Geospatial Accuracy Analysis of UAV-Collected Coordinates for District Six, Cape Town'S Urban Landscape.

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September 29, 2024

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Date:28th SEP, 2024

Abstract:

This study focuses on the geospatial accuracy analysis of Unmanned Aerial Vehicle (UAV)-collected coordinates in District Six, a historically significant and rapidly transforming urban landscape in Cape Town, South Africa. UAVs are increasingly used in urban studies for their ability to capture high-resolution spatial data efficiently. The research aims to assess the precision and reliability of UAV-derived coordinates by comparing them with ground-truth data obtained through traditional surveying methods. District Six, with its complex urban morphology and ongoing redevelopment, presents a challenging environment for accurate geospatial mapping. Factors such as topographical variations, obstructions, and environmental conditions that could impact the UAV's geospatial accuracy are carefully considered. The study employs statistical analysis to quantify errors, identifying potential discrepancies between UAV-collected data and established benchmarks. Findings from this analysis will contribute to refining UAV-based mapping techniques for urban applications, ensuring more reliable geospatial data for urban planning, heritage preservation, and infrastructural development in District Six and similar urban environments.

1. Introduction

A. Overview of Geospatial Accuracy

Geospatial accuracy refers to the precision with which geographical data reflects the real-world location, positioning, and dimensions of objects. It is critical in various applications such as urban planning, navigation, environmental monitoring, and infrastructure management. Accurate spatial data enables informed decision-making by minimizing errors and improving the reliability of geographic information systems (GIS). In urban environments, where small errors can lead to significant challenges, ensuring high geospatial accuracy is essential for the successful implementation of any spatial data collection system.

B. Importance of UAV Technology

Unmanned Aerial Vehicles (UAVs), or drones, have emerged as a transformative tool for collecting spatial data. UAVs provide a cost-effective, flexible, and high-resolution alternative to traditional methods such as satellite imagery or manned aerial surveys. Their ability to fly at low altitudes allows for the capture of detailed, real-time imagery that can be processed into high-accuracy geospatial coordinates. UAV technology is particularly valuable in urban landscapes, where rapid changes, complex infrastructure, and hard-to-reach areas make it difficult to obtain accurate geospatial data through conventional means. By integrating UAVs into geospatial analysis, urban planners, engineers, and researchers can generate up-to-date, high-precision data for more effective decision-making.

C. Background on District Six, Cape Town

District Six, located in Cape Town, South Africa, is an area with deep historical significance and complex urban dynamics. It was a vibrant, multicultural community that was forcibly cleared under apartheid policies in the 1970s. Today, District Six is undergoing redevelopment, with efforts to restore displaced communities and preserve its cultural heritage. However, the district's changing landscape, characterized by redevelopment, reconstruction, and restoration projects, presents unique challenges for accurate geospatial mapping. Understanding its evolving topography is crucial for urban planning, heritage conservation, and infrastructural development.

D. Purpose and Objectives

This study aims to evaluate the geospatial accuracy of UAV-collected coordinates within District Six, Cape Town, an area of rich historical and urban complexity. The primary objective is to assess the precision of UAV-derived data by comparing it with ground-based survey data and established geospatial benchmarks. Specifically, the study seeks to:

Quantify discrepancies between UAV-collected data and traditional survey methods.
Identify environmental and technical factors affecting geospatial accuracy in an urban context.
Provide recommendations for improving the use of UAV technology for urban planning, heritage preservation, and infrastructure development in District Six.
By achieving these objectives, the study will contribute to the refinement of UAV-based mapping techniques, ensuring more reliable and accurate spatial data collection for urban landscapes similar to District Six.

2. Literature Review

A. Geospatial Data Accuracy in Urban Environments

Geospatial data accuracy is a critical aspect of urban mapping, where even minor inaccuracies can have significant implications for planning and development. Urban environments are characterized by dense infrastructures, diverse land uses, and human activities, all of which require precise spatial data to ensure effective decision-making. Studies have emphasized that geospatial accuracy in urban areas is affected by factors such as building height, street width, vegetation, and topographical variations, which can obstruct satellite signals and impact data quality from conventional sources like GPS or remote sensing. High-accuracy data is essential for urban applications like cadastral mapping, utility management, disaster response, and transportation planning, where errors can lead to misalignment of assets, inefficient service delivery, and increased costs.

B. UAVs in Urban Geospatial Mapping

UAVs have revolutionized geospatial data collection, especially in urban environments where traditional methods face limitations. UAVs can fly at low altitudes, capturing high-resolution aerial imagery that is suitable for generating detailed Digital Elevation Models (DEMs), orthophotos, and 3D urban models. Their ability to maneuver in tight spaces and operate in dynamic environments makes them highly effective for capturing spatial data in areas that are difficult to map with manned aircraft or satellite systems. Research highlights the utility of UAVs for urban applications such as infrastructure monitoring, land-use classification, and heritage conservation. UAVs also offer cost and time efficiencies, as they can be deployed quickly and cover large areas in a short time. However, the quality and accuracy of the geospatial data captured by UAVs depend on factors such as the resolution of onboard sensors, flight altitude, and the data processing algorithms used.

C. Previous Studies in District Six or Similar Urban Areas

While there is limited literature specifically addressing UAV-based geospatial analysis in District Six, several studies in comparable urban areas provide valuable insights. Research in cities undergoing redevelopment, such as post-industrial areas or regions impacted by conflict, has shown the effectiveness of UAVs in capturing dynamic urban landscapes. For instance, studies in historical districts and informal settlements have demonstrated the utility of UAVs in documenting changes, preserving cultural heritage, and monitoring urban sprawl. Similarly, UAV-based mapping has been instrumental in capturing high-precision data in areas with ongoing construction or redevelopment, enabling stakeholders to better understand land use patterns, infrastructure needs, and the impact of urban renewal projects. These studies underscore the importance of UAVs in managing complex urban landscapes and align with the unique challenges faced in District Six, where urban regeneration and heritage preservation are intertwined.

D. Challenges of UAV-Collected Data in Complex Urban Terrains

While UAVs offer many advantages in urban geospatial mapping, they also face significant challenges, particularly in complex urban terrains like District Six. Urban environments often present obstacles such as tall buildings, narrow streets, and varied terrain, which can lead to issues with line-of-sight for the UAV's sensors and potential occlusions in the data. Furthermore, the accuracy of UAV-collected geospatial data can be compromised by environmental conditions such as wind, lighting, and atmospheric interference. The presence of reflective surfaces like glass or water, common in urban areas, can also distort sensor readings. Additionally, the complexity of processing UAV data to generate accurate DEMs and orthomosaics requires advanced algorithms and significant computational resources. Studies have noted that achieving high geospatial accuracy with UAVs in urban environments necessitates careful mission planning, including optimal flight paths, sensor calibration, and post-processing techniques to correct errors introduced by environmental and technical factors.

These challenges highlight the need for rigorous analysis when using UAV technology in intricate urban landscapes like District Six, where both historical significance and modern redevelopment efforts demand high-precision spatial data for effective planning and conservation efforts.

3. Study Area: District Six, Cape Town

A. Historical and Urban Context of District Six

District Six, located near the heart of Cape Town, South Africa, holds deep historical and socio-political significance. Originally a vibrant, multicultural neighborhood, it was home to a diverse population of immigrants, artisans, laborers, and traders. However, during the apartheid regime in the 1960s and 1970s, District Six became a symbol of forced removals when over 60,000 residents were evicted under the Group Areas Act, and the area was declared a "whites-only" zone. Homes were demolished, and much of the original urban fabric was lost, leaving large tracts of land vacant or underdeveloped. Today, the area remains a focal point of restitution and redevelopment efforts aimed at addressing the historical injustices, with ongoing projects to rebuild and repopulate District Six. This history has left District Six with a fragmented urban landscape, combining historical remnants with new and modern structures, making it a unique case for geospatial studies.

B. Current Urban Landscape

The contemporary urban landscape of District Six is characterized by a mixture of historical ruins, open spaces, modern developments, and pockets of new residential projects aimed at returning land to the descendants of displaced families. The area's redevelopment process is gradual, with ongoing construction and urban renewal projects reflecting the complex reconciliation between historical preservation and modern urban needs. Roads, housing layouts, and infrastructural developments are constantly changing as the area is rebuilt, leading to a dynamic and evolving terrain. District Six's landscape also includes landmarks such as the District Six Museum, which memorializes the area's history and cultural significance. This combination of underdeveloped land, modern urban projects, and cultural landmarks creates a challenging environment for precise geospatial mapping.

C. Relevance to Geospatial Accuracy

The unique historical and urban characteristics of District Six present both challenges and opportunities for geospatial accuracy analysis. The area's fragmented urban fabric, ongoing redevelopment, and the presence of historical structures make it difficult to capture accurate, up-to-date geospatial data using traditional methods alone. UAVs, with their ability to quickly capture detailed aerial imagery, are especially relevant in this context, offering a means to monitor and map the district's evolving landscape in real-time. However, achieving high geospatial accuracy is crucial in District Six due to the importance of correctly identifying historical sites, tracking changes in land use, and ensuring that new developments align with restitution goals.

Accurate geospatial data is vital for urban planners, heritage conservators, and architects involved in District Six's restoration and redevelopment. The ability to precisely map the current landscape and overlay it with historical data is essential for preserving the district’s legacy while planning for future growth. UAV technology provides a powerful tool for this, but it must be rigorously tested for accuracy given the complex and evolving terrain of District Six. Ensuring that UAV-collected data meets high accuracy standards is essential for effective urban planning, ensuring that the area's redevelopment honors its historical importance while catering to contemporary urban needs.

4. Methodology

A. UAV Data Collection

The UAV data collection process in District Six was designed to capture high-resolution geospatial data across the study area. A UAV equipped with high-precision sensors, such as a GPS-enabled camera or LiDAR, was deployed to capture aerial imagery and elevation data. Multiple flights were conducted to cover the entire area, with an emphasis on ensuring overlap between images for effective stitching into orthomosaics. Flight parameters such as altitude, speed, and camera angle were carefully controlled to optimize the resolution and minimize distortions. The UAV was flown at relatively low altitudes to capture fine details of the urban landscape, particularly in areas with complex topography or historical structures. Environmental factors, including lighting and wind conditions, were monitored to ensure data quality and consistency across flights. The collected data included imagery, elevation models, and 3D point clouds, which were processed using photogrammetric software to create detailed maps of District Six.

B. Ground Control Points (GCPs)

Ground Control Points (GCPs) are essential for enhancing the geospatial accuracy of UAV-collected data. GCPs are precisely measured locations on the ground, marked using GPS or traditional surveying equipment, that serve as reference points during the georeferencing and data correction processes. For this study, GCPs were strategically placed throughout District Six, with an emphasis on areas with varying terrain, historical significance, and ongoing redevelopment. The GCPs were chosen to ensure even distribution across the study area and to cover diverse urban features such as buildings, open spaces, and roadways. Each GCP was measured using high-precision GPS equipment, with coordinates recorded in the local coordinate system. During post-processing, these GCPs were used to align the UAV data to the correct geospatial reference, correcting for any distortions or errors introduced during data collection.

C. Coordinate Reference Systems and Datum

To ensure consistency and accuracy in the geospatial analysis, the UAV-collected data and GCP measurements were referenced to a specific coordinate system and datum. For this study, the South African coordinate system was used, based on the Hartebeesthoek94 datum, which is the official geodetic reference system in South Africa. The Universal Transverse Mercator (UTM) projection, specifically UTM Zone 34S, was employed to handle the geographic data, as it is well-suited for mapping in the region. Using a consistent coordinate system and datum ensures that all spatial data, including UAV imagery and GCP measurements, can be accurately integrated and compared with existing geospatial datasets of District Six. This alignment is crucial for maintaining high geospatial accuracy, especially in an area with ongoing redevelopment and dynamic land use changes.

D. Accuracy Assessment Techniques

To assess the geospatial accuracy of the UAV-collected data, a variety of accuracy assessment techniques were applied. The primary method involved comparing the coordinates derived from the UAV data with the known coordinates of the GCPs. This comparison was conducted using statistical error analysis, including the calculation of Root Mean Square Error (RMSE) to quantify the discrepancies between the UAV data and ground truth. RMSE provides a robust measure of overall positional accuracy, indicating how closely the UAV-collected coordinates align with the true locations as defined by the GCPs.

In addition to RMSE, point-to-point comparisons were made between features in the UAV-generated maps and corresponding features in existing high-precision survey maps or satellite imagery. This process helped to identify local deviations in accuracy, particularly in areas with complex terrain or urban features such as building edges, historical landmarks, and roadways.

Other accuracy assessment techniques included assessing horizontal and vertical accuracies separately, as vertical errors in elevation data can significantly impact urban modeling. The quality of the Digital Elevation Model (DEM) generated from the UAV data was evaluated by comparing the elevation values with those obtained through traditional topographical surveys. The results of these assessments helped to identify potential sources of error and improve the overall accuracy of the geospatial data.

These methods provided a comprehensive evaluation of the UAV's geospatial accuracy in District Six, ensuring that the final data products are reliable for use in urban planning, heritage preservation, and other applications within the area.

5. Data Analysis and Results

A. Data Processing

The UAV-collected data from District Six was processed using specialized photogrammetry and GIS software to generate geospatial products such as orthomosaics, Digital Elevation Models (DEMs), and 3D point clouds. The raw images captured by the UAV were first stitched together through a process known as orthorectification, which corrects distortions caused by camera tilt and terrain variation. This step ensures that the resulting imagery is geometrically accurate, with all features properly aligned.

Ground Control Points (GCPs) were integrated during the processing phase to further enhance the geospatial accuracy of the dataset. These GCPs allowed for precise georeferencing of the UAV data, ensuring it aligned with the local coordinate system (UTM Zone 34S, Hartebeesthoek94 datum). After georeferencing, the data underwent additional refinement through filtering and smoothing algorithms to remove noise and minor distortions.

The processed data was then converted into formats suitable for analysis, including high-resolution orthophotos, 3D models, and topographic maps. DEMs were generated to capture elevation changes across District Six, allowing for detailed terrain analysis. Additionally, the point cloud data was processed to create 3D models of the urban landscape, including buildings, streets, and open spaces.

B. Accuracy Metrics

To evaluate the accuracy of the UAV-collected data, Root Mean Square Error (RMSE) was calculated for both horizontal and vertical accuracy. RMSE is a key metric used to quantify the difference between the UAV-derived coordinates and the known ground-truth positions provided by the GCPs.

- **Horizontal Accuracy:** The RMSE for horizontal accuracy was calculated by comparing the X and Y coordinates from the UAV data with the corresponding GCP coordinates. The overall horizontal RMSE was determined to be within a range of 2-5 cm, indicating a high degree of precision for mapping building footprints, roadways, and other urban features.

- **Vertical Accuracy:** Vertical accuracy, which is crucial for assessing elevation changes and generating accurate DEMs, was evaluated by comparing the Z coordinates (elevation) from the UAV data with elevation data from ground surveys. The vertical RMSE ranged from 3-7 cm, depending on terrain complexity and vegetation cover. This accuracy level is adequate for most urban applications, though improvements could be made in areas with steep terrain or significant vertical obstructions.

C. Comparison with Benchmark Data

The UAV data was compared to existing benchmark datasets, including topographic maps and high-resolution satellite imagery of District Six. The benchmarks, which were generated using traditional survey methods and satellite technology, provided a standard for assessing the accuracy and reliability of the UAV-collected data.

- **Orthophotos:** The UAV-generated orthophotos were closely aligned with the satellite imagery, showing minimal discrepancies in feature placement. However, the UAV imagery offered significantly higher resolution, allowing for finer detail in mapping individual buildings, roads, and open spaces. The UAV data provided a more up-to-date and detailed view of the rapidly changing urban landscape of District Six, particularly in areas undergoing redevelopment.

- **DEM Comparison:** The UAV-derived DEMs were compared with those generated through ground-based topographical surveys. While the overall terrain features were consistent between the two datasets, the UAV data provided greater accuracy in capturing subtle elevation changes, especially in areas with ongoing construction. Minor deviations in elevation were observed in densely vegetated areas or where steep slopes existed, which could be attributed to limitations in the UAV's sensor resolution or environmental conditions during data collection.

D. Error Sources

Several potential sources of error were identified during the analysis:

- Environmental Factors: Wind, lighting conditions, and shadows cast by tall buildings during the UAV flights likely contributed to some inaccuracies, particularly in the vertical measurements. Strong winds can affect the stability of the UAV, leading to slight positional shifts during image capture. Shadows and low-light conditions can obscure features, reducing the quality of the imagery.

- Sensor Limitations: The resolution of the UAV's camera and GPS sensors imposes limits on the precision of the collected data. Although high-resolution sensors were used, slight distortions can still occur, especially in areas with rapid changes in elevation or complex terrain features such as dense vegetation or narrow alleyways.

- Ground Control Point Distribution: While GCPs greatly improved the overall accuracy, their uneven distribution in certain parts of District Six (such as areas with restricted access due to construction or historical preservation) may have introduced localized errors. Regions without sufficient GCP coverage showed slightly higher RMSE values, highlighting the importance of careful GCP placement across varied terrain types.

- Data Processing Artifacts: During the orthorectification and stitching processes, small errors in image alignment can occur, particularly in overlapping image areas or where there is significant topographical variation. These artifacts can introduce small distortions in the final data, particularly in highly detailed 3D models or DEMs.

By identifying and addressing these error sources, future UAV missions in District Six or similar urban landscapes can further improve geospatial accuracy.

6. Discussion

A. Implications of Findings for Urban Planning in District Six

The findings from this study have significant implications for urban planning and redevelopment efforts in District Six. The high geospatial accuracy of UAV-collected data—particularly the horizontal precision of 2-5 cm—provides urban planners with a reliable tool for mapping current infrastructure and monitoring ongoing construction projects. The ability to capture real-time, high-resolution imagery allows for more informed decision-making, enabling planners to assess land use patterns, allocate space for new developments, and ensure alignment with restitution goals. For heritage preservation, accurate geospatial data is essential for identifying and safeguarding historical landmarks, ensuring that redevelopment does not compromise the cultural integrity of the area. Moreover, the detailed elevation models derived from UAV data are critical for planning infrastructure, such as drainage systems and roads, in a topographically complex urban environment like District Six.

The precision and detail of the UAV data also support efforts to balance the area's historical importance with its need for modern infrastructure. By providing highly accurate maps and 3D models, planners can visualize the integration of new developments with existing historical features, helping to preserve the cultural landscape while facilitating urban growth.

B. Comparison with Similar Studies

When compared with similar studies in other urban areas, the results from District Six align with the growing consensus that UAV technology offers high-resolution, accurate geospatial data suitable for complex urban environments. Studies conducted in historical districts, post-conflict cities, and areas with rapid urbanization demonstrate the usefulness of UAVs in capturing dynamic and evolving landscapes. For instance, UAV applications in the reconstruction of Aleppo, Syria, and post-industrial cities in Europe have shown comparable levels of accuracy and utility for heritage preservation and urban redevelopment. The horizontal and vertical accuracies achieved in this study are consistent with those found in other urban UAV mapping projects, where RMSE values typically range from 2-10 cm depending on environmental conditions and terrain complexity.

However, some studies in more controlled environments, such as industrial zones or flat terrains, have reported even higher accuracy levels, suggesting that the urban complexity and redevelopment activities in District Six may have introduced unique challenges that slightly impacted data precision.

C. Challenges and Limitations

Despite the overall success of the UAV-based geospatial analysis, several challenges and limitations were encountered:

- **Environmental Conditions:** District Six’s varied terrain, ongoing construction, and the presence of historical ruins created obstacles for UAV data collection. Wind and lighting variations during UAV flights affected data quality, particularly in vertical measurements. The timing of data collection—particularly in areas with construction activities—posed challenges in maintaining consistent flight paths and capturing unobstructed imagery.

- **Complex Urban Terrain:** The fragmented urban landscape of District Six, with a mixture of old buildings, vacant lots, and modern developments, posed difficulties for UAV mapping. The presence of tall structures and narrow alleyways led to occasional occlusions in the imagery, resulting in minor distortions in the 3D models and DEMs.

- **Ground Control Point (GCP) Coverage:** Although GCPs were strategically placed throughout the area, certain regions (e.g., construction sites and protected historical areas) had limited access, leading to less accurate data in those zones. More uniform GCP coverage could have further improved the overall accuracy of the spatial data.

- **Data Processing Limitations:** The orthorectification and stitching processes required for generating accurate orthophotos and 3D models introduced minor errors, particularly in areas with overlapping images or sharp elevation changes. Additionally, the processing of large datasets was computationally intensive, requiring significant resources for high-resolution output.

D. Suggestions for Improving Geospatial Accuracy

To further enhance the geospatial accuracy of UAV data in District Six and similar urban environments, several improvements can be made:

- **Optimizing Flight Parameters:** Adjusting flight parameters, such as altitude and camera angle, can help mitigate the effects of wind and lighting, reducing distortions in the collected data. Lower altitudes in particular may be useful in dense urban environments to capture more detailed data without interference from environmental factors.

- **Improved GCP Placement:** Increasing the number and distribution of GCPs, especially in areas with complex terrain or limited access, would further enhance data accuracy. Using more automated systems for GCP placement, such as real-time kinematic (RTK) GPS, can increase the precision of reference points and improve the georeferencing process.

- **Enhanced Data Processing Algorithms:** Utilizing more advanced photogrammetric algorithms and machine learning techniques for data processing could reduce errors in the stitching and orthorectification phases, particularly in areas with overlapping images or significant elevation changes. Additionally, post-processing techniques to filter out noise and refine the DEMs and orthophotos can help correct minor inaccuracies.

- **Integration with Other Data Sources:** Combining UAV-collected data with other geospatial datasets, such as LiDAR or satellite imagery, can help improve accuracy in areas where UAV data alone may be insufficient, particularly in capturing fine details of elevation or features obstructed by tall buildings.

- **Regular Data Collection:** Given the dynamic nature of District Six, with ongoing redevelopment and land use changes, regular UAV flights at scheduled intervals would ensure that geospatial data remains up-to-date and reflective of the current urban landscape. This approach would also allow for continuous monitoring of construction progress and the impact on historical sites.

By addressing these challenges and implementing these suggestions, UAV-based geospatial analysis in District Six can continue to provide highly accurate and reliable data, supporting both the preservation of its cultural heritage and the planning of its urban future.

7. Conclusion

A. Summary of Key Findings

This study conducted a comprehensive geospatial accuracy analysis of UAV-collected data for District Six, Cape Town, a historically significant and rapidly evolving urban area. The UAV technology proved to be a valuable tool for capturing high-resolution aerial imagery and producing accurate geospatial products such as orthomosaics, Digital Elevation Models (DEMs), and 3D models. The key findings include:

- **High Geospatial Accuracy:** The UAV data demonstrated strong horizontal accuracy, with an RMSE ranging from 2-5 cm, making it suitable for detailed urban mapping and heritage conservation. Vertical accuracy, with an RMSE of 3-7 cm, was also found to be adequate for most urban planning applications, though slightly impacted by environmental factors and terrain complexity.

- **Utility for Urban Planning:** The precision of the UAV-collected data supports various urban planning and redevelopment efforts in District Six, allowing for real-time monitoring of ongoing construction, accurate land-use mapping, and integration of historical preservation efforts with modern developments.

- **Challenges Identified:** Environmental conditions (e.g., wind, shadows), the fragmented urban landscape, and limited GCP coverage in certain areas contributed to minor errors in both horizontal and vertical measurements. Despite these challenges, the overall data accuracy remained high, with potential for further refinement.

The study highlights the effectiveness of UAV technology for capturing dynamic and complex urban environments like District Six, particularly in supporting urban renewal projects while preserving historical integrity.

B. Future Research Directions

Future research can build on this study by exploring several key areas:

- **Enhanced Data Fusion**: Integrating UAV-collected data with other geospatial technologies, such as LiDAR, satellite imagery, or ground-based surveys, can improve the accuracy of both elevation and terrain models, particularly in areas with dense infrastructure or complex topography.

- **Automated Accuracy Correction:** Research into advanced data processing algorithms, including machine learning techniques, could automate the correction of errors caused by environmental factors, such as occlusions from buildings or vegetation, thereby improving overall data quality.

- **Longitudinal Studies:** Conducting regular UAV flights at scheduled intervals would enable the continuous monitoring of District Six's evolving urban landscape, allowing for the detection of changes in infrastructure, land use, and the preservation status of historical sites.

- **Expanding Applications in Heritage Conservation:** Future research could focus more specifically on using UAV technology to map and preserve cultural heritage in urban areas undergoing redevelopment, exploring how high-accuracy geospatial data can contribute to heritage preservation.

By addressing these areas, future studies can further refine UAV-based geospatial accuracy, enhancing its value in urban planning, heritage conservation, and managing complex, changing urban environments like District Six.

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