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Prototyping an immersive virtual reality training system for urban-scale evacuation using 360-degree panoramas

Z Feng[1], C Liu[2], V A González[2], R Lovreglio[1] and D Nilsson[3]

[1] School of Built Environment, Massey University, New Zealand

[2] Department of Civil and Environmental Engineering, University of Auckland, New Zealand

[3] Department of Civil and Natural Resources Engineering, University of Canterbury, New Zealand

Z.Feng1@massey.ac.nz

Abstract. Urban-scale evacuation may take place because of disasters or emergencies. Efforts have been made to enhance the preparedness of communities for urban-scale evacuation. For instance, wayfinding systems are installed and implemented in tsunami-prone regions, indicating the evacuation routes to high ground or inland. However, communities tend not to familiarise themselves with wayfinding systems and the best evacuation routes because tsunami evacuation drills are not normally carried out given the challenges to plan and run them. This study proposes a rapid development approach for immersive virtual reality (IVR) training systems suited to urban-scale evacuation. This approach utilises 360-degree panoramas to represent an urban environment in IVR, getting rid of the process of 3D modelling or reality capture to reconstruct a virtual urban environment. The 360-degree panoramas used in this study were directly acquired via a 360-degree camera. Immediate feedback is applied as a pedagogical approach to inform users. The training objective is to make users capable of identifying evacuation signs and the best evacuation route. This paper outlines a development framework to demonstrate the prototyping workflow of a 360-degree panoramic IVR training system suited to urban-scale evacuation. 360-degree panoramic IVR requires low levels of development efforts and computational resources. Therefore, urban-scale evacuation drills become possible to be rolled out easily and quickly to a wider population using 360-degree panoramic IVR.

1. Introduction

Disasters and emergencies often require urban-scale evacuation as key safety procedures to reduce the impacts on humans and societies. Huge efforts have been made to enhance resilience in response to disasters and emergencies. However, the human tolls in the last decades show that it is far from enough to enhance the preparedness of communities. For instance, during the Australian bushfire season 2019-2020, over 5900 buildings were destroyed, and at least 34 people were killed [1]. The 2004 Indian Ocean earthquake and tsunami killed an estimated 230,000 people in 14 countries [2]. These cases show that disasters have brought numerous losses to human society and the economy.

One possible solution to mitigate the impact on humans is to provide evacuation training to communities [3,4]. To date, different approaches have been used to deliver training and provide key information about evacuation procedures, such as evacuation drills and seminars. However, the literature has pointed out that these traditional approaches may not be effective and have several limitations [5]. One of the major limitations is that these approaches are not credible enough to deliver effective training outcomes [6,7]. It is risky, unethical, and costly to expose people to hazards during training. Therefore, people do not get the chance to practice in realistic scenarios and familiarise themselves with actual hazards. Another limitation is that traditional training has limited capabilities to provide training feedback to induvial people [8,9]. Without such assessment, training effectiveness is jeopardised as people do not receive constant feedback about whether they did during training was right or wrong. More importantly, urban-scale evacuation drills are almost unpractical to execute as these drills can be heavily disruptive to the operational activities and daily lives of entire communities.

Alternatively, immersive virtual reality (IVR)-based training has been emerging for disasters and emergencies in recent years [10]. IVR engages users through three core mechanisms: immersion, interactivity, and user involvement [11]. Therefore, IVR can offer life-like scenarios where users interact with virtual environments and solve challenges. Chittaro and Buttussi [12] argue that IVR enhances the perception of users through high-level physiological and emotional arousal. Krokos et al. [13] claim that IVR helps users focus on tasks, leading to improved memory recall. Previous studies demonstrate that IVR has the potential to be an effective training tool. Especially, IVR has the capability to present a virtual replica of a real-world environment. This could be ideal for urban-scale evacuation training, which could have minimal disruption on daily urban activities. However, the studies focusing on IVR for urban-scale evacuation are still lacking in the literature. One possible reason could be that the modelling process for a virtual environment on an urban scale is tedious and the computational resources to render such a heavy model in IVR is huge.

In order to fill the aforementioned knowledge gaps, this study aims to investigate the use of 360-degree panoramas to develop an IVR training system for urban-scale evacuation. This methodology is applied to a portion of the Orewa community in Auckland, New Zealand. This prototyping exercise allows the identification of the benefits and limitations of the proposed prototyping solution. This paper provides an overview of the existing applications of 360-degree panoramic IVR in Section 2. The proposed prototyping workflow is proposed in Section 3, while discussions and future works are provided in Section 4.

2. 360-degree panoramic immersive virtual reality

There are different visualisation techniques to construct and present a virtual environment for IVR. 360-degree panoramas could be one of the easiest approaches because complicated 3D modelling processes are not required. However, this solution requires specific pieces of hardware to generate content for digital experience. Nowadays, 360-degree cameras equipped with multiple fish-eye lenses are available in the consumer market, such as DJI Action 2, GoPro Max 360, or Insta360 One X2. The prices of these 360-degree cameras range from USD $399 to USD $499. These 360-degree cameras are capable of outputting a 360-degree panorama directly via one shot without extra post-processing. 360-degree panoramas provide viewers with omnidirectional representations of an environment, delivering a replica of the real world [14]. 360-degree panoramas can be viewed via different devices, such as smartphones, tablets, computer screens, or head-mounted displays. It is argued that a viewer could obtain a high level of sense of presence when viewing 360-degree panoramas via head-mounted displays [15]. This makes 360-degree panoramas promising to serve different purposes in IVR.

360-degree panoramic IVR has become popular in the literature. Eiris *et al.* [16] conduct a comparative experimental study to investigate the use of 360-degree panoramas for construction safety training. Results indicate that participants identified more hazards in non-IVR than 360-degree panoramic IVR. One possible reason could be that participants were overloaded in 360-degree panoramic IVR with complete graphical details and information of a virtual environment; however, non-IVR is more simplified, cleaner, and less realistic. Kim and Lee [17] integrate 360-degree panoramic videos into IVR for auditing streetscape quality. Results suggest that 360-degree panoramic IVR is appropriate for auditing audio-visual items, such as behavioural qualities, sense of space, and overall street atmosphere. Results also indicate that 360-degree panoramic IVR generates consistent auditing outcomes with field audits. Feng *et al.* [18] investigate exit choice behaviour during evacuation with an IVR simulator streaming 360-degree videos. After comparing with a field experiment, results show that the 360-degree panoramic IVR simulator is applicable to study the exit choice of pedestrians in evacuation.

Previous studies have highlighted the capabilities and validity of 360-degree panoramic IVR for various applications. However, the use of 360-degree panoramic IVR on emergency training is yet to be implemented, especially about large-scale events. For emergency training, different elements and mechanisms may be required to develop a virtual environment. For instance, the representation of a hazardous event, the navigation through a region, the interaction of behavioural responses, and the feedback and assessment to behavioural responses.

3. Prototyping workflow

The prototyping workflow of a 360-degree panoramic IVR training system suited to urban-scale evacuation involves six stages: (1) planning, (2) capture, (3) visualisation, (4) navigation, (5) augmentation, and (6) interaction. The proposed workflow is illustrated in Figure 1 and discussed in the following paragraphs.

3.1. Planning

The first essential step of the proposed workflow is the planning of the evacuation routes and storylines that are going to be available in the training system. This planning stage has direct impacts on the following stages of the development process. For instance, the planning of evacuation routes decides the capture points to acquire 360-degree panoramas on sites in Stage 2 and the sequence to visualise panoramas in IVR in Stage 3, and the planning of storylines determines the overlaying information and data to augment the panoramas in IVR in Stage 5.

In this study, a portion of the Orewa community in Auckland has been chosen as the testing region. Given its proximity to the ocean, this part of Auckland is a tsunami-prone area. As such, the people in this area need to be trained to identify the shortest path to take to get away from coastlines and reach an area with a sufficient height above sea levels, namely high ground. In order to achieve this training outcome, it is essential to start training in a place close to coastlines and make people identify the shortest route to evacuate to high ground. For the proposed IVR training system, the starting point of the evacuation route is the intersection of West Hoe Road and Hibiscus Coast Highway (see the star icon in Figure 2). Starting from this intersection, according to the tsunami evacuation signs installed on sites, the best evacuation route follows West Hoe Road to inland and turns to West Hoe Heights to high ground (see the solid black line in Figure 2). The evacuation route in this study stops at the intersection of West Hoe Heights and Orewa Heights Crescent (see the diamond icon in Figure 2). The total length of the route is around 925 metres. The proposed IVR training system aims to teach people about recognising tsunami evacuation signs and the best evacuation route in the selected region.

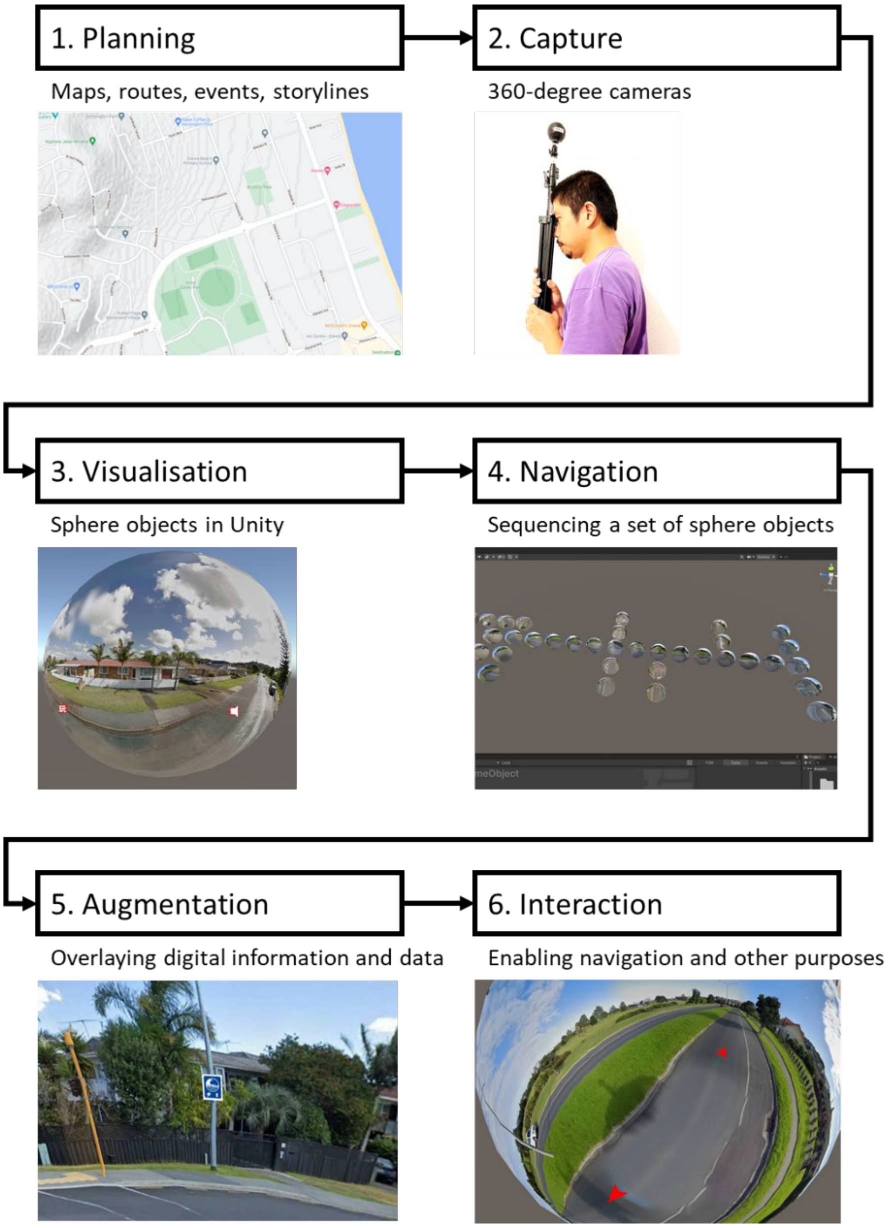

Figure 1. The prototyping workflow of a 360-degree panoramic IVR training system suited to urban-scale evacuation.

3.2. *Capture*

Next, the capture stage takes place. 360-degree cameras can be used to gather the 360-degree panoramas of the selected area. In this work, we used 360 FLY 4K to capture 360-degree panoramas on sites. According to the evacuation route planned in Stage 1, a set of panoramas can be acquired consecutively from the beginning to the end of the route. In order to provide smooth navigation in IVR, a constant physical distance between two capture points shall be maintained for two consecutive panoramas. In this study, 18 panoramas were captured along the best evacuation route, with a distance being about 50 metres between two capture points (see the star, solid circle, and diamond icons in Figure 2). In addition to these 18 primary panoramas, extra panoramas along the evacuation route were captured as well. These extra ones form up wrong evacuation routes around the intersections on the best evacuation route, serving as distractions (see the hollow circle icon in Figure 2). In total, 34 panoramas were acquired on sites to develop the proposed training system further.

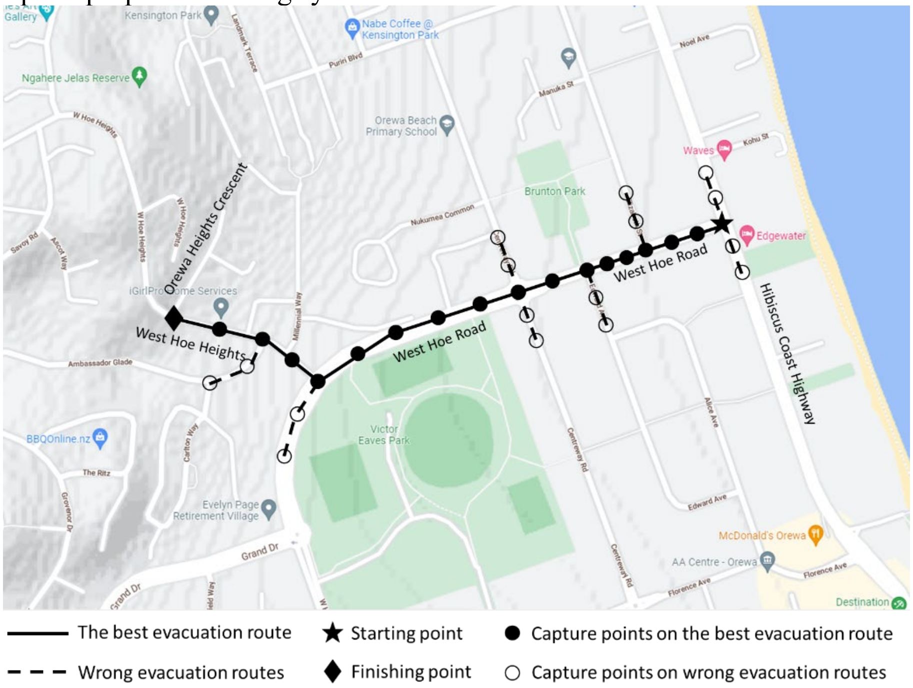

Figure 2. The testing region, evacuation route, and capture points.

3.3. *Visualisation and navigation*

After obtaining 360-degree panoramas, the visualisation stage takes place. This stage requires the use of game engines (e.g., Unity or Unreal) to visualise panoramas in IVR. A typical workflow to visualise a panorama in Unity involves the following steps: creating a sphere object, applying a panorama as a material to the shader of the sphere, and setting up a camera at the centre of the sphere.

The centre of the sphere is equivalent to the capture point of a panorama; therefore, a user is able to view a panorama through the camera in IVR from the capture point of a panorama, enabling the first-person perspective and creating the illusion to be in the space surrounded by 360-degree panoramas. The same workflow can be applied to all the panoramas, resulting in a set of sphere objects in Unity, as illustrated in Figure 3.

Following the visualisation of 360-degree panoramas, navigation can be introduced in IVR. Since a panorama is an image that does not have depths, navigation cannot be made as normal walking within a panorama in IVR. An alternative approach for navigation is to teleport a user between two consecutive panoramas. This can be achieved by changing the position of a camera from the centre of a sphere object to the centre of another sphere object. Therefore, from a user's perspective, navigation is taking place. It is worth noting that sphere objects can be placed in a way following the sequence of capture points from the beginning to the end of the route as executed in Stage 2 (see Figure 3). Meanwhile, a camera is required only for the first sphere object (i.e., the beginning of a route). For the rest of the sphere objects, the same camera can be transited to the centre of them via a script. By doing this, a user can virtually walk along the predefined route in IVR. In addition, in order to provide a better user experience in IVR, transition effects can be applied when a user is teleporting from one panorama to another, for instance, blurring, stretching, or fade-in and fade-out. A similar use of blurring and stretching is adopted in Google Street View.

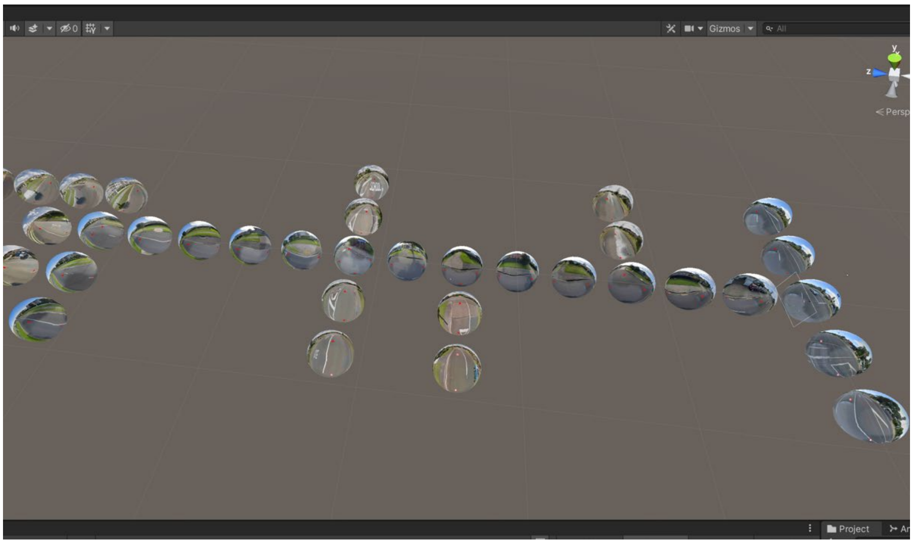

Figure 3. Sphere objects applied with 360-degree panoramas in Unity

3.4. Augmentation and interaction

Augmentation (i.e., Stage 5) can be applied to the 360-degree panoramas in IVR. The augmentation stage overlays additional digital information, data, objects, animations, annotations, visual effects, or sound effects onto panoramas. Augmentation can bring several effects. Firstly, augmentation can augment an event of a storyline in IVR. The panoramas taken on sites may not contain sufficient representation to reflect the desired event. For instance, falling and breaking objects can be overlaid to augment a panorama for an earthquake event [19]. In this study, we synthesised a soundtrack to augment the tsunami event in IVR, including urban background noise, cry, scream, sirens, helicopter noise, and tsunami alarms. Secondly, augmentation can serve instructional purposes in a training system. In this study, we used larger tsunami evacuation signs (i.e., static images) to cover the original ones captured in panoramas since the original ones are not clear and obvious in IVR. These tsunami evacuation signs indicate the directions to high ground according to the evacuation route (see Figure 4). Since the proposed IVR training system is a cluster of individual panoramas, each panorama may need its own augmentation based on the storylines planned in Stage 1.

The last stage of the development is to bring interaction into IVR. The interaction may serve different purposes. For navigation purposes, directional arrows can be introduced for each individual panorama (see Figure 5a). A user may turn their body around to change directions and click on an arrow to move forward (i.e., transit to the next panorama). For training purposes, information and feedback can be displayed as instructional methods according to the actions taken by a user. In this study, we used a real-time progress bar to display the evacuation progress of a user (see Figure 5a). This progress bar monitors the positions of a user rather than the time spent. If a user moves off the best evacuation route (e.g., turns to a wrong way at an intersection), the running man on the progress bar will not move forward. If a user always stays on the correct evacuation route, the progress bar will show the progression of a running man from the beginning to the end. Another type of interaction applied in this study is immediate feedback. When a user keeps moving along a wrong path, textual and graphical feedback is prompted, informing the user that they are off the best evacuation route and should turn back (see Figure 5b). Meanwhile, a sound effect is activated, enhancing this immediate feedback from a second channel. When a user reaches the destination of the best evacuation route (i.e., high ground), another immediate feedback is triggered to confirm the correct actions taken by a user and congratulate them on their timely evacuation efforts. This immediate feedback includes graphics, texts, and sounds.

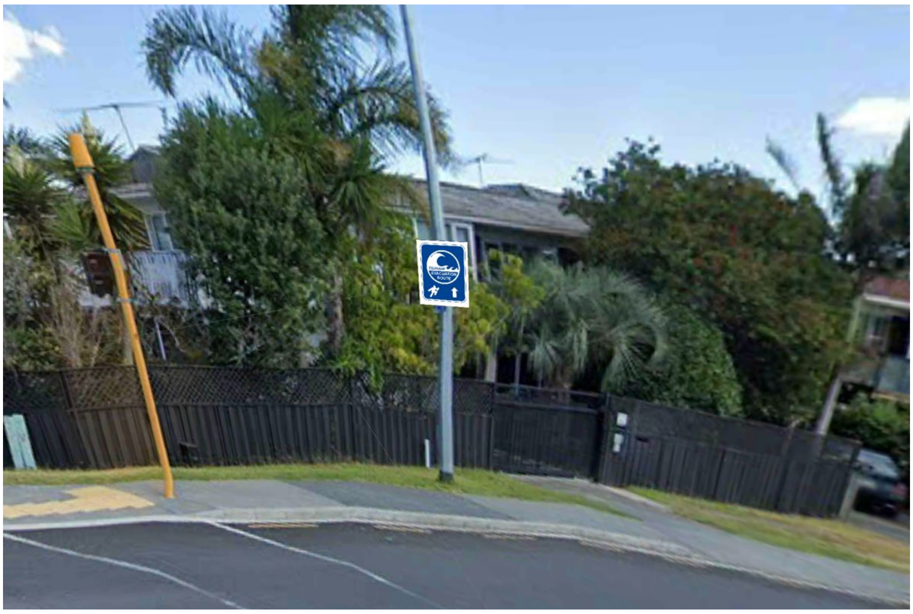

Figure 4. An evacuation sign is augmented in this panorama

(a) (b)

Figure 5. (a) Directional arrows as the navigation options available for users; a progress bar displays the evacuation progress. (b) Immediate feedback is given to users to turn around and get back to the best evacuation route.

4. Discussions and Future Works

This study proposes the use of 360-degree panoramas for IVR-based urban-scale evacuation training. A prototyping workflow is discussed, including six development stages. As a result, a prototype suited to tsunami evacuation training is developed. This training prototype is designed to teach users about identifying evacuation signs and the best evacuation route in a selected region. Users can learn by doing; in other words, users can explore and walk through the best evacuation route to familiarise themselves with it.

One of the advantages of the proposed solution is that there are no major development requirements for the IVR experience on an urban scale. In fact, many existing IVR training systems require major efforts to develop 3D models representing virtual environment where training is taking place [20]. The virtual environment might be developed from scratch or existing 3D models [21]. 360-degree panoramas are more user-friendly that require out-of-shelves cameras which are largely available in the commercial market. Moreover, 360-degree panoramic IVR can provide a high level of ecological validity [18]. It is almost impossible to cover every single detail in 3D modelling; therefore, IVR based on 3D models has fewer details than IVR based on 360-degree panoramas since panoramas are visual replicas of the real world [16]. 360-degree panoramic IVR might be more effective to teach wayfinding and spatial knowledge since users can practise in a virtual environment which is the exact same as the real world.

Another advantage of 360-degree panoramic IVR is that it requires low rendering efforts. Previous IVR applications require high-performance devices (i.e., computers or standalone IVR headsets) to render the virtual environment in IVR. The computational resources required for 360-degree panoramic IVR is much less since panoramas are just images [19]. Benefiting from this, training applications using 360-degree panoramas can be easily rolled out to a wider population with low-end devices, such as normal smartphones integrated with IVR cardboards.

4.1. Limitations

This study has several limitations. Firstly, only a small number of 360-degree panoramas was captured on sites and used for the development of the proposed IVR training system (i.e., 18 panoramas across a 925-metre route). As a result, the distance between two consecutive capture points is large (i.e., around 50 metres). This may lead to an unnatural perception about navigation in IVR when a user is moving from one panorama to another. If a normal step length (around 70-80 centimetres) is adopted for the distance between two capture points, then in our case, around 1156-1321 panoramas would be required for a 950-metre route. A large number of panoramas may lead to a tedious development process for an IVR system. Meanwhile, it is not feasible for a user to click a button to move forward thousands of times. Future research can look into the impacts of the distance between two consecutive capture points on user experience and training outcomes. Also, the different approaches to acquire, visualise, and navigate between panoramas can be investigated in future research, making it feasible to manage a huge number of panoramas.

Secondly, influenced by the first limitation, this study only considers one primary evacuation route (i.e., the best evacuation route) with one starting point, one finishing point, and a few branches as distractions. This study does not include the entire Orewa region. Consequently, the variety of scenarios in the IVR training system is limited. If the virtual environment in IVR can cover a broader area, it becomes possible to investigate the wayfinding behaviour in evacuation and the impacts of different factors and decision-making on evacuation performance. Also, a complete map can sever a range of training objectives (e.g., different starting or finishing points), enabling personalised training experience.

Thirdly, it is limited to augment 360-degree panoramas to represent a dynamic case since panoramas are static images. In other words, it is challenging to augment, animate, or modify an existing element within a panorama. For instance, if other people (e.g., pedestrians) or vehicles are captured in a panorama, they remain still in IVR when a user is viewing this particular panorama. Similarly, chaos, damage, or deconstruction caused by emergency cases can hardly be augmented since a panorama shows a normal environment that is captured under a normal circumstance. This limitation may directly impact the sense of presence, influencing the behaviours yielded in IVR and the effectiveness of training outcomes. Future research can investigate this issue.

4.2. Future research

This study has a few research objectives to achieve in the future research stage. First, an experiment is planned to test the user experience and training effectiveness of the proposed IVR training system. Second, a controlled experiment is expected to explore and compare the levels of immersion and their impacts on training effectiveness. The investigation of levels of immersion could include three types of 360-degree panoramas: a paper-based one, a non-immersive one, and an immersive one. Third, this study will be expanded to explore solutions to address the limitations discussed in Section 4.1.

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