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Point Cloud-Based and Multi-Source Data Fusion for Monitoring the State of Conservation of the Defensive Walls of the Historic Town of Mértola, Portugal

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***Abstract* – This paper presents a multi-source point cloud methodology for the conservation state monitoring and three-dimensional documentation of the defensive walls of the Historic Town of Mértola, Portugal. Two Terrestrial Laser Scanner (TLS) campaigns conducted with a 5-month interval were compared to detect and map inter-annual structural displacements along a critical wall section. A partial wall collapse recorded in the winter of 2025 was documented through a UAV photographic survey of the area, whose data were merged with the TLS dataset to reconstruct the pre-repair geometry and quantify the volume of lost material, demonstrating the value of point cloud-based methods for assessing damage in historic masonry. Complete 3D models of two wall sections were generated by integrating TLS, UAV photogrammetry, airborne LiDAR data and 360º spherical imagery, overcoming the geometric limitations of each individual technique. Additionally, a controlled metrological experiment using a test object of known geometry is presented to characterise the influence of scanner viewing angle and range on point cloud quality, providing a quantitative basis for interpreting displacement measurements in complex survey configurations.**

Keywords* – *Terrestrial Laser Scanning, UAV photogrammetry, Point cloud fusion, Heritage monitoring, Masonry walls, Sustainable Cities and Communities

I. INTRODUCTION

This paper presents the application of a multi-source point cloud fusion methodology to the defensive walls of Town of Mértola (Fig. 1), a town of recognised cultural heritage significance undergoing active conservation assessment. In March 2025, a partial collapse occurred in the Clock Tower-Market (CTM) wall section, resulting in a visible cavity that was subsequently documented through a UAV-based photographic survey to visualize the CTM wall status. Since overlapping photographs were taken of the cavity area, it was possible to perform photogrammetric processing and reconstruct the cavity's geometry, and estimate the volume of lost material before restoration. This event highlights the critical role of systematic point cloud-based monitoring for the detection and quantification of damage in vulnerable masonry structures, particularly when such localised failures may remain unrecorded prior to repair interventions.

Fig. 1 Overview of Town of Mértola.

Two terrestrial laser scanning (TLS) campaigns, conducted in September 2025 and February 2026, were co-registered to enable the assessment of inter-annual structural displacements across the CTM section. Additionally, the March 2025 UAV dataset was integrated with the September 2025 TLS data to reconstruct the 3D model of the affected area.

To ensure geometrically complete representations, multi-source 3D models combining TLS, UAV photogrammetry and airborne LiDAR data were generated for the CTM section. For the Western Wall (WW), located near Mértola Castle, 360º spherical imagery was additionally incorporated. These integrated models support a more comprehensive structural assessment and provide a robust basis for heritage documentation.

Furthermore, a controlled experimental study will be conducted at LNEC campus to evaluate the influence of laser scanning incidence angle on point cloud quality, providing insight into geometry limitations observed in the field data.

II. RELATED RESULTS IN THE LITERATURE

The use of point cloud technologies for heritage monitoring has grown substantially over the past decade, particularly in the context of deformation analysis and preventive conservation. Lercari (2019) demonstrated the potential of multi-temporal terrestrial laser scanning (TLS) surveys combined with the Multiscale Model-to-Model Cloud Comparison (M3C2) algorithm to quantify material loss in earthen archaeological structures over extended periods, establishing a replicable workflow aligned with conservation monitoring frameworks [1]. The M3C2 algorithm itself, originally introduced by Lague et al. (2013), provides a robust method for direct comparison of 3D point clouds, particularly suited for rough and complex surfaces typical of heritage structures [2].

Similarly, Sánchez-Aparicio et al. (2024) evaluated 3D imaging techniques for structural assessment of masonry retaining walls, showing that point cloud comparison methods such as cloud-to-cloud (C2C) and M3C2 can provide objective and accurate alternatives to traditional visual inspection [3]. The detection and quantification of specific pathologies in historic masonry, such as bulging and deformation, have also been addressed using geometric analysis of point clouds. Hu et al. (2023) proposed a plane-fitting method applied to TLS data to identify deformation areas in ancient city walls, demonstrating the effectiveness of model-based approaches for extracting structural anomalies [4].

The complementarity between TLS and UAV-based photogrammetry is widely recognized in heritage documentation workflow. Fazio et al. (2023) demonstrated that TLS provides high-accuracy data for vertical façades, while UAV photogrammetry effectively captures upper and inaccessible areas, enabling more complete 3D reconstructions [5]. A similar integration strategy was presented by Tsioukas et al. (2024), who employed co-registration techniques within CloudCompare to combine TLS ans UAV-SfM datasets for heritage modelling and visualization [6]. In the context of historic fortifications, Moyano et al. further demonstrated the integration of TLS, UAV photogrammetry, and terrestrial imaging into HBIM environments for the Almohad Wall of Cáceres, addressing accessibility constraints comparable to those encountered in Mértola [7].

Beyond local-scale acquisition, airborne LiDAR has been increasingly used to provide broader topographic context. Cappellazzo et al (2023) showed that integrating ALS, UAV and TLS datasets enhances geospatial consistency and enables multi-scale analysis, particularly in complex or vegetated environments [8]. The registration of heterogeneous point clouds remains a critical challenge, with Jung et al. (2024) proposing coarse-to-fine iterative closest point (ICP) strategies to improve alignment between datasets of varying density and acquisition geometry [9]. The foundations of ICP-based registration methods were established by Besl and McKay (1992), whose work remains central to point cloud alignment techniques [10].

Despite these advances, the influence of acquisition geometry on point cloud quality, particularly in TLS surveys, remains an important but less frequently quantified aspect. Factors such as incidence angle, distance to target and surface orientation can significantly affect point density, noise and measurement accuracy. To address this gap, the present study will include a controlled experimental assessment of TLS data acquired at varying incidence angles and distances, enabling the evaluation of their impact on geometric quality. This experimental component will provide a metrological perspective to interpret observed variations in data quality within the Mértola case study, where steep topographic differences and long acquisition distances introduce non-uniform scanning conditions.

III. DESCRIPTION OF THE METHOD

The proposed methodology integrates multi-temporal TLS, UAV photogrammetry, airborne LiDAR, and spherical imaging to support deformation analysis and 3D reconstruction of heritage wall structures. The approach is structured into four components addressing measurement, fusion and metrological characterisation.

A. Multi-temporal TLS Co-registration and Displacement Detection

Two TLS campaigns were acquired in September 2025 and February 2026 using multiple scan positions to ensure complete façade coverage. Each campaign was independently registered into a unified point cloud using GNSS-RTK referenced Ground Control Points (GCPs), ensuring a consistent geodetic framework [11].

Inter-epoch co-registration was performed in CloudCompare using a hierarchical alignment strategy combining manual pre-alignment and Iterative Closest Point (ICP) optimisation over stable façade regions assumed invariant over time [12]. Registration quality was assessed through RMSE computed on these reference areas, providing an empirical estimate of residual misalignment.

Surface displacement was quantified using the Cloud-to-Cloud (C2C) distance computation implemented in CloudCompare. This approach determines the nearest-neighbour distance between point clouds, providing a direct measure of geometric differences between epochs [12]. Although more sensitive to point density variations and surface roughness than normal-based methods, it enables a straightforward assessment of surface changes over the analysed façade [2].

The 2025 dataset was used as the reference cloud for distance computation. A statistical detection threshold was defined based on the combined effects of registration uncertainty and local surface variability, ensuring that only differences exceeding the expected measurement noise were interpreted as potential deformation [13].

B. *Cavity Documentation and Volumetric Assessment*

A UAV photographic survey was conducted following the partial collapse event of March 2025. This collapse led to rehabilitation interventions made during the Summer of 2025. Image acquisition combined oblique viewpoints to ensure complete geometric coverage of the cavity interior and to minimise occlusions. The images were processed to generate a dense 3D point cloud of the cavity.

The resulting point cloud was subsequently integrated with the TLS dataset acquired in September 2025, which provides a geometric representation of the post-collapse wall surface and serves as a proxy for the pre-collapse condition in the affected area.

Volumetric estimation was performed through reconstruction of the cavity boundary and computation of differential volume between the integrated datasets, enabling quantification of material loss associated with the collapse event [14].

C. *Multi-source Point Cloud Fusion*

Complete 3D reconstructions of the CTM and Western Wall (WW) sections were generated by integrating TLS, UAV photogrammetry, airborne LiDAR data from the Portuguese Directorate-General for Territory (DGT) [15], and 360º spherical imagery (this one used in WW only).

Data fusion was performed within a unified GNSS-referenced geodetic framework using common Groud Control Points. This multi-sensor integration enables consistent modelling of façade geometry, upper architectural features and surrounding terrain, supporting both structural and heritage documentation [16].

D. *Metrological Characterisation of Viewing Geometry Effects*

Field observations indicated a systematic degradation of point cloud quality with increasing range and oblique incidence angles, manifested as reduced point density and increased geometric noise [17].

To quantify these effects, a controlled experiment will be conducted using a rigid polystyrene artefact composed of planar and cylindrical surfaces. Scans will be acquired under controlled variations of range and viewing geometry.

Planar deviation analysis will be used to assess angle- and range-dependent noise, while cylinder-fitting residuals will provide a geometry-invariant estimate of reconstruction accuracy. The results will establish a metrological basis for interpreting TLS-derived deformation fields under variable acquisition geometry.

IV. RESULTS AND DISCUSSIONS

The comparison between the two TLS campaigns revealed C2C displacement values predominantly in the maximum range of approximately 1 to 1.5 cm, being the majority towards the interior of the wall. These values are consistent across most of the analysed façade, with no spatially coherent deformation patterns observed.

Considering the combined effects of TLS measurement noise and registration uncertainty, these displacement magnitudes are interpreted as being within the expected uncertainty envelope of the measurement system. As such, no significant structural changes can be confidently identified.

The cavity dataset derived from UAV photographs was successfully integrated with the TLS reference model, enabling a coherent 3D representation of the collapse area. Preliminary volumetric reconstruction indicates that the merged dataset provides sufficient geometric continuity for estimating material loss, although the final volumetric values are still subject to refinement during post-processing validation.

The multi-source fusion of TLS, UAV, airborne LiDAR and spherical imagery resulted in a geometrically consistent representation of both CTM and Western Wall sections. Initial inspection confirms improved spatial completeness compared to single-source datasets, particularly in occluded or inaccessible areas.

The controlled experiment on viewing geometry effects has not yet been completed. However, field observations from the CTM dataset already indicate a clear dependence of point cloud quality on range and incidence angle, motivating the need for a controlled metrological validation. The planned experiment will provide quantitative relationships between acquisition geometry and point cloud uncertainty.

Overall, the preliminary results confirm the feasibility of the proposed multi-sensor workflow, while highlighting the importance of acquisition geometry and registration uncertainty in the reliability of deformation analysis.

V. CONCLUSIONS AND OUTLOOK

This work presents a multi-sensor methodology for the geometric analysis and documentation of historic wall structures, combining multi-temporal TLS, UAV photographic, LiDAR data and 360º spherical images and multi-source data integration. The application of the C2C algorithm enabled the detection of surface changes between survey epochs, with observed variations remaining within the expected uncertainty range of the measurement system, indicating no significant structural deformation.

The integration of UAV-derived data with TLS proved effective for the reconstruction and volumetric assessment of collapse features, while multi-source point cloud fusion improved the spatial completeness of the 3D models.

Ongoing work includes the completion of the controlled metrological experiment to quantify the influence of acquisition geometry on point cloud quality and its impact on displacement measurements. These results will support a more rigorous uncertainty assessment and will be incorporated in future developments of this study.

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REFERENCES

[1] **Lercari, N.**: *Monitoring earthen archaeological heritage using multi-temporal terrestrial laser scanning and surface change detection*, Journal of Cultural Heritage, No. 37, 2019, pp. 166–177.

[2] **Lague, D.; Brodu, N.; Leroux, J.**: *Accurate 3D comparison of complex topography with terrestrial laser scanner: Application to the Rangitikei canyon (N-Z)*, ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 82, 2013, pp. 10–26.

[3] **Sánchez-Aparicio, L.J. et al.**: *Experimental evaluation of 3D imaging technologies for structural assessment of masonry retaining walls*, Results in Engineering, Vol. 21, 2024.

[4] **Hu, Y. et al.**: *A study on the detection of bulging disease in ancient city walls based on fitted initial outer planes from 3D point cloud data*, npj Heritage Science, Vol. 11, 2023.

[5] **Fazio, L. et al.**: *Combination of terrestrial laser scanning and UAV photogrammetry for 3D modelling and degradation assessment of heritage building*, npj Heritage Science, 2023.

[6] **Tsioukas, V. et al.**: *Using TLS, UAV, and MR methodologies for 3D modelling and historical recreation of religious heritage monuments*, Journal on Computing and Cultural Heritage, 2024.

[7] **Moyano, J. et al.**: *Integration of SfM, TLS and UAV techniques for HBIM of the Almohad Wall of Cáceres*, ISPRS Archives, 2018.

[8] **Cappellazzo, M. et al.**: *Integrated airborne LiDAR–UAV methods for archaeological mapping in vegetation-covered areas*, ISPRS Archives, Vol. XLVIII-M-2-2023, 2023, pp. 357–364.

[9] **Jung, J. et al.**: *Multi-source point cloud registration for urban areas using a coarse-to-fine approach*, GIScience & Remote Sensing, 2024.

[10] **Besl, P.J.; McKay, N.D.**: *A method for registration of 3-D shapes*, IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 14, No. 2, 1992, pp. 239–256.

[11] **Habib, A. et al.**: *Integration of terrestrial laser scanning and photogrammetry for infrastructure monitoring*, Photogrammetric Engineering and Remote Sensing, Vol. 76, No. 11, 2010, pp. 1215–1225.

[12] **Girardeau-Montaut, D.**: *CloudCompare - distance computation tools*, 2016. Available: https://www.cloudcompare.org/doc/wiki/index.php/Distances_Computation

[13] **Wheaton, J.M.; Brasington, J.; Darby, S.E.; Sear, D.A.**: *Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets*, Earth Surface Processes and Landforms, Vol. 35, 2010, pp. 136–156.

[14] **James, M.R.; Robson, S.**: *Straightforward reconstruction of 3D surfaces and topography with a camera: accuracy and geoscience application*, Journal of Geophysical Research: Earth Surface, Vol. 117, 2012.

[15] **Direção-Geral do Território (DGT)**: *National airborne LiDAR dataset of Portugal*, Available: https://www.dgterritorio.gov.pt

[16] **Remondino, F.**: *Heritage recording and 3D modeling with photogrammetry and 3D scanning*, Remote Sensing, Vol. 3, No. 6, 2011, pp. 1104–1138.

[17] **Lichti, D.D.**: *Error modelling, calibration and analysis of an AM–CW terrestrial laser scanner system*, ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 61, No. 5, 2007, pp. 307–324.