Integrated Surveying of the Igreja da Penha in Rio de Janeiro: Planimetric and Altimetric Documentation for Heritage and Cadastral Purposes

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Key words: heritage, preservation, photogrammetry, GNSS, LiDAR, 3D Cadastre

SUMMARY

This study presents an integrated approach to 3D documentation of the Basilica of Our Lady of Penha, integrating multiple geotechnologies to support heritage conservation and analysis. GNSS surveys, aerial photogrammetry using a UAV, terrestrial laser scanning (TLS), and conventional topographic methods were combined to generate sparse and dense point clouds, a textured 3D model, and a georeferenced orthomosaic. Ground control points (GCPs) ensured high spatial accuracy, while confidence filtering improved data reliability. The results enabled precise geometric representation, architectural analysis, detection of potential deformations, and the creation of a multidimensional dataset suitable for restoration planning, long-term monitoring, and scientific studies. The methodology demonstrates the effectiveness of combining complementary data acquisition techniques for sustainable cultural heritage management.

RESUMO

Este estudo apresenta uma proposta de documentação tridimensional da Basílica de Nossa Senhora da Penha, integrando múltiplas geotecnologias para apoiar a conservação e análise do patrimônio. Foram combinados levantamentos GNSS, aerofotogrametria com UAV, varredura por laser scanner terrestre (LST) e métodos topográficos convencionais, resultando em nuvens de pontos esparsas e densas, modelo 3D texturizado e ortomosaico georreferenciado. Pontos de controle no solo (GCPs) garantiram alta precisão espacial, enquanto a filtragem por índices de confiança aumentou a confiabilidade dos dados. Os resultados permitiram representação geométrica precisa, análise arquitetônica, detecção de possíveis deformações e a criação de um conjunto de dados multidimensional adequado para planejamento de intervenções, monitoramento de longo prazo e estudos científicos. A metodologia demonstra a eficácia da combinação de técnicas complementares de aquisição de dados para a gestão sustentável do patrimônio cultural.

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1. INTRODUCTION

Historical objects and buildings represent essential material records for understanding different stages of societal development. In the case of preserved constructions, their architectural features provide valuable evidence for analyzing cultural patterns and social behaviors, while also revealing the dynamics of land use and territorial organization over time (Hassan and Fritsch, 2019).

However, unlike historical objects, buildings are exposed to human and environmental interferences, such as winds, rainfall, and extreme natural events, which may lead to structural pathologies. In this context, several geotechnologies have been employed to explore the potential for documenting and preserving these constructions within a digital environment (Palčák, M.; Kudela, P.; Fandáková, M. and Kordek, J., 2022).

The three-dimensional surveying of historical buildings has become an increasingly important practice within the field of cartographic engineering, especially in the context of cultural heritage preservation. A representative example of this application is the study carried out at the Sanctuary of Our Lady of Penha, located in Rio de Janeiro. The aim of the project was to conduct a three-dimensional (3D) surveying, both internal and external, of the building, with a focus on digitally documenting its structural and architectural features.

The Basilica of Our Lady of Penha is one of the most significant centers of Marian devotion in Brazil and stands out as a symbol of popular Catholic faith in Rio de Janeiro. Its origin dates back to 1635, when Captain Baltazar de Abreu Cardoso, saved from a snake attack after praying to Our Lady of Penha, built a chapel in gratitude (Fernandes, 2022). Over the centuries, the site gained relevance with the foundation of the Brotherhood of Our Lady of Penha in 1728, the construction of the 382-step staircase in 1819, expansions carried out during the 19th and 20th centuries, and its elevation to the rank of Minor Basilica by Pope Francis in 2016 (Igreja da Penha RJ, 2025). The complex currently also houses the Hall of Miracles, a museum, and cultural exhibition spaces, reinforcing its importance as both a spiritual and cultural landmark (Figure 1).


Figure 1. Church of Penha, Rio de Janeiro.

In addition to its architectural relevance, the sanctuary also embodies expressions of popular culture, represented by the traditional Festa da Penha, one of the most emblematic religious and cultural celebrations in Rio de Janeiro. Popularized with the arrival of the railway in the late 19th century, the festivity became the city's second largest in the early 20th century, blending devotion with music, carnival traditions, and social critique. Its influence inspired renowned Brazilian composers such as Noel Rosa, Cartola, João Bosco, and Luiz Gonzaga, consolidating the sanctuary not only as a place of worship but also as a reference of cultural identity (Saba, 2022).

Given its dual spiritual and cultural importance, the preservation of the Basilica of Penha demands innovative approaches. At this intersection, geotechnologies have emerged as decisive tools, offering new perspectives for the safeguarding of heritage.

The preservation of historical heritage presents constant challenges, and geotechnologies have emerged as crucial tools in this process. Techniques such as terrestrial laser scanning (TLS), drones, and photogrammetry enable the generation of detailed digital models and georeferenced datasets, offering valuable support for restoration, conservation, and public dissemination of cultural assets. These technologies also ensure the preservation of critical information that might otherwise be lost over time, due to human activity or unforeseen events.

Beyond documentation, geotechnologies integrate historical, architectural, and environmental data, providing a multidimensional perspective of heritage contexts. Digital atlases, orthophotos, and specialized cartography improve the surveying accuracy and facilitate heritage management, while emerging resources such as 3D printing, virtual and augmented reality, and artificial intelligence introduce new possibilities for representation, education, and analysis. This integration reinforces both technical and cultural approaches to heritage protection (Burda; Martinelli, 2014).

Recent advances, particularly the use of RPAs (Remotely Piloted Aircraft) combined with photogrammetry and 3D laser scanning, have expanded the scope of applications. The capacity to produce highly accurate three-dimensional models allows for the detection of structural damage, monitoring of conservation status, and simulation of interventions. As a result, geotechnologies contribute not only to heritage recording but also to sustainable management practices that ensure long-term preservation.

In this context, the present study aims to apply an integrated methodology combining GNSS, total station, drone-based photogrammetry, and terrestrial laser scanning to produce high-precision three-dimensional models of the Basilica of Our Lady of Penha (Figure 2). The goal is to support strategies for restoration, conservation, and dissemination of this historical and cultural heritage, contributing both to technical advances in cartographic engineering and to the long-term safeguarding of one of Rio de Janeiro’s most important landmarks.

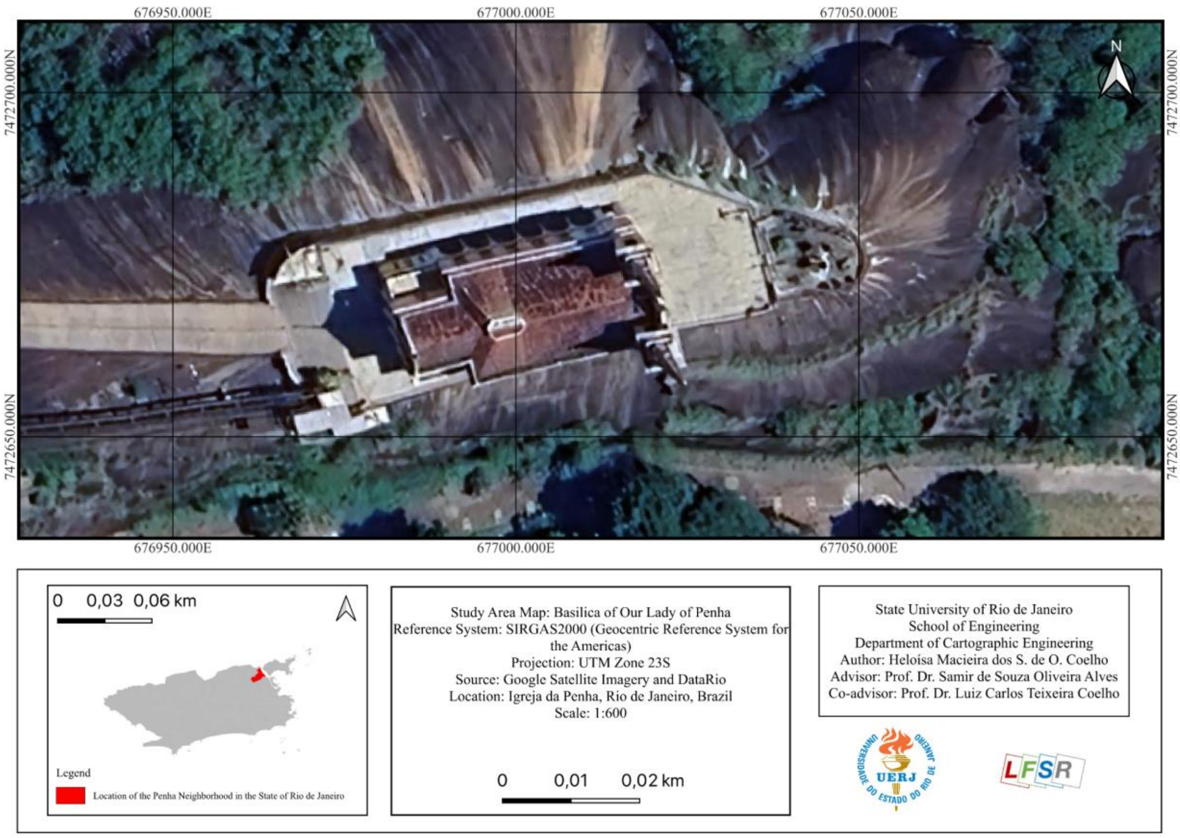

Figure 2. Situation Map for the surveyed area.

2. 3D SURVEYING IN CULTURAL HERITAGE PRESERVATION

The three-dimensional surveying of objects and buildings has been increasingly explored through the development of new sensors introduced to the surveying and geomatics engineering market. Currently, the growing autonomy and level of detail provided by such technologies are

being investigated regarding their applicability to cultural heritage and the performance of different surveying methodologies.
Hassan and Fritsch (2019) conducted a systematic review of the state of the art on the use of TLS, photogrammetric surveying, and the integration of both for 3D cultural heritage preservation. The authors compared the advantages and disadvantages of each technique and demonstrated that data integration can enhance the geometric and visual quality of the models, as well as improve the automation of processes such as point cloud registration.
Additionally, Llabani and Abazaj (2024) carried out the external 3D survey of the Clock Tower in Tirana, Albania, using TLS. Their goal was to generate a digital model that could serve conservation, research, and educational purposes. Challenges such as scan registration, data processing, and dataset integration were also evaluated. Accuracy was assessed by comparing the 3D model target coordinates with those measured through a topographic survey using a total station. The obtained three-dimensional root mean square error (RMSE) was approximately 2.5 cm, indicating that TLS surveying is an effective approach for analyzing, monitoring, and documenting cultural heritage.
Jo and Hong (2019) performed the digital 3D documentation of the Magoksa Temple, in the Republic of Korea, by combining TLS and UAV photogrammetry data. The authors evaluated the accuracy of each product using ground control points and by comparing homologous points on the ground and on the buildings between datasets. Results showed that TLS provided superior positional accuracy, particularly in the vertical component, while UAV photogrammetry offered better coverage of elevated areas such as roofs. Discrepancies between UAV- and TLS-derived coordinates (X, Y, Z) were found but remained within acceptable margins, with RMSE values ranging from millimeters to a few centimeters depending on the axis. The resulting point clouds were integrated into a single registered digital model.
It is important to highlight that 3D surveying enables the generation of products that go beyond geometric modeling. Stylianidis E, Evangelidis K, Vital R, Dafiotis P Sylaiou S. (2022) conducted laser scanning and photogrammetric surveys in two cases: the Ottoman Soap Factory in Lod, Israel, where part of the structure had collapsed, and the Ottoman Bathhouse in Apollonia, Greece. In the latter case, the authors developed, in addition to the 3D model, immersive experiences through Extended Reality applications. They concluded that digital documentation not only serves as a record for future interventions but can also promote the reintegration of these buildings into local social life and foster stakeholder engagement. The authors also emphasized that emerging technologies, such as immersive experiences, may enhance the perceived cultural value of heritage sites, provided they are supported by rigorous historical documentation and institutional collaboration.

3. MATERIALS AND METHODS

To achieve this goal, an integrated methodological approach was adopted, combining different data acquisition techniques as illustrated in Figure 3.

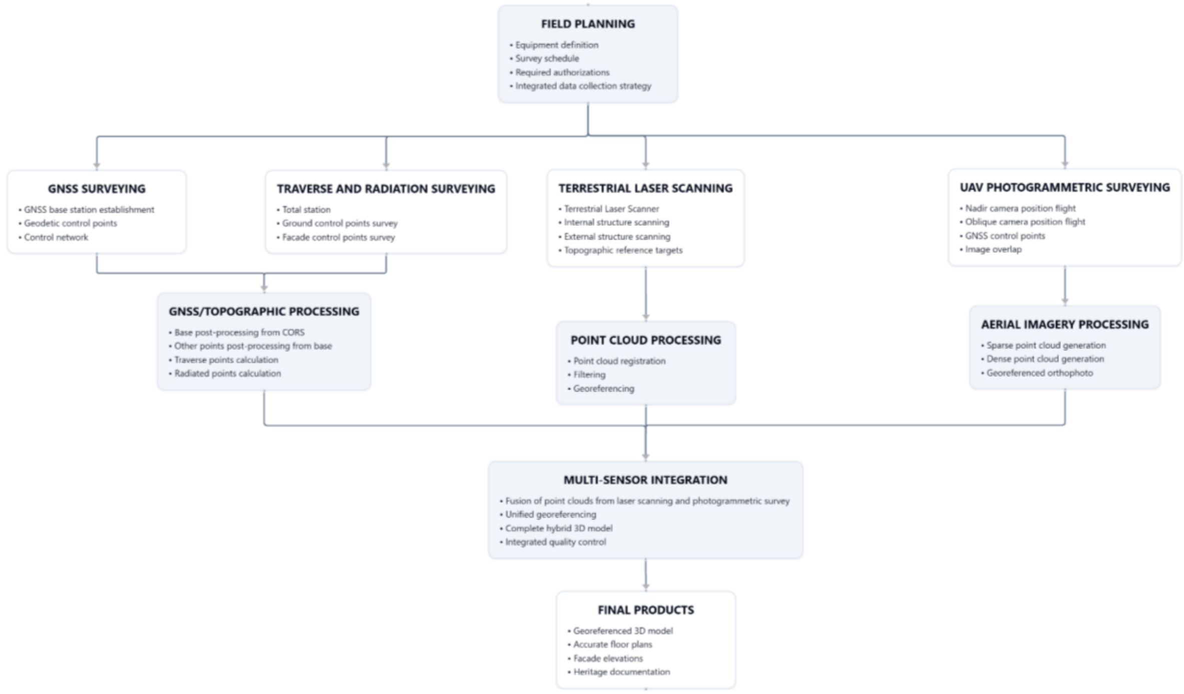

Figure 3. Flowchart of the activities carried out

3.1 Materials

Various geospatial surveying equipment was employed, including a GNSS CHC X91 receiver (TX/RX), DJI Phantom 4 UAV, RIEGL VZ-600i Terrestrial Laser Scanner, total station, prisms, and printed targets on the ground and façade. These resources provided essential support for data capture, georeferencing, and integration of multiple information sources.

3.1.1 Precise Point Positioning

GNSS (Global Navigation Satellite System) surveys were performed using a GNSS CHC X91 receiver with TX/RX functionality (Figure 4) to accurately determine the coordinates of ground control points. This step was essential for defining the geodetic reference system and for the subsequent photogrammetric stage, given that the UAV used did not have an RTK (Real-Time Kinematic) system.

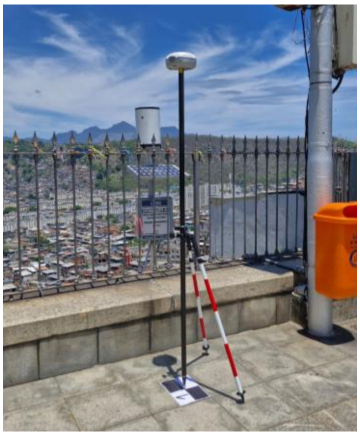

Figure 4. GNSS (Global Navigation Satellite System) receiver and antenna.

3.1.2 Aerial ARP surveying

Following this, aerial surveys were carried out using a DJI Phantom 4 UAV (Figure 5), which recorded videos at a rate of 1920x1080 FullHD, aimed at capturing video frames of the building's façades and roof. Cross-flight paths were executed with the camera in nadir orientation, as well as three additional flights with the camera in an oblique position. This enabled the acquisition of suitable images for an accurate and complete digital reconstruction of the church's structure.

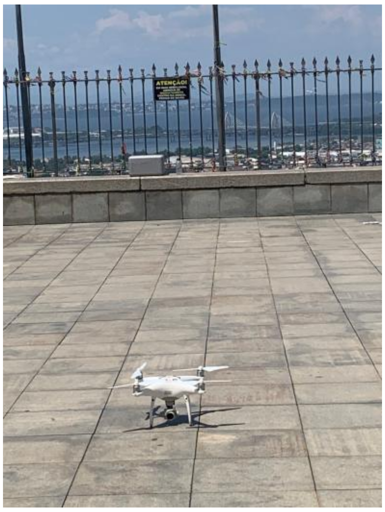

Figure 5 - Aerial ARP surveying.

3.1.3 Laser Scanner

Additionally, laser scanning technology was employed using the RIEGL VZ-600i, allowing the generation of a dense and detailed 3D point cloud of the building's interior (Figure 6). This technology is based on the emission of laser beams to measure distances with high precision, resulting in millions of points that represent both the internal and external surfaces of the structure.

Figure 6. LiDAR surveying undertaken inside the church.

3.1.4 Conventional Topography

Complementarily, two traverses were carried out: a closed traverse (primary traverse) and an open traverse (secondary traverse), with the purpose of determining the control targets coordinates placed inside and outside the building. The closed traverse was established around the sanctuary and allowed for external target surveying, while the open traverse was connected to the primary traverse and enabled the determination of coordinates for the internal targets. These procedures ensured data alignment and consistency across the acquired dataset.
Subsequently, point clouds were aligned to ensure seamless integration between the photogrammetric point cloud and the LiDAR data. The use of a topographic surveying enabled proper stitching between models and georeferencing a large number of ground control points ensured a centimetric accuracy in the drone ARP surveying.

3.2 Methods

To achieve a comprehensive 3D documentation of the Basilica, an integrated methodological approach was applied. Ground control points were first established using a GNSS CHC X91 receiver (TX/RX) to define the geodetic reference system with high precision. Complementary terrestrial surveying was conducted using a total station and prisms to determine the coordinates of internal and external targets, ensuring alignment between datasets. Aerial surveys were then performed with a DJI Phantom 4 UAV, capturing images and video frames from both nadir and oblique perspectives to generate a detailed photogrammetric model of the façades and roof. Simultaneously, a RIEGL VZ-600i Terrestrial Laser Scanner was used to acquire dense 3D point clouds of both interior and exterior surfaces. Subsequently, all point clouds were aligned and integrated, combining photogrammetric and LiDAR data to produce accurate and seamless 3D models.

3.2.1 Post-Processing of Aerial Images

The 3D modeling of the building followed a structured workflow, starting with the identification and matching of image correspondences. To reduce inconsistencies in homologous pairings, a gradual filtering based on the number of image connections was applied, ensuring an optimal configuration for reconstruction quality particularly in oblique camera position, where pairing errors are more frequent.
Subsequently, camera parameters were refined through autocalibration to correct lens distortions and enhance the geometric accuracy of the image set. The Fit Additional Corrections option was enabled during the Optimize Camera Alignment step, providing supplementary adjustments that improved the precision of the final alignment.
Ground control points (GCPs) obtained in the field with a dual-frequency GNSS receiver were integrated into the model using indirect georeferencing, as the UAV lacked an onboard RTK system. Coordinates were imported into Agisoft Metashape and organized into separate tables for ground and façade points. These points were classified as: (i) GCPs for model adjustment and georeferencing, and (ii) Check Points for evaluating positional accuracy. The dense point cloud was then generated from the sparse cloud using the Depth Filtering: Mild parameter. Point colors and confidence indices were computed in Ultra High quality, and low-confidence points were filtered out (Dense Cloud Confidence: 2–255). Finally, after georeferencing the sparse cloud, the 3D model and orthomosaic were produced, with interpolation disabled to preserve the original point cloud accuracy.

3.2.2 Post-Processing of TLS Data

The post-processing of data acquired with the TLS involves the organization and preparation of the multiple point clouds captured during the surveying. This initial step is essential to ensure data quality and consistency, allowing for the subsequent merging of partial clouds into a single three-dimensional model. It includes checking point density, removing noise, and preliminary surface classification. Additionally, control targets positioned on the ground and façades of the building serve as reference points for georeferencing, ensuring that measurements are accurately aligned with the geodetic coordinate system. Proper preparation of these point clouds is crucial for subsequent registration, integration with other sensors, and generation of detailed 3D models.
The methodology was organized sequentially to ensure geometric quality and consistency of the final model. The surveying was developed by VZ-600i terrestrial laser scanner, distributed at 106 scan positions that guaranteed complete building coverage. Each position recorded high-density point clouds, totaling more than 3 billion points, in addition to panoramic images that support visual analyses and the possibility of future texturing. In addition, GNSS observations were collected at each position, with several RTK fixed solutions presenting errors on the order of centimeters. The removal of outliers contributed to data refinement and increased the reliability of the global referencing. The equipment also automatically recorded roll, pitch, and yaw values at each station, providing additional geometric control and facilitating alignment between positions.
The TLS processing was carried out in the RiSCAN PRO software and it was configured with standard processing effort, a closure distance of 0.25 m, and plane-to-plane correspondence. This step optimized the relative positioning between stations and ensured stability and coherence of the dataset. The final result was a consistent, georeferenced, high-density three-

dimensional model, suitable for applications in heritage documentation, 3D modeling, and cartographic studies requiring high precision.

4. RESULTS

4.1 Results of Aerial Photogrammetry (ARP) Processing

The 3D processing of the building produced several products that allowed detailed and accurate documentation of the heritage asset. The sparse point cloud provided the initial reconstruction from image matching, revealing the overall geometry and highlighting potential mismatches, while serving as the foundation for the dense cloud. Processed in Ultra High quality, the dense cloud offered a significant increase in detail, including point colors and confidence indices, enabling in-depth analysis of architectural elements and detection of possible deformations or material loss.

From the dense cloud, a textured 3D model (mesh with build texture) (Figure 7) was generated, accurately representing the building's surfaces and allowing detailed visualization and planning for interventions or restoration. The texture quality reflected the initial alignment and image resolution, emphasizing the importance of camera optimization and point filtering. Additionally, a georeferenced orthomosaic was created without interpolation to preserve point cloud accuracy, providing a heritage documentation, and serving as a reference for temporal monitoring.

The workflow including homologous pair filtering, camera parameter optimization, and GCP insertion and classification ensured high geometric accuracy in the final model. Confidence indicators in the dense cloud allowed low-quality points to be filtered out, improving measurement precision and model reliability. Indirect georeferencing using GCPs proved effective even without an onboard RTK system, ensuring correct spatial alignment. Nevertheless, areas with complex geometry or repetitive textures remain challenging, highlighting the need for additional checks and filtering to maintain product quality.

Figure 7. Preliminary 3D model of the Penha Church and its limits.

The results obtained from the photogrammetric processing enabled a detailed reconstruction of the study area. A total of 1,173 images were used, captured at an average altitude of 39.5 m, resulting in a spatial resolution of 1.47 cm/pixel and covering an area of approximately 1,340 m². The image alignment produced a total of 558,132 tie points, with 3,752,462 projections and a mean reprojection error of 0.76 pixel, indicating good consistency in the internal adjustment. For quality control, 9 Ground Control Points (GCPs) and 5 Check Points were employed. Their spatial distribution is presented in Figure 8. The Root Mean Square Error (RMSE) for the GCPs was 46.4 cm in total, while for the Check Points it was 29.5 cm, highlighting greater reliability in the independent validation points.

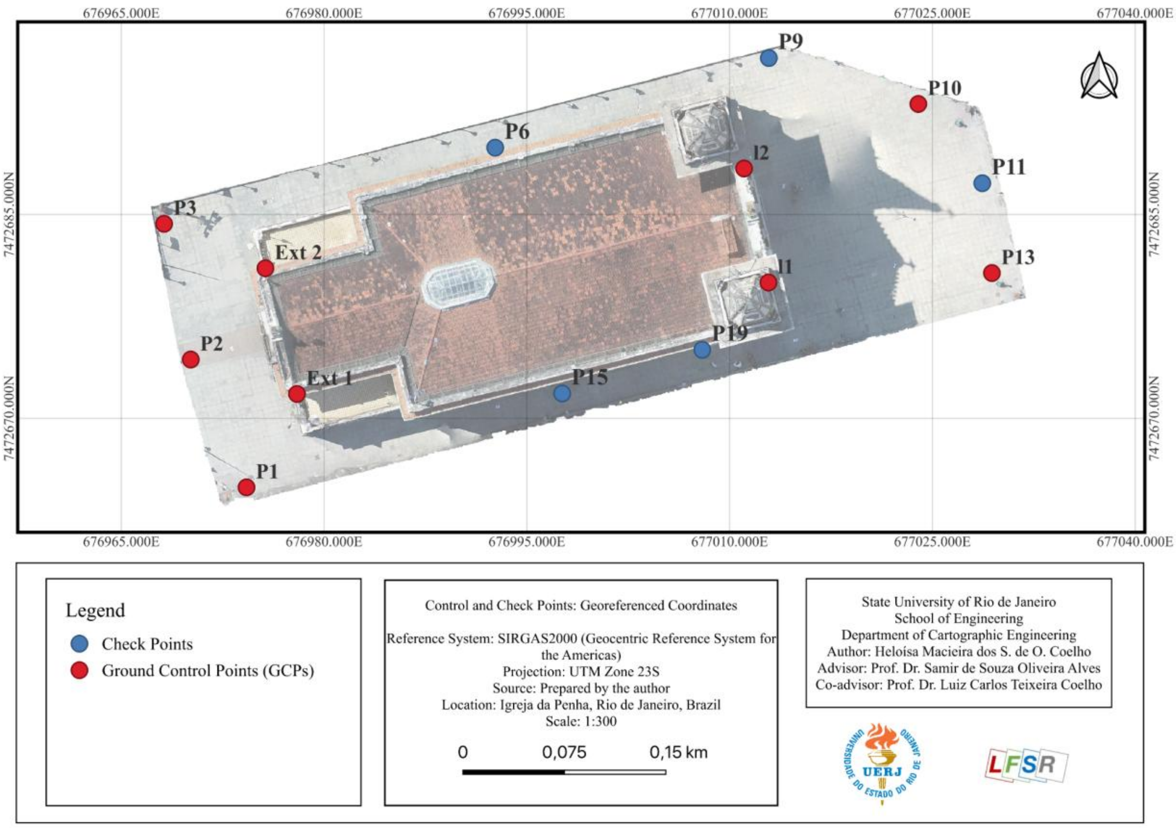

Figure 8. Map of Control and Verification Points: Georeferenced Coordinates.

The dense point cloud (Figure 9) consisted of 297.3 million points, providing a detailed representation of the mapped surface. Based on this dataset, the resulting 3D model (Figure 6) contained 5,641,840 faces and 2,830,261 vertices, textured in a mosaic of 8,192 x 8,192 pixels. The reconstruction process was carried out without interpolation, preserving the original characteristics of the data.

Figure 9. Dense point cloud.

The final orthomosaic (Figure 10) generated had dimensions of 9,443 x 8,098 pixels, referenced to the SIRGAS2000 / UTM Zone 23S coordinate system, yielding a georeferenced product ready for cartographic applications.

Figure 10. Orthomosaic.

These results demonstrate the feasibility of non-interpolated processing for high-resolution and high-accuracy reconstructions, producing consistent cartographic outputs suitable for topographic analyses and territorial monitoring.

4.2 Terrestrial Laser Scanning (TLS) Processing Results

The processing of the project, developed through multi-station adjustment (MSA) in RiSCAN PRO software, demonstrated very solid and consistent results. Data acquisition included 106 scan positions with the VZ-600i laser scanner, reaching more than 3 billion points. This density ensured not only full coverage of the object of study but also a high level of detail for further analyses, supporting high-precision applications in documentation and 3D modeling.

The GNSS positioning data integrated into the survey showed outstanding performance. Several stations achieved RTK fixed solutions, with horizontal and vertical errors ranging from millimeters to a few centimeters, providing high reliability for the geodetic referencing of the dataset. The removal of GNSS outliers contributed to refining the results and eliminating possible distortions.

Another key aspect was the large number of planar patches identified in the three processing phases, which was essential for robust cross-referencing between stations. The consistency in surface alignment in north-south, east-west, and horizontal directions demonstrated that the registrations were performed with excellent geometric correspondence, reinforcing the quality of the spatial adjustment.

The adjustment procedure followed optimized parameters, such as a reduced gap closure (0.25 m) and standard-level processing effort, which balanced efficiency and precision. This configuration resulted in a stable mesh, free of significant discrepancies between stations, ensuring continuity and coherence of the final model.

Finally, the integration between scanning and orientation measurements (roll, pitch, and yaw) recorded by the equipment provided additional control of geometry during processing. Combined with the large number of images captured alongside the point clouds, this integration enhances the potential for further analyses, such as texturing and photographic representations of the 3D model.

In summary, the strengths of the processing were comprehensive coverage, high point density, centimeter-level GNSS accuracy, robustness in plane-to-plane correspondence, stability of the adjusted mesh, and integration of complementary data, all of which consolidate the quality of the cartographic product and its applicability in research and heritage documentation of high demand.

4.3 Integration of Aerial and Terrestrial Data for 3D Model Generation

The integration between the dense point clouds obtained by the RPA and the TLS surveying was performed in RIEGL's RiSCAN PRO software (Figure 11). The association between the two datasets was carried out within the project coordinate system (PRCS), allowing the terrestrial point cloud and the aerial information to be aligned in the same reference frame. This integration ensured spatial compatibility between the products, expanded the coverage of the surveyed area, and enabled the generation of a more complete 3D model, in which the details captured by the laser scanning were complemented by the RPA's point cloud. The methodology reduced gaps, improved model continuity, and ensured greater consistency in the final result.

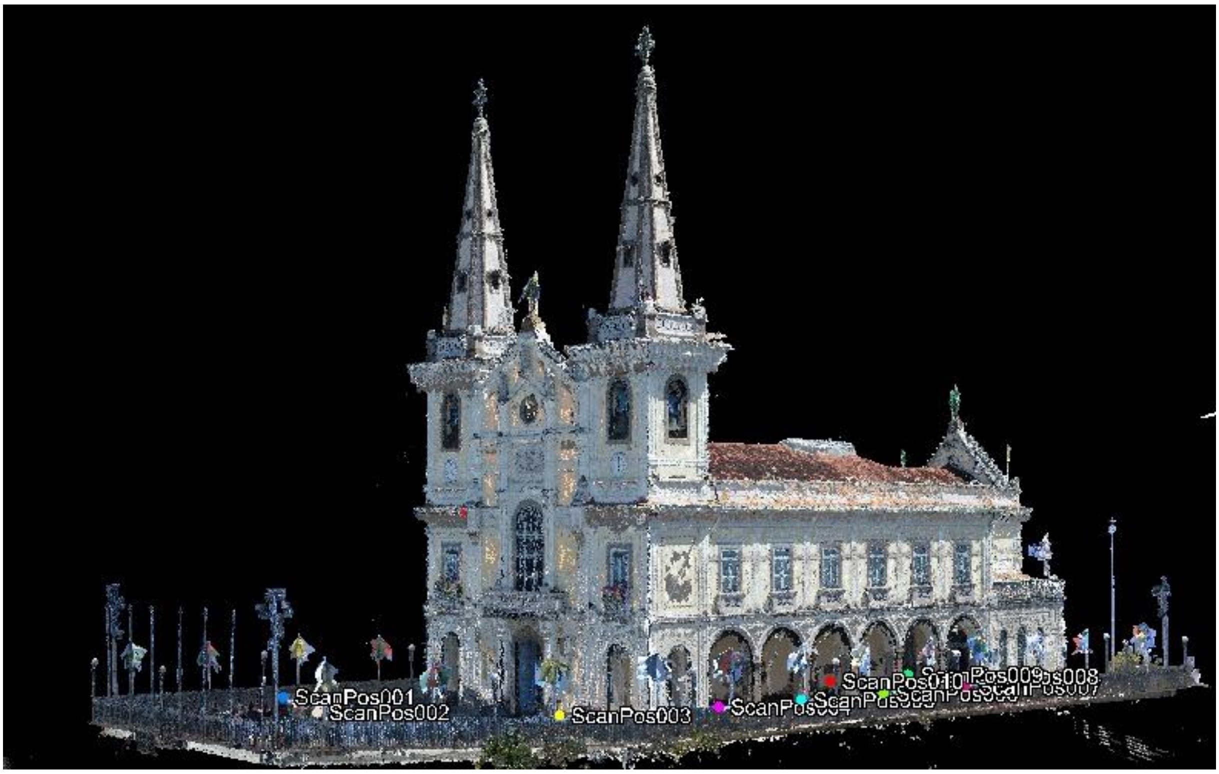

Figure 11. Alignment of aerial and terrestrial point clouds.

5. DISCUSSION AND CONCLUSION

Whilst this model requires refinement (most notably the reprocessing of photogrammetric data at higher resolutions), it is possible to say that the integration of the various surveying techniques resulted in a precise and comprehensive three-dimensional documentation of the Church of Penha. The products generated serve as valuable tools for historical heritage conservation, supporting applications such as digital modeling of architectural elements, structural analyses, intervention planning, and digital preservation. Thus, the results underscore the importance of using geotechnologies as a means to support the appreciation and protection of built cultural heritage.

The integrated use of geotechnologies including GNSS surveying, aerial photogrammetry, terrestrial laser scanning (TLS), and conventional topographic methods proved highly effective for the detailed documentation and analysis of the Basilica of Our Lady of Penha. The combination of sparse and dense point clouds allowed for progressive refinement of the 3D model, ensuring accurate geometric representation and enabling the detection of potential deformations or material loss. The textured 3D model and georeferenced orthomosaic provided complementary visual and metric information, supporting both architectural analysis and long-term monitoring strategies.

The implementation of ground control points (GCPs) and their classification as control and check points ensured high spatial accuracy, even without an onboard RTK system on the UAV. Applying confidence indices and filtering in the dense cloud increased data reliability, while

integrating TLS data added precision, particularly for capturing complex internal geometries. This multidimensional approach combining photogrammetry, laser scanning, and conventional topography highlighted the importance of rigorous methodology in heritage documentation, ensuring both metric precision and visual fidelity.
Overall, the methods employed not only produced a comprehensive record of the heritage asset but also demonstrated the potential of geotechnologies to support restoration planning, conservation monitoring, and sustainable management. The study emphasizes that combining different data acquisition techniques is essential for safeguarding cultural heritage, providing robust and detailed datasets that can guide future interventions and support comparative analyses and scientific studies.
Ultimately, this study highlights that the data integration by RPA and TLS is crucial for achieving highly detailed, accurate, and reliable 3D documentation of cultural heritage sites. By combining the complementary strengths of aerial and terrestrial data, the methodology not only enhances geometric precision and visual completeness but also ensures that conservation and restoration efforts are informed by robust, multidimensional datasets. The results reinforce that such integrated geotechnological approaches are indispensable for the effective preservation, monitoring, and sustainable management of built heritage.

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BIOGRAPHICAL NOTES

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