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An On-site and Off-site Collaborative Safety Monitoring Framework using Augmented and Virtual Reality for Near-miss Incidents

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Abstract: The emergence of Building Information Modelling (BIM), reality data, Virtual Reality (VR), and Augmented Reality (AR) has significantly enhanced the collaboration between stakeholders in construction management. The utilization of VR/AR devices holds considerable potential for monitoring safety in complex and constrained working environments on the construction site. On the other hand, near-miss incidents remain an important early sign of struck-by accidents. However, research on early warning and prevention methods for this risk is still limited. This paper, therefore, presents a framework for on-site and off-site collaborative safety monitoring framework using augmented and virtual reality for near-miss incidents. In the proposed framework, three phases to develop a VR/AR-based safety monitoring system include (1) construction safety simulation environment, (2) localization-based interaction system, and (3) safety monitoring system. The system can undertake the processing of data and enables communication among disparate VR/AR devices. VR clients are observational tools and offer guidance, while the AR client stays onsite for construction tasks. All clients connect to a processing computer, which also works as a host. The system embedded in the AR device can trigger an alarm or receive signals from the VR client when a near-miss issue happens. Additionally, all device clients possess the capability to share data acquired from onsite monitoring cameras, thereby fostering effective discussions and decision-making. The efficacy of this cross-platform system has been validated through the implementation of an outdoor coordination case study.

Keywords: Virtual Reality (VR), Augmented Reality (AR), safety monitoring, near-miss

1. INTRODUCTION

Virtual Reality (VR) and Augmented Reality (AR) have been recognized as greatly supportive technologies for the architectural, engineering, and construction (AEC) industry in recent years with the capability to create an immersive, multisensory three-dimensional (3D) environment. Those technologies serve as innovative tools that facilitate visualization and communication among diverse stakeholders and aid decision-making, particularly in the context of construction design, education, and safety monitoring. Nevertheless, multiple challenges exist in terms of collaboration processes during construction which are often associated with ineffective communication between all the project partners [1]. The difficulties are caused by the absence of information about the existing conditions of the building. Such information, however, can be assigned by combining data from different sources, such as as-planned Building Information Modeling (BIM) model and point clouds. Together with the renaissance provided by VR/AR head-mounted devices (HMD), the user can experience a simulation of the dynamic construction site with a completed field of view, therefore, improving the performance of safety monitoring on the construction site.

Among various hazards, objects and equipment struck-by stood as the second biggest reason for occupational injuries in the US construction sites [2]. Previous statistics showed that more than 60% of fatalities in excavation works from 1992 to 2002 in the US were caused by struck-by accidents [3]. Data collected between 2011 and 2015 by the Center for Construction Research and Training (CPWR), reported in [4], revealed that nearly half of the casualties resulting from struck-by accidents (specifically, 384 out of 804 cases, or 47.8%) were associated with vehicle collisions. Furthermore, over half of these accidents (220 out of 384 cases, or 57.3%) occurred due to vehicles operating within the construction site. To overcome this issue, many studies have focused on dealing with the struck-by issues, however, the research on near-miss incidents to raise an early warning is still limited. Generally, if any near-miss cases are recognized and alerted, workers shall have more time to avoid this hazard. Therefore, this paper presents a framework that can enhance user's cognitive abilities to raise awareness of near-miss incidents in construction by exploiting the advancement of VR/AR performance.

The framework includes three main phases, which are (1) construction safety simulation environment, (2) localization-based interaction system, and (3) safety monitoring system. The output of this framework is an alerting mechanism that can be sent to the onsite AR devices, showing them the appropriate warnings and instructions for near-miss hazards of moving objects around. It is expected that this approach of alerting may contribute to the safety monitoring and decision-making support system that can be embedded in other VR/AR inspection methods.

2. RELATED WORK

Many studies have explored the applications of reality data and VR/AR simulation for safety monitoring in construction, particularly the risk of collision onsite. In this section, we will examine the latest research and categorize it into the following categories: studies of near-miss incident prevention in construction, vision-based data collection for onsite near-miss safety monitoring, and benefits of using VR/AR in construction safety monitoring.

2.1. Studies of near-miss incident prevention in construction

The construction industry, characterized by its dynamic and hazardous work environments, continually struggles with safety challenges. While catastrophic struck-by accidents draw significant attention, the subtle realm of near-miss incidents has not yet deserved equal interest. These near-misses, defined as events that cause no harm to property and no injuries to personnel, therefore narrowly avoid becoming accidents [5]. Thus, prevention methods serve as early warning signals, offering invaluable opportunities for safety improvement. Currently, different approaches have been examined in the search for effective warning mechanisms. Recognizing that construction workers-on-foot being too close to hazardous areas and equipment have higher threats of damage, Teizer and Cheng [6] have introduced a framework to automatically identify proximity hazards and measure proximity hazard indicator (PHI). This indicator helps to determine the number of events that might lead to struck-by hazards. The method requires multiple sensors to collect data on worker operation, equipment position, and geo-referenced hazard areas. Lin and Guo [7] proposed a novel method for detecting near-miss struck-by events on construction sites. By leveraging inertial measurement units (IMUs), their decision tree model achieves impressive real-time monitoring precision (97.0%) and recall (87.8%). The wearable hardware device enhances detection accuracy, contributing to proactive safety measures. Sakhakarmi et al. [4] developed a wearable hazard communication system using a tactile-based artificial sensory system to notify workers of potential collision hazards through vibration signals. However, the test participants still experienced lost signals and had to stand without doing any construction activity. Lee et al. [8] proposed an audio-based safety recognition system that can consistently monitor a diversity of construction risks, including collision threats. Immediate notifications of hazardous situations and instructions that can be sent to workers are the most beneficial of this system. However, mixed noises emitted from different activities could not be classified effectively. As a result, the accuracy of sound classification of this approach was decreased. Furthermore, these methods could not visualize the situation of site conditions; hence no report of near-miss incidents was recorded in detail.

2.2. Vision-based data collection for onsite near-miss safety monitoring

Compared to other conventional and sensory methods, computer vision technology is often used in construction site monitor monitoring sites since it can enable the early identification of potential issues, allowing prompt corrective actions [9]. By applying machine learning algorithms, computers can extract spatial information for each entity, including workers and equipment, as well as geometric features of the site, and then use them for safety prevention. Kim et al. [10] developed a vision-based object-centric safety assessment system in which the vision-processing module detected movement using the Gaussian mixture model (GMM) for background subtraction in the captured images and tracked the detected objects with Kalman filter algorithms. The system was used to assess the potential of struck-by within a range of 18 meters of an object. Yan et al. [11] found limitations in the two-dimensional (2D) image pixel-based data, including the spatial relationship distortion and occlusion of heavy vehicles. Yet 3D object detection was suggested to estimate the 3D spatial relationship between construction workers and heavy vehicles in real-time. Vision data can additionally be used for 3D scene reconstruction or segmentation, which is beneficial for finding an obstacle-free path for automated vehicle guiding [9]. Golovina et al. [12] mentioned near-miss incidents as "*close call*" events and emphasized that cloud-based data management with Camera-Monitor-Systems (CMS) could be advantageous to tackle this problem. Nonetheless, a research gap exists concerning the prevention of near-miss incidents in construction sites. Despite the significance of near-misses as early indicators of potential accidents, comprehensive research addressing effective prevention strategies remains limited.

2.3. Benefits of using VR/AR in construction safety monitoring

Simultaneously using modern information technologies, such as BIM and VR/AR, can help to share construction activities and safety-related information [13]. Golovina et al. [14] combined BIM and spatiotemporal data when measuring proximity hazard parameters and weights to avoid struck-by and near-miss interactions between workers-on-foot and construction equipment. One experiment in this research was executed in a virtual space before testing in a controlled outdoor environment. Acknowledging the inattentiveness of workers while working, a virtual road construction environment was created in [15], which could provide simulated accidents without causing harm to participants. The proposed computational approach in this study is believed to be able to predict inattentive behaviors to repeatedly exposed approaching hazards. Delgado et al. [16] clearly stated that VR/AR could present a more realistic visualization of a built asset, which contains more information for stakeholder engagement in different construction phases. In terms of construction safety use case, both technologies can provide a risk-free working area that is useful for construction hazard identification, safety training, inspection, and instruction. The authors also confirmed several challenges to using VR/AR in safety monitoring, including the lack of appropriate customized hardware, lack of interoperability in cross-system practice, and lack of standardized evaluation.

3. METHODOLOGY

Figure 1 shows our conceptual framework for generating a near real-time intelligent observation platform that can provide a combined VR/AR safety monitoring system. The system is developed by using Unity as a base for multiple VR/AR devices, observing and monitoring safety-related objects in near real-time, particularly the near-miss incidents between moving equipment and workers.

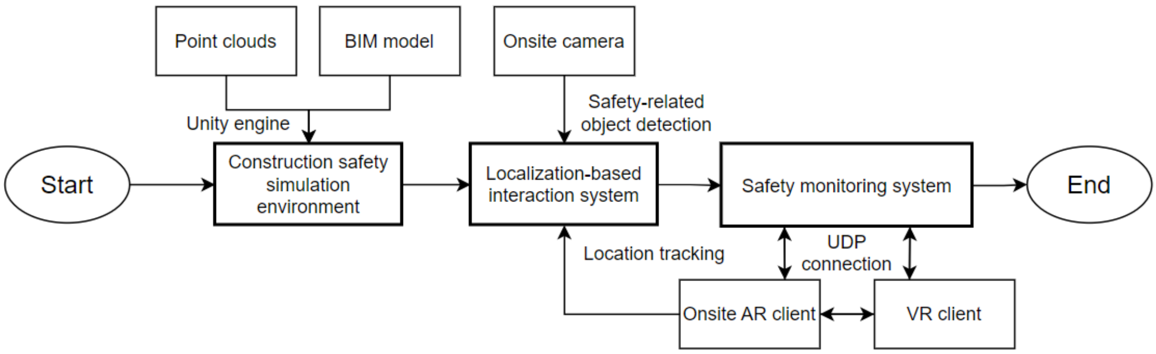

Figure 1. The framework of the reality-based safety monitoring system for near-miss incidents on construction site

3.1. Construction safety simulation environment

The first phase of the framework is the *"construction safety simulation environment."* This is a scenario that consists of the as-planned BIM model of the existing buildings and point clouds of the construction site. They will be added to Unity to simulate the working environment that replicates the current state of the construction site. By having point clouds, users can have better visualization of the current conditions of the site. At present, the Unity engine appears to be the most common platform that can support VR/AR application development. To align the generated scene to the real world for AR experience, a QR-code marker is implemented. Both the BIM model and point clouds are anchored to this marker position. Other safety-related objects such as human beings, moving machines, signs, and obstacles are also created as prefabs, which are prebuilt in the Unity assets. Those objects will be triggered to indicate the potential near-miss incidents by detection and location-based algorithms, which will be presented in the next section.

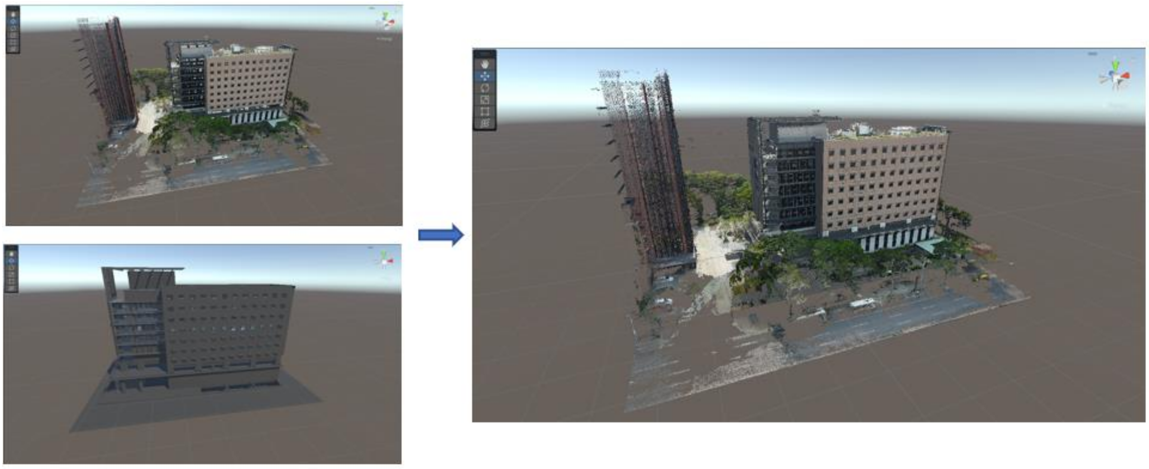

Figure 2. Aligning BIM model and point clouds in Unity

3.2. Localization-based interaction system

The next phase is the *"localization-based interaction system"*, which is responsible for detecting moving objects through an onsite camera. The captured video is processed by a computer connected to the camera. Detected objects including moving machinery, workers, and/or the AR user then will be represented in the created simulation environment as relevant game objects (for example, spheres and cylinders with different colors). To determine the location of an object in the virtual scenario, we first specify the camera pose in the generated point clouds (**Figure 3**), then extract the depth map of that camera scene. In this figure, the position of the fixed camera is circled. Other camera positions belong to the drone capturing images for the point clouds reconstruction.

Figure 3. Camera pose is defined in the generated point clouds

Having this depth map helps to estimate the 3D coordinates of the object in the entire point clouds. Such coordinates are subsequently projected to the Unity coordinate system with a transformation matrix. The perspective projection is based on calculations in [17].

3.3. VR/AR safety monitoring system

The last phase in the proposed framework is the VR/AR-based *"safety monitoring system"*. In this step, the construction safety simulation environment is built into the VR and AR devices. Those clients connect to the processing computer by Wi-Fi. Signals, which are strings of coordinates, are transmitted among clients by UDP connection. Currently, we do not have the appropriate customized software and hardware for this specific multiple-client connection. As a result, the movement of any detected object will be simulated and synchronized to different devices in the near real-time. The purpose of this framework is to recognize the potential for near-miss incidents; therefore, a warning will be triggered when an approaching object comes close to an individual on the scene. According to previous research in [10, 14], a safety range of 18 meters is set up for near-miss alert. In our concept, the AR user can use an AR gadget to work onsite while being tracked by the safety monitoring system. This built-in system, which is expected to be embedded as a function of other applications, will show an alert if a near-miss happens. On the other hand, VR users can stay in the office to observe the entire scenario and provide necessary warnings or instructions to the AR user. Combining automated detection and alerting, and manual observation and warning probably improves the performance of the safety system, whereas the unawareness of workers and staff remains during the construction phase.

4. EXPERIMENT

4.1. Case study

In this research, a scenario-based design of the near real-time intelligent observation system was developed and tested with an Oculus Quest 2 for VR experience and a Microsoft HoloLens 2 for AR experience. The experiment aims to validate the performance of the system based on object detection and location-based tracking. The case study uses an academic building, which is currently having some construction activities in its car parking area, for the experiment.

4.2. Initial result

Following the proposed framework, a simulated environment consisting of the mentioned academic building is created in the first place. The BIM model and point clouds of the building are prepared and aligned in Unity. The BIM model of the building is converted to FBX, which contains information on the geometry and materials used for the building. The point clouds are reconstructed from images using Structure-from-Motion (SfM) pipeline. A QR-code is attached to the BIM model that supports localizing the building area when implementing this case study. After having the scenario created, we use a fixed camera to capture a general view of the car park. Moving objects will be detected in the video, streamlined by this camera. In this study, YOLOv8 is used as it is one of the most accurate deep-learning methods for object detection. The computer processes this detection, defines the 2D position of objects in each frame of the record, estimates its 3D coordinates in the point clouds, and encodes it for transferring. The coordinates represented in strings are transmitted to all working VR/AR clients, and they will be decoded by those devices. The speed of signals sent is based on the performance of the computer when processing detection and encoding.

In terms of testing the safety monitoring system, we need to first scan the QR code onsite to check the alignment of the BIM model and the real building. In the HoloLens view, the BIM model and point clouds can be turned off to keep the device's performance stable. The onsite camera is connected to the processing computer, which must run as a host for the entire scenario. This computer then detects the humans and moving objects in the record captured by the camera. Signals of the transformed coordinates are continuously transmitted to the devices' ports in the Wi-Fi network, using a UDP connection established by the Photon Fusion service. When VR and AR users turn on the function to activate the proposed system, they will receive the coordinates of all objects detected in the previous step. When the moving object is less than 18 meters close to the human, a warning sign will be triggered and appear in front of the AR user. To help the AR user recognize the direction of the moving objects, directional indicators are scripted to visualize how the objects are approaching from the blind spots of the user. The results of this process are shown in Figure 4. In this figure, the left illustration is Unity Editor's view, in which the moving vehicle is represented by a pink sphere. The right illustration presents the AR view, which shows an alert sign and a blue indicator pointing to the the approaching object.

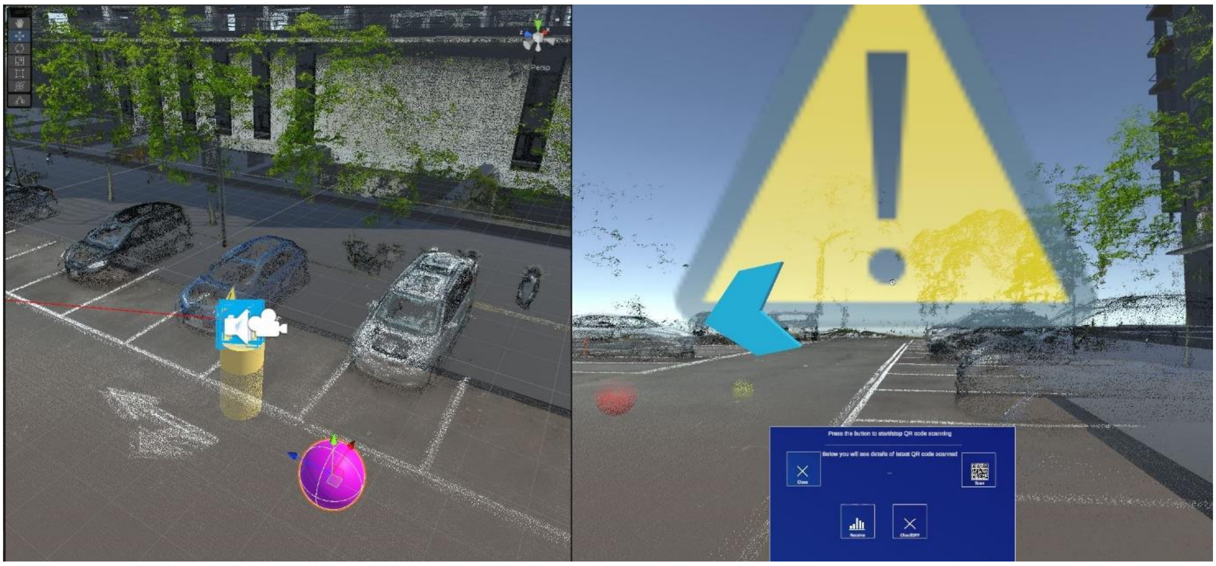

Figure 4. Unity view (left) and AR view (right) of the test

Simultaneously, the simulation of the generated scenario can be observed in the VR gadget. In this virtual environment, the user who observes the entire scenario on the computer can freely change his view. Both the VR user and the computer user can interact with some safety objects for planning purposes. Figure 5 below shows the view of the VR user moving around, checking the space, and observing the AR user (which is represented by a yellow cylinder). Also, when discovering potential near-miss hazards, as the sphere is approaching the cylinder from behind, the VR user can actively send a notification to other clients. The note can be seen in all clients. For example, the notifications appear in the computer user's view in Figure 6.

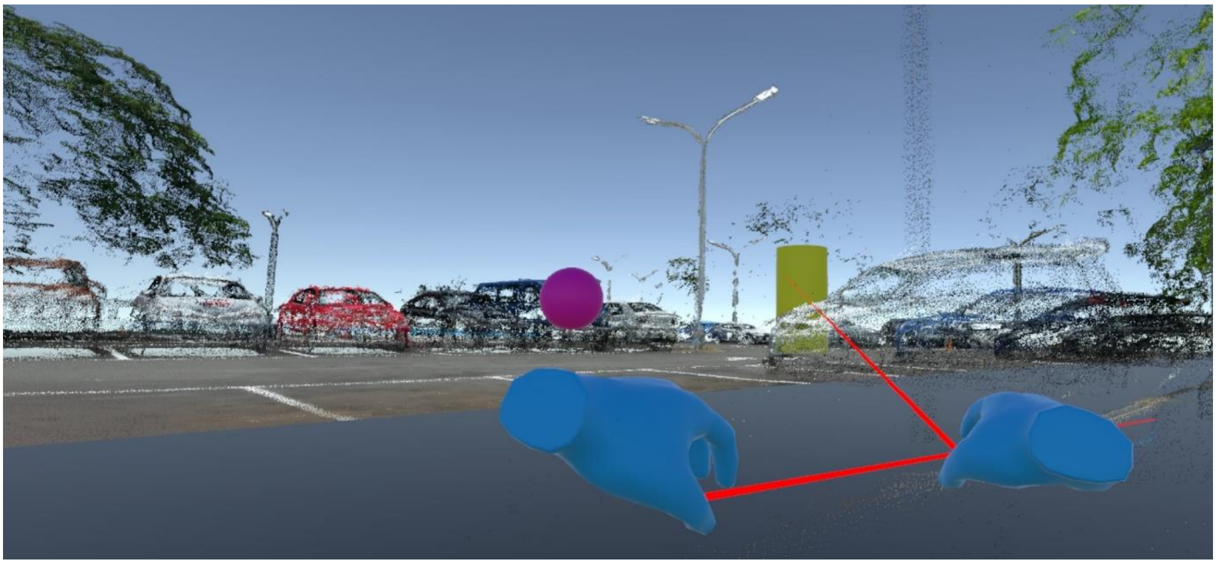

Figure 5. View of the VR user in the case study

Figure 6. Different Unity view when the notification is sent by the VR user

The monitoring system developed in this research comprises different packages for AR and VR usage. However, there are challenges arising when combining those packages since this is one of the initial prototypes of the VR/AR cross-platform system in construction safety monitoring. This leads to underperformance in some graphic illustrations and effects. Optimization of the system, such as designing a user interface (UI), will be made in the future.

5. CONCLUSION & FUTURE WORK

In this study, a framework of the reality-based safety monitoring system for construction near-miss incidents is presented. The developed monitoring system can work on the VR and AR devices so that VR/AR users can visualize the movement of objects in near real-time. In the case study, when an object approached the AR user from behind, a near-miss alert was successfully activated. At the same time, the VR user could observe the situation and be able to send notifications if necessary.

Results of the case study show that the proposed framework has significant potential for recognizing near-miss incidents, thus providing an early warning for workers and staff onsite. Nonetheless, the established system still has limitations. First of all, the detected object's coordination still drifts if the onsite camera is located in an unstable position, as well as having occlusions. Using HoloLens' camera as the second source to capture reality data is suggested to solve this issue. Secondly, the application still cannot work in real-time because its transferring speed is heavily dependent on the network performance onsite, which only works well in close range. Another issue belongs to the development of the cross-platform system. At the moment, VR and AR applications are mainly developed in Unity, which was originally a game engine, and construction-supported assets have not been common yet. Therefore, future research should focus on optimizing algorithms to speed up the detection process and improve the work of each device.

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