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A Novel Immersive Virtual Reality Platform for Health and Safety Training of Construction Workers

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16. Abstract

Health and safety (H&S) training in the construction industry is paramount, given the sector's high injury and fatality rates. Traditional training tends to exhibit over-reliance on passive methods of instruction, bringing challenges associated with knowledge retention and engagement. This study leverages virtual reality (VR) to enhance H&S training through immersive virtual environments (IVE)s and serious gaming. Laser scanning data captured from an active highway construction site created a highly realistic IVE. This environment was then leveraged to build a virtual reality platform containing modules for construction safety training using Unreal Engine 5 (UE5). Users navigate these modules, interacting with objects to identify hazards and learn about safety guidelines. All platform construction scenarios are parametric, so context-specific training can be implemented. Evaluation of the module's realism, usability, and potential for enhancing traditional training programs was performed through beta testing on a user group composed of experts in both construction safety and computer science. The results of this research demonstrate the potential of VR in creating immersive and engaging training experiences, which could lead to improved safety performance outcomes in highway construction operations.

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The Impactful Resilient Infrastructure Science & Engineering consortium was established in the Department of Civil and Environmental Engineering in the Swanson School of Engineering at the University of Pittsburgh to address the challenges associated with aging transportation infrastructure. IRISE is addressing these challenges with a comprehensive approach that includes knowledge gathering, decision making, design of materials and assets and interventions. It features a collaborative effort among the public agencies that own and operate the infrastructure, the private companies that design and build it and the academic community to develop creative solutions that can be implemented to meet the needs of its members. To learn more, visit: https://www.engineering.pitt.edu/irise/.

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A Novel Immersive Virtual Reality Platform for Health & Safety Training of Construction Workers

The Impactful Resilient Infrastructure Science and Engineering (IRISE) Consortium

Final Report

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Contents

Abstract

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1 Literature Review

Health and Safety protocols (H&S) are a top priority in the infrastructure construction. Only about 7% of the world's labor is in construction, yet approximately 20% of all workplace fatalities in the US happen on construction sites [52]. The National Safety Council [25] estimates that each fatality has an average cost of $1.34 million for a company. One in every ten construction workers garners a non-fatal injury yearly, a value that is 70% higher than that of any other industry in the US. Workers in the 25-34 age range have the highest injury rate, and 43% of road workers have less than one year of experience [50] (see table 1). This demonstrates how H&S training should focus on the youngest generation of workers.

Number of Years	Percentages
Less than 1 year	43%
1-2 years	27%
3-4 years	13%
5-7 years	9%
8-10 years	2%
11+ years	6%

Table 1: Tenure of Road Construction Workers in 2021

Safety has been a popular research topic in construction for a long time. However, improvements should be expected with quickly advancing technology and comparatively stagnant training methods. Construction continues to be one of the most dangerous fields, so any potential advantages should be considered.

This report summarizes the current H&S training practices and how virtual reality has been implemented. The findings will help provide insight into how best to reproduce training modules in a Virtual Reality environment.

1.1 Traditional Training Methods

1.1.1 Laws and Regulations

The Occupational Safety and Health Administration (OSHA) is the United States Department of Labor regulatory body responsible for setting safe and healthful working conditions standards. They conduct occasional work zone visits, maintaining their standards and remediating hazards. Random OSHA safety inspections reduce worker injuries by 9.4% and reduce injury costs by 26% [53]. These improvements come with no expense to employment and sales.

OSHA sets standards to prevent injury and fatality in a work zone and provides training, outreach, education, and assistance. It is the responsibility of the construction manager to incorporate a proper level of training into their work zone. Health and Safety training can be seen as an investment that will pay back fewer injuries, better morale, lower insurance premiums, and fewer fines [66].

1.1.2 OSHA Training

The most popular Health and Safety training for construction workers and foremen are the OSHA 10- and 30-hour programs, respectively. The 10-hour program is primarily intended for entry-level workers. The 30-hour training program is intended to provide workers with some safety responsibility and a greater depth of training. The course has four types depending on the concentration: construction, general industry, maritime industry, and disaster site workers.

OSHA does not require construction workers to undergo training; they simply provide the training and encourage people to participate. Several states carry laws requiring construction workers/overseers in specific sectors to have OSHA training certifications [44]. Table 2 shows the training requirements for ten different states.

1.1.3 Traffic Control Training

Traffic control training is provided by every state Department of Transportation (DOT) and required training in nearly every state [4]. This training can be completed at any state-recognized provider. Traffic control is universally recognized as one of the most dangerous jobs on a worksite [48, 68]. Training for traffic controllers involves a review of proper flagging signals, procedures, and practices for various dangerous situations.

State	OSHA Certification Requirements
Connecticut	All construction workers for public building projects paid for (in part or in full) by state funding where the total cost is over $100,000 are required to take OSHA-authorized training.
Florida	All construction employees in Miami-Dade County are required to take OSHA-authorized training prior to employment on public or private contracts valued in excess of $1,000,000.
Massachusetts	Construction workers for any public sector projects are required to take OSHA-authorized training.
Missouri	All construction workers on public work projects (state or municipal) are required to take OSHA-authorized training.
Nevada	All construction employees (10-hour) and supervisors (30-hour) are required to take OSHA-authorized training within 15 days of being hired.
New Hampshire	All construction workers on public works projects with a total cost over $100,000 are required to take OSHA-authorized training.
New York	All workers on public works contracts greater than $250,000 are required to take OSHA-authorized training (or a pre-approved equivalent program).
Pennsylvania	All employees (10-hour) and at least one supervisory employee (30-hour) of licensed contractors are required to take OSHA-authorized training if they are performing permitted construction or demolition work within the city of Philadelphia.
Rhode Island	All workers on municipal and state construction projects with a total cost of $100,000 or more are required to take OSHA-authorized training.
West Virginia	Workers on any public improvement project with a total cost in excess of $50,000 are required to take OSHA-authorized training.

Table 2: State Based OSHA Training Requirements [44]

1.1.4 Construction Site Safety Inspection

Safety inspectors must be trained to recognize hazards and effectively judge the safety of a worksite. Certification and training requirements vary by state [51]. Some states have on-the-job training and in-house certification. In contrast, others require individuals to be trained by the variety of organizations available (International Code Council, International Association of Plumbing and Mechanical Officials, International Association of Electrical Inspectors, and International Association of Certified Home Inspectors) [51].

Bridge inspectors are federally regulated by the National Bridge Inspection Standards (NBIS). The NBIS required basic qualifications for all bridge inspections affiliated with a state DOT, federal agency, or tribal government [84]. In addition, many departments have additional qualification requirements. For example, the Pennsylvania Department of Transportation (PENNDOT) requires bridge inspectors to complete an initial 15-day training course and pass a final exam [83]. Additionally, individuals must attend a refresher training course every 2 years, take a certification exam every 2 years, and have sufficient education in the engineering field.

1.2 Barriers to Effective Training

Despite a steady flow of research focusing on designing and delivering construction training programs, construction safety remains a global issue [2]. There are a variety of factors surrounding the lack of practical training. Primarily, these factors are the training itself and the employer's ability to train. According to a survey conducted by [43], employees frequently feel like they do not need safety training, the person teaching them is not credible, and the provided training does not provide adequate physical demonstrations. Figures 1, 2, and 3 show survey responses regarding the reception of formal safety training among a class of roofing contractors.

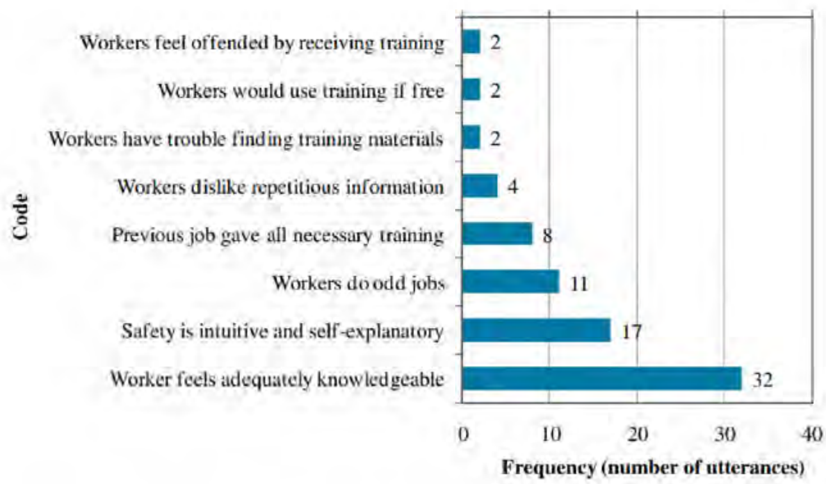


Figure 1: Barriers of formal safety training from Hung et al. (2013) [43]

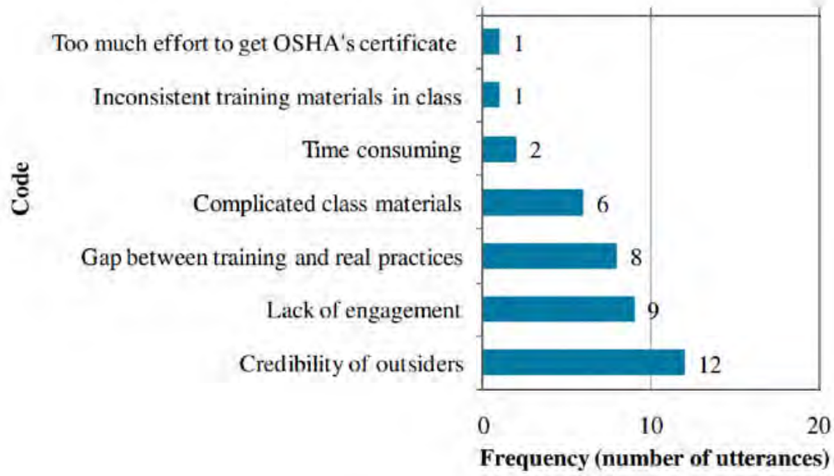


Figure 2: Problems of formal safety training from Hung et al. (2013) [43]

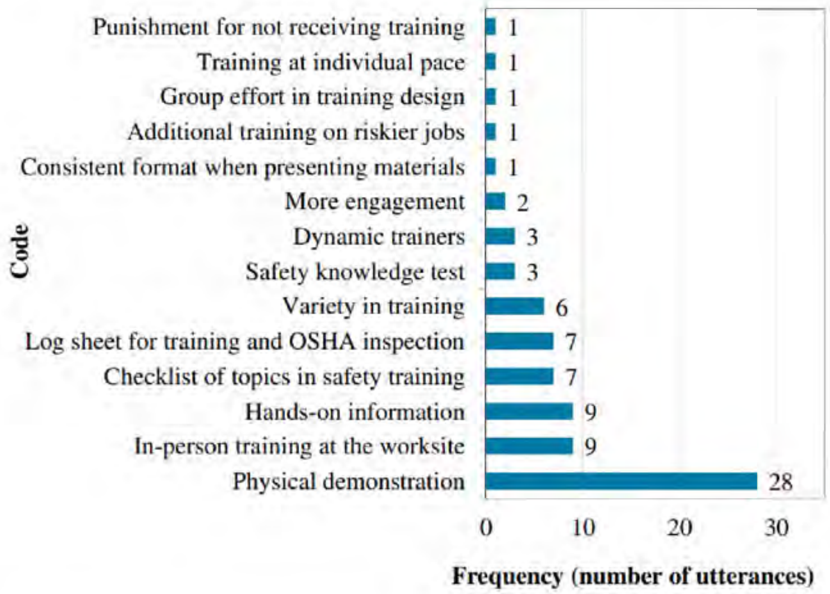


Figure 3: Recommendations for improving formal safety training from Hung et al. (2013) [43]

1.3 Modern Applications of Virtual and Extended Realities

Virtual Reality (VR), Augmented Reality (AR), and Extended Reality (XR) are terms used to define technologies that modify perceived reality. New realities have become increasingly popular in engineering, construction, and architecture to meet the demand for improved visualization since they were introduced to the field in the 1990s [90].

Virtual reality (VR) is a simulated environment created through computer technology that immerses users in a three-dimensional, interactive experience [45, 79]. By wearing a

VR headset and other sensory technologies, the user receives the virtual environment as their reality. VR headsets use head trackers to allow movement within the simulation. VR differs from AR or XR in that VR completely disconnects from the outside environment. VR is primarily used in entertainment, such as video games or media.

Academics and professionals disagree regarding when and how best to differentiate XR and AR. Some view XR as an umbrella term that refers to any form of VR or AR. Alternatively, some view XR as a unique type of new reality that seamlessly mixes the real world with the virtual world [70].

According to Varjo [86], a high-end virtual reality hardware developer, Augmented reality means that "*that the user is experiencing the real reality while certain virtual elements are projected on top of it*." This contrasts with their definition of Mixed reality, which "*combines the best aspects of both VR and AR. It is all about merging virtual content with the real world in an interactive, immersive way. In Mixed Reality, virtual objects appear as a natural part of the real world, occluding behind real objects*". As such, those who develop the technology often have different definitions than those who perform research.

1.4 Available Examples of VR Applications

The concept of "learning by doing" is a unique benefit to virtual reality training. A study by [88] focused on skill training for a variety of VR applications. These applications are broad, from sports [82] to paramedic training [77], proving an attainable pipeline of VR creation to implementation for a large scope of training tasks exists. VR training has applications in a large variety of fields and many successes worth studying.

The largest employer in the United States is Walmart, employing 2.3 million people. Followed by Amazon, employing 1.5 million [80]. Both companies are using VR to improve their workforce training efficiency [17]. For companies such as these, who hire hundreds of thousands of new employees each year and have relatively high turnover, saving time and money on training is incredibly valuable.

Retail companies are using VR/XR to improve branding and marketing. Companies such as Lego and Nike use in-store AR to present to customers what the product looks like outside of the box. Ikea and PPG Paints created AR phone apps for homeowners to imagine how products will look in their house [11].

Augmented reality has played a role in many manufacturing and industrial warehouses in improving worker efficiency. AR can improve object interaction, tracking, and analysis in real time [26]. The Boeing Company uses Augmented Reality glasses to improve the productivity of their assembly [32]. AR glasses can identify a task, provide the user's current task, and provide instructions to speed up their work. This includes guidance in the assembly process [89] and warehouse navigation for item picking [31].

Medical professionals, who are constantly required to continue their education, have found virtual reality to be a valuable improvement in their training by providing a "rich, interactive, engaging educational context, thus supporting experiential learning-by-doing"

[57]. Medical training in VR has been growing in popularity and has found popularity in specializations such as rehabilitation, disability management, surgical training, psychological diseases therapy, and analgesic modality [54]. Medical training is primarily conducted through real-life or simulated experiences, and VR has been seen as an upgrade in the simulations.

VR has found a role in the education process to make information more engaging and accessible. According to a study by [60], a surveyed group of STEM students preferred VR education technology over traditional lab technology. When the knowledge retention of VR education was studied, the immediate recall was almost the same as traditional education. However, long-term knowledge retention favors VR [5]. Specifically, the control group was more likely to recall incorrect information than the experimental group. The example recall scores from this study are shown in Table 3

	Immediate Mean	Immediate SD	Delayed Mean	Delayed SD
Control	14.46	5.35	10.33	5.43
Experiment (VR)	14.15	5.24	13.69	6.43

Table 3: Recall scores for VR and traditional learning experiment [5]

Compared to two-dimensional mediums, VR has a unique ability to fully display an A&E drawing in the same dimension as the model itself. This causes many architects and engineering designers to embrace the new technology [27]. Du et al. [28] presented a multi-user unified VR platform to improve the engagement of contractors, architects, engineers, and clients. The BIM VR platform was found to improve engagement and understanding for all parties involved in the project. Roach et al. [71] developed a CAD VR modeling software, which was compared to other similar software (Google Blocks & MakeVR pro). The VR modeling software was found to be more intuitive and quicker to learn than traditional CAD software.

Utilizing VR/AR allows A&E designers to more accurately perceive how their design changes impact the overall project. Berg & Vance [6] investigated design decision-making in virtual reality. Virtual Reality is capable of presenting designs effectively during design meetings, allowing for decisions to be validated or design changes to be made. The study found that VR is most helpful at differing stages of the design process, depending on the role of each team. Teams working on the early-concept idea phase found VR used VR effectively initially, and the manufacturers found VR most useful in the end.

1.5 Review of VR/XR-Based Construction Health and Safety Training

As Virtual Reality becomes more affordable and obtainable, it is becoming a realistic option for companies and organizations looking to improve their safety training. Benefits such as competitive costs, realistic experiences, and large-scale simulations lead many to believe this is the future of H&S training. Although research in this field has been productive, there is yet to be an all-in-one high-quality health and safety training program available fully in virtual reality. Haslam et al. [40] address that workers' attitudes and approach to safety will be negative if the delivery is ineffective. Although learning occurs on the job, this attitude can foster bad habits and put workers at risk.

1.5.1 Competitive Cost

Health and safety training is a substantial investment for construction companies. According to the American Society of Safety Professionals [74], companies can expect returns between $4 and $6 for each $1 they invest in safety and health. Virtual Reality training eliminates the need for physical training facilities and equipment. Likewise, VR training eliminates the costly process of hiring and scheduling professional health and safety trainers. Hilfert and König [41] developed a low-cost safety training program using commercial products available for a total of ~$2000. Compared to the cost of the OSHA 10-hour training course (~$70), this example will break even after training 29 employees.

VR enables individualized approaches to training, saving time and resources. A trainee can repeat portions of the training until they are proficient without hiring additional trainers or scheduling multiple sessions. Trainees can participate anywhere with the proper hardware and an internet connection, regardless of the distance to the specific worksite they are training for. VR is not always cheaper than lecture-based training, but the costs are frequently comparable. Overall, the competitive costs of VR compared to traditional methods make it an attractive option to companies looking to optimize their health and safety training.

1.5.2 Context-Specific Experiences

VR allows for training experiences to be tailored towards any specific work site. Programs such as Unity and Unreal Engine connect directly to BIM models, allowing for large-scale simulation. Individuals can enact "Learning-by-doing" with training activities that are as close to their specific job as possible. Learning by doing is a powerful concept because it allows individuals to develop their skills and deepen their understanding through actual experience. VR puts the trainee into a realistic simulation, training them to recognize dangers like they would on the job. Liang et al. [55] built a realistic, physics-based serious game for underground rock-related hazards safety training using Unity 3D. The simulation will prepare individuals for loose rocks that may move if force is applied. The realistic and immediate physics feedback makes the training more immersive and helps people become more familiar with the dangers of an underground mine.

Vahdatikhaki et al. [85] describe improvements in "context-realism" by incorporating the Internet of Things. Many available training simulations are unrealistic because they lack information from the actual sites being used. Thus, incorporating more data into the simulation increases realism and leads to a more useful simulation. Figure 4 shows the

Visualization of data fusion and model development for game engine basic context-specific environments.

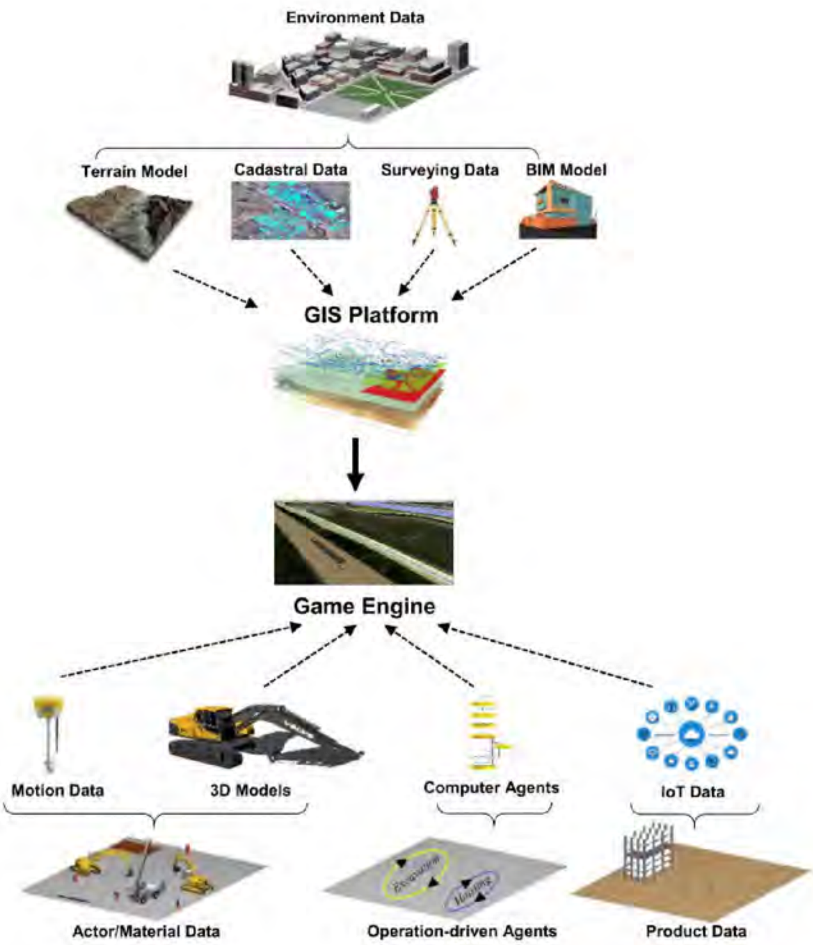


Figure 4: Visulization of data fusion and model development [85].

1.5.3 Engagement and Effectiveness

Traditional training for construction (lectures, videos, demonstrations) has been shown to be largely ineffective compared to more engaging forms of instruction. According to Burke et al., [15], the most engaging forms of instruction (hands-on learning in a realistic setting) are approximately three times as effective than the less engaging forms of instruction. Sacks et al. [72] ran experiments to test if VR is a viable high-engagement training method. His results found individuals trained with VR lowered their risk assessments compared to those trained traditionally, finding VR to be a highly effective engaging form of instruction.

The maximum benefits of VR are still likely to be underestimated [72]). VR scenarios are time-consuming and technically difficult to build. The recent advancements in 3D rendering, such as the release of Unreal Engine 5, have dramatically increased the maximum level of realism capable of being produced. Context-realism (Vahdatikhaki et al, 2019) will allow trainees to interact with the simulation more realistically, bringing the benefits of VR training closer to the absolute ceiling.

1.6 Examples of VR Health and Safety Training Programs

1.6.1 Hazard Recognition

Virtual reality is a great tool for hazard recognition, as the 3D environment activates your senses similarly to being on an actual worksite. Jeelani et al. [46] developed a stereo-panoramic environment for hazard recognition using Unity (see Figure 5). The simulation highlighted the importance of personalized training and realism to maximize the effectiveness of hazard recognition. Several types of hazards were available, such as temperature, biological, chemical, electrical, gravity, mechanical, motion, pressure, radiation, and sound. The results were positive, supporting the expectation that learning would be effectively facilitated through personalized, realistic simulation. The hazard recognition and management scores from this study are seen in Figure 6.

Figure 5: Accident Simulations for Hazard Recognition [46]

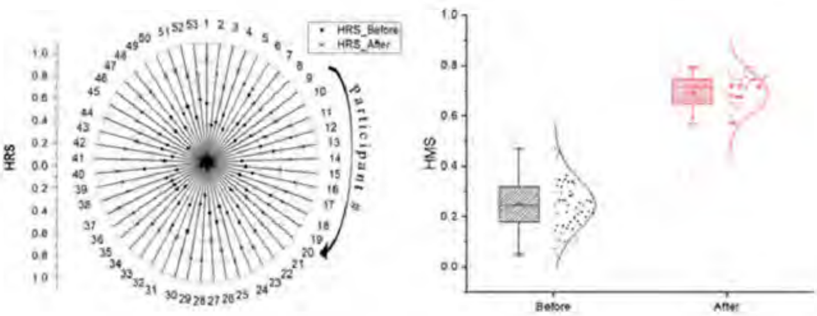


Figure 6: HRS (Hazard Recognition Score) and HMS (Hazard Management Score) Before and After VR training [46]

Moore et al. [58] developed a 360-degree panorama hazard recognition test and a VR hazard recognition test to compare the identification of OSHA's focus-four hazards (fall, struck-by, caught-in-between, and electrical). The panorama was a collection of 360-degree scenes depicting real worksites with hazardous conditions. Although more realistic than a VR simulation, panoramic representations contain more noise which can be seen as messy. The data from Moore's experiments found individuals were able to identify slightly more hazards in VR than in the panorama.

1.6.2 Fall Protection

Virtual Reality can effectively emulate the feeling of being at heights, making it a valuable tool for novice individuals preparing to work at high altitudes [18]. Chander et al. [18] generated a VR simulation to test an individual's postural sway (Horizontal movement around the center of gravity) at various heights (see Figure 7). Postural sway is an indicator of fall risk. Too much postural sway indicates an inability to maintain a static position. Chander's study was meant to determine if VR could train individuals to become more comfortable working at heights and improve their postural sway. The results were consistent with medical literature, which states postural sway increases as an individual gets higher up, and plateaus around 20 m [75]. These results support VR as a tool for fall protection and training.

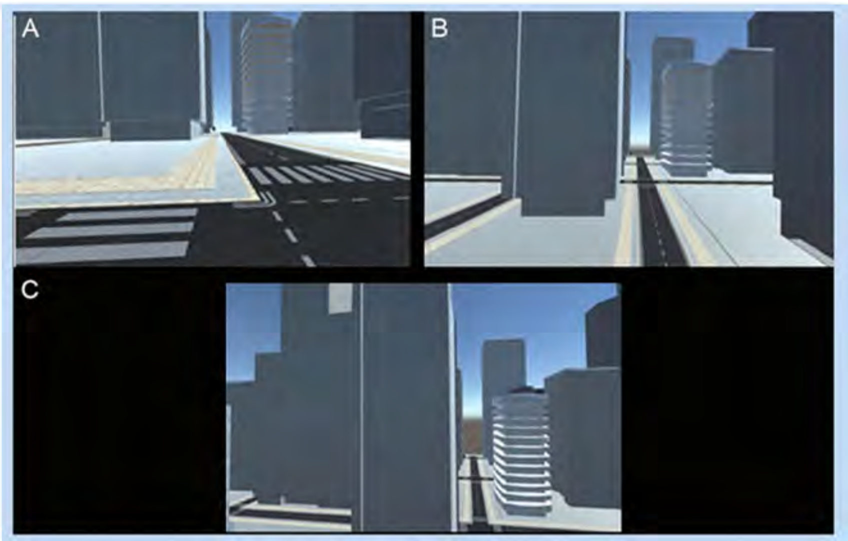


Figure 7: Height Exposure VR Environments at (A) Ground Level (B) 40 ft (C) 120 ft [18]

Virtual reality offers immersive training opportunities to engineers and managers who aren't frequently experiencing the worksite the same way as labor. Engineers and managers who frequently make decisions regarding safety preventative measures must also be trained. Brioso et al. [14] argued for the use of VR when determining the optimal preventative measure for fall risk. VR was compared to videos and used to choose the best fall protection measure using the CBA (choose by advantages) system (see Figure 8. Based on opinions from the panel of project engineers and managers, virtual reality was viewed as a more comprehensive way to understand the situation and make an appropriate decision.

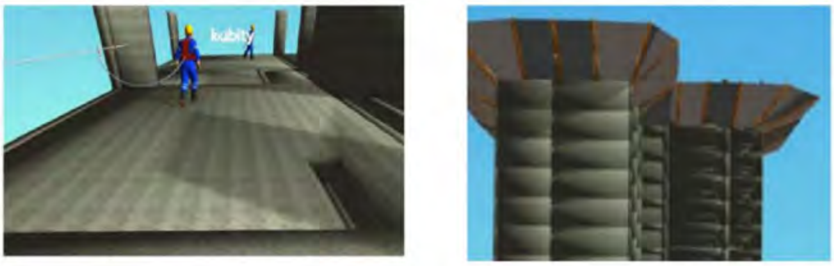


Figure 8: Virtual Reality Environment Depicting a Lifeline Harness and a Safety Net [18]

1.6.3 Emergency Management

Virtual Reality has found a role in numerous government agencies and academic institutions as a tool to prepare for emergencies. The New York City Office of Emergency Management, The Los Angeles Police Department, and the DHS Federal Emergency Management Agency are all public sector organizations that prominently use VR to improve their emergency preparation [42].

In the event of an emergency, evacuation procedures must be fully known and understood by everybody in danger. And in situations where every second matters, finding the optimal evacuation plan is crucial. VR is a powerful tool to compare evacuation effectiveness and investigate emergency scenarios [3]. Arias et al. [3] ran virtual reality evacuation experiments to test a variety of evacuation plans for a new build project. The simulation tested various types of installation (flashing lights, static or dynamic signage, and a robot giving directional guidance) (see Figure 9). The experiment had 26 participants, who all rated the realism of the simulation highly (see Figure 10). This example effectively used the presence of realism in a VR simulation to plan escape routes during the design process of a building project.

Figure 9: VR Exit Signage from Emergency Management Simulation [3]

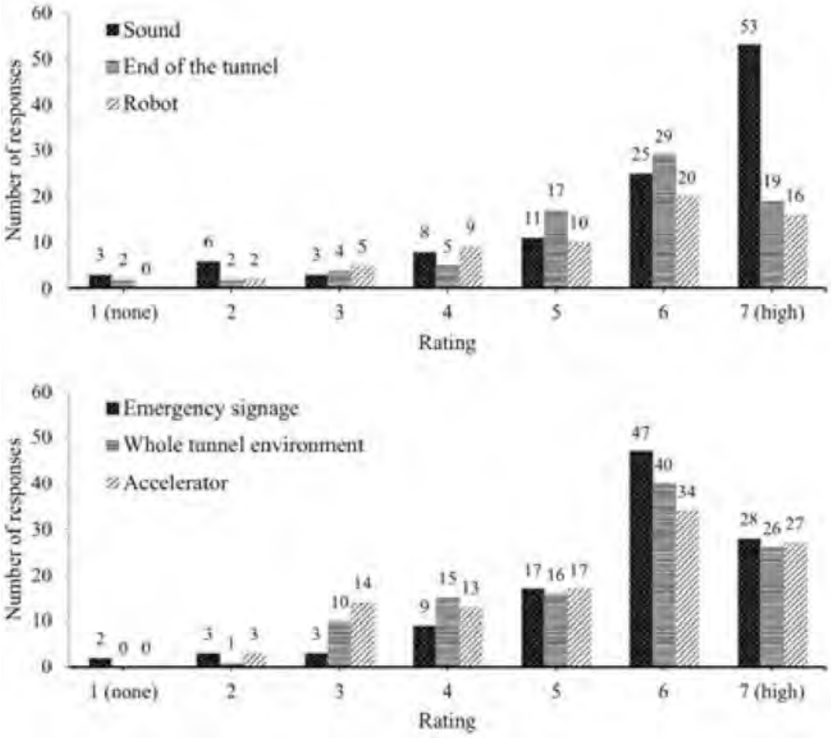


Figure 10: Realism Rating Survey Results from emergency management simulation [3]

1.6.4 Skill Training

Many technical skills cannot be effectively trained without active experience. Yet, in many cases, inexperienced individuals risk injury to themselves or others while learning. This is especially true for construction, as skilled trades are often high-risk jobs. Virtual Reality offers the opportunity for individuals to gain realistic experience with protection from the job's dangerous conditions. Borba et al. [13] built a training simulator for the operation of power lines which used trackers on external tools. Trackers give the simulation a more physical feel and allow for practice and learning-by-doing (see Figure 11). The recent technological advances with XR allow for outside tools to be effortlessly tracked in the simulation. Osti et al. [67] found success in training individuals for skilled trades using simulated tools. An extended reality environment would allow for these tools to show in the simulation and give a more realistic training experience.

1.7 Preliminary Conclusions

Construction continues to be one of the most dangerous occupational fields around the world. Effective Health and Safety protocols are seen as a top priority in the construction field. Once OSHA introduced their H&S standards, a decrease in fatalities and injuries occurred. Despite this improvement, fatalities and injuries have been relatively stagnant since then.

Figure 11: User interacting with the simulation using physical tools [13]

The literature agrees that H&S training is a valuable investment for employers, yet current training practices are low in engagement.

Virtual Reality is a high-engagement, cost-effective alternative to lecture-based training methods. Technology has become much more advanced, making realistic simulations much more attainable. Several specialized simulations have been produced by researchers, with positive reception from individuals. VR, AR, and XR have found a role in a variety of fields such as retail, industrial, medicine, and education. Construction safety researchers have a growing interest in incorporating VR into the field. As technology improves, creating realistic training programs that can fully train an individual will become much more efficient and will be deployable on a large scale.

1.7.1 Existing Gaps in Literature

Despite a healthy number of publications and a growing research interest in Virtual Reality for Health and Safety training, there is still no high-quality, all-in-one training program available. The training programs that are available do not provide enough realism to accurately measure the maximum benefits of VR. The training programs developed are not known to be used by any organization or employer in any considerable context, making the effectiveness of training in the long term unknown.

Further research should be conducted to maximize the realism of the VR simulation and increase its scope so that a trainee can become fully trained only using VR. Although many researchers are confident in VR's potential for remote training, the process of VR training an individual who isn't local is largely untested. Deployment of a training program is likewise unclear.

Extended and Mixed Reality allows physical tools to appear and be used inside the training simulation. Research on H&S training that incorporates the video pass-through available with this technology is incomplete. There is likely an opportunity to increase the realism of the simulation with this technology, and it should be studied further.

The ambiguous definition of XR leads to inconsistent research about the technology and difficulty in conducting a literature review on the topic. The question of whether XR is its own type of technology or an umbrella term for all virtual reality types has yet to be solved. Although a variety of academics have argued for a specific definition, this issue will likely only be solved with time as technology matures.

2 Introduction

The Occupational Safety and Health Administration (OSHA) is the regulatory body from the United States Department of Labor responsible for setting standards for safe and healthful working conditions. Since being established in 1971, OSHA standards and inspections have reduced worker injuries and fatalities without sacrificing employment or sales [52]. Companies that support a culture of H&S see positive impacts on productivity and performance, rendering H&S a high return on investment strategy [30]. Despite OSHA's improvements to safety outcomes and the rapid evolution of technology, injury statistics have remained stagnant in recent years [8]. OSHA provides H&S training for construction workers and foremen commonly known respectively as the 10- and 30-hour certifications [65]. The 10-hour program is primarily aimed at entry-level workers, while the 30-hour training program is intended to provide workers with safety responsibility and a greater depth of training. The training programs are delivered through in-person instruction or in an online format, with identical content being presented. The safety information for construction workers (10-hour course) highlights the major hazard categories that cause injuries and fatalities, known as the focus four [63]: (1) falls, (2) caught-in or -between, (3) struck-by, and (4) electrocution. In addition, the courses cover personal protective equipment (PPE), health hazards, material handling, and tools. Workers' reviews of health and safety training are frequently negative. From a survey of those who completed OSHA's 10-hour course, only 32.5% regarded the training as relevant, and 41% believed their instructor was either 'ineffective' or 'very ineffective' [87].

Safety knowledge is one of the key metrics to predict future safety performance [76]. However, teaching is less successful when there is an overreliance on low-engagement teaching methods [61]. The most engaging forms of instruction (such as hands-on learning in realistic settings) are approximately three times as engaging as the less engaging instruction (such as lecture- and slide-based learning) [16]. This stems from the fact that students learn more from doing than from listening [56]. To this end, there is a critical need to integrate interactive elements into traditional H&S training to maximize engagement and knowledge retention.

VR-based serious gaming offers new opportunities to develop engaging modules for H&S training and provide an effective sensorial experience. The current state-of-the-art includes several VR applications within the construction H&S industry [73, 47, 59]. However, there currently are no readily available high-fidelity H&S training programs based on serious VR gaming.

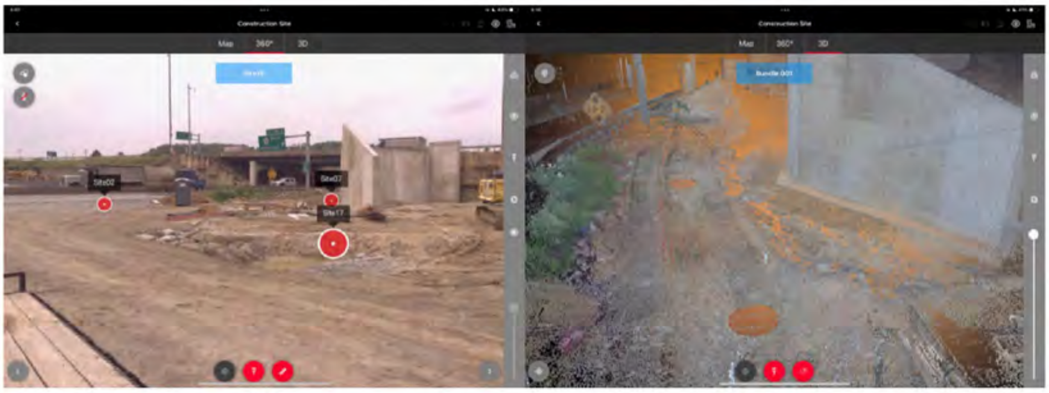
Within this framework, the main novelty proposed in this work is the development of an immersive VR serious game for H&S training of construction workers. The game aims to improve knowledge retention through several immersive experiences, maximizing realism in the simulation. Special attention was devoted to the virtual environment and the safety content to ensure that the provided information is consistent with the available traditional H&S modules. A high-fidelity three-dimensional environment was built from point cloud data obtained through laser scanning of an active highway construction site. Additionally, all hazards were built from teaching examples used in established safety training courses, linking the serious game to well-established real-world contexts.

3 Reality Capture

The use of high-fidelity laser scan data provides opportunities to improve contextual information while maintaining realism when developing immersive VR environments. Point cloud data has been effectively used to build IVEs for various infrastructure applications [69, 12]. The process of turning a point cloud into a high-fidelity environment is, however, a laborious, time-consuming task, as the complex scenes described by the point cloud require manual processing to be converted into IVEs. While creating landscapes and objects with simplified geometry is generally faster, achieving high fidelity greatly increases the complexity of the operations. Therefore, expert judgment is required to find the balance between accuracy and cost.

In this work, a high-fidelity point cloud of an active highway construction site was captured. This scan was taken in July of 2023, and access to the site was provided by Golden Triangle Construction Company. This project was the conversion of the I-70 and Route 51 interchange in Westmorland County, PA, from a cloverleaf to a diverging diamond. Scanning was performed using the Leica BLK360 scanner, a standalone laser scanner that captures up to 360,000 points per second within a 360° field of view at an accuracy of 6mm within 10m distance [1]. For each scan, the scanning device was placed in an open space and ran a data collection cycle. As the data was collected, a coverage map on a nearby tablet was constantly updated such that the team would know when and where to move the scanner. Figure 12 shows the research team running a data collection cycle with the Leica scanner nearby. Figure 13 shows the view from the tablet, which displays spatially referenced 360° images of the site (A) and an auto-aligned low-density preview of the point cloud.

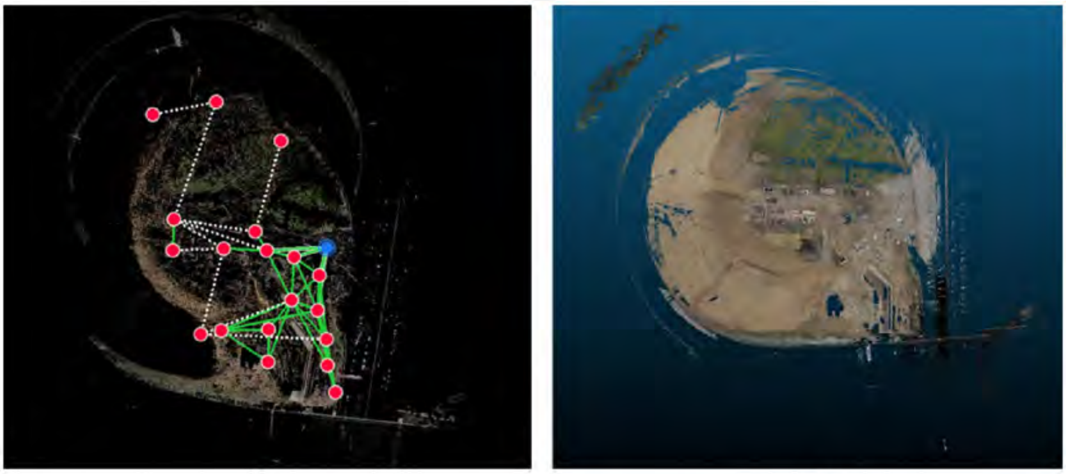
Figure 12: Research team performing a data scanning cycle with the Leica BLK 360.



(A) (B)

Figure 13: 360° spatially referenced images (A) and low-density point cloud preview (B).

The scanning process culminated in 22 individual scans, for a total of ~350,000,000 unique points. Automated alignment is first performed from the individual scans using links by time, distance, or similar points between static scenes [39], as shown in Figure 14 (A) These auto alignments are suitable for a rough estimate of the scene, but manual adjustments are required when processing the data. Figure 14 (B) shows the full-resolution scene before the data processing.



(A) (B)

Figure 14: Low resolution (A) and high resolution (B) auto-aligned scenes.

The individual scans are large in file size and include various imperfections. Figure 15 shows scan #1/22 from the site, highlighting three common sources of error: (A) random points far from the scan location, (B) reflections of nearby objects, and (C) unwanted captures of moving objects such as nearby workers (reflective vests). Additionally, nearby scans contain millions of overlapping points that are valuable for spatial alignment but redundant in the final output. As such, manual data processing was conducted on each individual scan. To simplify the point cloud, a two-step process was employed: (1) coincident point removal, and (2) manual segmentation and noise removal. At the end of the process, the point cloud contained roughly 60,000,000 points (for a ~80% reduction in size). The final point cloud after all data processing is displayed in Figure 16

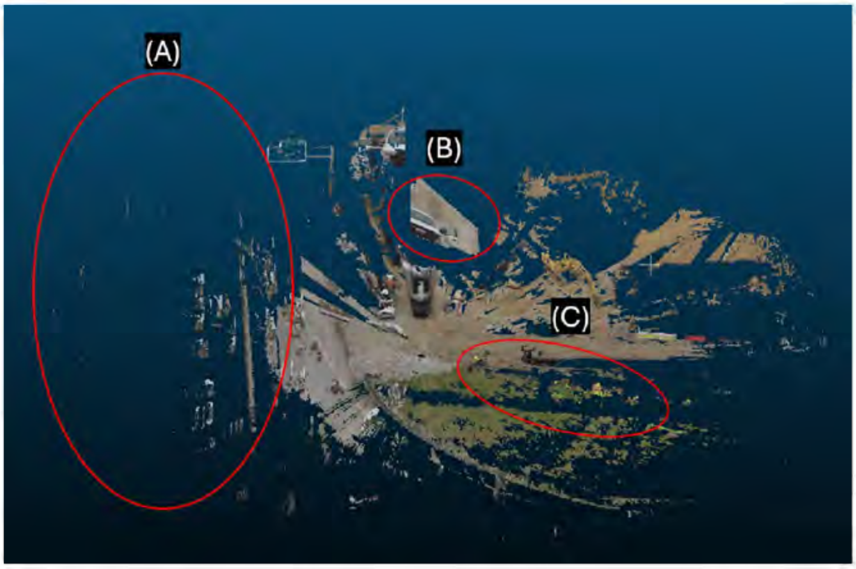


Figure 15: Scan #1/22 with common sources of error highlighted.

Figure 16: Full high-fidelity point cloud of the active highway construction site.

4 Environment Creation

The first step in the construction of the IVE was converting the terrain point cloud data into a height map, which allowed for the surface elevation to be materialized in VR. The so-obtained point cloud was segmented to differentiate between the terrain and the constructed objects. This process was done manually, removing features such as built objects, roads, and construction materials from the scene so that only the ground remained.

Given that the landscape scene exhibits areas with incomplete registration of data, synthetic points were interpolated for each area. This process encompasses three steps: (1) manual line fitting surrounding the missing data, (2) mesh generation using Delaunay 2.5D triangulation [19], (3) mesh sub-sampling (see Figure 17). Once the landscape was filled, the points were recolored with a height ramp and rasterized into a 2.5D image [19]. This is referred to as a 2.5D image since it displays the two-dimensional horizontal location spatially and the height via color intensity. This image acts as a height map, in which each pixel represents the elevation of the corresponding location.

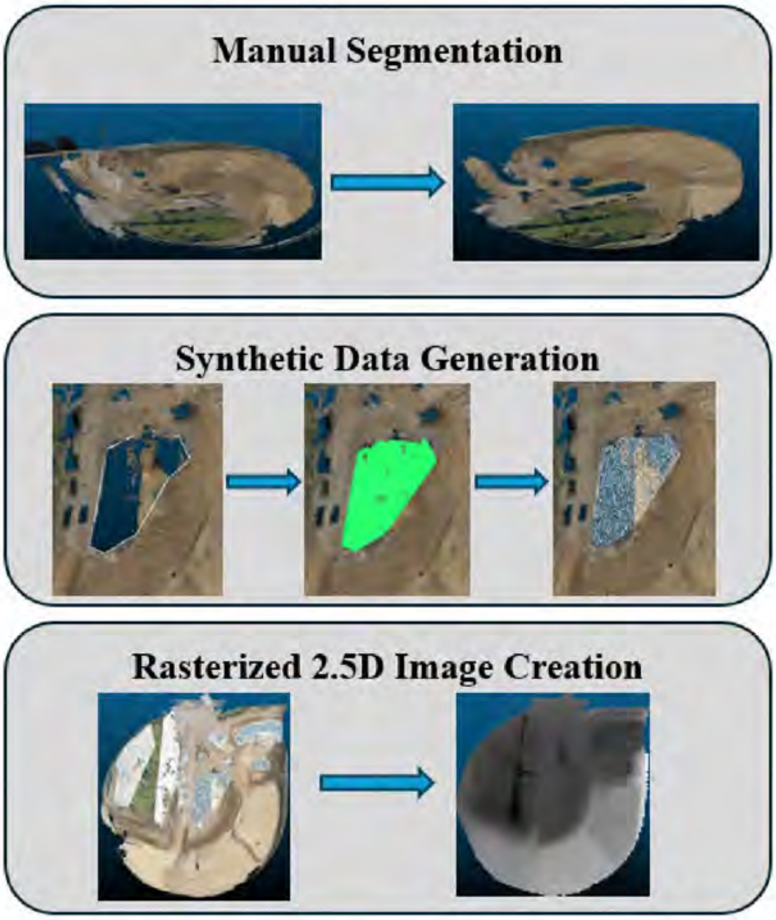


Figure 17: Full high-fidelity point cloud of the active highway construction site.

From this point, the VR platform was built using Unreal Engine 5 (UE5) [37]. The engine was chosen for its advanced rendering capabilities, a robust toolset for incorporating external data and objects, and its interface to VR simulations. Within UE5, terrain may be represented using a static mesh or a landscape component [35]. The key difference is that static meshes are pre-defined and non-deformable, while dynamic meshes used for landscapes are flexible and can be modified in real-time. For this application, landscape components are used such that the terrain may be adjusted for each construction scenario. To build the landscape component, the 2.5D height map image was imported into UE5, the maximum and minimum height values from the point cloud data were input, and the landscape component was generated.

The various materials in the terrain were manually "painted" on the scene with the UE5 landscape painter tools to reproduce the appearance of the construction site scan. In this instance, grass, light gravel, and heavy gravel materials were created and painted on the landscape similarly to the appearance in Figure 16. These materials automatically blend when painted near to each other for a smooth look and adapt to future landscape changes which were necessary for some construction scenarios. Material textures were created using a sample of the desired surface texture along with an image of the corresponding normal map, which encodes surface details such as bumps and grooves by manipulating how light interacts with the material. Figure 18 shows the texture image and normal map for the three primary textures listed previously.

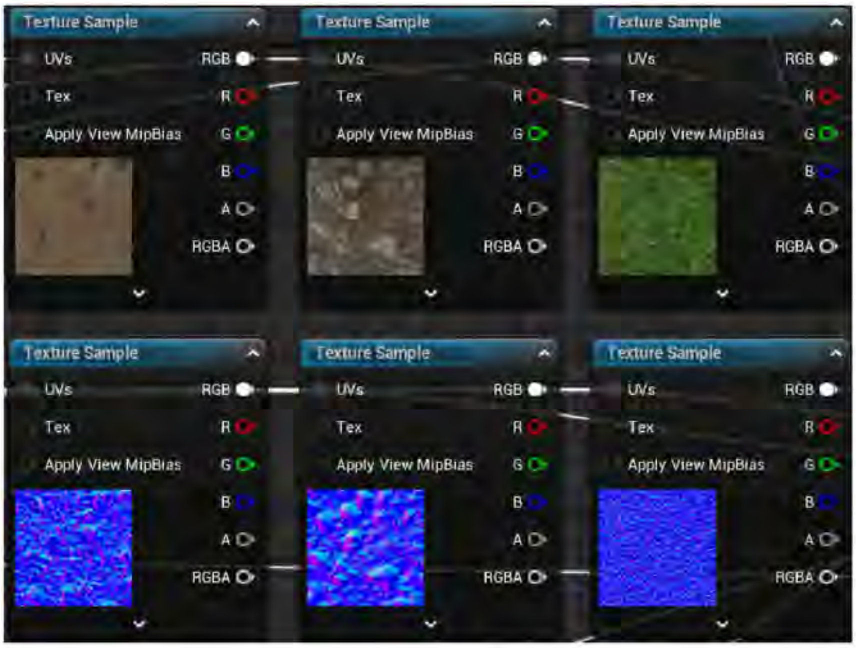


Figure 18: Texture and normal map samples used within the construction site landscape.

The road design of the construction site was reproduced using spline tools in UE5. Splines build a continuous path of iterated meshes along anchor points, locally adjusting the meshes and landscape as needed to build roads. Circular roads were designed around the site, immersing the user in the construction interchange. Splines are similarly used to iterate center-line barriers and guide rails along the roads, replicating the linked real-world environment. Figure 19 shows the spline setup for the interchange loop.

Accessory items, such as trees and vegetation, were built using the Procedural Content Generation (PCG) tool in UE5. PCG builds random environments within a defined bounding box filled with static meshes of random size, location, and rotation [37]. The use of PCG allows for the creation of diverse and natural-looking forests without the need for manual placement of the assets. Additionally, PCG was customized to include several different types of trees and vegetation, weighted such that the resulting scene is consistent with the region. The logic graph for PCG of trees is shown in Figure 20. The logic graph is a condensed display of the process, which: (A) samples the landscape surface to randomly pick points at the corresponding heights, (B) creates a random seed (visually displayed by a 0-1 grayscale cube) which transforms the points with varying rotations, offsets, and scales, and (C) Spawns static meshes from the predefined pool of available options.

Figure 19: Spline setup for the interchange loop.

Figure 20: Logic graph and example of procedural content generation (PCG)

Objects such as signs and infrastructure components were manually placed to match the captured point cloud data. These assets were collected from a variety of open-source repositories. The base scene with landscape, barriers, roads, vegetation, and other object types is reported in Figure 21. Other environments not based on the materialized construction site were developed as well and used as the main menu of the platform and the tutorial. The main menu is simply a large open space with a 3D menu which the player uses to start a learning/testing level. The tutorial level is meant to act as a construction office, and this space is where the VR user learns the controls associated with using the platform. Figure 22 shows the design of these two environments.

Figure 21: Constructed base VR environment: (A) top view, (B) 3D view.

Figure 22: Preview of the (A) main menu level and (B) tutorial level.

5 Blueprints

Code within UE5 is often developed through Blueprints [34]. Blueprints is a visual programming language that allows developers to design game logic using a node-based interface. Like traditional programming languages, Blueprints allows for the creation of dynamic objects, user interfaces (UI), and other gameplay elements. The VR platform presented was built using the Blueprint programming language exclusively.

When working in Unreal Engine, any three-dimensional space is defined as a level. The level represents the game environment or world. In this case, the virtual reality environment was built inside a level and then duplicated many times to generate different levels for different construction testing scenarios. As described previously, levels that are uncoupled from the construction environment were built for use in the tutorial and the main menu.

Blueprints are attached either to objects in the scene or to the level itself. When attached to objects, the Blueprint script governs the level's behavior and interactions within the broader context of the game environment. This approach allows for level-specific logic, such as triggering events when the player begins the game or tracking gameplay progression.

Blueprints may also be attached directly to objects. This method is best for mechanisms that repeat over many different levels, such that the code is consistent between them. When attached to an object, this will either take shape as an "actor" or a "pawn". Actor is the base class for all objects in an Unreal Engine level. It represents anything that can be placed in a scene, such as static meshes, lights, or volumes. The code attached to these objects may change details about the actor itself, such as size or location, or trigger gameplay events. A Pawn is a subclass of Actors that represents anything that can be possessed or controlled by a player or AI. It is typically used for characters or controllable entities. As such, in this platform, pawns are used for the user characters and NPCs.

5.1 Non-Player Controlled Characters

A framework to deploy Non-Playable Characters (NPCs) in the scenes and materialize construction operations was developed to develop immersive construction scenarios. UE5 provides users with the Metahumans plugin [36], which provides tools for creating high-fidelity representations for NPCs. Leveraging this capability, a collection of construction workers was generated. For the generated construction workers, features such as PPE, movement, and construction tools were parametrized so they can be adjusted for the specifications of each training module and construction scenario.

A basic model was generated using the designer provided by the plugin to parametrize Metahumans. The designer allowed for the customization of human features, such as skin color, hair, age, facial features, and body type. The designer also provides limited clothing options, such as jeans, slacks, sweaters, and t-shirts. Five basic Metahumans were built in the designer to be parametrized into NPC construction workers for H&S training modules.

The base models were deconstructed into the character assets. Each Metahuman is built from four character assets (i.e. Face, Feet, Legs, and Torso). A character asset contains the visual asset, and a bone structure represents the asset's movement capabilities. When attaching a construction item to a Metahuman, the items were either flexible (i.e., clothing, harnesses) or rigid (i.e., tools, hard hats, glasses). Flexible items adapt to fit the form of the Metahuman based on movement, unlike rigid items which will never deform. The relevant character asset was exported into Blender [7] to attach flexible items, and the construction item was added to the asset as a layer. Once fit, the items were combined and attached to the bone structure, and the asset was exported back into UE5. Visbility toggles attached to the Metahuman parametrizes the asset between that with the construction item and that without. Rigid construction items are attached to a specific bone and move with the bone without deforming the item's static mesh.

The level sequencer [38] was used to create animation assets to animate the Metahuman to perform construction activities. Animation assets can either play on a loop or be triggered via Blueprint code after certain in-game events. The animations connect to the bones between all four character assets to create smooth movement, and the flexible construction items deform accordingly to create realistic NPCs. A visual framework of Metahuman parametrization with construction items is displayed in Figure 23.

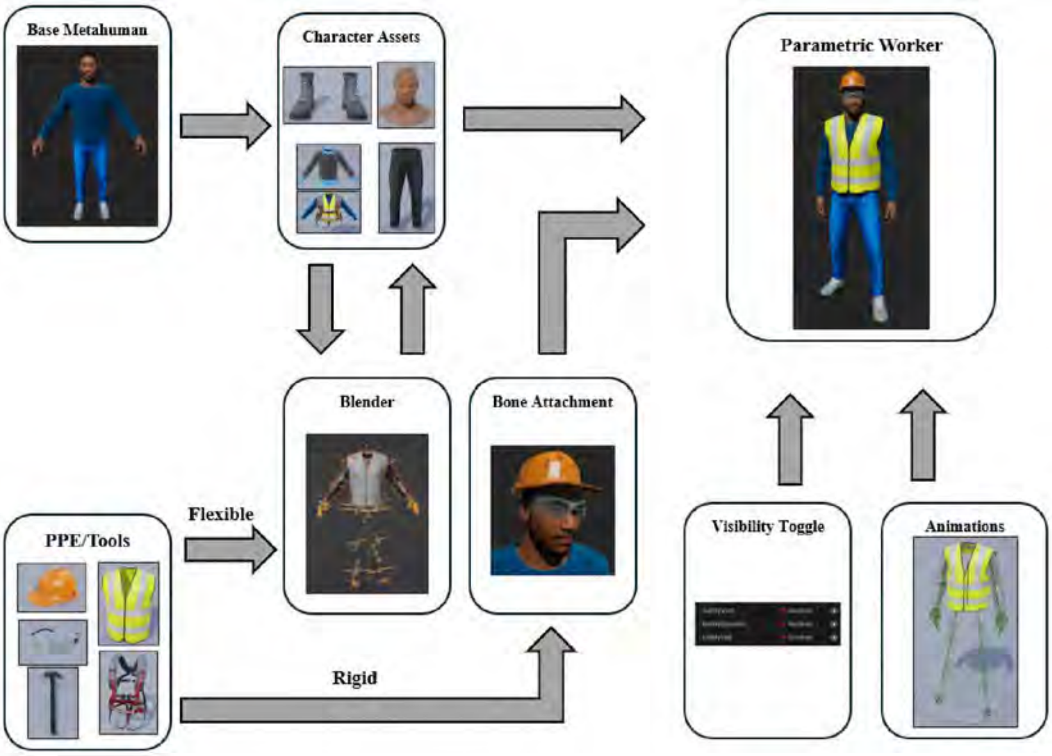


Figure 23: Framework for parametrization of Metahumans in UE5 for construction activities.

5.2 Vehicles

The static meshes for construction vehicles, as found in the Epic Games content pack, do not have built-in functionalities for rendering movements. To this end, all vehicles must have wheels and body components defined separately to allow for realistic animations to be rendered. Blender's vehicle rigging plugin was used in this project. The plugin allows for the extrusion of the wheels from the body of the vehicle and defines them as a separate object class (see Figure 24 (A)). Wheels are classified as either front or back wheels, where the front wheels are provided with an extra degree of freedom for rotation around the z-axis. UE5 defines the location and weight of the vehicle body for proper physics rendering (see Figure 24 (B)).

(A) (B)

Figure 24: Blender (A) and Unreal Engine 5 (B) Vehicle Component Classes.

5.3 Virtual Reality Pawn

The virtual reality pawn (or VRPawn) is the object class predefined within UE5, which the VR player controls. This acts as the digital representation of the user, and the attached code defines how the user interacts with the platform. The VRPawn is rendered simply as a generic VR headset within the environment. The VR player does not have a rendered body. The camera attached to the headset (see Figure 25) represents the player's virtual eyeballs.

Additionally, the VRPawn defines the motion controller and allows it to interact with the environment. When properly connected to the base stations, the motion controller renders given the VR player at the matching virtual location relative to its position in real life. The motion controller creates an aim vector, equipping the user to point at objects throughout the construction environment.

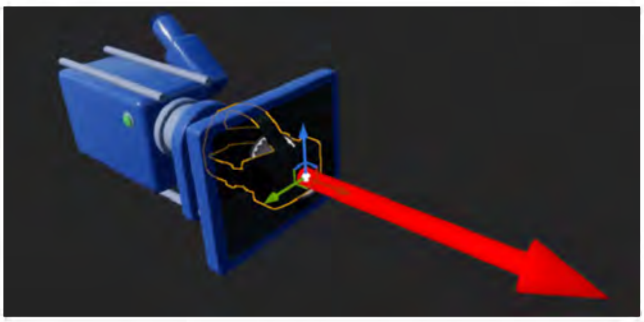


Figure 25: The VRPawn as it appears in the asset viewport.

The vast majority of the default code inside the VRPawn was kept; however, the default button mappings were removed to be recreated for this project's specifications. Additionally, only the code for the left controller was removed, as this platform only requires one controller. An aiming beam was added so the VR player could get visual feedback about where they were pointing. This aim beam represents a line trace generated 10 times per second. This line trace (as shown in Figure 26) builds a vector beginning from the controller 10 meters forward. If the line trace is interrupted by any actors or pawns in the level, the return value will be **True**, and the variable **Out Hit Hit Actor** will return a reference to the hit object.

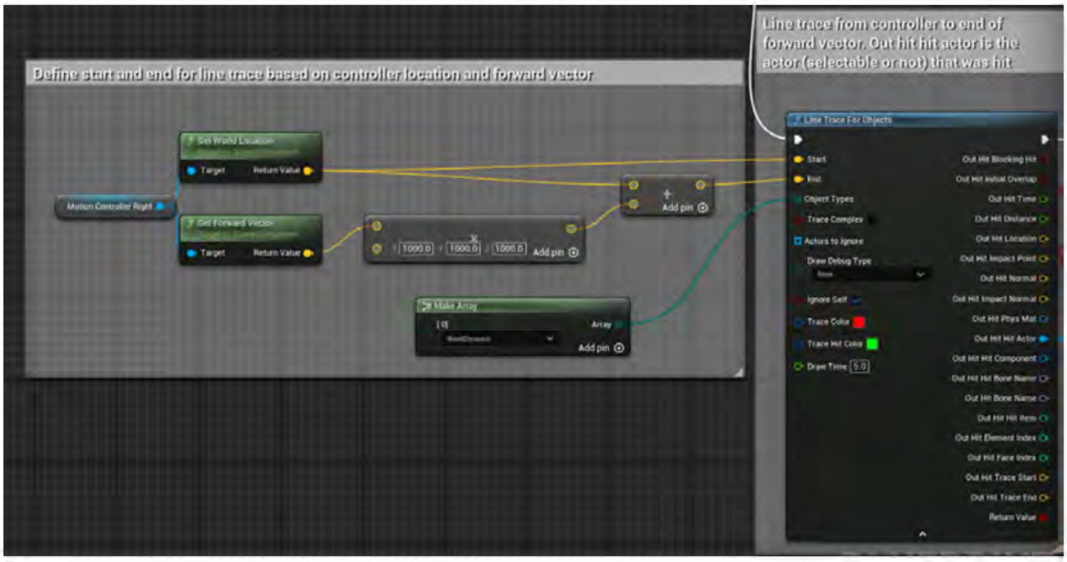


Figure 26: The blueprint code for the line trace generated 10 times per second.

5.4 Selectable Objects

A class of actors called "Selectable_actor" was developed such that any static mesh could become an item to be interacted with in a module. It was not seen as advantageous for the user to be able to interact with every single object in the scene, so only those relevant to training (either as hazards, NPCs, or deliberate red herrings) could be selected. As such, the line vectors created by the VRPawn first check if the discovered actor implements this Blueprints class before continuing with the code. When the player aims at a selectable actor (thus interrupting the line vector as described in section 5.3), it will gain a blue decal as shown in Figure 27. The VR player, while hovering, may press on the controller's main trigger to select the object, which will turn this decal green and keep it as such unless the user toggles the selection by pressing the trigger again.

Each selectable actor stores a Boolean variable indicating if it is representing a safety hazard. If True, a unique hazard ID and a short text explanation of the type of hazard are generated at the start of the game. Additionally, an optional audio clip is attached to any selectable actor. The audio clip is played immediately if the user is in a learning module or during the feedback period in a testing module. Each module comprises several construction scenarios, each having a physical location within the level.

Figure 27: The VR user hovering a selectable actor.

5.5 Locomotion

The primary consideration when designing user navigation was to maintain a threshold for immersion and realism while simultaneously providing a user-friendly interface to the game. VR locomotion techniques can be physical or artificial [10]. Physical techniques include walking-in-place, room-scale movement, or arm swinging. Artificial techniques, such as teleportation or joystick input, require the user to use an input device.

VR sickness, commonly known as motion sickness, is caused when visual perception of the environment does not match the body's sensory inputs. In VR, visual perception of the surroundings becomes disconnected from reality. When movement is added to a VR environment, the sensory inputs become mismatched from the visual movement experienced, which can cause motion sickness. Approximately one-third of the population is susceptible to motion sickness [78]. At the same time, it cannot be expected that the trainees have enough experience using VR to be accustomed to the locomotion in the game. Particularly, given the breadth of construction operations simulated herein, and the physical size of the construction site rendered in the IVE, locomotion plays a central role in the delivery of the constructed training modules.

For the aforementioned reasons, an artificial technique was preferred. Controller-based locomotion via joystick input is appealing, as it is seen to maximize immersion in the scene without requiring a large training space. However, it is the most likely method to cause VR sickness due to the continuous visual movement not matching the physical sensations [9]. For this reason, user locomotion was built using controller-based teleportation. Teleportation brings several advantages, as it tends to lead to faster trial times and restricts the user from moving to areas of the scene unrelated to training [9]. Users toggle the visibility of teleportation hotspots by holding a controller button. While the button is being held down, light blue hotspots appear scattered throughout the environment, allowing the user to point and click any of them to instantly teleport to that location.

When a hotspot is hovered, such that the player is aiming correctly, it gains a green color as shown in Figure 61. Additionally, once a hotspot has been visited, it gains a pale color (figure 62), such that the VR player understands where they've visited and where they haven't. An example of teleportation hotspots spread throughout a module is seen from an aerial view in Figure 63.

Figure 28: Teleportation hotspots from the view of the VR player.

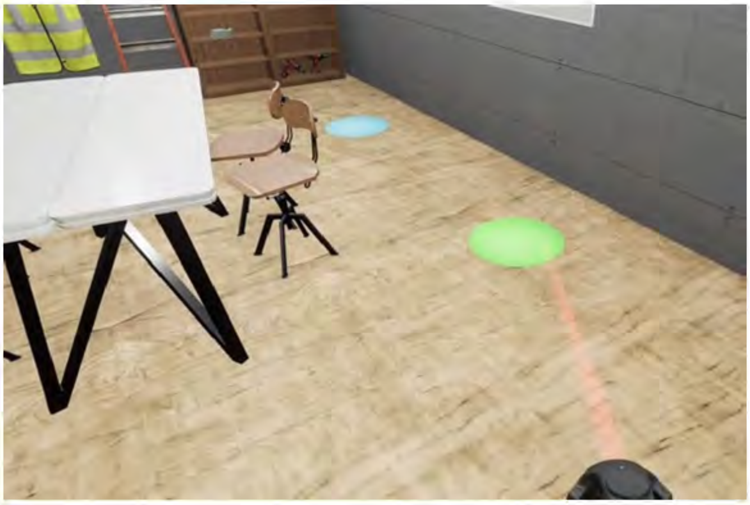


Figure 29: Teleportation hotspot from the view of the VR player hovering with the VR controller.

Figure 30: Teleportation hotspot which has been visited from the view of the VR player.

Figure 31: Aerial view of the teleportation hotspots spread throughout a learning module.

Figure 32 shows the Blueprints logic for the teleportation bubble visibility mechanic, which shows the user where the hotspots are while the side controller button is being held. Figure 33 shows the Blueprints logic for the teleportation itself when a bubble is selected. When moving the player, their vertical location must be adjusted, such that their relative distance to the ground stays consistent regardless of the height they're moving to.

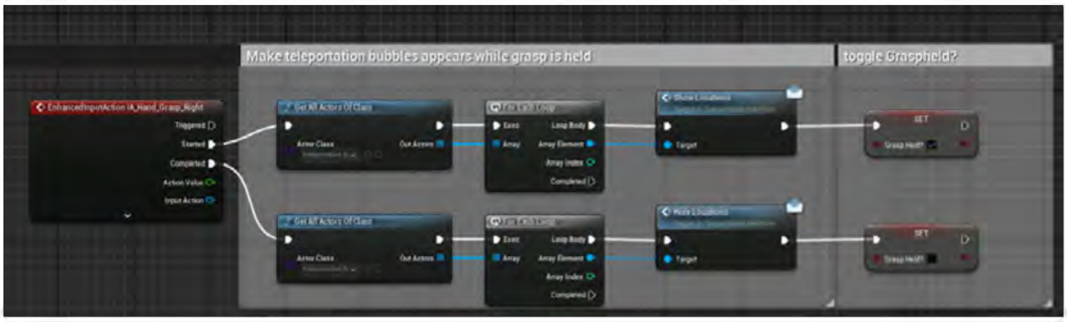


Figure 32: The Blueprints logic for the toggled visibility of teleportation hotspots.

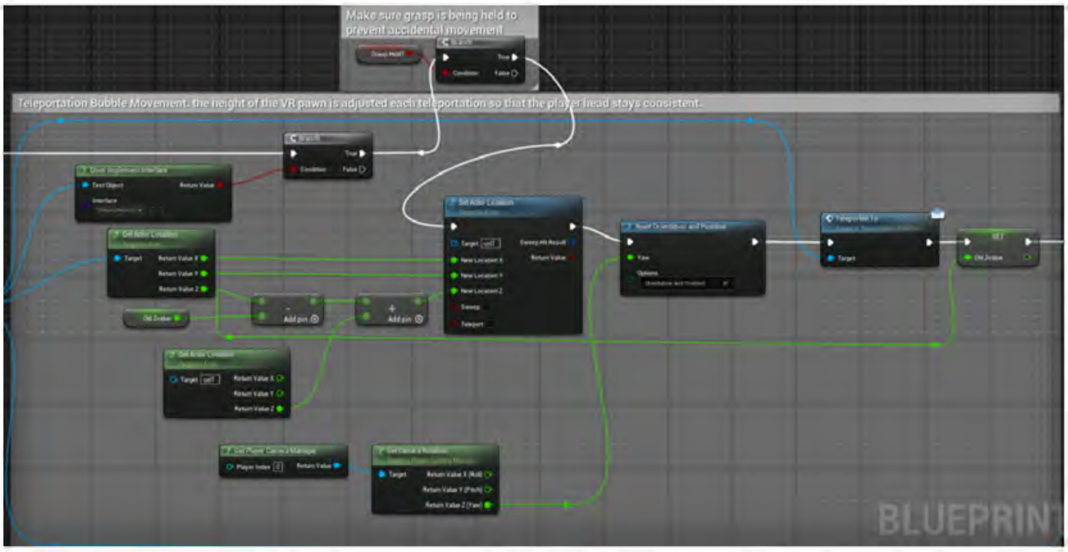


Figure 33: The Blueprints logic for teleporting the VRPawn when a hotspot is selected.

5.5.1 Aerial and Vehicle View

two additional locomotion features present in the platform are Aerial View and Vehicle View. Both these features serve the same purpose in the context of health and safety training for construction applications: providing the trainee with a point of view that they would not regularly get on the job. Vehicle view is a feature where players can teleport inside a non-moving vehicle by selecting it with their controller. This allows them to understand the blind spots and visibility of vehicles they may not regularly use on the job so that they can work safely around them in the future. Aerial view, only available after the player can finish a module, teleports the player into the sky so that they can see the layout of the site from a bird's eye view.

5.6 Gamestate Tracker

The gamestate tracker is an actor in every playable level of the platform. This actor, which appearance-wise appears as a concrete brick with menus (see Figure 34), holds the Blueprints for most events, which track gameplay progression throughout a level. The gamestate tracker additionally holds several gameplay variables. This includes counters for how many objects the user has interacted with in the environment, the number of correct and incorrect answers for tests, and references to objects and locations in the environment.

Figure 34: The gamestate tracker as it appears in the asset viewport.

When the level begins (also known as Event: BeginPlay), the gamestate tracker performs the following actions to initialize the construction environment for the VR player:

1. Creates a reference to the player pawn such that details about the VR player can be tracked as they progress through modules.
2. Sets the starting height of the VR player's camera. If the height is set incorrectly, the user may feel shorter or taller than is realistic (the ground starts at their knees or far below their feet).
3. Check if the module has capabilities for aerial view; if yes, store the location and rotation the VR player will be teleported to in this view.
4. Assign unique hazard identification numbers to the health and safety hazards inside the module.

A zoomed-out view of the gamestate tracker scope is shown in Figure 35. This image serves to display the scope of the tracking mechanics.

Figure 35: A zoomed-out view of the Blueprints within the gamestate tracker.

5.7 Menus

Menus are created using widget Blueprints. Widget Blueprints are tools in UE5 that design user interfaces (UIs) using a visual designer and logic graph. To interact with menus, the VRPawn's motion controller has a widget interaction capability attached to it. Unreal Engine predefined this code.

The menus in the platform are used in two main contexts: (1) selecting a module to complete in the starting world and (2) interacting with the gamestate tracker during a module to check progress and receive feedback. Within the main menu, the 3D widgets are created (similar to the appearance of the gamestate tracker described in section 5.6) Figure ?? shows the framework of the main menu 3D asset, which is placed in front of the VR player a the start of the game.

Figure 36: The Blueprints framework for the main menu 3D asset.

The custom events that trigger different menu configurations are activated by the menu buttons themselves, allowing for navigation through various nested menus. Figure 37 shows the designer panel of the main menu, which appears in front of the player at the start (figure 22 (A)), and the corresponding Blueprints graph which triggers a menu change using a reference to the main menu 3D asset in Figure 36.

(A) (B)

Figure 37: (A) Designer panel and (B) Blueprints graph for the starting menu.

Some menus, such as those used for tracking the VR player's selections and giving feedback, use content functions to determine the text value displayed to the user (see Figure 38. As the user progresses through a module, updates are sent to the gamestate tracker to refresh the variables, which represent the number of hazards selected, the number of correct selections, the number of incorrect selections, and the total number of selectable hazards. These updates are then read by the content functions to update the menus that appear to the user. The content functions (see Figure 39 update automatically when the variables change.

Figure 38: VR user receiving feedback on their safety performance in a testing module.

(A)

(B)

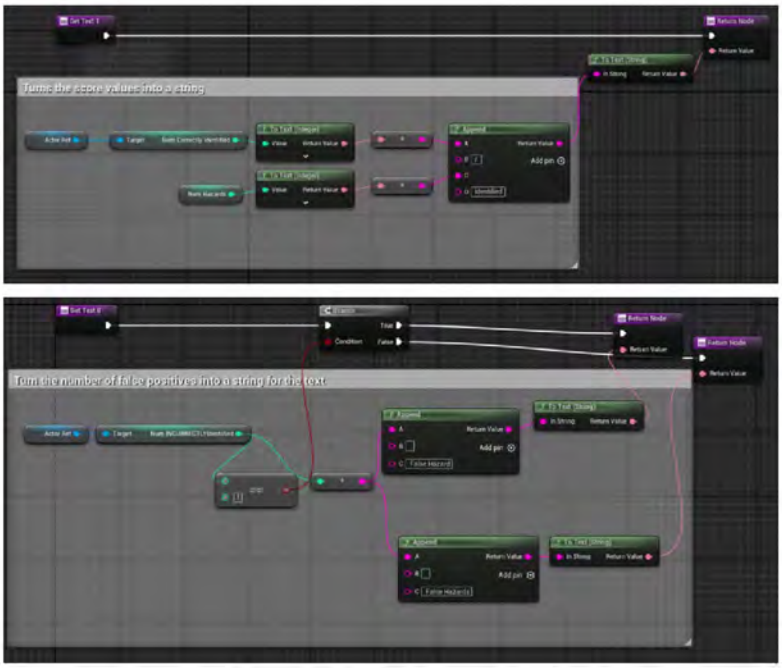


Figure 39: Content functions for the menu in Figure 37 for the (A) first and (B) second labels.

The menus found during a module are described herein. The variables represented using **X**, are filled in using content functions during a module.

- **"Hazards Selected"**: The box under this label is updated as the user selects actors in the environment.

- **"X/X Identified"**: Used in *testing* modules to score the VR player based on how many of the hazards in the scene they were able to identify. The variable X is defined after the user clicks **Submit** in the previous menu.
- **"X False Hazards"**: Used in *testing* modules to provide a secondary score for the VR player based on how many objects in the scene they marked as hazardous but were actually safe. The variable X is defined after the user clicks **Submit** in the previous menu.
- **"X Topics Reviewed"**: Used in *learning* modules to remind the user how many construction scenarios they reviewed inside the environment. The variable X is defined after the user clicks **Submit** in the previous menu.

The buttons within these menus can be interacted with via the VR controller:

- **Submit**: Used to transition to the recap menu. After submitting, the VR player may re-navigate the environment; however, they will be unable to select anything.
- **Next Level**: Used to transition to the next level of the platform. The label text for this button may change depending on the upcoming level. At the end of a module, the text will usually read **Menu**
- **Toggle Guide**: Once answers are submitted in a *testing* module, the selectable objects in the environment will gain a decal color based on their hazard condition and if it was selected by the VR player. This button displays a guide for the user to understand these decal colors (see Figure 43.)
- **Aerial View**: Transitions the VR player into an aerial view of the construction environment, allowing them to see the site layout from a new perspective. The text for this button will change to **Ground View** if the user is in the aerial view, allowing them to return to the environment.

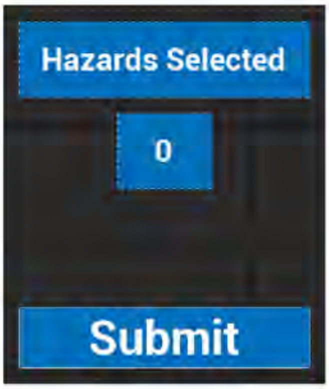


Figure 40: UI for module tracking before submitting answers.

Figure 41: UI for recapping a testing module.

Figure 42: UI for recapping a learning module.

Figure 43: Guide for understanding highlights in the environment during recap.

Figure 43 displaying what various decal colors represent is useful for the VR player as they re-navigate the environment after submitting their answers in a *testing* module. Selectable objects gain the following decal colors based on the corresponding conditions:

- **No color**: The object is not a hazard and was not selected (true negative)
- **Blue**: The object is not a hazard but it was selected (false positive)
- **Green**: The object is a hazard and it was selected (true positive)
- **Red**: The object is a hazard and it was not selected (false negative)

6 Educational Framework

According to a study conducted by Wilkins et al. [87], successfully conveying the dangers and the possibility of injury should return the highest level of compliance with safety standards. If the content inside the platform is relevant and engaging, workers are expected to have greater safety knowledge leading to higher safety performance. However, building high-quality safety scenarios in VR is a challenging and time-consuming process. A deep understanding of common hazards and the technical requirements that OSHA recommends is necessary. Digital assets that represent tools, materials, workers, etc. must be defined and properly placed in the simulations. All hazards should be annotated so that explanations are clear when providing feedback to the user. Additionally, the player must be able to fully perceive the scenario to choose and understand the correct interactions.

The proposed platform provides a tutorial and a combination of learning/testing modules based on the focus four hazards defined by OSHA [63]. A typical construction office transformed into an IVE is the setting for the preliminary tutorial. Within this IVE, auditory instructions guide the user as they learn how to select objects, move through the environment, and receive feedback. After completion of the tutorial training, the user is transported to the construction site described previously. On the site, the user learns how to navigate the larger environment and experiments with the features of the platform. The modules within this platform are of two types: (1) learning modules and (2) testing modules.

Learning modules place users in a high-fidelity IVE of the site with a variety of construction scenarios. As the user navigates the IVE, they may prompt a scenario by selecting an NPC with their controller to receive an auditory explanation of the relevant safety guidelines. The audio clip also describes what corrective actions may need to take place. This approach allows users to engage with safety training actively and contextually, learning about specific hazards while being immersed in the construction environment.

Testing modules do not provide immediate feedback to the user, but allow them to navigate the site, selecting only actors which they believe represent safety hazards. To this end, a mix of hazardous and non-hazardous selectable actors are present, with the goal of evaluating the user's knowledge on H&S. As the user points at objects, they gain a highlight if selectable (see Figure 27). When selected, actors will remain highlighted to signify that they are currently selected. After the user is finished navigating the site and submits their answers, they have the opportunity to re-navigate the site, with each selectable actor displaying a new highlight based on its hazard condition and the user's response. The user will also receive a full report of all the correctly identified hazards, as well as false positives and negatives (see Figure 38)

6.1 OSHA Construction Hazard Image Database

All of the scenarios were built with direct reference to OSHA safety standards. A dataset of construction hazard images, including 509 images annotated with a description of the reported hazard, the relevant code with the OSHA standards, and the recommended corrective action, was used [64]. The images, specifically the construction hazard portion, were rebuilt within the construction site IVE. Table 4 shows the number of examples received in each category from the dataset. Figure 44 shows a random sample of images from the dataset.

Category	Count
Falls	100
Machine Guarding	79
Electrical	40
Chemical Hazards	33
Excavations	31
Scaffolds	27
PPE	26
Construction	25
General Industry	20
Cranes Lifting Devices	19
Clip Art	17
Silica	16
Maritime	14
Housekeeping	14
Fire	10
Powerlines	10
Forklifts	8
Ergonomic	6
Compressed Air	5
Lockout	3
Bloodborne Pathogens	2
Asbestos	2
Radiation	1

Table 4: Safety Categories and Their Counts

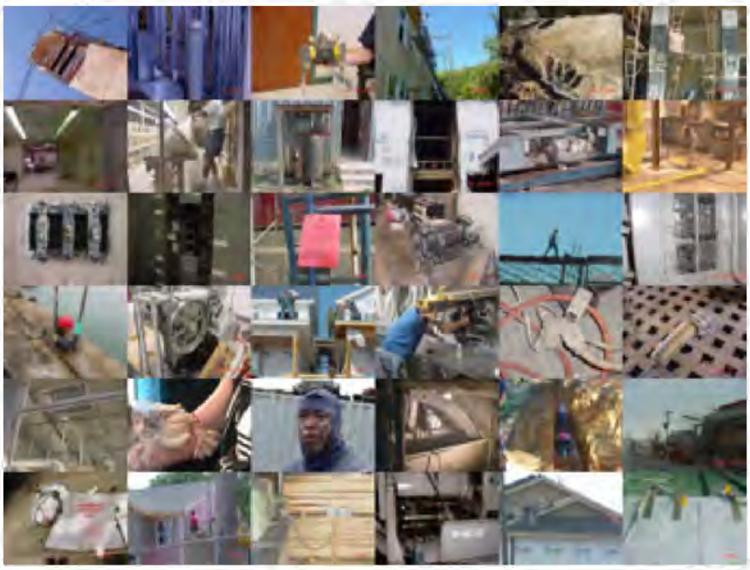


Figure 44: Sample images from the construction hazards photo dataset.

6.2 Instructions for Custom Modules

For future development where one wishes to create a custom learning/testing module, here are the instructions they should follow.

1. Create a plan of what construction scenarios will be in the module. Define the module type (learning or testing). Through either images or text, have a clear plan for each construction scenario in the module (including red herrings if the module is for testing).
2. Create a copy of the base environment/level found in the "Levels" folder of the UE5 project.
3. The gamestate tracker in this scene is (by default) one for a testing module. If building a learning module, replace the gamestate tracker with the "Gamestate_Tracker_LEARNING" actor.
4. for each construction scenario, use the parent classes "Selectable_parent" (for static meshes) and "Selectable_worker" (for NPCs) to build the scenario using standard UE5 best practice for modeling. for each object/worker, fill out the variables in the details panel to the specifications of this construction scenario (see Figure 45). Custom sounds can be recorded manually or with a program like ElevenLabs [29].
5. Populate the environment with Teleportation bubbles by copying the one provided in the base level such that users can go anywhere they need.

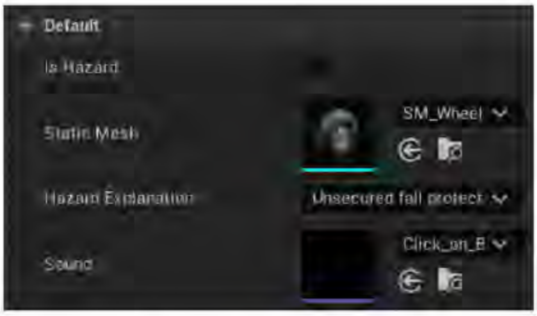


Figure 45: Customizable hazard options for creating custom modules.

7 Evaluation

The methodology for evaluating the effectiveness of the proposed approach is an adaptation of the framework for expert-based evaluation of virtual environments [**vahdatikhaki2019beyond**, 33]. A technical panel of 9 experts was formed, composed of: construction professionals (6 individuals) with expertise in health and safety, as well as faculty members and graduate students in computer science (3 individuals). The construction professionals group included representatives from private-sector companies and government organizations. The group estimated that an average of 68% of their job is spent on construction health and safety, and reported an average of 17 years of experience. Three described their job as 'safety inspector/management', two described it as 'construction management', and one as 'education/research'. All six have a bachelor's degree in a related field, and two have a master's degree. The computer science experts were invited for testing because of their experience with computer systems and human-computer interaction. All members of the panel were knowledgeable about the scope of the project.

Each participant was asked to complete the tutorial level, which introduced how to use the platform and familiarized them with the construction site IVE. After the tutorial, they completed one of the available modules. This two-pass approach first allows for an understanding of how the platform works before they evaluate the technical details. Each participant trial lasted ~15 minutes, with the majority of time spent on the full construction site module. The evaluation was conducted in two phases. First, each participant separately filled out a questionnaire. Secondly, a focus group was held, allowing the evaluators to discuss with each other and give more specific recommendations.

The survey utilized multiple-choice questions to assess the quality of specific platform components. Responses were measured on a 1-5 Likert scale, with descriptive labels (e.g., "Yes/No," "Likely/Unlikely," "Easy/Difficult") provided for each response. Responses closer to 5 indicate a positive response, such as very easy, yes, or very likely, whereas responses closer to 1 indicate a negative response. Questions are evaluated in two major areas: user interaction/experience and educational content. Extended response questions were present in the survey to guide future work. Responses are reported by means of radar plots, showing the mean and standard deviation, as presented in the following.

7.1 User Interaction and User Experience Evaluation

Questions in this category refer to the methods and tools used to interact with the virtual environment and the user's comfort during the simulation. The participants were asked the following questions: (Q1) "Are you pleased with the teleportation movement used in the simulation?", (Q2) "How difficult/easy was it to use the VR controller?", (Q3) "How difficult/easy was it to use the 3D menus?", (Q4) "Are you pleased with the comfort of the headset?", (Q5) "Did you experience any difficulty balancing?", (Q6) "Did you experience any VR sickness/motion sickness?", and (Q7) "When inside the aerial view, did you experience any fear of heights?". The responses are reported in 46.

The user interactions of the platform were received positively but many of the questions report significant standard deviation. The responses regarding ease of use for menus and teleportation movement were spread, with responses ranging between 2 (fairly difficult) and 5 (very easy). The variation of responses highlights the importance of building game controls that are intuitive for every participant and indicate room for improvement. Despite the variation, mean scores were positive for all the questions.

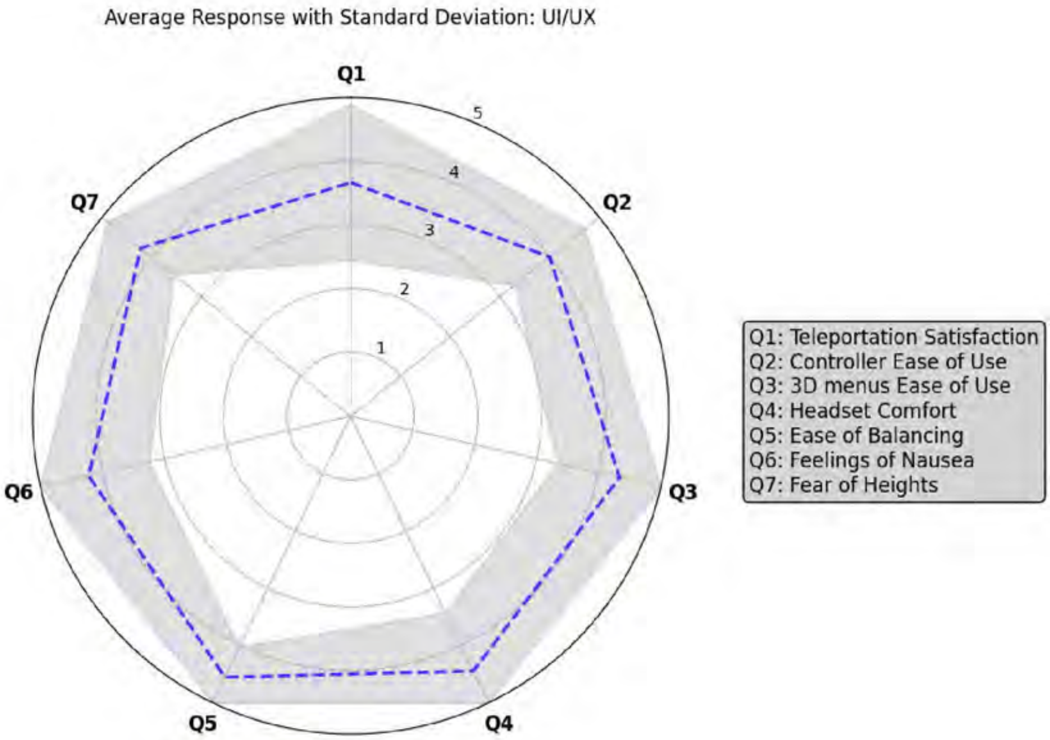


Figure 46: Radar plot for Evaluation of user interfaces and user experiences.

Moreover, the VR trials did not cause significant discomfort to the participants. Median responses for balancing, VR/sickness, and fear of heights exhibit values in the range of 4 to 5. As seen in question 6, only one participant reported experiencing motion sickness, while the rest either had none or very little. The low levels of discomfort indicate that VR-based training can be effectively designed to mitigate safety concerns, but the variation acknowledges that some participants can be more prone to nausea.

7.2 Educational Content Evaluation

Presentation refers to the realism, immersion, and engagement of the platform. The participants were asked the following questions: (Q8) "How realistic did the VR environment look?", (Q9) "Is the first-person vehicle view useful for training modules?", (Q10) "Is the aerial view useful for training modules?", (Q11) "Did the audio voiceover effectively communicate instructions as you progressed through the tutorial?", (Q12) "Did the lessons taught inside the construction office effectively prepare you to navigate the site?", (Q13) "Based on the examples you saw, how well did the simulation recreate equivalent health and safety hazards?", (Q14) "How clear was the educational content?". (Q15) "How immersive did the VR environment feel?", and (Q16) "How engaging did you find the VR experience?". The collected responses are reported in 47.

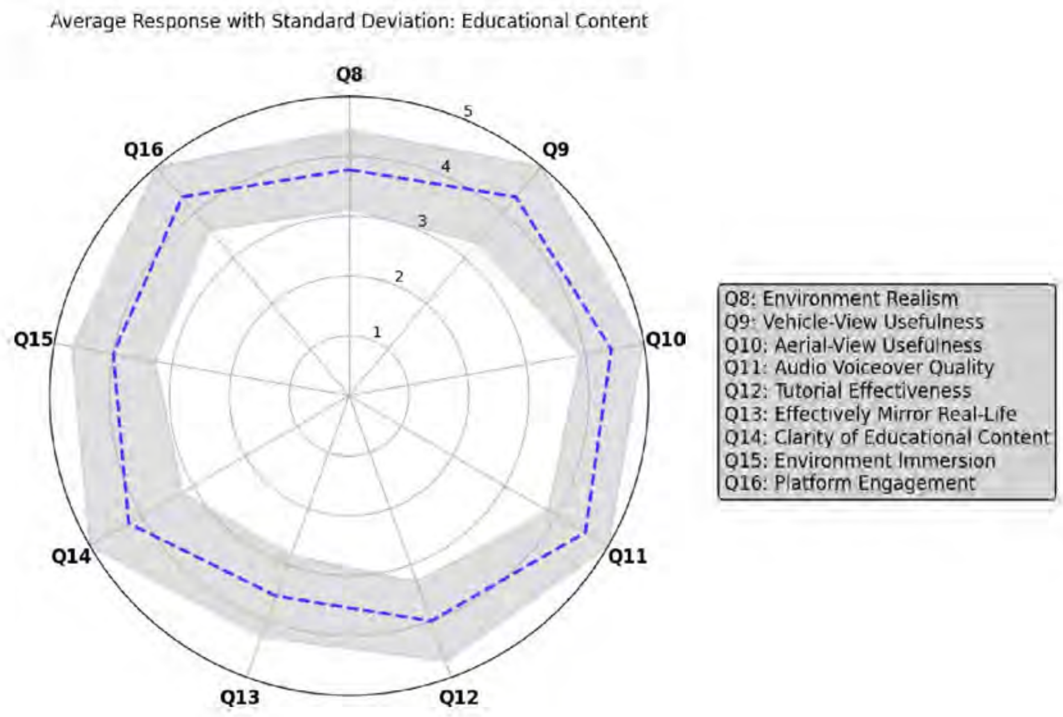


Figure 47: Box plots for evaluation responses regarding educational content.

The VR experience successfully captured the attention and interest of the technical panel. The consistency in high ratings across realism, immersion, and engagement suggests that the IVEs effectively recreated a compelling and believable simulation. The high level of engagement indicates that VR-based training can potentially overcome one of the main limitations of traditional health and safety training - maintaining participant interest and motivation.

The specific features and instructions used to deliver educational content were received positively by the technical panel. Features such as first-person vehicle view and aerial view were viewed as useful in delivering training, receiving a median response of 5 and 4, respectively. Responses regarding the tutorial instruction were positive, indicating that the short introduction was effective in aiding users to familiarize themselves with the simulation and the controls. Question 13, regarding how well the simulation recreated equivalent health and safety hazards, received a mean score of 3.6 and ranged between 3 and 5, showing general positive responses with a notable variation. Question 14, focusing on how clear the educational content was, received a high median score (4), and a wider range of responses (2-5). Responses indicate general optimism that VR can be used as a medium to represent these hazards and deliver H&S educational content.

8 Conclusions

This study presented a novel immersive IVE for H&S training of construction workers. Utilizing these environments for construction H&S training is expected to increase engagement, improving knowledge retention and performance. Evaluation of the platform from construction professionals and computer science experts demonstrates the usefulness of this medium as a teaching tool. A panel composed of safety and VR experts found the platform to be highly realistic, immersive, and an effective medium for presenting information on construction hazards. The use of various perspectives (such as first-person vehicle view and aerial view) and clear instructional audio were specifically noted for their effectiveness in enhancing learning outcomes.

The evaluation highlighted that while most participants found the user interactions manageable, there still is a need for improvement in making the controls more intuitive for all users, including those who may be less familiar with VR technology. Although this platform successfully mitigated most reports of discomfort, motion sickness occurred during platform testing.

Overall, this study demonstrated the potential of immersive VR environments to be employed as a valuable tool for H&S training in the construction industry. By combining realistic simulations with engaging content delivery, VR-based training can complement traditional methods, offering an engaging and effective learning experience.

9 Limitations

This platform does not fully cover all construction safety topics or the detailed technical standards that are delivered during traditional training. The OSHA construction safety training course aimed at new construction workers consists of 10 hours of in-depth lecture content, which is an impractical time scale for VR content delivery. Therefore, while VR can be highly effective for experiential learning and reinforcing specific concepts or scenarios, it currently can not replace the depth and breadth of information covered in traditional lecture-based training. Thus, this platform is envisioned as a supplementary tool that enhances understanding and expands upon the concepts covered during the lectures.

The learning curve for VR is a factor to be considered in the further development of the training modules. Familiarizing with the specific interaction mechanisms of the platform requires user engagement, especially when non-traditional methods of user interaction and navigation are involved. Additionally, regardless of how the IVE is designed, users may still experience VR sickness, the effects of which may prevent users from completing the VR training or impact their ability to concentrate for the remainder of the session.

Concerns related to the cost of H&S training must be taken into account in the deployment of the proposed platform. Such costs include the cost of the VR equipment and associated workstations. Moreover, VR headsets can only accommodate a single user at a time, which might lead to additional costs associated with the delivery of training to large classrooms. Additionally, market penetration of VR technology is not currently high enough to envision this platform to be deployed in the self-guided online courses popular in the industry.

10 Future Work

Future work will focus on further development of the toolset and the introduction of additional construction settings. Defining a rollout plan will involve collaboration with industry partners and testing the VR modules with real-world construction workers and safety supervisors. Feedback collected from the trials will inform subsequent improvements and fine-tuning of the educational material, with the ultimate goal of providing testing modules that best complement H&S lectures. This includes defining the optimal role for this platform in the classroom via collaboration with industry partners.

A study to measure the engagement of virtual reality H&S training employing formal attention metrics such as eye-tracking will be conducted. Eye tracking data is seen as valuable information for assessing hazard recognition [62, 49]. Leveraging this data would provide more quantitative insights into the effectiveness of the proposed VR training.

The work presented herein opens up the possibility to define a novel framework for developing IVEs from laser scans obtained from construction sites. In the future, this could provide defined methodologies to convert real-life projects into advanced, context-specific IVEs suitable for workforce training.

A significant limitation identified during this project is the lack of a comprehensive, publicly accessible construction hazard dataset. While OSHA references a hazard dataset in its own training materials, it is offline and only available via a CD-ROM that must be obtained by directly contacting OSHA—a method that is outdated and inefficient in the modern era. Additionally, this dataset was in an inefficient format and had to be manually converted to a more relevant and accessible data structure. The image collection has not been updated since 2008. This presents a clear opportunity to develop a digital, open-access hazard dataset tailored for use in construction safety research and training. With the growing advancements in artificial intelligence, such a dataset could be leveraged to train or test AI models for hazard detection, risk assessment, and safety optimization. By incorporating diverse and high-quality data into a centralized platform, future research could significantly improve AI-powered tools for identifying hazards, ultimately enhancing workplace safety and management.

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A Module Details

This section outlines the 8 prebuilt modules and the answer key of the hazards. There are 2 modules for each of the focus four modules, one teaching module and one learning module. The photos of real-life examples are from the OSHA Region 4 photo database [64]. This was a former initiative of the OSHA Atlanta office to reach out to regional branches for their best examples of construction safety hazard images. This dataset is still used for health and safety training.

The VR scenarios built off of real-world references are not exact copies but are simply meant to recreate an equivalent hazard. As such, the educational concepts are consistent but many details are different. For the following sections, the photo on the left is the real-world reference image, and the photo on the right is the VR construction scenario. The description for each construction scenario is copied verbatim from the OSHA Region 4 photo database.

A.1 Falls

A.1.1 Falls Testing Module

Description	Osha Reference
Shows employee exposed to a 35-foot fall hazard from a scaffold.	1926.451(g)(1)(vii). "For all scaffolds not otherwise specified in paragraphs (g)(1)(i) through (g)(1)(vi) of this section, each employee shall be protected by the use of personal fall arrest systems or guardrail systems meeting the requirements of paragraph (g)(4) of this section."

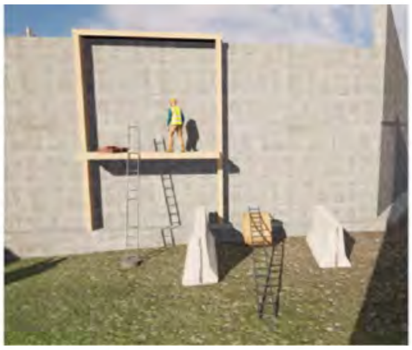
Description	Osha Reference
Photo show ladder used to access roof. The ladder was not extended over three feet beyond the roof, nor was the ladder secured to the roof.	1926.1053(b)(1). "When portable ladders are used for access to an upper landing surface, the ladder side rails shall extend at least 3 feet (.9 m) above the upper landing surface to which the ladder is used to gain access; or, when such an extension is not possible because of the ladder's length, then the ladder shall be secured at its top to a rigid support that will not deflect, and a grasping device, such as a grabrail, shall be provided to assist employees in mounting and dismounting the ladder. In no case shall the extension be such that ladder deflection under a load would, by itself, cause the ladder to slip off its support."

Description	Osha Reference
Walking the crane boom. The employee is using the crane boom to access a point not accessible by a ladder.	1926.1051(a). "A stairway or ladder shall be provided at all personnel points of access where there is a break in elevation of 19 inches (48 cm) or more, and no ramp, runway, sloped embankment, or personnel hoist is provided."

Description	Osha Reference
Supported scaffold poles, legs, posts, frames, and uprights did not bear on base plates and mud sills or adequate firm foundation.	1926.451 (c)(2). "Supported scaffold poles, legs, posts, frames, and uprights shall bear on base plates and mud sills or other adequate firm foundation."

A.1.2 Falls Learning Module

Description	Osha Reference
Planks used as scaffolding balanced on unstable objects.	1926.451(c)(2)(ii). "Unstable objects shall not be used to support scaffolds or platform units."



Description	Osha Reference
Employees working on improperly constructed scaffolding system.	1926.451(b)(3). "Each platform on all working levels of scaffolds shall be fully planked or decked between the front uprights and the guardrail supports "

Description	Osha Reference
Every flight of stairs having four or more risers shall be equipped with standard stair railings or standard handrails as specified.	1926.1052(c)(1). "Stairways having four or more risers or rising more than 30 inches (76 cm), whichever is less, shall be equipped with:"

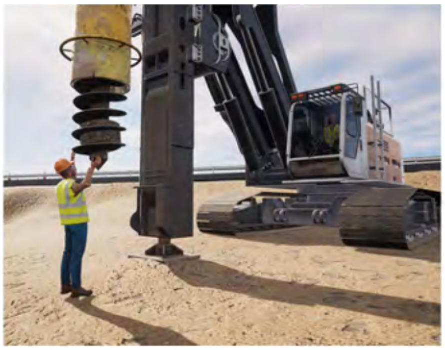
Description	Osha Reference
The photo shows the employee moved to the side (horizontally), approximately 10 feet. The anchorage point is not directly behind the employee. If this employee fell he would free fall more than 6 feet.	1926.502(d)(16)(iii). "Personal fall arrest systems, when stopping a fall shall be rigged such that an employee can neither free fall more than 6 feet (1.8 m), nor contact any lower level."

A.2 Caught-in or -between

A.2.1 Caught-in or -between Testing Module

Description	Osha Reference
This photo depicts a spoil pile that was placed too close to the edge of the excavation. This exposes any one in the excavation to a possible cave-in hazard.	1926.651(j)(2). "Employees shall be protected from excavated or other materials or equipment that could pose a hazard by falling or rolling into excavations. Protection shall be provided by placing and keeping such materials or equipment at least 2 feet (.61 m) from the edge of excavations, or by the use of retaining devices that are sufficient to prevent materials or equipment from falling or rolling into excavations, or by a combination of both if necessary."

Description	Osha Reference
Employee capping/sealing a 12 inch water main casing in trench 12 feet in deph and 27 feet in length was not provided with a safe means of egress.	1926.651(c)(2). "Means of egress from trench excavations. A stairway, ladder, ramp or other safe means of egress shall be located in trench excavations that are 4 feet (1.22 m) or more in depth so as to require no more than 25 feet (7.62 m) of lateral travel for employees."



Description	Osha Reference
Employees working in a log shredder without locking out the machine.	1910.147(c)(1). "Energy control program. The employer shall establish a program consisting of energy control procedures, employee training and periodic inspections to ensure that before any employee performs any servicing or maintenance on a machine or equipment where the unexpected energizing, start up or release of stored energy could occur and cause injury, the machine or equipment shall be isolated from the energy source, and rendered inoperative."

Description	Osha Reference
Employeees exposure to struck-by hazards presented improperly stored materials.	1910.176(b). "Secure storage. Storage of material shall not create a hazard. Bags, containers, bundles, etc., stored in tiers shall be stacked, blocked, interlocked and limited in height so that they are stable and secure against sliding or collapse."

A.2.2 Caught-in or -Between Learning Module

Description	Osha Reference
This image depicts a trench which does not need protection since it is thin and shallow.	1926.652(a)(1). "Each employee in an excavation shall be protected from cave-ins by an adequate protective system designed in accordance with paragraph (b) or (c) of this section except when: Excavations are made entirely in stable rock; or excavations are less than 5 feet (1.52m) in depth and examination of the ground by a competent person provides no indication of a potential cave-in."

Description	Osha Reference
Fan blades not properly guarded.	1910.212(a)(5). "Exposure of blades. When the periphery of the blades of a fan is less than seven (7) feet above the floor or working level, the blades shall be guarded. The guard shall have openings no larger than one-half (½) inch."

Description	Osha Reference
This is an excavation that is approximately eight feet deep. It is approximately four feet wide at the bottom, and eight feet wide at the top. The excavation is not properly shored, sloped or otherwise protected to prevent a cave-in hazard. The excavated material (spoil) is not stored and maintained at least two feet away from the edge of the excavation. There is not a safe means to egress or exit the excavation that is within 25 feet of the employees.	1926.652(a)(1). "Each employee in an excavation shall be protected from cave-ins by an adequate protective system designed in accordance with paragraph (b) or (c) of this section except when: Excavations are made entirely in stable rock; or excavations are less than 5 feet (1.52m) in depth and examination of the ground by a competent person provides no indication of a potential cave-in."

Description	Osha Reference
No employee should be in proximity to moving vehicles or equipment unless they are in full view of the operator, and workers should avoid working near heavy equipment if unnecessary to prevent being caught between the machine and a stationary object.	1926.601(b)(4), "No employer shall use any motor vehicle equipment having an obstructed view to the rear unless: The vehicle has a reverse signal alarm audible above the surrounding noise level or the vehicle is backed up only when an observer signals that it is safe to do so."

A.3 Electrocution

A.3.1 Electrocution Testing Module

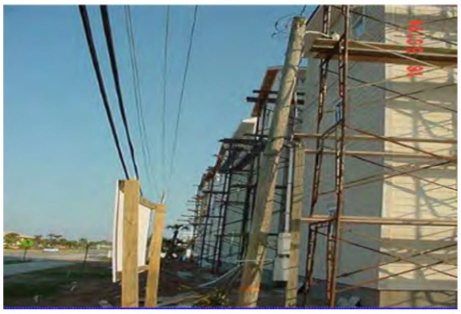
Description	Osha Reference
Electrical equipment, the cord, was not free from a recognized hazard, the flexible cord's outer insulation was damaged exposing the inner cords.	1926.403(b)(1). "The employer shall ensure that electrical equipment is free from recognized hazards that are likely to cause death or serious physical harm to employees. Safety of equipment shall be determined on the basis of the following considerations... Electrical insulation."

Description	Osha Reference
Picture shows an employee operating the "Kobelco" back-hoe within inches from the overhead power lines.	1926.416(a)(3). "Before work is begun the employer shall ascertain by inquiry or direct observation, or by instruments, whether any part of an energized electric power circuit, exposed or concealed, is so located that the performance of the work may bring any person, tool, or machine into physical or electrical contact with the electric power circuit. The employer shall post and maintain proper warning signs where such a circuit exists. The employer shall advise employees of the location of such lines, the hazards involved, and the protective measures to be taken."

Description	Osha Reference
No employer should permit a worker to work in such proximity to any part of an electric power circuit that the worker could contact the electric power circuit in the course of work.	1926.416(a)(1). "No employer shall permit an employee to work in such proximity to any part of an electric power circuit that the employee could contact the electric power circuit in the course of work, unless the employee is protected against electric shock by deenergizing the circuit and grounding it or by guarding it effectively by insulation or other means."

Description	Osha Reference
Fire danger: exposed fray wire near flamable post.	1910.303(b)(1). "Examination. Electric equipment shall be free from recognized hazards that are likely to cause death or serious physical harm to employees. Safety of equipment shall be determined using the following considerations:"

A.3.2 Electrocution Learning Module



Description	Osha Reference
Scaffold was erected 4.5 feet from 7.2 kV power line.	1926.451(f)(6). "The clearance between scaffolds and power lines shall be as follows: Scaffolds shall not be erected, used, dismantled, altered, or moved such that they or any conductive material handled on them might come closer to exposed and energized power lines than as follows: Less than 300 volts, 3 feet minimum distance. 300 volts to 50 kv, 10 feet minimum distance."

Description	Osha Reference
Crossing electrical line is unsupported over workers in a trench.	1926.651(b)(4). "While the excavation is open, underground installations shall be protected, supported or removed as necessary to safeguard employees."

Description	Osha Reference
Outlet box missing cover.	1910.305(b)(2)(i). "All pull boxes, junction boxes, and fittings shall be provided with covers identified for the purpose. If metal covers are used, they shall be grounded. In completed installations, each outlet box shall have a cover, faceplate, or fixture canopy. Covers of outlet boxes having holes through which flexible cord pendants pass shall be provided with bushings designed for the purpose or shall have smooth, well-rounded surfaces on which the cords may bear."

Description	Osha Reference
Employer manufactured and installed flammable container grounding cables and grounding rod.	1926.404(f)(6). "Grounding path. The path to ground from circuits, equipment, and enclosures shall be permanent and continuous."

A.4 Struck-by

A.5 Struck-by Testing Module

Description	Osha Reference
Storage of products not secure exposing employees to falling objects.	1910.176(b). "Secure storage. Storage of material shall not create a hazard. Bags, containers, bundles, etc., stored in tiers shall be stacked, blocked, interlocked and limited in height so that they are stable and secure against sliding or collapse."

Description	Osha Reference
An employee was given a pair of safety glasses to be worn over his prescription glasses, which did not incorporate corrective lenses mounted behind the protective lenses.	1926.102(a)(1). "The employer shall ensure that each affected employee uses appropriate eye or face protection when exposed to eye or face hazards from flying particles, molten metal, liquid chemicals, acids or caustic liquids, chemical gases or vapors, or potentially injurious light radiation."

Description	Osha Reference
Employees below the work area were not wearing hard hats.	1926.100(a). "Employees working in areas where there is a possible danger of head injury from impact, or from falling or flying objects, or from electrical shock and burns, shall be protected by protective helmets."


Description	Osha Reference
This picture shows an area where employees where working applying thermo plastic paint while working between the deceleration lane and the main highway lane.	1926.200(g)(1). "At points of hazard, construction areas shall be posted with legible traffic control signs and protected by traffic control devices."

A.5.1 Struck-by Learning Module


Description	Osha Reference
Photo shows an employee without a high visibility vest or traffic control being exposed to traffic. An employee had been struck by a vehicle in the general area wher this photo was taken.	1926.651(d). "Exposure to vehicular traffic. Employees exposed to public vehicular traffic shall be provided with, and shall wear, warning vests or other suitable garments marked with or made of reflectorized or high-visibility material."


Description	Osha Reference
Employees working in sawmill were exposed to the hazard of being struck by flying wood chips and debris from trimmer saws.	1926.102(a)(1). "The employer shall ensure that each affected employee uses appropriate eye or face protection when exposed to eye or face hazards from flying particles, molten metal, liquid chemicals, acids or caustic liquids, chemical gases or vapors, or potentially injurious light radiation."

Description	Osha Reference
Steel pipe rolling off truck.	1910.176(b). "Secure storage. Storage of material shall not create a hazard. Bags, containers, bundles, etc., stored in tiers shall be stacked, blocked, interlocked and limited in height so that they are stable and secure against sliding or collapse.radiation."

Description	Osha Reference
A lift truck was attempting to lift several unsecured gas cylinders to the second floor of a construction site.	1926.350(a)(2). "When cylinders are hoisted, they shall be secured on a cradle, slingboard, or pallet. They shall not be hoisted or transported by means of magnets or choker slings."

B User Manual

This section works as a user guide for the platform developed within the IRISE project titled "A Novel Immersive Virtual Reality Platform for Health & Safety Training of Construction Workers." This document aims to provide those using the Virtual Reality (VR) platform the guidance needed to set up the hardware and software, and run training sessions for those preparing to work on an active construction site.

B.1 Physical Setup

The following hardware items are required to run the Virtual Reality Platform (also referred to as the "platform" or "program"):

- Large open space (Minimum: 5ft x 5ft, Maximum: 12ft x 12ft)
- Virtual Reality headset (Recommended: HTC Vive Pro 2)
- One virtual reality controller (Recommended: HTC Vive controller)
- Two virtual reality base stations (Recommended: SteamVR base station 2.0)
- One external speaker (Recommended: JBL Flip 5)

The computer running the program must meet the following system requirements as described by HTC [22].

Component	**Recommended system requirements**
Processor	Intel Core i5-4590 / AMD Ryzen 1500 equivalent or better
GPU	NVIDIA GeForce RTX 2060 / AMD Radeon RX 5700 equivalent or better
Memory	8 GB RAM or more
Video output	DisplayPort 1.4 or newer required to use headset's full resolution
USB port	1x USB 3.0 or newer
Operating system	Windows 10, Windows 11

Table 5: Recommended System Requirements for VR Capable Computer

Component	Minimum system requirements
Processor	Intel Core i5-4590 / AMD Ryzen 1500 equivalent or better
GPU	NVIDIA GeForce GTX 1060 / AMD Radeon RX 480 equivalent or better
Memory	8 GB RAM or more
Video output	DisplayPort 1.2 or newer
USB port	1x USB 3.0 or newer
Operating system	Windows 10

Table 6: Minimum System Requirements for VR Capable Computer

B.1.1 Planning the Training Space

The play area is the virtual boundaries of the VR headset [24]. For the user to interact with VR objects, they must be physically within the play area. Users must be provided with an open space free of obstacles to use the platform safely. When wearing a virtual reality head-mounted display (HMD), the user cannot see the ground; thus, tripping hazards must be minimized.

Most VR headsets require base stations to anchor the corners of the play area and track the user within the space (see fig. 48 for a diagram example and fig. 49 for an example from the DISCOVER Lab at the University of Pittsburgh). A base station acts as a wireless device for the computer to track the rotation and location of the HMD. Base stations can either be attached directly to the wall or freestanding with a tripod. Regardless of placement style, base stations must be higher than the height of the VR user and a recommended minimum of 6.5 ft [23].

Figure 48: Example of base stations anchoring the corners of the play area. Image from HTC Vive support page [21].

Figure 49: Base station setup for the DISCOVER lab at the University of Pittsburgh.

Many VR headsets use inside-out tracking instead of, or in addition to, base station tracking. When both options are available, base station tracking is usually more accurate, however inside-out tracking may still provide a high quality experience depending on the headset model. For the recommended headset (HTV Vive pro 2), base station tracking is better.

The computer should be near the play area, such that the HMD can be plugged into the computer without stretching the cord extensively. Additionally, areas with strong light may negatively affect the performance of the base station [23]. The cord of the HMD may represent a tripping hazard for the user depending on the length and if managed properly. The health and safety training professional overseeing the session should pay attention to the relative position of the cord and the user's feet.

B.2 Usage

This section details the instructions for setting up the software to run the platform and for using it while the program is running.

B.2.1 Installing software

The following pieces of software must be installed on the computer's main hard drive.

1. Flagship software for the VR headset, for the recommended headset: Vive Console [20]

2. SteamVR [81]

3. Virtual Reality Health & Safety Trainer

To install Vive Console, visit https://www.vive.com/us/setup/vivepro2/, and run the software. To download SteamVR, install the Steam launcher at https://store.steampowered.com/about/download, and inside the launcher, search for SteamVR in the "store" tab. The folder containing the Virtual Reality Health & Safety Trainer launcher should be preinstalled on the machine.

B.2.2 Initializing SteamVR

Once the VR headset is plugged into the computer, the base stations are set up, and a charged controller is available, SteamVR can be enabled to pair all the devices with eachother. Start by launching SteamVR through the Steam Launcher. If the HMD and base stations are plugged in correctly, the window will appear similarly to fig. 50.

Figure 50: SteamVR once launched with Base stations and HMD plugged in.

The VR controller will not be paired automatically. To connect it, click the menu button in the top left, and direct to the device connection page using the steps shown in fig. 51. Once paired, the main window will highlight the controller icon between the hmd and base station icons in fig. 50.

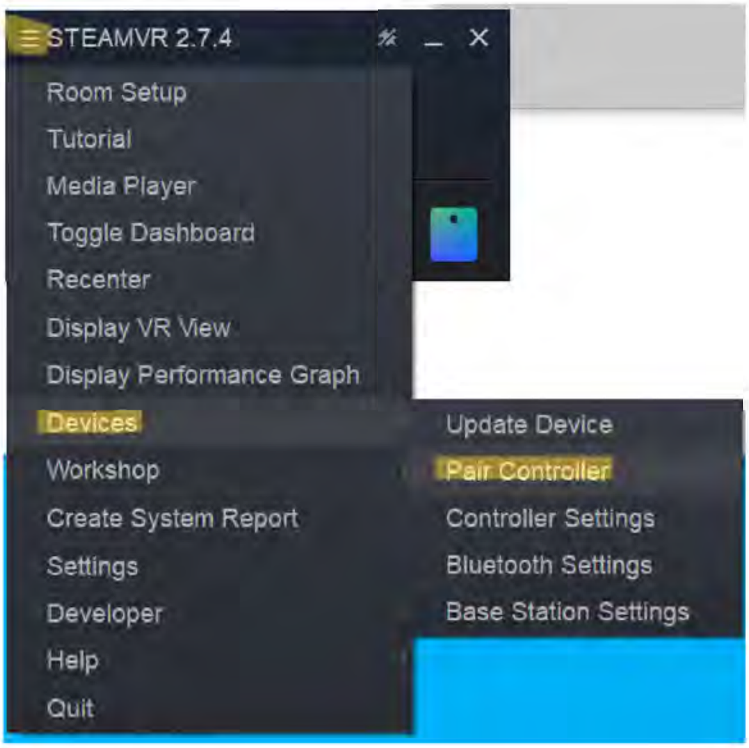


Figure 51: SteamVR steps to pair controller.

B.2.3 Starting the VR platform

To start the VR platform, open the folder containing the program files, and launch the file *VRH&STrainer.exe*, as shown in fig. 52. Do not edit the other files. You may right click on the *.exe* file to create a shortcut on another part of your computer.

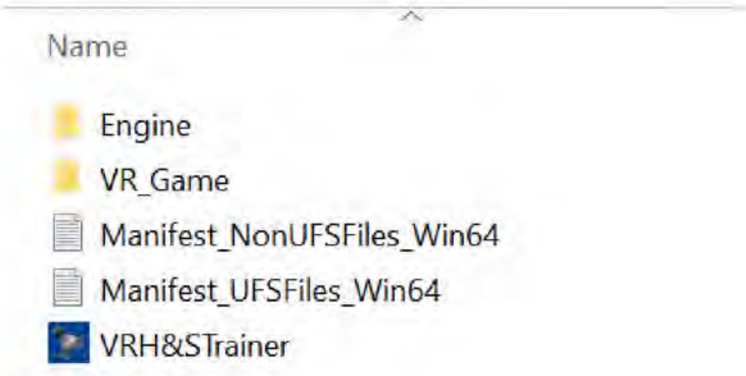


Figure 52: Virtual reality platform launcher & engine files.

B.2.4 Controls

The program interacts with the virtual environment using three buttons on the controller and motion-tracking capabilities. The three buttons are labeled in Fig. 53

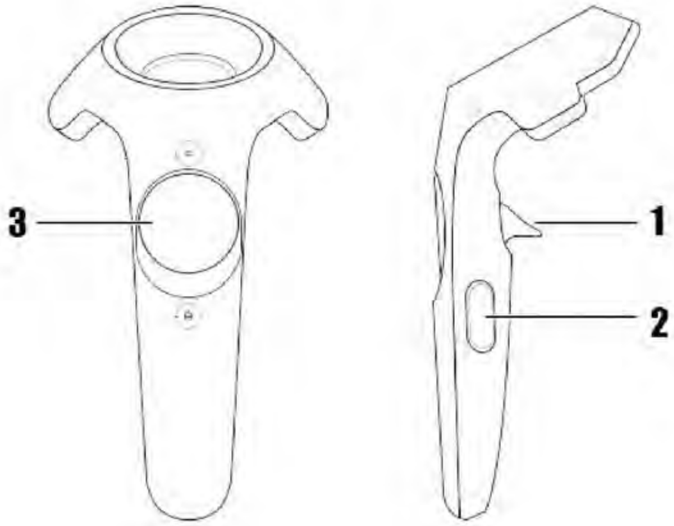


Figure 53: HTC Vive controller with buttons labeled.

The buttons are used for the following actions inside the program:

- **Button 1**: Used to select objects or teleport. If anything in the platform is to be selected, it is done using this button.
- **Button 2**: Used to toggle the visibility of teleportation bubbles in the scene (a process described more in the subsection *"Moving throughout the environment"*). This button appears on both sides of the controller stem, and pressing either one triggers the same input.
- **Button 3**: Used to repeat the last audio played in the environment. This can be used to repeat instruction in the tutorial, or informational audio clips in various modules.

It is important to hold the controller properly while using the program. The controller must be held with a loose grip, resting the thumb on the circular button **3** and the index finger on button **1**. The middle and ring finder curl around the stem, allowing them to easily press the button **2**. Figure 54 and 55 show an example of the proper way to hold the controller.

Figure 54: HTC Vive controller being held (front view).

Figure 55: HTC Vive controller being held (side view).

B.2.5 Pregame menus

When loading into the game, the VR player will begin in an empty space with a 3D menu (see figure 56. Although the menu is usually in front of them, depending on the orientation of the HMD during setup, the VR player may have to turn around to find it. This menu exists at a fixed point in 3D space, thus the user must locate it by rotating their view. The menu will always be within range of the user in this pregame area.

The pregame menu has three options:

- **Levels**: Opens a new menu to decide between starting a *learning* module or a *testing* module. This option should be selected for VR user is navigate to their desired module.
- **Tutorial**: Launches the tutorial module, where the VR user will practice selecting objects, teleporting throughout the scene, and completing hazard recognition tasks.
- **Quit**: Quits the program.

When navigating the *levels* option, the VR user first will choose between completing a *learning* or *testing* module (see figure 57). Each section has four options, matching the major hazard categories OSHA described as the focus four [**OSHAFocusFour**]. For each selection, the 3D menu will open the final set of options before opening a module (see figure 58 and 59.

Figure 56: VR Starting environment with main menu for navigating the platform.

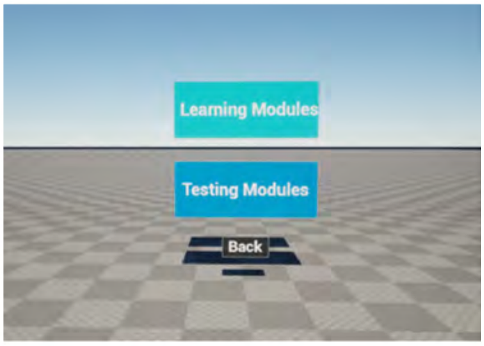


Figure 57: VR Starting environment with menu for types of modules.

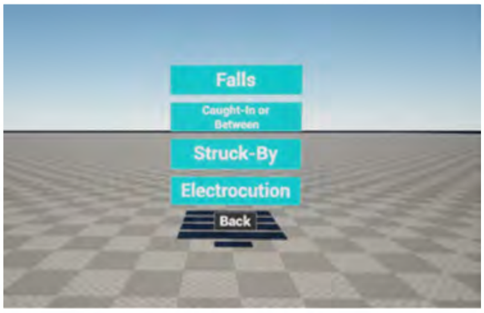


Figure 58: VR Starting environment with menu for starting a learning module.

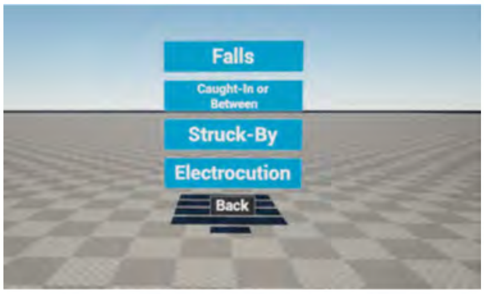


Figure 59: VR Starting environment with menu for starting a testing module.

B.3 Moving throughout the environment

The VR player is provided the capability to move throughout the VR environment using the teleportation hotspots created for each module. This method is used because it mitigates potential VR sickness and provides guidance as to where in the environment the VR player should visit before submitting their answers.

To teleport inside of the VR environment, press down on the side button of the controller stem, as described in section B.2.4. While this button is held, all teleportation hotspots will become visible. An example of a teleportation hotspot from the point of view of the VR player is seen in figure 60. The VR player can click on these hotspots to instantly teleport to that location. When a hotspot is hovered, such that the player is aiming correctly, it gains a green color as shown in figure 61. Additionally, once a hotspot has been visited, it gains a pale color (figure 62), such that the VR player understands where they've visited and where they haven't. An example of teleportation hotspots spread throughout a module is seen from an aerial view in figure 63.

Figure 60: Teleportation hotspots from the view of the VR player.

Figure 61: Teleportation hotspot from the view of the VR player hovering with the VR controller.

Figure 62: Teleportation hotspot which has been visited from the view of the VR player.

Figure 63: Aerial view of the teleportation hotspots spread throughout a learning module.

B.3.1 Selecting objects

The VR controller's aim beam which is used for teleportation and menus is likewise used to select objects. Selectable actors in the construction environment will gain a light blue highlight while hovered (see figure 64). Once selected, this highlight will turn permanently green. (see figure 65). The number of selected objects inside the scene is constantly updated, and shown in the 3d menu tracker (figure 40 which appears in each module.

In learning modules, objects which can be selected trigger a voiceover explanation of the nearby construction scenario. In testing modules, there is no auditory feedback when selecting a selectable actor. When an object is selected in the testing module, the variables keeping track of correct and incorrect answers will update, thus at the end of the module the VR user's score is displayed.

Figure 64: Selectable object hovered with the VR controller.

Figure 65: Selectable object which was selected by the VR user.

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