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Laser Scanning for Underground Monitoring: Insights from the Copenhagen Metro

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Abstract: Ensuring the sustainability and long-term durability of infrastructure depends heavily on how well we can monitor structures over time. Accurate, consistent data on how buildings and underground structures behave is essential for making informed decisions about their maintenance and safety. One of the most effective tools for this purpose is laser scanning. It's a fast, contact-free method that creates detailed 3D models of surfaces by capturing dense point clouds in just minutes. While laser scanning offers clear benefits such as speed, precision, and complete surface coverage it hasn't been widely used in the past. Laser scanning adoption has been limited by high equipment costs, accuracy concerns, and complex data handling. Recent improvements in technology and integration with tools like BIM are beginning to overcome these challenges, making the method more practical for structural monitoring. This paper explores the application of laser scanning and other digital technologies for underground monitoring, focusing on the Copenhagen Metro's M4 extension to Sydhavn and Valby. Monitoring with this methodology involves processing point clouds using a consistent template and grid. Significant changes are identified by variations in the projection cells, making these differences easy to detect. By combining advanced monitoring with sustainable design practices, we can build infrastructure that's not only safer and more durable, but also more in tune with the needs of our environment and future generations.

Keywords: Metro infrastructure; laser scanning; point cloud; underground monitoring

1. Introduction

Underground infrastructure development presents complex engineering challenges, where safety, durability, and environmental responsibility must be carefully balanced. As urban areas continue to grow and demand for public transport increases, expanding metro networks becomes a priority. In such settings, continuous and reliable monitoring of underground structures is essential, not only to identify structural changes and validate design assumptions but also to mitigate potential risks before they escalate into costly or dangerous issues. Among the tools now shaping the future of underground monitoring, Terrestrial Laser Scanning (TLS) has emerged as a leading solution. This technology offers rapid, non-contact data acquisition with high spatial resolution and dense 3D point clouds, changing the monitoring paradigm from sparse, point-based to holistic surface-level observation (Teng et al., 2022). TLS allows engineers to detect and assess subtle deformations and movements in tunnels, station walls, and excavation faces over time, providing the insight needed to make informed, proactive decisions during construction. TLS's effectiveness for geometry validation, excavation profile control and construction management, outperforming traditional surveying in speed and detail (Gikas V., 2012).

A notable example of TLS application is the M4 metro line extension in Copenhagen, which connects the city center to the evolving districts of Sydhavn and Valby. Designed and delivered by TUNN3L JV

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with Arup as a multidisciplinary design partner, the project placed strong emphasis on sustainability, digital innovation, and structural performance. TLS was implemented extensively throughout the project to monitor tunnels and station boxes, generating a continuous flow of spatial data to support design validation and construction management. To interpret and visualize these large point cloud datasets, the project team used the OPSIS software platform for deformation analysis. OPSIS enabled the projection of 3D point clouds onto fitted surface templates and their subdivision into statistical grids. This allowed small deformations to be tracked over multiple time intervals with a high degree of precision. The software generated 2D projection maps, animated surface changes, and time-series graphs helping engineers detect anomalies early and respond effectively.

The Copenhagen Metro case illustrates how combining TLS with powerful data analysis platforms can transform structural monitoring from a passive task into a proactive strategy. This integration not only improved safety and quality during construction, but also supported the long-term sustainability goals of the metro network ensuring that modern infrastructure evolves in step with both urban growth and environmental responsibility.

This paper is structured as follows: Section 2 presents the methodology from data acquisition to software processing; Section 3 presents scanning results for tunnel portals, atrium walls, and V-beams; Section 4 concludes with the effectiveness of TLS-OPSIS integration for structural deformation monitoring.

2. Methodology

The deformation monitoring approach employed during the Copenhagen Metro M4 line extension integrates Terrestrial Laser Scanning (TLS) with advanced point cloud analysis using the OPSIS software platform. This combined methodology enables accurate, non-invasive, and consistent tracking of surface deformations throughout all stages of underground construction. By capturing dense, high-resolution 3D data and systematically assessing changes over time, it allows for early detection of structural shifts and potential issues. This proactive monitoring enhances overall project reliability, reduces risks associated with unexpected deformations, and supports data-driven decision-making. Ultimately, the approach contributes significantly to the sustainable management and long-term durability of underground infrastructure, ensuring safety and resilience in a complex urban environment.

2.1. Data acquisition using TLS (Topcon GLS-2000)

The Topcon GLS-2000 terrestrial laser scanner was used as the primary scanning instrument. (Fig. 1b) Known for its high accuracy and reliability in construction and infrastructure environments, the GLS-2000 captures dense 3D point clouds with millimeter accuracy. Scans were conducted at various stages during construction, capturing the geometry of tunnel portals, station walls, and other structural elements.

All TLS scans were georeferenced using existing polygonal points from the previously developed geodetic control network of the construction site. These control points served as a stable spatial reference base, ensuring that all point cloud datasets from different epochs were precisely aligned and comparable. This approach eliminated the need for artificial markers and significantly improved repeatability across measurements.

2.1.1. Development of the geodetic control network

Before starting the TLS scans, a reliable geodetic control network was established to provide a solid reference framework. High-precision total station Leica TS16 (Fig. 1a) was used to create a polygonal network of control points around and within the construction area. These points were carefully positioned and measured with millimeter-level accuracy to ensure stability throughout the project. This network enabled precise alignment and comparison of all subsequent scans, which was essential for effective deformation monitoring.

(a) **(b)**

Fig. 1. Measuring technologies used in the project: (a) Leica TS16 total station for geodetic control network establishment, (b) Topcon GLS-2000 terrestrial laser scanner for detailed 3D data acquisition.

2.1.2. Measurement Error Analysis

To ensure the reliability of TLS data, potential measurement errors were carefully assessed, including instrument limitations, as well as systematic and random errors. The geodetic control network, established with a high-precision Total station, provided accurate orientation and georeferencing for all scans. During scanning, the TLS instrument was oriented using these control points, with each individual scan defined as a "station" with precise coordinates and orientation. This procedure ensured accurate registration of scans and the generation of correctly georeferenced point clouds.

Table 1. Orientation and registration errors of TLS scan stations.

X	Y	Z	Occ.	Inst. Height	BS	Backsight Error X	Backsight Error Y	Backsight Error Z
1000.000	1000.000	2.535	A2	1.535	A3	0.003	0.000	-0.001
981.890	998.652	2.531	A1	1.526	A2	0.000	0.001	0.000
1032.630	999.708	2.543	A4	1.548	A3	0.003	0.000	0.000
1033.229	1012.283	2.584	b4	1.565	A5	0.002	0.001	-0.001

Additional control points, which were not used for registration, were also measured to validate the accuracy of the registered datasets. Comparisons between these points and the registered point clouds confirmed an overall accuracy of approximately ±3 mm.

Table 2. Validation of TLS measurements using Total Station data

Point	X	Y	Z	Error X	Error Y	Error Z
A5	1050.545	1000.000	2.580	0.003	0.000	0.002
B3	1015.432	1011.798	2.632	0.000	0.001	0.003
B2	998.733	1011.628	2.633	0.000	0.002	0.002
B5	1044.344	1016.825	2.550	0.002	0.001	0.002

This methodology allowed true structural displacements to be distinguished from measurement errors, ensuring that deformation monitoring results could be confidently applied to design evaluation and construction decision-making.

2.2. Software processing of point clouds

After data acquisition, the dense 3D point clouds captured by the Topcon GLS-2000 were imported into the OPSIS software platform for detailed analysis. This platform is designed to handle large volumes of spatial data efficiently, allowing for comprehensive processing and interpretation. The monitoring workflow efficiently processes point cloud data by projecting it onto a mathematically defined reference surface, conducting detailed statistical analyses within grid cells, filtering out noise, and producing precise deformation maps and comprehensive reports to support accurate structural evaluation.

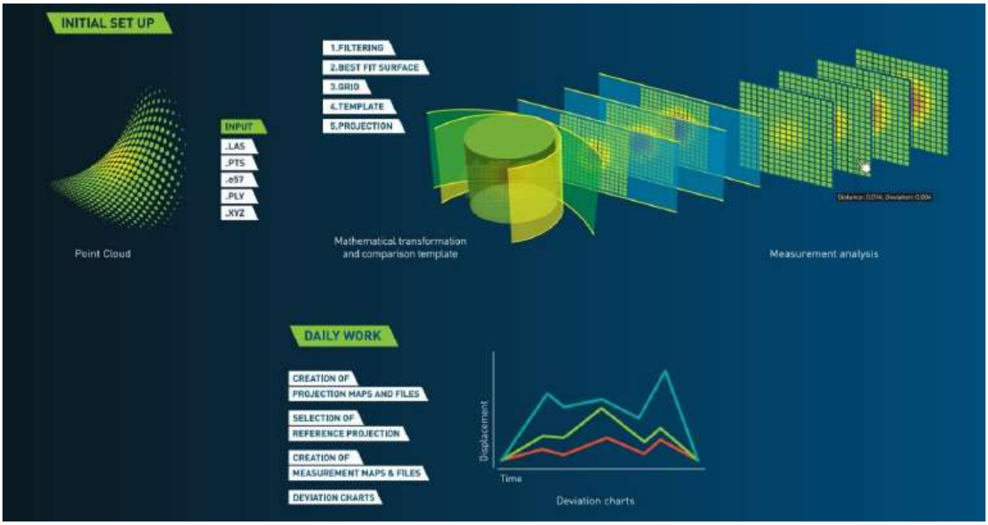
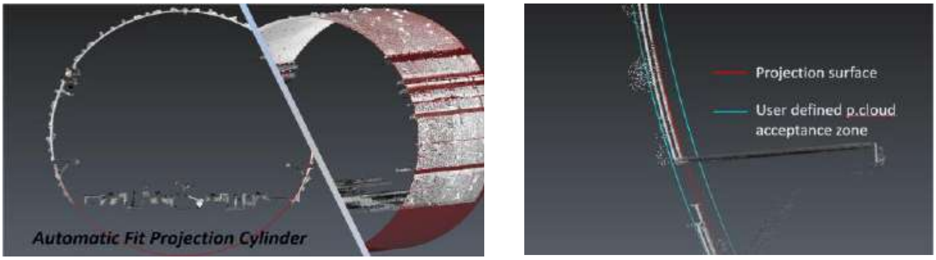


Fig. 2. Workflow and deliverables in OPSIS monitoring procedures.

2.2.1. Projection of point cloud onto reference surface

Once captured, the point clouds were imported into the OPSIS software platform, where a mathematically defined 3D reference surface, called a template was fitted to the geometry of the structure. Depending on the shape of the monitored surface, the template could be a plane, cylinder, or conical surface, similar to those used in standard mathematical projections.

The template was then subdivided into a uniform square grid of user-defined cell size. Within each grid cell, all point distances to the template surface were evaluated statistically. Cells were only accepted if the standard deviation of point distances met quality criteria, ensuring data reliability.



(a) **(b)**

Fig. 3. Processing of point clouds: (a) Automatic projection processing, (b) Cleaning unnecessary "Phantoms" during point cloud projection onto a mathematical surface.

2.2.2. Noise filtering and tolerance Control

In OPSIS, noise filtering works by checking how far each scan point is from the fitted template surface. We define a tolerance zone around that surface in our case set to ±5 mm, so that only points inside the zone are kept, while anything outside is treated as an outlier (phantom). The size of the zone is chosen in relation to the scanner's accuracy, usually about 3–5 times the instrument's natural measurement noise. Setting it this way gives a good balance: it removes spurious points without discarding real surface changes. The result is cleaner, more consistent data between scans, which in turn improves the reliability of the deformation measurements.

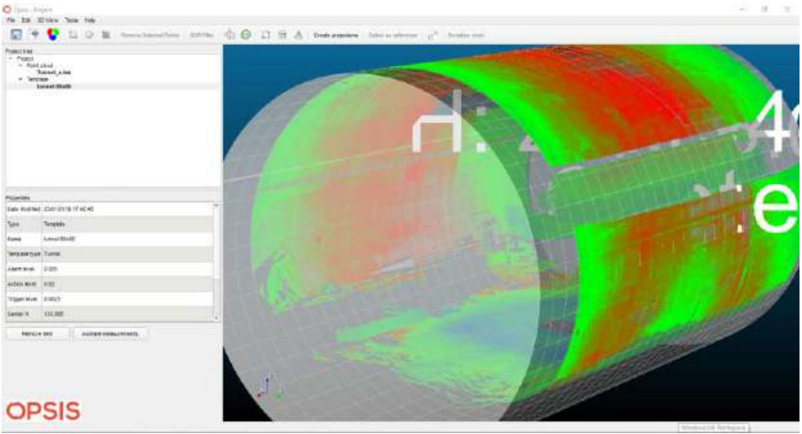


Fig. 4. 3D visualization of tunnel template creation using OPSIS software.

2.2.3. Temporal monitoring and surface deformation visualization

Each new TLS scan, aligned using the same geodetic reference and surface template, was compared with previous datasets to track changes over time. By observing variations in the values of individual grid cells, localized surface deformations could be clearly identified. These changes were visualized through 2D projection maps, animated sequences, and time-series deformation graphs. This intuitive visual output made it easier for engineers to spot early signs of structural movement and respond proactively, improving decision-making and helping to prevent potential issues before they became critical. Additionally, the measured deformations were compared not only with previous scans but also directly against the original design situation, allowing for a clear assessment of how the structure's actual behavior aligned with design expectations and safety thresholds. This comparison ensured that any deviations were identified early and evaluated in the context of acceptable limits, supporting effective risk management throughout the project.

3. Results and Discussion

The implementation of TLS and OPSIS analysis across various segments of the Copenhagen Metro M4 extension provided valuable insights into both the structural performance of underground elements and the broader utility of point cloud data within construction workflows. Beyond its role in deformation monitoring, the high-resolution data proved essential for a range of practical application most notably in generating precise as-built models used for the design and fabrication of prefabricated components. In the constrained and geometrically complex environments typical of underground construction, this level of detail helped ensure dimensional accuracy, minimized on-site adjustments, and improved the overall efficiency and coordination between design, manufacturing, and installation processes.

3.1. Scanning of the tunnel portal

An important application of TLS was the scanning of the tunnel portal, where high-resolution point cloud data served both monitoring and design purposes. Beyond tracking potential deformations, the data enabled precise vectorization of the as-built geometry, forming the basis for accurate digital models. These models were crucial for the design and fabrication of prefabricated components, ensuring that each element matched the real-world conditions of the site. By relying on this detailed and reliable reference, the installation process became more efficient, with fewer adjustments needed on-site. This case underscores the broader utility of TLS technology not only as a tool for structural monitoring but also as a bridge between digital design and efficient, high-quality construction.

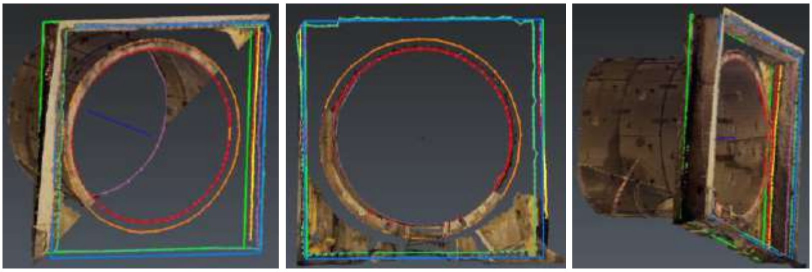


Fig. 5. Point cloud-based vectorization of tunnel opening.

3.2. Scanning of stations atrium walls

The additional scanning of the atrium walls at the metro stations provided highly detailed 3D models that formed the basis for a thorough assessment of their current condition. By comparing the latest laser scan data with the original design models, even the smallest deformations or deviations from the planned geometry could be identified.

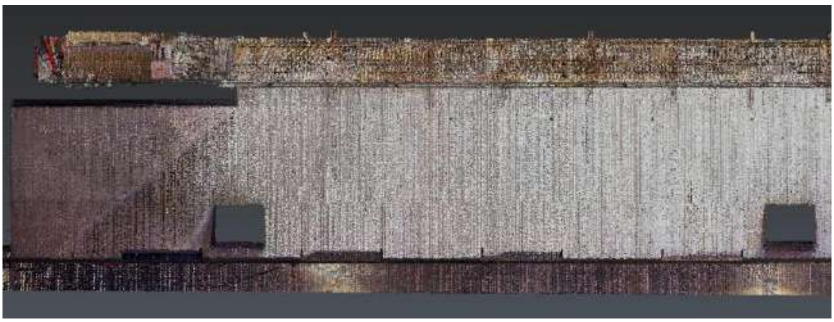


Fig. 6. Detailed point cloud data of a portion of the atrium wall.

This methodical approach not only enhances the accuracy of maintenance planning but also supports predictive modeling to prevent future deterioration, ensuring the long-term safety and functionality of the metro infrastructure.

Fig. 7. Comparison of actual vs. reference geometry of atrium walls, visualized through OPSIS.

For the atrium walls, quantitative deformation metrics were closely integrated into the project's risk management protocols. A 15 mm deformation threshold was established to trigger alarms and guide adjustments in the prefabrication of components. Real-time TLS data were continuously compared with the original design, and any deviations exceeding this limit prompted immediate corrective actions or design modifications. This proactive, data-driven approach ensured that potential structural issues were addressed early, safeguarding both construction quality and overall project safety.

3.3. Scanning of V-beams

As part of the broader structural documentation and quality control process, terrestrial laser scanning (TLS) was applied to capture the geometry of prefabricated V-beams used in the station construction. The high-resolution point cloud data enabled accurate verification of the beams' as-built dimensions against the design models. This was particularly important for ensuring proper alignment and fit during installation, minimizing the need for adjustments on site.

Working with TLS and OPSIS came with its own set of challenges. One significant limitation was access to complex and constrained spaces, such as areas with scaffolding, high walls, or narrow corridors. Scanning difficult or tall areas, such as the 12 m-high atrium walls, required multiple setups and repeated scans to capture everything accurately. Reflective surfaces, aligning scans, and managing large amounts of data added further complexity. These challenges were overcome through careful planning, repeated measurements, and detailed post-processing.

4. Conclusion

The application of Terrestrial Laser Scanning (TLS) combined with the OPSIS software platform demonstrated a highly effective approach for monitoring structural deformations throughout the Copenhagen Metro M4 extension project. This method enabled precise, non-invasive tracking of changes in critical infrastructure elements, allowing early detection of localized movements and supporting timely, informed decisions during construction. Beyond monitoring, the rich point cloud data served multiple purposes supporting the accurate fabrication and installation of components like tunnel portals, atrium walls, and prefabricated V-beams. By reducing the need for on-site adjustments and rework, the workflow enhanced construction efficiency and accuracy. The experience highlights how integrating advanced scanning technologies with intelligent software tools can strengthen structural reliability and sustainability in complex underground projects, setting a strong example for future infrastructure development.

References

Afrazi, M., Jahed Armaghani, D., Afrazi, H., Fattahi, H., Samui, P., 2025. Real-time monitoring of tunnel structures using digital twin and artificial intelligence: a short overview. *Deep Undergr Sci Eng.*,1-16. https://doi.org/10.1002/dug2.70029

Arup – Copenhagen M4 Metro Line to Sydhavn and Valby. Available online:
https://www.arup.com/projects/copenhagen-m4-metro-line-to-sydhavn-and-valby/
(accessed in 2025).

Boskovski, M., 2023. Application of laser scanners in the reconstruction of cultural heritage objects, Master thesis. University of Ss. Cyril and Methodius in Skopje, Faculty of Civil Engineering, Skopje, North Macedonia.

Gikas, V., 2012. Three-dimensional laser scanning for geometry documentation and construction management of highway tunnels during excavation. *Sensors*, 12(8), 11249–11270. https://doi.org/10.3390/s120811249

Jia, D., Zhang, W., Liu, Y., 2021. Systematic Approach for Tunnel Deformation Monitoring with Terrestrial Laser Scanning. *Remote Sensing*, 13(17), 3519. https://doi.org/10.3390/rs13173519

OPSIS – Every Point Matters. Available online: https://www.opsis-scan.com/
(accessed in 2025).

Teng, J., Shi, Y., Wang, H., Wu, J., 2022. Review on the Research and Applications of TLS in Ground Surface and Constructions Deformation Monitoring. *Sensors*, 22(23), 9179. https://doi.org/10.3390/s22239179

Topcon GLS-2000. Available online: https://mytopcon.topconpositioning.com/support/products/gls-2000
(accessed in 2025).