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A gaze-based interaction method for large-scale and large-space disaster scenes within mobile virtual reality

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Abstract

A three-dimensional (3D) visualization of disaster scenes based on mobile virtual reality (VR) can improve the application scenarios and emergency service capabilities of traditional 3D visualization of disaster scenes. Because a smartphone needs to be placed into a mobile head-mounted display, conventional touch scene interaction cannot be used by mobile VR, and the user's gaze usually serves as the default scene interaction method. However, the existing gaze-based interaction methods for mobile VR scenes are passive scene interaction methods and cannot meet the basic interaction requirement for actively roaming through and exploring large-scale and large-space disaster scenes. Therefore, this study focuses on gaze-based mobile VR interactions to satisfy the various interaction requirements of large-scale and large-space disaster scenes. First, a dynamic user interface (UI) generation method for gaze interaction in large-scale and large-space disaster scenes is proposed to solve the problem of the active exploration of mobile VR disaster scenes. Second, disaster scene exploration and disaster information query methods based on a dynamic UI and gaze are proposed. Finally, using a flood disaster as an example, a prototype system and associated experiments are discussed. As indicated by the experimental results, the gaze-based mobile VR interaction methods addressed in this study can effectively support users in actively roaming through and exploring large-scale and large-space disaster scenes, disaster simulation analysis, and the interactive querying of disaster information within mobile VR, making the effective interaction of mobile VR disaster scenes possible.

1 | INTRODUCTION

Disasters often lead to many casualties and a large amount of property loss (Liu et al., 2017; Patel & Srivastava, 2013; Shultz & Galea, 2017; Skakun, Kussul, Shelestov, & Kussul, 2014; Yin, Wang, Zhang, Yan, & Wei, 2017). Virtual geographic environments (VGEs) can be described as a kind of digital geographic environment generated by computers and related technologies that users can use to experience and recognize complex geographic systems and further conduct comprehensive geographic analyses (Chen & Lin, 2018). Disaster VGEs, namely a three-dimensional (3D) visualization of disaster scenes, can directly display the current, past, and future conditions of a disaster area and provide intuitive information support and decision-making analysis functions for all kinds of personnel related to disaster emergencies (Guo et al., 2020; Li et al., 2019, 2020, 2021; Zhang et al., 2019, 2020). It is of great significance to mitigate the potential adverse effects caused by disasters. At present, much work has been conducted in this field. According to the hardware system used, these works can be divided into two main categories, namely, personal computer (PC)-based 3D visualization of disaster scenes (Catulo, Falcão, Bento, & Ildefonso, 2018; Cheng, Chen, & Cao, 2019; Li, Li, Chen, Zheng, & Liu, 2018; Lu, Yang, Xu, & Xiong, 2020; Redweik, Teves-Costa, Vilas-Boas, & Santos, 2017; Winkler, Zischg, & Rauch, 2018; Wu et al., 2019; Zhi, Liao, Tian, Wang, & Chen, 2019) and PC virtual reality (VR)-based 3D visualization of disaster scenes (Feng, González, Amor, et al., 2020; Feng, González, Trotter, et al., 2020; Fujimi & Fujimura, 2020; Jacquinod & Bonaccorsi, 2019; Lin, Cao, & Li, 2020; Mossel et al., 2021; Tibaldi et al., 2020; Wang, Hou, Miller, Brown, & Jiang, 2019). The 3D visualization of disaster scenes based on PC VR has a stronger sense of immersion and can give people a more immersive experience. However, since 3D disaster visualizations on the basis of PC and PC VR systems are performed indoors, these two kinds of work show an obvious lack of mobility, especially the 3D visualization of disaster scenes based on PC VR, so existing research on the 3D visualization of disaster scenes cannot satisfy the requirements for outdoor 3D visualization of disaster scenes. Due to the urgency and scientificity of disaster emergency responses, all types of emergency personnel in different locations (especially outdoor emergency response personnel) need to perceive and recognize disaster environments faster and better, which will require more mobile and immersive visualizations of 3D disaster scenes.

With the development of smartphones, mobile head-mounted displays (HMDs), and the mobile internet, mobile VR has gradually entered people's lives (Jeong & Kim, 2016; Powell, Powell, Brown, Cook, & Uddin, 2016). Through mobile VR, users can become immersed in a virtual environment, regardless of where they actually are (Han & Kim, 2017; Kim, Choi, Chang, & Kim, 2020). Thus, mobile VR realizes the integration of immersion and mobility. Currently, there are three main types of mobile VR: (1) ordinary smartphones plus low-priced mobile HMDs; (2) specific brands of high-performance smartphones plus specific mobile HMDs, such as Samsung's flagship smartphones plus Gear VR; and (3) more expensive all-in-one machines, which include only mobile HMDs and no smartphone, such as Oculus Quest 2 launched by Oculus in September 2020 (Reality Labs, 2020). Among the three types of mobile VR, the first type is undoubtedly the best in terms of universality, because it does not require the brand and performance of smartphones, and corresponding mobile HMDs are still very cheap. For mobile VR to play a role in disaster emergency response, mobile VR must first have good universal applicability. For this reason, the mobile VR mentioned in this study refers to the first type of mobile VR, that is, an ordinary smartphone placed into a cheap mobile HMD.

Since mobile VR is both mobile and immersive, it is of great significance to study the 3D visualization of disaster scenes based on mobile VR. Obviously, the 3D visualization of disaster scenes based on mobile VR can enhance the mobility and immersion of the traditional 3D visualization of disaster scenes and can improve the application scenarios and emergency service capabilities of the traditional 3D visualization of disaster scenes.

However, the 3D visualization of disaster scenes based on mobile VR faces many challenges (Hu, Zhu, Li, Zhang, Hu, et al., 2018), and scene interaction is one of them. Because a smartphone needs to be placed into a mobile HMD, conventional touch scene interaction cannot be used by mobile VR. At present, mobile VR mainly involves the following four scene interaction modes: (1) using gaze to achieve scene interaction, such as mobile VR video playback (Powell et al., 2016), object selection on a table (Kim, Lee, Jeon, & Kim, 2017), card selection in a game (Han & Kim, 2017), and menu selection in a scene (Huang et al., 2019); (2) toggling a magnet button to achieve scene interaction, such as the start and stop of scene roaming (Powell et al., 2016) or the reset of the user viewpoint (Kim, Lee, Kim, Song, & Lee, 2020); (3) using handheld interactive devices (such as a game handle, Bluetooth handle, or joystick) to achieve scene interaction, such as the use of a gamepad to move one user's position (Shen, Liu, Zheng, & Cao, 2019), the use of Samsung Gear VR and a Bluetooth controller to achieve scene interaction (Levin, Shults, Habibi, An, & Roland, 2020), and the use of a mini joystick for forward/backward movement along a fixed path (Powell et al., 2016); and (4) using virtual gestures to achieve scene interaction, such as the direct integration of a motion control device (e.g. Leap Motion controller) on a mobile HMD to indicate playing cards and object selection in card games (Han & Kim, 2017), or navigating a scene and interacting with scene objects with the help of a Leap Motion controller worn on the wrist (Park & Lee, 2019). Compared with other methods, gaze interaction does not require additional input devices and has become the default scene interaction method for most mobile VR applications (Kim, Lee, Jeon, & Kim, 2017). Therefore, it can be more widely used in mobile VR disaster scene interaction. In view of this, this study only discusses gaze-based mobile VR disaster scene interaction methods.

The premise of gaze interaction is that the user must be able to see clearly or see the interaction object. The existing gaze-based interaction methods for mobile VR scenes mainly enable the selection of objects and menus in a small-scale and small-space scene and the movement of a user in a virtual scene. The selection of objects or menus in small-scale and small-space scenes based on gaze involves fixing a user's point of view in a certain place; by changing the direction of their line of sight, the user can see clearly all fixed objects or menus in the small-scale and small-space scene and then gaze at them to achieve scene interaction. This scene interaction method is used by most mobile VR applications, such as mobile VR video playback (Powell et al., 2016) and card games (Han & Kim, 2017). Gaze-based user movement refers to changes in user location along a fixed path for the roaming exploration of scenes (Atienza, Blonna, Saludares, Casimiro, & Fuentes, 2016), that is, by gazing at the preset scene interaction object to change the user's position to the preset position.

Existing gaze-based mobile VR scene interaction is passive, fixing the user's point of view position or allowing changes in the user's position only along a fixed path. This approach is not conducive to the user's active exploration of a scene. However, disaster scenes are usually large-scale and large-space geographic scenes, and the active roaming exploration of such scenes is considered to be a basic scene interaction requirement. For instance, users should be able to change their location without restrictions on their ability to translate, rotate, and zoom into a scene to promptly perceive and recognize macroscopic and microscopic disaster information, such as the scope of a disaster and the damage to a house. The existing gaze-based method for changing a user's position is to change the user's position to a preset position by gazing at a preset scene interaction object. This method will have the following two problems in large-scale and large-space disaster scenes: (1) users usually cannot see the preset scene interaction objects and are unable to interact (even if users can be fixed close to the scene interaction objects, it is still difficult to see the scene interaction objects in large-scale and large-space disaster scenes as the user's line of sight direction can change at will); and (2) even if a user can occasionally see the preset scene interaction object, if the gaze interaction takes the user to the preset position, it does not meet the requirement that the user needs to change his position unrestricted in the disaster scene, and if the user's position changes freely according to his/her interaction (such as zooming out the scene), the user usually cannot see the preset scene interaction objects, which makes it impossible to further interact with the scene. Undoubtedly, the existing gaze-based interaction methods for mobile VR scenes cannot meet the basic interaction requirement for actively roaming through and exploring large-scale and large-space disaster scenes in mobile VR.

In addition to basic scene roaming exploration, mobile VR disaster scenes require other interaction capabilities, such as the ability to support interactive disaster information querying and disaster simulation control. Because of these scene interaction requirements, this study examined gaze-based mobile VR scene interaction methods for large-scale and large-space disaster scenes. The remainder of this article is organized as follows. Section 2 describes the gaze-based mobile VR interaction methods for large-scale and large-space disaster scenes. In Section 3, a prototype system is introduced, and gaze-based mobile VR disaster scene interactions supported by this prototype system are demonstrated. The conclusions of this study are given in Section 4, together with discussions on its contributions and future work plans.

2 | METHODOLOGY

2.1 | Overall framework

The overall framework of this article, as shown in Figure 1, consists of two parts. First, a dynamic user interface (UI) generation method is proposed to generate dynamic UIs perpendicular to a user's line of sight so that the user can clearly see the interaction objects in large-scale and large-space disaster scenes. On the premise that a user can clearly see these interaction objects, the user gazes at an interaction object. Then, the interaction object being gazed at is determined, and the corresponding interaction object function is triggered to achieve scene interaction. Second, diverse representation and adaptive scheduling of disaster scene data are carried out to build mobile VR disaster scenes. For detailed construction and optimization methods of mobile VR disaster scenes, refer to Hu, Zhu, Li, Zhang, Zhu, et al. (2018). Then, based on a dynamic UI and gaze, the interaction of large-scale and large-space disaster scenes, such as active scene roaming exploration, disaster routing simulation control, and interactive disaster information queries, can be realized.

2.2 | Dynamic UI generation method for disaster scene interaction

In a VR scene, the traditional keyboard/mouse human–computer interaction mode based on a two-dimensional interface is no longer applicable, and users look forward to simple and natural interaction modes. Gaze interaction considers the characteristics of a human eye's field of view and head swing. This interaction refers to emitting a ray from the center of a user's line of sight vertically forward (Han & Kim, 2017). The ray direction represents the gaze direction, and the front end of the ray uses a point (i.e. the gaze point) as a mark. When the ray or gaze direction intersects an object in a virtual 3D scene, an event associated with the object is triggered to achieve scene interaction.

As mentioned in the Introduction, existing gaze-based interaction methods for mobile VR scenes cannot meet the basic interaction requirement for actively roaming through and exploring large-scale and large-space disaster scenes in mobile VR. To effectively solve the problems faced by gaze interaction in large-scale and large-space disaster scenes, this study proposes a dynamic UI generation method for mobile VR disaster scenes. In a certain plane perpendicular to a user's line of sight at a relatively short distance from the user, this method dynamically creates various scene interaction UIs to ensure that the user can clearly see these UIs and gaze. The principle of the method includes the following three parts: (1) specifying the UI position in the camera coordinate system (i.e.

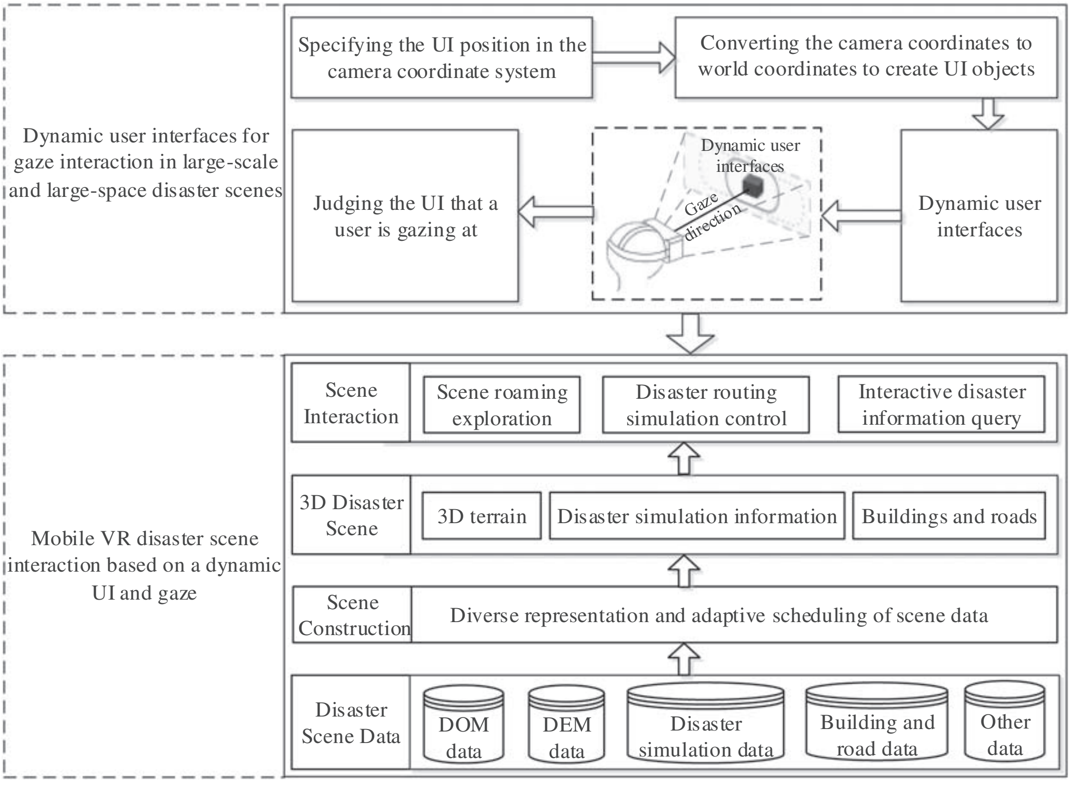

FIGURE 1 Overall framework

the eye coordinate system); (2) converting the camera coordinates to world coordinates to create UI objects; and (3) judging the UI that a user is gazing at. These parts are introduced separately below.

2.2.1 | Specifying the UI position in the camera coordinate system

In a plane (denoted *P*) perpendicular to the negative *z* axis (this axis represents a user's line of sight direction) in the camera coordinate system, the 3D camera coordinates of each node of a UI object and the 3D camera coordinates of the central point of a UI object are specified, as shown in Figure 2.

The 3D camera coordinates of each node of a UI object are marked $V_{A\text{-}1\text{-}C}$, $V_{A\text{-}2\text{-}C}$, and $V_{A\text{-}3\text{-}C}$, where *V* denotes the node; *A* represents the UI object; 1, 2, and 3 represent the first, second, and third nodes of the UI object, respectively; and *C* represents the camera coordinates. The 3D camera coordinates of the central point of a UI object are marked A_C and B_C, where *A* and *B* represent UI objects and *C* represents the camera coordinates. The plane *P* is expressed as:

$$A(x - x_0) + B(y - y_0) + C(z - z_0) = 0 \quad (1)$$

Here, (*A*,*B*,*C*) represents the normal vector of plane *P*, where a user's line of sight or the negative *z* axis of the camera coordinate system is used to represent the normal vector of plane *P*; and (x_0, y_0, z_0) represents a known point on plane *P*, where the intersection point of plane *P* and a user's line of sight is used to represent the known point on plane *P*.

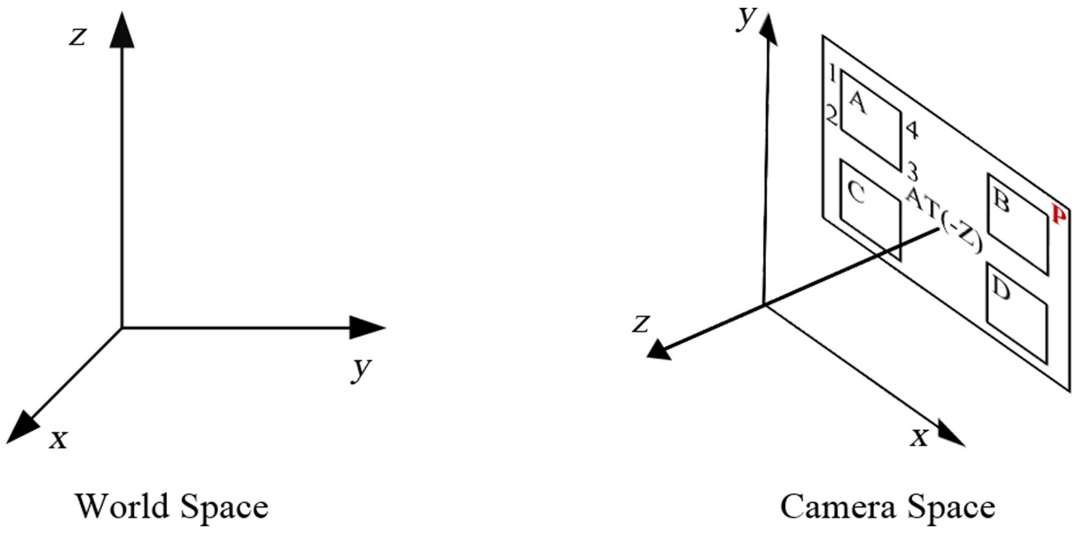

FIGURE 2 Schematic diagram of the specified UI position in the camera coordinate system

2.2.2 | Converting the camera coordinates to world coordinates to create UI objects

The 3D camera coordinates (e.g. $V_{A\text{-}1\text{-}C}$, $V_{A\text{-}2\text{-}C}$, $V_{A\text{-}3\text{-}C}$) of each node of each UI object are transformed using the camera inverse view transformation to obtain the 3D coordinates of these nodes in the world coordinate system (expressed as $V_{A\text{-}1\text{-}W}$, $V_{A\text{-}2\text{-}W}$, $V_{A\text{-}3\text{-}W}$, ..., where V represents the node; A represents the UI object; 1, 2, and 3 represent the first, second, and third nodes of the UI object, respectively; and W represents the world coordinates). This transformation is described by:

$$\begin{Bmatrix} x \\ y \\ z \\ 1 \end{Bmatrix}_W = \text{CameraInverseViewMatrix}_{4\times4} \begin{Bmatrix} x \\ y \\ z \\ 1 \end{Bmatrix}_C \quad (2)$$

In the above formula, C represents the camera coordinates, W represents the world coordinates, and CameraInverseViewMatrix is a 4 × 4 matrix representing the camera inverse view transformation. CameraInverseViewMatrix is the inverse matrix of the camera view matrix CameraViewMatrix:

$$\text{CameraViewMatrix} = \begin{vmatrix} R_x & R_y & R_z & 0 \\ U_x & U_y & U_z & 0 \\ D_x & D_y & D_z & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} * \begin{vmatrix} 1 & 0 & 0 & -M_x \\ 0 & 1 & 0 & -M_y \\ 0 & 0 & 1 & -M_z \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (3)$$

In the above formula, D is the positive z-axis direction in the camera coordinate system, which is just the opposite of a user's line of sight; U is the direction of the positive y axis in the camera coordinate system, that is, the upward direction of the camera; R is the positive x-axis direction in the camera coordinate system, which can be calculated by the cross product of D and U; and M represents the position of the camera in the world coordinate system.

The 3D world coordinates (e.g. $V_{A\text{-}1\text{-}W}$, $V_{A\text{-}2\text{-}W}$, and $V_{A\text{-}3\text{-}W}$) obtained by coordinate transformation are used to create UI objects in disaster scenes. Likewise, the 3D camera coordinates of the central point of each UI object (e.g. A_C, B_C) are transformed using the camera inverse view transformation to obtain the 3D coordinates of these central points in the world coordinate system (expressed as A_W, B_W, ..., where A and B represent UI objects and W represents the world coordinates).

2.2.3 | Judging the UI that a user is gazing at

The intersection point between the user's new line of sight direction and plane P represented by Equation (1) is calculated when the user is in the gaze state. Additionally, the 3D world coordinates of this intersection point and the 3D world coordinates of the central points of each UI object (e.g. A_W and B_W) are used to determine the UI object at which the user is gazing. Thus, the corresponding UI object function is triggered to achieve disaster scene interaction, as shown in Figure 3.

Using this dynamic UI generation method can maximize convenience for users to gaze, thereby effectively realizing disaster scene interaction. To illustrate the gaze-based interaction process of large-scale and large-space disaster scenes within mobile VR, this study also designed a multilevel virtual UI for mobile VR disaster scenes, as shown in Figure 4. Each level of UI in Figure 4 can be generated using the dynamic UI generation method introduced above.

First, when a user's head exhibits some action, such as lowering the head to a certain angle, the startup UI will appear around the user's line of sight. Then, the user can gaze at the startup UI to dynamically create a second-level UI in a plane perpendicular to the user's line of sight. This interface includes a scene roaming UI, a scene query UI, a scene simulation analysis UI, and a closing UI. When the user gazes at these UIs, the scene will react accordingly. For example, when the user gazes at the zoom UI, the scene will perform a zoom operation. When the user gazes at the scene simulation analysis UI, the third-level UI will appear. After the third-level UI appears, the user can gaze at the corresponding UI to perform the scene simulation analysis function. For example, when

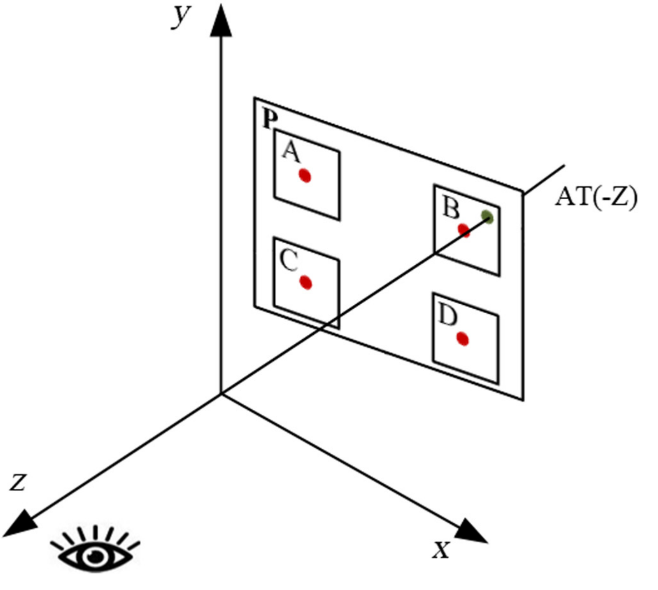

FIGURE 3 Schematic diagram of gaze and judging the UI being gazed at

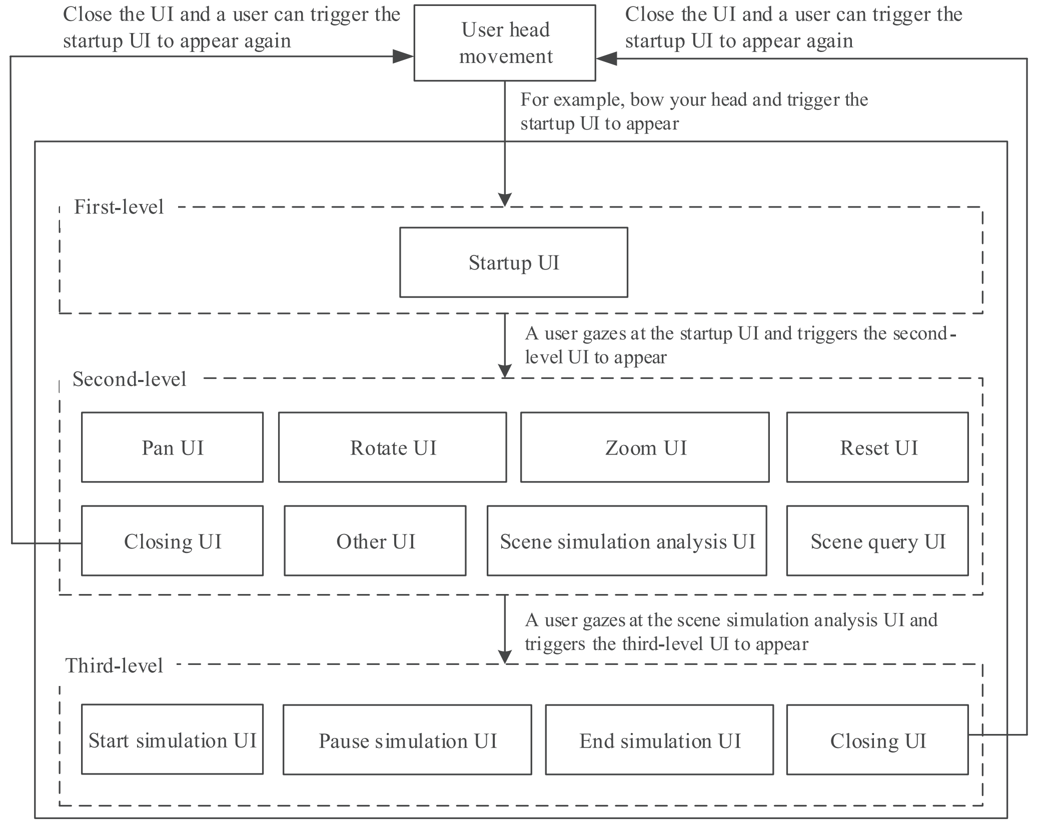

FIGURE 4 A multilevel virtual user interface for mobile VR disaster scenes

the user gazes at the startup UI, simulation information will appear in the scene. Finally, the user can gaze at the closing UI in the second- and third-level UIs to close the UI. After the UI is closed, the user can repeat the above process and interact with the scene again.

2.3 | Gaze-based interaction with disaster scenes within mobile virtual reality

Unlike simple interaction modes such as the selection of objects and menus in a small-scale and small-space scene and the movement of a user in a virtual scene (Atienza et al., 2016; Powell et al., 2016; Han & Kim, 2017; Kim et al., 2017), interaction with mobile VR disaster scenes also requires active roaming exploration and query analysis. The following subsections briefly introduce the gaze-based scene roaming exploration method and disaster information query method.

2.3.1 | Gaze-based disaster scene exploration method

The gaze-based interactive exploration of disaster scenes requires a user to bow their heads (down to a certain angle, such as 20°) to trigger the generation of dynamic UI objects, then the user can interact with the VR disaster scenes by gazing at these dynamic UI objects. Common mobile VR scene interaction exploration includes active

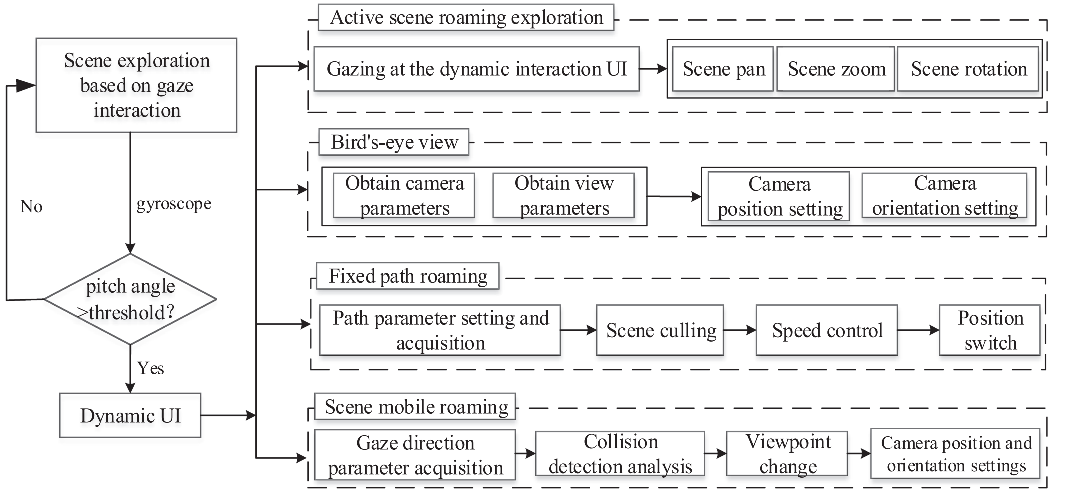

FIGURE 5 Gaze-based disaster scene exploration method

scene roaming exploration, bird's-eye view, fixed path roaming, scene mobile roaming, etc. The gaze-based disaster scene exploration method is shown in Figure 5.

Active scene roaming exploration refers to gaze at the dynamic interactive UI to implement operations such as translation, rotation, and zooming of disaster scenes. Bird's-eye view refers to browsing the disaster scenes from a fixed position and perspective at high altitude to quickly perceive the global information of the disaster scenes. Fixed path roaming refers to the user's interactive roaming in the scene according to a preset path and camera posture. Scene mobile roaming refers to the realization of scene mobile roaming exploration at low altitude with the gaze direction as the forward direction.

2.3.2 | Gaze-based disaster information query method

Disaster information is the truest reflection of a disaster situation. Roaming exploration of disaster scenes cannot be used to deeply understand the disaster situation, but an interactive query of disaster information can help users understand disaster situations in depth and enhance users' comprehensive and in-depth understanding of disaster scenes. For mobile VR disaster scenes, users can query disaster information, such as information on the disaster itself, damage to buildings, and disaster assessment results, through gaze-based interaction methods. The gaze-based disaster information query method is shown in Figure 6.

First, the system should determine whether the user is gazing and whether the user's line of sight intersects with the disaster scene if the user is gazing. Then, the point of intersection should act as the center to find scene objects, such as buildings, roads, or some schematic symbols, within a certain range of the point of intersection if the user's line of sight intersects the scene. If there are scene objects within a certain range of the point of intersection, then the attribute information of the scene objects is displayed, including the information reflecting the disaster itself (such as the disaster scope, disaster level, and occurrence time), building damage information (such as the building damage degree and damaged area), statistical information (such as casualties and economic property losses), disaster assessment and analysis information (such as disaster causes and disaster impact), and emergency plans. This attribute information can be stored and managed through a database, such as the SQL Server database.

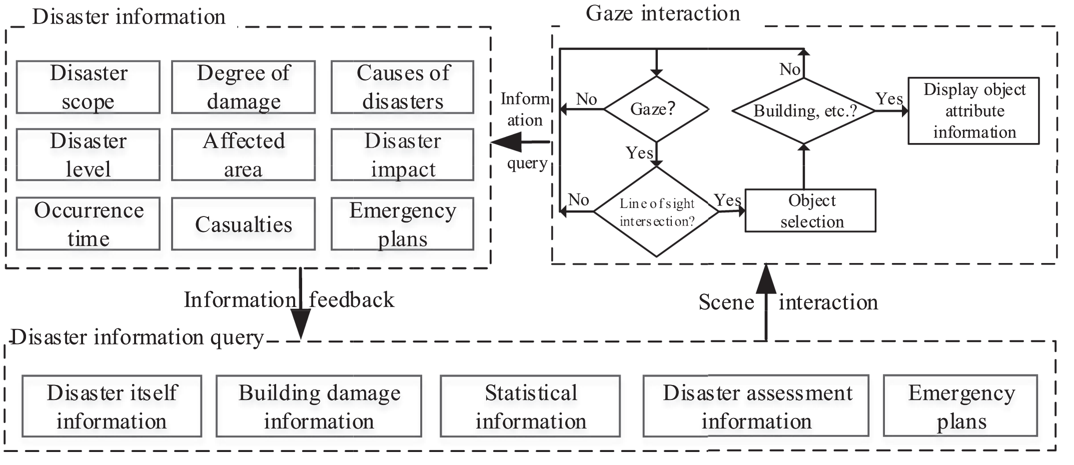

FIGURE 6 Gaze-based disaster information query method

3 | IMPLEMENTATION OF THE PROTOTYPE SYSTEM AND SCENE INTERACTION ANALYSIS

Floods are the most common natural disasters (Hu, Zhu, Li, Zhang, Zhu, et al., 2018; Wallemacq, 2018). Therefore, this study uses a flood disaster as an example to illustrate the gaze-based interaction method for large-scale and large-space disaster scenes within mobile VR.

3.1 | Implementation of the prototype system

Considering the weak storage and processing ability of smartphones, the prototype system was constructed with a browser/server (B/S) architecture to exploit high-performance servers to store and process a large amount of data involved in disaster scene construction and avoid the need for users to download and frequently update specific application (APP) programs under the client/server (C/S) architecture (Hu, Zhu, Li, Zhang, Zhu, et al., 2018). The network server of the prototype system was built by Node.js v8.12.0, storing the data involved in the construction of disaster scenes. In addition, the server uses the SQL Server database to store the attribute information involved in a disaster information query. Cesium, HTML5, and JavaScript were used to implement the browser side of the prototype system. Cesium was utilized because it is a popular open-source library for 3D virtual globes and adequately supports stereoscopic rendering and dynamic visualization of cross devices and cross platforms without plugins (Cesium, 2021). The experiments were conducted in a flood dam failure area (Zhu et al., 2015). The experimental area is approximately 244.72 km^2 (18.4 × 13.3 km). The experimental data include terrain data, house data, flood routing simulation data and attribute data. Their expression form and data volume are shown in the literature (Hu, Zhu, Li, Zhang, Zhu, et al., 2018). Browsers supporting WebGL and HTML5 (e.g., Chrome and Firefox) could be used to run the prototype system. The visual effect that was realized by the prototype system on the Chrome browser of a smartphone is presented in Figure 7.

3.2 | Scene interaction

In this study, the method described above is used to realize the interaction of mobile VR flood disaster scenes based on gaze, including scene roaming exploration, flood routing simulation control, and the interactive query of flood disaster information, which are introduced separately below.

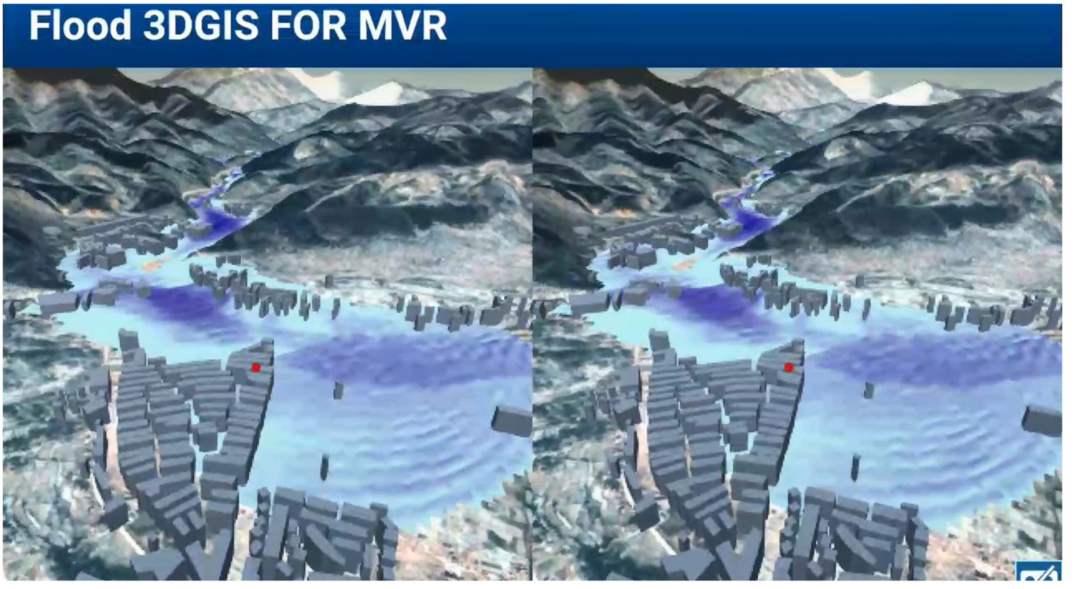

FIGURE 7 Screenshot of the prototype system on a smartphone

3.2.1 | Scene roaming exploration

The Open button appears when a user wears a mobile HMD and tilts his/her head down more than 20°; the corresponding stereo rendering is shown in Figure 8. The red dot above the Open button in Figure 8 is the gaze point. When the user gazes at the Open button (the gaze effect is shown in Figure 9a), the scene roaming exploration menu will appear, as shown in Figure 9b.

The scene roaming exploration menu contains some functions for exploring a 3D flood scene (e.g., panning, rotation, zooming, and jumping to the preset scene view of the prototype system). The menu consists of 14 menu items, which appear along two rows. The functions of the first row (from left to right) are zooming in, zooming out, panning left, panning right, panning up, panning down, and returning to the preset scene view of the prototype system. The functions of the second row (from left to right) are rotating to the left, rotating to the right, rotating upwards, rotating downwards, querying interactive flood information, opening the flood routing simulation menu, and closing the scene roaming exploration menu. A user should only have to gaze at a menu item to activate the corresponding function. For instance, the camera will return to the system's preset position and orientation when a user gazes at the "Reset" menu item; the preset scene view is shown in Figure 9c. The effect of zooming out of a scene after a user has continuously gazed at the zoom-out menu item from the preset scene view is shown in Figure 9d.

3.2.2 | Flood routing simulation control

The flood routing simulation control menu will appear when a user gazes at the "Simulation" menu item on the scene roaming exploration menu, as shown in Figure 10a. The menu comprises six menu items. The functions (from left to right) are starting flood routing, pausing flood routing, continuing flood routing, ending flood routing, roaming along the flood routing route, and turning off the flood routing simulation control menu. The effect of flood routing is shown in Figure 10b.

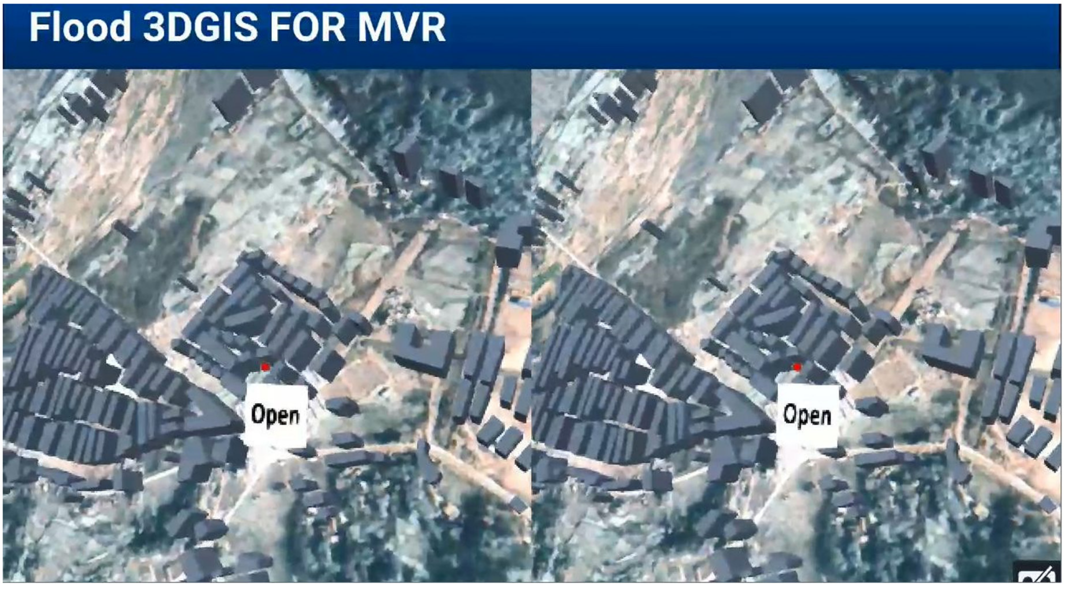

FIGURE 8 The Open button appears when a user tilts his/her head down at a certain angle

3.2.3 | Interactive query of flood disaster information

The scene roaming exploration menu will disappear when a user gazes at the "FloodInfo" menu item on the scene roaming exploration menu. Subsequently, the user can gaze at a house in a 3D flood scene (the gaze effect is shown in Figure 11a), and the system will show the flood information around the house. As shown in Figure 11b, the house gazed at by a user turns blue, and the system indicates that the house is flooded for over 30 hr.

3.3 | User experience analysis

We recruited 60 participants to experience the prototype system, including 30 males and 30 females, aged between 20 and 30 years old, including undergraduate, postgraduate, and doctoral students. All of them have a GIS technological background but no experience with the existing mobile VR applications. Participants used their own smartphones and the Baofeng Mojing CC HMD (Beijing, China), a cheap mobile HMD, to experience the prototype system. The experience was performed in a wireless Wi-Fi network environment with a bandwidth of 20 Mbps, and the prototype system was run using the Chrome browser on iOS and Android smartphones.

To avoid any influence of the experience sequence on the results, the 60 participants were randomly divided into Groups A and B (30 participants in each group). Group A first experienced the mobile VR flood disaster scene with the existing gaze interaction methods (that is, a user looks at scene interaction objects to achieve scene interaction at a fixed position or changes the user's position to the preset position by gazing at the preset scene objects) and then experienced the mobile VR flood disaster scene with the interaction method proposed in this article, while group B experienced the mobile VR flood scenes in the reverse order. When using the existing gaze interaction method, we added some fixed-position scene interaction objects or menus at prominent positions (such as the top of a mountain) of the scene, such as the start flood routing symbol and moving position symbol, as shown in Figure 12. When participants experience the mobile VR flood disaster scene with the interaction method proposed in this article, the following tasks need to be completed:

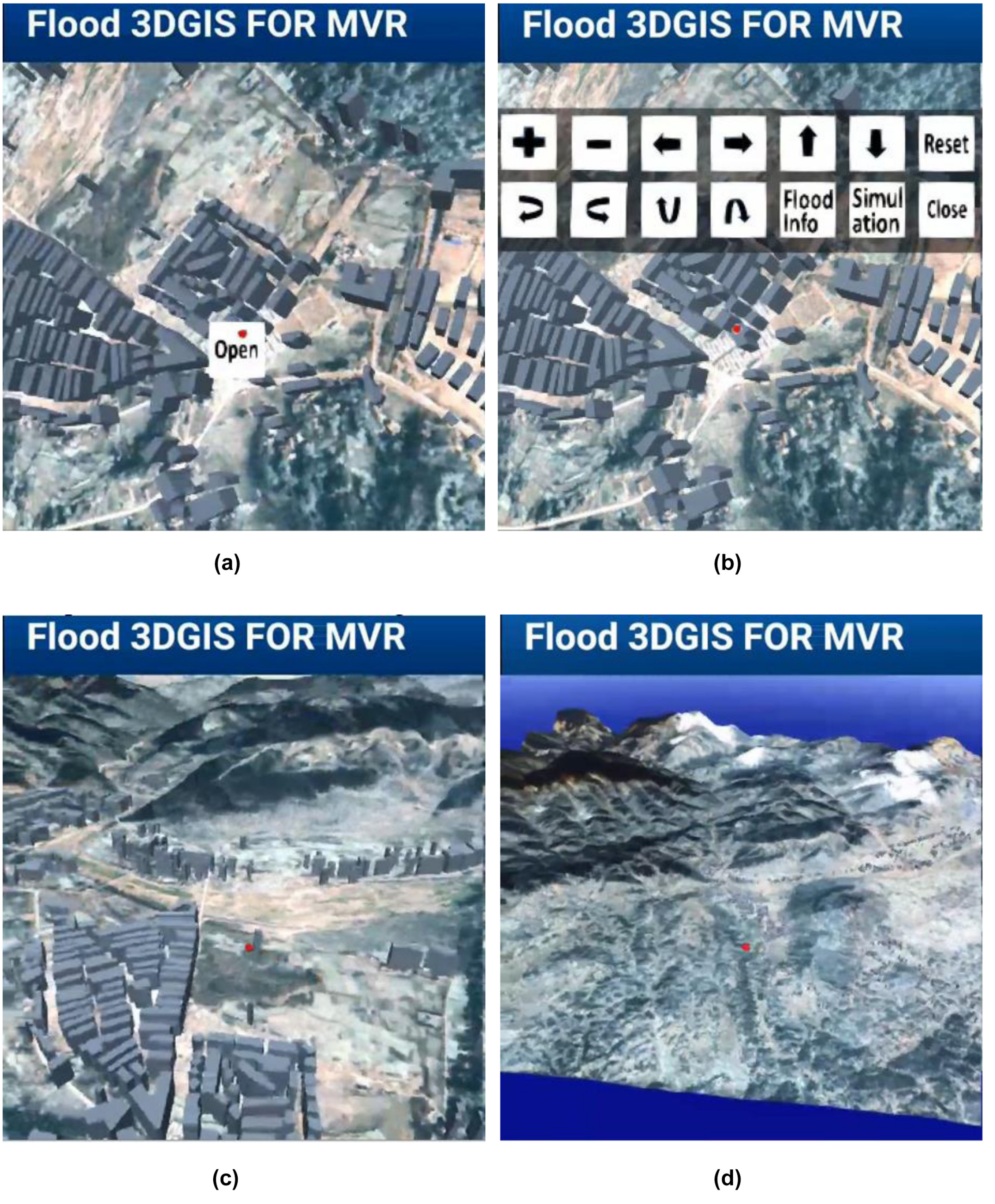

FIGURE 9 Some monocular rendering screenshots about the scene roaming exploration: (a) gazing at the Open button; (b) scene roaming exploration menu; (c) preset scene view of the prototype system; and (d) effect of zooming out of a scene after a user has continuously gazed at the zoom-out menu item from the preset scene view

1. Perform flood disaster scene roaming.
2. Conduct flood routing simulation control.
3. Perform flood disaster information query.

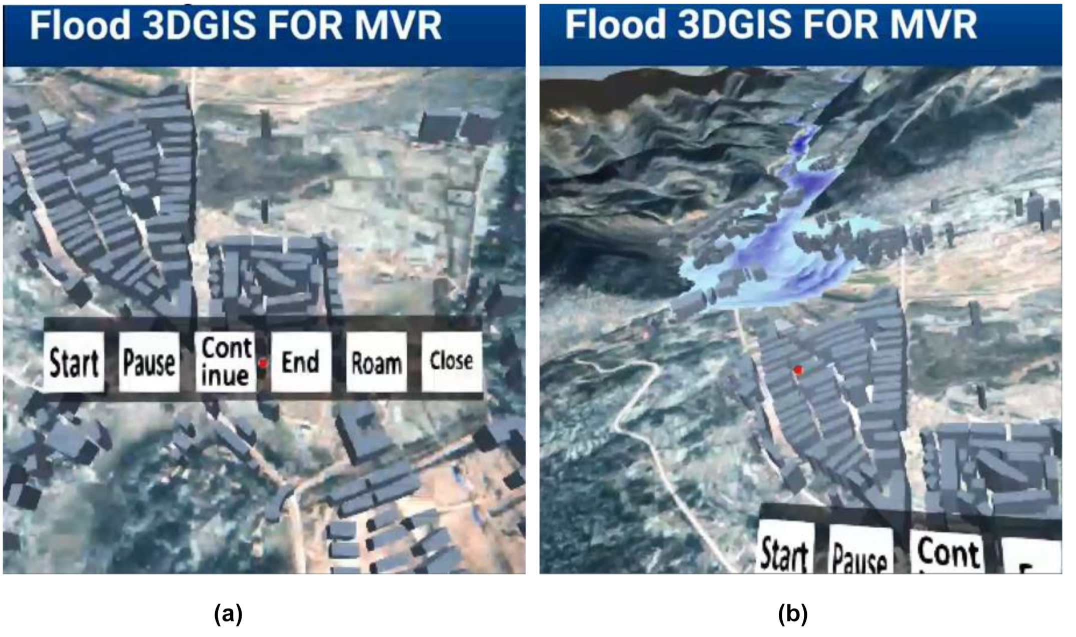

FIGURE 10 Some monocular rendering screenshots about the flood routing simulation control: (a) flood routing simulation control menu; and (b) effect of flood routing

After a brief explanation of the prototype system, participants experienced the prototype system to complete the above tasks. After each participant experienced the prototype system, they completed a questionnaire, which included the following items.

- **Q1** When experiencing a large-scale and large-space mobile VR disaster scene with the existing gaze interaction methods (that is, a user looks at scene interaction objects to achieve scene interaction at a fixed position or changes the user's position to the preset position by gazing at the preset scene objects)—so without the interaction method proposed in this article—a HMD user will face the following two situations: (1) he or she usually cannot see the preset scene interaction objects, can only aimlessly change the direction of the line of sight at a fixed point of view, and cannot perform effective scene interaction; and (2) he or she seldom sees the preset scene interaction objects (such as the moving position symbol), and after gazing and interacting with the moving position symbol, even if the user's position is changed to the preset position, the user usually cannot see the surrounding preset scene interaction objects in a large-scale and large-space disaster scene (equivalent to the first case), resulting in the failure of effective scene interaction.
- **Q2** When experiencing a large-scale and large-space mobile VR disaster scene with the interaction method proposed in this article, a HMD user can perform efficient scene roaming.
- **Q3** When experiencing a large-scale and large-space mobile VR disaster scene with the interaction method proposed in this article, a HMD user can carry out flood evolution simulation control.
- **Q4** When experiencing a large-scale and large-space mobile VR disaster scene with the interaction method proposed in this article, a HMD user can conveniently query flood disaster information.
- **Q5** Based on the interaction method proposed in this article, it is easy to use the prototype system.
- **Q6** Based on the interaction method proposed in this article, the prototype system is of good practical use in disaster emergency situations.
- **Q7** When experiencing a large-scale and large-space mobile VR disaster scene with the interaction method proposed in this article, I don't feel motion sickness.

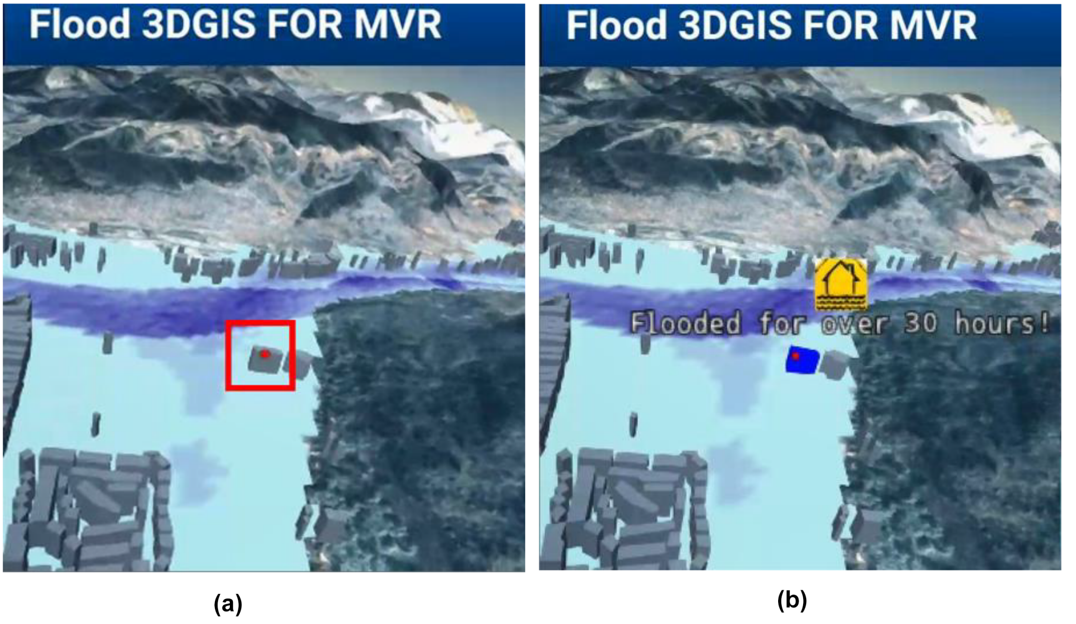

FIGURE 11 Some monocular rendering screenshots about the interactive query of flood disaster information: (a) effect of a user gazing at a house (as shown in the red frame); and (b) flood information pertaining to the blue house

These were answered using a seven-point Likert scale (Noguera, Barranco, Segura, & Martínez, 2012), where 7 means "strongly agree," 4 means a neutral opinion, and 1 means "strongly disagree." At the end of the experiment, a total of 60 questionnaires were collected. There were 30 valid questionnaires in Group A and 29 valid questionnaires in Group B, totaling 59 valid questionnaires. A statistical analysis of the questionnaire results is shown in Table 1.

The answer to the first question shows that the participants unanimously agreed that in a large-scale and large-space disaster scene, using the existing gaze interaction method, a user cannot interact effectively with the scene (Q1, mean = 7.00, minimum value = 7). This also illustrates the necessity of conducting research on the interaction method proposed in this article. When participants experience the mobile VR flood disaster scene using the interaction method proposed in this article, they believe that the prototype system can perform efficient scene roaming (Q2, mean = 6.53, minimum value = 6), can perform flood evolution simulation control (Q3, mean = 6.66, minimum value = 6), and can facilitate flood disaster information querying (Q4, mean = 6.37, minimum value = 5). In the process of scene interaction, participants felt that it was easy to clearly see the interaction objects and gaze in a large-scale and large-space disaster scene. Therefore, they believe that the prototype system is easy to use (Q5, mean = 6.03, minimum value = 5). Participants also feel that when using the prototype system, there is no need to resort to additional equipment (such as interaction devices), and they only need to use their own smartphones and cheap mobile headsets to experience immersive disaster scenes. Therefore, they believe that the prototype system is of good practical use in disaster emergency situations (Q6, mean = 6.20, minimum value = 5). Since the frame rate of the disaster scene can be guaranteed to exceed 50 frames [a construction and optimization method of mobile VR disaster scenes from Hu, Zhu, Li, Zhang, Zhu, et al. (2018) is adopted], the participants do not feel obvious motion sickness (Q7, mean = 5.78, minimum value = 5).

From the above user experience, the gaze-based mobile VR disaster scene interaction method proposed in this article is feasible. In the prototype system, the active roaming exploration of large-scale and large-space flood

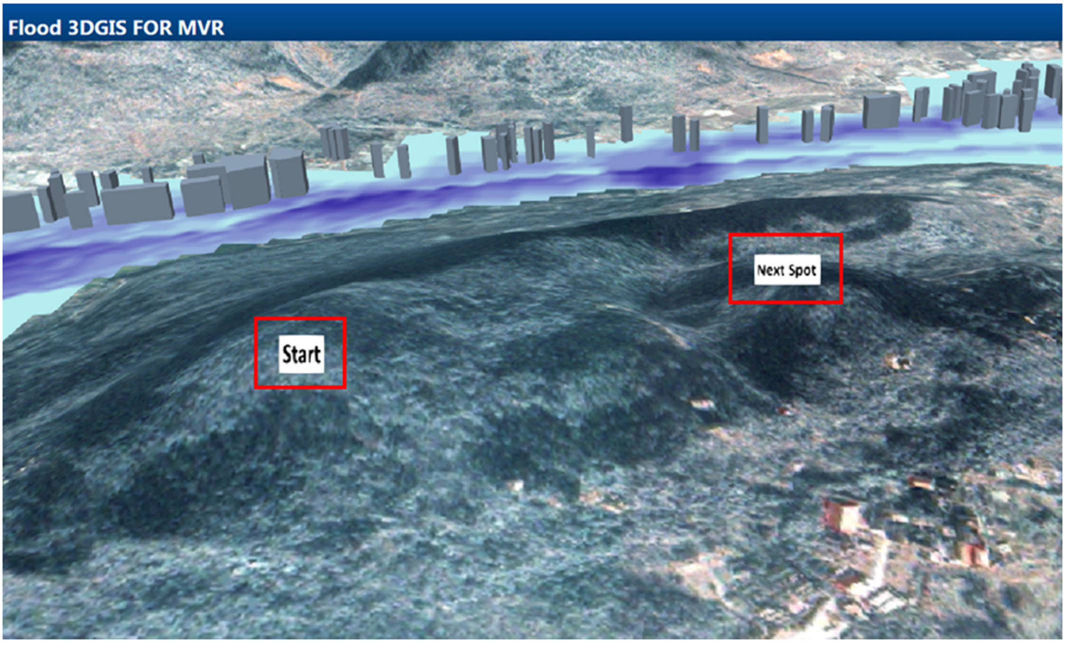

FIGURE 12 Some scene interaction objects with fixed positions (as shown in the red frame, note the start flood routing symbol on the left and the moving position symbol on the right)

TABLE 1 Statistical analysis of questionnaire results

Question	Mean	Standard deviation	Minimum value	Lower quartile	Median	Upper quartile	Maximum value
Q1	7.00	0.00	7	7	7	7	7
Q2	6.53	0.50	6	6	7	7	7
Q3	6.66	0.47	6	6	7	7	7
Q4	6.37	0.75	5	6	7	7	7
Q5	6.03	0.80	5	5	6	7	7
Q6	6.20	0.84	5	5	6	7	7
Q7	5.78	0.78	5	5	6	6	7

disaster scenes, flood evolution simulation control, and flood disaster information interactive queries are effectively realized, making the effective interaction of mobile VR disaster scenes possible.

4 | CONCLUSIONS AND FUTURE WORK

We introduced a gaze-based mobile VR interaction method for large-scale and large-space disaster scenes. For large-scale and large-space disaster scenes, a dynamic UI generation method for gaze interaction was proposed, and a gaze-based interaction mechanism for a mobile VR disaster scene was established. A prototype system was developed to realize the gaze-based active roaming exploration of large-scale and large-space disaster scenes, flood evolution simulation control, and flood disaster information interactive query, which proved the effectiveness of the method proposed in this study. The main contributions of this study are described as follows.

First, a dynamic UI generation method for gaze interaction in large-scale and large-space disaster scenes was proposed to solve the problem of the active exploration of mobile VR disaster scenes. Various scene interaction UI objects are dynamically created in a certain plane perpendicular to the user's line of sight at a relatively short distance from the user to ensure that the user can clearly see these UI objects and gaze at them to realize the effective interaction of large-scale and large-space disaster scenes in mobile VR mode.

Second, a gaze-based interaction mechanism for a mobile VR disaster scene was established. Gaze-based mobile VR disaster scene interactions were described, and the disaster scene exploration method and disaster information query method based on dynamic UI and gaze were proposed.

Finally, based on the Cesium open-source framework, a mobile VR prototype system for flood disaster immersive exploration and interaction was developed. The prototype system can run on common smartphones. With the help of a smartphone and a cheap mobile HMD, a user can realize the immersive exploration of and interaction with a flood scene.

Despite the achievements described above, this article has some shortcomings. For example, only gaze interaction is adopted, which requires time to wait for the end of the countdown or for users to confirm that the intersecting scene interaction object is the desired interaction object and users cannot immediately perform interactions after gazing. Future work will explore the interaction method that combines gaze and voice for large-scale and large-space disaster scenes. Voice interaction is a very natural way of interaction. We can study the scene interaction method by combining voice and gaze. For example, after users gaze, the voice command system can be used to indicate the immediate execution of the scene interaction to avoid unnecessary user waiting.

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