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A Methodological Framework for Mapping Coastline Spatiotemporal Changes Using UAV Airborne LiDAR

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Abstract:

The coastline marks the boundary between the sea and the mainland and is one of the fundamental components of topographic maps and charts. The International Commission for Geographic Data recognizes it as one of the 27 surface elements (Sun et al. 2023). Coastlines have unique geographic and dynamic characteristics, as their position, shape, and trend constantly change. Additionally, coastlines hold significant resource value; approximately 50% of the global population lives within 100 kilometers of a shoreline. This proximity encourages the exploitation of marine resources along the coast for economic and social benefits (Toure et al. 2019). Climate change, natural factors, and excessive human intervention have resulted in significant damage to coastal zones, making them particularly vulnerable, especially evident in the rapid temporal and spatial scale changing of shorelines. As coastlines are posed to dynamic changes, they are not invariable lines and vary over time and space. Thus, mapping and visualizing such a rapidly changing boundary and the variability and trends of erosion and accretion on a large scale need a different approach.

In this study, we aim to develop a methodology for creating VR geovisualizations of coastline spatiotemporal changes leveraging UAV and airborne LiDAR. In this approach, we correlate cartographic scale and point density per m² with spatial resolution in the three-dimensional space to map and visualize the temporal changes of the coastline in a VR environment. Skala Eresou Beach, located in southwestern Lesvos, was selected as a study area. This 3-kilometer-long coastline is characterized by an extensive sandy beach interspersed with striking rocky outcrops, reflecting the region's rich geological and geomorphological history. Volcanic formations, dating back to the Miocene period and the influence of strong southern winds, play a significant role in shaping coastal erosion and sediment deposition processes. Eresos Beach represents a highly dynamic coastal environment, making it an ideal scientific observation and study site.

Given the dynamic nature of coastlines and their vulnerability to natural and anthropogenic factors, it becomes imperative to explore whether modern technologies can effectively tackle the challenges of mapping and visualizing these rapidly changing boundaries in 3D space. Questions arise regarding the methodological framework to be followed for VR geovisualization approaches. Is there a correlation between cartographic scale and the data acquisition derivatives from airborne LiDAR sensors in the context of ultra-high-resolution 3D geovisualizations within VR environments? Are these point cloud data suitable for accurately representing spatiotemporal variations of coastal zones in 3D space?

This study explores the point density of LiDAR data in relation to cartographic scale requirements and the three-dimensional spatial resolution necessary for VR mapping applications. Our approach offers new insights into the development of accurate mapping and VR geovisualization, broadening the existing literature on using UAVs and LiDAR in mapping applications (Culver et al. 2020). The proposed methodology enables the long-term monitoring and documentation of shoreline dynamics. Results, such as high-accuracy Digital Terrain Models (DTMs) and georeferenced point clouds, provide valuable tools for analyzing erosion and changes in the coastal environment, considering the impacts of climate change and anthropogenic interventions (Novais et al. 2023). LiDAR data-driven geovisualizations in virtual reality environments allow for precise modeling of topography and shorelines. Integrating georeferenced data in VR platforms facilitates the comparison of shoreline configurations across different time periods. This approach enhances the understanding of erosion and sediment deposition rates and enables the assessment of climate change impacts. Moreover, VR-based geovisualizations are a useful tool for specialists and non-specialist users, providing an immersive experience to understand complex geomorphological changes (Çöltekin et al. 2020).

The study's methodology involved several key stages. Initially, a scale investigation and flight planning were conducted using two UAVs: the DJI Matrice 300 equipped with a LiDAR sensor (ZENMUSE L1) and the DJI Mavic 3E with an RGB sensor. A total of 14 flights were carried out under varying conditions of altitude (50-70 meters) and speed (2-6

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m/s), achieving a maximum point density of 943 pts/m². Following this, fifty Ground Control Points (GCPs) and Check Points (CPs) were strategically placed along the coastline and georeferenced using RTK GPS to ensure high positional accuracy. Subsequently, data processing was performed to generate georeferenced 3D point clouds, Digital Elevation Models (DEMs), and orthomosaics with resolutions reaching up to 1.5cm. Finally, the processed data were utilized to develop Virtual Reality (VR) geovisualizations, enabling the temporal comparison of shoreline configurations within a dynamic 3D environment.

The integration of 3D geovisualization technologies facilitates the comparison of data with identical characteristics over time, enabling effective long-term monitoring of coastal dynamics. The combination of UAV and LiDAR technologies is a significant tool for cartography and the development of advanced cartographic products. Furthermore, VR-based 3D geovisualizations transcend the limitations of static maps, offering an enhanced cartographic approach that improves user experience, communication, and understanding of dynamically evolving spatiotemporal phenomena. Utilizing a 3D virtual space provides a distinct advantage, offering an immersive perspective for analyzing complex geomorphological changes. Future work should focus on further utilizing these advancements to explore additional applications in environmental monitoring and their representation and symbolization approaches in the 3D virtual space of VR environments.

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