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РОЗРОБКА ПРОГРАМНОГО ЗАСОБУ ДЛЯ ВІЗУАЛІЗАЦІЇ ВЕЛИКИХ ОБ'ЄМІВ ПРОСТОРОВИХ ДАНИХ В ГЕОІНФОРМАЦІЙНИХ СИСТЕМАХ

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DEVELOPMENT OF A SOFTWARE TOOL FOR VISUALISING LARGE VOLUMES OF SPATIAL DATA IN GEOGRAPHIC INFORMATION SYSTEMS

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The exponential growth in geospatial data, driven by advances in satellite imagery, remote sensing, IoT sensors, and mobile mapping technologies, presents a formidable challenge for modern Geographic Information Systems (GIS). As spatial datasets increase in volume and complexity, efficient and scalable visualisation tools become paramount. Traditional GIS platforms

often struggle to maintain performance and interactivity when handling large, multidimensional spatial datasets, particularly in real-time or web-based environments. This research presents the development of a software tool designed to address these limitations by providing high-performance visualisation of massive geospatial datasets. The tool leverages modern graphics rendering techniques, including WebGL and GPU acceleration, to ensure smooth vector and raster data rendering at multiple zoom levels. It also integrates hierarchical spatial indexing (e.g., quadtrees, R-trees) and level-of-detail (LOD) algorithms to optimise data retrieval and reduce latency.

Keywords: spatial data, geovisualisation, GIS, WebGL, big data rendering, real-time mapping, geospatial analytics.

In recent years, the volume and granularity of spatial data have expanded rapidly due to the proliferation of data acquisition technologies such as remote sensing satellites, LiDAR-equipped drones, GPS-enabled mobile devices, and distributed environmental sensors. These datasets often encompass terabytes of heterogeneous, high-dimensional information, including topographic layers, land cover maps, climate records, and urban infrastructure models. Traditional Geographic Information Systems (GIS) were not originally designed to handle such scale, leading to degraded performance, latency issues, and limited interactivity when visualising or manipulating large datasets in real-time. Consequently, there is a growing demand for specialised visualisation tools to manage and render massive geospatial data with high efficiency, scalability, and responsiveness.

This study addresses this challenge by presenting a software tool for visualising large volumes of spatial data within GIS environments. The tool was designed to operate in desktop and web-based contexts, accommodating diverse deployment scenarios

such as urban analytics dashboards, field survey platforms, and real-time emergency response systems. Core design principles included performance optimisation, modular architecture, and compatibility with existing geospatial data standards and infrastructures.

The technical foundation of the tool relies on modern rendering pipelines powered by WebGL and GPU-based processing. These technologies allow for the parallel processing of graphical primitives and seamless rendering of raster and vector geospatial data. The tool employs spatial indexing mechanisms such as R-trees and quadtrees to enhance further performance, efficiently segment and retrieve spatial features based on user interactions like panning, zooming, or filtering. These indices are complemented by Level-of-Detail (LOD) techniques that dynamically adjust the resolution and complexity of rendered elements based on the user's viewport and zoom level, reducing computational overhead while maintaining visual fidelity.

In addition to rendering performance, data management and interoperability were key concerns. The tool supports ingestion of standard geospatial formats, including Shapefiles, GeoJSON, TopoJSON, and Cloud Optimised GeoTIFFs. It also offers compatibility with Web Map Services (WMS) and Web Feature Services (WFS), enabling integration with geospatial servers and public data repositories. A modular parser system extends the tool's capabilities to accommodate new data formats or transformation pipelines. Furthermore, a data caching layer was introduced to minimise redundant retrievals and allow offline access in bandwidth-constrained environments.

The user interface was designed to ensure intuitiveness and interactivity without sacrificing performance. It includes real-time legend updates, on-demand attribute inspection, multi-layer overlay toggling, and time-series data playback for temporal datasets. The tool supports WebSocket connections and incremental rendering updates to maintain synchronicity between data sources and the visual layer for dynamic or streaming spatial data sources, such as vehicle tracking or weather sensor networks.

To evaluate the tool's effectiveness, a series of controlled experiments were conducted using open geospatial datasets, such as satellite imagery from Copernicus, urban zoning data from OpenStreetMap, and high-resolution elevation models. Benchmarking tests were performed across different hardware configurations and web browsers to assess frame rates, memory consumption, and initial load times under varying data volumes. The results indicated that the tool could render multi-gigabyte datasets while maintaining frame rates above 30 FPS on mid-range hardware, and up to 60 FPS on machines with dedicated GPUs. The tool demonstrated significant gains in rendering latency and responsiveness compared to traditional GIS viewers and web mapping libraries.

The experiments also highlighted the tool's ability to support user-driven analytical workflows. For example, in an urban heat mapping application, the system could visualise daily temperature variations overlaid on land use patterns, with users applying filters by time, location, and surface material. In another scenario focused on disaster response, real-time flood modelling data was streamed into the viewer to guide evacuation planning and infrastructure protection. These use cases demonstrated the tool's technical capabilities and practical value in decision-making contexts where spatial awareness is paramount.

Several challenges emerged during development and testing. Handling inconsistencies and gaps in public geospatial datasets required robust data validation routines and fallback rendering strategies. Performance bottlenecks due to excessive rendering of fine-grained vector features were mitigated using spatial generalisation techniques and vector tiling. Additionally, differences in browser implementations of WebGL necessitated cross-platform compatibility checks and rendering fallbacks.

Future enhancements to the tool include integrating 3D terrain visualisation using elevation data meshes, supporting augmented and virtual reality interfaces, and implementing machine learning-based feature classification and anomaly detection. Work is

also underway to enable server-side pre-processing of spatial data for use cases requiring ultra-low-latency rendering or bandwidth-limited deployment.

The broader significance of this research lies in its contribution to visual analytics within GIS. As spatial datasets continue to grow in size and complexity, the visual component of GIS becomes a limiting factor in their utility. By enabling efficient, scalable, and user-friendly visualisation of large spatial datasets, the proposed tool enhances the value of geospatial information in fields ranging from smart city planning and infrastructure development to biodiversity conservation and climate science.

In conclusion, the presented software tool offers a robust, standards-compliant, and performance-oriented solution for visualising large volumes of spatial data in GIS contexts. Its integration of modern rendering technologies, advanced indexing and data management strategies, and emphasis on interactivity and scalability make it a valuable asset for a wide range of geospatial applications. The results of empirical testing confirm its viability as a next-generation GIS visualisation platform capable of meeting the demands of contemporary spatial data analysis.

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