. The following questions relate to campus-specific data and are for information purposes only. Feel free to answer in whatever form you desire. Note that we may follow up for clarification purposes.

1. What data do you collect?
2. How do you use the data you collect?
   How long do you keep this data, and are there requirements for retention?
3. How frequent do you use the data (i.e., up to the minute, daily, weekly, monthly, term to term, or annual)?
4. What data do you wish you had?
5. Who are your stakeholders?
6. Do you share your data? If yes, with whom?
7. Is there anyone else on campus to whom we should send this survey?

Thank you for your time. If you prefer us to contact you in a mode other than through your UTEP email, please let us know.

Figure 4. Document. Survey for Campus Stakeholders

The survey was distributed to a list of 12 targeted campus stakeholders, whose names are withheld for privacy. Unfortunately, despite several reminders, we did not receive any feedback. Rather than continuing to pursue this avenue of stakeholder engagement, the research team elected to establish a relationship with campus stakeholders at the workshop (Task 7 – Community Engagement Workshop) and work from there moving forward.

Task 2 – Reality Capture of Existing Conditions

This task included three subtasks. Task 2.1 was to create a base layer model using existing data as described in Task 2.1 – Base Layer Creation from Existing Data. Task 2.2 included reality capture of the IDRB as described in Task 2.2 – Reality Capture of Campus Building using LiDAR. Task 2.3 focused on the transportation network as described in Task 2.3 – Reality Capture of Existing Transportation Signage Data.

Task 2.1 – Base Layer Creation from Existing Data

An important component of DT is visualization capacity. While not necessary to achieve the pure functionality of a DT, visualization supports deeper understanding and intuition of DT by humans, and serves to support stakeholder outreach, education, workforce development, and dissemination. Our case study included two primary simulation capacities – namely a BIM model and a transportation network microsimulation. To help connect the two and create a rich environment to visualize the scenario, a base layer was required.

Task 2.1.1 – TNRIS Aerial LiDAR Data

The base layer is primarily a geometric replica of the as built environment. The first effort to create this utilized aerial LiDAR data captured in 2014 by the Texas Natural Resource Information System (TNRIS) for the purposes of flood planning by FEMA. The dataset is publicly available from the TNRIS website (https://tnris.org/). The data includes 77 individual files in .LAZ format. The data is point cloud data, including three dimensional coordinates for each point, with the vertical component referenced to sea level. The data is in meters. The raw data was processed to create a digital surface model and digital terrain model. The former includes all vertical appurtenances (i.e, buildings, trees, etc) and the latter is simply the ground elevation. Through comparison of the two, buildings were identified on the university campus, as shown in Figure 5.

Figure 5. Image. Campus building rendering extracted from TNRIS LiDAR data

As this data set was created in 2014, there have been some changes to campus. Most notably, the IDRB was not yet built in 2014. In fact, the former building, Burges Hall, is still visible in the data. This building was manually removed from the base layer. However, this required the team to create a new model of the IDRB, as described in Task 2.2 – Reality Capture of Campus Building using LiDAR.

Task 2.1.2 – Transportation-related Data

The transportation network was built initially off two existing data sources. The first was a shapefile of roadway centerlines provided by the City of El Paso. The second was origin and destination data for the campus network from a prior research project (Cheu & Ruiz, 2021).

The existing transportation network was input into VISSIM, the selected simulation platform for transportation data. In terms of the physical infrastructure, this base model included travel lanes, signal heads and signal timing, and signs (i.e., stop and yield). This model was later updated with the data collected in Task 2.3 – Reality Capture of Existing Transportation Signage Data.

The synthetic data for the intersections of interest (Schuster Ave. and Sun Bowl Dr., and Schuster Ave. and the freeway ramps) was provided by the City of El Paso Street and Maintenance Department; this data includes traffic volumes per turning movement and traffic signal timings. Figure 6 shows the signal timing plan in VISSIM, for the Schuster Ave. and eastbound I-10 intersection; Figure 7 shows the signal timing for the various phases at the Schuster Ave. and Sun Bowl Dr. intersection.

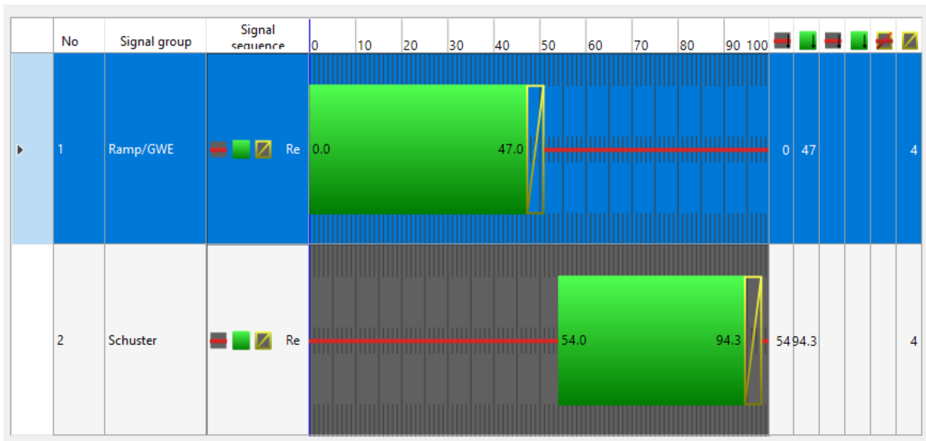


Figure 6. Image. Signal group for ramp at Gateway East and Schuster

Figure 7. Image. Signal input for Sun Bowl and Schuster intersection

The peak hour turning movement data for the intersection at Schuster and eastbound I-10 was collected in September 05, 2012. The peak hour turning movement data for Schuster and Sun Bowl intersection was taken on Thursday October 04, 2021. The data includes the count for left turns, straight, and right turns from each approach.

The total vehicle counts for the turning movement at the peak hour was determined as between 8:00 a.m. and 9:00 a.m. The values used for the simulation input in VISSIM for the total vehicle count are shown in appendix.

Model Input: Static routing decisions were used in the model to represent how vehicles flowed through the transportation network (i.e. how many vehicles chose to go straight versus turn). The relative flow values for the vehicle inputs were based on the traffic turning movement counts from data provide by the city and also obtained from previous research. The relative flow values for the intersections in this network (Schuster Ave. and Gateway East Ramp, Schuster Ave., and Sun Bowl Dr.) were obtained from documents provided by the City of El Paso. The vehicle input for Sun Bowl Southbound was retrieved from previous publicly available research conducted by the university.

Vehicle routing decisions for roundabouts and inlet ramps to interstate highway (I-10) have equivalent distribution turning movements due to limited availability of data. The roundabout next to the campus entry point was not assigned equivalent distribution for vehicle decision. Adjusted data from previous research was included for roundabout routing decision values (Cheu & Ruiz, 2021). The traffic decision heading into campus is less because of the controlled entry point.

Task 2.2 – Reality Capture of Campus Building using LiDAR

Task 2.2.1 – LiDAR Data Collection

A 3D model of the IDRB was created using a BLK 360 laser scanner from Leica Geosystems (Figure 8). The laser scan was used to create a point cloud of the infrastructure system (without the need for design drawings) for externally exposed components. To perform the scans, the Field Cyclone 360 app on any mobile device was used on-site to remotely control the scanner and to view the raw 3D point clouds immediately after scanning. The app was essential on-site for quality control of field scans, to keep track of the scans, and to piece together the point cloud data using edge computing technology. The software was used to manually select the general position of each individual scan to align and combine the scans. The allowed the project team to verify quality of the scan and area of interest and rescan if needed.

Figure 8. Image. Leica BLK 360 Terrestrial Laser Scanner (left) and sample set-up (right)

The scanning took approximately three to six minutes per scan depending on the quality and the detail of the scan. The scanning process for the building took 12 individual scans to generate the point cloud needed to reconstruct the building. An additional seven scans were made to capture the surrounding transportation network, roundabout, adjacent parking garage, and Sun Bowl Dr. The scanning locations and pattern can be seen in Figure 9. In addition, the second floor of the interior of the building was scanned to include the lobby area and hallways. The full interior of the building could not be scanned because of access restrictions. The interior that was scanned was not included BIM model because the scenario adopted was focused on the building exterior and transportation network.

Figure 9. Image. Aerial-View of Scanner Location Placement

After gathering the necessary scans around the area, Cyclone Register 360 was used for on-site tagging of measurements, videos, images, text, or voice files to the point cloud. When the scans were not well aligned, the software was used to adjust the point cloud or rescan. After creating the point cloud and aligning the scan accurately, the file was shared to Autodesk Recap for conversion to a file type compatible with Autodesk Revit (i.e., .rcp). In this case, point cloud data was imported into Revit to manually use a point-to-point tracing method to generate the three-dimensional model for the external characteristics of the building (I.e., walls, doors, windows, and roof). Table 1 summarizes the number of scans, time taken for those scans, and the number of points collected for the point cloud.

Table 1. Data Collection Details

	Scanning	Registration	No. of Points
Data Collection	19 scans	4 hours	142,145,570

Task 2.2.2 – Manual Construction of BIM Model

The material sections were identified and assigned using the design drawings (provided by UTEP) and then manually applied. The walls were traced, extruded, and assigned a material section. A similar process was followed to include windows and doors at the correct position. The roof was approximated using the design drawing since the terrestrial laser scan was not able to capture any point above the roof ledge. Table 2 describes the number of elements per component category and the time spent adding those elements to the IDRB BIM model; Figure 10 shows the completed BIM model.

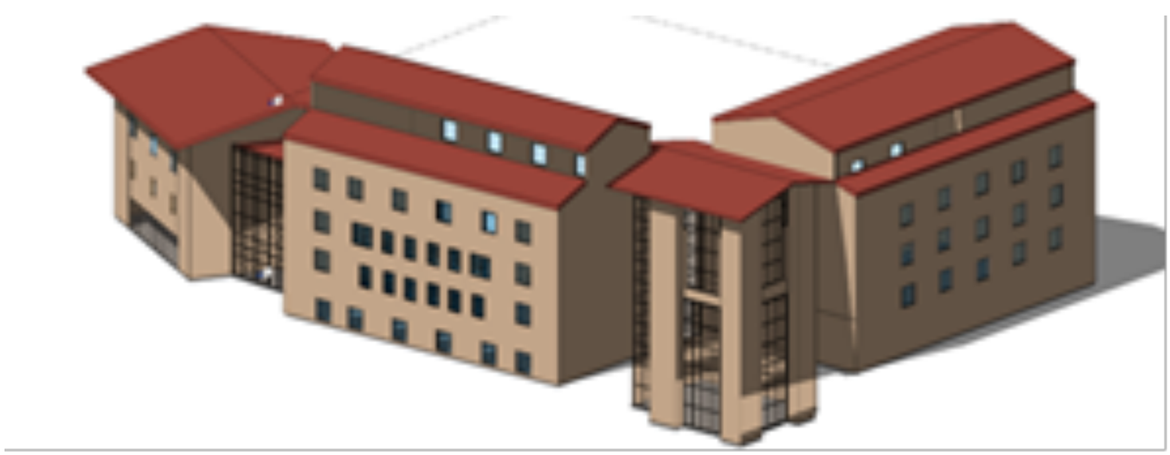


Figure 10. Image. IDRB building BIM model

Table 2. Scan-to-BIM Reconstruction Time

	Component	Count	Total Time (hrs)
Scan-to-BIM	Windows	80	5
	Doors	8	2.5
	Walls	10	3
	Roof	7	3
			13.5

Since the laser scan captures only the external exposed geometrical information, the material sections were selected and assigned based on the specifications from the design drawings and visually identifiable material (e.g., glass windows and doors, walls, etc.). The entire model must be done manually and is, therefore, more time-consuming.

The point cloud generated from the scans can be seen in Figure 11 for the IDRB building at UTEP created using the Leica BLK360 laser scanner. This 3D model can be scanned in black and white to compensate for big data storage, to decrease individual scan duration, and to optimize laser scanner battery life. The Leica BLK 360 allows for not only color but thermal readings at the time of the scan. Figure 12 shows the surrounding transportation system, including a roundabout, near the IDRB building. Figure 13 shows the east side of the IDRB and a pedestrian bridge.

Figure 11. Image. Point Cloud of IRDB

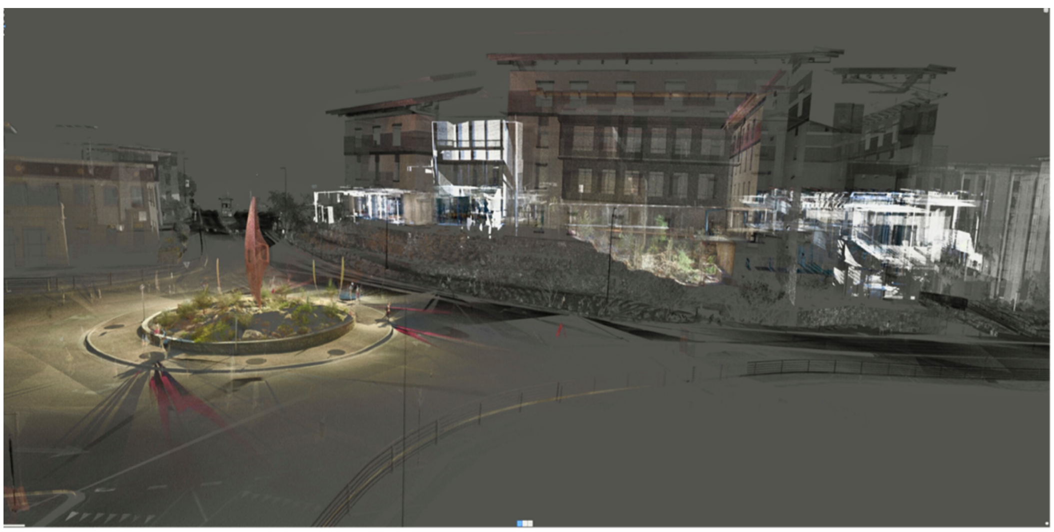


Figure 12. Image. West-view of Point Cloud IDRB and Surrounding Transportation Network

Figure 13. Image East view of IDRB building

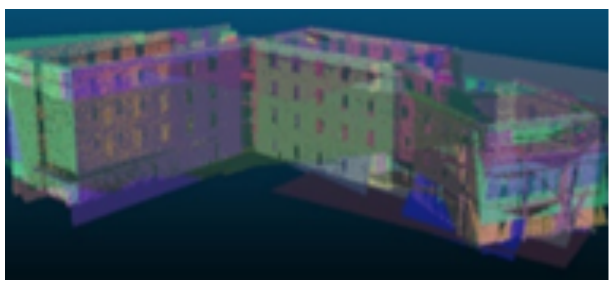
The following steps outline the general methodology used for the creation of a LiDAR to BIM model:

I. Laser scanning of the building
   a. Place laser scanner at key point to capture detail scan building (number of scans depends on building size, shape, and access)
   b. Check the scans on-site using mobile device application
   c. Rescan if needed
   d. Automated update of point cloud to storage
II. Transfer point cloud data from cloud storage to computer (software manipulation)
   a. Large data files become time consuming at data transfer and manipulation
III. Align scans in Cyclone Register
   a. Check all scans are aligned correctly
   b. Manual approximate adjustment
   c. Artificial Intelligence finished alignment
IV. Classification of the files (compatibility with BIM model software)
   a. Convert file depending on the software that is going to be used
V. Open the file in the BIM software
   a. Import as point cloud file
   b. Choose the point cloud file as .rcp

Task 2.2.3 – Automated Approaches to Model Reconstruction from Point Cloud Data.

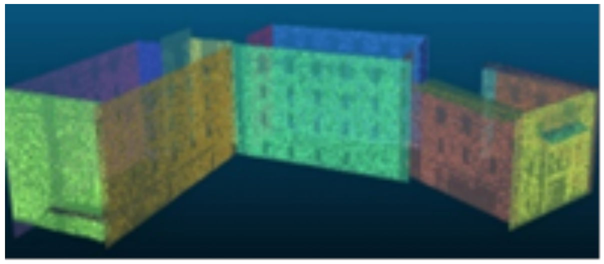
To improve the time to reconstruct a virtual model directly from the point cloud of the IDRB, various three-dimensional reconstruction algorithms were explored. The two methods selected were Random Sampling and Consensus (RANSAC) algorithm and the Oriented Point Sampling (OPS) algorithm. These methods were selected based on 1) the ability to reconstruct a virtual model directly from the captured point cloud data, 2) the reduction in time to reconstruct the model, 3) the computational efficiency of the reconstruction, 4) the ability to detect planes for the plane-like nature of the exterior walls of the building, and 5) to automate the reconstruction process of the building. These methods were investigated to determine the level of detail (LOD) for which the automated approaches reconstruct the virtual model.

The RANSAC algorithm detects planes by computing the normal of the point and assigning a plane to point clusters within the specified input parameters. For this algorithm an open-source software was used for its user-friendly point cloud data management and simple iterative process for various input parameters. In addition, noise filtering, subsampling, normal computation, and file compatibility for export to other modeling software. The point cloud data was subsampled and saved as separate files to record the computational requirements and total time to generate the virtual model. A random subsampling of 1%, 2%, and 3% from the original point cloud were selected. The time to generate the model, number of planes detected, number of inliers per plane, and processing time to detect a single plane was recorded for the original and each subsampled data set. The resultant models for RANSAC can be seen in Figure 14 and the OPS resultant models can be seen in Figure 16.



(a)

(b)



(c)

Figure 14. Image. RANSAC Reconstruction for Subsampled Data (a) 1%, (b) 2%, and (c) 3%

The point cloud data was subsampled, and the times per subsampling, the number of planes detected, and processing time to generate the RANSAC mode are recorded in Table 3. The model was created under 12 seconds for the external geometry of the building. The algorithm oversimplifies the point clusters to random planes and assigns random orientation. The RANSAC algorithm works best when the point clusters present a clear distinction between the planes to detect. Therefore, a lower subsample yielded a simplified external geometrical replica of the building with clear distinction of the planes (as shown in image C in Figure 14). The plane detection and the convergence of the planes for the best fit model was done within 1.73 seconds with only 19 planes detected. A higher subsample generated random planes with incorrect orientations for various point clusters.

Table 3. RANSAC Processing Time

Subsampling	No. of Planes	Processing Time (s)	Subsampling Time (s)
3	264	11.671	34.338
2	36	3.681	33.887
1	19	1.713	34.098

The processing time when compared to manual approaches significantly reduced the time to generate the model for reconstructing the external geometry of the building. This is limited to the external geometry with no material properties of the building when compared to the BIM model. An approach to incorporate material detailing to the RANSAC model was explored by importing to BIM software. The RANSAC resultant model was converted into a point cloud data file type and imported in the Revit as an intermediary step to reconstruct the model using the approximate geometry and assigning material section characteristics. The imported file to the BIM software can be seen in Figure 8. The colors were randomly assigned to generated planes. These were maintained after export into the BIM software.

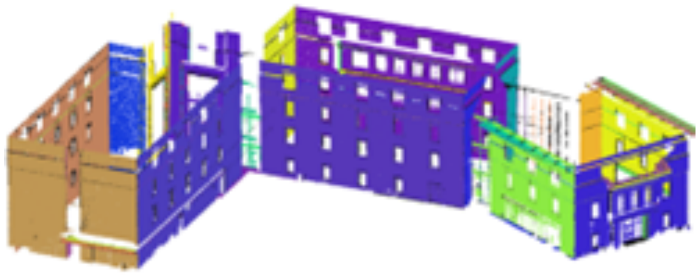
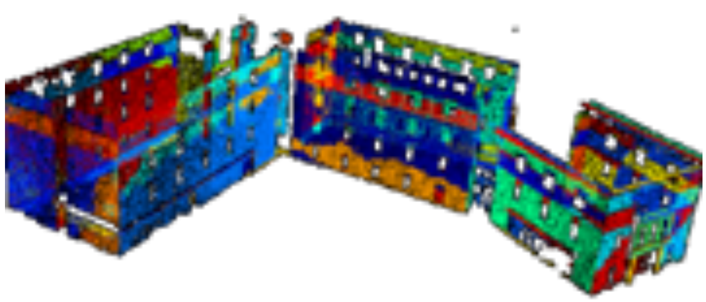


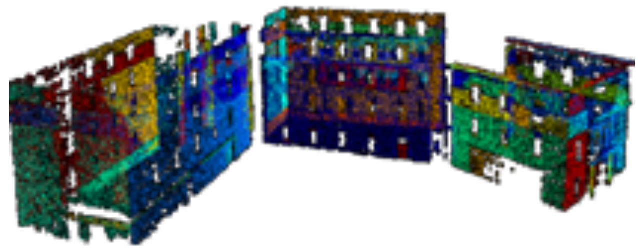
Figure 15. Image. RANSAC Model Imported to Revit

The second algorithm model selected was the Oriented Point Sampling (OPS) algorithm. This approach is supposed to reduce the time required to generate a three-dimensional reconstruction from the captured point cloud data. The algorithm uses a single point to detect a plane then converge the point clusters into a plane. The algorithm was developed by Victor Amblard to optimize the computational requirement when using point cloud data. The requirement to run the algorithm are: 1) Download of point cloud and boost libraries, 2) manual installation and integration of depreciated libraries, 3) generating a cmake file by adjusting the correct paths for the algorithm.

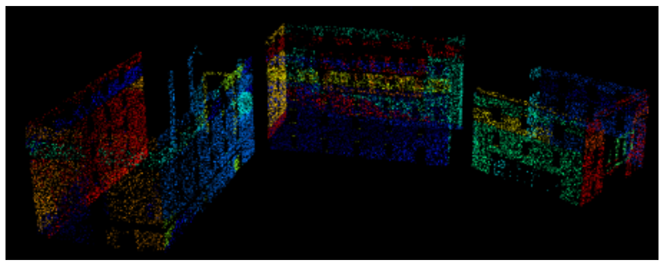
The same randomly subsampled point cloud data files were used (3%, 2%, and 1%). A file conversion from .e57to a file format .pcd was performed using cloud compare open source software. The output file from the file conversion was then used as the input for the OPS algorithm. The resultant models for the OPS algorithm subsampled point clouds can be seen in Figure 9.



(a)



(b)



(c)

Figure 16. Image. OPS Algorithm Subsampled Reconstruction

The OPS reconstruction performs best when there are sufficient points to detect and generate the planes. This approach produced an accurate three-dimensional model for a subsample of 3%. Any reduction in the number of points reduces the quality of the model. The best-fit virtual model using the algorithm was produced with 88 planes in approximately 2 minutes (shown in Table 4).

This algorithm-generated model present its own unique limitations. The algorithm is limited to the visualization tool in the point cloud library. This prevents the model from being export to additional simulation software and digital twin platforms. In addition, no material section and material properties can be added to the model.

Task 2.2.4 – Summary of Reality Capture of Buildings using Terrestrial LiDAR

These methods each present the individual benefits when reconstructing a virtual model from the point cloud data. To summarize the three-dimensional reconstruction methods each present distinct benefit and disadvantages:

1) BIM model using Revit
    a. A high-fidelity model to include material properties
    b. BIM model is time consuming when compared to automated methods
2) Automated methods using algorithm approaches
    a. OPS

    i. Automated the reconstruction process using mathematical calculations
    ii. Direct import of point cloud data
    iii. No application to integrate material properties
    iv. No export of generated file
b. RANSAC
    i. Automated the reconstruction process using mathematical calculations
    ii. Assign random plane to point clusters based on input parameters
    iii. Direct import of point cloud data
    iv. No application to integrate material properties
    v. Export option available to improve model and include material properties

Table 4. OPS Subsampling Time

Subsampling (%)	No. of Planes	Average Iterations	Avg. Inliers/Plane	Total Time (s)
3	88	204	1233	123.267
2	73	311	971	64.295
1	44	375	752	17.204

A paper showing the qualitative comparison of the reconstruction methods was published at the ASCE International Conference for Transportation and Development by Julio Gallegos and Jose Luis Lugo. The resultant model's algorithm generated BIM lacked certain DT ready qualities. The model is limited by the external characteristics of the building with limited information of additional structural elements, utilities, and hidden components. The DT model reconstruction is dependent on the use of the model and for the serviceability of the surrounding transportation network the visual of the three-dimensional geometric characteristics of the exterior building is sufficient for visualization purposes of the surrounding infrastructure.

The algorithm generated models in specific proved to be useful as an intermediary step to achieve a BIM model of the building to include detailed geometry, windows, doors, and roof. All attempted reconstruction methods can be improved in terms of accuracy of the building characteristics, compatibility with real-time data, and efficiency when creating the model.

Task 2.3 – Reality Capture of Existing Transportation Signage Data

Task 2.3.1 – Data Collection

To determine the transportation signage to include in the DS model, the pre-existing transportation network asset data (e.g., signage, pavement markings, etc.) for the entire campus network was recorded semi-automatically from video footage. The data recorded included signage designation, the orientation of the signage (i.e., which cardinal direction the sign is facing), side of the street where the sign is located (e.g., NE, NW, SE, SW, or the center of the street), latitude, longitude, and altitude. This data was collected using a mounted GoPro (model: HERO8 Black) attached to the exterior windshield of a car. The longitudinal and latitude coordinates for each sign were extracted for each individual transportation asset for a given point in the video recordings. Different portions of the campus were recorded by driving campus roadways, ensuring to capture the entrances and exits of the parking lots and garages located on and around campus. A total of 30 videos were collected. These videos ranged in length from 37 seconds to nearly 12 minutes.

Task 2.3.2 – Data Extraction and Analysis

From these videos, the camera telemetry data was extracted into a CSV file – most importantly, the latitude, longitude, and altitude associated with each timestamp from the videos. To collect the data, the videos were manually reviewed by moving through the different frames of a video until an object of interest was located. The objects of interest considered for data collection are:

- Traffic signs
- Pavement markings
- Utility access hole covers
- Trashcans
- Lampposts
- Fire Hydrants
- Traffic Control Stations
- Storm Drains

The object of interest was considered as close to the vehicle as possible when the object was just outside of the frame of the video, as seen in Figure 17.

Figure 17. Image. Vehicle as it approaches the sign (left) and vehicle as the sign is just out of the frame (right)

At this frame, the timestamp was recorded into a CSV file, as well as the object description with MUTCD code (if applicable; some objects did not have a MUTCD code, such as the pavement markings), the orientation of the sign, and the side of the street the sign is on. The object description with the MUTCD code was organized into a dropdown menu, with the MUTCD code followed by the description – see Figure 11.

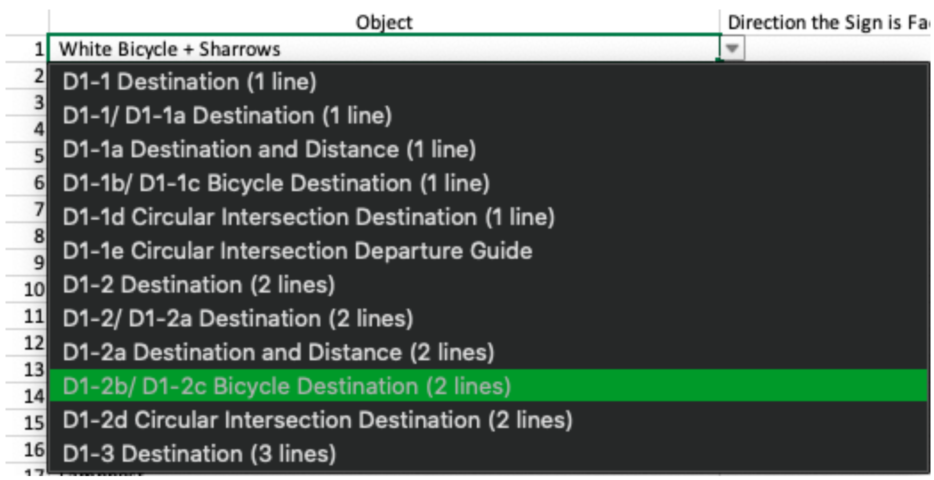


Figure 18. Image. Dropdown menu of object code and description

A program was developed to associate the timestamps of an object with the corresponding latitude, longitude, and altitude for that timestamp. The program either matched the timestamps exactly (e.g., where both documents had the timestamp 00:42.7), or it matched the timestamp that came immediately before. Figure 19 shows a portion of the output of the program, providing a visualization of the comparison. The program wrote a new CSV file combining the information from the GoPro telemetry data CSV file and the CSV file containing the objects of interest.

```
Home file (Route# CSV):    1 00:03.3
Away file (gryo-gps CSV): 7 00:03.2
Lat: 31.7696763
Long: -106.5083334
Altitude: 1172.996

Home file (Route# CSV):    2 00:04.4
Away file (gryo-gps CSV): 12 00:04.3
Lat: 31.7697159
Long: -106.5083746
Altitude: 1173.026
```

Figure 19. Image. Comparison of two CSV files to match timestamps

The dataset includes a total of 1,835 identified assets. Combined with the videos, this provides a valuable, manually created dataset for machine learning applications focused on identification of traffic assets, which was out of the scope of this project.

Task 3 - Integrate Simulation and Information Models with Reality Capture

This task focused on integrating the two primary digital models utilized for this project with the reality capture base layer; namely the IDRB BIM model, the VISSIM Transportation Model, and all the data collected in Phase 1. Each are discussed in turn, and the process for combination to create a DS model is discussed in Task 4 – Develop a Digital Shadow Model of Campus.

Task 3.1 – Creation of IDRB model for integration into DS

The IDRB BIM model was created as part of Task 2.2 – Reality Capture of Campus Building using LiDAR. However, the proprietary format utilized by Autodesk REVIT was not compatible with any integration tools. As we felt we no longer needed the construction progress for visualization purposes, we elected to convert the REVIT model to SketchUp (.skp) which is a much more ubiquitous file type for integrating with other software. This model maintained LOD 300.

Task 3.2 – Addition of Signage to Reality Capture Base Layer for Transportation

The transportation network signage data was input in VISSIM manually. For example, the pole and sign dimensions were retrieved from the Manual on Uniform Traffic Control Devices (MUTCD) standards. Then, an image of the sign was imbedded into the sign linked to the VISSIM software. The traffic signage was added to the model manually by drag and drop tool based on the approximated latitude and longitudinal coordinates extracted from the data collection in Phase 1. An example of a traffic sign input into VISSIM can be seen in Figure 20.

The model includes a total of 83 transportation signage from a combination of signs, traffic signals, and lampposts. Additionally, 71 pavement markings unique to VISSIM (i.e., pavement markings not available in the VISSIM pavement network object sections) were added to the network.

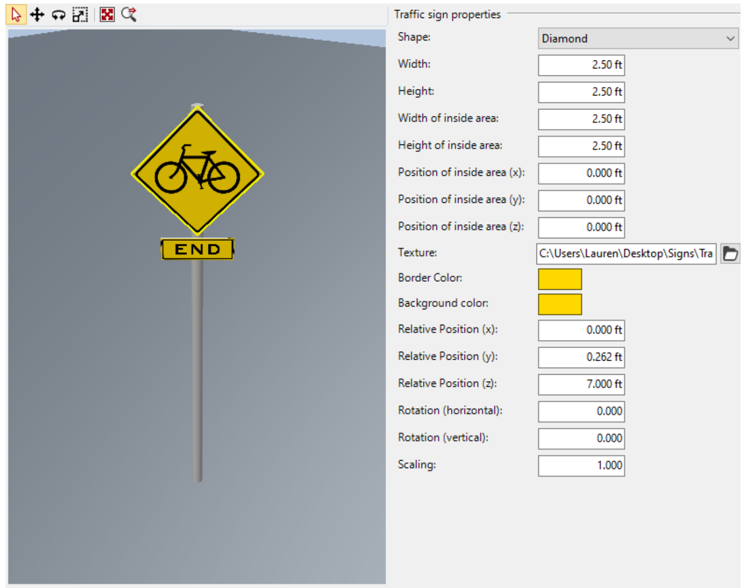


Figure 20. Image. Traffic sign Properties input via MUTCD specifications

Task 4 – Develop a Digital Shadow Model of Campus

As previously stated, the purpose of this project was to work towards a DT application for a college campus. The goal was to achieve a Digital Shadow (DS) model. A DS model has the same primary components as a DT; namely a real system component (in this case, operational transportation infrastructure and a construction site) with sensors that produce data to support decision-making and a digital replica of the real system with some decision-making intelligence. The primary difference is that the DS includes only communication from real to digital systems. The digital component does not communicate back to the real system. The target DS system for the project is depicted in Figure 21. As stated in Challenges and Assumptions, construction on the IDRB has completed, and the transportation network is not currently instrumented. Adding instrumentation was out of the scope of this project, meaning we could not create a true DS system inclusive of the operational infrastructure. We pivoted to create a digital shadow where the real system component was also a digital model, as depicted in Figure 22.

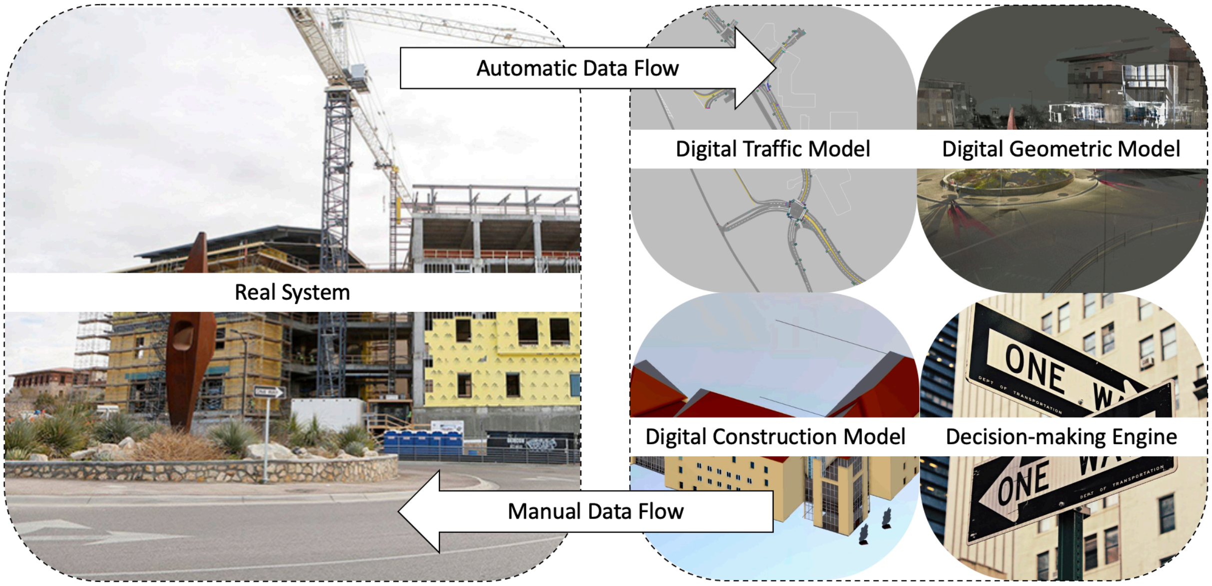


Figure 21. Diagram. Target Digital Shadow System

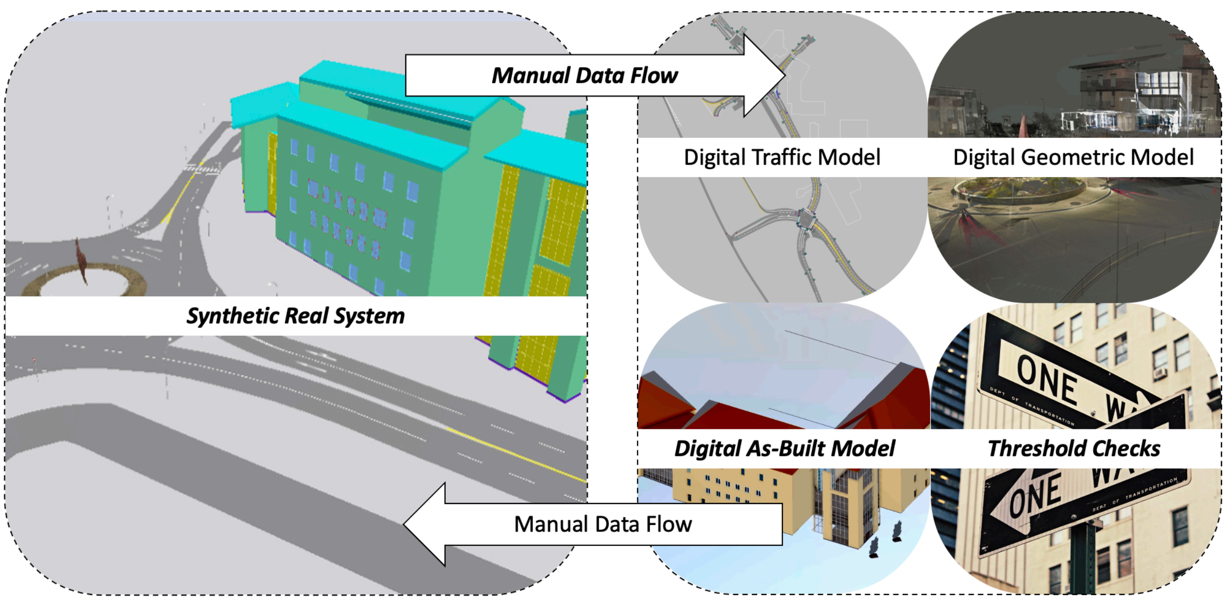


Figure 22. Diagram. Achieved Synthetic Digital Shadow System

The synthetic DS system presented some unique challenges. The primary challenge was that the transportation network model, created in VISSIM, would have to serve as both the real system component (data producer) and the digital replica component (data consumer). However, due to licensing issues, we could not have two instances of the VISSIM model running concurrently. Therefore, the DS model would have to run sequentially. In either capacity, the VISSIM model would have to be dynamic, meaning that it could change mid-simulation. In the case of the replica real system, the VISSIM model would have to be altered from free flow conditions to include an interruption to traffic that represents the system disturbance scenario. In the case of the virtual system component, the VISSIM model would have to take input from the real system and model a change behavior to determine if and when a change should occur. Figure 23 illustrates how the real system interacts with the virtual system to form the digital shadow given the aforementioned limitations.

This simulation change behavior was achieved via an Application Programming Interface (API) and Component Object Model (COM) programming. COM programming allows for dynamic alternation of the VISSIM model, but it is not without some limitations. Model interventions have to be prescribed, but they can be triggered based on certain thresholds. In the case of the DS, the traffic interruption was predefined as described in Task 5 - Simulation of Campus Digital Twin and Visualization Demonstration.

The other notable challenge with the synthetic DS system was inclusion of construction of IDRB. Since the as-built BIM model was not made available from the contractor responsible for the construction of IDRB, we elected to include only an as-built BIM model.

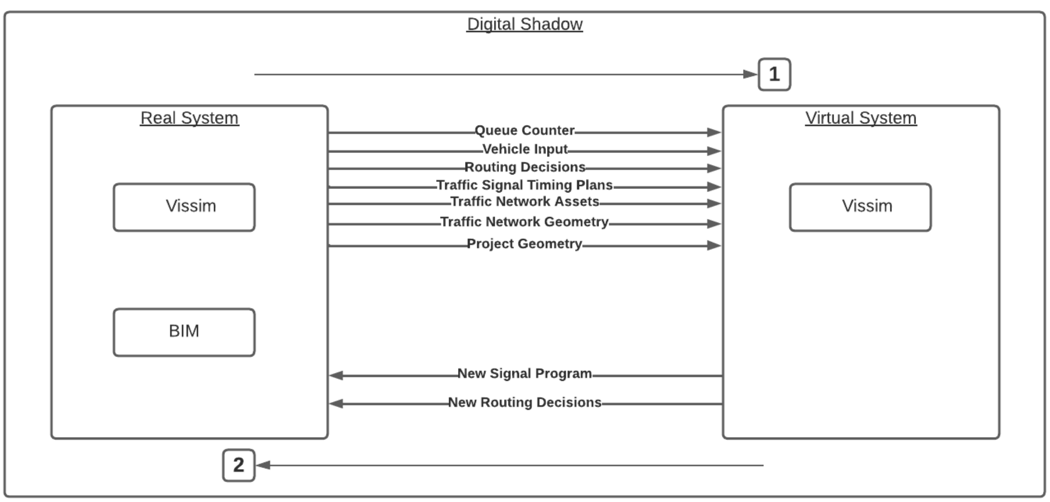


Figure 23. Diagram. Digital Shadow using Vissim Models

Task 5 - Simulation of Campus Digital Twin and Visualization Demonstration

Task 5.1 – Traffic Interruption Scenario Development

The modeling scenario the team wanted to test with a Digital Shadow model is the interruption of the surrounding transportation network due to the construction of the Interdisciplinary Research Building, specifically, having northbound Sun Bowl Dr. traffic be blocked due to a construction vehicle. This scenario was frequently observed anecdotally during the construction of IDRB by the research team. The Sun Bowl 2 parking lot was used for construction staging and traffic was frequently interrupted to allow the tower crane to pick materials from the lot and bring them on site. It was also observed that there was not a lot of redundancy in the transportation network in that vicinity that would allow for rerouting or detours during these short closures. For the purposes of the scenario, an alternative route was proposed through Sun Bowl 2 parking lot to accommodate northbound traffic on Sun Bowl Drive when there is a complete closure of the road. Figure 24 shows the transportation network modeled to analyze this scenario.

Figure 24. Image. Traffic simulation overall layout with satellite view

The scenario simulated within VISSIM was a short-term obstruction used at the southernmost entrance of the roundabout at Sun Bowl Drive and W. University Avenue. In lieu of a crane, a construction vehicle would occupy the two northbound (NB) lanes of Sun Bowl Drive. This results in a queue developing in the NB direction. When the queue length exceeded a certain threshold, traffic was rerouted through the SB2 parking lot to the roundabout on W. University Avenue heading eastbound (EB). The two southbound (SB) lanes of Sun Bowl Drive will remain open during this scenario because any rerouting would have required a substantially larger network model. The blockage event was scheduled to last 30 minutes. Figure 25 shows the blockage event and the alternative route vehicles would take to circumvent the blockage. Note that the reroute passed through the portion of the lot that was dedicated for construction. This was done for simplicity's sake.

Figure 25. Image. Close view to alternative route for construction scenario

Analysis of the scenario as described above indicates that the proposed reroute of traffic through the Sun Bowl 2 parking lot would have a been a feasible solution to the traffic interruptions and a DT model would have been useful in identifying and demonstrating the efficacy of this solution. Moreover, if data was available on queue length and that the network was equipped with sufficient ITS technology, this option could be triggered automatically by a DT system once it was originally established. Additionally, if southbound traffic from the roundabout was blocked as well, the parking lot could have accommodated the portion of southbound traffic approaching from the I-10 exit, but there would still be a requirement to accommodate traffic from southbound Sun Bowl and University Ave. A larger scale and more complete DT model would support developing those solutions as well.

Task 5.2 - Visualization Scenarios with Senior design students

To facilitate dissemination and workforce development regarding DT technology, the UTEP Civil Engineering Senior Design Capstone course was involved in the project. This term, each senior design team, comprised of between four and six students, worked on a campus improvement project of their own design. As part of their project, each team was invited and encouraged to collaborate with the research team to conduct a terrestrial LiDAR scan of their site. The scan point cloud data was used as a visual to aid in the conception of their design ideas. Some teams used the point clouds to quantitatively determine project requirements like terrain contours for survey purposes. The team projects ranged from building renovations and replacement, pedestrian bridge for improved accessibility to adjacent buildings, and parking space expansion. The scans at each site were added to the reality base capture layer to help support the development of a more detailed campus model. The Senior Design laser scanning includes the following sections of the university campus:

- Advising Center
- Bell Hall
- Benedict Hall
- Centennial Plaza
- College of Business Administration Building
- Schuster Garage (external and Internal scan)

A senior design team was interviewed to briefly describe the project idea, whether they were familiar with the technology before their project, the experience using laser scanning technology, and the applications given to the point cloud data obtained from the scan. The following question were asked to the Desert Design senior design group and the responses were summarized:

1. Describe what your senior design project.

   Response: The project was to demolish two currently underutilized buildings on campus (Bell Hall and Benedict Hall) and add a new 4-story academic building. The new building will house the mathematics department. The goal was to expand the office spaces for faculty, graduate researchers, and teaching assistants by allocating space at the top 2 floors (floors 3 and 4). The 2nd floor was designated for classroom space and the first floor includes a lobby open to students and includes a convenient store. The team designed the floor plan, building frame structure, and the foundations.

2. What was your experience using LiDAR before senior design?

   Response: The team had not used or had any knowledge of what a LiDAR scanner was and the uses of the scan before the senior design application.

3. How did your senior design team use the point cloud data from the laser scan?

   Response: The senior design team used the point cloud data to create a model in Revit. This was helpful to understand the measurements of the land currently occupied by the existing buildings. The point-to-point measurement were helpful to identify the height, and to develop a floor plan to optimize the use of the space available after the demolition. The team was able to identify the need to extend the construction of the project north to complete the project.

4. Did the use of LiDAR help in the design of the senior design project using or find any other applications for this technology?

   Response: The team was able to import the point cloud into Revit and used to measure the new floor plans created in AutoCAD to the existing building occupied space. The point cloud data was super helpful to know where the building was going to lie, spacing of window floor plan of floor, and to gain perspective of the in the sizing and use of the available space. The construction of the senior design project is inside the university campus with limited space to use for the construction of the new academic building.

5. Did the team plan for a staging yard for the construction and a plan to get material into construction site? If so, did having a LiDAR scan help plan for the space to use in the construction phase?

   Response: Yes, the team had a staging yard and the point cloud data from the LiDAR scan was indeed helpful when allocating a large enough space as access point to the construction site and staging yard.

Task 6 - Gap analysis and Roadmap to Full Digital Twin Model

This project, by design, was focused on creating a DS model as a step towards a full DT model. As described previously, synthetic data was leveraged, and the “real” component of the DS model was created using simulation as well as the digital component. From the perspective of understanding the process of developing a true DT model, the execution of this project was invaluable.

Task 6.1 – Gap Analysis for Full DT Model The digital shadow was combination of the data into a digital traffic simulation model. The model simulated a traffic interruption for the construction of the IDRB. The construction scenario was the transport of construction material to the construction site across the road. This process creates a temporary closure of the road. To mitigate the queue build-up, an alternative route was proposed through the parking lot.

The simulation models the traffic buildup due to the closure and rerouted the vehicles to the proposed alternative route. To visualize the construction building in the simulation software (i.e. PTC VISSIM) a BIM model was created using point cloud data from a terrestrial LiDAR scanner. The scenario simulated was the closure of Sun Bowl Dr. during the construction phase of the building. Since the building is constructed several input parameters were approximated. In addition, existing traffic light data and previously acquired data was used for the input parameters. This includes the vehicle counts at each intersect, the light signal time, and the construction interruption time for the simulation.

The digital shadow produced in this case was an intermediary step to achieve a true understanding of the requirement of a functional DT of the campus. The list of various DT applications for campus systems can be seen in Table 8. Various gaps in the data collection, data processing, and feedback to affect the transportation network were identified.

A digital shadow was achieved for the IDRB's surrounding transportation network (shown in Figure 26). The team defined a digital shadow as a one-way data flow collected from the physical infrastructure. The data was obtained from various sources:

1. Laser scanning for exterior of IDRB
2. Video footage and manual extraction of highway assets
3. Traffic light signal timing (provided by city of El Paso)
4. Peak hour vehicle turning movements (provided by city of El Paso)
5. Vehicle count from previous research (Southbound Sun Bowl Dr)

1. Real-time data collection methods
   - Sensor installation
   - Private data collection agencies
   - Access to existing local data collection technologies
2. Decision to affect the simulation scenario
   - Implement threshold to indicate a change in the physical space (automated or semi-automated)
   - Digital LED sign to inform incoming traffic of the decision
3. Expansion of the application of DT in campus
   - Buildings, pedestrian bridges, parking
   - Based on available real-time data source
   - Acquisition of new sensing methods

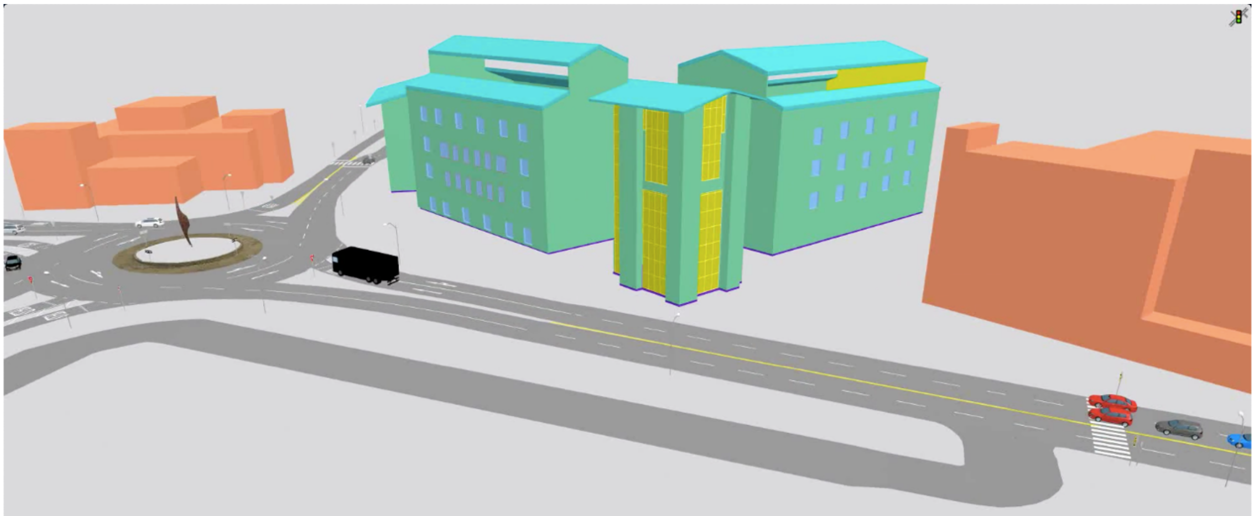


Figure 26. Image. Simulation of IDRB Construction Scenario

The simulation model using synthetic data proved to effectively model the traffic scenario with a need to improve on the data input and simulation visualization. Several assumptions were made for the simulation. For example, the weight of the vehicle decision. This affects the routes each vehicle will choose when approaching the area of interest. The collection of the data for identifying and predicting the decision vehicles make needs additional research to improve the accuracy of the daily driving behavior in the simulated transportation network.

A DT for campus can be expanded to include information from campus user, buildings, access, security, utilities, communication network, transportation behavior, and parking (as shown conceptually in Figure 27 and in more detail in Figure 28). This is a matter access to the current available data sources already monitored by the campus officials. A potential partnership for access to these data sources was discussed in the workshop session. The schematic shown in Figure 28 presents a campus digital twin that includes the flow of data and information that is currently collected from campus operations across several domains.

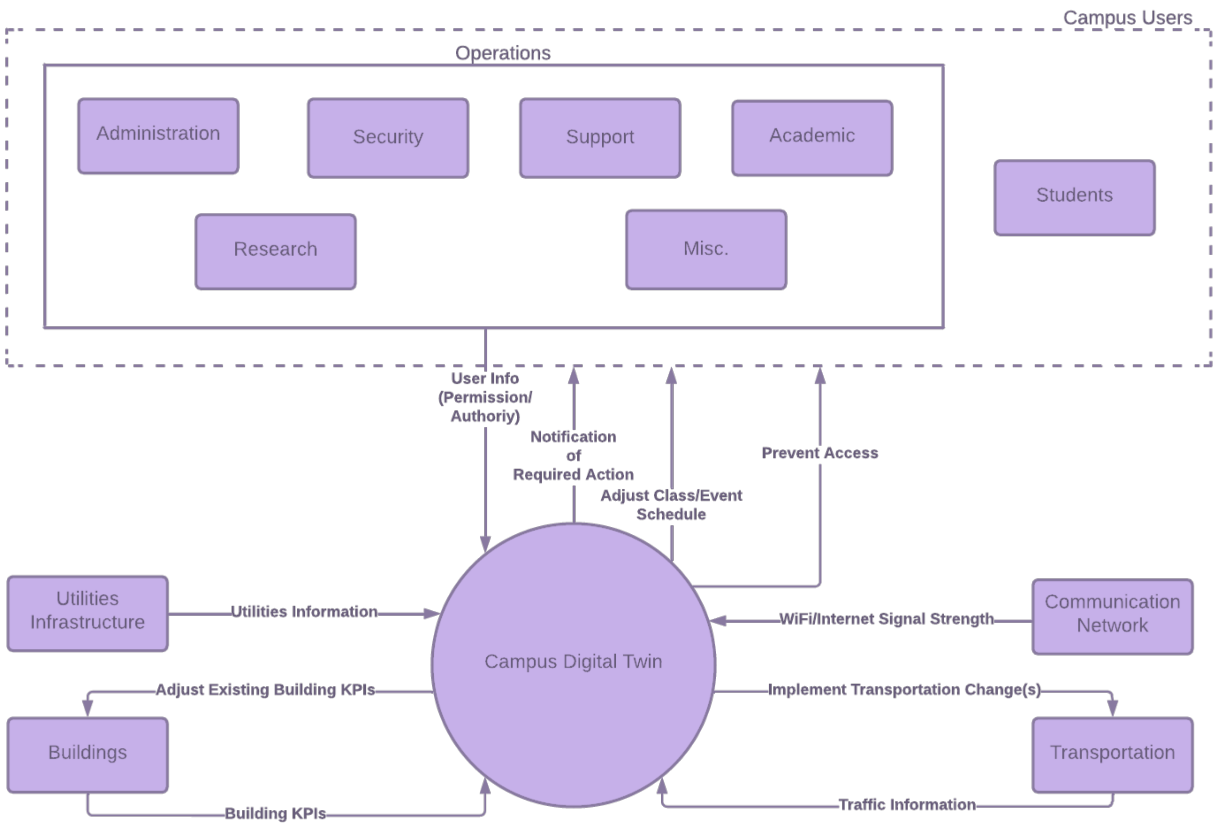


Figure 27. Diagram. Conceptual Digital Twin Diagram

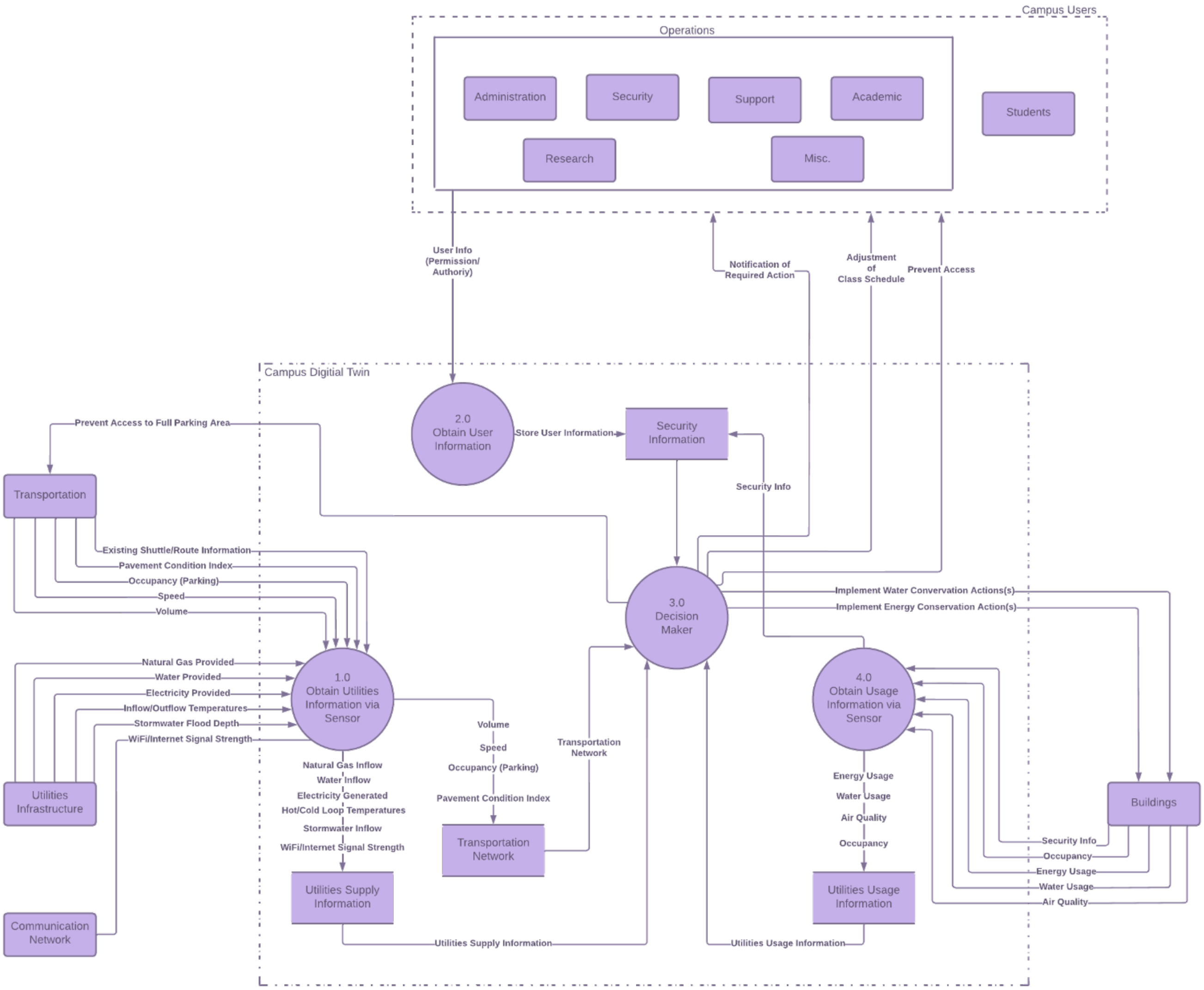


Figure 28. Diagram. Full Campus Digital Twin

Task 6.2 – Roadmap to Full DT Implementation

The vision for a campus DT as depicted in Figure 28 includes numerous campus systems outside of transportation and construction. Inclusion in DT requires certain components be present. Table 5 lists out specific campus systems that could be included in a DT application. The table is broken down as follows:

- Domain – which part of campus in which the systems falls (i.e., physical, human, natural)
- System Category – a general system type (i.e., building, transportation)
- System – a specific description of the system to be included
- Measure – a system parameter that is measurable and of interest
- Sensor – how the measure can be tracked

- Trigger – a threshold of the measure from the sensor that would indicate action is required
- Action – the event which would happen when the trigger is exceeded
- Timescale – the scale of time over which action would occur

It is worth noting that the timescales range from nearly instantaneous to months. This differs from traditional applications of DT where real-time action is critical. Civil infrastructure requires action over large time scales.