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Comparative Accuracy Assessment of Point Cloud Registration Methods in Terrestrial Laser Scanning: A Case Study of a Mosque Façade

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Abstract

Point-cloud registration, the alignment of multiple overlapping terrestrial laser scanning (TLS) stations into a single coordinate system, is the most error-sensitive stage of the TLS workflow, since any residual misalignment propagates into every derived product. Quantitative comparisons of different registration strategies on the same real-world dataset remain scarce, particularly for architecturally complex façades. This paper compares four registration strategies available in commercial TLS software (Cloud-to-Cloud, Target-Based, Top-View, and a combined Topview-and-Cloud-to-Cloud approach) together with a target-based manual refinement, using the same cleaned eight-station scan of a university mosque façade acquired with a FARO Focus 3D X330 scanner. Each strategy is evaluated by mean point-position accuracy and inter-scan overlap. Among the automatic strategies, the combined Topview-and-Cloud-to-Cloud method gave the lowest maximum error (± 11.6 mm) and the Top-View method the largest (± 32.9 mm). The target-based manual refinement outperformed all automatic strategies, reducing the mean point error to ± 4.1 mm and raising the minimum overlap to 16.5%. The results show that high overlap alone does not guarantee geometric accuracy, and that target-based manual registration remains the most reliable strategy for detailed façades.

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Contribution to the field statement:

This study provides the first controlled, field-based comparison of four point-cloud registration strategies on identical terrestrial laser scanning data of a mosque façade, quantifying how each affects point-position accuracy and inter-scan overlap and showing that high overlap alone does not guarantee geometric accuracy.

Highlights:

- Four registration methods compared on identical TLS façade data.
- Target-based manual alignment gave the best accuracy (± 4.1 mm).
- Top-View projection produced the largest error (± 32.9 mm).
- High inter-scan overlap did not guarantee geometric accuracy.

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1. INTRODUCTION

Terrestrial laser scanning (TLS) has become one of the primary surveying techniques for acquiring dense, high-accuracy three-dimensional (3D) representations of the built environment. A single scan station, however, can rarely capture the complete geometry of an object such as a building façade, because of occlusions, a limited field of view, and range-dependent point-density loss. TLS is now firmly established across the architecture, engineering and construction (AEC) domain [1], from bridge condition monitoring [2] to construction scan planning [3]. Complete 3D coverage therefore requires several partially overlapping scans acquired from different



stations, which must then be transformed into a single, common coordinate system through a process known as point-cloud registration [4], [5].

Registration is widely regarded as the most error-sensitive stage of the entire TLS workflow: any misalignment between adjacent scans propagates directly into the combined point-cloud model and, from there, into every derived product — 3D models, cross-sections, deformation measurements [6], and the geometric or volumetric quantities extracted for engineering use [7], [8], [9], [10]. Recent research has increasingly explored learning-based and cross-source registration to improve robustness on complex data [11], [12], [13]. Two broad families of registration strategy are used in practice. Target-based (control-point) methods rely on artificial reference objects spheres, checkerboards or paper targets placed in the overlap zone of adjacent scans, at the cost of additional field time for target placement. Targetless, cloud-based methods instead align scans directly from the geometry of the overlapping surfaces, most commonly through variants of the Iterative Closest Point (ICP) algorithm [14], and are faster to deploy in the field but more sensitive to surface geometry, point density, and the quality of the initial coarse alignment [15], [16]. Recent critical syntheses of classical and learning-based registration approaches [17] and comprehensive reviews of deep-learning registration [18] confirm that no single strategy is optimal across all data sources and scene types.

Despite the practical importance of this choice, quantitative, side-by-side comparisons of different registration strategies applied to the very same field dataset the same instrument, the same scan stations, and the same evaluation criteria remain comparatively scarce in the literature, particularly for architecturally complex façades that combine large planar wall surfaces with fine ornamental detail such as a minaret, a dome, or cornice mouldings [19].

This paper addresses this gap through a controlled, field-based comparison of four registration strategies commonly available in commercial TLS processing software Cloud-to-Cloud, Target-Based, Topview-Based, and a combined Topview-and-Cloud-to-Cloud approach applied to the same eight-station terrestrial laser scan of a university mosque façade, acquired with a FARO Focus 3D X330 scanner [4]. For each strategy, both the automatic and the subsequently manually refined alignment are evaluated and compared in terms of mean point-position accuracy (mm) and inter-scan overlap percentage. Because the same raw scan data are used as input to all four methods, differences in the resulting accuracy can be attributed to the registration strategy itself rather than to differences in data acquisition.

The remainder of this paper is organised as follows. Section 2 describes the principles of the four registration strategies, the geodetic coordination (georeferencing) of TLS models [5], [20], the study area and instrument, and the field and office workflow. Registered TLS point clouds also underpin as-built building information modelling of civil structures such as bridge components [21]. Section 3 presents the resulting accuracy and overlap statistics. Section 4 discusses the practical trade-offs between the methods, and Section 5 concludes the paper with recommendations for practitioners selecting a registration strategy for similar façade-scanning projects.

2. METHOD

This section summarises the principles underlying the four registration strategies compared in this study and the geodetic coordination of the resulting model. Registration transforms the individual scans, each recorded in its own instrument-centred coordinate system, into one common reference frame; georeferencing then relates that frame to a national or global (e.g., WGS-84) coordinate system [5].

2.1. Coarse and fine registration

The output of a scan taken at a single station is a 3D point cloud expressed in the instrument's own local coordinate system, whose origin lies at the centre of the scanner mirror; the coordinate system therefore changes with every station at which the instrument is set up [5]. Building a complete 3D model of an object requires all the individual station clouds to be brought into one common reference frame. This alignment step is termed registration, and the associated passage from a local scan coordinate system to a global one is termed transformation.

Two overlapping point clouds are related by a rigid-body transformation consisting of a 3×3 rotation matrix, built from the three rotation angles between the coordinate systems, and a translation vector [5]. When one cloud is taken as the reference and successive clouds are aligned to it one after another, small residual errors accumulate along the chain, so that the last-registered scans are the least accurate. To limit this effect, a global adjustment can be applied after the sequential alignment so that the transformation parameters of all clouds are computed simultaneously and the residual error is distributed homogeneously across the whole model rather than piling up at the end of the chain [5].

In practice, registration is usually carried out in two stages: a coarse (approximate) alignment that brings the clouds roughly into position, followed by a fine alignment that minimises the residual distances between corresponding surfaces. The fine stage is most commonly performed with the Iterative Closest Point (ICP) algorithm, which repeatedly pairs each point with its nearest neighbour in the reference cloud and solves for the rigid transformation that minimises the mean-square distance between the pairs [14]. ICP has become almost a



de-facto standard for fine registration and is frequently used to refine the result of any coarse alignment, whichever coarse method was applied [5], [14].

2.2. Target-based registration

Target-based (control-point) registration relies on artificial reference objects placed in the overlap zone of adjacent scans and captured by each of them. Two target types are common: highly reflective spheres of known diameter and precise roundness (Figure 1), and printed checkerboard targets [15]. The centre of a sphere can be located accurately from any viewing direction, which makes spheres well suited to registration from arbitrary scanner positions; a checkerboard, by contrast, is a flat target whose central intersection is used as the reference point, and it does not yield a reliable reference when it is seen at a steep, near-grazing angle relative to the scanner [15].

If at least three well-distributed reference points are common to a scan pair, the transformation parameters between the two coordinate systems can be determined mathematically [16]. Because the accuracy of the whole model depends on how well these targets are identified, both the type of target and its spatial layout have a measurable effect on registration accuracy, and target placement therefore requires careful planning before scanning begins [15], [22], [23]. The registration of complex heritage interiors and façades has been examined in detail in recent case studies comparing feature-based and mobile-mapping approaches [24], [25], and terrestrial laser scanning is now a standard tool for the geometric documentation of cultural-heritage structures [26]. The main cost of the method is the additional field time needed to position and, where geodetic coordination is required, to survey the targets.



Figure 1. Placement of a reference sphere used as a registration target. From S. W. Nazari, M.S. thesis, 2020 [4].

2.3. Cloud-to-cloud (targetless) registration

Not all registration software requires artificial targets. Targetless, cloud-to-cloud registration instead aligns scans directly from the surfaces and edges captured in the overlapping regions of the point clouds themselves [15]. Where a scan pair shares a sufficiently large overlap, the many points on the common surfaces provide enough geometric constraint to solve for the transformation without any dedicated targets.

The quality of a cloud-to-cloud result is, however, sensitive to the geometry of the scene, to the size of the overlap between adjacent scans, and to the point density in the overlap zone; large planar surfaces with little distinctive relief, moving objects, reflective materials, and gaps such as open windows or doors all tend to introduce invalid points and degrade the alignment [15]. Cloud-to-cloud alignment also depends on a reasonable initial (coarse) position, and its result is commonly refined with ICP to reach the final accuracy [5], [14]. Recent work continues to improve the robustness and efficiency of ICP-based fine registration, particularly for target-free and time-series point clouds [27].

2.4. Topview-based and combined registration

In addition to target-based and cloud-to-cloud alignment, commercial TLS software offers a top-view (plan-projection) strategy, in which the scans are aligned primarily using their projection onto a horizontal plane. This approach is convenient when the stations are distributed around an object at broadly similar heights, as is typical of a façade survey, but the plan projection discards much of the vertical detail that distinguishes one surface from another.

A combined Topview-and-Cloud-to-Cloud strategy first uses the top-view projection for a robust coarse alignment and then refines it with a cloud-to-cloud step, aiming to combine the stability of the plan-based coarse stage with the surface-level accuracy of the cloud-based fine stage. The fusion of data from different platforms, such as mobile and terrestrial laser scanning, poses similar strategy-selection challenges [28]. These two strategies, together with target-based and pure cloud-to-cloud registration, are the four methods compared in this study.



2.5. Geodetic coordination (georeferencing)

Registration brings the individual scans into one common reference frame, but that frame is still arbitrary. Relating it to a national or global coordinate system, such as one based on WGS-84 datum parameters, is a separate step known as geodetic coordination or georeferencing [5]. The correlation between the two coordinate systems can be described by six transformation parameters; the scale factor is generally negligible and may be omitted [5]. Two approaches are available. In indirect georeferencing, the point cloud is tied to control points whose geodetic coordinates are already known, determined beforehand with a total station or GNSS receiver; at least three well-distributed control points are required, and using more improves the accuracy of the transformation [16]. In direct georeferencing, the scanner itself is centred over a point of known coordinates and oriented to a second known point, in a manner analogous to a total-station set-up, or it is equipped with integrated GNSS so that each scan is obtained directly in the geodetic coordinate system [5], [16], [29]. Direct georeferencing removes the need for a dense network of control points but requires the instrument to be levelled, centred and oriented with care, since these operations directly affect the achievable accuracy [5].

2.6. Study area and instrument

The study object is the Farabi Mosque, located on the Farabi Campus of Zonguldak Bülent Ecevit University (ZBÜ) in Zonguldak, Türkiye. The exterior of the mosque was surveyed to produce a complete 3D point-cloud model of its façades, providing a compact but architecturally varied test object that combines large planar wall surfaces with more detailed elements.

Scanning was carried out with a FARO Focus 3D X330 terrestrial laser scanner (Table 1), a phase-based instrument that records the 3D (x, y, z) position of each measured point together with a colour value. Eight scan stations were established around the building (Figure 2). At each station a 10-minute scan was acquired using an equal-weighted measurement mode with an outdoor profile, a point rate of 29.1 MP/s, 4x quality, a horizontal field of view of 0–360°, a vertical field of view of 0–180°, and colour capture enabled. Reference spheres were used as registration targets, and the stations were arranged so that each scan shared at least three sphere tie points with its neighbours.

Table 1. Acquisition and processing parameters of the terrestrial laser scan of the Farabi Mosque façade (instrument specifications from [4]).

Parameter	Value
Instrument	FARO Focus 3D X330
Measurement principle	Phase-shift
Measurement range	0.6–330 m
Ranging accuracy	±2 mm at 25 m
Measurement rate	976,000 points/s
Field of view (vertical × horizontal)	300° × 360°
Integrated colour camera	70 MP
Number of scan stations	8
Scan duration per station	10 – 60 min
Registration targets	Reference spheres (≥ 3 tie points per scan)
Processing software	FARO Scene 2019

2.7. Field data acquisition

The field campaign was carried out in two stages. A reconnaissance survey of the site was conducted first, on 2 November 2019, to match the details of the mosque against the intended coverage and to decide where the scan stations should be placed. The scanning itself was performed on 13 November 2019 with the FARO Focus 3D X330. This two-stage preparation planning the station positions and, separately, planning the positions of the reference spheres used to coordinate the scanned surfaces was intended to save time during scanning, to obtain good-quality data, and to support the subsequent registration stage.



Figure 2. Positions of the eight scan stations around the Farabi Mosque before and after scanning. From S. W. Nazari, M.S. thesis, 2020 [4].

The eight stations were positioned around the mosque so that the target spheres were visible from several directions, since a sphere that appears in more than one scan makes registration easier; the centre of each sphere serves as the reference point. At each station a 10-minute scan was recorded, and each scan was set up to see at least three sphere tie points in the areas of overlap with adjacent scans.

2.8. Registration workflow

After the field campaign the scan data were transferred to a workstation and processed in FARO Scene 2019. An initial attempt to register all eight stations directly, using the full 360° horizontal data as recorded, was unsuccessful even though the scans shared common point clouds; the automatic registration failed because the 360° scans contained a large amount of point-cloud noise from objects around the mosque that did not belong to the target building.

For this reason the processing was organised around two conditions. In the first, automatic registration was applied to the raw scans before the extraneous point clouds were removed. In the second, the noise around the target building was cleaned using clipping-box and polyline selection to delete points that did not belong to the mosque (Figure 3) and the scans were then registered manually using the target-based approach, in which sphere tie points, common points between scans, and common planar surfaces were used to align the clouds (Figure 4). After cleaning, 35,700,815 points were retained for the manually registered model. The noise removed at this stage originated from objects surrounding the mosque neighbouring buildings, vehicles and vegetation that fell within the 360° field of view but did not belong to the target structure. It should be noted that the raw total point count prior to cleaning was not recorded in the source dataset [4]; consequently, the exact proportion of points removed cannot be quantified retrospectively, and the retained figure of 35,700,815 points defines the effective input common to the manual registration.

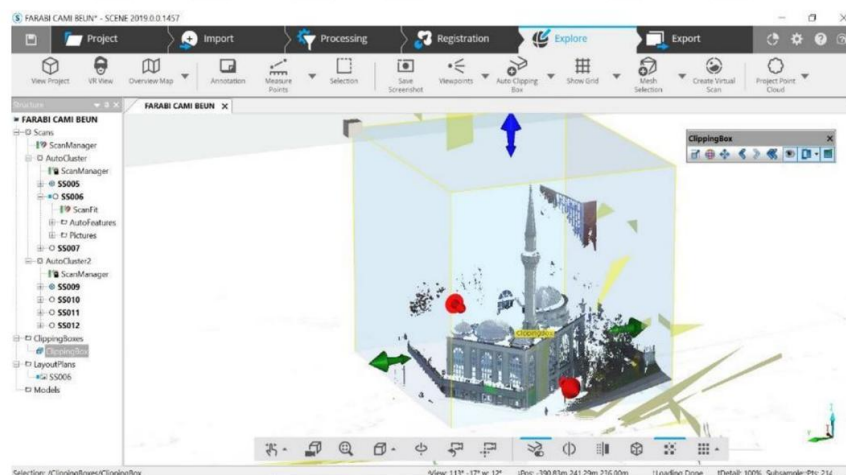


Figure 3. Removal of extraneous point-cloud noise with a clipping box in FARO Scene 2019. From S. W. Nazari, M.S. thesis, 2020 [4].

On the cleaned data, four registration strategies available in FARO Scene 2019 were then tested so that they could be compared on identical input: Cloud-to-Cloud, Target-Based, Top-View, and a combined Topview-and-Cloud-to-Cloud approach. Because all four strategies were applied to the same eight-station dataset, any difference in the



resulting accuracy or overlap can be attributed to the registration strategy itself rather than to differences in data acquisition.

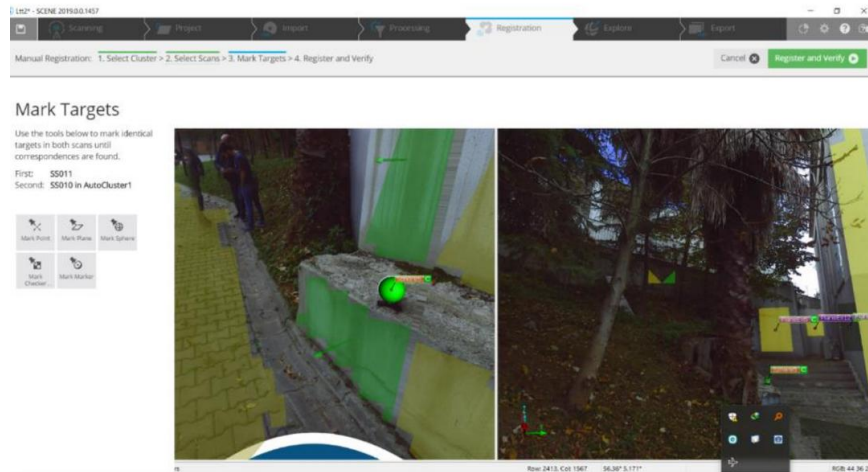


Figure 4. Identification of a common target between two scans during manual, target-based registration. From S. W. Nazari, M.S. thesis, 2020 [4].

3. RESULTS

3.1. Point-position accuracy

The four registration strategies were compared on the same cleaned eight-station dataset in FARO Scene 2019. Table 2 reports, for each method, the maximum and mean point-position error and the minimum inter-scan overlap achieved. For reference, the table also includes the manually refined Cloud-to-Cloud alignment, which was carried out to reduce the mean error further after the automatic methods had been run.

Table 2. Comparison of the four automatic registration methods and the manual refinement, on the same eight-station scan of the Farabi Mosque façade (FARO Scene 2019).

Registration method	Maximum point error ($\pm$ mm)	Mean point error ($\pm$ mm)	Minimum overlap (%)
Cloud-to-Cloud	13.8	5.2	3.5
Target-Based	16.8	6.9	5.9
Top-View	32.9	13.3	10.9
Topview-and-Cloud-to-Cloud	11.6	5.5	10.8
Target-based manual refinement	8.4	4.1	16.5

Among the four automatic strategies, the combined Topview-and-Cloud-to-Cloud method gave the lowest maximum point error (± 11.6 mm), while pure Cloud-to-Cloud gave the lowest mean error (± 5.2 mm) but the smallest overlap (3.5%). The Top-View method produced by far the largest errors (maximum ± 32.9 mm, mean ± 13.3 mm), consistent with the loss of vertical detail inherent in a plan projection, although it achieved a relatively high overlap (10.9%). The subsequent manual refinement, driven by sphere targets and common surfaces, reduced the maximum error to ± 8.4 mm and the mean error to ± 4.1 mm better than any of the automatic strategies while also producing the highest overlap (16.5%). These differences are summarised graphically in Figure 5.

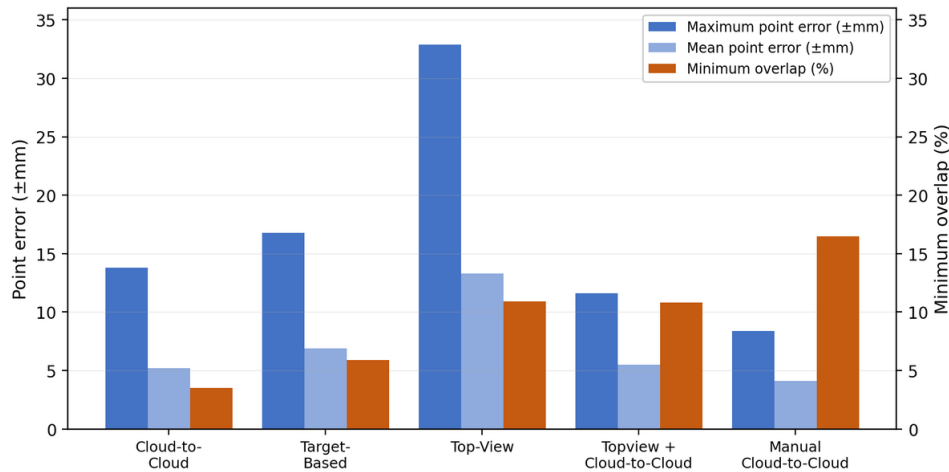


Figure 5. Comparison of maximum point error, mean point error, and minimum overlap for the four automatic registration methods and the manual refinement (data from [4]).

3.2. Inter-scan overlap

The overlap results reinforce the accuracy findings. Considered across the whole eight-station model, automatic registration achieved a minimum overlap of about 10.9%, whereas the manual, target-based refinement raised the minimum overlap to about 16.5%. In other words, the manual approach delivered both smaller residual errors and larger, more reliable overlap between adjacent scans, at the expense of the additional office time required to clean the point clouds and to identify sphere targets and common surfaces by hand.

Table 3. Per-session registration statistics for the manual, target-based alignment of the eight scans (data from [4]).

Scan session	Links	Maximum point error (±mm)	Mean point error (±mm)	Minimum overlap (%)
SS009	4	4.6	2.8	20.8
SS012	3	5.7	4.0	16.5
SS010	3	5.7	4.1	28.0
SS005	3	8.4	4.3	18.8
SS011	3	4.5	3.2	16.5
SS006	2	6.6	4.6	51.2
SS007	3	8.4	6.3	18.8
SS013	1	4.0	4.0	45.4

As Table 3 shows, the manual registration linked the eight sessions with between one and four inter-scan connections each; the mean point error per session ranged from ±2.8 mm to ±6.3 mm, and the minimum overlap from 16.5% to 51.2%. Sessions with fewer links, such as SS013 with a single link, still achieved acceptable errors because they were tied to well-distributed sphere targets; these per-session results are shown in Figure 6.

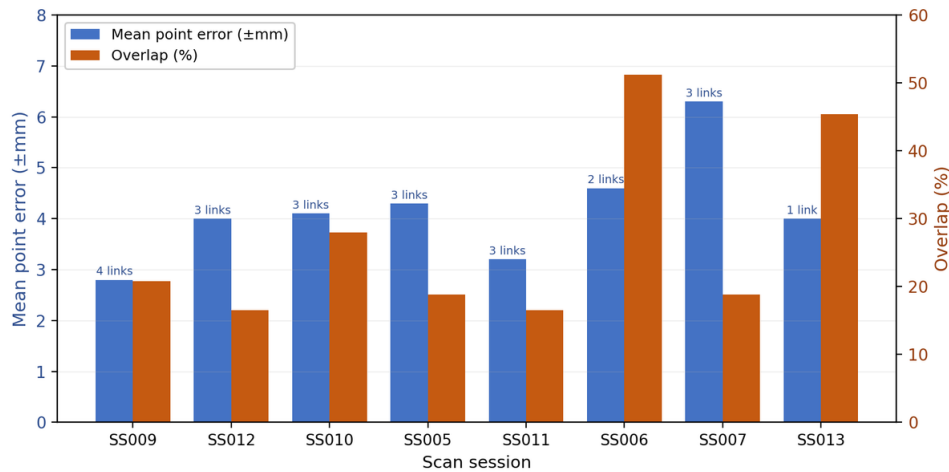


Figure 6. Per-session mean point error and overlap for the manual, target-based registration; the number of inter-scan links is annotated on each session (data from [4]).

3.3. Visual comparison of registered models

A visual inspection of the registered models is consistent with the numerical results. The Top-View alignment left visible offsets between adjacent façade scans, whereas the target-based manual alignment produced a clean, continuous point-cloud model of the mosque exterior (Figure 7).

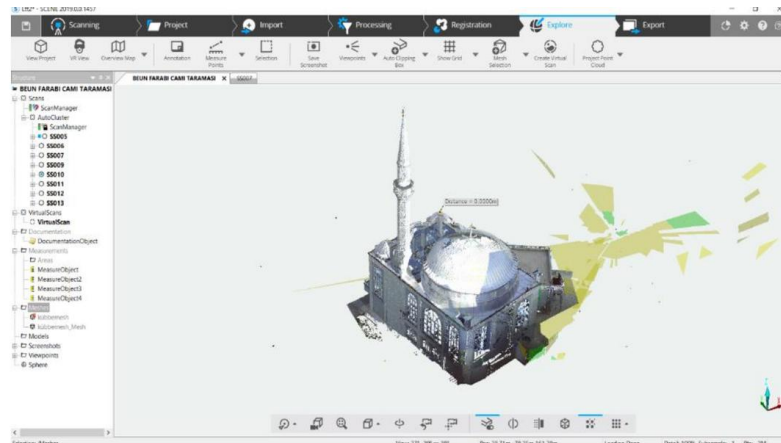


Figure 7. The registered 3D point cloud of the Farabi Mosque façade after target-based manual registration. From S. W. Nazari, M.S. thesis, 2020 [4].

4. DISCUSSION

The comparison highlights a clear trade-off between speed of acquisition and final accuracy. Targetless methods, in particular Cloud-to-Cloud, are attractive because they require no artificial targets in the field and are therefore quicker to deploy; on this dataset, Cloud-to-Cloud even achieved the lowest mean error among the automatic strategies. However, its very small overlap (3.5%) makes the result fragile, and the automatic alignment of the raw 360° scans failed altogether until the extraneous point clouds surrounding the mosque had been removed. This is consistent with the known sensitivity of cloud-based alignment to scene geometry, overlap and point density [15], and with the more general observation that registration is the most error-sensitive stage of the TLS workflow [7], [8].

The Top-View strategy performed worst in terms of accuracy, which is expected: projecting the scans onto a horizontal plane for alignment discards much of the vertical detail that distinguishes one part of a façade from another, so the residual errors are large even though the nominal overlap is comparatively high. The combined Topview-and-Cloud-to-Cloud approach recovered much of this accuracy, giving the smallest maximum error among the automatic methods, which supports the idea of using a robust plan-based coarse alignment followed by a surface-based fine alignment.

The best overall result was obtained with the target-based manual refinement, which produced both the smallest errors (maximum ± 8.4 mm, mean ± 4.1 mm) and the largest overlap (16.5%). This is in line with the literature on



target-based registration, where the type and layout of targets have a direct effect on the achievable accuracy [15], [16]. The cost is additional office and field effort: the point clouds had to be cleaned of noise before manual registration, and sphere targets and common surfaces had to be identified by hand. For a compact but detailed object such as a mosque façade, where fine ornamental detail must be preserved, this additional effort is justified by the substantially higher accuracy, particularly where the registered model will subsequently be used for structural safety diagnosis or BIM-based analysis [30], [31].

The main limitation of this study is that it is based on a single object scanned with one instrument, so the absolute error values should not be generalised uncritically to other scenes; the relative ranking of the methods, however, is consistent with their underlying principles. Future work should repeat the comparison on several objects of differing geometry and, where high absolute accuracy is required, combine the target-based approach with geodetic coordination so that the registered model is tied to a national or global coordinate system [5], [16]; integrating TLS with UAV photogrammetry, as in recent cultural-heritage documentation studies [32], could also improve coverage of the upper façade and roof.

A further methodological consideration concerns the dependence of the automatic strategies on a manual pre-processing step. Although the four strategies were compared on identical cleaned input, the automatic registration of the raw 360° scans failed until the surrounding noise had been removed by hand. The performance reported here for the automatic methods therefore reflects their behaviour on already-cleaned data rather than on unprocessed field scans, and the noise tolerance of the automatic algorithms on raw data was not itself quantified. A related limitation is that the registration was carried out within the closed, commercial FARO Scene 2019 environment. While the mathematical basis of the coarse-fine and ICP-based alignment is described in Section 2, the internal parameters actually applied by the software such as the ICP search radius, the maximum number of iterations, and the convergence and overlap thresholds are not exposed to the user and could not be reported. This limits the exact numerical reproducibility of the results; future work using open or fully parameterised registration pipelines (for example CloudCompare or programmatic ICP) would allow these thresholds to be stated explicitly and varied systematically.

Finally, the accuracy assessed in this study is relative: it quantifies the internal, station-to-station consistency of the registered model through residual point errors and inter-scan overlap. Because no external ground control points measured with a total station or GNSS receiver were incorporated, the absolute geodetic position accuracy of the model was not independently validated. For applications requiring positioning in a national or global reference frame, the target-based registration should be combined with geodetic coordination and the absolute RMS error reported against independent control, as outlined in Section 2.5 [5], [16].

5. CONCLUSION

This study compared four point-cloud registration strategies available in commercial TLS software Cloud-to-Cloud, Target-Based, Top-View, and a combined Topview-and-Cloud-to-Cloud approach on the same eight-station terrestrial laser scan of the Farabi Mosque façade, acquired with a FARO Focus 3D X330 scanner. Because all four methods were applied to identical cleaned input, the differences in their results can be attributed to the registration strategy itself.

Among the automatic strategies, the combined Topview-and-Cloud-to-Cloud method gave the smallest maximum error, pure Cloud-to-Cloud gave the smallest mean error but the least overlap, and the Top-View method performed worst overall. The target-based manual refinement outperformed all of the automatic strategies, yielding the smallest errors (maximum ± 8.4 mm, mean ± 4.1 mm) and the largest overlap (16.5%), at the cost of additional cleaning and manual target identification.

For façade-scanning projects in which fine architectural detail must be preserved, the results support a practical recommendation: use a targetless method for a rapid first alignment, but plan for reference spheres and target-based manual refinement when the highest accuracy is required, and remove extraneous point-cloud noise before registration so that automatic alignment does not fail. Where the model must also be positioned in a national or global coordinate system, target-based registration should be combined with geodetic coordination.

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Conflicts of Interest

The authors report no conflicts of interest.



- [20]Karasaka, L. (2012). *Mobil yersel lazer tarama sistemlerinin fotogrametrik röleve projelerinde kullanılabilirliği üzerine bir çalışma* [Doctoral dissertation, Selçuk University].
- [21]Wang, Q., Sohn, H., & Cheng, J. C. P. (2018). Automatic as-built BIM creation of precast concrete bridge deck panels using laser scan data. *Journal of Computing in Civil Engineering*, 32(3), Article 04018011. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000754](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000754)
- [22]Xu, Y., Wang, Y., Yang, J., & Zhang, J. (2025). Two-stage terrestrial laser scan planning framework for geometric measurement of civil infrastructures. *Measurement*, 242, Article 115785. <https://doi.org/10.1016/j.measurement.2024.115785>
- [23]Zhu, J., Wang, D., Fu, Z., Zhang, Z., & Han, W. (2025). BIM-based terrestrial laser scanning path planning for large-scale civil infrastructure. *Automation in Construction*, 176, Article 106247. <https://doi.org/10.1016/j.autcon.2025.106247>
- [24]Markiewicz, J., Kot, P., Markiewicz, Ł., & Muradov, M. (2023). The evaluation of hand-crafted and learned-based features in terrestrial laser scanning–structure-from-motion (TLS-SfM) indoor point cloud registration: The case study of cultural heritage objects and public interiors. *Heritage Science*, 11(1), Article 254. <https://doi.org/10.1186/s40494-023-01099-9>
- [25]Conti, A., Pagliaricci, G., Bonora, V., & Tucci, G. (2024). A comparison between terrestrial laser scanning and hand-held mobile mapping for the documentation of built heritage. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-2/W4-2024, 141–147. <https://doi.org/10.5194/isprs-archives-XLVIII-2-W4-2024-141-2024>
- [26]Yakar, M., & Yilmaz, H. M. (2025). The use of terrestrial laser scanning technology in the documentation of cultural heritage. *Cultural Heritage and Science*, 6(2), 138–148. <https://doi.org/10.58598/cuhes.1801497>
- [27]Yang, Y., & Holst, C. (2025). Piecewise-ICP: Efficient and robust registration for 4D point clouds in permanent laser scanning. *ISPRS Journal of Photogrammetry and Remote Sensing*, 227, 481–500. <https://doi.org/10.1016/j.isprsjprs.2025.06.026>
- [28]Cong, B., Li, Q., Liu, R., Wang, F., Zhu, D., & Yang, J. (2022). Research on a point cloud registration method of mobile laser scanning and terrestrial laser scanning. *KSCE Journal of Civil Engineering*, 26(12), 5275–5290. <https://doi.org/10.1007/s12205-022-0366-0>
- [29]Lachat, E., Landes, T., & Grussenmeyer, P. (2017). Investigation of a combined surveying and scanning device: The Trimble SX10 scanning total station. *Sensors*, 17(4), Article 730. <https://doi.org/10.3390/s17040730>
- [30]Ham, N., & Lee, S.-H. (2018). Empirical study on structural safety diagnosis of large-scale civil infrastructure using laser scanning and BIM. *Sustainability*, 10(11), Article 4024. <https://doi.org/10.3390/su10114024>
- [31]Zou, J., Xie, X., Zhou, B., Zhang, M., & Zhao, Y. (2025). A BIM-construction interaction method for construction monitoring based on laser scanning point cloud. *Structural Control and Health Monitoring*, 2025, Article 9918445. <https://doi.org/10.1155/stc/9918445>
- [32]Ulvi, A. (2021). Documentation, three-dimensional (3D) modelling and visualization of cultural heritage by using unmanned aerial vehicle (UAV) photogrammetry and terrestrial laser scanners. *International Journal of Remote Sensing*, 42(6), 1994–2021. <https://doi.org/10.1080/01431161.2020.1834164>