Virtual and Augmented Reality Applications for Environmental Science Education and Training

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1. Introduction

Cyberinfrastructure systems and applications are broadly used for information retrieval and management in environmental domain (Muste et al. 2012, Li et al. 2015, Rathje et al. 2017, Essawy et al. 2018). Integration of new technologies, including web-based platforms with real-time knowledge generation capabilities, into environmental problem solving paved the way for realistic simulations of environmental conditions for in-depth analysis (Demir et al. 2018, Jones et al., 2018). Evaluation of natural events for inspection and planning purposes require the combined analysis and optimization of various datasets (e.g. digital elevation model, weather conditions, forecasting models, infrastructure information, financial data, vulnerable population) (Sit et al. 2019, Krajewski et al. 2017, Demir and Szczepanek 2017). Complemented with real-world physics and environmental dynamics, these parameters can effectively be presented in a virtual environment (Boulos et al. 2017).

With the increased prevalence of smartphones and popularity of artificial intelligence (AI), substantial research and development have been made in pursuit of more cost-effective and high-performance sensor technologies (Deng et al. 2013, Li 2016) and graphical processing units, which led to the production of affordable virtual and augmented reality devices (Anthes et al. 2016). These developments allowed researchers in many fields (e.g. astronomy, psychology, medicine) to create controlled virtual environments that allow users to interact with digitally-generated stimuli (Freine and Ott 2015, Cipresso et al. 2018, Joda et al. 2019). In the field of environmental sciences and disaster management, public, scientists, decision-makers, and professionals can benefit from virtual and augmented reality applications to simulate various environmental scenarios for a realistic and safe workspace that allows repetition and precise measurements (Hsu et al. 2013, Nunes et al. 2018).

In this chapter, we provide a variety of use cases (i.e. applications) that utilizes virtual and augmented reality in disaster management, and environmental data retrieval, analysis, and visualization. Design goals of these applications broadly include increasing public awareness regarding natural disasters with engaging graphics and interaction, communicating environmental information efficiently and effectively to educate K-12 and college-level students, providing a decision support system for environmental planning and disaster management, training first responders and maintenance staff, and advancing conventional real-time environmental data retrieval and processing.

The remainder of this chapter is organized as follows. Section 3 provides a literature review to summarize the previous work on implementing AR/VR in natural disaster sciences. Section 3 describes the use cases focusing on the recreation of a realistic flood scenario with purposes of increasing awareness, providing decision support, and educating stakeholders. Section 4 focuses on AR/VR applications in real-time environmental data acquisition, and its processing and visualization. Section 5 provides conclusions along with the future directions.

2. Background

Various studies have shown how virtual and augmented reality can be used to advance the conventional disaster management and response approaches (Schwarz et al. 2016, Jung et al. 2016, Vichitvejpaisal et al. 2016, Alharthi et al. 2018, Sharma et al. 2019). One of the most prominent application intermediates to apply AR/VR in environmental science is smartphones due to their prevalence. Using smartphones, many studies showed the potential and benefits of using AR to access and display disaster data in its geospatial context (Itamiya et al. 2019). Tsai and Yau (2012) presented a mobile application that calculates the best route for evacuation from disaster areas and informs the user by outlining the route on the camera feed of the smartphone with AR. The Whistland system (Luchetti et al. 2018) is an example of retrieving crowdsourced disaster-related information from real-time Twitter feed for display as an AR overlay to the smartphone camera to visualize data and information on their originating sources, and it also provides detailed analysis on a web-based analytics application. Mirauda et al. (2018) developed a mobile application to provide hydrological sensor measurements and model results in an intuitive and context-informed way using AR overlays to augment point of interests (e.g. hydrometric stations). Veas et al. (2012) introduced a mobile AR application for on-site enhanced environmental monitoring and demonstrated it with two case studies yielding positive results from the participants. Fedorov et al. (2016) presented a unique approach to utilize computer vision techniques to identify mountain silhouettes and compare the extracted information to available DEM data in order to annotate the mountain and provide useful information (e.g. peak name, distance) to users as AR overlays.

In addition to data retrieval and presentation, AR/VR solutions are also developed for visualizing data resources and analyzing information in-situ or virtual environments (Reyes and Chan 2017). Ready et al. (2018) presented a virtual reality application for HTC Vive that recreates a 3D model for Japan, consisting of terrain and buildings, to allow a user to interact with various data resources to access hydrological time-series data in an easily interpretable way for disaster management. Haynes et al. (2018) developed a mobile augmented reality application to visualize potential floods on-site and integrates real-time sensor readings (e.g. water level, soil moisture, and humidity) with the vision of allowing stakeholders to use the application for flood risk management. In their after-experiment survey, the results show that users who are involved in flood management and experienced with smartphone usage while having less experience in 3D modeling found the AR application's visualizations easy to understand. Macchione et al. (2019) proposed a virtual environment to recreate an urban environment (e.g. buildings, streams, roads, levees, textures) to simulate hydraulic dynamics during different flood scenarios using an open-source 3D graphics creation application (i.e. Blender).

Several recent studies presented how AR/VR can be used for immersive disaster simulations for education, emergency management, decision-making, and evacuation drills (Smith and Ericson 2009, Mitsuhara et al. 2016, Pratama et al. 2018, Bernhardt et al. 2019, Ooi et al. 2019). Kawai et al. (2015) proposed an AR-based tsunami evacuation drill system in which the users are required to escape from a disaster scenario in a limited period of time. The disaster simulations are processed on server-side and transferred over the internet to the client device for display in smart glasses (i.e. Moverio). Iguchu et al. (2016) developed a gamified disaster evacuation training framework with a specific emphasis on supporting teachers educating students on disaster response. The system allows users to immerse themselves into various scenarios using a smartphone and interact with virtual students via voice commands. Federal Emergency Management Agency (FEMA) offered IMMERSED, an HTC Vive-based VR experience to educate community leaders and public on flood mitigation strategies by letting users to experience several scenarios (e.g. exploring the damage in a flooded neighborhood, leading a stranded person to a safe zone from a flooded school). The application walks the user through same scenarios while describing different types of actions for hazard mitigation planning (FEMA 2018). Wang et al. (2019) described a VR-based flood risk management system that aims to simulate floods for Sponge cities by integrating hydrodynamic models and topographic data into a 3D environment developed for Oculus Rift and presented a case study for Fengxi, China.

3. AR/VR Applications for Disaster Preparedness and Management

Augmented and virtual reality applications present an opportunity to develop fully immersive experiences to recreate real-time and historical disaster scenarios in a controlled experimental environment that allows repetition. Two case studies (i.e. Flood Action VR, HoloFlood) are presented in this section to demonstrate the workflow of creating both virtual and augmented reality solutions for disaster education, preparedness, and management. Various data resources (e.g. hydrological, geographical, meteorological) have been utilized to power both applications which are retrieved from organizations including the United States Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), The Weather Channel (TWC), Iowa Flood Center (IFC), and ArcGIS City Engine.

When simulating any natural event, one of the pillars of simulation's success is the accurate representation of environment and underlying dynamics. In the case of flooding, high-resolution terrain along with elevation metadata is vital for water inundation and flow calculations. For the case studies, digital elevation model (DEM) data is used to recreate the world surface and enhanced by satellite images mapped on 3D terrain objects. Critical infrastructures (e.g. buildings, bridges, dams, roads) and objects with secondary importance (e.g. trees, traffic lights, park benches) are retrieved from ArcGIS. For natural events, disaster (e.g. flood extent, depth, return period, watershed characteristics) and weather-related (e.g. precipitation duration and intensity, wind speed and direction, humidity, temperature, visibility) data are retrieved from historical sources, model forecasts, and real-time sensor readings. These data resources are available for use in specific application scenarios depending on the context and device capabilities.

Though different use cases may require the use of specific resources and integration of different capabilities, the basis (i.e. the core) of the mixed reality-based disaster management applications is the procedural generation of realistic environmental scenes. This includes high-resolution terrain models (i.e. Digital Elevation Model), satellite imagery, roads, building and infrastructure models, textures, and their appropriate placement on the scene which requires the clamping of structures to the terrain. While they are not directly linked to the disaster simulation, objects that enhance the realization experience (e.g. trees, electric poles, park benches, traffic lights and signs) can be included given that the performance of the device is capable for rendering the scenes.

The main development environments for the framework are Unity3D and ESRI City Engine. Unity3D is a cross-platform game-engine capable of producing augmented and virtual reality experiences, and ESRI City Engine is a 3D modeling software focused on generating virtual urban environments. The main reasons for choosing these platforms are their advanced physics capabilities, rich 3D resources, and export functionalities that allow flexible development and easy integration. The core 3D components of the immersive disaster management and education framework, as described in the previous paragraph, are modeled and constructed (e.g. clamping of buildings onto 3D terrain object) using City Engine and exported in FBX file format to be used for scene generation in the game engine. Disaster simulations, water physics, object animations, and interaction methods are then developed using the game engine, which has the capability of creating immersive experiences that can be ported into various AR/VR headsets and presentation channels (i.e. smartphones, web-based platforms) with little modifications to the original application. Figure 1 describes the system architecture for creating an immersive disaster management and education framework (e.g. Flood Action VR, HoloFlood) using real-time and historical environmental datasets.

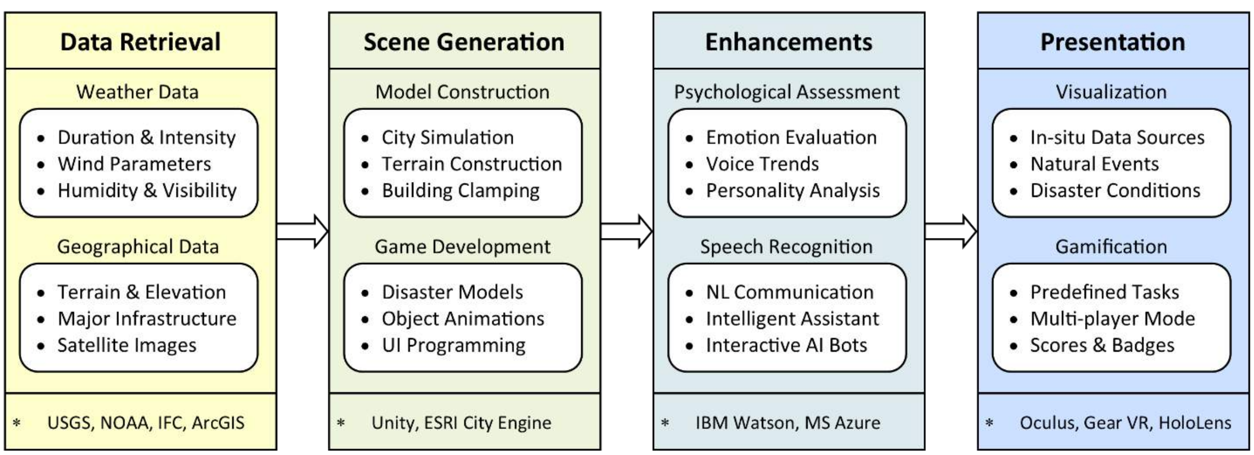


Figure 1: System-Level Architecture for an Immersive Disaster Management and Education Framework

3.1. Case Study on Virtual Reality

Flood Action VR is a virtual reality framework that utilizes real-time and historical weather, disaster, and geographic data to construct a 3D gaming environment to increase public awareness for extreme events (Figure 2). It also provides an immersive and interactive environment for training and education on disaster preparedness and response (Sermet and Demir 2018b). It integrates a voice-enabled intelligent assistant (i.e. The Flood Expert, Sermet and Demir 2018a) that is capable of comprehending and responding to complex environmental queries in natural language (NL) due to its integration with an information-centric flood ontology (Sermet and Demir 2019). The main focus of the game is to let users achieve several tasks (e.g. escaping from the flood zone, rescuing those in need, and transporting medicine and emergency supplies) within a limited time during an extreme disaster scenario while simulating intense weather conditions. The scenarios can be based upon real events and forecasts as well as custom setups. In-game navigation is done by flying a rescue drone. Interactions with the system can be made in different forms including voice-based natural language commands and default input methods (e.g. gesture, controller, touchpad) of the client device. When users are interacting with the system or other players using their voice, the system is equipped with functionality to analyze voice trends to detect emotional and psychological state.

In addition to the base 3D model of a location, Flood Action VR integrates several enhancements for a complete immersion using the real-time or historical weather conditions in various aspects of the scene. Weather conditions (e.g. precipitation type and intensity, cloudiness, visibility) are set up with using the retrieved weather data. Utilizing the wind speed and direction, a directional wind animation is created in a way that allows interaction with other 3D objects in the scene. High-quality tree models that are animated by the effect of the wind are created and placed in roadsides and parks. To avoid the high computational cost of animating tree and leaf models with the wind, a conditional rendering mechanism is implemented to change the quality of the tree object and cancel the wind-affected animation as the user gets away from the tree object. Most importantly, realistic water objects are created using the retrieved flood scenarios and animated in accordance with the environmental conditions (e.g. wind, sun, floating objects). Properties of the water object include environment reflection, refraction of color and distortion, and the shape and speed of the waves, which can be adjusted according to the computational capabilities of the client device.

Figure 2: Screenshots from Flood Action VR game for Samsung Gear VR

3.2. Case Study for Augmented Reality

HoloFlood (Demir et al. 2018) is an augmented reality framework for simulating historical, current, or forecasted flood scenarios as a hologram, structured from the 3D model of a selected location. It also provides property-specific estimations for structural and content damage as well as the vulnerable population. Scientists, decision-makers, emergency responders, and stakeholders can use HoloFlood to examine the ways a city would be affected by different types of floods and benefit from HoloFlood as a decision support tool during disaster planning and response situations. It allows collaborative inspection of the holographic simulation by multiple stakeholders to pave the way for next-generation decision support systems. The application is mainly designed for use with see-through displays (e.g. Microsoft (MS) HoloLens) (Figure 3) and smartphones with augmented reality capabilities.

Main use cases of the system can be summarized as follows. The routes for emergency responders and evacuation of affected citizens can be analyzed by considering a variety of possibilities in terms of speed and safety. Safe and accessible areas and locations can be determined to transport and deliver emergency supplies such as medication and food. By using the estimations for flood damage and vulnerable population at a property during a flood with certain extent, evacuation priorities and most efficient allocation of resources can be determined to minimize the loss of lives and economic damage. Floodplain managers can utilize the system for damage estimation based on HAZUS dataset as well as the data collected from the tax assessors, where available (Yildirim and Demir 2019). HAZUS is a standardized methodology for estimating potential damages from natural disasters including floods.

Figure 3: A snapshot of HoloFlood placed on a conference room table.

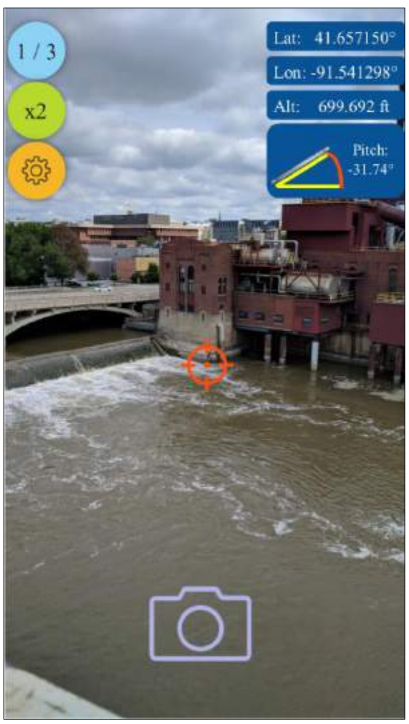
4. AR/VR Applications for Environmental Visualization and Data Analysis

Massive amount of environmental data is being generated at a rapidly increasing pace due to developments and investments in sensor technologies (Ebert-Uphoff et al. 2017) and crowdsourcing (Sit et al. 2019) which are fueled by the increased awareness for sustainability (Bibri 2018) and climate change (Weber et al. 2018) as well as the efforts for disaster preparedness and mitigation. Making good use of this large-scale datasets requires intelligent and efficient approaches for access, analysis, and communication to the stakeholders (Krajewski et al. 2017, Demir and Beck 2009). These approaches include the presentation of structured data via web-based platforms in forms of 2D visualizations and interactive tools (Demir et al., 2009) and intuitive and gamified decision-support frameworks to allow stakeholders to make informed decisions (Carson et al. 2018). Augmented and virtual reality can be utilized to develop next-generation data retrieval, on-site analysis, and in-depth visualizations in the environmental field as highlighted by the case studies described in the remaining of this section.

4.1. Environmental Data Retrieval and Sensing

Augmented reality is a beneficial tool to develop modern data sensing approaches. It provides the opportunity to guide a user to perform complex measurements and data collection with intuitive methods. Sermet et al. (2019) presented several geometry-based approaches to measure water stage using prevalent sensors found in smartphones. All approaches presented in the study require a user to take a picture of a point of interest, which is an intersection of water body with land, and assess the real-world elevation of the surface of the water body (Figure 4a). The study outlines how AR beacons and known structures can be used as a reference point to calibrate sensor readings, perform more accurate surveys, guide users to survey locations that are in more need of data points, and present previous measurements for that location and relevant information as an AR overlay.

In addition to data sensing, AR-based cyber tools can serve as a practical intermediary to communicate raw data and information to users in the appropriate spatiotemporal context. As an example, a smartphone-based AR application is developed (Demir et al. 2018) to allow the enhancement of real-time camera feed by creating interactive AR layers (i.e. overlays) for nearby sensors (e.g. water level sensor, rain gauge, soil moisture gauge) to access data resources (Figure 4b). The application filters the sensors based on proximity determined by the user and resizes the representative icons to create a perception of distance.



(a)

(b)

Figure 4: (a) Smartphone-based stream stage measurement (b) AR layers for visualizing nearby sensors on a smartphone

Another use case for enhanced data communication is the inspection and measurement of power line sag using AR-enabled smartphone applications (Sermet et al. 2018). An Android application was developed to effectively and safely inspect overhead power line sag in terms of the line's sag tolerance and distance to nearby obstacles (e.g. trees) and ground using image processing. For known locations, information boxes are generated with various useful information including the last maintenance date, previous sag measurements with neighboring poles, and action messages to reflect if the pole or line needs maintenance. These boxes are overlaid to the camera stream and placed on top of the electric poles at sight using AR (Figure 5).

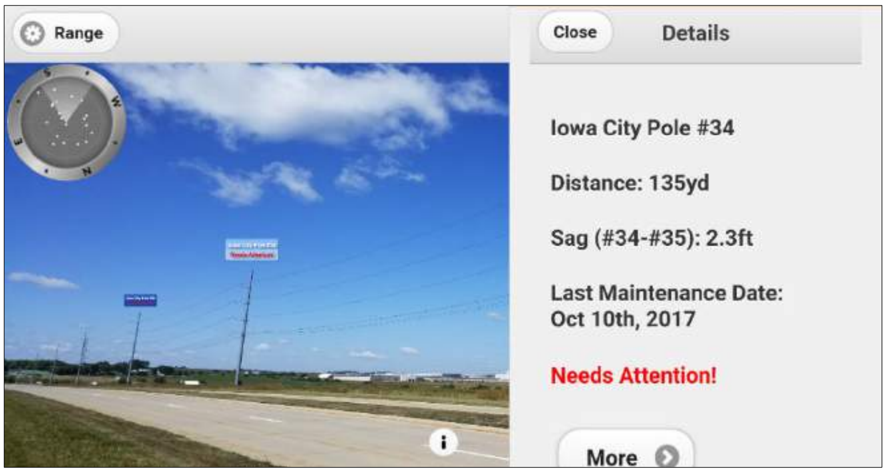


Figure 5: A screenshot from the Android application to show AR overlays for power line inspection.

4.2. Hydrological Simulations and Disaster Education

A major motivation for use of AR/VR in disaster sciences is the education of hydrological processes and natural disasters to public and students in K-12 or college levels. Mixed reality (XR) technologies can bring the fun factor to the education applications with gamification and interactive nature of these platforms. XR can allow students to experiment with environmental phenomena to see outcomes that were impractical or impossible to be reproduced in real life. An example of such initiatives is the web-based hydrological simulation system (Demir 2014) developed at the University of Iowa. The system can simulate hydrological concepts (e.g. watershed, precipitation, river network, flood inundation and mitigation) that are controlled by the instructor and students to create different flood scenarios and implement flood mitigation strategies while providing realistic visualizations to assess the potential structural and environmental damage. The system is accessible from a web browser as a 3D interactive environment, on smartphones as an AR application using a marker (Figure 6a), and on VR devices (e.g. Oculus Rift) as an immersive VR application.

In addition to education, augmenting real-life locations that are in interest to stakeholders is an effective tool in increasing awareness. The literature suggests that a notable percentage of people are undermining the effects of disasters which contributes to the lack of preparatory activities leading to increased damages and casualties (Burningham et al. 2008). A realistic flood visualizer is developed (Demir et al. 2018) using 360-degree panoramic imagery by integrating a layer of advanced water simulation (Figure 6b). The flood visualizer allows users to choose any place on 2D map that has a 360-degree imagery available and generates an interactive virtual reality instance that can be viewed on a web platform, VR headsets, and smartphones. The main advantage of the tool is to provide a unique and immersive experience on how floods affect communities and giving users a feeling of empathy. Thus, it paves the way for individuals to take roles in disaster preparedness efforts by increasing their interest.

(a) (b)

Figure 6: a) A snapshot of educational hydrological simulation environment b) A screenshot of panoramic imagery augmented with realistic flood visualization.

5. Concluding Remarks and Future Directions

The use of augmented and virtual reality technologies shows great potential for applications in environmental and disaster studies in the contexts of decision-making, education, and increasing awareness. Conventional data sensing approaches can be complemented with modern data collection methods using AR to reduce the cost of sensor deployment and maintenance in terms of invested time and resources and increase data coverage complementing conventional sensor technologies. Furthermore, AR-based data collection approaches can enable citizen science applications for crowdsourcing geospatial data, thus, decreasing the cost of computational resources supported by an agency or an organization. These developments can be facilitated by several factors including the advancements in mobile sensor technologies in terms of accuracy, size, and cost. Another factor is the newly-available 5G cellular network technology that will result in increasing mobile streaming capabilities for faster transfers of complex and high-resolution 3D models, denser sensor coverage and data points with a more comprehensive and detailed reporting.

Immersive simulation environments can support advanced analysis and scenario evaluation applications in decision support systems. The presented applications serve as prototypes and a demonstration of the potential of AR and VR applications in environmental science education and training. They also highlights various opportunities for advancement and directions for future research. Collaborative activities in immersive simulations is vital for allowing stakeholders from different physical locations to work on a common goal. AR and VR applications can support the new science of socio-hydrology which treats people as an important part of the water cycle through water consumption, pollution of freshwater resources, policies, and technology (Sivapalan et al. 2012). For 3D representation of real-world features, structural and terrain-related data need to be shared in a consensual format for easy integration to immersive systems to support the vision of global and generalized simulation platforms. Physics-based scientific dynamics and animations need to be incorporated into these applications to examine the chain-reactions caused by extreme events and human intervention. Benefiting the recent developments in deep learning and artificial intelligence in general, detailed simulations of people and their behaviors during various environmental scenarios can be developed and integrated into immersive frameworks.

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