3D Visualization of Terrain Surface for Enhanced Spatial Mapping and Analysis

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Abstract. Visualization of terrain surface finds many applications indifferent area of earth sciences, GIS, and geomatics. With advent of advanced computer graphic algorithms and their HPC implementation through GPU, realistic and high-fidelity visualization of terrain surface is possible. Geographic Information Science (GIS) has made considerable strides since the introduction of 3D terrain visualization facilitating accurate visualization, analysis and measurement of geospatial events and attributes. This paper discusses the significance of different terrain visualization techniques with a special emphasis on 3D visualization.

How 3D terrain visualization is useful in photogrammetry, LiDAR, and aerial imagery, maps can generate detailed models of terrains, buildings, and objects. These techniques enable users to explore geographic features from various angles, zoom in for detailed analysis, and even simulate virtual environments. The applications of 3D maps are diverse and far-reaching. In virtual reality, they can create immersive environments for training, simulations, and gaming. In remote sensing, they aid in understanding natural resources, urban planning, and disaster management. In scientific visualization, they enable researchers to analyze complex spatial data and model real-world phenomena. In GIS, 3D maps enhance spatial analysis, decision-making, and communication of geospatial information.

In conclusion, the evolution of 3D maps in GIS has revolutionized how geographic information is visualized and analyzed, with potential applications in various domains. Advancements in technology continue to drive the development of 3D maps, transforming how we perceive and interact with spatial data, making it more realistic and meaningful.

Keywords: 3D Map · GIS · terrain visualization · photogrammetry · remote sensing · DEM

1 Introduction

Geographic Information System (GIS) has revolutionized the way we collect, store, manage, and analyze spatial data. GIS has been widely used in various fields such as urban planning, environmental management, natural resources, disaster management,

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and transportation. One key aspect of GIS is map visualization, which allows users to interpret and understand complex spatial data in a visual format. Over the years, the evolution of GIS has witnessed significant advancements in 3D map visualization techniques, enabling users to interact with geographic data in more immersive and realistic ways. In this article, we provide a brief history of GIS, discuss the importance of 3D visualization in GIS, and present the purpose and scope of the article.

1.1 History of GIS

Geographic Information System can be traced back to the 1960s when the first computer-based mapping systems were developed. These early systems were limited in functionality and primarily used for data storage and retrieval. In the 1970s, the development of computer hardware and software enabled the creation of more advanced GIS systems, which were used primarily for land use planning and natural resource management. In the 1980s, the introduction of desktop computers and affordable GIS software made GIS more accessible to a wider range of users, including government agencies, academia, and private industries. With the advent of the internet in the 1990s, web-based GIS emerged, allowing users to access and share spatial data over the internet. Today, GIS has become an integral part of many disciplines and continues to evolve with advancements in technology.

1.2 Importance of 3D Visualization in GIS

The introduction of 3D visualization has added a new dimension to GIS, allowing users to visualize and analyze geographic data in three dimensions, which provides a more realistic and immersive experience. 3D visualization in GIS allows users to represent spatial data in a more accurate and intuitive manner, providing insights into the spatial relationships between objects and their vertical dimension. It has become a valuable tool in various fields such as urban planning, architecture, disaster management, and virtual tourism. For example, in urban planning, 3D visualization can help city planners to assess the impact of proposed developments on the surrounding environment and visualize the potential changes in the city's skyline. In architecture, 3D visualization can aid in the design and visualization of buildings and structures in their real-world context. In disaster management, 3D visualization can assist in understanding the terrain and topography of affected areas, aiding in emergency response and evacuation planning. In virtual tourism, 3D visualization can provide virtual tours of natural landscapes and cultural heritage sites, enhancing the visitor experience. The importance of 3D visualization in GIS cannot be overstated as it adds a new dimension of understanding and analysis to spatial data.

1.3 Purpose and Scope of the Article

Purpose of Article

1.3.1 Historical Overview

This subsection aims to provide a brief history of GIS, tracing its development from the early computer-based mapping systems to the present-day web-based GIS. It highlights the key milestones in the evolution of GIS and sets the context for the introduction of 3D map visualization.

1.3.2 Importance of 3D Visualization

This subsection discusses the significance of 3D visualization in GIS, emphasizing its role in enhancing the understanding and analysis of spatial data. It provides examples of how 3D visualization has been applied in various fields such as urban planning, architecture, disaster management, and virtual tourism, illustrating its importance in diverse applications.

Scope of the Article

1.3.3 Review of 3D Visualization Techniques

This subsection provides an overview of the different techniques and technologies that have been used for 3D map visualization in GIS, including photogrammetry, lidar, virtual reality, and augmented reality. It discusses the advantages, limitations, and applications of each technique, providing a comprehensive review of the current state of 3D visualization in GIS.

1.3.4 Applications of 3D Visualization

This subsection presents the diverse applications of 3D visualization in GIS, showcasing examples from various fields such as urban planning, architecture, environmental management, disaster management, and tourism. It highlights the unique benefits and challenges of using 3D visualization in each application domain, providing insights into the practical use cases of 3D visualization in GIS.

1.3.5 Challenges and Future Directions

This subsection discusses the challenges and limitations of 3D map visualization in GIS, such as data integration, interoperability, and usability. It also highlights the emerging trends and future directions in 3D visualization, including advancements in technology, data sources, and user interface design. This subsection provides insights into the potential opportunities and future developments in the field of 3D map visualization in GIS.

2 Traditional 2D Map Visualization

2.1 Overview of Traditional 2D Map Visualization

Traditional 2D map visualization has been the foundation of GIS, providing a visual representation of spatial data on a flat surface. It involves the use of symbols, colors, and other graphical elements to convey information about the spatial features, attributes, and relationships. 2D map visualization has been widely used for spatial analysis, decision making, and communication in various fields such as urban planning, environmental management, transportation, and agriculture. It has proven to be effective in visualizing geographic data, identifying patterns, and making informed decisions.

2.2 Limitations of 2D Map for Spatial Analysis and Decision Making

Despite its widespread use, traditional 2D map visualization has certain limitations that can hinder spatial analysis and decision making. One of the main limitations is the lack of depth perception, which can make it challenging to understand the 3D nature of spatial data. This can result in misinterpretation of spatial relationships and inaccurate analysis. Another limitation is the inability to represent complex spatial features and their interactions in an intuitive manner, such as visualizing the interior of buildings, underground infrastructure, or complex terrains. Additionally, 2D maps can sometimes fail to effectively convey the scale, elevation, and other three-dimensional characteristics of spatial data, which can impact decision making in certain applications.

2.3 Need for More Advanced Visualization Techniques

The limitations of traditional 2D map visualization have led to the development of more advanced visualization techniques, particularly 3D map visualization in GIS. 3D visualization techniques enable the representation of spatial data in a more immersive and intuitive manner, providing a better understanding of the spatial relationships, scale, and elevation. They allow for the visualization of complex spatial features and their interactions, providing a more realistic and holistic view of the data. Furthermore, 3D visualization techniques can enhance spatial analysis and decision making by enabling more accurate measurement, simulation, and prediction of spatial phenomena.

3 Early Attempts at 3D Visualization

3.1 First Attempt at 3D Visualization for GIS

The first attempts at 3D visualization for GIS can be traced back to the 1960s and 1970s when computer graphics technology was in its infancy. Researchers and practitioners started exploring ways to represent geographic data in three dimensions, aiming to provide a more realistic and immersive view of the data. These early attempts involved the use of simple wireframe models, basic shading techniques, and limited interactive capabilities. The focus was primarily on visualizing terrain and topographic features, with limited consideration for other types of spatial data [1].

3.2 Challenges in Generation of 3D Maps

Generating 3D maps in GIS during the early attempts posed several challenges. One of the main challenges was the limited availability of computer graphics technology and computing power, which constrained the complexity and realism of the visualizations. The lack of standardized data formats and interoperability made it difficult to integrate and visualize different types of spatial data in a cohesive manner. The absence of user-friendly interfaces and interactive tools also limited the usability and accessibility of 3D visualization tools. Additionally, the lack of adequate data sources for elevation, texture, and other 3D attributes posed challenges in creating realistic and accurate 3D maps.

3.3 Examples of Early 3D Visualization Tools

Despite the challenges, several pioneering efforts led to the development of early 3D visualization tools for GIS. One of the notable examples is the "SYMAP" system developed in the 1960s by Howard Fisher, which allowed for the creation of simple 3D maps by overlaying elevation data on topographic maps. Another example is the "Geographic Information Visualization and Analysis System" (GIVAS) developed in the 1970s by David Rhind and colleagues, which allowed for the visualization of 3D terrain models and other spatial data. The "SYMAP" and "GIVAS" systems laid the foundation for subsequent advancements in 3D visualization techniques and technologies in GIS.

4 Advancements in 3D Visualization Technology

4.1 Development of Advanced 3D Rendering Engines

The development of advanced 3D rendering engines has been a significant milestone in the evolution of 3D visualization technologies for GIS. These rendering engines utilize sophisticated algorithms and techniques to generate realistic and visually appealing 3D graphics. One notable example is the "OpenGL" rendering engine, which has been widely used in GIS applications for rendering 3D models and visualizing terrain data. Another example is the "Unity" game engine, which has gained popularity in GIS for its real-time rendering capabilities and support for advanced visual effects. These advanced 3D rendering engines have enabled the creation of high-quality and interactive 3D visualizations in GIS, allowing for more effective communication and decision-making.

4.2 Integration of GIS Data with 3D Models

The integration of GIS data with 3D models has been a significant advancement in 3D visualization technologies for GIS. This integration allows for the seamless overlay of GIS data, such as satellite imagery, aerial photographs, and vector data, on top of 3D models, enabling a more comprehensive and contextual understanding of the spatial relationships [2]. This integration has been facilitated through the use of Geographic Information System Markup Language (GISML), which provides a standardized format for encoding and exchanging GIS data in 3D visualizations. The integration of GIS data with 3D models has opened up new possibilities for advanced spatial analysis and decision-making in GIS, allowing for more accurate and insightful visualizations.

4.3 Terrain Visualization Techniques for 3D

Digital Elevation Models (DEM): DEMs are raster representations of terrain elevations that are widely used in 3D GIS. They can be derived from various sources, such as LiDAR, photogrammetry, or satellite imagery [3]. The process involves data acquisition, pre-processing (e.g., filtering, interpolation), and post-processing (e.g., visualization, analysis). DEMs are commonly used for terrain analysis, hydrological modeling, and visualization in 3D GIS [4] (Fig. 1).

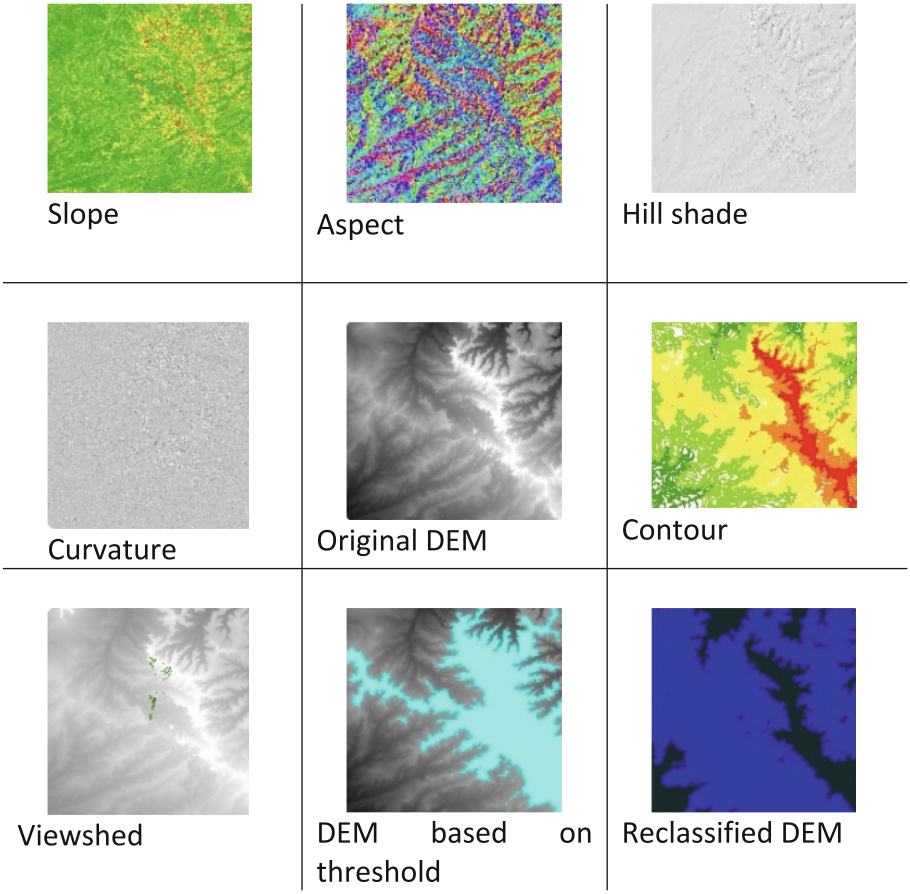

Fig. 1. Analysis of DEM

Triangulated Irregular Networks (TIN): TINs represent terrain as a network of non-overlapping triangles, defined by their vertices and associated elevations. TINs are preferred for their ability to accurately capture complex terrain features, such as cliffs or overhangs. The process involves data acquisition, triangulation, and post-processing (e.g., visualization, analysis). TINs are commonly used for terrain modeling in applications like urban planning, flood modeling, and slope stability analysis.

The following figure is an illustration of how a triangulated irregular network dataset is created using a subset of the nodes from source triangulated irregular network. We can see as an output, thinning of the oversampled data from the input (Fig. 2).

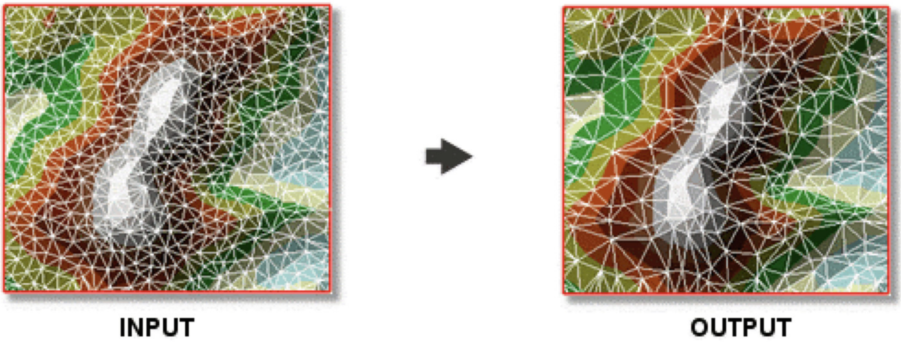

Fig. 2. Generation of TIN

Interpolation Techniques: Interpolation methods, such as Inverse distance weighting (IDW), kriging, spline, and nearest neighbour, estimate terrain elevations at un-sampled locations based on known elevation values. These techniques involve mathematical equations that use nearby elevation values to estimate elevations at un-sampled locations. The process involves data acquisition, selection of interpolation method, parameterization, interpolation, and post-processing (e.g., visualization, analysis). Interpolation is widely used for generating smooth terrain surfaces from sparse elevation data, and is used in applications like land use planning, viewshed analysis, and habitat modeling.

Photogrammetry: Photogrammetry is a technique that uses overlapping aerial or satellite imagery to extract terrain elevations. It involves capturing multiple images from different viewpoints and using geometric and radiometric properties of the images to estimate terrain elevations. Photogrammetry requires complex algorithms, such as bundle adjustment, triangulation, and orthorectification, to accurately estimate elevations [5]. The process involves image acquisition, image processing, feature extraction, and terrain elevation estimation. Photogrammetry is commonly used for terrain mapping in applications like topographic mapping, forest inventory, and coastal zone management. The Fig. 3 is an example of an 3d structure of a port being generated through photogrammetry.

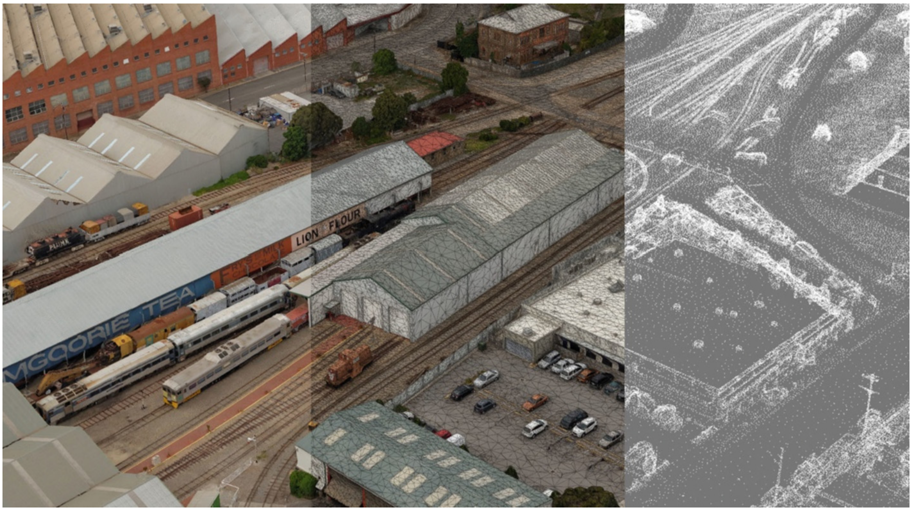

Fig. 3. 3D city model (port Adelaide), being generated through photogrammetry

4.4 Examples and Comparison of Modern 3D Visualization Tools

There are several modern 3D visualization tools that have emerged with advancements in 3D visualization technologies for GIS. These tools provide various features and functionalities for creating and interacting with 3D visualizations. For example, "ArcGIS Pro" by Esri is a popular GIS software that provides advanced 3D visualization capabilities, including the ability to create realistic 3D scenes, integrate GIS data with 3D models, and perform advanced spatial analysis in a 3D environment. "Google Earth" is another widely used tool that allows for the exploration of 3D maps and satellite imagery in a virtual globe environment. "Cesium" is an open-source JavaScript library that enables the creation of web-based 3D visualizations with high interactivity and customization [8]. These modern 3D visualization tools provide a wide range of visualization options, including tabular, charts, and graphs, for presenting and analyzing spatial data in a visually compelling manner (Fig. 4).

The generated 3D scatter plot visually compares the performance, user interface, and data analysis aspects of different GIS software, including ArcGIS Pro, QGIS 3, ArcGIS Desktop, Hexagon Geomedia, and MapInfo Professional. The X-axis represents performance, the Y-axis represents user interface, and the Z-axis represents data analysis. Each software is represented by a marker in the plot, with its position on the three axes indicating its respective ranking in terms of performance, user interface, and data analysis. The color of the marker is determined by a color palette, and the legend in the upper left corner of the plot provides the mapping of colors to the respective software. The plot provides a visual comparison of these parameters for the different GIS software, allowing for a quick understanding of how they rank against each other in terms of performance, user interface, and data analysis.

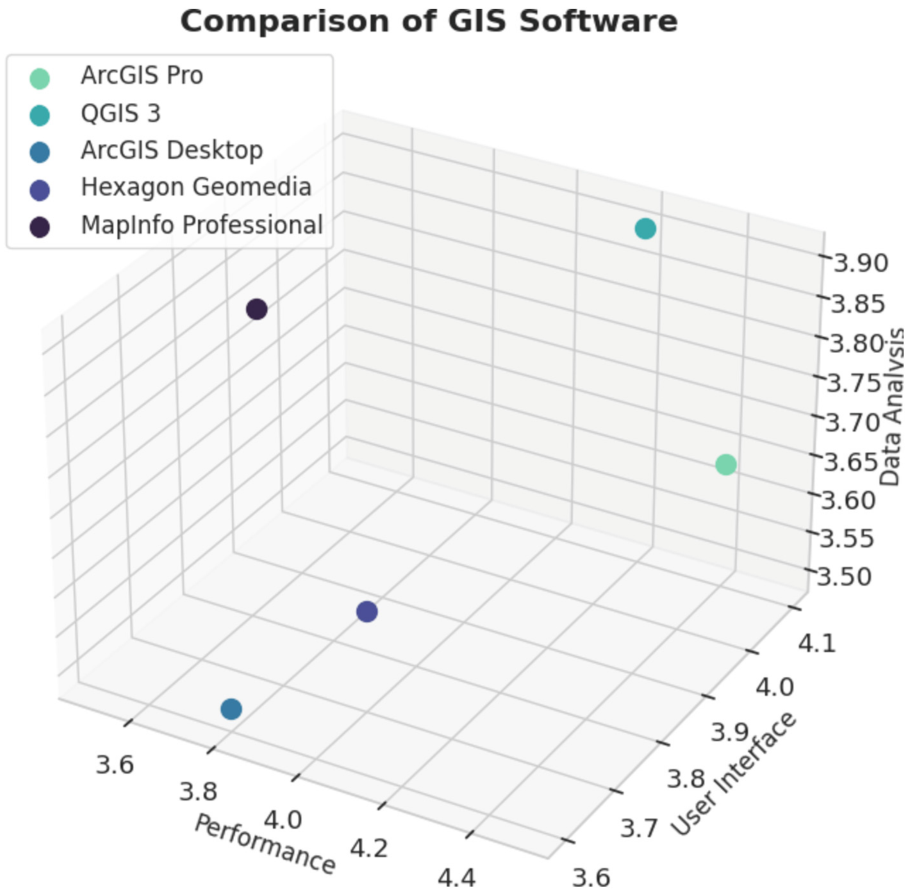

Fig. 4. Comparison of GIS software through 3D scatter plot

5 Applications of 3D Visualization in GIS

5.1 Urban Planning and Architecture

3D visualization has revolutionized urban planning and architecture by providing an immersive and interactive way to visualize complex urban landscapes. It allows urban planners and architects to create realistic 3D models of cities, buildings, and infrastructure, which can be used for various purposes. For instance, 3D visualization enables the assessment of the impact of new developments on the urban environment, the simulation of different scenarios to optimize city planning, and the visualization of future urban designs to engage stakeholders and the public. Moreover, 3D visualization facilitates urban design and architecture by allowing architects to visualize and manipulate building designs in a virtual environment, leading to more informed decisions and improved designs.

5.2 Natural Resource Management

3D visualization has transformed the field of natural resource management by providing a powerful tool for visualizing and analyzing complex spatial data related to natural resources. For instance, in forestry, 3D visualization allows the creation of realistic models of forest landscapes, enabling the assessment of tree height, density, and species distribution for better forest management. In geology, 3D visualization helps in the exploration and mapping of mineral resources by visualizing subsurface geology and identifying potential resource-rich areas. Additionally, 3D visualization facilitates the visualization and monitoring of environmental changes, such as deforestation, land degradation, and habitat fragmentation, aiding in the conservation and sustainable management of natural resources.

5.3 Emergency Response and Disaster Management

3D visualization plays a crucial role in emergency response and disaster management by providing situational awareness and decision support tools for response teams. During disasters, 3D visualization allows the visualization of real-time data, such as weather patterns, flood extent, or fire spread, facilitating the assessment of the situation and the planning of response strategies. It also aids in the communication of critical information to decision-makers, emergency responders, and the public, leading to more effective and coordinated responses. Furthermore, 3D visualization supports the pre-disaster planning and preparedness efforts by visualizing vulnerable areas, evacuation routes, and infrastructure networks, enabling better decision-making and resource allocation.

5.4 Military and Defense Applications

3D visualization has significant applications in the military and defense sectors, where it aids in mission planning, training, and decision-making. For instance, in military operations, 3D visualization allows the visualization of terrain, infrastructure, and potential threats, facilitating the planning of strategic and tactical operations. It also supports military training by providing realistic virtual environments for simulations and exercises, leading to improved preparedness and decision-making skills. Additionally, 3D visualization enables the visualization of intelligence, surveillance, and reconnaissance (ISR) data, aiding in situational awareness and decision-making in defense operations.

Here are some examples where GIS has been reported to have contributed to military and defense operations:

Battlefield Situational Awareness: GIS technology is used to create maps and visualize real-time data, providing military personnel with critical situational awareness information such as troop movements, terrain analysis, and enemy locations. This helps in making informed decisions and planning military operations effectively.

Intelligence, Surveillance, and Reconnaissance (ISR): GIS is used to gather, analyze, and visualize spatial data from various sources, such as satellite imagery, aerial photography, and ground-based sensors, to support military intelligence and surveillance efforts. This helps in monitoring and analyzing enemy activities, identifying potential threats, and planning countermeasures.

Logistics and Supply Chain Management: GIS is used to optimize the movement of personnel, equipment, and supplies by analyzing geographic data such as transportation routes, supply depots, and storage facilities. This helps in efficient allocation of resources and coordination of logistics operations, especially in remote or hostile environments.

Crisis Response and Disaster Management: GIS is used to support disaster management and humanitarian relief efforts by providing real-time information on affected areas, infrastructure damage, evacuation routes, and distribution of resources. This helps in coordinating emergency response efforts and allocating resources effectively.

6 Challenges and Future Directions

6.1 Challenges Faced by Developers and Researchers in Creating Accurate and Realistic 3D Models

Accuracy of Data: Spatial data used for creating 3D models, such as elevation data, satellite imagery, and 3D building models, may have inherent errors and inaccuracies that can affect the quality of the 3D models [6]. Ensuring accurate and precise data acquisition is critical for creating realistic 3D representations of the real world in GIS.

Complexity of 3D Modeling Techniques: 3D modeling involves complex algorithms and computations to generate 3D representations from 2D spatial data. Developing and implementing accurate 3D modeling algorithms can be challenging, requiring expertise in computer graphics, mathematics, and spatial analysis. Furthermore, the scalability and performance of 3D modeling techniques can be a challenge when dealing with large and complex geographic datasets.

Diversity and Heterogeneity of Data Sources: Different data sources in GIS may have varying levels of detail, accuracy, and format, making it challenging to create seamless and realistic 3D representations. Ensuring consistency and compatibility among different data sources is crucial for creating accurate and realistic 3D models in GIS.

In summary, the challenges in creating accurate and realistic 3D models in GIS include data accuracy, complexity of 3D modeling techniques, and diversity and heterogeneity of data sources. Overcoming these challenges requires advanced data acquisition and processing techniques, as well as expertise in computer graphics, mathematics, and spatial analysis.

6.2 Need for Better Data Acquisition and Processing Techniques

To address the challenges in creating accurate and realistic 3D models, there is a need for better data acquisition and processing techniques in GIS. Accurate and high-resolution data acquisition methods, such as LiDAR (Light Detection and Ranging) and photogrammetry, can provide more precise and detailed elevation data for creating realistic 3D models. These data acquisition techniques can capture fine-grained details of the terrain, vegetation, and buildings, enabling more accurate and realistic 3D representations.

In addition to data acquisition, data processing techniques play a crucial role in creating accurate and realistic 3D models. Advanced data processing techniques, such as feature extraction, data fusion, and data integration, can help in integrating diverse and heterogeneous data sources to create seamless and realistic 3D representations. These techniques can also address the challenges of scalability and performance by optimizing the processing algorithms for large and complex geographic datasets.

6.3 Potential for Virtual and Augmented Reality in GIS

Virtual and augmented reality (VR/AR) technologies have the potential to revolutionize the way we interact with GIS data in 3D visualizations [7]. VR allows users to immerse themselves in a virtual environment and interact with 3D models in a more natural and intuitive way. AR, on the other hand, overlays virtual content on the real world, allowing users to visualize and interact with GIS data in real-time and real-world context.

The use of VR/AR in GIS can enhance the user experience and enable more effective spatial analysis and decision-making. For example, military and defense applications can benefit from VR/AR by providing realistic and immersive training environments for soldiers, visualizing battlefield situational awareness, and planning military [9].

7 Future Scope

7.1 Augmented Reality/Virtual Reality (AR/VR) Integration

Use-case: Imagine a team of urban planners tasked with designing a new city district. They need to analyse the existing terrain, consider various infrastructure options, and ensure the optimal use of available space. Traditionally, they would rely on 2D maps and blueprints to visualize the project. However, with the integration of augmented reality (AR) in their GIS platform, the planners now have access to a more immersive experience.

Using AR glasses and mobile devices, the planners can walk through the proposed district while visualizing 3D terrain models overlaid with real-time data. They can virtually see buildings, roads, and parks on the terrain, allowing them to assess the impact of their design choices in a realistic context. For instance, they can visualize the shadows cast by buildings at different times of the day, evaluate potential flood risk areas, and even simulate how the district would look during extreme weather conditions. This interactive AR integration empowers planners to make more informed decisions and engage with stakeholders effectively.

7.2 Real-Time Data Integration

Use case: During a wildfire outbreak, emergency response teams are challenged with rapidly changing terrain conditions and spreading fire patterns. With real-time data integration in their GIS system, the response teams can access up-to-date information from satellite imagery, weather sensors, and drones.

Using a tablet-based GIS application, the teams can visualize the current fire front in real-time on a 3D terrain model. The GIS platform automatically updates the terrain model with live satellite data, showing the precise location of the fire front and potential areas of concern. Additionally, the system overlays the terrain with temperature, wind direction, and humidity data, enabling the teams to predict the fire's future behavior more accurately.

By utilizing real-time data integration, the emergency response teams can efficiently allocate resources, plan evacuation routes, and coordinate firefighting efforts. This capability saves crucial time and helps in mitigating the impact of wildfires on communities and the environment.

7.3 AI-Driven Terrain Analysis

Use case: An environmental conservation group is monitoring the habitat of endangered species in a vast national park. Traditional methods of manually identifying and tracking habitats are time-consuming and resource-intensive. To address this challenge, they adopt an AI-driven terrain analysis approach in their GIS platform.

Using machine learning algorithms, the GIS system automatically analyses satellite imagery and LiDAR data to identify distinct terrain features relevant to the species' habitat [12]. The AI model can recognize specific vegetation patterns, water bodies, and geological formations that are critical to the species' survival. As a result, the conservationists can quickly identify potential areas of interest, track changes in habitat over time, and prioritize conservation efforts efficiently.

The AI-driven terrain analysis not only enhances the accuracy of habitat identification but also enables the conservation group to focus their limited resources on protecting the most crucial areas for endangered species.

7.4 Collaborative 3D Visualization

Use case: A team of urban designers, architects, and landscape planners is collaborating on a large-scale urban redevelopment project. Each team member brings expertise in their respective domains, and effective collaboration is essential for successful outcomes.

Using a cloud-based collaborative 3D visualization platform, the team can work together in real-time, regardless of their physical locations. Each member can access the 3D terrain model and make modifications, such as adding buildings, parks, or roads, while the changes are instantly visible to others. Furthermore, they can leave comments, annotations, and suggestions directly on the terrain model, fostering seamless communication and idea sharing.

In a virtual meeting, the team gathers to discuss the proposed changes while navigating the 3D terrain collaboratively. This immersive experience allows them to understand the spatial relationships better and make informed decisions collectively. The collaborative 3D visualization platform streamlines the design process, reduces coordination efforts, and facilitates a more cohesive approach to urban planning.

7.5 Environmental Monitoring and Climate Change Visualization

Use case: A team of environmental researchers is studying the impact of climate change on glaciers in a remote mountain range. To visualize the changes over time, they employ an advanced GIS platform that combines historical satellite imagery with present-day data.

The GIS system generates a 3D terrain model of the glacier using high-fidelity satellite mapping. By comparing this model with historical data, the researchers can observe the glacier's retreat and measure its changing volume. Additionally, they overlay temperature and precipitation data on the terrain to understand the climate conditions influencing glacier behaviour.

Through animated visualization, the researchers observe the glacier's progression over several decades, highlighting the alarming rate of ice loss due to climate change. This powerful visual representation aids in raising awareness among policymakers and the public about the urgency of climate action.

7.6 Mobile 3D Visualization Platforms

Use case: A team of geologists is conducting fieldwork in a remote and rugged terrain, surveying geological formations and collecting rock samples. In the past, they had to rely on traditional handheld GPS devices and paper maps for navigation, making it challenging to correlate their findings with the larger terrain context [10].

With the adoption of mobile-based 3D visualization platforms, the geologists can now access a portable GIS system on their tablets or smartphones. The platform offers real-time 3D terrain visualization, allowing them to identify geological features more accurately and understand their spatial relationships [11].

During their field surveys, the geologists can quickly validate their observations by visualizing their collected data on the 3D terrain model. This real-time feedback enhances the quality of their findings and ensures the integration of their data into the larger GIS database seamlessly.

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