



Review Article:

Terrestrial Laser Scanning for Deformation Monitoring of Civil Engineering Structures and Tunnels: A Review

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Abstract

Terrestrial laser scanning (TLS) is an established non-contact technique for capturing dense, millimetre-accurate three-dimensional point clouds, and its use for deformation monitoring has expanded rapidly over the last two decades. This review focuses on the two application domains with the most demanding accuracy requirements: structural health monitoring of above-ground civil engineering structures (buildings, bridges and retaining walls) and deformation monitoring of tunnels. Literature published mainly between 2017 and 2025 is synthesised to describe the point-cloud change-detection strategies used to derive deformation from repeat scans (point-to-point, cloud-to-cloud, cloud-to-mesh and multiscale model-to-model cloud comparison, M3C2) and the main error sources that limit deformation-grade accuracy. Reported case studies show that, under controlled scanning geometry and registration, TLS can resolve structural and tunnel-lining displacements at the millimetre to sub-centimetre level, competitive with total-station and levelling networks while offering full-field rather than discrete-point coverage. Turkish research groups have contributed actively to terrestrial and mobile laser scanning for documentation and deformation studies. Persistent challenges are registration-error propagation, sensitivity to incidence angle and environmental conditions, and the lack of a standardised accuracy-verification procedure. Permanent and mobile scanning, automated point-cloud processing and sensor fusion with fibre-optic and satellite-radar techniques are the most promising directions.

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Contribution to the field statement:

This review takes a narrower focus than earlier terrestrial laser scanning reviews: deformation monitoring of above-ground civil engineering structures and tunnels. It compares the main point-cloud change-detection methods and error sources, reports representative accuracies for each application type, and identifies open gaps in accuracy verification and continuous monitoring.

Highlights:

- Scanning detects millimetre-level deformation of structures and tunnels
- Four point-cloud comparison methods are compared and evaluated
- Registration error and scan geometry limit the achievable accuracy
- Permanent scanning and sensor fusion are the main future directions

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1. Introduction

Terrestrial laser scanning (TLS) captures dense three-dimensional point clouds of an object or surface by measuring, from a fixed station, the range and angular direction of hundreds of thousands of laser pulses per second. Since its establishment as a surveying and mapping tool in the early 2000s, TLS has offered millimetre-level positional accuracy over ranges of tens to hundreds of metres, together with the ability to record a complete, contactless geometric record of an object in a single occupation.

Civil engineering structures and underground openings are subject to continuous, often slow, geometric change arising from static and dynamic loading, foundation settlement, material creep and shrinkage, groundwater fluctuation, seismic action and, in the case of tunnels, stress redistribution during and after excavation. Detecting such deformation early is essential to structural safety and serviceability, yet conventional monitoring instruments, precise levelling, extensometers, robotic total stations tracking discrete prisms, and Global Navigation Satellite System (GNSS) receivers, deliver information only at a limited number of pre-selected points. Because deformation rarely concentrates uniformly at those points, discrete-point networks can miss localised movement, and their installation and long-term maintenance are labour-intensive. TLS, by contrast, records the entire visible surface of a structure at each epoch, so that deformation can, in principle, be recovered anywhere on that surface by comparing successive point clouds.

The importance of TLS as a deformation-monitoring tool is reflected in the rapid growth of the associated literature. Bibliometric surveys report that only a few dozen relevant studies were published annually before 2005, whereas several thousand papers on TLS-based deformation monitoring appeared between 2012 and 2022, with an especially sharp rise in tunnel- and bridge-oriented work over the past decade [1, 2]. Figure 1 illustrates this trend and the increasing share of civil-engineering applications within it.

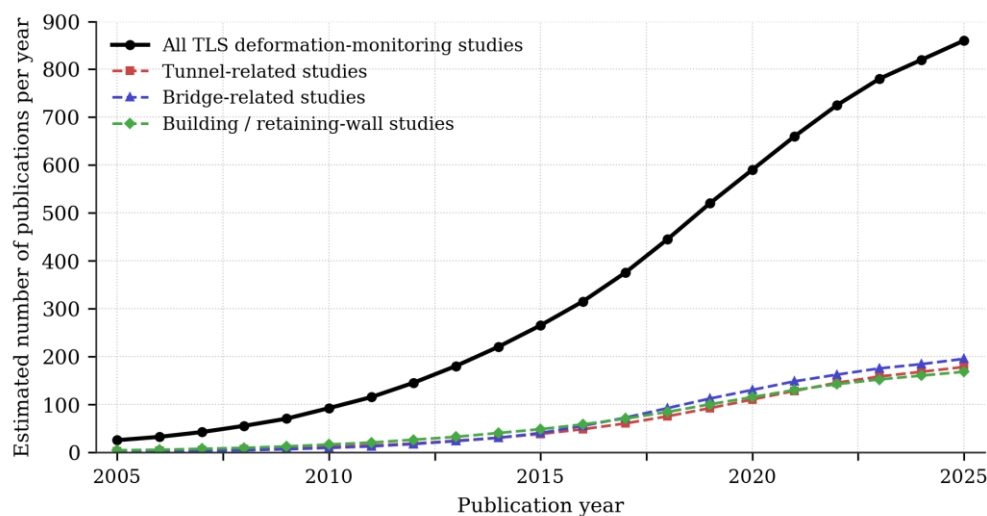


Figure 1. Publication trend of TLS-based deformation-monitoring studies (2005 to 2025). Values up to 2022 are synthesised from the bibliometric summaries reported by Shen et al. [1] and Teng et al. [2]; the values shown for 2023 to 2025 are an indicative extrapolation of that trend and do not represent counts reported in those sources.

The application fields of TLS in civil and environmental engineering are broad, spanning building documentation, cultural-heritage recording, rockfall and landslide assessment, coastal-profile monitoring and open-pit mining, in addition to deformation monitoring narrowly defined. Turkish research groups have been especially active in the documentation strand: terrestrial laser scanning has been used to record historical and cultural assets such as caravanserais and heritage mansions [3, 4], and integrated pipelines that merge terrestrial scanning with unmanned-aerial-vehicle photogrammetry have become common for heritage building information modelling [5]. In the Zonguldak hard-coal basin, long-running programmes have monitored mining-induced ground subsidence and its effect on the built environment using geodetic and radar-interferometric techniques [6]. A companion review by the present research group surveys this wider set of application fields. To avoid duplicating that material, and to allow a more detailed treatment of the methods and accuracy achievable specifically for deformation monitoring, the present review is deliberately restricted to two domains in which deformation quantification is the primary objective of the TLS survey: the structural health monitoring of above-ground civil engineering structures, including buildings, bridges and retaining walls, and the deformation monitoring of tunnels and other underground openings, both during construction and throughout their operational life.

The remainder of this paper is organised as follows. Section 2 describes the review methodology and summarises the measurement and point-cloud change-detection principles that underlie TLS-based deformation monitoring, together with a comparison against conventional monitoring techniques. Section 3 reviews reported applications, separately for buildings and structures and for tunnels. Section 4 discusses the main challenges identified across the reviewed literature and the directions in which the field appears to be moving. Section 5 concludes the paper.



2. Method

This article is a narrative review rather than a systematic one, and its evidence base was assembled through a structured search rather than a formal meta-analytic protocol. Candidate publications were identified from Scopus-, Web of Science- and Google Scholar-indexed sources using combinations of the keywords terrestrial laser scanning, TLS, point cloud, deformation monitoring, structural health monitoring, tunnel convergence and change detection. Priority was given to peer-reviewed journal articles published in English and Turkish between 2017 and 2025, supplemented by earlier foundational studies that first established TLS-based deformation-measurement principles. Studies were included only if they reported a TLS-based method applied specifically to derive quantitative deformation, displacement or change information for a building, bridge, retaining structure or tunnel; general TLS application surveys, purely airborne or unmanned-aerial-vehicle-borne laser-scanning studies, and studies limited to as-built documentation without a deformation or change-detection component were excluded unless directly relevant for comparison.

Five prior review articles were identified as directly relevant to the scope of the present work. They are summarised in Table 1 to position the contribution of this paper against the existing review literature.

Table 1. Prior review articles on TLS-based deformation and structural monitoring most closely related to the present study.

Review article	Year	Primary focus	Main contribution
Mukupi et al. [7], Survey Review	2017	Change detection, structural deformation	Registration, error modelling and mm-level detection
Rashidi et al. [8], Remote Sensing	2020	Bridge monitoring with TLS	Decade-long bibliometric survey and research-gap analysis
Kaartinen et al. [9], Sensors	2022	LiDAR-based structural health monitoring	Cross-domain review of bridges, tunnels, walls, heritage
Teng et al. [2], Sensors	2022	Ground surface, dams, tunnels, tall structures	Comparison of four point-cloud comparison methods
Shen et al. [1], Measurement	2023	TLS deformation monitoring in engineering	Bibliometric review and error-source classification

Compared with these five reviews, the present paper takes a narrower application focus (buildings, bridges, retaining walls and tunnels) and reports representative accuracy figures for each application type, serving as a practical reference rather than as a comprehensive bibliometric survey. Where appropriate, representative point-cloud examples from published case studies are reproduced under the Creative Commons Attribution licence, or with the explicit permission of the original authors, to illustrate the workflows discussed in Section 3; full attribution is provided in each caption.

2.1. Principles of TLS-based deformation monitoring

A TLS-based deformation survey compares point clouds of the same object acquired at two or more epochs, following the generic workflow shown in Figure 2. After each scan is registered into a common reference frame, either a local coordinate system tied to stable control points and targets outside the deforming zone, or a georeferenced system, the epochs are compared to compute a deformation or change field.

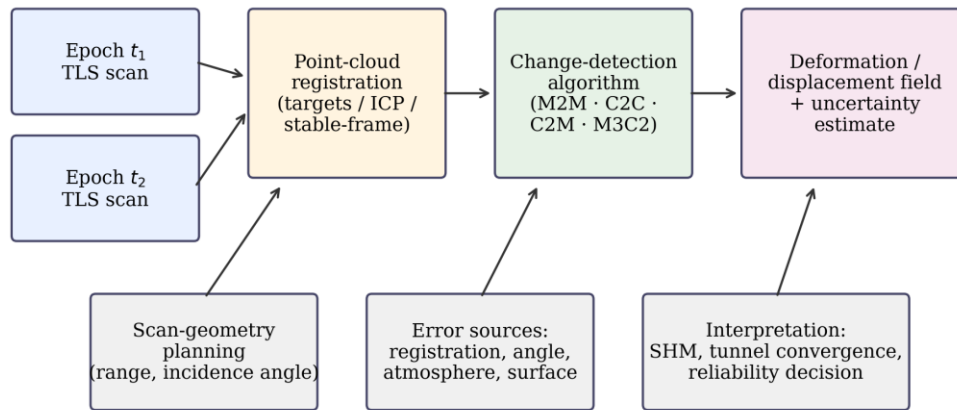


Figure 2. Generic workflow of TLS-based deformation monitoring, from repeat-epoch acquisition through registration and change detection to the interpretable deformation field. Adapted from Mukupa et al. [7] and Shen et al. [1]. Abbreviations: ICP, iterative closest point; M2M, point-to-point or point-to-mesh distance; C2C, cloud-to-cloud; C2M, cloud-to-mesh; M3C2, multiscale model-to-model cloud comparison; SHM, structural health monitoring.

Four families of point-cloud comparison method dominate the reviewed literature [1, 2]. Their principles are illustrated schematically in Figure 3. The simplest, point-to-point or point-to-mesh nearest-neighbour distance (M2M), computes the distance from each point in one epoch to the closest point or triangulated surface element in the other; it is computationally inexpensive but sensitive to point-density variation and local surface roughness. Cloud-to-cloud (C2C) comparison extends this idea using local point-cloud neighbourhoods rather than single points, improving robustness on rough or vegetated surfaces. Cloud-to-mesh (C2M) comparison instead compares a point cloud against a reference mesh built from the other epoch, which can improve accuracy on smooth, well-defined surfaces such as concrete or masonry walls. Multiscale model-to-model cloud comparison (M3C2), which computes distances along locally estimated surface normals at a scale chosen to match the roughness of the surface being monitored, has become a widely adopted standard for irregular surfaces because it explicitly propagates a local uncertainty estimate for every measured distance [10]. Where the monitored surface lacks distinct, trackable geometric features, as is often the case for a freshly excavated tunnel face, displacement-field approaches that track local surface patches between epochs, rather than simple distance fields, have instead been used.

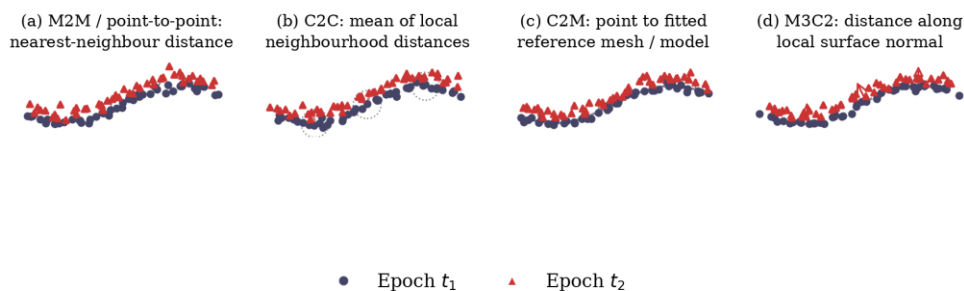


Figure 3. Schematic comparison of the four main point-cloud change-detection methods: (a) point-to-point or M2M nearest-neighbour distance; (b) cloud-to-cloud (C2C) local-neighbourhood mean; (c) cloud-to-mesh (C2M) point-to-model distance; (d) multiscale model-to-model M3C2 distance along the locally estimated surface normal. Adapted from Lague et al. [10] and Teng et al. [2].

The relative strengths and weaknesses of these four methods are summarised in Table 2, based on the comparative analyses reported by Teng et al. [2] and Shen et al. [1].

**Table 2.** Comparison of the main point-cloud comparison methods used in TLS-based deformation monitoring.

Method	Basic principle	Reported strengths	Reported limitations
M2M	Nearest-neighbour distance between two clouds	Simple; no meshing required	Sensitive to density variation and roughness
C2C	Local neighbourhood-based distance	More robust than M2M on rough surfaces	Neighbourhood scale influences the result
C2M	Distance between a cloud and a reference mesh	Accurate on smooth planar surfaces	Requires reliable mesh reconstruction
M3C2	Distance along local normal, at matched scale	Provides local uncertainty; standard for irregular surfaces	Averaging can smear artefacts on rough or occluded areas

Reported deformation-grade accuracy is governed less by the nominal instrumental range accuracy of the scanner than by the accumulation of several secondary error sources. These include the angle of incidence between the laser beam and the scanned surface, which degrades range precision on surfaces struck obliquely; environmental effects, particularly temperature gradients and, in tunnels, humidity and dust; and, most significantly, the propagation of point-cloud registration error into the derived deformation field when the reference targets or control points used for registration are not perfectly stable between epochs [11, 12]. The principal error sources reported in the reviewed literature and their approximate typical magnitudes are summarised in Table 3. Because deformation is by definition a small quantity compared with the overall dimensions of the object being scanned, even sub-millimetre registration inconsistencies can dominate the measured signal, and several of the studies reviewed in Section 3 devote particular attention to isolating a genuinely stable reference frame for this reason.

Table 3. Principal error sources affecting TLS-based deformation monitoring and their reported approximate magnitudes.

Error source	Physical origin	Typical magnitude	Mitigation
Range noise	Time-of-flight uncertainty; electronics	1 to 5 mm at 50 to 100 m	Averaging; longer scan windows
Incidence-angle effect	Oblique beam and surface geometry	Large data loss above 70 degrees [2]	Multi-station coverage; geometry planning
Registration error	Target instability; ICP convergence	0.5 to 5 mm; occasionally larger	Stable reference frame; redundant targets
Atmospheric refraction	Temperature and humidity gradients	0.1 to 1 mm per 10 m	Correction models; short scan windows
Surface reflectivity	Wet, dark or specular surfaces	Systematic offsets of a few mm	Radiometric correction; multi-angle scans

2.2. Comparison with conventional monitoring techniques

Relative to total-station and precise-levelling networks, which track a small number of discrete prism or target points at high temporal resolution and, under favourable conditions, sub-millimetre accuracy, TLS trades some point-wise accuracy for spatially continuous, full-field coverage obtained without physical access to the structure [13]. This is a particular advantage where deformation is not known in advance to concentrate at specific points, or where installing prisms or extensometers is impractical, for example on a tunnel lining during active excavation. GNSS provides high-accuracy, continuous monitoring of a small number of accessible exterior points but cannot be used inside tunnels or on internal structural elements. Satellite radar interferometry (InSAR) offers regional-scale, low-cost monitoring of ground and building settlement from repeat satellite passes and has been applied successfully to mining-induced subsidence in the Zonguldak basin [6], but its spatial resolution and revisit frequency are generally too coarse to resolve element-level structural deformation, and its measurements are limited to the sensor line of sight. The literature reviewed here therefore tends to treat these techniques as complementary rather than competing: several recent studies combine TLS with robotic total stations, fibre-optic strain sensing or InSAR to obtain both the spatial completeness of point-cloud data and the temporal density of continuous point sensors. The overall comparison is summarised in Table 4.

**Table 4.** Terrestrial laser scanning compared with conventional deformation-monitoring techniques.

Technique	Spatial coverage	Typical reported accuracy	Key limitation
Levelling / total station	Discrete points	Sub-mm to 1 mm	Installed targets; sparse coverage
GNSS	Discrete exterior points	mm to cm (real-time kinematic, RTK)	No signal inside tunnels or indoors
TLS	Full-field (entire surface)	mm to sub-cm [1, 2]	Registration-error propagation; geometry sensitivity
Satellite InSAR	Regional, line-of-sight	mm per year at regional scale	Coarse resolution; cannot isolate element-level movement [6]

3. Results

Case studies of TLS-based deformation monitoring are distributed unevenly across civil-engineering application types. Bridge- and tunnel-related work together account for roughly half of the reviewed studies, followed by buildings and retaining walls; dams and tall structures such as chimneys and towers make up smaller but well-established shares (Figure 4). The two subsections that follow examine the above-ground structural applications and the tunnel applications in turn.

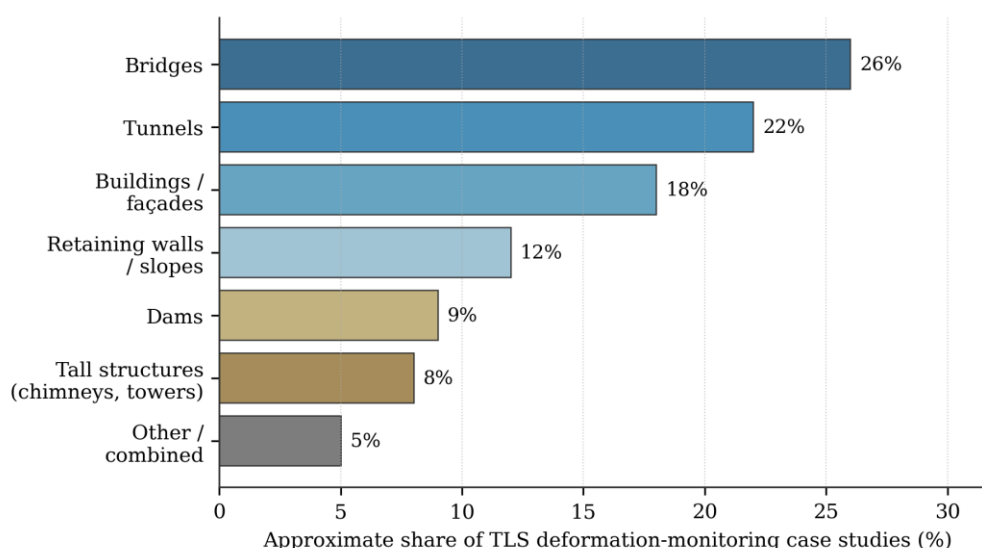


Figure 4. Approximate distribution of TLS deformation-monitoring case studies across civil-engineering application domains, synthesised from the reviews of Kaartinen et al. [9], Teng et al. [2] and Shen et al. [1].

3.1. Deformation monitoring of buildings and structures

In areas affected by underground mining, ground subsidence can induce progressive cracking and distortion in overlying brick-concrete buildings. In the Zonguldak hard-coal basin, decades of geodetic and radar-interferometric monitoring have quantified such mining-induced movement of the ground surface and the built environment [6], providing the regional context in which point-cloud methods are now being applied at the level of individual structures. A wall-length-based monitoring index derived from segmented and boundary-fitted TLS point clouds has been proposed specifically for this setting, in which the length of each wall, computed from fitted boundary lines, is compared between repeat scans to flag walls undergoing significant deformation without requiring targets installed on the building itself [14].

Bridge decks and superstructures have received particular attention because their deformation under load, or over time, is a direct indicator of structural condition. TLS scans acquired before and during controlled load testing have been used to extract the bending profile of a bridge deck; because a single continuous scan already samples the whole span, this profile can be compared directly against numerical predictions without sensors pre-installed at specific locations [15]. A sliding-window surface-fitting method has more recently been proposed to derive a continuous bridge deformation mode from TLS data, together with an accompanying error model that separates and quantifies the contribution of each processing step to the overall uncertainty budget [16]. Figure 5 shows a representative example of the resulting TLS-derived bridge deformation mode reported by Zhou et al. [16]. For historic or structurally sensitive bridges where physical instrumentation is undesirable, combined TLS

and photogrammetric surveys have been used to build a georeferenced inventory model that can serve as a zero-epoch reference for future deformation assessment [17]. Deformation-analysis methods tailored to specific structural forms, such as arch and beam bridges, have also been developed to account for the characteristic displacement patterns of those forms [18].

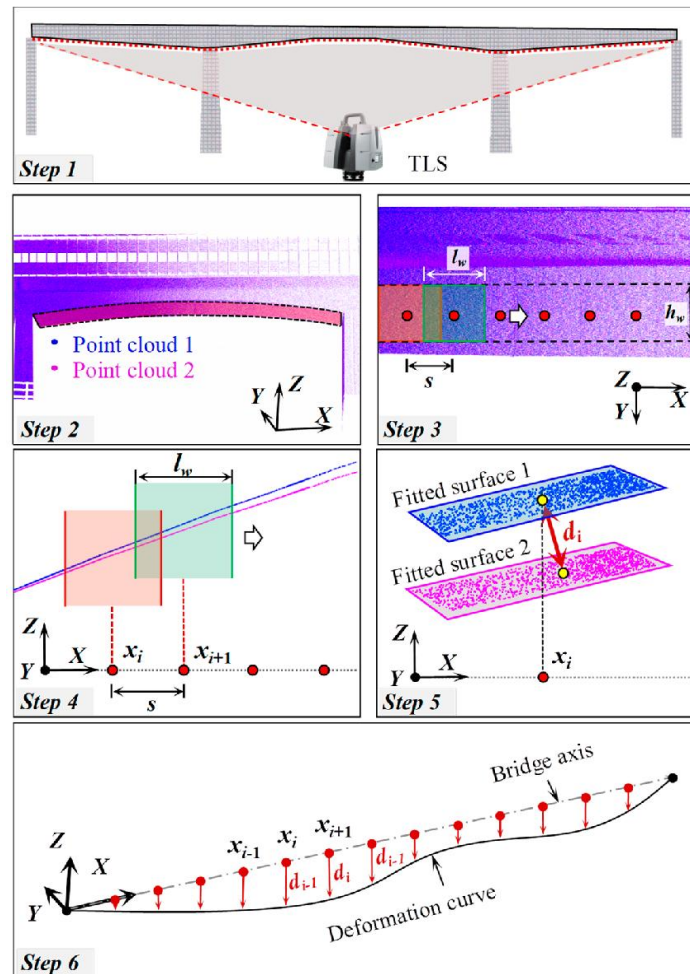


Figure 5. Example of a TLS-derived bridge deformation mode from repeat scans, illustrating the sliding-window surface-fitting workflow and the associated error budget. Reproduced from Zhou et al. [16], Remote Sensing 16(13):2263, licensed under CC BY 4.0.

Because retaining walls typically present a smooth, near-planar surface, achieving the sub-centimetre precision needed to detect their serviceability-limit deformations is a demanding test of TLS accuracy. Controlled experiments using laboratory-simulated deformation scenarios have shown that, while raw TLS deformation estimates can range from a few millimetres to several centimetres depending on scan geometry and comparison method, careful control of scanning distance, incidence angle and point-cloud comparison method (C2C, C2M or M3C2) can bring the achievable accuracy down to the one-to-two-millimetre range required for practical retaining-wall assessment [19]. Figure 6 illustrates the experimental setup and the corresponding TLS-derived deformation map reported by Algadhi et al. [19]. More broadly, reviews of TLS- and mobile-laser-scanning-based structural health monitoring across bridges, roofs, historic and heritage buildings and retaining structures confirm that non-contact, full-field damage and deformation detection is now a mature complement to visual inspection for a wide range of civil infrastructure [9, 11].

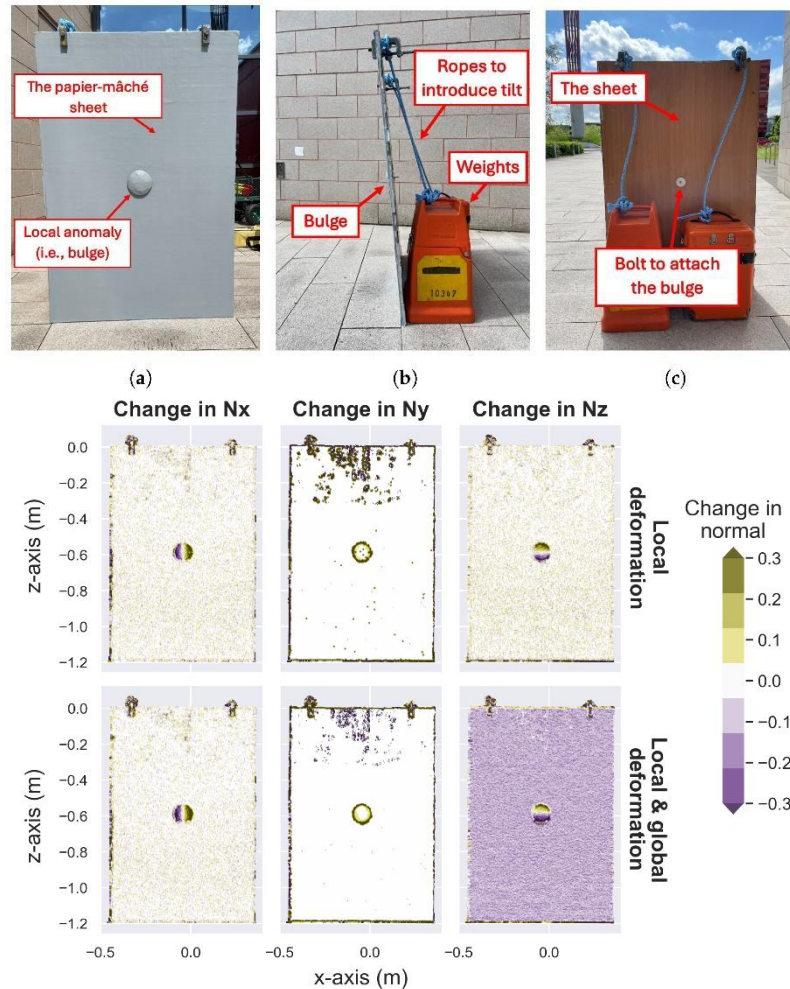


Figure 6. Example of TLS-based experimental assessment of local surface-anomaly detection on a wall specimen using controlled scenarios and multiple point-cloud comparison algorithms (C2C, C2M, M3C2). Reproduced from Algadhi et al. [19], Remote Sensing 16(24):4647, licensed under CC BY 4.0.

3.2. Deformation monitoring of tunnels

Inside a tunnel, TLS is used to monitor two related but distinct phenomena: the convergence of the excavated cross-section, expressed as the change in horizontal or vertical diameter relative to the design profile, and the deformation of the installed lining once support or secondary lining has been placed. Traditional monitoring by total station requires reflective targets to be installed at a limited number of cross-sections and is correspondingly slow to densify along a long tunnel drive; TLS instead scans the full circumference of each cross-section it captures, and a moving instrument or a series of static setups along the tunnel axis can build a continuous longitudinal deformation record [20].

Because a tunnel lacks the external, unambiguous reference points available above ground, extracting a reliable deformation signal first requires reconstructing a stable reference geometry from the point cloud itself. Systematic approaches that reconstruct the tunnel centreline from unorganised point-cloud data, using moving least-squares fitting, and then project each cross-section onto planes normal to that centreline, have been proposed to give a consistent reference frame against which cross-sectional convergence can be measured and the tunnel overall safety status assessed [21]. Figure 7 illustrates a representative point-cloud cross-section and the fitted reference geometry from the systematic tunnel-monitoring workflow of Jia et al. [21].

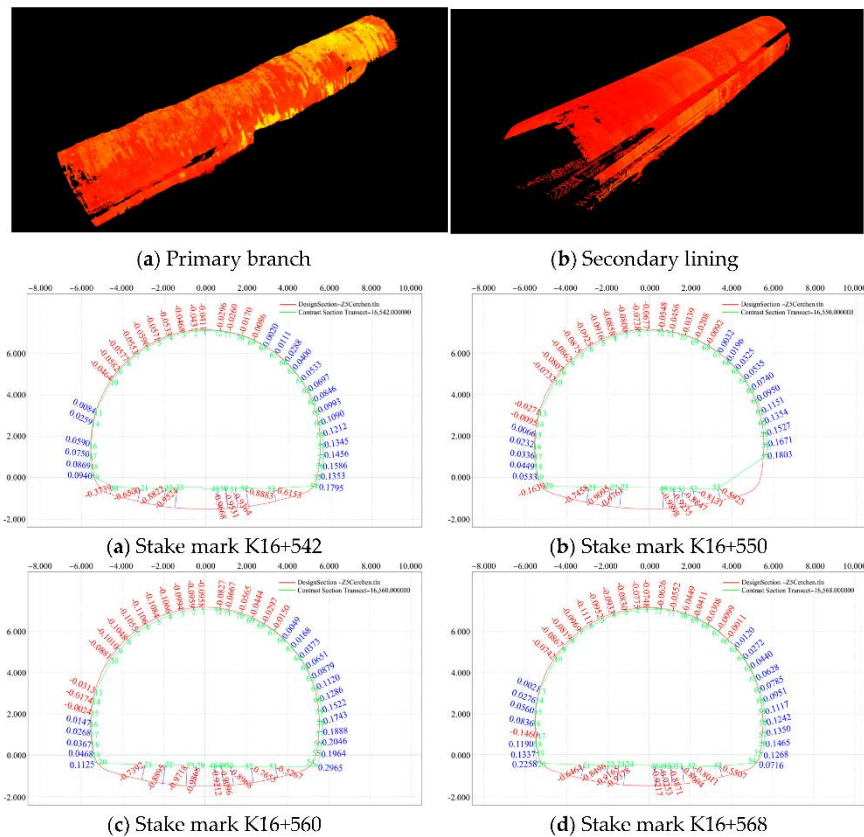


Figure 8. Example of TLS-based full-section deformation monitoring of a high-altitude fault-affected tunnel, showing repeat-epoch comparison of the arch crown against the design contour line. Reproduced from Tan et al. [22], Sensors 24(8):2499, licensed under CC BY 4.0.

Table 5. Representative TLS-based deformation-monitoring applications reviewed in this study.

Monitored object	TLS-derived quantity	Reported accuracy	Reference
Mining-affected masonry buildings	Wall-length change	Index-based detection	[14]
Bridge deck / superstructure	Deformation mode (deflection)	mm level with error budget	[16]
Retaining wall	Out-of-plane deformation	1 to 2 mm (optimised geometry)	[19]
Tunnel cross-section	Convergence (radial displacement)	Low mm level	[21, 22]
Tunnel lining / support	Radial deformation vs design	mm level	[20]

4. Discussion

Across the studies reviewed in Section 3, TLS is consistently reported to achieve millimetre-to-sub-centimetre deformation accuracy for both above-ground structures and tunnels when scanning geometry, registration and the point-cloud comparison method are carefully controlled, a level of performance broadly comparable with the discrete-point techniques it complements, while additionally recovering the full-field spatial distribution of deformation rather than values at isolated points. This full-field capability appears to be the main reason TLS has been adopted specifically where the location of expected deformation is not known in advance, such as an entire building facade above a mining-affected area or a full tunnel cross-section, rather than as a wholesale replacement for high-frequency point monitoring.

A recurring practical constraint is the sensitivity of the derived deformation to the acquisition geometry. Figure 9 illustrates two of the dominant effects reported in the literature: reported range precision degrades approximately linearly with scanning distance and, more markedly, with the incidence angle of the laser beam on the scanned surface; and above an incidence angle of roughly 70 degrees, the point-cloud density retained on the scanned surface drops sharply, with a large proportion of returns lost [2, 12]. These effects place a lower bound



on the deformation that can be reliably detected in field surveys, particularly for tall or elongated structures scanned obliquely from limited station locations.

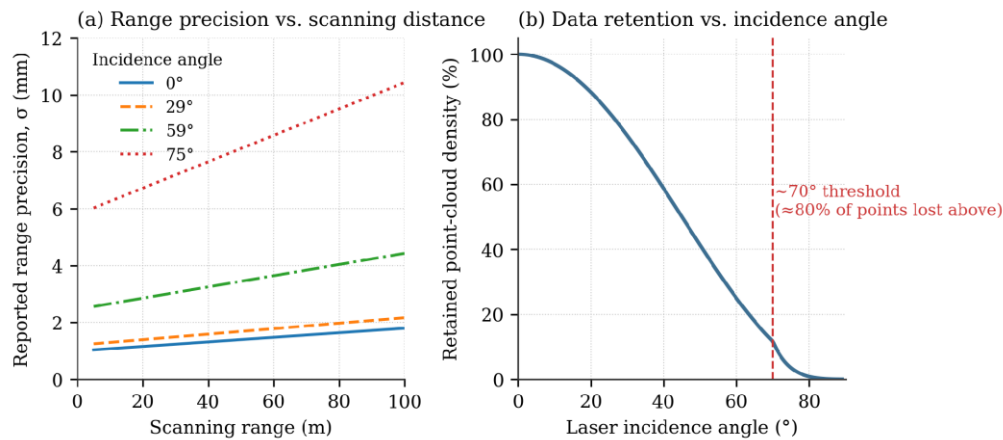


Figure 9. Effect of scanning geometry on TLS point-cloud quality: (a) reported range precision as a function of scanning distance for four incidence angles; (b) proportion of usable points retained on the scanned surface as a function of incidence angle. Trends reflect the observations of Teng et al. [2] and the incidence-angle threshold reported by Gordon et al. [12].

Several open issues recur across the reviewed literature. First, deformation-grade accuracy remains highly sensitive to the propagation of point-cloud registration error, and several studies note that this error source, rather than the scanner nominal range accuracy, most often limits the smallest deformation that can be reliably detected [11, 12]. Second, no standardised, instrument-independent procedure yet exists for verifying the deformation-monitoring accuracy of a given TLS instrument and workflow under field conditions, so reported accuracies are not always directly comparable between studies that use different scanners, targets and comparison algorithms. Third, most published case studies remain campaign-based, comparing a small number of discrete epochs, which limits their ability to characterise short-term or reversible movement such as thermal cycling.

The reviewed literature points toward several directions likely to address these gaps. Permanent or near-continuous TLS installations would allow deformation to be tracked as a genuine time series rather than through discrete campaigns, if their cost and data-processing burden can be reduced. Automated and machine-learning-assisted point-cloud segmentation and change detection, already used to separate the tunnel face from surrounding debris, is likely to reduce the manual effort currently required to process each epoch. The rapid uptake of wearable and mobile laser scanning in Turkish documentation and cadastral practice [3–5] is a further sign of this diffusion and suggests an obvious next step towards structural deformation monitoring. Finally, sensor fusion combining TLS with fibre-optic strain sensing, robotic total stations or satellite InSAR offers a route to obtaining both the spatial completeness of point-cloud data and the continuous temporal resolution that point sensors provide, and several of the studies reviewed here already report early implementations of this combined approach [6, 20].

5. Conclusion

This review has examined the use of terrestrial laser scanning for deformation monitoring in two application domains that place particularly demanding accuracy requirements on the technique: above-ground civil engineering structures and tunnels. Deliberately narrowing the scope in this way, and separating it from the broader survey of TLS application fields presented in a companion paper by the same authors, has allowed a more detailed treatment of the point-cloud comparison methods, error sources and reported accuracies specific to deformation monitoring. The reviewed literature shows that, given careful control of scanning geometry, registration and comparison method, TLS can resolve structural and tunnel-lining deformation at the millimetre to sub-centimetre level, providing full-field coverage that complements rather than replaces conventional discrete-point monitoring techniques. Registration-error propagation, the lack of a standardised accuracy-verification procedure, and the largely campaign-based nature of existing case studies remain the principal limitations. Continued progress in permanent and mobile scanning, automated point-cloud processing, and sensor fusion with fibre-optic and satellite-radar techniques is expected to extend TLS-based deformation monitoring toward more continuous, more automated and more standardised practice.

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Conflicts of Interest

The authors report no conflicts of interest.

Data Availability Statement

No new data were created or analysed in this study. Data sharing is not applicable.

Institutional Review Board Statement

Not applicable; this study did not involve humans or animals.

CRedit Author Statement

Shah Wali Nazari: Conceptualisation, Methodology, Investigation, Writing – original draft. Veli Akarsu: Supervision, Validation, Writing – review & editing. All authors have read and approved the final manuscript.

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