Developing an Immersive Virtual Reality Interface for Urban Digital Twins: Integrating CAVE and HMD Systems for Enhanced Urban Analysis

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ABSTRACT

Understanding urban environments is challenging due to dynamic changes in population, climate, traffic, and infrastructure. Our research leverages Digital Twin and Virtual Reality (VR) technologies to create an immersive interface for urban analysis. We explore two directions: (1) reviewing and experimenting with methods to capture, store, and render realistic virtual cities, and (2) implementing an immersive VR setup using CAVE and Head-Mounted Displays (HMDs) for urban digital twins. This work enhances user immersion through precise 3D replication, supporting better decision-making in areas like pollution management, infrastructure, traffic, and disaster response.

Keywords: Urban Digital Twin, Virtual Reality Interfaces, Cave Automatic Virtual Environment (CAVE), Head-Mounted Displays (HMDs), Urban Simulation

INTRODUCTION

The objective of this research is to develop an affordable, immersive Virtual Reality (VR) platform for visualizing urban digital twins with high-quality, real-time rendering. The system is designed for portability, ensuring deployment in workshops and events, and is capable of integrating real-time data from IoT sensors as well as historical datasets like population and traffic patterns. Using VR technologies, such as Head-Mounted Displays (HMDs) and Cave Automatic Virtual Environment (CAVE) systems, the platform provides immersive experiences of urban areas, allowing users to explore 3D models in a highly realistic virtual environment. The system's architecture is modular, enabling flexible simulation of urban scenarios including infrastructure changes, environmental conditions, and disaster responses. Built on platforms like Unity and ArcGIS, it supports layered data integration and 3D spatial visualization, facilitating enhanced decision-making in domains such as pollution control, urban planning, traffic optimization, and emergency management.

SYSTEM ARCHITECTURE

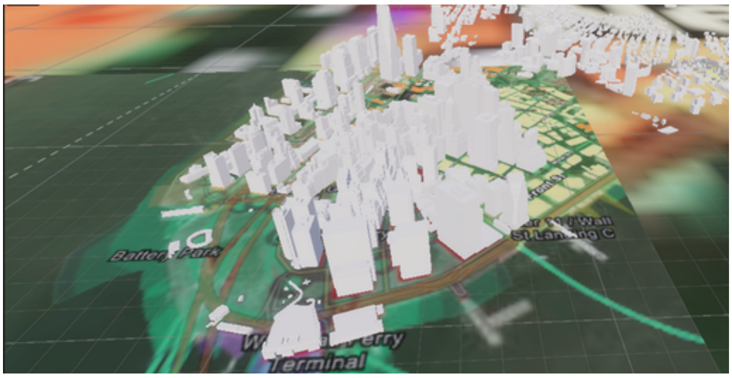
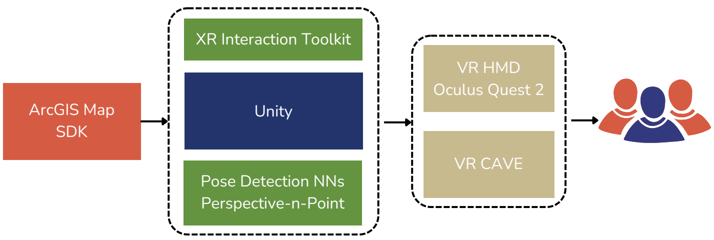


Fig. 1. Integration of ArcGIS map data with Unity

The architecture of the proposed system is designed to integrate immersive VR technologies with real-time urban data. Two VR systems are implemented: a Head-Mounted Display (HMD) setup and a Cave Automatic Virtual Environment (CAVE) setup. These systems allow for interactive exploration and analysis of urban digital twins, enhancing user immersion and decision-making processes.

- **Platforms:** The system is built on the Unity engine, with real-time data rendered using the ArcGIS platform. The combination provides an interactive environment for users to explore urban models.
- **Data Integration:** The system gathers data from IoT sensors, historical datasets, and 3D models. ArcGIS provides real-time map updates, displaying detailed urban features such as 3D building models, traffic density, air quality, temperature, pollution levels, and population data, ensuring the system remains up-to-date with changing urban conditions.



VR HEAD-MOUNTED DISPLAY (HMD)

The VR Head-Mounted Display (HMD) system allows users to explore the digital twin in an immersive, first-person environment. Using the Oculus Quest 2 as the primary device, the user interacts with the 3D model through head and hand tracking, enhancing their sense of presence within the virtual urban space. The ArcGIS camera is attached to this avatar to ensure the rendering from the user perspective.

- **XR Interaction Toolkit:** This toolkit provides user avatars and controllers for interacting with the VR environment.
- **Real-time Interaction:** Users can navigate, teleport, and interact with urban elements such as buildings, roads, and traffic flows, using a highly intuitive interface. Real-time feedback ensures immediate response to user inputs.

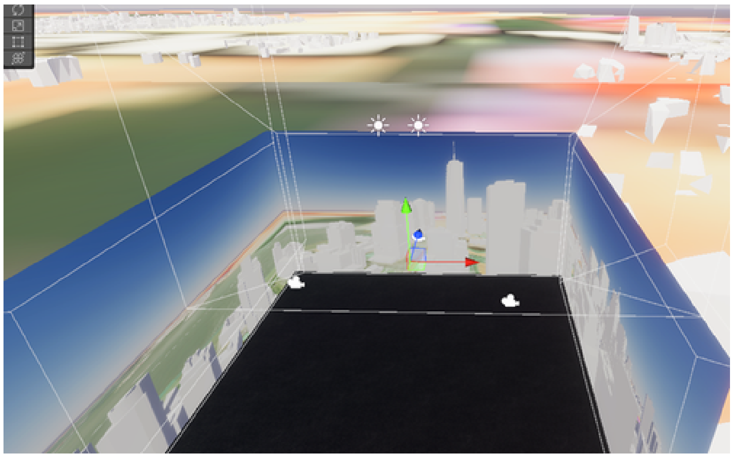


Fig. 2. VR CAVE setup with three display walls for immersive experience

VR CAVE

The CAVE setup features a multi-display environment for collaborative, immersive urban simulations. Unlike HMD systems, CAVE environments enable multiple users to interact with a shared digital twin simultaneously, fostering collaborative teamwork in urban planning scenarios. The displays are front-projected onto three walls, creating a room-sized immersive environment with full 270-degree coverage. The system is designed to calibrate dynamically to any environment, independent of a fixed coordinate framework, which allows for flexible deployment.

- **Projection Mapping:** The system uses orthographic cameras to accurately map virtual displays to physical ones. A key aspect of this process is synchronizing the projected views with the user's perspective to maintain the illusion of depth and ensure immersive interaction.
- **Posture Detection:** Pose estimation using PoseNet is enhanced with MobileNet and ResNet deep learning models to track users' body positions. The captured data dynamically updates the projection matrix, ensuring that interaction remains accurate regardless of user position, without needing external tracking devices.
- **Perspective-n-Point (PnP):** The PnP algorithm computes the 3D positions of keypoints based on 2D image data. This algorithm is crucial in dynamically adjusting the CAVE's projection matrix by re-calibrating axis alignments, thus ensuring that the immersive scene adapts accurately to user movements and orientation.

EXPECTED RESULTS

This research aims to finalize a proof-of-concept VR system for smart city digital twins, starting with the POLITEHNICA Bucharest campus and designed to scale to other urban environments. ArcGIS will store textured 3D models, IoT sensor data, and feature-rich layers, while Unity provides high-quality, real-time rendering. The system will support immersive visualization in both VR HMD and CAVE setups, enabling users to explore and interact with urban environments in real-time, facilitating the identification of potential issues and testing of infrastructure under various conditions and scenarios.

CONCLUSION AND FUTURE WORK

Future work will focus on acquiring and integrating additional ArcGIS resources from the national archives of Romania to enrich the urban digital twin dataset. This will include historical maps, cadastral data, and other relevant geospatial information. Furthermore, we will incorporate data from IoT sensors installed by researchers at POLITEHNICA Bucharest National University of Science and Technology, such as air pollution monitors, parking availability sensors, temperature gauges, and garbage collection sensors, to create a dynamic and responsive virtual environment. For the CAVE environment, experiments will be held to balance the number frames per second with the inference time for posture detection of the user in the 3D coordinates of the real world, to create a seamless interaction. Furthermore, gesture recognition will be added to facilitate teleportation and menu selection in the CAVE virtual scene.