An Audio-based Digital Twin Framework for Transportation Construction

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Abstract
Federal and state transportation agencies and professionals are overwhelmed with the responsibility of not only constructing and supervising new roadways but also managing their maintenance. Since roadway projects often stretch for several miles, monitoring project progress and updating changes accordingly via a manual method is a prominent challenge. To address this issue, this study aims to explore a sound-based digital twin system that can allow project managers to remotely handle and monitor multiple projects across hundreds of miles simultaneously, enabling quick access to data for more informed and accurate decision-making. The aim is to explore the feasibility and accuracy of a digital twin system for remotely monitoring and managing transportation construction. This study includes the development of the digital twin framework by identifying the required dataflow, technologies, hardware systems, and their interconnectivity that are necessary for the system establishment to enhance the efficiency of the transportation infrastructure construction projects, as well as understand the benefits and limitations of using such system.

Keywords: Digital twin, transportation construction, project management, sound recognition

1 Introduction
With the increase in vehicular travel in the US, the need for constructing additional roads that can mitigate the growing issues of congestion has significantly increased. While the route miles have only increased by 3% between 1982 and 2002, vehicle miles of travel have increased by 79% (USDOT 2004). Furthermore, the US roadway infrastructure is continuously aging and deteriorating, calling for regular maintenance work. This work often gets stalled due to delays in procuring resources, poor performance and productivity, as well as unfavorable environmental conditions, among other factors. Ensuring that these construction and maintenance projects are executed as per schedule without unnecessary delays or other issues is of utmost importance as these work zones are detrimental to the traffic flow and often lead to congestions and public dissatisfaction. A real-time continuous and autonomous progress monitoring system can help to identify productivity issues and unforeseen risks that may be a cause of delay in future at a very early stage and help supervisors and construction managers to make decisions accordingly. Traditional approaches for identifying risks related to performance and progress are generally manual in nature. As such, the root causes of the issues often go unidentified or are identified at a stage when the damage is already done. Construction of infrastructure projects is always challenging as it is not only important to keep their tasks on track but also continuously monitor the quality of work produced at job sites. Any delay or lapse in quality is detrimental to the economy as well as the safety of the commuters who will be using the infrastructure in the future.

To overcome the limitations of manual efforts, automated monitoring and identification has been presented as a promising approach for robust management on a construction site (Park et. al., 2016). In recent times, researchers have been exploring innovative methods for integrating data acquisition methods such as sensors, vision-based tracking, global positioning systems (GPS), ultra-wide band (UWB), and radio frequency identification (RFID) to collect real-time field data in construction (Brilakis et al., 2011; Golparvar-Fard et al., 2009; Park et al., 2015; Turkan et al., 2012; Teizer et al., 2007; Cheng and Teizer, 2013). However, only acquiring real-time data from the construction sites does not solve the problem completely. The construction industry is in need of a system that can also process this huge amount of data in real time, thereby providing critical information for decision-making in a timely manner. Furthermore, the changes resulting from the decisions made also need to be updated into the ongoing-project's database and work progress with minimal human intervention. A robust data acquisition and autonomous processing system can then be beneficial for the industry in terms of real-time data sharing, decision-making, and updating among the various stakeholders involved in the project. In this regard, the digital twin technology, which is slowly gaining popularity in the field of construction, has been explored mainly for the operation and maintenance phases. A digital twin is a dynamic virtual model of a process, system, or service that calls for the incorporation of contextual and sensor data from the physical world into the twin platform to enable real-time monitoring and timely analysis of problems before they actually arise (Madni et al, 2019). This study includes thorough investigation of the applications and the benefits of the digital twin system for transportation projects like roads, highways, and bridges.

2. Objectives

Digital twin technology is based on the concept of mimicking the scenario on a virtual platform by means of sensor data that are continuously streamed into a virtual platform from the real-world. This sensor data helps identify the exact current state of a project in the virtual world and simulate the ongoing and future activities accordingly to identify risks and unforeseen circumstances, leading to informed decision-making. However, to enable real-time progress monitoring, not only a continuous bi-directional exchange of data and information is required, but also the incoming data and information must be processed and analyzed in real-time. Current research studies have mostly concentrated on a vision-based construction digital twin concept that incorporates laser-scanners and other image-based data obtained from the real-world to simulate and identify future conditions and risks (Pan and Zhang, 2021; Stojanovic et. al, 2018), but they are incapable of rapidly handling data in real-time mainly due to the high processing power required for image-based data. On the other hand, almost all construction activities produce noise as an inevitable by-product. Even minor activities using handheld tools produce some amount of noise like hammering for installing road signs and clanking and thuds produced from handling various tools involved in road painting. This noise can be captured and analyzed for identifying the ongoing activity. In this study we aimed to develop a sound-based digital twin model that can capture noise produced from real-world construction sites and process sound data for identifying the current state of the project with diverse simulation of future events. The previous studies have proven significant reliability and benefits of a sound-based approach for construction activity identification and event monitoring (Scarpiniti et. al., 2021; Lee et. al., 2020a; Lee et. al., 2020b; Maccagno et. al., 2020; Xie et. al., 2019a; Sherafat et. al., 2019; Zhang et. al., 2018). Sound sensors unlike a vision-based monitoring system requiring on-site cameras, drones, or laser-scanners do not require high computational power as sound data is comparatively light-weight enabling real-time analysis and field monitoring. Sound data when compared to image data require less storage space. It is comparatively less expensive than image- data in terms of data collection and processing, and does not require a certain level of illumination like the visual-based tracking (Cheng et. al., 2016; Lee, et. al., 2020a; Xie et. al., 2019a; Xie, et. al 2019b). The objectives of this study are two-fold:

1. Provide a conceptual framework of a sound-based digital twin platform that can be established with respect to transportation construction, focusing on progress monitoring and automated schedule update.
2. Develop a real-time, cloud-based, completely automated prototype based on the proposed framework as a proof of concept.

3. Methodology: A Sound-based Digital Twin

The digital twin platform has been extensively studied for use in the maintenance phase of civil infrastructure (Yoon, et. al, 2018; Lu and Brilakis, 2019). However, there are considerably fewer studies where the construction phase is concerned. The first and foremost challenge in the construction phase is that, initially, there is no physical model and the virtual model needs to build itself as the project progresses physically. This leads to the fundamental debate whether developing such a platform even if it supports the objective of digital twin, can be called a digital twin or not (Rasheed et. al, 2019). Second, construction environment being dynamic, collecting real-time data is difficult. Third, there are underlying issues of interoperability caused by data collected in different formats, not being compatible with the data exchange standards such as Model View Definitions (MVD) specified in the Industry Foundation Classes (IFC) format. Fourth, larger projects will involve big data analysis which may be difficult to conduct in real-time due to lack of adequate computational power.

3.1 Framework

A digital twin for transportation construction can be a virtual representation of the objects, equipment, workforce, etc. and their condition in real-time that enables automatic and instantaneous surveillance of various aspects of construction such as quality, progress, productivity and so forth. To examine the feasibility and the potentials of a digital twin for construction phase, this study proposes a new digital twin framework for construction monitoring and management of roadway projects that not only supports automated assessment in the construction phase but also provide a system for real-time detection and notification of potential risks and problems from analyzing the real-time data collected from on-site sensors. The processes and activities involved in roadway construction are dynamic in nature and therefore such a project can involve innumerable circumstances, risks, unforeseen conditions, etc. Attempting to identify all such events and simulating all aspects of the construction process is neither practical nor feasible for a single digital twin system to handle, due to the current technological and processing limitations. Therefore, in this study we restricted the ability of the sound-based digital twin platform to only identify activities and locations of equipment and workers to accurately model the progress of the project and thereby identify any risks related to delay and productivity. A Deep Neural Network (DNN) algorithm was used for activity identification, which analyzed the sound of various equipment and machinery captured by sound sensors on the site to identify the active machineries and equipment and thereby the ongoing activity. Since roadway construction are horizontal projects, the GPS location of the ongoing activity provided an estimate of the current progress of the project. In addition to wearable sensors and Raspberry Pi for data collection and transmission, this study utilizes Microsoft Azure for developing the cloud-based system and Blender application for providing the virtual simulation environment required for 3D visualization. Figure 1 shows the framework of the prototype.

The framework mainly encompasses three major steps towards assessing the construction project for predicting future situations. The first step is to identify the current situation of the project with the help of data relayed in real-time by various sensor devices used in the construction site. In this step, it is important to identify the type of data that will be required as per the objective of the digital twin system and choose sensors accordingly. Also, seamless data transfer depends on all-time continuous connectivity which can be made possible with the help of a Wi-Fi system on the site. For example, in our study the objective of the digital twin was to accurately identify the progress made in the construction of roadways and provide autonomous update on any expected delays, productivity issues, and thereby changes required in the schedule. Therefore, activity identification and current job location were two major information that were required to accurately gauge the progress of the project. We used sound sensors and GPS sensors for identifying the required information. A local system in the form of the Raspberry Pi was used for connecting the sensors to the cloud-based platform in order to transmit the data in real-time. It also helped to convert the files in an interoperable format before sending to the cloud.

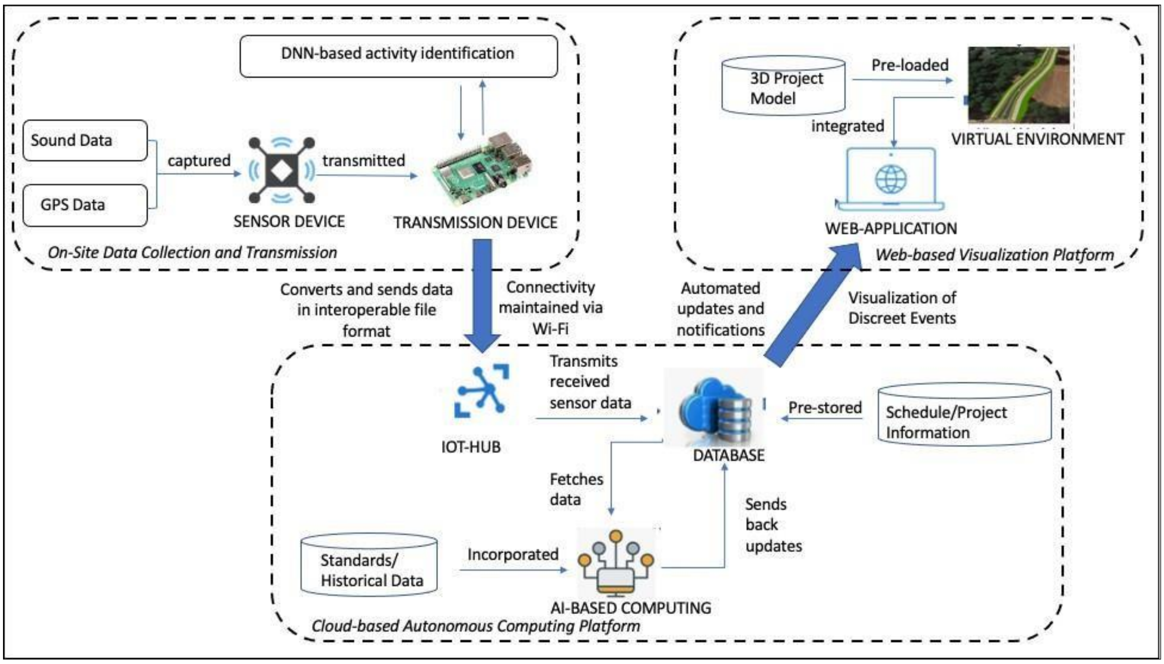


Figure 1. Framework of Sound-based Digital Twin for Transportation Construction

The second step in the framework is to store and process the acquired data using AI and other computational analysis in order to capture any changes from the as-planned. In this study, a DNN- based sound classification algorithm was used for identifying the ongoing activities at the job site. The sensor data sent by the Raspberry Pi was transmitted to the cloud via the IoT Hub, which allows for continuous storage of the data in databases. These databases also allow for pre-storing project data such as schedule information and resource allocations in this case. Various applications of the cloud platform were then used to fetch the required sensor and project data from the database, process and compare the outcomes with standards already coded into their algorithms and send the processed output back to the database. Comparing the current progress with the expected from the schedule and the work-cycles, allowed for the identification of possible productivity issues.

The third step in the framework is to enable the visualization of the updates in both 2D and 3D formats on a user-friendly interface. While 2D formats such as maps, graphs, and charts help to quickly grasp the statistics involved, 3D formats such as a BIM model in a virtual environment allows for simulating discreet events and visualizing the process as-occurring in the real world. This helps to gain those insights that can only be obtained through manual observation and inspection, remotely without the need for the supervisor to be physically present at the construction site. In this study, we utilized a web-based application that allowed for visualizing the project location on a map, all relevant statistics through graphs and charts, and also integrated a simulation application that helped to create the virtual environment for hosting the 3D model of the project. This web-based visualization platform allowed for data-sharing, remote monitoring, discreet event simulation.

3.2 Principal Features of Digital Twin for Transportation Construction

The proposed framework was developed using advanced state-of-the art technologies that included a DNN-based sound classification model for accurate identification of ongoing activities, low-cost and light-weight wearable sensors that provide a dynamic characteristic to the data collection process, and a cloud-based computing with a web-based visualization platform that allows for real-time data sharing. In this research, we used the Microsoft Azure platform as the main cloud-based platform for collection, storage, computing and visualization of field data and Blender application for hosting the project model for visualization. In addition, a wearable sensor including Raspberry Pi was used for linking the sensors with Microsoft Azure. The principal features of the system are described in detail in the following sections.

3.2.1 DNN-based Sound Classification for Activity Identification

The architecture of the DNN algorithm used in this study consists of an input layer, two hidden layers with 100 units in each, and an output layer. The Adam algorithm and the categorical cross-entropy were used for optimization and calculation of loss function respectively (Kingma and Ba, 2015), along with a sampling rate of 22.5 kHz. A sound library consisting of 14 categories of construction equipment and machinery was created for the development and testing of the algorithm. All sound data collected were split into short segments of 2s in length and were manually cleaned to remove all overlapping sounds and background noises as they were not suitable for training the algorithm.

The entire library consisting of 2700 sound samples was randomly split into training and testing sets in the ratio of 7:3. The training of the model had an accuracy of over 95% across all classes. For best results, it is recommended that sound data for training the classifier be collected from the on-going project itself before the start of each activity. This will ensure that all environmental and surrounding parameters as well as machinery/ equipment related parameters such as wear and tear and material used will get captured and help to identify the active machineries more accurately.

While testing the model with new data, there two types of tests conducted: (1) Single-file test that consisted of testing individual pre-processed sound sample, and (2) Real-time test that consisted of continuous testing of unprocessed sound samples. A sound sample, 2s in length, was randomly collected in every iteration for identification of ongoing activity. Since sound produced by machinery is considerably louder than human voice, personal speech and conversation of workers only appeared as indistinct background noise. Furthermore, the system is not programmed to store any of the real-time data to further ensure the privacy of the workers. The real-time test was a more accurate representation of the real-world situation as it is not possible to pre-process the sound sample before predicting the activity in real-time. The accuracy for each of the individual classes for both the tests is shown in Table 1:

Table 1: Accuracy of individual classes in single-file and real-time testing

Classes	Single-file Accuracy	Real-time Accuracy
Excavator	93.33%	76%
Concrete Mixer	100%	100%
Compactor	100%	72%
Bulldozer	100%	96%
Dumper	100%	72%
Dragline	100%	16%
Vibrator	46.67%	84%
Crusher	100%	100%
Shovel	100%	100%
Roller	93.33%	92%
Grader	100%	92%
Distributor	53.33%	76%

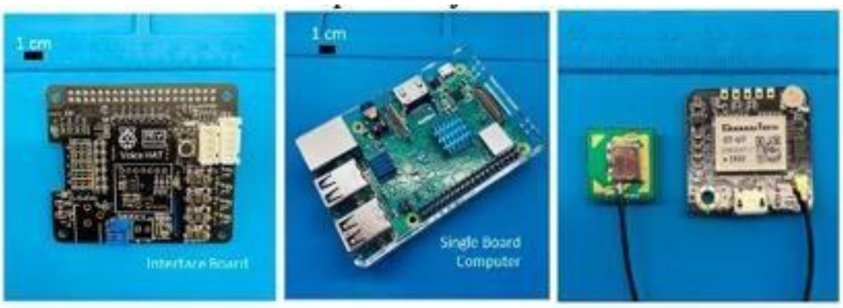
Paver	100%	72%
Scraper	93.33%	0%
Average	**91.42%**	**74.86%**

As is evident from the table above, while certain classes like Concrete Mixer, Crusher, and Shovel that produces unique sound were classified with 100% accuracy, others such as Vibrator and Distributor were misclassified in the Single-Test and Scraper and Dragline were misclassified in the real-time test. The reasons for the misclassification can be attributed to 2 causes:

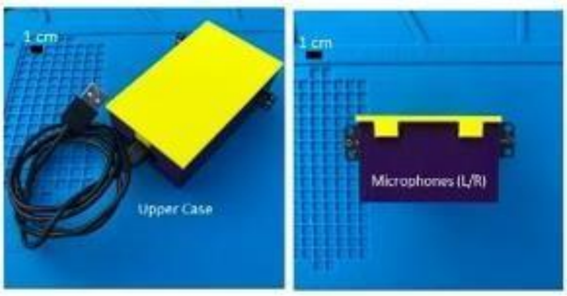
- Two or more equipment or machinery may have same motorized parts and therefore produce similar sound that is difficult for the algorithm to distinguish.
- Some equipment or machinery may be used along with other equipment and machinery in close proximity allowing sound from both systems to more or less always overlap.

3.2.2 Wearable Sensors for Data Collection

A construction site is naturally dynamic and continues to change as the task advances. A static sensor fixed at a specific area could be disadvantageous in such an environment as it would require relocation to suitable spot past the capturing scope of the sensor. Likewise, there is high possibilities that the sensors might come in the way of workers, equipment, and machinery and may cause unwanted damage and hassle. A wearable sensor, on the other hand, provides the required dynamic characteristic to data collection. A prototype of a low-cost and light-weight wearable sensor was developed for this study. It consists of a sound sensor array through a custom board capable of periodically sending audio files to the online cloud database with user- adjustable period and sampling rate. In addition, it contains a GPS antenna for geolocation reporting that is included with the Wi-Fi card. A custom packaging was developed for the sensors with an outer dimension of 88mm x 55mm x 30mm including space for a rechargeable li-ion battery and a micro-USB connection for power or reprogramming. A Raspberry Pi 3B+ (Raspberry Pi Foundation) was used to optimize the limitations of on-board storage, data pre- processing, and implementing complete remote access to a desktop environment on the board in order to modify code and fetch any on-board data for troubleshooting. Figure 2 and Figure 3 below show the individual parts and entire custom packing of the wearable sensor respectively.



(a)



(b)

Figure 2. a) Parts of the wearable sensor device: Sensor Interface, SBC, and GPS breakout board, b) Prototype with all integrated parts

3.2.3 Cloud-based Autonomous Computing and Visualization

The IoT Hub on the cloud platform receives the sensor data in the JSON format that can be easily stored in the SQL database and integrated with other applications. A web-based application was developed for computing and processing the incoming and pre-stored data on the database and providing a user-friendly interface for viewing the critical information. This web-based application was hosted on the Microsoft Azure. In addition, the Blender application was used for hosting the virtual environment for visualizing simulations on the 3D model. This application was also capable of fetching data from the SQL database on Azure. Since the transportation projects are horizontal and linear, the movement of the sensors along the project path as the project progresses can be a useful method for detecting project status. The web-application depicts pointers which indicate the location of the sensors that continuously update their position on the map as per the GPS coordinates received in the telemetry message from the sensors. Figure 3 shows the interface of the web-application developed for the users. Each pointer in the map depicts the location of an individual roadway construction project.

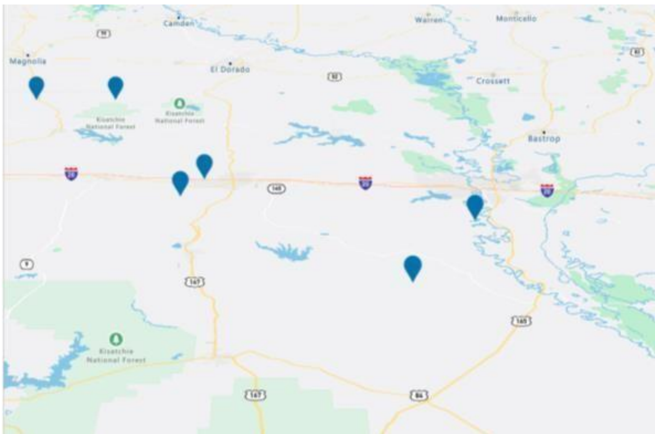


Figure 3. The user-interface of the web application

The web-application was developed in a way that it can pull any set of analyzed data from the database relevant to each sensor and display the data using visual analytics in a way suitable for users to quickly interpret meaningful information. The supervisor can easily click on the pointer to look at the log to visualize the real-time sensor data. For any digital twin, the ability to replicate the real-world scenario on the virtual platform and to receive critical updates about deviations from as-planned activities in real-time is a critical factor. It is the key element that can enable project supervisors to remotely monitor ongoing activities in the job site, and make critical decisions based on updates obtained in real-time. However, achieving a dynamic 3D model that can autonomously replicate the real-world scenario and provide valuable updates in real-time is a challenge. The virtual platform incorporated in this study allows for importing 3D models in standard formats like .fbx, .obj, and even .ifc, and has the ability to conduct simulations based on data sent by sensor devices stored in the SQL database on the Azure platform. It uses the geometric information of the 3D model and real-time data obtained from the sensors to simulate the various objects in the model. All possible interactions between the model-objects based on pre-decided purpose of the digital twin and various real-life situations can be simulated in the platform through simple coding. This platform also allows for collecting real-time observation from the actual job-site using the virtual model as it is in sync with the physical world. An additional application for performing computation and analysis on data obtained from visualization on the virtual platform was developed. This application was then integrated with the visualization interface. A new tab known as 'Report Link' was created on the visualization interface that allows for obtaining real-time project update in text format. Figure 4 shows the different modes for viewing data, model, and updates developed as a part of the visualization interface for a corresponding activity in the real world. Since most construction activities are repetitive in nature, the developed system uses the cyclic pattern of construction activities for developing the simulation model. It is the principle for identifying productivity issues and causes of delays in the project. The as-planned work-cycle needs to be identified from the project site and coded into the virtual environment for the system to enable the simulation. The simulation is then guided by the sensor data obtained in real-time from the construction job-site, and simultaneously compared with as-planned project data to identify any changes in real-time. These changes are then propagated throughout the entire project to identify any future risks and unfavorable situations such as clashes in schedule, delays in project completion date, etc. The critical information, thus obtained, are then combined, and represented in the report, such that they can be available to all stakeholders through data sharing. Figure 5 shows a snapshot of a report that was generated while the system was being tested on an asphalt paving activity conducted at a roadway construction site located on the I-55 service road between Ruddock and La Place, Louisiana, USA.

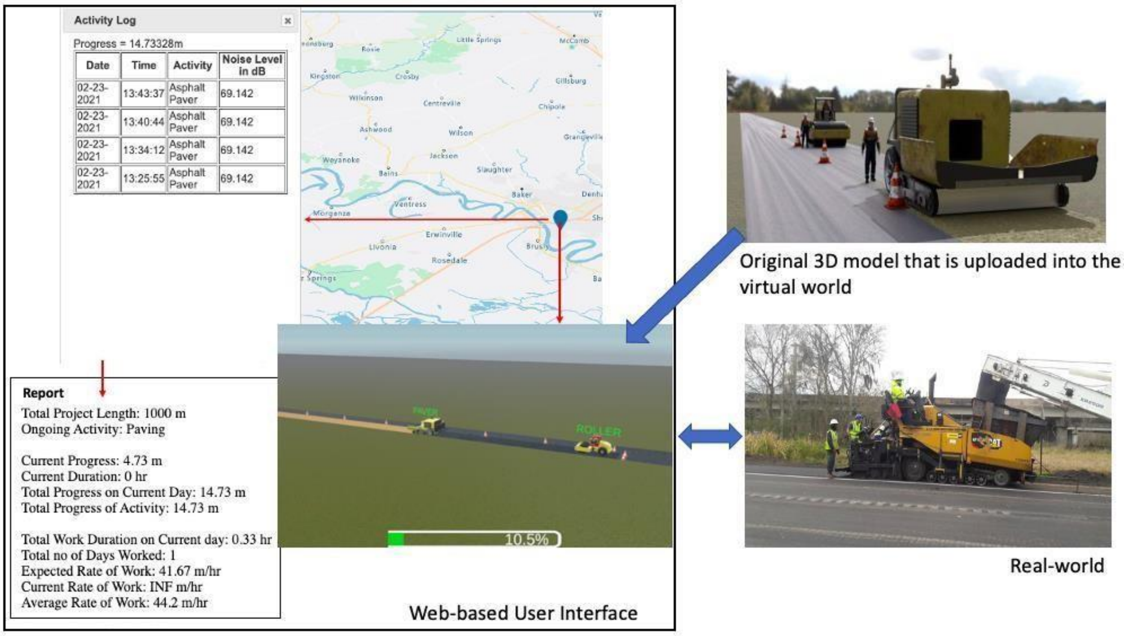


Figure 4. The web-based interface and the corresponding real-world

REPORT

Total Project Length: 1000 m
Ongoing Activity: Paving

Current Progress: 6.64 m
Current Duration: 0.05 hr
Total Progress on Current Day: 14.73 m
Total Progress of Activity: 14.73 m

Total Work Duration on Current day: 0.38 hr
Total no of Days Worked: 1
Expected Rate of Work: 41.67 m/hr
Current Rate of Work: 132.71 m/hr
Average Rate of Work: 38.43 m/hr

Status: Behind schedule
Required Rate of Work for finishing job on Schedule: 41.72 m/hr
Current Idle Time: 0 hr
Total Idle Time on Current Activity: 0.07 hr
Average Idle Time Per Day on Current Activity: 0.07 hr

Next Activity in Schedule: Road Painting and Reflectors
Expected start date as per Schedule: 02/26/21
Expected start date as per Average Rate of Work: 02-26-2021
Machinery and Equipment Involved: Striping machines

Expected Project Completion Date as per Schedule: 02/26/21
Expected Project Completion Date as per Average Rate of Work: 02-26-2021

Figure 5. Snapshot of report from Field Testing

4 Limitations

The development and incorporation of digital twin in the field of construction in general is still in the nascent phase. This study is merely a small attempt to identify the key factors and principles on which such a system may be developed in the future, and to identify possible challenges for developing such a system. During the feasibility analysis of this study, it was found that developing a digital twin system for roadway projects would be considerably easier than building projects. Unlike building projects, roadway projects run horizontally enabling easier tracking, involve lesser components in terms of activities and processes, and have a higher degree of similarity amongst various projects, as far as designing and construction are concerned. Thus, the prototype in this study was specifically developed for roadway projects. However, during the development of this prototype, several limitations and challenges due to lack of advanced technology were identified which are as follows:

- Quality is an important factor in construction and rework may be required after quality inspection. Though the proposed digital twin framework can integrate real-time quality control using visual data from the site, currently it is beyond the scope of this study, and may be integrated in future studies.
- The relay of the data from the wearable sensor to the Raspberry Pi occurs in almost real-time but the same cannot be said about the relay of telemetry data to the cloud-platform as it is highly dependent on the network connection and server traffic. Therefore projects in remote areas may suffer from connectivity issues and disruptions.
- Currently the system can complete iteration of data capture and visualization of output every 30 s, which is the maximum to near real-time that we have achieved. However, with the availability of higher processing power, availability of 5G technology worldwide, and further integration of edge computing, this can be significantly reduced.
- The DNN algorithm requires a project-specific sound library for training the model. The library must contain the sound data of the exact model and brand of the equipment and machinery. Furthermore, a higher accuracy can be achieved only if the training data is collected from the project-site itself, as this would allow inclusion of environment and materialrelated parameters specific to the project.
- In the real world, the sound sensors may capture sound from multiple equipment or machinery at the same time or may capture background noise along with the equipment sound, making classification difficult for the DNN algorithm.

5 Conclusion

A digital twin system for construction monitoring of roadway projects is a significant step towards the technological advancement in the construction industry. This platform can not only help in timely identification and mitigation of risk but also facilitate the creation of data repositories that can help the construction industry to accomplish future projects with lesser hindrances. A digital twin platform can accommodate for open data sources that can allow construction companies to accurately analyze and plan their project in the pre-construction phase. An all-time connectivity and seamless data transfer between the physical and virtual models can allow the construction companies to monitor multiple projects simultaneously and remotely. This will reduce the need for multiple supervisors and managers to be physically present on the construction site for the monitoring of project status. In addition, the incorporation of interoperability and continuous intelligence can allow the digital twin to handle common issues and risks by itself, allowing the project managers and supervisors to deal with more complex and unique problems that are specific to the project. Once the supervisors and managers have found suitable solutions to these unique issues, they can be added to the system for reference, while working for similar projects in the future.

This study established prototype of the digital twin system for autonomous monitoring and surveillance of transportation construction and maintenance projects using low-cost and light- weight wearable sensors. A DNN algorithm was adopted for sound classification and construction activity identification. Based on this approach, the types of dynamic training dataset have been considerably restricted to only planned types of activities. The research outcome involves new knowledge on the implications of sound recognition in the transportation construction sector for real-time monitoring and forecasting of work progress and task performance without any human effort. In addition, the new framework has significant impacts on workflow optimization, work performance monitoring, and the cost/schedule overrun mitigation of diverse construction projects for roads, highways, bridges, and tunnels. It is expected that the developed theoretical framework for detecting construction activities through building the schedule-based dynamic sound data training, can be possibly extended in other areas having the potentiality of adopting acoustic data analysis and recognition, such as fault detection, and unmanned manufacturing. Automated monitoring is one of the most promising methods for accurate and continuous monitoring of safety performance on a construction site.

In addition, this study also explores the framework for a user-friendly interface for visualizing all project related data streamed to a cloud-based computing platform in real-time. The raw data is processed in the cloud computing platform and the results are displayed using visual analytics to enable supervisors and project managers to easily identify issues and use the information for timely decision making. The interface also allows for viewing the BIM model of the project where the supervisors can visually compare the scheduled progress of the project with the actual progress. Although the framework has been proposed with respect to roadway construction project, the proposed framework can also be applied to a building construction projects. However, since building construction projects involve different floor plans and configurations of the site, identifying work cycles, and modeling simulations of workers, equipment, and other objects may be difficult to obtain due to its complexity. It may not be possible to use a generic work-cycle simulation model for all construction projects and require modeling of unique simulations as per the project requirement. Thus, the proposed framework can be expected to add the innovative scientific knowledge and new logical theory that can pose significant impacts on the workflow optimization and the accurate task-performance measurement of transportation construction projects like roads, highways, and bridges.

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