An Augmented Reality System Architecture for Flood Management

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Abstract: Flooding represents a considerable danger to both human lives and possessions, rendering it a prevalent natural hazard. Navigation and risk assessment methods, in dynamically changing flood environments, are dependent on flood visualization methods. Addressing the limitations of 2D visualization as well as Virtual Reality (VR) setups that are employed in off-site simulations, this paper presents the system architecture of a novel system for real-time urban flood management utilizing head-worn AR, integrating extreme scale data. Our system architecture will offer a depiction of urban flood inundation in the city of Dortmund, Germany, dynamically visualizing potential evacuation routes and water levels, on-site, in urban areas, while rescuers are in operation. The system's integration with large-scale data analytics will allow the dynamic combination of weather forecasts, sensor networks, historical flood data and urban topography.

1 INTRODUCTION

Amidst the increasing frequency and severity of flooding incidents in recent years, emergency response and rescue operations face significant challenges. Navigation and risk assessment methods, in dynamically changing flood environments, are dependent on flood visualization methods, which should efficiently communicate risk, without amplifying hazards for first responders (Carver, 2019). Modern digital visualization tools are increasingly vital in enhancing the management of flood risks in urban areas (Leskens et al., 2017). Rather than commonly used 2D visualization (Towe et al., 2020), prominent technologies, including virtual reality (VR), augmented reality (AR), and digital twin simulations, are extensively utilized to depict urban flood scenarios (Oyshi et al., 2022). Among these, VR has gained extensive usage (Calil et al., 2021), (Sermet and Demir, 2019) informing for simulated scenarios, without, though, awareness of the real world. While research effort focusing on urban flood visualization are dedicated to the phases of readiness and prevention, there is a noticeable gap in the capabilities for real-time observation and handling of urban flooding events in AR (Bakhtiari et al., 2023). The reliance on mobile phones or tablets in previous AR urban flood visualization has constrained on-site operations because interaction is not hands-free (Mirauda et al., 2018).

This paper introduces the architecture of a novel system for real-time urban flood management utilizing the capabilities of head-worn AR, integrating extreme scale data. Previous work has been limited to utilizing low-scale static data for visualization (Sarri et al., 2022). Our system's architecture, when implemented, will visualize multiple urban flood scenarios by consuming dynamic data, enhancing users' situational awareness through cutting-edge AR. According to the system architecture presented, the user will wear a Hololens 2 AR headset, allowing for hands-free operation. Our system will dynamically generate potential evacuation routes and predicted flood level on-site, in real-time, contributing to the planning of an efficient rescue. This represents a notable advancement over past work, where routing to avoid pluvial floods was primarily conducted within VR environments, focusing on simulation rather than operation on the field.

Our contributions include:

- A novel AR-based system architecture for flood visualization that utilizes extreme scale and complex data analytics regarding critical urban infrastructure and weather forecasts, based on open data sources. Our system's architecture offers a depiction of urban flood inundation and will dynami-

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cally simulate potential evacuation routes and water levels. Unlike VR that confines rescuers in immersive simulations in laboratories, our system encompasses on-site rescuers' intervention.

- An AR system architecture that integrates a first-person perspective for situational awareness improvement allowing users to experience seamless integration of the real-world enriched with digital elements based on spatial data such as topography, urban networks, densities and uses, and weather forecast data, keeping users informed.
- Enhanced decision-making of flood risks and safe navigation paths based on AR visualization but also awareness of real-world surroundings, integrating emergency response protocols, ensuring safety navigation paths.

2 RELATED WORK

2.1 Augmented Reality and Floods

In addressing the increasing frequency of global flooding events and the need for heightened public awareness, past work showcases AR as an effective medium for educating the public on local flood risks (Tomkins and Lange, 2019), (Puertas et al., 2020). Users are able to engage with potential flood levels in their local flood zones, by leveraging an AR app that offers in-situ modeling of basic 3D building prototypes (cuboids) along a riverside, facilitating the visualization of an augmented flood plane (Haynes and Lange, 2016). Notably, users can actively adjust the flood plane height, enhancing the interactive experience. A real-time prototype for mobile augmented reality (MAR) is put forward merging real-time building model updates, interactive flood visualization, and seamless integration with live sensor readings, including water level, humidity, and soil moisture, accessible through a network (Haynes et al., 2018). These sensor readings contribute to detailed real-time annotations. Feedback indicates the need for increased geometric model complexity to enhance operation on-site. A MAR coastal erosion 3D visualization system is put forward leveraging geographical data visualizing future shoreline changes due to coastal erosion (Katsiokalis et al., 2020). The study operates under challenging, for screens, outdoor bright lights achieving accurate registration of 3D sea segments with the real-world coastline, viewed seamlessly through a smartphone screen. However, the application's efficiency is affected during bad weather and sea waves, causing the 3D content to drift in the scene. MAR systems require the user to hold a mobile device which, while flooding is taking place, is restrictive. To address this issue, our system architecture provides 3D visualization utilizing head-worn AR, enabling users to operate hands-free, while forecasting of events is streamed to the AR user, in real-time.

Another approach for effective flood visualization, is combining AR with a 3D-printed terrain model (Zhang et al., 2020). The study explores adaptive flood data processing and hybridizing virtual flood and terrain models. The researchers simulate a barrier lake dam-break scenario, comparing between a flood visualization placed on a 3D printed terrain model and one on a 3D digital terrain model. Results show improved flood hazard understanding when a 3D printed model is involved. In our work, we offer a system architecture which includes real-time urban flood management, through head-worn AR on-site rather than in the control room, without the need for 3D printed models.

2.2 Urban Management

Flooding is one of the serious natural climate concerns, that is intensified by climate change and can cause major economic, social, and environmental consequences. Urban flooding, which refers to the inundation of a densely populated area due to excess rainfall on a continuous and impervious stretch of land that mostly arises due to an overwhelming capacity of the drainage system and reduced infiltration rate, (Eldho et al., 2018) is a major problem in many parts of the world. Urban flooding, which can originate from coastal, pluvial, or fluvial flooding (Figure 1), is the primary source of flood losses worldwide. Among the categories of flood hazards, pluvial flooding, which is brought on by excessive precipitation combined with insufficient stormwater infrastructure or restricted infiltration capacity, has traditionally received less attention as it is thought to be controlled and generally causes less harm. Nonetheless, data indicate that pluvial flooding is a major contributor to cumulative damage over time, and that hazard exposure changes, aging infrastructure, urbanization, and global warming are all increasing the likelihood of these catastrophes, while the necessary infrastructure to mitigate floods is lacking in most urban areas, rendering them acutely vulnerable (Brody et al., 2022). The exposure of an urban area to flooding comprises the population, its uses and infrastructure, environmental and cultural assets, economic activities, and all the city's elements and facilities that cause changes in physical processes, socioeconomic growth, migration, and economic changes. The growing trend of urban flooding is a global phenomenon that has become an important field of study and provides a significant challenge, especially for modeling communities and urban planners.

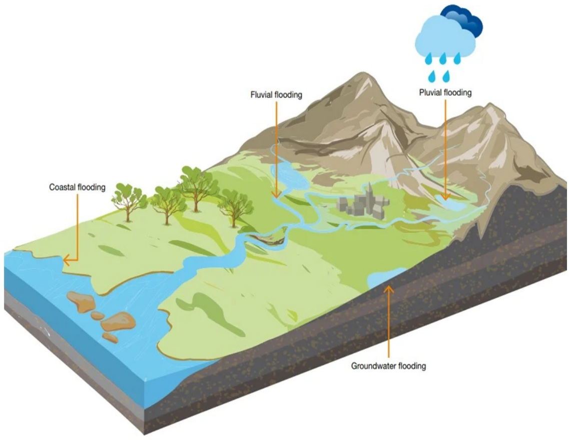

Figure 1: Types of urban flood

Urban planning must balance competing needs and maximize benefits from waterfront economic and recreational activities and ecosystem services while ensuring minimum loss of life and property through safe location, safe construction, and safe activities. Flood risk reduction measures are categorized into structural and nonstructural measures. The structural measures are mainly major public projects that require moderate-to-major planning and design efforts, while on the other hand, the nonstructural measures aim to improve urban planning and management. The nonstructural measures can be categorized into emergency planning and management, including warning, evacuation, preparedness, and flood insurance; speeding up recovery to increase resilience by enhancing building design and construction; and flood avoidance and reduction. The last category is directly linked with urban planning as it is related to land use planning as land use, public spaces, relocation, and forestation plans, and architectural planning as dry and wet flood proofing techniques, structural retrofitting or reinforcement, and facility maintenance and repair plans (Abdrabo et al., 2022). Effective flood risk management is related to urban planning factors, such as the adjustment of urban infrastructure, and land-use practices that can integrate sustainable drainage systems, create impermeable surfaces, preserve and restore natural floodplains, incorporate green infrastructure, propose limits in the construction of flood-prone areas, and formulate emergency response plans (Cea and Costabile, 2022), (Ajtai et al., 2023). Our proposed system architecture addresses the management of urban floods with the use of hydro-meteorological, topography, and urban data that ensure real-time rescue operation and coordination.

3 SYSTEM OVERVIEW

This paper proposes the system architecture for AR-based flood visualization. An innovative approach is put forward for designing a system managing urban floods and conducting on-site rescue operations in real-time through the use of head-word AR, combined with large-scale data integration. Targeting to enhance real-time decision-making in flood scenarios, our system's architecture facilitates effective coordination and execution of rescue operations. Utilizing AR headsets, first responders and emergency management personnel will access and interact with real-time visual representations of urban floods, including water levels, affected areas, and safe routes. The system's integration with large-scale data analytics will allow the dynamic combination of weather forecasts, sensor networks, historical flood data and urban topography. The result of data processing is stored in Kafka topic(s). Subsequently, the Hololens 2 device connects to the corresponding topic through a client as a consumer and receives the appropriate messages. Upon receipt of the message from the AR device, it undergoes processing to isolate the valuable information necessary for visualization. The AR environment is designed in a way that ensures vital information like flood level forecasting will be accessible without overwhelming the user or blocking users' field of view. The head-mounted AR device offers a hands-free experience, enabling users to remain fully engaged with their surroundings while receiving crucial data updates and navigational assistance.

3.1 Urban Management: Dortmund

The proposed AR-based flood visualization system is going to be evaluated in Dortmund. The city of Dortmund, situated in the metropolitan area of Ruhr and the heart of Westphalia, is in the catchment area of three river systems, and has a stable population of 590.000 according to the 2024 census. It is a postindustrial city that, in recent years, has been developing the sectors of IT, logistics, and biotechnology. In recent decades, many plans have attempted to manage the profound structural change in the economy and create the future of the municipality and region. The authorities, inhabitants, and experts of the city aim to develop fewer industrial sites, more residential areas, a lot more landscape, and more area for nature. Urban

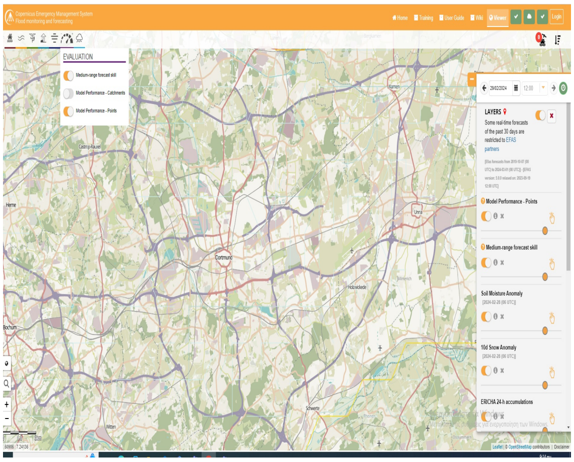

Figure 2: Copernicus Emergency Management system: Flood monitoring and forecasting

planning promotes equality and balance between the economic, environmental, and social sectors, sustainability, and participation in all planning strategies, and aims to establish a reliable framework for public and private investment in public space, retail, office buildings, housing, and large-scale projects (Sierau, 2005). Dortmund has suffered from floods in its current history, so it is important to manage floods in a way that will secure resilient urban environments. In this direction, images that create a sense of 3D space and depth create a more realistic and interactive experience for the viewer, so they can provide important information for flood management (Bakhtiari et al., 2023). AR can be applied to indicate the progress and expansion of the flood occurrence and to assess the flood damage and vulnerability of urban structures. AR models of the built environment enhances realism and enables more accurate assessments of flood damage. Hence, combining AR technology with flood data can provide decision-makers with valuable insights in urban flood management (Schröter et al., 2018).

The urban elements that need to be visualized are related to the city's exposure hazards and vulnerability. These are topography data as Global digital terrain models (DTMs)—Shuttle Radar Topography Mission (SRTM) and Multi-Error-Removed Improved-Terrain (MERIT) as well as locally available data such as laser imaging, detection, and ranging (LiDAR); high-resolution satellite or orthophoto imagery; drone survey data; and bathymetric surveys of water bodies (Ferguson, et al., 2023). Data to be integrated may be the Hydrometeorological data global datasets such as Multi-Source Weighted-Ensemble Precipitation (MSWEP) or European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) or the Copernicus Emergency Management system for flood monitoring and forecasting (Figure 2) and local datasets with time series of rainfall and winds, water levels, or river discharges. Another important urban element is the existing flood protection infrastructure and numerical models for flood hazard modeling, as well as the layout and dimensions of primary and secondary drainage infrastructure such as road drainage, canals, culverts, pump stations, and tidal gates, as well as the dimensions and characteristics of coastal or fluvial embankments, dunes, and existing hydrological, hydraulic, and risk models (Ferguson et al., 2023). Existing flood, exposure, or vulnerability data such as global or local flood hazard maps, (mapped flood hot spots), OpenStreetMap data, cadastre system data, building types, population distribution, and characteristics are also elements that may be visualized as having decisive role in flood management. Finally, the city's infrastructure, such as roads, drinking water, sanitation, drainage, and flood protection infrastructure; health care and school facilities; and environmental and cultural assets; are urban elements that have a decisive role in city's resilience and urban flood management. In the proposed system architecture, the available data are the available data sets from the EU sites as Copernicus browser (Copernicus Browser, 2024), the European floodsviewer (European floodsviewer, 2024), fire data (Copernicus fire data, 2024) and urban data as mobility networks, public infrastructures, available 3d models, e.t.c

3.2 System Architecture

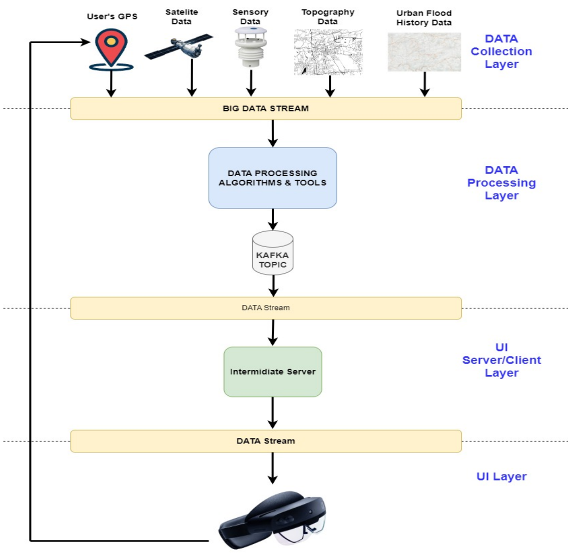

Figure 3: System Architecture and Layers

The proposed architecture, as illustrated in Figure

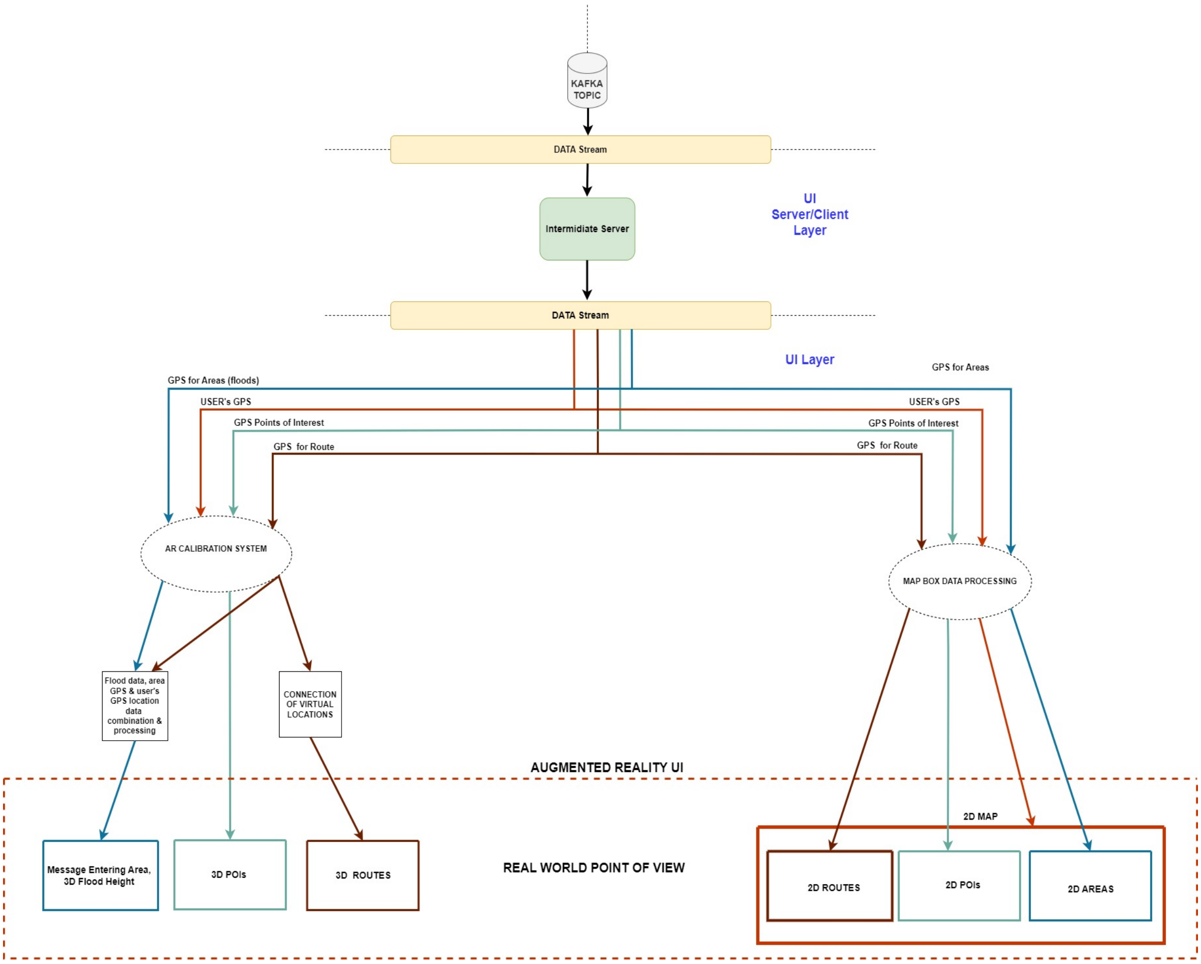

Figure 4: AR Design

3 and Figure 4, integrates both static and dynamic into the DATA Processing Layer. These sources include geo-location data, information from weather sensors, topography data, flood history records, satellite imagery, and the user's GPS location. The data undergoes mostly real-time processing within the Data Processing layer, utilizing machine learning algorithms and big data processing tools such as Apache Flink. Continuously, the processing results include forecasts of water levels in urban floods, identification of dangerous and safe areas and establishment of evacuation routes stored in a Kafka Topic. The data from the Kafka Topic is retrieved through an intermediate server located in the Server/Client Layer and is formatted in GeoJSON (GeoJSON, 2016). The server deserializes the GeoJSON data before transmitting it to the HoloLens 2 device. In Hololens 2, data undergoes additional processing to align real-world data with the AR world coordinate system. Hololens 2 user interfaces and interaction is being developed in Unity3D, employing the Mixed Reality Toolkit (MRTK3, 2023).

3.3 Design of the AR Experience

When on-site, the user will wear the Hololens 2 which is connected to the appropriate Kafka topic via the intermediate server. When the HoloLens 2 device connects to the server, it begins consuming the data required for visualizing valuable information. As seen in Figure 4, the data consumed from the server undergoes two different processes simultaneously:

- A process which visualizing the given data into the 3D world
- A process for visualizing the data on a 2D map, which map will be positioned in the upper right corner of the field of view (FOV) of the HoloLens 2.

Our AR visual components design, included in the proposed architecture, is based on five different patterns: a) **Proxy**, which is a visualization near the user that resembles a referent that is farther away, b) **Panel** is a conventional visualization shown together with the real world objects, semantically linked to a referent, but lacks a geometric relationship to the physical environment, c) **Labels** are a pattern typically used in an embedded view. Labels are intended to supply additional information to referents, d) **Glyphs** that are simply visual encodings of some information associated with one or more referents, which are placed so they are touching the referent(s) and e) **Trajectories** which are a special kind of glyph that connects two or more endpoints (Lee et al., 2023). The information that we will be visualized on the Hololens 2 is:

2D Map: The pattern that we use for 2D map component is the "**Proxy**". The 2D map will be always be centralized around user's GPS location. Additionally, on the map, routes, points of interest (schools, hospitals etc) and areas will be displayed. We use the mapbox platform for 2D Map visualization and for conversion processing (Mapbox, 2010).

Routes: We begin by receiving a set of GPS locations retrieved from a GeoJSON file from the "Line String" property. For real-world visualization, the pattern that we use is the "**Trajectory**". We will then align the real GPS locations with the local coordinate system of the Hololens 2 device through an AR calibration process and visualize those points on the real world. We will connect these points one by one with a line, starting from the user's GPS location which is also aligned with the local coordinate system of the Hololens 2 device. For the 2D map visualization, we follow the same logic, with the only difference being the calibration process, which must be aligned with the 2D map coordinate system. The 2D map visualization object will be toggled on and off to ensure that the user's field of view (FOV) remains unobstructed. A concept of route is illustrated in Figure 5.

Figure 5: Route Visualization Concept

Points of Interest (POI): Utilizing the **Glyph** pattern, we apply the same logic as with "Routes" to visualize any point of interest on a 2D map and in the 3D world. The key difference is that we don't connect these points with lines A concept of point of interest visualization is illustrated in Figure 6.

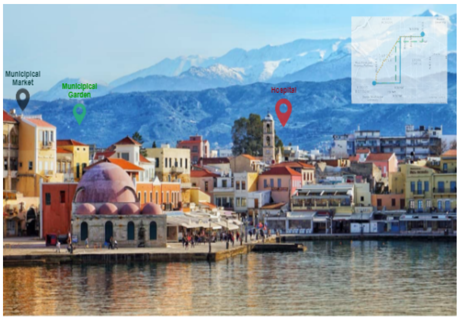

Figure 6: POI Visualization Concept

Areas: Following the same logic as with "Routes", we extract valuable data from the GeoJSON residing in the "Polygon" property. Next, we will generate GPS points on the 2D map and connect them sequentially with lines, connecting also the last point with the first. In the real world, a message will be displayed on lens utilizing the "**Panel**" pattern, informing the user that they have entered a specific area by combining the user's GPS location with the defined area shape.

Flood (Areas): We consider the "Floods" as "Areas," and we follow the same logic as described above for visualizing them both in the 2D map and in the 3D world. The key difference is that in the 3D world, we will also visualize the possible water levels that may be reached during the next time window in a manner that does not obstruct the user's field of view (FOV), utilizing the **Panel** pattern. A concept of "Flood" visualization is illustrated in Figure 7.

Figure 7: Flood Area Visualization Concept

4 CONCLUSIONS

This paper proposes a novel system architecture for AR flood visualization that will, when implemented, utilize extreme scale and complex data analytics regarding critical urban infrastructure and weather forecasts, based on open data sources. Our system architecture dynamically visualizes potential evacuation routes and water levels, while a rescuer wears AR apparatus and moves on-site. We expect that the first-person perspective of head-word AR will improve situational awareness and allow informed decisions and intervention in high-risk areas. Initial testing will be conducted in the area of Dortmund, Germany. Our system will be complemented by gaze-based interaction, allowing for hand-free operation as well as level-of-detail management of digital information, as superimposed onto the real-world so that the real-world is not obstructed. Moreover, rescuers' physiological monitoring will allow communication of distress.

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