Towards Remote Construction Site Analysis: From Laser Point Clouds to Virtual Reality Applications

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Abstract -

Efficient construction monitoring and project visualization are vital in civil engineering: they promote safety, minimize costs, and ensure adherence to design plans. With advances in reality capture techniques, such as LiDAR, point clouds have emerged as a powerful tool for digitizing large-scale scenes with excellent accuracy. However, the challenges of processing and visualizing large-scale point cloud data remain significant, particularly for applications in horizontal infrastructure projects. In this case study, a point cloud-based digital reconstruction of an interchange conversion project was developed to aid in defining best practices for data processing of large-scale point clouds and to develop novel digital tools to enable remote construction site inspection and analysis. The obtained models are leveraged to provide insights on three advanced methodologies for data exploration: (1) desktop interfaces for accessible remote monitoring, (2) holographic interfaces for collaborative visualization, and (3) immersive virtual environments for enhanced interaction and simulation. These three methods are compared for accessibility, opportunity, and their potential to improve decision-making and project outcomes in construction monitoring and analysis.

Keywords -

Point clouds; Laser Scanning; Virtual Reality; Construction Monitoring; Construction Simulation

1 Introduction

Infrastructure systems in the United States are poised for significant investments over the coming years, given the aging conditions and urgent need for renovation [1]. When developing and completing large construction projects, it is crucial to ensure that each step is executed accurately and according to specifications to maintain the structural integrity and overall performance of the completed systems [2]. Errors in construction processes can compromise safety, increase costs, and decrease the lifespan of the built infrastructure. To that end, there are broader consequences with poorly monitored projects, such as premature demolition and replacement - which have significant environmental impacts [3]. Given that greenhouse gas emissions are strongly correlated to the construction of public infrastructure [4], it is evident that poorly monitored projects, which may require early demolition and rebuilding, can exacerbate environmental impacts. If methods to extend infrastructure lifespan are not implemented, the repeated cycle of demolition and rebuilding will deplete environmental resources and contribute significantly to greenhouse gas emissions.

Recent advancements in digitalization and the rise of intelligent automation are driving a technological shift in the construction industry, enhancing the effectiveness of construction monitoring [5]. By leveraging innovations in reality capture, computer vision, robotics, and artificial intelligence, companies can improve data capture for complex infrastructure project management [6, 7]. In particular, rapid advancements in laser scanning technology have revolutionized the ability to capture detailed spatial information for infrastructure projects. LiDAR is a technique that uses laser beams to precisely measure distances and generate detailed three-dimensional representations of physical spaces. From the capture, data fusion with HDR imaging provides RGB information to each registered point in the cloud [8]. LiDAR devices are generally attached to a ground-based fixture (terrestrial laser scanning - TLS) or an aerial vehicle (aerial laser scanning - ALS). The capability of producing high-density scans at a relatively low cost enables the digitalization and automation of advanced construction management procedures [9]. LiDAR data can similarly streamline the capture of geometric information for computational analysis of infrastructure [10]. As such, research into advanced methods of data acquisition, exploration, and management [11] supports the development of accurate and reliable workflows for construction applications.

As data collection methods in the construction industry advance, adopting effective processes to convert data into accessible formats is crucial for effective visualization to enable remote inspection and monitoring. [12]. Since the information that operators need to extract from point clouds is very technical, there must be a clear workflow for processing and visualization to make it operable. Cleaning raw point cloud data for large-scale scenes is a laborious, time-consuming task, requiring manual processing and expert judgment by skilled operators. Data storage considerations are also relevant [13], thus requiring a balance between accuracy and cost.

Leveraging point cloud data in civil engineering projects comes with many challenges. Due to the capture devices' technical constraints, point cloud data of active construction sites will contain several different types of noise [14]. When capturing ongoing projects, fully closing the site or nearby streets to traffic and workers is often impractical, resulting in the presence of unintended people and equipment in the scene [15]. Additionally, remote site monitoring requires a large amount of human judgment and expertise. As such, using effective methods to visualize data is highly important to complete the task. With technology improving, there is a need to test new methods and prove viability for applications in the industry [16].

Advanced visualization methods to explore site data are becoming more viable as consumer-grade virtual reality (VR) and holographic hardware become more accessible. Immersive virtual environments (IVEs) are a frequently used research tool to simulate and navigate digital environments [17]. When IVEs are built using computer graphics engines, custom modules and simulations based on point cloud data can fulfill the unique needs of individual projects. IVEs have successfully been used in applications such as health and safety training [18], digital twin modeling [19], and project visualization [20]. In this context, point cloud data obtained in real-life conditions can improve the IVEs by providing greater detail of the scenes and greater contextual realism of the specific settings being materialized [21].

There is a need for studies regarding data management, visualization, and exploration methods for point cloud data of large-scale construction scenes [9]. The capabilities for structural assessment have been well documented [22]; however, work to define the best practices for point cloud-based construction monitoring of large-scale horizontal infrastructure projects is needed. This paper introduces a novel workflow for processing and visualizing point cloud-based reconstructions of horizontal infrastructure projects, with a particular focus on identifying critical challenges in data processing and exploring effective methods for data exploration. A case study on an active highway construction site demonstrates the practical application of the proposed approach. The study presents a comprehensive analysis and comparison of various visualization and exploration techniques, including desktop computer programs, holographic 3D environments, and immersive virtual environments (IVEs), to evaluate their capabilities in extracting technical information and enabling remote construction site monitoring and inspection.

2 Methodology

2.1 Data Collection

An active construction site during an interchange conversion project (i.e., transition from a cloverleaf to a diverging diamond interchange) in Southwestern Pennsylvania was chosen as the case study. The location is of interest due to the active work zone, non-uniform terrain conditions, and various structures at different construction stages. The scan was performed on one cloverleaf loop to be replaced and the surrounding highway and state route.

The laser scan was conducted using the Leica BLK360 terrestrial scanner (see Figure 1 (A)). The BLK360 features a 360,000 points-per-second scan rate and can capture information at a range of up to 60 meters with a point accuracy of approximately 6 mm at 10 meters. The laser scanner has a 360° horizontal and a 300° vertical field of view. For each scanning iteration, the BLK360 (mounted on a tripod) was positioned in an area of interest, and the scanning cycle was initiated using a wireless connection through a portable device. After completion of the scanning cycle, the portable device provided a 360° image of the location and a low-density preview of the captured point cloud (see Figure 1 (C)).

The data collection process employed the following method: firstly, the scanner was placed at an initial location, and a scan was performed. For each successful scan, the device was moved to a nearby location where the following scan would have significant overlapping data such that an automated alignment link would be created. Links appear on top of a low-density site map, with green links found to be especially strong [23] (See Figure 1 (B)). Using the scan previews, the work continued until data was captured of the whole site. Special focus was provided to the portions of the site with the most active work ongoing.

2.2 Data Processing

The point clouds were then processed to simplify the data. For each scan, a two-step process was performed. (1) Automated coincident point removal among nearby scans and (2) removal of noise through automated statistical outlier removal and manual segmentation. Statistical outlier removal identifies and removes points that deviate significantly from their neighbors. It calculates the average distance of each point to its k nearest neighbors and removes those exceeding this average within a multiple of the standard deviation. The process is controlled by two input parameters: k, which defines the number of neighbors, and a multiplicative factor for the standard deviation, which determines the threshold for removal [24]. In this case, the parameters of $k = 6$ and a multiplication factor of 1 were used. The predominant occurrences of noise were vehicles driving down the interstate and around the site,

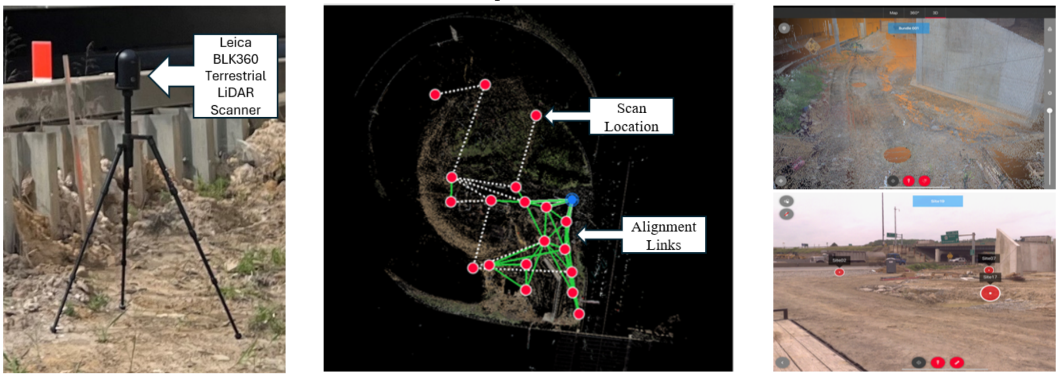

Figure 1. Leica BLK 360 Terrestrial Scanner (A) Site map with scan locations and alignment links (B) and scan preview via low-density point cloud and 3D image (C).

workers moving throughout the project, and lasers bouncing off reflective surfaces. In many cases, the scanner captured an object, but the object is inconsistent between scans and thus must be removed. Additionally, since the data collection process involved intentionally overlapping scans, nearby scans have many identical points. Coincident points included automated removal of overlapping data and, since the scanning device is less accurate as points are captured from further distances, low-density captures at further distances were removed during the manual segmentation process. Each scan was processed individually to remove noisy data, addressing the described instances of floating points, partially captured moving objects, and reflections.

For example, Figure 2 shows the cleaning of scan #1. In Figure 2 (A), the initial scan has a significant amount of noise from the nearby highway, inaccurate data from the reflection of a nearby truck, and workers in high visibility vests moving around the site. Figure 2 (B) shows the resultant point cloud after the coincident point removal and manual segmentation-noise deletion. By performing the cleaning workflow, the scan improved via the removal of reflection noise, partially captured workers and vehicles, and lower accuracy points captured far from the scan location. Along with being a more accurate capture of the true site conditions, this model also becomes more operable with a significantly lower file size (8̃9% reduction).

Another significant issue encountered was the misalignment of scans without vertical features. Scans which primarily consisted of the ground surface had inaccurate alignment in the vertical direction when performing automated adjustments, leading to inaccuracies in the dataset. Manual fine-tuning in the vertical direction was performed as a solution.

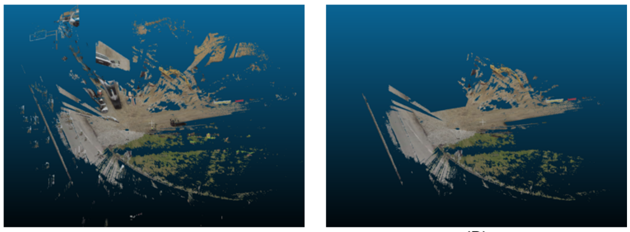

Figure 2. Example of data processing for scan #1. (A) Before and (B) after.

2.3 Data Exploration

The resulting high-fidelity point cloud can be leveraged for construction monitoring and project visualization activities. The following section describes three methods for data exploration, remote monitoring, and visualization: (1) desktop interface, (2) holographic interface, and (3) immersive virtual environments. A scenario-based evaluation was employed to validate the utility of these interfaces for data exploration to enable remote construction site analysis. This process did not involve comparison to project plans or reference measurements, but instead was a feasibility study for the visualization methods. In this process, the research team defined and performed standard tasks using the processed digital models to assess each interface's strengths, weaknesses, and capabilities. First, measurements of key structural elements—such as reinforced concrete walls, rebar spacing, wall angles, and foundation depths—were taken to verify that the built conditions could be measured. Second, feasibility of progress tracking and collaboration capabilities was assessed. Finally, the assessment of terrain elevations was undertaken to ensure that earth mobility could be captured. Additionally, informal interviews and visualization trials with construction operators conducted during on-site data collection and through visits to the lab provided further insights into the methods' viability for construction monitoring tasks, and strengths or weaknesses as a collaboration and presentation tool.

2.3.1 Desktop Interface

For performing remote construction monitoring, the desktop interface (also known as 3D keyboard mouse) refers to a technician exploring the point cloud to make observations regarding project status, site layout, and gathering as-built measurements. Accessing the data in this capacity can be advantageous given the highly accessible nature of desktop computers and point cloud-compatible software. Additionally, many CAD and BIM workflows have compatible integration with point clouds [25, 26].

Considering point cloud data's high accuracy and precision, project status can be judged based on deviations from the planned design. At the same time, site layout assessments help verify spatial arrangements and identify potential conflicts or errors in construction. This method similarly helps maintain a safe and productive site layout. One significant object of interest in the captured data is the reinforced concrete wall, which will eventually support new sections of the roadway. Figure 3 (A) captures the measurements built from this construction feature. Such measurements include rebar spacing, wall angle, visible depth of foundation, and terrain elevation differences along the site. Measurements can be transformed into as-built drawings or 3D static mesh components.

The primary disadvantages of desktop workflows stem from the limited field of view and spatial understanding of the three-dimensional model viewed in a two-dimensional medium. As such, desktop workflows offer a limited sense of scale compared to 3D visualization methods. However, desktop workflows are typically more accessible and user-friendly, as they leverage widely familiar interfaces and are consistent with the majority of users' prior experience.

2.3.2 Holographic Interface

Another data exploration technique is using holographic models to represent the point cloud in 3D without relying on a head-mounted display (HMD). HMDs can be constraining when viewing 3D models, depending on the pixel density of the HMD. As such, holographic technology such as the Axiom Hologram Table [27] provides the technician with a semi-immersive representation of the project without sacrificing visual fidelity. An example of the construction site point cloud on the holographic table is shown in Figure 3 (B).

Holographic interfaces enable collaborative data exploration with multiple users. In the case of the Axiom device featured in Figure 3 (B), two can be wearing spatially tracked 3D glasses and controllers, and two more can be wearing non-tracked glasses. The difference between tracked and non-tracked glasses is that tracked glasses adjust the view of the hologram based on the user's physical orientation around the table. Non-tracked glasses copy the holographic view from the tracked glasses. As such, those with non-tracked glasses must stand near the tracked user to get an effective view of the scene. This device also features an audience view monitor, allowing spectators to understand what model is being presented to the users. Technicians leverage a remote controller to perform remote site construction site analysis operations, such as measuring construction features, rotating and scaling the environment, and creating presentations using multiple 3D files to display multiple project phases.

This workflow's disadvantages come from the technology's highly specific hardware and software requirements. This type of technology has a high entrance cost compared to the highly available consumer-grade desktops and HMDs. The models must be converted into a proprietary file type so the system can project them holographically. Some complex 3D files containing dynamic scenes are not compatible.

2.3.3 Immersive Environments

For this application, two types of immersive environments were explored: (1) viewing the three-dimensional point cloud in the first person and (2) a high-fidelity 3D reconstruction of the point cloud.

Point clouds can be loaded into applications such as Unreal Engine 5 (UE5) and navigated in VR [28]. Such applications can be advantageous compared to 3D images, as the high accuracy of point clouds should lead to improved spatial context. UE5 provides advanced modules and templates for VR applications and a dedicated LiDAR plugin. As such, point clouds can be uploaded directly and explored in the engine. The first-person point of view for this environment is shown in Figure 3 (C). VR-based toolsets are available for remote monitoring to capture measurement data [29], and can effectively reproduce the same construction monitoring tasks performed using the other visualization methods.

To build a high-fidelity 3D reconstruction of the site, UE5's environment modeling tools were leveraged to rebuild the model as a landscape component and several static mesh components. The landscape component represents the terrain of the site. The key difference between a static mesh and a landscape component is static meshes are non-deformable and predefined. In contrast, landscape components are dynamic - they can be modified in real time. Dynamic landscapes help simulate diverse construction scenarios, such as excavations. The point cloud was manually segmented to exclude everything but

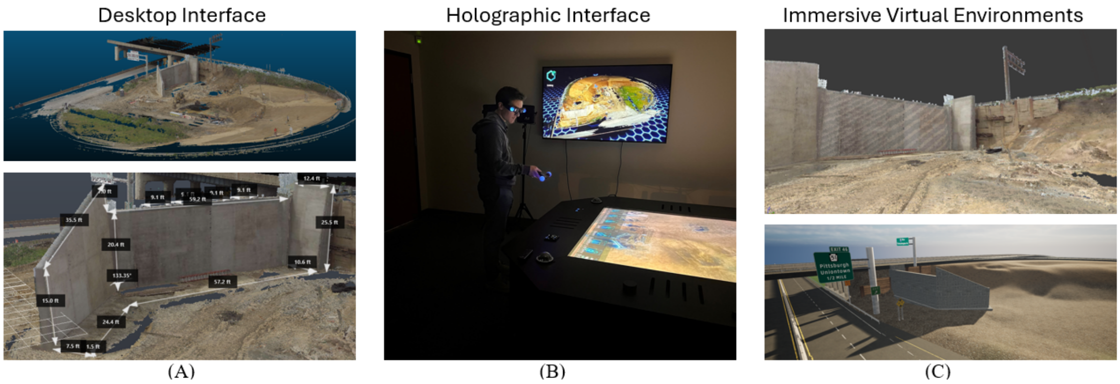

Figure 3. Methods of data exploration for remote monitoring and viewing simulations: desktop interface (A), holographic interface (B), and immersive virtual environments (C).

the surface elevation to generate the landscape component. Given this landscape-only point cloud contained missing data, synthetic points were interpolated by generating a Delaunay 2.5D mesh [30] in those areas and sub-sampling the mesh into points. The obtained point cloud was recolored with a height ramp and rasterized into a 2.5D height map image. The height map image was uploaded directly into UE5 to build the landscape (see Figure 4 (A)). Once the landscape was generated, objects of interest from the point cloud were created to fill the environment with infrastructure components relevant to the scene. Objects of interest can be meshed using software such as Reality Capture [28]. Figure 5 shows an example of generating a mesh from the reinforced concrete wall central to the site. Additionally, the objects can be rebuilt manually using the measurements obtainable (see Figure 3 (A)). The roads of the highway interchange were built using a spline tool. Splines build a continuous path of iterated meshes along anchor points, locally adjusting the meshes and landscape to build highways. A similar technique was used to iterate center-line barriers and guide rails along the roads. Figure 4 (B) displays a sample of the VR scene.

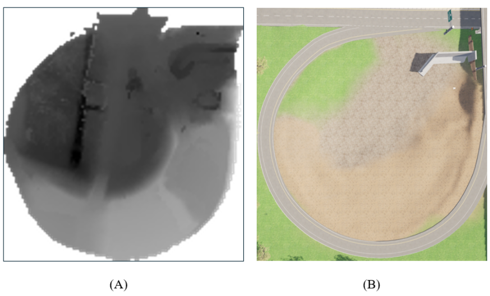

Figure 4. (A) Rasterized 2.5D image and (B) high-fidelity model for VR

This model is helpful for applications where the construction site is relevant as a foundation for a larger project. IVEs can be equipped with code to enable user interaction. This interaction increases the engagement of the model, which is known to increase knowledge retention for the user [31]. For example, various construction scenarios could be built on this scene for immersive construction health and safety training, contextually linked to the project. Additionally, coupled with data fusion from sensors, this technique can be used to build digital twin models.

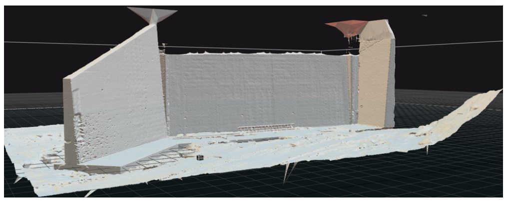

Figure 5. Reinforced concrete wall meshed using Reality Capture.

The primary disadvantages of VR methods are the entrance price and physical comfort considerations. Although HMDs are becoming more available to consumers, there is an additional need for a high-performance computer to run the simulation. Additionally, only one user can use VR at a time, constraining the collaboration capabilities of the analysis. Regarding physical comfort, users may experience VR sickness (also known as motion sickness), given that the visual perception of their surroundings differs from the physical sensations. When artificial movement is added to a VR simulation, the visual and physical senses of the user do not match, causing motion sickness. Since approximately one-third of the population is highly susceptible to motion sickness [32], extended use of VR is not always practical.

3 Results and Discussion

The work's results are presented as an evaluation of data processing and recommendations for best practices in visualization and data acquisition.

The original data capture comprised 20 successful scans, totaling $\tilde{5}$00,000,000 unique points, and was roughly 10.7 Gb in storage. After performing the methodology explained in Section 2.2, instances of duplicate points and noisy data were removed and a clean point cloud was obtained (see Figure 6 (A)). In the first step, where coincident points were extracted, 75.9% of the initial data was removed. After performing the noise removal, there was a cumulative point reduction of 87.21% and a total file size reduction of 89.04% from the original scan, which shows the significant amount of unnecessary and inaccurate data that can be removed after data collection. This processed point cloud, along with being a more accurate representation of the scene, has lower computational costs and storage requirements than the unprocessed version. The obtained data was dense in points despite the size reduction, and, as shown in Figure 6 (B), there is a high concentration among the construction features of the work site. This high concentration is valuable for precise measurements of construction features.

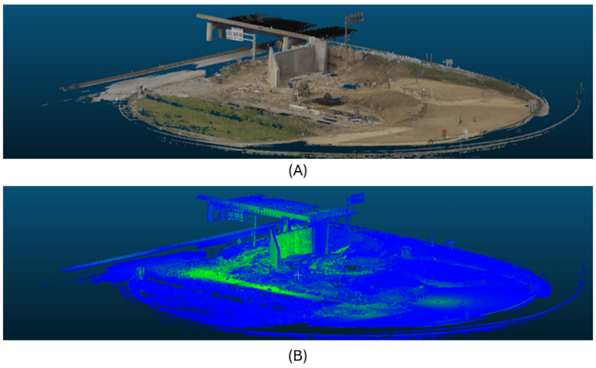

Figure 6. (A) Full point cloud after data processing and (B) Point density after data processing, visualized with a color scale: blue (lowest density) to red (highest density).

Three methods of data exploration were reviewed. Provided with a processed dataset, an expert can make judgments regarding the construction quality with easier access to many details of the site than would be available with an in-person visit. In all three methods, the standard tasks were able to be performed, thus displaying feasibility for these methods to enable remote inspection of construction sites. The efficiency and difficulty of each method for remote monitoring activities are highly dependent on the technicians' experience using the technology. Since most users are expected to have significantly more experience interacting with desktop interfaces, they were found to be the most accessible for remote monitoring. Holographic data visualization methods were found to be best used as a collaborative tool or for presentation purposes. Multiple users can review the 3D data in a semi-immersive environment. Given the depth perception and spatial rendering, participants can see the full scope of the data intuitively. As a presentation tool, the holographic interface is found to be a memorable and engaging method of presentation. For all methods, measurements of construction features were replicable. IVEs are effective for applications where the user should interact with the environment. Immersive virtual environments were found to be similarly engaging and memorable experiences for displaying projects compared to holographic ones.

Based on the described case study, the following best practices are proposed for future applications of virtual construction site analysis of horizontal infrastructure:

1. The TLS scans should be captured across the work zone so that nearby captures overlap in data, and areas with the most significant construction features are prioritized.
2. Engage in manually cleaning the data to remove artifacts such as floating points, partial objects, and reflections—additionally, leverage coincident point removal to eliminate overlapping data. While aligning, pay special attention to the vertical alignment links - especially in areas where the scan primarily captures terrain.
3. Leverage different visualization techniques depending on the use case of the data. For accessible remote monitoring, prioritize desktop interfaces. Use immersive techniques such as holographic interfaces and IVES for presentations, collaborative data exploration, or activities involving interaction with the model.
4. When building a high-fidelity IVE, separate the landscape from the construction features to create an environment with a well-defined terrain before adding construction features. Leverage the measurement techniques or meshing capabilities available from point clouds to recreate objects of interest accurately.

4 Conclusion

This study introduced a novel workflow for processing and visualizing point cloud-based reconstructions of horizontal infrastructure projects, through discussion of dealing with common types of noisy data relevant to construction sites and an exploration of data exploration methods. The data collection and processing were described to help define best practices for large-scale terrestrial point cloud capture of horizontal infrastructure. Additionally, a data processing framework was explored which highlights the significant amount of either unnecessary or noisy data within point clouds of active horizontal construction sites. To judge the viability of remote project monitoring and simulation rendering, data exploration methods were surveyed, with an emphasis on the most advanced technological methods available. The highlighted methods were desktop interface, holographic interface, and immersive virtual environments. These advanced techniques proved promising for remote inspection and analysis of construction sites. Each method was found to be viable when performing standard construction monitoring tasks such as observing construction features, taking measurements, and presenting information. However, all methods require individual expertise for efficient operations in both site inspection and collaboration activities.

This work enables a formal quantitative study to improve understanding and analysis of the efficiency and difficulty of each method, along with assessment of cognitive load within larger groups of users. Future work will focus on developing the high-fidelity 3D model into practical use cases. Industry partners have been identified to guide this development. The work presented opens the possibility of defining a novel framework for developing IVEs from laser scans obtained from construction sites. In the future, this could provide a defined methodology to convert real-life projects into advanced, context-specific IVEs suitable for simulation.

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References

[1] American Society of Civil Engineers. 2021 report card for america's infrastructure, March 2021. URL `https://www.infrastructurereportcard.org/`. Accessed: 2024-12-16.

[2] Guiwen Liu, Kexi Xu, Xiaoling Zhang, and Guomin Zhang. Factors influencing the service lifespan of buildings: An improved hedonic model. *Habitat international*, 43:274–282, 2014.

[3] Jingjing Wang, Yurong Zhang, and Yuanfeng Wang. Environmental impacts of short building lifespans in china considering time value. *Journal of Cleaner Production*, 203:696–707, 2018.

[4] Yichen Qian, Renjin Sun, Jun Zhao, Sasa Song, and Pinchen Wang. How does public infrastructure construction influence co2 emissions? a global case. *Frontiers in Environmental Science*, 10:1048297, 2022.

[5] Federica Geremicca and Melissa M Bilec. Searching for new urban metabolism techniques: A review towards future development for a city-scale urban metabolism digital twin. *Sustainable Cities and Society*, page 105445, 2024.

[6] Mohammadsaeid Parsamehr, Udara Sachinthana Perera, Tharindu C Dodanwala, Piyaruwan Perera, and Rajeev Ruparathna. A review of construction management challenges and bim-based solutions: perspectives from the schedule, cost, quality, and safety management. *Asian Journal of Civil Engineering*, 24(1):353–389, 2023.

[7] McKinsey & Company. Rise of the platform era: The next chapter in construction technology, 2023. URL `https://www.mckinsey.com/industries/private-capital/our-insights/rise-of-the-platform-era-the-next-chapter-in-const` Accessed: 2024-12-16.

[8] Imanol Munoz-Pandiella, Marc Comino Trinidad, Carlos Andújar, Oscar Argudo, Carles Bosch, Antonio Chica, and Beatriz Martínez. Gain compensation across lidar scans. *Computers & Graphics*, 106: 174–186, 2022.

[9] Yingbo Zhu, John C Brigham, and Alessandro Fascetti. Lidar-rgb data fusion for four-dimensional uav-based monitoring of reinforced concrete bridge construction: Case study of the fern hollow bridge reconstruction. *Journal of Construction Engineering and Management*, 151(1):05024016, 2025.

[10] Alessandro Fascetti and Caglar Oskay. Multiscale modeling of backward erosion piping in flood protection system infrastructure. *Computer-Aided Civil and Infrastructure Engineering*, 34(12):1071–1086, 2019.

[11] Osama Moselhi, Hassan Bardareh, and Zhenhua Zhu. Automated data acquisition in construction with remote sensing technologies. *Applied Sciences*, 10 (8):2846, 2020.

[12] Sajjad Einizinab, Kourosh Khoshelham, Stephan Winter, Philip Christopher, Yihai Fang, Eric Windholz, Marko Radanovic, and Songbo Hu. Enabling technologies for remote and virtual inspection of building work. *Automation in Construction*, 156: 105096, 2023.

[13] Chamin Nalinda Lokugam Hewage, Debra F Laefer, Anh-Vu Vo, Nhien-An Le-Khac, and Michela Bertolotto. Scalability and performance of lidar point cloud data management systems: A state-of-the-art review. *Remote Sensing*, 14(20):5277, 2022.

[14] Qian Wang, Yi Tan, and Zhongya Mei. Computational methods of acquisition and processing of 3d point cloud data for construction applications. *Archives of computational methods in engineering*, 27(2):479–499, 2020.

[15] Thomas Kanzok, Falk Süß, Lars Linsen, and Paul Rosenthal. Efficient removal of inconsistencies in large multi-scan point clouds. 2013.

[16] Juan Manuel Davila Delgado, Lukumon Oyedele, Thomas Beach, and Peter Demian. Augmented and virtual reality in construction: drivers and limitations for industry adoption. *Journal of construction engineering and management*, 146(7):04020079, 2020.

[17] Jack M Loomis, James J Blascovich, and Andrew C Beall. Immersive virtual environment technology as a basic research tool in psychology. *Behavior research methods, instruments, & computers*, 31(4): 557–564, 1999.

[18] Rafael Sacks, Amotz Perlman, and Ronen Barak. Construction safety training using immersive virtual reality. *Construction Management and Economics*, 31(9):1005–1017, 2013. ISSN 0144-6193.

[19] Johanna Pirker, Enrica Loria, Saeed Safikhani, Andreas Künz, and Sabrina Rosmann. Immersive virtual reality for virtual and digital twins: A literature review to identify state of the art and perspectives. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 114–115. IEEE, 2022.

[20] Lilia Potseluyko, Farzad Pour Rahimian, Nashwan Dawood, Faris Elghaish, and Aso Hajirasouli. Game-like interactive environment using bim-based virtual reality for the timber frame self-build housing sector. *Automation in Construction*, 142:104496, 2022. ISSN 0926-5805.

[21] Dimitrios Bolkas, Jeffrey Chiampi, John Chapman, and Vincent F Pavill. Creating a virtual reality environment with a fusion of suas and tls point-clouds. *International journal of image and data fusion*, 11 (2):136–161, 2020.

[22] Elise Kaartinen, Kyle Dunphy, and Ayan Sadhu. Lidar-based structural health monitoring: Applications in civil infrastructure systems. *Sensors*, 22(12): 4610, 2022.

[23] Leica Geosystems. Cyclone register 360 plus help / cyclone register 360 /review and optimize, 2024. URL https://rcdocs.leica-geosystems.com/cyclone-register-360/latest/creating-links. Accessed: 2024-12-19.

[24] CloudCompare Developers. Cloudcompare documentation, 2024. URL https://www.cloudcompare.org/doc/. Accessed: 2024-12-19.

[25] Autodesk, Inc. *Autodesk AutoCAD 2022 Help Documentation - About Working With Point Clouds*, 2022. URL https://help.autodesk.com/view/ACD/2022/ENU/?guid=GUID-C0C610D0-9784-4E87-A857-F17F1F7FEEBE. Accessed: 2024-12-20.

[26] Autodesk, Inc. *Autodesk Revit 2022 Help Documentation - About Point Clouds*, 2022. URL https://help.autodesk.com/view/RVT/2022/ENU/?guid=GUID-BD499295-84DD-4BDE-B60D-73008AFBC791. Accessed: 2024-12-20.

[27] Axiom Holographics. Axiom Holographics Hologram Table, 2024. URL https://axiomholographics.com/devices/hologram-table/. Accessed: 2024-12-18.

[28] Epic Games. Unreal engine 5.5 documentation, 2025. URL https://dev.epicgames.com/documentation/en-us/unreal-engine/unreal-engine-5-5-documentation. Accessed: February 27, 2025.

[29] Daniel Garrido, Rui Rodrigues, A Augusto Sousa, Joao Jacob, and Daniel Castro Silva. Point cloud interaction and manipulation in virtual reality. In *2021 5th International Conference on Artificial Intelligence and Virtual Reality (AIVR)*, pages 15–20, 2021.

[30] CloudCompare. Cloud compare documentation: Alignment and registeration, 2015. URL https://www.cloudcompare.org/doc/wiki/index.php/Alignment_and_Registration#Alignment.

[31] Michael J Burke, Sue Ann Sarpy, Kristin Smith-Crowe, Suzanne Chan-Serafin, Rommel O Salvador, and Gazi Islam. Relative effectiveness of worker safety and health training methods. *American journal of public health*, 96(2):315–324, 2006. ISSN 0090-0036.

[32] Craig R Sherman. Motion sickness: review of causes and preventive strategies. *Journal of travel medicine*, 9(5):251–256, 2002. ISSN 1195-1982.