CXR: Communal eXtended Reality for Immersive, Situated, On-Road Experiences

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Fig. 1. Participants trying the geo-located multi-user CXR on a moving bus

To engage communities in planning processes, we have developed a Communal eXtended-Reality (CXR) bus tour that depicts the possible impacts of climate change. This paper describes the geo-synchronized multi-user extended reality system we developed to provide a situated and shared experience to promote community engagement. We describe (a) our technical implementation of the CXR system, which geo-locates and orients the view each participant has of the virtual tour within the frame of the moving vehicle, (b) advances in the modeling of the digital twin environment of the tour critical to association with the real-life location, and (c) our fall-back system, which allows people who feel disoriented or motion-sick to continue along with the content of the tour. In addition to describing our system and protocol, we detail technical challenges we encountered and resolved in our preliminary deployment tests.

CCS Concepts: • **Human-centered computing → User studies**; • **Human-centered computing Mixed / eXtended reality**;

Additional Key Words and Phrases: Human-Computer Interaction(HCI), communal eXtended reality, system development, multi-user XR reality, community engagement, VR in car, geo-located VR, digital twin, Unity, design, social awareness, climate change, environmental awareness

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1 INTRODUCTION

Extended reality (XR) has become a powerful tool to engage broader audiences to see and use information that matters the most to them in an intuitive and embodied way [34]. XR encompasses any technology that alters reality by adding virtual elements to the physical world, including a spectrum of immersive technologies such as Virtual Reality (VR), Mixed Reality (MR), Augmented Reality (AR), and combinations and variations of those [35]. One exciting opportunity we made possible using this technology is the ability to let a large group of people have a common immersive experience. This can be helpful for motivating and grounding community discussions about future issues or community development. We named our effort for shared extended reality experiences as **Communal eXtended Reality** (CXR).

We have developed a CXR system that offers a group of people an immersive environment composed of shared VR experience situated on-road and geo-located, to enable community engagement around the issue of climate change and flooding in an island community. In this paper, we describe our technical development and implementation of the CXR system, as a first step toward developing an effective community engagement tool. A preliminary deployment test of the XR on road prototype yielded promising results, illustrating proof of concept and indicating that this tool's implementation can elicit genuine communal responses from users.

Shared XR experiences for community engagement have been explored by researchers in Santa Cruz, Stanford, and Israel, among other places [1, 5, 29, 39, 44]. These engagements have shown that it is possible to attract audiences to discuss complex issues [5, 10] and to motivate discussions with strong emotional triggers [3, 5]. In parallel, XR has increasingly found application in moving vehicles. For example, XR has been used for on-road simulation of driving or autonomous vehicle riding experiences for passengers [11, 12, 15, 22, 30, 31, 38, 42, 49]. While XR simulations are becoming more accessible for community engagement, most are implemented in lab-like environments, with individual participants for experiments or interviews [5, 32]. Similarly, while XR in the Car is becoming more popular, to the best of our knowledge, it has not been used for a group of people at the same time or for purposes of community engagement.

Our system adds two understudied dimensions to the immersiveness of such experiences: first, by creating communal multi-user experiences; second, by developing geo-located on-road virtual scenarios. Moreover, it contributes a key case for using shared immersive experiences for community engagement.

Our CXR system was developed to be experienced while people were riding a local shuttle bus, traversing the physical space for the purpose of community engagement. We chose Roosevelt Island as the deployment site for our system, considering its Utopian urban planning built around the vision of waterfront development for people of different income levels and age groups [17, 47, 48]. For the CXR system development, we utilized a Digital Twin (DT) environment of Roosevelt Island, which was developed in previous research. We made advances in the modeling that were critical to associating the visualized depictions to the real-life location.

Following this introduction, we review related works regarding shared XR experiences, the state-of-the-art in on-road XR technology, and the use of digital twins in urban planning and community development. We then elaborate on the CXR system requirements and our development and validation processes, describing the XR environment, advances in modeling the DT, and the fall-back system to mitigate the challenges we encountered in test rides. We also describe the technical protocol to deploy our CXR system so that others might develop their own Communal XR bus ride experiences.

Finally, we conclude with a discussion of potential opportunities and issues with developing and deploying Communal XR experiences.

2 RELATED WORK

Within the spectrum of the virtuality continuum of degrees of immersion, Extended Reality (XR) is an umbrella term that encompasses any sort of technology that alters reality by adding virtual elements to the physical or real-world environment to any extent, blurring the line between the physical and the virtual world [15, 43, 43]. Below, we present how our work relies on and extends previous works that explored shared XR experiences, XR in the car developments, and use of digital twins for urban planning and community development.

2.1 Shared XR experiences for community engagement

Extended reality (XR) simulations have been used as alternatives for the general public, stakeholders, and policymakers to learn about environmental and societal risks in a shared, interactive and safe environment [1, 44] and to engage them in issues at the urban scale [9].

Previously, VR experiences have supported community engagement in environmental issues and especially climate change by 1) delivering information and increasing understanding of causes and consequences of climate change [29, 33], 2) allowing communities to feel connected emotionally to matters of concern by sharing their first-hand or relatable experiences [16, 28] and 3) providing opportunities for them to participate, act, mitigate and adapt [45]. Increased immersion in the media made from photogrammetry, artistic work, and three-dimensional models[5] has allowed for communication of future risks, and severity of environmental issues, helped enhance pro-environmental behavior[18], and provided for entertaining and impactful communication [3, 33]. Familiarity with locations portrayed in VR, have led to increased awareness, initiation of dialog on more immediate issues for the community, and triggered stronger emotional reactions [3, 5]. Sharing of VR experiences among stakeholders has attracted audiences to discuss these complex issues and has also been helpful as a tool for fundraising for environmental causes [5, 10].

Despite knowing such benefits, developing renderings of long-term adaptation solutions that appropriately balance realistic options and visionary concepts has been challenging, as stakeholders often do not agree on the details of the final visuals or the narration accompanying them [5, 18]. Additionally, these XR experiences are often shared asynchronously with stakeholders [5, 32], not allowing them to share experiences [14] or have co-located interactions. XR is yet to provide experiences that promote synchronous, co-located, communal exchange of experiences.

2.2 Extended reality on the road

The use of head-mounted displays (HMDs) in vehicles has been growing in academia and industry. Commercial solutions for in-vehicle XR include Holoride[1] and VRCoaster[2]. In the academic context, CHI researchers have recently investigated and explored other possible usages of on-road VR systems. For example, the CarVR project [15] - an arcade-like shooting game tracks a non-virtual car's motion and renders the corresponding visual perspective of a passenger in the virtual space. Besides entertainment, research related to meditation [38] and education [24] has been conducted using VR in cars. For example, Driving with the Fishes [38] used in-vehicle VR to provide participants with a calm, mindful underwater experience. Another system, VR-OOM, used low-cost VR technology to create an in-vehicle driving simulation system [12].

[1]https://www.holoride.com/en
[2]https://www.vrcoaster.com/en

A common issue faced by such on-road VR systems is motion sickness, which is triggered by the conflict between the motion rendered in the HMDs and the perceived motion of the actual car [30]. The discordance between the two eventually leads to motion sickness [41]. Prior works have explored strategies that synchronously map real-world vehicles' speed to the depicted movement in VR to tackle this issue [15, 24, 38] and suggested that coordinated sensory cues from vision (received from VR) and the vestibular system (received from the real world) could increase enjoyment and immersion while reducing motion sickness [1, 8, 19]. Coordination between vision perceived from the VR Headset and the movement perceived by the vestibular senses enhances the level of immersion and circumvents the risk of motion sickness [42].

Another technical challenge of on-road VR systems is the mismatch between the rotation of the vehicle and the virtual environment, which limits the current use of VR HMDs inside moving vehicles [15]. Rotations of the vehicle are interpreted as the user's head movements and result in unintended shifts of the virtual environment for the user. To balance between real-world awareness and VR Immersion in on-road VR, a substitutional reality can be used i.e, using the 3D model of the entire in-car space as a one-to-one mapping and selective rendering using the 2D real-captured photo of the specific operation part. [24]. Another solution used is simulated displays with ambient vehicle information, such as the journey progress and the vehicle speed to reduce the mismatched perception between the real and simulated realities [25].

2.3 Digital twins for urban scenario simulation

A Digital Twin (DT) is a virtual representation of a place, process, product, or service [13], that uses real-time data to enable monitoring of systems, prevent problems before they occur, and to develop new managing strategies, opportunities, and decision-making tools [8]. The concept of a DT is closely linked to the extended virtuality continuum [40] - with a DT, there is a spectrum of possibilities between the physical world and its virtual representation. The virtual model constantly synchronizes data from the physical environment, and the information contained in the virtual model might send feedback to the real world [36].

Examples of city-scale DTs are still in their infancy [7, 20, 46], but can be seen in the planning of Virtual Singapore, SideWalks' efforts in Toronto, CityZenith planning of the Indian city of Amaravati [21], Glasgow's Future City initiative or Cambridge university's National Digital Twin project [2, 26]. As appealing and fascinating as city-scale DTs are for urban planners [2] or the environmental sensing uses for park management [4, 6], their use for community resiliency has not been fully explored [27, 37].

Our CXR system builds upon the state-of-the-arts in the above-mentioned three fields and further extends each of them: CXR is inspired by existing shared VR experience for community engagement and adds the **situated, on-road aspects** to it. CXR builds on existing applications of on-road VR experiences for entertainment and education and adds the **Communal** multi-user aspect and the purpose of community engagement to it. The development of our CXR system was built using an existing DT model of Roosevelt Island [citation anonymized]. For this project, we needed to enhance the DT to update changing landmarks and to facilitate super-imposing provisional features. To our knowledge, CXR's transformation of the DT to be a tourable model is one of the first of its kind in urban planning and community engagement. It enables new features and proposals stemming from the community engagement sessions to inform proposals and enhancements to the real-world community using the DT.

3 SYSTEM REQUIREMENTS

Our CXR system is developed by a multi-disciplinary team with backgrounds in computer science, human-robot interaction, and urban technology, and led by an architect and urban planner who focuses on the use of technology for visualization and community engagement. To develop our system's requirements we had the support of a community liaison who assisted us with building our relationship with the local community representatives in charge of operating the shuttle used for this study. During the research and development of our system, we met these representatives several times for their input, to address their concerns, and keep them apprised of the project plans.

To promote community awareness and engagement, we defined our system's requirements as follows:

- **Communal:** To encourage communal action and co-located experiences of extended reality, we needed to develop shared experiences and enable people from the community to see the expected changes alongside their neighbors. We needed to let their mutual and collective understanding of the forecasted future to unite and empower them to take action.
- **Inclusive and Easy-to-Use:** Since our audience is mainly composed of residents who wished to be informed about climate change and leaders who influenced environmental policies, the system needed to be easy to use and inclusive to as many people as possible. This meant that we wanted to accommodate people of different ages, with different familiarity and experience with gaming and VR technology, and to accommodate accessibility needs for people who might have mobility, sight or audio impairments as much as was possible.
- **Situated:** We learned how projections from the NYC Department of City Planning show that a 100-year flood will put most of the site of our case study and deployment, Roosevelt Island, underwater Figure 1. Previous research indicates that the idea of such a catastrophic flood does not feel real to the public [19, 23]. This disconnect has implications for emergency preparations, individual and municipal decision-making and community resilience. For this reason, to bring a sense of immediacy and localized understanding to our community partners, our system needed to be based on their familiar environment and viewed on-site.
- **Compelling and Immersive:** Although there are guidelines in previous research on ways to depict the impacts of climate change or other planning scenarios for stakeholder input, we learned from our community engagement experts that fearful end-of-days climate scenarios may lead to anxiety and disheartened inaction and are less effective toward positive change. To bring engagement and promote community awareness, our system needed to be an immersive experience that visualizes the expected change but refrains from scaring people with a doomsday experience and rather provides enough insight to lead to action.

4 CXR SYSTEM DEVELOPMENT

Based on these initial requirements, we have developed a system that creates an immersive, situated communal experience. This is how we mapped our requirements to our system elements:

- Compelling and immersive ——————> A panoramic video.
- Situated ——————————————————-> Digital twin animated with Unity.
- Communal ————————————————–> Shared bus ride
- Easy to use ————————————————–> VR headsets controlled by one phone app.
- Inclusive ——————————————————> Fall back system of a 2D movie projected on a screen.

To build a system that is inclusive and easy to use and, at the same time, immersive and compelling, we choose XR as the primary medium. We classify our system to be an XR environment because it superimposes a digital VR environment upon the physical island topography. We have termed it a communal XR environment because it creates a shared social experience by combining several shared immersive modalities, such as a shared soundtrack, the common moving vehicle, and a shared virtual environment.

We have constructed the immersive bus XR environment with two situated spaces, one within the other: The space inside the bus and the island's unique locations vulnerable to climate change. Accordingly, the virtual environment replicates the bus' 3D model and the island's digital twin. While each participant uses a VR headset that geo-locates and orients the view, they are all experiencing the tour within the frame of the moving vehicle. Hence, the XR environment combines VR headsets that provide complete immersion and at the same time unifies the individualized experiences by a shared location on a shared moving vehicle. The movement of the bus in the real world changes the virtual reality according to the location. In addition, the common audio track connects the participants. As such while they cannot see each other, they can feel the social presence of their neighbors on the bus, hear each other, and hear the same soundtrack.

4.1 The physical experience design and setup

To make the physical environment as inclusive and accessible as possible, we based our system development on a specific bus model and made arrangements with the local bus service to use only that specific bus. To reduce the mismatch between the VR view in the HMDs and the movement of the bus, we choose a bus layout with seats facing forward. This design decision limited the number of participants we could host to 15 people per ride. We visited the bus headquarter for several rapid prototyping sessions. We measured and recorded the bus dimensions and placed cardboard boxes and sheets to simulate the final design. Based on our rapid prototyping sessions, we prepared a sketch with our initial system design (Figure 7.a is a more advanced version of the original sketch). Due to our limited access to the actual bus, we built a Bus Simulator in our lab by marking the actual interior bus layout with tape on the floor, as elaborated in Figure 2. The simulator accelerated our work process and allowed us to rapidly examine design alternatives.

We iteratively developed and tested the design of the physical environment, first in the simulator and then in the bus. We had to prototype and experiment with numerous design alternatives to reach a level of correspondence between the virtual and physical world to meet our design requirements

4.2 The virtual experience design

The virtual experience covered both communal physical terrain and a common narrative experience. We developed a script to situate the ideas (on climate change and flooding) we hoped to discuss with the familiar home environment that the bus would drive through. In addition to being timed to coincide aspects of the script with landmarks in the physical or virtual space, the scripted experience is designed to give enough information but not overload participants or make them feel hopeless about their future. We carefully curated information from city and state open-source data-sets and web pages[3] to create a 15 minute script.

4.2.1 Advances in modeling the digital twin. We constructed the Roosevelt Island Digital Twin based on NYC 3D model from the NYC Department of City Planning[4] and the 3D data of Google Earth[5]. However, for this project, advances in modeling the DT environment were needed to associate the visualized depictions in the DT with the real-life location. The available open-source model of NYC features abstract representations of building volumes and heights. We needed

[3] For example, Sea Level Rise https://sealevelrise.org/states/new-york/, NOAA Tides and Currents https://tidesandcurrents.noaa.gov/waterlevels.html
[4] https://www1.nyc.gov/site/planning/data-maps/open-data/dwn-nyc-3d-model-download.page
[5] https://www.google.com/maps/place/Roosevelt+Island/

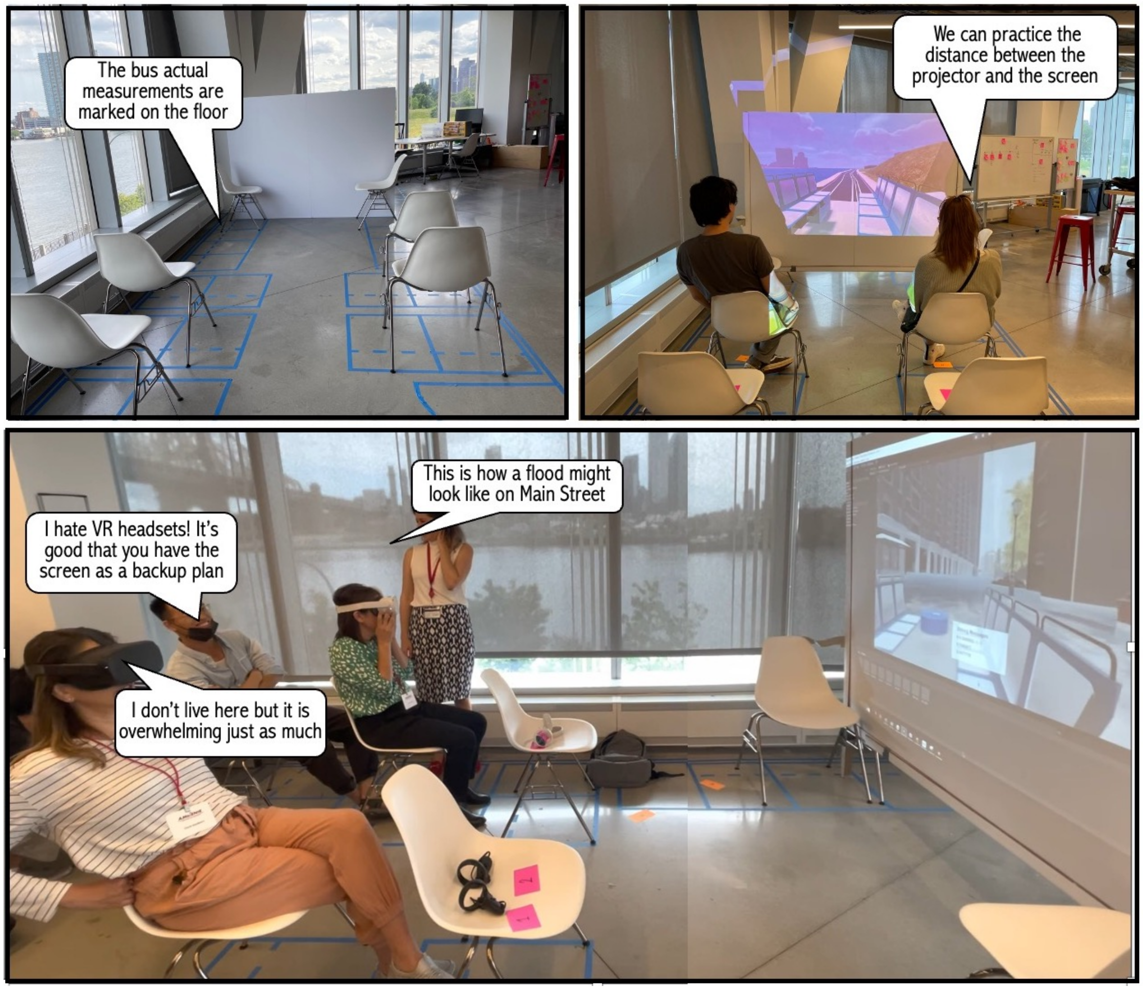

Fig. 2. The Bus Simulator enabled micro adaptations to optimize the physical experience for comfort.

a more realistic model to create a viable virtual environment to invoke the sense of presence and immediacy for the communal experience. To this end, we added 3D objects and details to the Roosevelt Island Digital Twin using the 3D modeling tool SketchUp[6]. We created the road system and topography of the island and added textures to the building facades based on photos taken on-site and using Google earth as a reference. We digitally modeled some essential buildings like educational institutions, religious complexes, retail corridors, and a subway station from scratch.

For a more realistic road experience, we imported our DT into the 3D interactive engine Unity[7] and populated the scene with additional key objects along the route, including stop signs, light poles, fire hydrants, and trash cans based on models from the Sketchup Warehouse[8]. These objects were imported to our Unity project and placed in the virtual

[6]https://www.sketchup.com
[7]https://unity.com
[8]https://3dwarehouse.sketchup.com/?hl=en

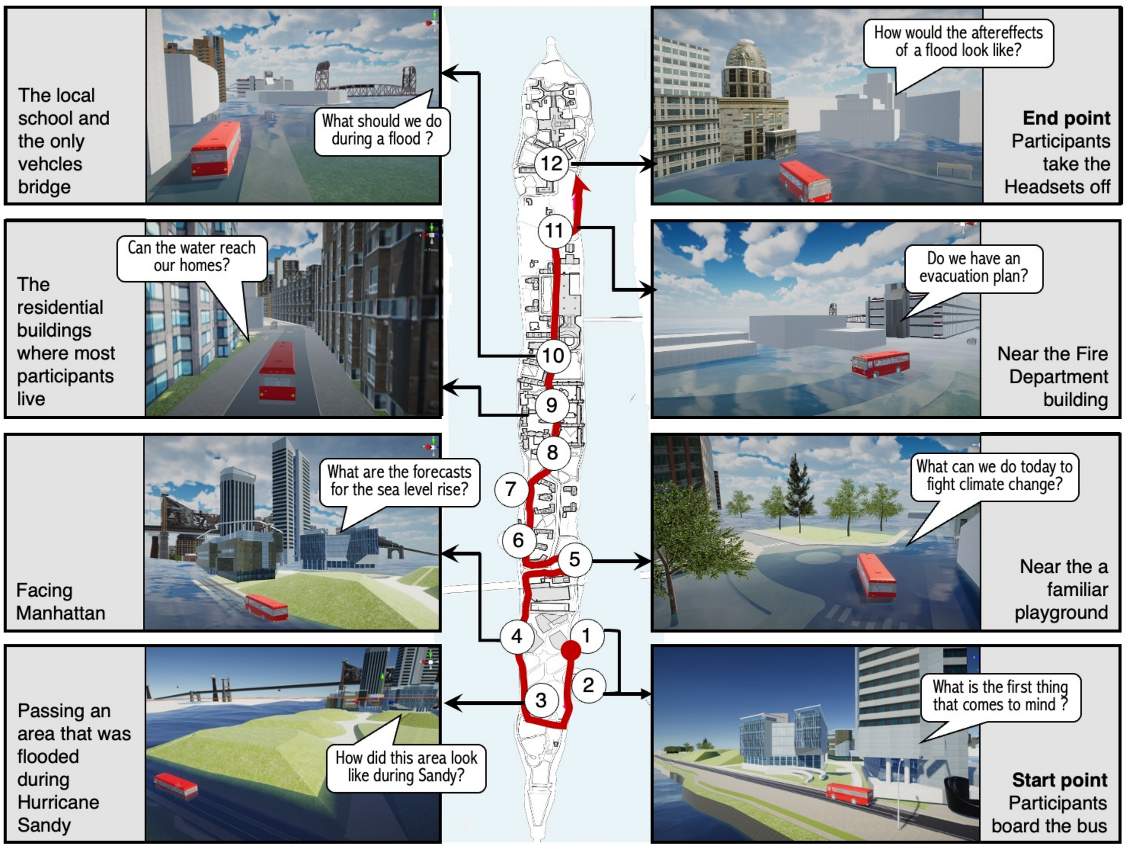

Fig. 3. The spatial layout for the CXR experience script

environment based on their actual physical locations. We also planted the terrain with trees[9] and grass[10]. Such rich details at the street level aimed to create higher realism and an increased sense of presence, enhancing the effectiveness of storytelling.

The virtual bus interior was crucial for the alignment and augmentation of the physical bus and the VR experience because of the proximity and immediacy of the bus interior to the participants. To make the bus resemble to its real-world counterpart, we created a detailed replication, using an open-source bus model from the Sketchup Warehouse, as well as our own sketches and measurements of the actual bus. We added textures and materials to the seats, railing, and floor. After the first two test rides, we decided to remove the virtual bus's roof, to increase the participant's field of view, allowing them to see more of the island's DT and better observe the environment around them.

4.2.2 Storytelling through the digital twin. As shown in Figure 3 we used the advanced version of the DT to develop the narrative of the XR experience and then used Unity to animate and bring it to life. Our script included nine climate change and flooding scenarios. Each of these scenarios was a departure from the default of having high correspondence

[9]https://assetstore.unity.com/packages/3d/vegetation/trees/mobile-tree-package-18866
[10]https://assetstore.unity.com/packages/2d/textures-materials/nature/grass-and-flowers-pack-1-17100

between the real and virtual worlds. The DT enabled us to construct the narrative for what might occur in each scenario predominantly through images and visualizations. Our nine scenarios are elaborated in Figure 4. Beginning with flooding the DT with a water level of everyone's WORST NIGHTMARE (Figure 4a), was meant to gain the participants' attention right from the start with a whale appearance leading to a comical relief. Next, moving to the SUPERSTORM SANDY scenario (Figure 4.b) was to reassure participants that this was the situation during the worst flood in recent years. Following that was a presentation of DT exemplified sea level rise forecasts for the next 100 years (Figure 4.c), STORM SURGE scenario (Figure 4.d), and PLANNING ALTERNATIVES (Figure 4.e) to show better climate-resistant design based on the NYC Comprehensive Waterfront Plan[11]. In the later part, we used the more densely built area of the DT to simulate flood scenarios such as TIDAL FLOODING (Figure 4.f), WHAT TO DO DURING A FLOOD (Figure 4.g), ending the ride with the AFTER A FLOOD scenario (Figure 4.i).

4.2.3 Animating the digital twin. Unity's simulation and animation systems allowed us to convert the static 3D model of the island into a dynamic experience. We implemented the environment system with the Enviro - Sky and Weather asset[12] from Unity Asset Store and created sunny, cloudy, and stormy weather and animated transitions in between to match the weather of our narrative. We simulated the waves using the URP Water[13] asset and animated the water level and wave strength through scripts to match different scenarios dynamically. We also programmed the animation of tree growing and fish flocking, and used the Cinemachine Dolly Cart[14] component to animate the swimming whale, floating cars, trash cans, and tree trunks. The animations collectively enriched the nine flooding scenarios of the ride.

We pre-rendered a cinematic 360-degree 3D movie of the scenarios along the path of the bus using Unity Recorder[15] on a PC, and developed a VR application that plays the video based on the real-time geo-location of the bus during the tour. This approach alleviated the requirements on the computation power that would have been needed to make real-time models and allowed higher complexity and realism in the visual representation.

4.3 Creating communal experiences in XR

Each participant experiences the simulated world individually, but we specifically designed interactions between the real and virtual worlds to enhance the communal experience. For example:

- Shared movement: By design, all of the participants are on the same bus, and moving through the physical and virtual landscape together; metaphorically, we designed this experience for them to feel that their destinies are shared. The inclusion of real physical movement in the experience was intended to increase the immediacy and presence of the scenarios and issues being discussed. To highlight this, for example, we added the on-road physical STOP traffic signs to the virtual environment, such that during the bus ride, the participants could see them in the VR, and the actual bus would stop. These moments were designed to draw a correlation between the physical and virtual worlds, a unifying experience the participants would not have from watching a video in a theatre together.
- Common soundtrack: The individualized experiences are unified by a common audio track. It is based on a dialog between two narrators; the "tour guide," standing in person in the front of the bus with the participants, and the "climate change expert," a pre-recorded voice-over that contributes the scientific and numerical information.

[11] https://www.nrpa.com/our-environment/nyc-comprehensive-waterfront-plan
[12] https://assetstore.unity.com/packages/tools/particles-effects/enviro-sky-and-weather-33963
[13] https://assetstore.unity.com/packages/vfx/shaders/urp-water-184590
[14] https://docs.unity3d.com/Packages/com.unity.cinemachine@2.3/manual/CinemachineDollyCart.html
[15] https://docs.unity3d.com/Packages/com.unity.recorder@2.0/manual/index.html

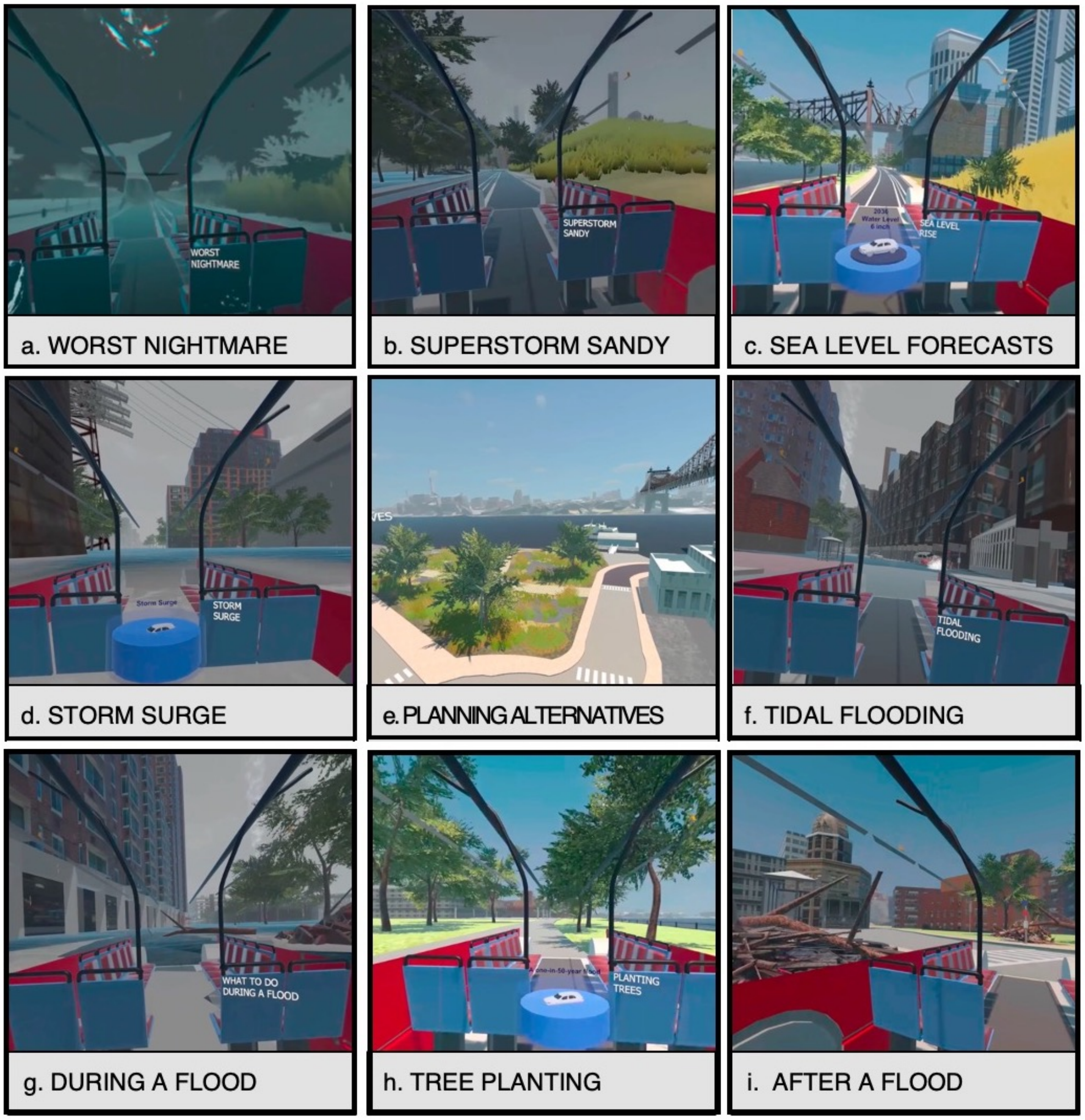

Fig. 4. Storytelling through the digital twin: nine scenarios

The dialog format aims to enhance engagement by positing the researcher on the same side as the participants, so they are all "learning from the expert." It also helps keep the audience alert and engaged by breaking the continuity of one voice, which can be monotonous. The experience was intensified with sound effects which we added on top of the narration: thunder when the narrator spoke about "worst case scenario" or rain and wave sounds when simulating a storm surge, water bubbles when the bus was emerges from "under water" or energetic music when mentioning planning alternatives.

- Shared viewpoints: By default, the view each participant has of the virtual world depends on which direction their head is turned. However, at times, we changed the camera's position to show a shared view; this was a strategy to achieve a coordinated joint response, a moment of interaction between the physical and virtual. In one scenario, for example, we changed every participant's point-of-view to a birds-eye view (Figure 4.e). As participants experienced it while sitting, the visual aspect was designed to create a roller-coaster-like feeling to invoke a vocal reaction from most people.
- Spectacle features: To enhance participants' awareness of one another, we added "spectacle features" in the virtual environment and script. For example, at one point when the bus was portrayed as being underwater, we showed a whale swimming by the bus. This outlandish "joke" in the script elicited exclaims and made everyone turn their heads at the same time (Figure 4.a), which we believe enhanced the communal sensation of the experience. Other features in the narrative – floating cars, a helicopter on one of the building roofs, a huge log crashing into the bus – were all designed to create moments in which the virtual world provokes unified reactions from the group in the real world.
- Scripted relief: we identified two places along the route to stop the virtual experience and allow the participants to check their location in the real world. We aimed to give them a few moments to relieve their eyes by taking the headset off. On the conceptual level, we also provided them with a moment in which they jumped back from the future into the present. We intended this contrast to allow them to learn that even though they are watching this experience individually, they are situated and connected with their community and other participants. Metaphorically this was a moment in which the participants were moving from the future into the present and back together.

4.4 Technical challenges and iterations

Before operating the system with community members, our multidisciplinary research team took several test rides. Each test ride brought to the surface technical challenges, such as mismatch between the video in the HMDs and the bus's orientation, and complaints about motion sickness. To resolve those technical challenges, we improved the system with each iteration; this is elaborated in Figure 5.

- **The first iteration** To create a low-cost, easy-to-use system, we developed the initial version of our ride using Google Cardboard HMDs[16]. (See Figure 5.a) First, we rendered a 360-degree video in Unity, played it on each participant's mobile phone, and then individually inserted it into the Google Cardboard HMDs. The main obstacle was the mismatch between the video and the bus's orientation. Since this particular HMDs has three degrees of freedom (DoFs), it could not detect the absolute position change caused by the bus turns; for example, this could cause issues where the participant's video showed the back of the bus while the bus was riding forward. With no orientation calibration system, participants had to manually take off HMDs and re-calibrate after every turn. In addition, the quality of the panoramic video and the level of immersivity did not satisfy our needs.
- **The second iteration** To give the participant the ability to adapt their orientation to that of the bus, we switched the designated VR HMDs [17]. (Figure 5.b) Compared to the Google Cardboard, Quest has a better display and paired controllers, which allows participants to adjust their view orientation. Although our new HMDs incorporates six DoFs, we only kept the rotational tracking for the participants to look around the

[16] https://arvr.google.com/cardboard/
[17] https://store.facebook.com/quest

a. We started self testing with the cardboard headsets

b. Moved forward to a second version on the designated VR Headset

c. Some of us felt car-sick…

d. We then started developing the Half Immersive mode

Fig. 5. The research group's test rides

panoramic scene naturally. We disabled the positional tracking because its low latency Inertial Measurement Unit (IMU) detects unwanted movement when there is non-zero acceleration to the bus system. To improve the synchronization between the physical and VR environments, we developed a GPS app to geo-locate all the HMDs based on the position of the bus; each headset then needed to have a hard-coded offset to represent where its seat was within the bus.

- **The third iteration** The third iteration of our system was developed primarily to reduce the severity of motion sickness. (See Figure 5.c and 5.d) In the VR app, improvements included a blackout screen that automatically blocked the entire field of view of the participants during bus turns. In the mobile app, we added a set of control buttons that allowed the operator to adjust the GPS data manually. This third iteration and persistent complaints about motion sickness also led us to develop a fall-back system that enabled the Partial Immersion mode.

4.4.1 Synchronizing the physical and VR environments: The GPS app. We developed an Android-phone based GPS app to be used by a researcher operating the Communal XR experience. This allows the operator to concurrently control the 15 HMDs and the projector during the bus ride. The app, shown in Figure 6., synchronizes the playback of the panoramic video with real-time geolocation. It updates and reads the GPS coordinates from the phone, converts the geo-data into a

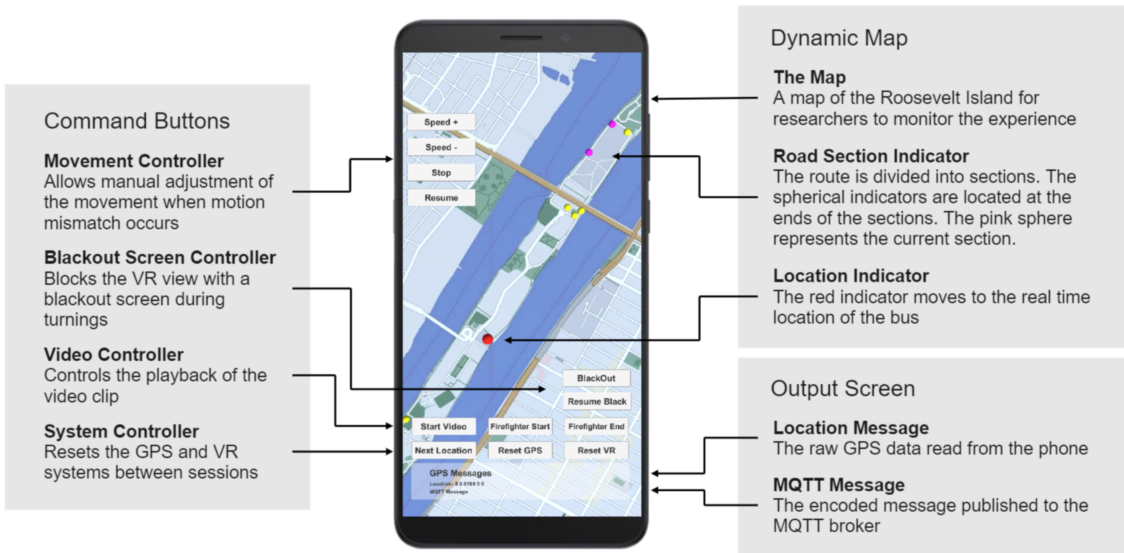

Fig. 6. The mobile app that controls the VR and projected video on the bus.

string message, and publishes the news to a central server using the MQTT network messaging protocol[18]. The central MQTT "broker" posts commands to the client HMDs and projector so as to synchronize the playback speed of the panoramic videos, change the active video clip, block the virtual view with a blackout screen while turning, and restart the session.

The Android GPS app consists of a map of Roosevelt Island, a collection of buttons, and an output screen. The map uses spherical indicators to display the geo-location of the phone and the road section that the bus is currently driving through. We placed several buttons on the app to allow manual takeover. During the ride, researchers could send commands to the MQTT broker by pressing soft buttons on the app interface to correct the GPS location in case of calibration errors or poor internet connectivity. The output screen of the app displayed the geo-location values and the published messages, to better enable the operator to monitor, debug and remedy any issues.

During each fixed update, the Android GPS app performed Algorithm 1. On arrival of the message every fixed update, the client systems, which included the video player apps in the HMDs and the projector, would individually perform Algorithm 2.

The video in the headset was aligned with the geographical location according to the message received on the previous update. Due to interference from surrounding tall buildings and the relatively low accuracy of the GPS data, we set the update rate to once per second to filter out inconsistent values. This update rate achieved a smooth experience during uniform motion. However, there was still a noticeable latency between real and virtual locations when the bus accelerated or decelerated. We added buttons to manually adjust the GPS data to overcome this obstacle.

In the second test ride, we tested the VR app that adjusts the playback speed of the video according to the message read from the MQTT broker. The second iteration featured an improved synchronization of the video and the physical

[18] https://mqtt.org

Algorithm 1 Android GPS Tracker

```
procedure OnFixedUpdate                                                   ▷ Called every fixed update
    currentGPS ← GPSfromPhone();                                          ▷ Read GPS Coordinate from the phone
    projectedPoint ← Project the currentGPS to the line of current road section;
    distanceRatio ← Distance(roadStart, projectedPoint)/Distance(roadStart, roadEnd);
    if distanceRatio > threshold then                                     ▷ Check whether to proceed to next road section
        roadIndex + +;
    end if
    specialCommand ← Integer encoding of the command;                     ▷ Assign special commands
    message ← roadIndex + distanceRatio + specialCommand;                 ▷ Append three values to one string
    Publish(message);                                                     ▷ Publishes the message to the MQTT broker
end procedure
```

Algorithm 2 VR or Projector Video Player

```
procedure OnMessageArrival                                                ▷ Called every fixed update
    message ← Message read from the MQTT broker;                          ▷ Process message
    roadIndex, distanceRatio, specialCommand ← Split(message);
    if roadIndex > videoIndex then                                        ▷ Check whether to proceed to next video section
        videoIndex ← roadIndex;
        PerformBlackout();
        Play(videoIndex);
    end if
    PerformSpecialCommand();                                              ▷ Perform Special Command from the MQTT broker
    videoRatio ← videoCurrentTimeInSeconds/videoTotalLengthInSeconds;     ▷ Adjust video playback
    playbackSpeed ← (distanceRatio − videoRatio)/deltaTime;
end procedure
```

movement. Nonetheless, some participants reported different degrees of motion sickness, especially during turnings and when the GPS signal was unstable.

4.4.2 Partial Immersion mode. To make sure that participants who felt uncomfortable using VR headsets were still a part of the communal experience, we developed the Partial Immersion mode. This fall-back system included a projection of the movie on a big whiteboard screen at the front of the bus, replacing the front window view. Figure 8.b shows this setting which allowed participants to continue the experience without HMDs. During our in-bus practice runs, we discovered that the Partial Immersion fall-back system serves another crucial role in the immersive experience: it grounds communication between the research team, the "tour guide," and the participants. While standing in front of the bus, the research team needed to know what the participants saw inside their VR HMDs throughout the tour.

5 SYSTEM DEPLOYMENT

In July 2022, we had our first ride with participants: a group of 20 early testing users from the university.[19] In this section, we describe aspects of the technical protocol critical to the deployment.

[19]This was followed by six Immersive Bus rides, during August, with between 8-15 community members in each (N=83). The research findings of the larger deployment and community engagement outcomes are outside of the scope for this system's paper and will be reported elsewhere.

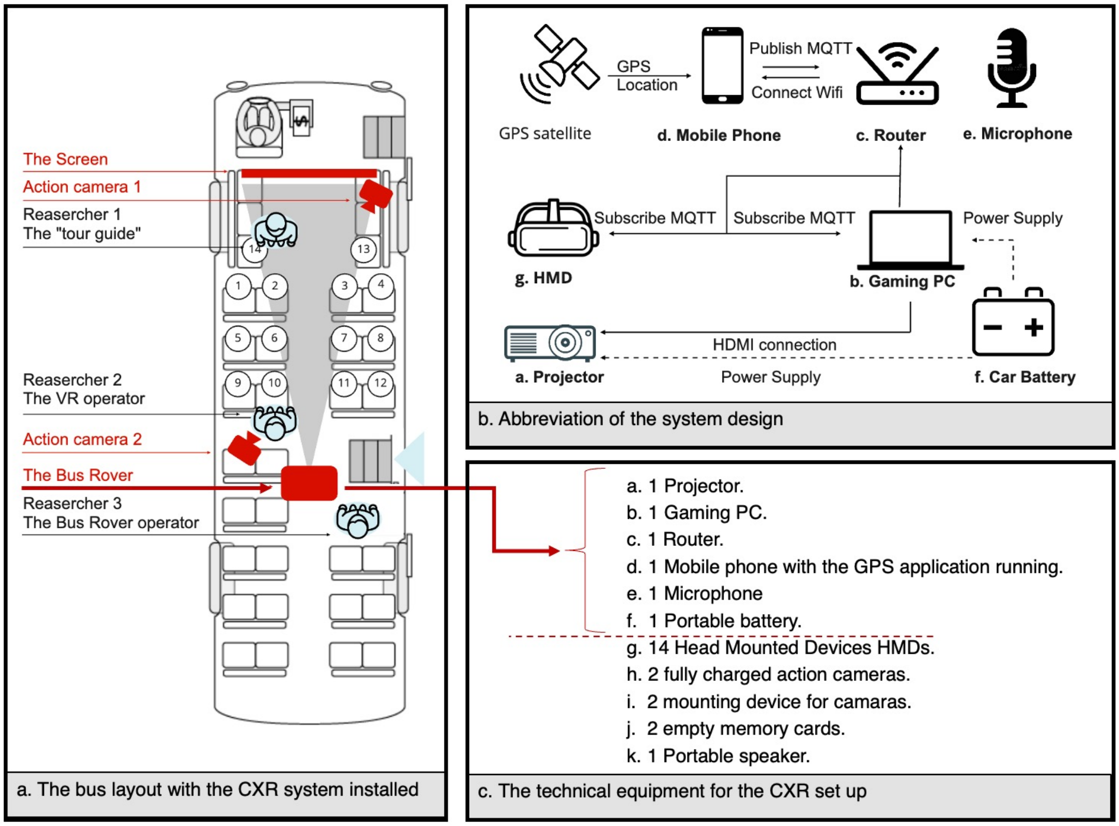

Fig. 7. Set up in the bus layout and technical system's abbreviations

5.1 Validation

Since the primary purpose of the CXR system was to enable sharing a communal experience, we validated CXR by having a pilot group from the community try the system and having them share their perspectives in a pre-ride and a post-ride focus group. These were augmented with corresponding surveys that were answered individually by each participant.

5.2 Preparing for the ride

For our real-world deployment in a third-party bus, it was important for us to be able to set up the CXR system quickly, and for the setup to produce similar outcomes each time it occurred.

To ease installation and setup, we integrated our technical setup onto a wheeled cart that we called the Bus Rover (Figure 8.a). This allows us to localize critical equipment and transport it from the lab to the bus efficiently. The Bus Rover includes the laptop, projector for the Partial Immersion fall-back system, as well the mobile router that networks the HMDs, the GPS app device, and the Partial Immersion system and the portable battery that powers all of the devices. High-strength Velcro patches are used to secure all of the parts to the cart.

Figure 7 shows the bus layout and the location of each part of the system while Figure 8. describes the steps for the bus setup, which include: a. Securing the Bus Rover, b. setting up the projection screen, c. mounting the action cameras, and d. placing the VR HMDs on each participant's seat.

a. **Securing the Bus Rover:** The Bus Rover was designed to sit at the back stairwell of the bus. To secure the Bus Rover, we built two metal arms to attach it to the upper staircase of the bus. One arm acts as an extra foot for the cart, and the other arm extends horizontally to wedge the cart in place. The installation begins in the lab, with a preliminary check that all components are on the Rover. The Rover is then transported on its own wheels to the bus and secured on the bus. The battery on the Rover is then powered and connected to the Partial Immersion laptop and projector.
b. **Set up the projection screen:** We place the Partial Immersion projection screen as close to the driver as possible, to give more room for the participants and to maximize the projected image from the Bus Rover projector. We prefabricated the screen out of two white foam boards (40X60 inch each); these are taped in the middle so that they can be transported folded but expanded to an 80"x60" surface in the bus.
c. **Mount the action cameras:** We utilized two action cameras to record the deployments. We set one of the cameras at the front of the bus and one at the back of the bus, so that we can capture all facial expressions and body gestures from participants. To overcome the limitation of action cameras' inability to capture audio in noisy environments, we also used professional recording devices to record the audio responses of all of the participants.
d. **Prepare the VR HMDs:** Before each ride, we uploaded the final version of the VR app to all 15 HMDs and made sure all were fully charged, and all VR controllers have working AA batteries. We placed one set of HMD and controllers on each seat, localizing each headset to its location in the bus.

Based on this protocol, the installation of the Bus Rover, screen, cameras and HMDs took an average of 25-30 minutes to set up before each tour.

5.3 The immersive tour

As elaborated in Figure 7.a. we needed at least three team members to run the CXR bus ride: The "tour guide" standing near the screen, narrating the story and operating the soundtrack. The VR operator was controlling the GPS app and troubleshooting participants' issues with headsets. The Bus Rover operator was responsible for the Partial Immersion mode, sitting behind the participants and controlling the laptop computer and projector.

Upon boarding the bus, the tour guide instructed the participants to their seats. The tour started with technical instructions on operating the headsets and what to do if people felt motion sickness. After ensuring all participants understood how to use the headset, the tour guide instructed to wear it and raise their hand if they need help.

Once the bus starts moving, the GPS app sends a single command to the VR movie to start playing. The soundtrack comes from an independent speaker so that all participants, regardless of their immersion level, are hearing the same soundtrack. The geo-located panoramic video lasts around 15 minutes from the south point of the island to the north, during which the bus stops at all STOP signs and crosswalks and the movie synchronizes to pause and continues according to the physical movement of the bus. At the end of the tour, the bus travels back to the starting point while the participants rest and contemplate with their HMD off of their heads.

Fig. 8. Rapid Prototyping to develop the Partial Immersion mode

5.4 Dismantling the system

Since the bus was an operative bus throughout the day and not dedicated only to our project, at the end of each ride, we were required to dismantle the system. The dismantling process included unsecuring the Bus Rover, making sure all components are still attached, and rolling it to the lab to charge all the components before the next tour. Similarly, all the HMDs were taken back to the lab to be checked and charged.

6 DISCUSSION

Our CXR system contributes to the growing range of XR technologies by applying XR technology to the challenge of creating a communal experience through a shared physical site for a group of participants. Our goal in our specific deployment of the CXR system was to set the stage for community engagement discussions about water level rise and flooding which might be caused by climate change and storm surges. However, we believe the platform and protocols for CXR have broader potential use for other researchers, artists, designers, and community developers. In this section, we review lessons from our development and deployment that provide insight into the challenges and opportunities of developing XR technology for communal experiences. We also review the limitations of our current system, in hopes that these might be improved upon by future technologies or clever system builders. Finally, we describe advances that the CXR system provides and suggest how they can be furthered in future applications.

6.1 Lessons from our development and deployment

Our system design goal was to create an inclusive, situated communal experience to enable community engagement. Here, we evaluate the system based on our early-testing users.

6.1.1 Communal. The shared movement, common soundtrack, shared viewpoints and spectacle features we built into CXR seemed to do the job of creating a shared experience. We found that the participants would speak aloud and converse with one another throughout the experience even though they could not see each other; this seemed to help bolster the sense that they were going through the experience together. The fallback system also seemed to help to maintain communality even when people could not use the headsets because it enabled people to see each other while taking the tour.

6.1.2 Situated. The primary way that the CXR system helps to situate the communal experience is by putting people into a shared moving environment and syncing it with a virtual rendition of their own familiar home environment. This approach to situated-ness created significant challenges, particularly developing a tourable version of the digital twin, and in aligning the physical and virtual locations while on the moving bus platform.

Despite imperfections in the geo-location, on the whole, our RI deployment of CXR achieved the goals of situatedness. Some early anecdotal indicators of that, for example, were that people called out names of the places they were familiar with, such as the school or the post office. This indicated to us that people felt like they were going through their community even though they were doing it in the VR environment.

Of course, we experienced technical difficulties; in some moments, the system fell short of being situated when the bus started moving or accelerating, and the movie did not and, people became vocal, made complaints, and asked fellow riders for clarification or feedback. Enhancing GPS accuracy can help avoid these moments in future versions of the CXR.

6.1.3 Compelling and immersive. It is difficult to separate out the contribution of the CXR system and the designed narrative in our evaluation of how compelling and immersive the bus tour experience was. However, we found that people were actively looking around throughout the tour, turning their heads in response to the audio narrative. Our post-ride focus group helped us to understand these aspects as our student participants were more vocal about their thoughts, more knowledgeable about the topic, and more eager to contribute after the immersive ride. Often immersive experiences—for example, in video games— are exaggerated and intense, and as such, we found it difficult to balance between providing an immersive and compelling narrative and visuals while also ensuring that participants do not feel discomfort, hopelessness, and worried about their future.

We discovered that our CXR system had an ironic trade-off between the immersive, situated, and communal parts of the experience. Because the simulation focused on the view outside of the bus, people deeply focused on the virtual environment could be distracted from attending to the other members of the group, and seem disoriented if someone talked to them or if their names were called. At the stage of technology today, those are inevitable trade-offs. It is possible this trade-off would not exist if the other passengers were rendered in the virtual simulation, but that could also cause distraction from the script and the ride. Future development of CXR systems might consider using Augmented Reality or avatars of other participants to try to achieve a both communal and immersive experience.

Fig. 9. Pilot study with a group of early testing users

6.2 Limitations

Our system has several limitations. The first is that our phone-based GPS experienced a lot of GPS latency. We had a one-second latency between the time the bus accelerates and the time the video playback follows due to the system's preset one-second fixed update rate for error filtering. One solution could be adding additional buttons in the mobile GPS app for more precise manual control during the acceleration phase. We have considered a different answer to disconnect the video from the GPS completely and control its playback manually, similar to the situation in a driving simulation. Should this be the solution, it will require a designated simulator driver to promptly imitate the bus drivers' actions. We could also improve our hardware and software system with cameras or inertial measurement units to improve GPS synchronization with optical tracking or inertial navigation system.

Another limitation is the quality of the digital graphics; improvements to the digital twin and animations are always possible. This work can be improved by adding more details, people, and movement and enhancing water features' visualization. Because our tour is based on a 3D movie, it is possible to render very complex models without a significant impact on our ability to play these in the headset. However, our framerate was relatively limited, and future technologies might particularly help on that front.

Beyond these technical limitations, we believe that it would be useful to explore the possibility of creating in-car, position-based, real-time, rendered avatars for a multiuser VR experience. Allowing participants to see each other on the bus can improve their sense of presence and communality.

6.3 Future applications

CXR system is unique in providing a shared group experience that covers terrain. We believe that CXR can be applied to other applications beyond those that we used in this deployment. Firstly, this system can be adapted to help people in other coastal communities at risk of rising sea levels or flood help to gain awareness and to encourage resiliency planning. The system can also be applied to draw awareness to other climate change risks, such as wildfires or melting icebergs, with an additional layer of narrative scenarios. This could be a considerable contribution to the management of natural or man-made disasters in cities.

New housing projects or any new development could also use versions of CXR for community engagement. In many cases, community push-back on development projects emerge out of fear of the unknown or from misunderstandings of the plans or their impacts. Sharing with the local community planning alternatives using the CXR can bridge the gap between developers, municipalities, and the community. This might mitigate the millions of dollars commonly spent on court litigation and objections over planning.

Deployed on a moving vehicle gives our CXR system an edge no other planning tool possesses. It connects stakeholders to the actual location from the ground-up, can cover more distance to reach many places on the same tour, and include people with disabilities or the elderly in the planning process. In addition, based on the visual common ground, it helps to combine knowledge and discussions of various stakeholders: developers, planners, decision-makers, and the community, a tool they all understand and can share.

The immersive, geo-located and shared aspects of CXR also has entertainment applications: some companies, such as VR coaster[20], have already used a similar design paradigm to enhance the roller coaster experience. As a shared experience, our system's strong linkage between participants' actual and virtual positions can be utilized to create solid **immersive experience games**. For example, it could be used for the **tourism industry** to develop immersive city tours or by **museums** to create a responsive XRs that unfolds the collection's stories in more engaging ways.

7 CONCLUSION

Many of our toughest problems require a communal response, and community action is made more possible by shared perspectives and experiences. This paper describes our technical development and implementation of the CXR system, which enables **Communal eXtended Reality** experiences. We believe the CXR system can be useful for helping people in local communities develop a common grounding on community challenges as the next step towards collective action. Our work proposes a novel system for enabling a communal situated geo-located experience, which can be useful for a variety of purposes. Based on our initial deployment and test rides with the CXR prototype, we believe this system's implementation can become a powerful community engagement tool. To this end, we offer detailed descriptions of our system design and technical deployment, as well as lessons we learned from our development and deployment of CXR.

8 ACKNOWLEDGMENTS

[20]https://www.vrcoaster.com/

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