Introduction to a Voxel-based Urban Digital Twin for Emergency Response Information Systems (ERISs)

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Abstract:

Digital maps are increasingly vital in emergency management, improving coordination, resource planning, and situational awareness. However, current systems often lack real-time data access and tailored solutions for first responders. While 2D visualizations remain dominant, 3D geodata and urban digital twins show significant promise in enhancing rescue efficiency, situational awareness, and dynamic updates (Wolf et al., 2022). This research introduces a voxel-based urban digital twin for Emergency Response Information Systems (ERISs). The proposed web-based prototype includes focus+context 3D visualization, resource visual tracking, and interactive scene observation to optimize response times and decision-making, establishing a foundation for a future ERIS platform.

The research focuses on firefighters as the primary user group due to their essential role in the early stages of emergency situations and large-scale incidents. To address the complexity of their tasks, a review of existing literature identified overlapping requirements for ERISs, and consultations with domain experts helped prioritize the most critical features for the initial phase of incident management (Volk and Sterle, 2021). Consequently, the application concept is designed considering effective 3D visualization of the incident area, integration and communication of smoke sensor and hydrant data, and the identification of entry points. Within this framework, ERIS users are divided into two roles: operators, who analyze incidents either on-site or remotely, and firefighters, who depend on the system to enhance situational awareness and operational efficiency. The scenario begins with an incident notification, such as a smoke sensor activation, prompting operators to assess the site, identify hydrant locations, and forward key information to firefighters as they head to the scene.

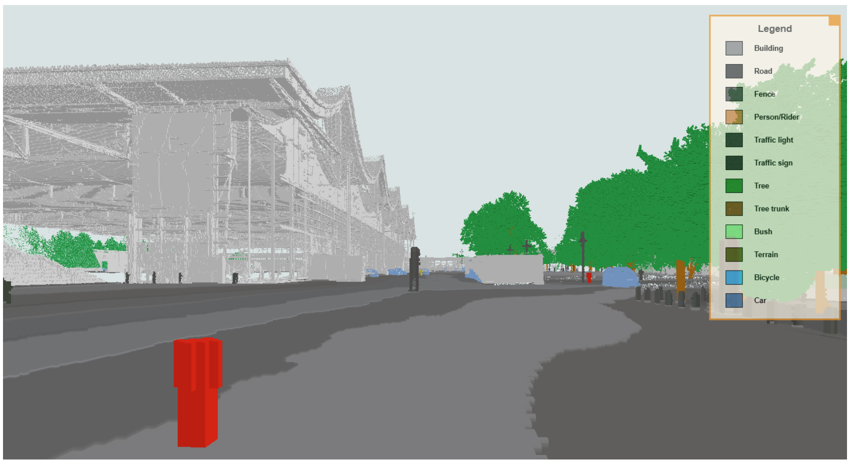

Figure 1. Voxel-based 3D urban digital twin.

To support the introduced scenario, the voxel-based urban digital twin is developed as a web-based application, integrating point cloud data, smoke sensor information, and hydrant details. For this purpose a high-resolution georeferenced point cloud is classified into 13 object types, while smoke sensor data are manually geolocated and hydrant information, including type and water throughput, was extracted and aligned with GIS tools. All data are integrated into a voxel grid with a 10 cm resolution. The 3D urban model is generated from the obtained grid using the Three.js library, which enables the creation of customized navigation tools and interactive visualization features. The resulting web application is presented through a 3D scene, allowing users to navigate it using four modes: ego view, flying, bird's eye view, and orthogonal 2D view. Each mode offers a unique perspective to support different analysis needs, from a walking perspective in ego view to an aerial view for strategic planning in bird's eye mode. Figure 1 presents the obtained voxel-based scene in the ego view, with hydrants identified by red coloring. In additioon, specialized interaction tools are implemented to allow users to observe geographical coordinates, voxel heights, and measure distances between two points within the scene.

Furthermore, a specific visualization approach is proposed to convey critical firefighting information. Emergency notifications are emphasized with blinking red backgrounds to indicate smoke sensor activation. Hydrant symbols are displayed based on their proximity to the incident, with opacity levels reflecting the distance. The focus+context technique enhances the visibility of important objects, such as hydrants and smoke sensors, by applying a gray-scale color scheme to the surrounding scene. Dynamic rendering ensures that occluded hydrants remain visible through a flashing effect, improving accessibility and visibility during operations.

Figure 2 demonstrates the general display of the application. The scene is shown in a bird's-eye view, visualized using the focus+context approach. In this visualization, critical information, such as the incident location (activated smoke sensor) and hydrant positions, is highlighted by de-emphasizing less important information through the applied grayscale. The hydrants and smoke sensors are represented by standard symbols according to VdS 2135 (VdS Schadenverhütung GmbH, 2024). Additionally, the hydrants are presented with varying opacity levels indicating their proximity to the incident. The nearest hydrant to the incident point is fully opaque and highlighted in green, while other hydrants have varying opacity based on their distance from the activated smoke sensor. This visual variable provides direct communication to the user about the closest and farthest hydrants without requiring additional text notifications. Furthermore, a 2D mini-map, visible in the right corner of the display, shows the current camera position, hydrant and smoke sensor locations, and indicates entrance points. The message in the lower right corner represents information about the activated smoke sensor.

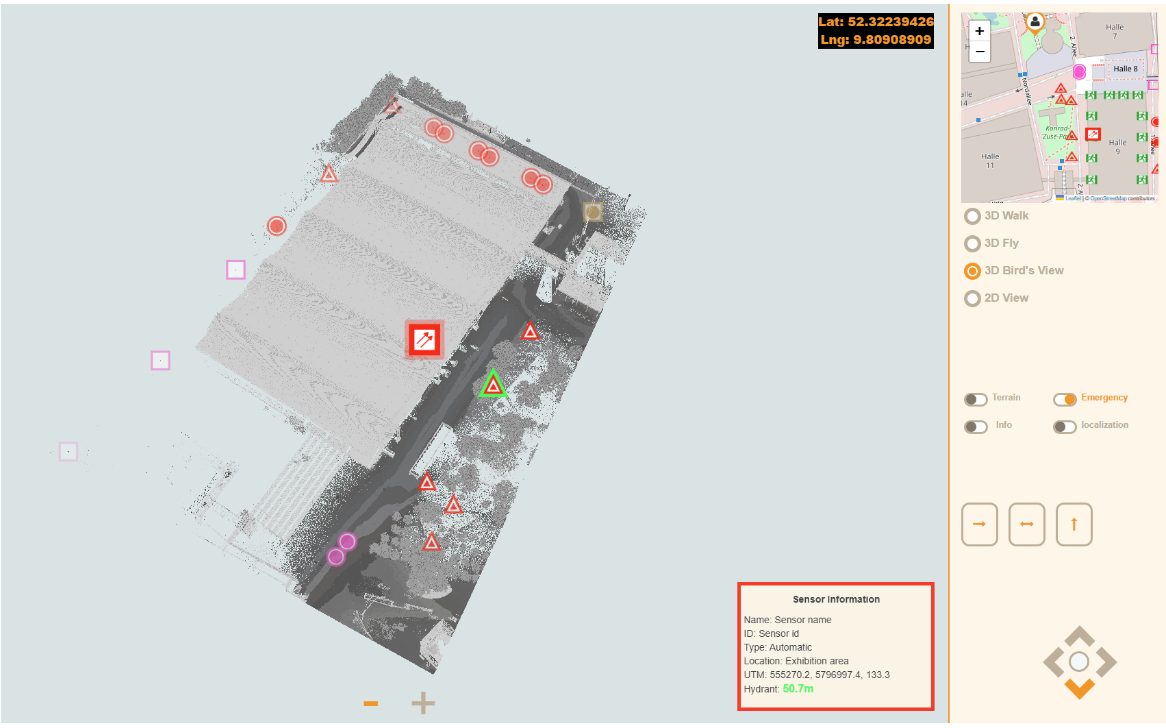

Figure 2. General view of the application with the visualization approach considering critical information for firefighter operations.

Future work in this research will focus on real-time updates, efficient data processing, and the incorporation of dynamic changes into the 3D voxel model. Additional features, such as 3D emergency routes and indoor floor plans, are also planned for implementation. Furthermore, VR/AR technologies will be explored to enhance emergency response tools. The ultimate goal is to develop a comprehensive, interactive system to improve firefighting and emergency management.

References

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