Insights of TLS-MLS Current Technology and Foresight for Future Development and Applications

Marco Scaioni [1,*], Huiyi Xu [2], Luigi Barazzetti [1], Manuel Garramone [1], Nicola Genzano [1]

[1] Politecnico Milano, Department of Architecture, Built Environment and Construction Engineering (DABC)
via Ponzio 31, 20133 Milano (Italy) – emails: [marco.scaioni, luigi.barazzetti, nicola.genzano]@polimi.it
[2] Politecnico Milano, Lecco Campus
via Previati 1/C, 23900 Lecco (Italy) – email: huiyi1.xu@mail.polimi.it

Abstract

This paper presents a critical overview of commercial solutions for terrestrial laser scanning (TLS) and portable mobile laser scanning (MLS). A review of current technology is reported, with emphasis on some key functions implemented in the latest-generation sensors. In the case of TLS, evidence is given to platforms for data sharing during acquisition, the support to the construction sector, the HDR imaging, the multiple georeferencing options, the enhancement of point-cloud quality, and the integration between range-measurement techniques. In the case of MLS, the highlight is on the contribution of AI, the imaging solutions, the development of long-range sensors, and the solutions for forestry. The paper also discusses the technology foresight, including aspects such as scan planning, accuracy evaluation, the growing use of AI in data processing, and the development of multispectral LiDAR for terrestrial platforms. A case study involving a complex historical building enables the assessment of both metric and operational performance of TLS and MLS approaches, highlighting strengths and limitations under specific survey conditions.

Keywords: Mobile Laser Scanning, Portable, SLAM, Static Terrestrial Laser Scanning.

1. Introduction

In the first 25 years of 2000, the development of *Laser Scanning* (LS) has represented one of the relevant technological breakthroughs in 3D surveying, leading to a new paradigm for topographic mapping and 3D modelling. While *Airborne Laser Scanning* (ALS) applications were already available during the latest decade of 1900 (Flood and Gutelius, 1997; Kraus and Pfeifer, 1998), *Terrestrial Laser Scanning* (TLS) has significantly developed after 2000, opening to a new way to carry out 3D modelling projects of buildings, infrastructures, natural sites, geological outcrops, and the like (Beraldin et al, 2002).
On the other hand, up until the success of the 'Structure-from-Motion' Photogrammetry (SfM – see Westoby et al., 2012; Granshaw, 2018), TLS seemed to be the unique solution for 3D modelling in *terrestrial* (or *close-range* – see Luhmann et al., 2020) applications. After that, both techniques have continuously developed in parallel way, trying more to corroborate their capabilities rather than competing (Grussenmeyer et al., 2011). The choice of the technique to be applied, when not constrained by budgetary reasons, depends upon multiple factors, such as:

- the *geometry* of the object/environment to be surveyed and modelled (e.g., TLS is more suitable for the indoor environment – Mill et al., 2013 –, while SfM may be preferred on large sites where images can be also collected using drones – Fugazza et al., 2018);
- the *geometric and radiometric texture of the surface* to be reconstructed at the required representation scale, since the dense image-matching algorithms adopted in the SfM pipeline may fail in some situations (Verykokou and Ioannidis, 2025); and
- the *accessibility* of the site, even though the chance of using drones to carry both digital cameras and LS sensors has opened new opportunities and changed some standard approaches (Mandlburger et al., 2023).

The development of *Mobile Laser Scanning* (MLS) was concurrent to TLS, since it exploited the GNSS/IMU integration, which had already reached a great maturity in ALS technology. In a first phase, cars and vans (mainly), trains, and boats were the platforms hosting MLS systems (Barber et al., 2008). In a second phase, MLS started to be implemented in more flexible and small platforms such as backpacks, handheld devices, bikes (Kukko et al., 2012), also referred to as *Portable Mobile Mapping Systems* (PMMS). This step paved the way to new applications requiring intensive data-acquisition work, and spanning through narrows, elongated, multi-storey, and underground places. These "portable" MLS instruments may implement IMU, GNSS and SLAM (*Simultaneous Location and Mapping*) technology. The latter can be based on LS data, images (visual SLAM) or both (Zhang et al., 2024). Today portable MLS has reached a very high operational and technical maturity to be considered a standard operational solution for 3D point-cloud acquisition.
This paper would like to review the current commercial technology on both TLS and portable MLS, highlighting the most relevant innovative solutions developed and implemented in the sensors available on the market. Rather than giving a review about these technologies, the purpose is to highlight new interesting functions that may help the performances but, especially, the operational capability of conducting sufficiently accurate, quick and complete 3D surveying in different environments. To this aim, the authors have browsed what is reported on the web by producers and relied on what they declared and proposed. Provided that the effort to be comprehensive and not to introduce biases in favour or against some vendors was made, the authors would like to apologize in advance for any possible mistakes or lack of completeness. For this reason, we also avoided to make any comparison between performances of different instruments. A more extensive analysis on this topic can be found in Xu (2025).
After briefly introducing the state-of-the-art of TLS (Sect. 2) and MLS (Sect. 3), in Section 4 some technological foresights for the future are reported, to let readers understand where LS technology for terrestrial applications is developing in the mid/long term. In Section 5 a case study afforded by the authors where both types of technologies have been applied is presented. In the end, discussion and conclusions are given in Section 6.

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-5-W3-2025-109-2025

2. Static Terrestrial Laser Scanning

2.1 Basic technology

Static Terrestrial Laser Scanning (TLS) is today a standard and consolidated technology for 3D, surveying which is commonly adopted in many research and application domains. Among these, it deserves to mention the paramount contribution given in the Geosciences (Telling et al., 2017), in Cultural Heritage documentation and preservation (Fassi et al., 2011), in the scan-to-BIM (Building Information Modelling) process (Skrzypczak et al., 2022), in the management of industrial plants (Son et al., 2015), in civil engineering (Gikas, 2012), in Forensics (Kowbuz, 2020), and in deformation measurement (Gonzalez-Aguilera et al., 2008), the latter also thanks on the development of techniques for comparing point clouds (Lindenbergh and Pietrzyk, 2015; Winiwarter et al., 2021).
Due to the consolidated state-of-the-art, we limit here the discussion to those specific innovative solutions that have been recently introduced in the market of TLS instruments (see Subsect. 2.2), while the basic knowledge can be retrieved from the technical bibliography (see, e.g., Vosselman and Maas, 2010; Shan and Toth, 2018). Moreover, we do not consider here all those sensors adopted for 3D reconstruction in the short-range environment, typically within a maximum range of a few metres, which exploit different technologies and cannot be classified under LS (see Hudson et al., 2020). 'Time-of-flight'/range cameras are considered here in this group and consequently neglected in the paper, though they have been largely investigated in the photogrammetric community (see, among others, Remondino and Stoppa, 2013; Altuntas et al., 2016).
Under the category of TLS, two different technologies for *range measurement* can be clearly distinguished:

1. *time-of-flight* (TOF) is based on the measurement of the time taken by each emitted laser beam to reach the object surface and return; in general, TLS instruments based on TOF may cover a longer range (up to a few kilometres) but at inferior precision (in the order of centimetres for distances of a few hundred metres). Some sensors also implement the option of recording the *full-waveform* (FWF) of the returned laser signal (Mallet and Bretar, 2009), which allows a better detection and classification of vegetation; and
2. *phase-shift* TLS, based on the measurement of the phase-shift between the emitted and returned laser beam, which is modulated in sinusoidal form; in general, these instruments may cover a shorter range (up to a few hundred metres) but at higher precision (in the order of millimetres for distances of a few tens of metres).

The most TLS sensors are based on a single technology from range measurement. They can span a panoramic (360°) horizontal field-of-view (FOV), while the scanning along each vertical section is mostly complete, excluding the sector in correspondence of the instrument basement (around 320°). Some long-range and very long-range TLS may feature a vertical scanning capability limited to a smaller window (around 80°).
All modern TLS instruments are equipped with levelling sensors, to be used for setting up the *intrinsic reference system* (IRS) in a local topographic datum. Often a GNSS sensor may provide geodetic- or navigation-grade absolute positioning. This data may help the registration and direct georeferencing of multiple scans from the same project, which is traditionally based on the use of *targets* as ground control points – GCPs (Alba and Scaioni, 2007; Wujanz et al., 2019), and/or *surface matching* algorithms (Pomerleau et al., 2013). After the first *ScanStation®* by Leica Geosystems (now at *P-Series®* – see Leica Geosystems, 2025), TLS instruments integrated those capabilities typical of theodolites, allowing the collimation of points and the registration of multiple stations based on geodetic traverses. This option has been implemented afterwards by other brands. On the other hand, several companies equipped standard theodolites with low-speed laser scanning options, providing a kind of versatile instrument to be used for multiple purposes. An example is reported in Lachat et al. (2017). Before analyzing some innovative key-solutions in modern TLS technology, is worth to be mentioned the recent integration of laser scanning point-cloud processing in photogrammetric software packages implementing the SfM pipeline (see, e.g., *Agisoft Metashape®* – Agisoft, 2025) as well as in CAD and BIM software packages.

2.2 Innovative key-solutions in TLS technology

2.2.1 Platforms for data sharing during acquisition. Some vendors developed web platforms able to share data among multiple users already at the data-acquisition stage. Provided that an internet connection is available (preferably 5G), data can be contemporarily displayed on computers, tablets and smartphones. For instance, Trimble (2025) developed SW *Trimble Perspective®* to control data collection in the field, in particularly for its *X-series®* 3D laser scanners. Data are shared among users by means of the web platform *Trimble Connect®*. In similar way, Leica Geosystems (2025) offers *Cyclone Register 360®* for the management of data collection and the platform *Cyclone Field 360®* to share data on remote devices.

2.2.2 Construction Management Support and Scan-to-BIM. TLS has played an important role since its introduction for *geometric modelling* (e.g., Park et al., 2007) and *structural monitoring* (Shen et al., 2023). On the other hand, with the development of BIM approach to manage the full construction process, the use of TLS point clouds for *monitoring the development of works* w.r.t. plans and time schedule has become a solution that quickly spread out, see Kim et al. (2024). This brought some vendors to integrate this process in the functions of their instruments/SW. For example, *Trimble X9®* allows direct export to Industry Foundation Classes (IFC), *Autodesk Revit®* and *AutoCAD®* formats for building/construction management (Trimble, 2025). The vendor reports that time for the *Scan-to-BIM* process of *industrial plants* may be reduced by 30-50% w.r.t. to manual modelling, though a final edit is still necessary.
The FARO (2025) company developed SW in this field to be integrated with the use of their *FARO Focus®* TLS instruments. *FARO As-Built®* is a point-cloud data processing SW targeted to the Scan-to-BIM workflow and construction work monitoring, which may be used directly in *AutoCAD®* and *Revit®* packages from Autodesk (2025). It also implements some functions for the automatic recognition and modelling of some industrial/civil construction elements. *FARO BuildIT Construction®* is a stand-alone SW package for quality control based on the automatic inspection of point-cloud data from construction sites. LS data are compared with BIM/CAD designed models and different types of deviations can be evaluated and reported. To this purpose, this SW also allows integrating *thermal infrared images* that can be overlaid to 3D point cloud data to detect temperature anomalies (Genzano and Colonna, 2025). Indeed, these may serve as indicators of cracks in walls, building pathologies in insulation layers, and water vapor leakage (see Melis et al., 2020).

2.2.3 HDR to improve RGB colours of point clouds. *High Dynamic Range* (HDR) is a technique that can improve the quality of RGB images when the content is illuminated in uneven way, see Barazzetti et al. (2012). By combining multiple

https://doi.org/10.5194/isprs-archives-XLVIII-5-W3-2025-109-2025

exposures to output a single image, the lighting range can be expanded and more details become visible in areas with different illumination. The implementation of HDR in *FARO Focus*® (FARO, 2025), in Leica Geosystems (2025) *BLK360*®, and in Zoller+Fröhlich (2025) *IMAGER® 5024/5016A* laser scanners allow to improve the quality of point-cloud colour information and to obtain a more realistic visualization. This option plays an important role in applications such as built-heritage documentation, where the colour content may be as important as the geometry of the object due the presence of decorations, paintings and other coloured architectural elements.

2.2.4 Multiple registration techniques. The first generation of TLS sensors was able to register/georeferencing scans based on artificial GCPs such as retroreflective markers, cylinders or spheres, or using checkboard targets (Alba and Scaioni, 2007). In some instruments (e.g., long-range laser scanners by Riegl company), each retroreflective marker was identified during data acquisition and scanned at the maximum resolution, independently from the resolution of the point cloud to capture. In other cases, recognition and measurement of targets was carried out during post-processing, when also some surface matching algorithms could be applied (see Subsect. 2.1). In the latest generation of TLS instruments, registration/georeferencing can be operated based on multiple techniques, which may work in corroborative way as well:

1. *direct georeferencing* (Lichti and Gordon, 2004; Scaioni et al., 2005);
2. *target-based*;
3. *feature-based* (natural and manmade features such as wall corners/columns);
4. *surface matching* algorithms (Pomerleau et al., 2013);
5. integration of image processing and IMU data for alignment based on *Visual SLAM*® (Leica Geosystems 2025).

The trend is to develop TLS sensors that already in the field can automatically align new scanned data w.r.t. previous scans collected on-site. In this way, on one side the user may assess the data continuity and successfully complete the acquisition. On the other, the operational complexity of the survey is reduced because the users do not have to manually align scans.

2.2.5 Automatic filtering of moveable objects. Since frequently the scene to be scanned may contain noise and non-permanent elements (e.g., pedestrians, vehicles, and clutter) disturbing the point cloud to acquire, some TLS sensors implement filtering tools that may detect and eliminate them. FARO (2025) reports that its data processing SW *Scene*® may enhances quality and eliminate over 80% of irrelevant data. Similar option is offered by Trimble (2025) *RealWorks*®, among others.

2.2.6 Combination of phase-shift and TOF measurement. Leica Geosystems (2025) *P Series*® TLS instruments combine both phase-shift technology with TOF for range measurement. This combination allows to exploit the most suitable technology in each zone of the scene to scan.

2.2.7 Mixed-pixel separation. When a laser beam hits a boundary of an object, it is partially reflected from it, and partially from other surfaces in the background. This 'mixed-pixel' phenomenon may result in ambiguity, see Lichti and Gordon (2004). Leica Geosystems (2025) *P Series*® TLS instruments can separate the content from the object and the background based on the reflected intensity combined with FWF analysis. The final point cloud will feature reduced blurring in correspondence of edges.

3. Portable Mobile Laser Scanning

3.1 Basic technology

As mentioned in the Introduction (Sect. 1) of this paper, MLS has been developed since the last decade of 1900 to allow acquisition from aircrafts (ALS). Later the same technology was exported to vehicles (Barber et al, 2008). In both cases, the rotating LiDAR sensor (usually more than ones in MLS) was coupled with an integrated navigation system including IMU and GNSS (Boguspayev et al., 2023). On the other hand, in ALS this solution is sufficient to provide a continuous positioning of each scan line. In MLS from road vehicles, the presence of obstacle to limit the GNSS signals (e.g., in tunnels or in urban canyons) pushed researchers to develop other solutions to continue the trajectory estimation based on the integration of other sensors (e.g., odometers) or based on *image-based* (visual) techniques. In this direction, thanks to the concurrent development of LiDAR technology and SLAM solutions (Akpınar et al., 2021), which determine the trajectory incrementally, it became possible to implement "portable" MLS systems (Kukko et al., 2012). First sensors were installed on backpacks (see, e,g., Polewski et al., 2019), then the miniaturization of technology allows to build instruments to be hand-held (Di Stefano et al., 2021)[1]. While static TLS requires several stations to accurately scan complex environments, portable MLS allow a better surveying of shadowed and obstructed areas, at a cost of a reduced total accuracy, in general in the order of a few centimetres (Urban et al., 2024).
The crucial aspect of MLS is the estimation of trajectory, which is already done in real-time onboard. After data acquisition, is possible to improve the quality of the recorded point cloud by re-processing GNSS data (if available) and by exploiting GCPs and/or loop-closures. This stage may remove those biases due to drift in real-time trajectory estimation based on IMU and SLAM observations.

3.2 Innovative key-solutions in MLS technology

3.2.1 Imaging solutions. RGB imaging is an important aspect of MLS data acquisition, since colour information is an important property of the final point cloud. MLS sensors from Trimble (2025) *MX*® Series are outfitted with multi-lens cameras (often with lenses in different orientations, such as front and side views) that collaborate to collect full image information and capture high-resolution panoramic-image data. Each frame image collected by the instrument is also automatically bound to the corresponding 3D point cloud, thereby achieving the generation of a coloured point cloud. This has numerous applications in fields such as road-asset management and urban planning. Similarly, the Stonex (2025) *X*® Series has a 360° rotating scanning head and multiple high-resolution cameras (such as the *X120GO*®, which has three 5Mpixel cameras), providing a wide FOV and the ability to obtain texture information synchronously. The NavVis (2025) *VLX2/3*® incorporate four cameras thanks to the solid body that can be fixed on the user's shoulders. Leica

[1] Some close-range sensors based on SLAM were developed first but limited to the acquisition of small objects, thus not treated here (see Subsect. 2.1).

https://doi.org/10.5194/isprs-archives-XLVIII-5-W3-2025-109-2025 | © Author(s) 2025. CC BY 4.0 License.

Geosystems (2025) *Pegasus*® is a backpacked MLS equipped with five cameras for capturing immersive 360° views.

3.2.2 Artificial Intelligence application. AI has already found a large application in MLS systems. Trimble (2025) *Business Center Mobile Mapping*® implements an AI-based automated recognition tool able to classify and extract common road elements (lane markings, fire hydrants, electrical boxes, etc.) from images. GeoSLAM (2025) *Hub*® and FARO (2025) *Cube-3D*® include a *Multi-Layer Perceptron* classifier that can automatically distinguish various categories of objects such as ground, buildings, and vegetation. Greenvalley Int. (2025) *LiDAR 360MLS*® can use AI algorithms to automatically detect various geographical features.

3.2.3 4D project construction tracking. FARO (2025) *Sphere XG*® SW enables 4D construction progress management, allowing users to view and share 3D point clouds and 360° photo documents on a single platform.

3.2.4 Long-range MLS sensors. The maximum distance covered by MLS sensors is in the order of some tens of metres up 100-120 m. There are also some instruments that may feature long-range measurement capability based on TOF technology usually implemented on cars. Leica Geosystems (2025) *Pegasus*® allows to reach up to 200 m. CHCNAV (2025) *AlphaUni*®, which integrates Riegl FWF digital laser technology, may reach up to 1450 m for the *UNI20*® and 1845 m for the *UNI20*® *UNI900*®/*UNI1300*® MLS sensors.

3.2.6 Solutions for forestry applications. Forestry is a domain where MLS has demonstrated a high operational potential for the reconstruction and modelling of trees, see Holvoet et al. (2025). In general, all MLS sensors may provide good datasets for this purpose, and vendors report about applications in the field. Zealquest (2025) *LiBackpack C50*® employs the Canopy Height Model and point-cloud segmentation techniques to retrieve parameters of single trees, such as position, height, crown width, and diameter at breast height.

4. Technology foresight

In this section we would like to address some aspects that in our opinion would attract the attention of companies and research institutions in the future (UNCTAD Secretariat, 2024). Some of them have already found applications in commercial products (e.g., AI), but they are addressed in the following since the expected impact is foresight to be even more impressive.
Before entering into some specific solutions, we should observe that static TLS and portable MLS are progressively going to merge into a unique technology. On one side, TLS integrate sensors for georeferencing which are also based on IMU/GNSS/SLAM technology. On the other side, MLS may also do static scanning providing higher resolution on some important detail. SW solutions already presented for data sharing (Par. 2.2.1), data processing (Par. 2.2.5) and those focused on specific applications (Par. 2.2.2) can be applied to both TLS and MLS.

4.1 Accuracy evaluation

Accuracy evaluation in TLS/MLS is a complex problem, since the *error budget* needs to consider multiple aspects such as: (1) the physics of the laser beam; (2) the instrumental errors; (3) the property of scanned surfaces; (4) the influence of the environmental conditions; and (5) the accuracy of registration/georeferencing, which in MLS has to account for the trajectory estimation as well. To these aspects, errors associated with point-cloud modelling should be also analysed when considering the accuracy of the final outputs (Salach et al., 2018). Many efforts have been done so far to investigate the error budget of TLS (see, e.g., Lichti and Gordon, 2004; Lichti, 2010; Wujanz et al., 2018; Kersten and Lindstaedt, 2022), less related to MLS (Taheri and Zhao, 2021). The authors think that a practical solution to accuracy evaluation for both TLS/MLS need to be deserved more attention, being this aspect crucial for many applications (e.g., in deformation measurement).

4.2 Scan planning

Scanning is planned so far based on the geometry of the object of interest and the experience of the operators, who decide how many and where scans should be captured. In similar way, the path of portable MLS is decided with subjective criteria. In recent years, many studies have been focused on techniques for *scan planning* in both TLS/MLS (see, e.g., Díaz-Vilariño et al., 2022). These studies are today more important because laser scanning is going to be implemented in robots (ground-based or drones), which could operate autonomously. In addition, the option to see real-time first results of scanning described at Par. 2.2.1 allows the application of techniques to drive new acquisitions for a better completion of the point cloud.

4.3 Artificial intelligence for point cloud classification

Artificial intelligence is expected to bring important development in classification of laser scanning data. For instance, *Machine Learning* (ML) and *Deep Learning* (DL) algorithms could be used for the automatic classification and target recognition of LiDAR data, thereby reducing the workload of data post-processing and improving the accuracy and the degree of automation, see Park and Cho (2022), Sarker et al. (2024).

4.4 Laser intensity and multispectral LiDAR

TLS/MLS sensors can record 3D coordinates of surveyed points, RGB values (if equipped with a camera) and *laser intensity* returns. The former can be exploited for many purposes such as scan co-registration, data interpretation/classification and to assess data quality (see a review in Scaioni et al., 2018). Almost the totality of these applications features an experimental character, with limited usage in the practice. Today, new methods for point-cloud segmentation/classification based on ML/DL may take advantage of laser intensity as an additional value to train neural networks. This increases the interest on exploiting laser intensity.
In addition, *multispectral laser scanning* has seen up until today a limited but promising development (Takhtkeshha et al., 2024), mostly in ALS platforms. On the other hand, its implementation in TLS/MLS would give a relevant contribution in view of a more efficient application of ML/DL techniques.

5. Test on the use of TLS/MLS

5.1 Presentation of the case study

To better understand the differences between TLS and MLS technology in practice, a comparison between two point clouds acquired in a complex heritage building is presented. The case study is the *Basilica di San Giacomo* in Como (Italy). The objective of the project is the production of a detailed digital reconstruction of the church for restoration purposes, with point clouds serving as the basis for measured CAD drawings and a BIM model (Garramone et al., 2023).

5.2 3D surveying with TLS

The first dataset was acquired with two laser scanners by FARO (2025) company: the *Focus S70®* and the *Focus HDR 130®*. Scans were collected in both interior and exterior spaces of the church, resulting in a dense point cloud that covered most surfaces, including narrow passages (e.g., spiral staircases) and the roof. The reconstruction of the upper part was completed by using SfM based on a photogrammetric block of images from a drone. Registration was performed using ICP, supported by targets measured with a *Leica TS30®* theodolite. A geodetic network was established to define a permanent reference system, to which laser scanning targets were added and measured with a theoretical accuracy of approx. ±2–3 mm, as indicated by the statistics of the least-squares adjustment. These targets were subsequently integrated into the scan registration process, confirming the quality of the alignment, with residuals of approx. ±3–4 mm.

The main drawback of high-quality static TLS is the considerable time required for data acquisition: two operators were engaged for approximately four working days. Nevertheless, given the project requirements (drawings and models at a scale of 1:50 or finer), static TLS remains essential in heritage applications, particularly when documenting complex architectures. This approach ensures not only the recording of small architectural details (decorations, etc.) but also the capture of geometric irregularities, such as wall deviations from verticality and variable thicknesses. Furthermore, archaeological excavations inside the church required dense and precise point clouds, since their irregular geometries could not be adequately documented with less detailed methods.

5.3 3D surveying with MLS

The second dataset was acquired with a portable MLS sensor Stonex (2025) *X70 GO®* equipped with a panoramic camera. As its name suggests, the maximum operating range is 70 m (at 80% reflectivity), which is well suited for architectural applications, while other versions of the instrument are designed for topographic or infrastructural surveys. The minimum working distance is 0.1 m, which is particularly advantageous for capturing narrow spaces, such as the staircase leading to the roof, where static TLS was problematic to be used. According to the manufacturer, the relative accuracy is about ±6 mm, though environmental factors may influence the performance. Error propagation is an inherent challenge in MLS acquisitions, and strategies to mitigate cumulative drift are therefore crucial.

The church was surveyed using the Stonex *X70 GO®* system in less than one hour, a substantial reduction in time compared to static TLS. The dataset was processed with the *GOpost®* SW provided with the instrument, integrating GCPs (targets) measured with the theodolite and also used for georeferencing TLS data. The results of the least-squares adjustment are reported in Table 1, demonstrating sub-centimeter accuracy. Some larger residuals were observed for points 31 (and 30, located nearby). This can be attributed to the characteristics of the target setup: the target was fixed on a surface where the base of the Stonex *X70 GO®* could not be properly positioned, leading to a slight misplacement. Interestingly, the MLS adjustment did not constrain the solution but correctly reported the expected error at the centimeter level. Overall, the statistics indicate satisfactory agreement with the theodolite measurements.

GCP	ΔX (m)	ΔY (m)	ΔXY (m)	ΔZ (m)
1	-0.001	0.007	0.007	-0.007
4	0.009	-0.007	0.011	0.011
5	-0.013	-0.005	0.014	0.008
30	0.012	-0.008	0.014	0.008
31	-0.025	-0.009	0.027	0.011
32	0.001	-0.001	0.002	0.000
51	0.000	0.007	0.007	-0.003
55	0.002	-0.002	0.003	0.000
100	-0.005	0.001	0.005	-0.002
2100	0.003	-0.002	0.004	0.002
Mean	**-0.002**	**-0.002**	**0.009**	**0.003**
RMSE	**0.010**	**0.006**	**0.012**	**0.006**

Table 1. Residuals on ground control points after georeferencing of the MLS point cloud (RMSE=Root Mean Squared Error).

5.4 Comparison between TLS/MLS point clouds

After georeferencing both TLS and MLS point clouds with a set of GCPs, both were compared. Instead of performing a complete comparison of the entire church, we selected three representative areas that illustrate the overall metric consistency between both datasets (see Fig. 1). A full comparison was not feasible since the acquisitions were conducted at different epochs, during which restoration works altered parts of the building, including the addition and removal of scaffolding and other elements.

The first area (A) concerns the apse of the church, scanned from the interior to capture the vault. The error distribution appears relatively homogeneous, except some specific areas that could not be captured from ground level due to occlusion by the cornice. The presence of glass elements also degraded the quality of the comparison. The overall discrepancy shows a standard deviation of 1.4 cm. When focusing on the masonry surfaces – i.e., the primary elements to be documented in this context – the error distribution is more consistent.

The second area (B) in Figure 1 shows a portion of the façade. Here, the statistics are more favorable, with a mean distance of 0.4 cm and a standard deviation of 0.4 cm. Concentrations of higher error occur in correspondence of major discontinuities, where the TLS acquisition provided superior coverage due to the greater number of scans. The error increases progressively with elevation, primarily affecting the noise and point density of the MLS dataset. At the top of the façade, approx. 15 m above ground level, the TLS point cloud still provides high density and reliable coverage, whereas the rapid MLS acquisition produces noisier data, making it difficult to clearly distinguish architectural features such as the window frame.

The third area (C) illustrates a top view of two vaults in a lateral aisle, separated by an arch. The surface is generally smooth, with error values slightly increasing in correspondence with the arch-vault discontinuity. Some minor differences are also visible along the ribs. Overall, the statistics on this smooth surface yield a mean discrepancy of 0.3 cm and a comparable standard deviation (0.3 cm), confirming a high level of metric correspondence between both point clouds.

5.5 Other considerations

Although metric accuracy is a fundamental parameter for evaluating the consistency of both datasets, other aspects such as point density, noise level, visibility of details, and additional qualitative factors must also be considered when the goal is an accurate and detailed reconstruction of the architectural object.

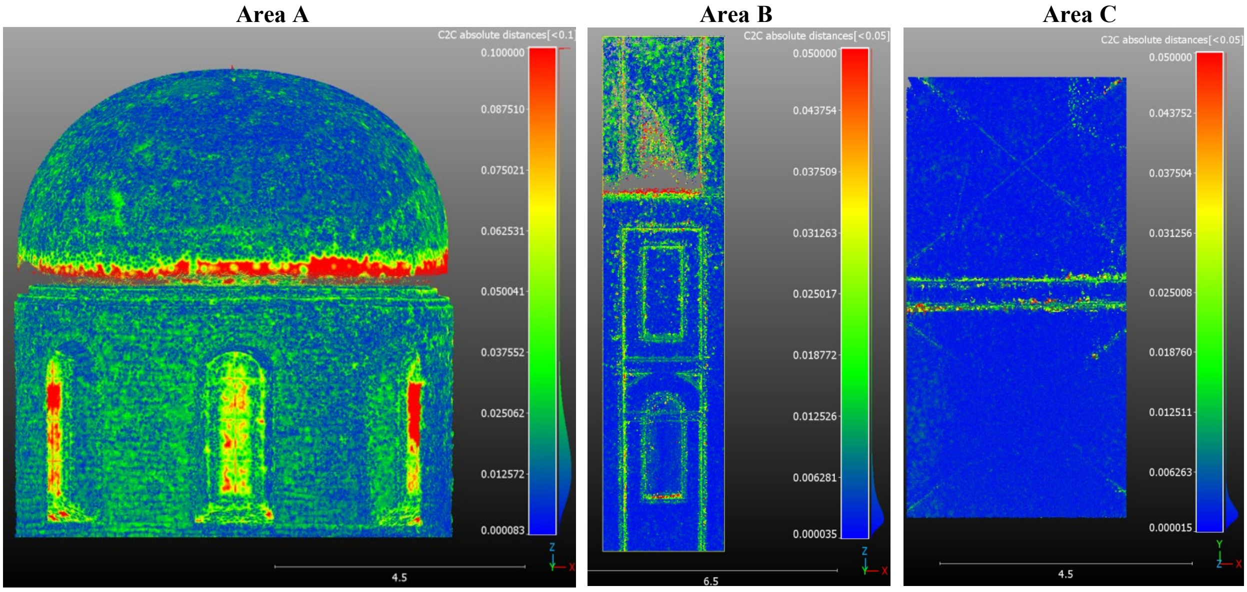

Figure 1. Metric discrepancies observed in three representative parts of the church, comparing both point clouds surveyed by static TLS and portable MLS.

For this reason, the project relied primarily on static TLS. However, in many applications where a lower level of detail is acceptable, MLS acquisitions may suffice.

Figure 2 presents a horizontal profile extracted from both datasets. As expected, the static TLS delivers less noise and higher precision; nevertheless, the profile of architectural elements can be clearly identified in both datasets. It should be noted that these sections were taken close to ground level. Additional strategies, such as the use of an extension pole, could further improve point density in higher areas.

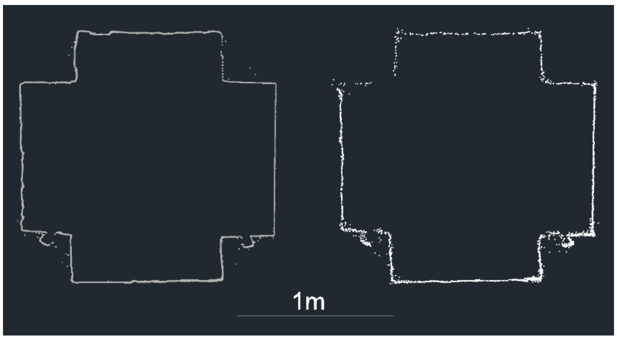

Figure 2. Comparison of cross-sections of the same column in both datasets: static TLS (on the left) and MLS (on the right).

6. Discussion and conclusions

This paper has provided an overview about the current commercial solutions for static Terrestrial Laser Scanning (TLS) and portable Mobile Laser Scanning (MLS) instruments. Since their introduction, that dated back to the first and the second decades of 2000, related technology has been continuously evolving, with some key solutions that offer unprecedented opportunity to practitioners.

An analysis of the technology foresight shows that the contribution of Artificial Intelligence, which is already supporting data processing, will amplify the future potential of both technologies. In addition, theoretical developments are expected to give an important added progress for accuracy evaluation and scan planning, while multispectral LiDAR is expected to be another area of development.

A case study reported in Section 5 demonstrates that static TLS and portable MLS approaches should not be regarded as competing techniques, but rather as complementary solutions that can be effectively integrated. For example, in the case of the surveyed church, the acquisition of narrow staircases was problematic with the TLS instrument, whereas capturing distant decorative elements of the vault was less feasible with the adopted MLS sensor. In general, the optimal strategy lies in combining both methods, adapting their use to the specific characteristics and requirements of each project.

While TLS/MLS technology is having big advancements, a last comment concerns the extension of new fields of applications (see, e.g., Genzano and Scaioni, 2025).

Acknowledgements

We would like to acknowledge the Stonex company for supporting the experiment of MLS surveying of the San Giacomo Basilica in Como, Italy.

References

Agisoft, 2025. Agisoft Metashape Features. https://www.agisoft.com/features/professional-edition/ (26/08/2025).

Akpınar, B. Performance of Different SLAM Algorithms for Indoor and Outdoor Mapping Applications. *Appl. Syst. Innov.* 2021, 4, 101.

Alba M., Scaioni M., 2007. Comparison of Techniques for Terrestrial Laser Scanning Data Georeferencing Applied to 3-D Modelling of Cultural Heritage. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 36-5/W47, 8 pages.

Altuntas, C., Yildiz, F., Scaioni, M., 2016. Laser Scanning and Data Integration for Three-Dimensional Digital Recording of Complex Historical Structures: The Case of Mevlana Museum. *ISPRS Int. J. Geo-Inf.*, 5(2), 18, doi:10.3390/ijgi5020018.

Autodesk, 2025. Autodesk Official Website. https://www.autodesk.com (30/08/2025).

Barazzetti, L., Remondino, F., Scaioni, M., 2012. Sequential Homography-Based Alignment for HDR image generation. *Adv. Mat. Res.*, 452-453, 1025-1029.

Barber, D., Mills, J., Smith-Voysey, S., 2008. Geometric validation of a ground-based mobile laser scanning system. *ISPRS J. Photogramm. Remote Sens.*, 63(1), 128-141.

Beraldin J.-A., Picard M., El-Hakim S.F., Godin G., Valzano V., Bandiera A., Lataouche D., 2002. Virtualizing a Byzantine Crypt by Combining High-Resolution Textures with Laser Scanner 3D Data. In: Proc. VSMM 2002, 25-27 Sept. 2002, Gyeongju (South Korea).

Boguspayev, N., Akhmedov, D., Raskaliyev, A., Kim, A., Sukhenko, A., 2023. A Comprehensive Review of GNSS/INS Integration Techniques for Land and Air Vehicle Applications. *App. Sci.*, 13(8), 4819, doi:10.3390/app13084819.

CHCNAV, 2025. CHCNAV Official Website. https://www.chcnav.com (29/08/2025).

Díaz-Vilariño, L., Previtali, M., Scaioni, M., 2022. Optimal Scan Planning for Surveying Large Sites with Static and Mobile Mapping Systems. *ISPRS J. Photogramm. Remote Sens.*, 192, 13-32, doi:10.1016/j.isprsjprs.2022.07.025.

Di Stefano, F., Chiappini, S., Gorreja, A., Balestra, M., Pierdicca, R., 2021. Mobile 3D scan LiDAR: a literature review. *Geomatics, Nat. Haz. Risk*, 12, 2387-2429.

FARO, 2025. FARO company official website. https://www.faro.com (26/08/2025).

Fassi, F., Achille, C., Fregonese, L., 2011. Surveying and modelling the main spire of Milan Cathedral using multiple data sources. *Photogramm. Rec.*, 26, 462-487.

Flood M., Gutelius C., 1997. Commercial implications of topographic terrain mapping using scanning airborne laser radar. *Photogramm. Eng. Remore Sens.*, 63(4), 327-329.

Fugazza, D., Scaioni, M., Corti, M., D'Agata, C., Azzoni, R.S., Cernuschi, M., Smiraglia, C., Diolaiuti, G.A., 2018. Combination of UAV and terrestrial photogrammetry to assess rapid glacier evolution and map glacier hazards. *Nat. Haz. Earth Syst. Sci.*, 18, 1055-1071, doi:10.5194/nhess-18-1055-2018.

Garramone, M., Jovanovic, D., Oreni, D., Barazzetti, L., Previtali, M., Roncoroni, F., Mandelli, A., Scaioni, M., 2023. Basilica di San Giacomo in Como (Italy): Drawings and HBIM to Manage Archaeological, Conservative and Structural Activities. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 48/M-2-2023, 653-660, doi:10.5194/isprs-archives-XLVIII-M-2-2023-653-2023.

Genzano, N., Colonna, R., 2025. 3D thermal volume mapping to assess the biological and physical characteristics of olive crops using remote sensing and photogrammetric methods. *Appl. Geomatics*, accepted for punlication.

Genzano, N., Scaioni, M., 2025. Update and Quality Assessment of GeoDBs in Urban Areas Based on SLAM Technology. In: Proc. of 'Symp. on Geospatial Technology: Vision and Horizons 2025,' Çanakkale (Turkey), 8-10 Oct. 2025.

GeoSLAM, 2025. Information on GEoSLAM HW/SW. https://www.faro.com/en/LP/Geoslam-migration (28/08/2025).

Gikas, V., 2012. 3D Terrestrial Laser Scanning for Geometry Documentation and Construction Management of Highway Tunnels During Excavation. *Sensors*, 12, 11249-11270.

Gonzalez-Aguilera, D., Gomez-Lahoz, J., Sanchez, J., 2008. A new approach for structural monitoring of large dams with a three-dimensional laser scanner. *Sensors*, 8, 5866-5883.

Granshaw, S.I. 2018. Structure from motion: Origins and originality. *Photogramm. Rec.*, 33, 6-10.

Greenvalley Int., 2025. Greenvalley International Official Website. https://www.greenvalleyintl.com/ (29/08/2025).

Grussenmeyer, P., Alby, E, Assali, P., Poitevin, V., Hullo, J.F., Smiciel, E., 2011. Accurate Documentation in Cultural Heritage by Merging TLS and High-Resolution Photogrammetric Data. In: Proc. SPIE 8085, 'Videometrics, Range Imaging, and Applications XI,' 21 June 2011, Munich (Germany), 808508.

Holvoet, J., and other 13, 2025. Terrestrial and mobile laser scanning for national forest inventories: From theory to implementation. *Remote Sens. Env.*, 329, 114947.

Hudson, R., Faraj, F., Fotopoulos, G., 2020. Review of close-range three-dimensional laser scanning of geological hand samples. *Earth-Sci. Rev.*, 210, 103321.

Kersten, T.P., Lindstaedt, M., 2022. Geometric accuracy investigations of terrestrial laser scanner systems in the laboratory and in the field. *Appl. Geomatics*, 14, 421-434.

Kim, J.-Y., Lee, D., Kim, G.-H., 2024. Measurement of Work Progress Using a 3D Laser Scanner in a Structural Framework for Sustainable Construction Management. *Sustainability*, 16(3), 1215, doi:10.3390/su16031215.

Kowbuz, D., 2020. How 3D scanning rebuilds crime scenes for courtrooms. *GIM Int.*, available online at: https://www.gim-international.com/content/article/how-3d-scanning-rebuilds-crime-scenes-for-courtrooms (19/08/2025).

Kraus K., Pfeifer N., 1998. Determination of terrain models in wooded areas with airborne laser scanner data. *ISPRS J. Photogramm. Remote Sens.*, 53(4), 193-203.

Kukko, A., Kaartinen, H., Hyyppä, J., Chen, Y., 2012. Multiplatform Mobile Laser Scanning: Usability and Performance. *Sensors*, *12*(9), 11712-11733.

Lachat, E., Landes, T., Grussenmeyer, P., 2017. Investigation of a Combined Surveying and Scanning Device: The Trimble SX10 Scanning Total Station. *Sensors*, 17(4), 730.

Leica Geosystems, 2025. Leica Geosystems Official Website. https://leica-geosystems.com/ (19/08/2025).

Lichti, D.D., S.J. Gordon, 2004. Error Propagation in Directly Georeferenced Terrestrial Laser Scanner Point Clouds for Cultural Heritage Recording. In Proc. of FIG Working Week, Athens, Greece, 22nd-27th May 2004, pages 16.

Lichti, D.D., 2010. Terrestrial laser scanner self-calibration: Correlation sources and their mitigation. *ISPRS J. Photogramm. Remote Sens.*, 65(1), 93-102.

Lindenbergh, R., Pietrzyk, P., 2015. Change detection and deformation analysis using static and mobile laser scanning. *Appl. Geomatics*, 7, 65-74, doi: 10.1007/s12518-014-0151-y.

Luhmann, T., Robson, S., Kyle, S., Boehm, J., 2020. *Close-range photogrammetry and 3D imaging. – 3rd Edition*. Walter de Gruyter, Berlin (Germany), p. 822.

Mandlburger, G., Kölle, M., Pöppl, F., Cramer, M., 2023. Evaluation of Consumer-Grade and Survey-Grade UAV-LiDAR. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 48-1/W3-2023, 99-106.

Melis, M.T., Da Pelo, S., Erbì, I., Loche, M., Deiana, G., Demurtas, V., Meloni, M.A., Dessì, F., Funedda, A., Scaioni, M., Scaringi, G., 2020. Thermal Remote Sensing from UAVs: A Review on Methods in Coastal Cliffs Prone to Landslides. *Remote Sens.*, 12, 1971, doi:10.3390/rs12121971.

Mallet, C., Bretar, F., 2009. Full-waveform topographic lidar: State-of-the-art. *ISPRS J. Photogramm. Remote Sens.*, 64(1), 1-16.

Mill, T., Alt, A., Liias, R., 2013. Combined 3D Building Surveying Techniques Terrestrial Laser Scanning (TLS) and Total Station Surveying for BIM Data Management Purposes. *J. Civil Eng. Manag.*, 19(Suppl. 1), S23-S32.

NavVis, 2025. NavVis Official Website. https://www.navvis.com (28/08/2025).

Park, H.S., Lee, H.M. Hojjat, A., Lee, I., 2007. A New Approach for Health Monitoring of Structures: Terrestrial Laser Scanning. *Comp.-Aided Civil Infrastr. Eng.*, 22. 19-30.

Park, J., Cho, Y.K., 2022. Point cloud information modeling: Deep learning–based automated information modeling framework for point cloud data. *J. Constr. Eng. Manage.*, 148 (2): 04021191, doi:10.1061/(ASCE)CO.1943-7862.0002227.

Salach, A., K. Bakuła, M. Pilarska, W. Ostrowski, K. Górski, Z. Kurczyński. 2018. Accuracy assessment of point clouds from LiDAR and dense image matching acquired using the UAV platform for DTM creation. *ISPRS Int. J. Geo-Inform.*, 7(9), 342.

Pomerleau, F., Colas, F., Siegwart, R., Magnenat, S., 2013. Comparing ICP variants on realworld data sets. *Autonom. Rob.*, 34, 133-148.

Polewski, P., Yao, W., Cao, L., Gao, S., 2019. Marker-free coregistration of UAV and backpack LiDAR point clouds in forested areas. *ISPRS J. Photogramm. Remote Sens.*, 147, 307-318, doi:10.1016/j.isprsjprs.2018.11.020.

Remondino, F., Stoppa, D., 2013. *TOF Range Imaging Cameras*. Springer-Verlag, Berlin Heidelberg (Germany).

Scaioni M., 2005. Direct Georeferencing of TLS in Surveying of Complex Sites. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 36-5/W17, 8 pages.

Sarker, S., Sarker, P., Stone, G., Gorman, R., Tavakkoli, A., Bebis, G., Sattarvand, J., 2024. A comprehensive overview of deep learning techniques for 3D point cloud classification and semantic segmentation. *Mach. Vis. App.*, 35, 67.

Scaioni, M., Höfle, B., Baungarten Kersting, A.P., Barazzetti, L., Previtali, M., Wujanz, D., 2018. Methods for Information Extraction from Lidar Intensity Data and Multispectral Lidar Technology. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 42-3, 1503-1510, doi:10.5194/isprs-archives-XLII-3-1503-2018.

Shan, J., Toth, C.K., 2018. *Topographic Laser Ranging and Scanning: Principles and Processing. 2nd edn*. CRC Press, Boca Raton, FL (US).

Shen, N., Wang, B., Ma, H.J., Zhao, X., Zhou, Y., Zhang, Z.X., Xu, J.H., 2023. A review of terrestrial laser scanning (TLS)-based technologies for deformation monitoring in engineering. *Measurements*, 223, 113684.

Son, H., Kim, C.M., Kim, C., 2015. 3D reconstruction of as-built industrial instrumentation models from laser-scan data and a 3D CAD database based on prior knowledge. *Autom. Constr.*, 49(B), 193-200, doi: 10.1016/j.autcon.2014.08. 007.

Skrzypczak, I., Oleniacz, G., Leśniak, A., Zima, K., Mrówczyńska, M., Kazak, J.K., 2022. Scan-to-BIM method in construction: assessment of the 3D buildings model accuracy in terms inventory measurements. *Build. Res. Inform.*, 50(8), 859-880, doi:10.1080/09613218.2021.2011703.

Stonex, 2025. Stonex Official Website. https://www.stonex.it/ (28/08/2025).

Taheri, H., Zhao, C.X., 2021. SLAM; definition and evolution. *Eng. Applicat. Art. Int.*, 97, 104032.

Takhtkeshha, N., Mandlburger, G., Remondino, F., Hyyppä, J., 2024. Multispectral Light Detection and Ranging Technology and Applications: A Review. *Sensors*, 24(5), 1669.

Telling, J., Lyda, A., Hartzell, P., Glennie, C., 2017. Review of Earth science research using terrestrial laser scanning. *Earth-Sci. Rev.*, 169, 35-68, doi: 10.1016/j.earscirev.2017.04. 007.

Trimble, 2025. Trimble company official website. https://www.trimble.com/ (19/08/2025).

UNCTAD (United Nations Comm. on Science and Technology for Development) Secretariat, 2024. Issues Paper on Technology Foresight and Technology Assessment for Sustainable Development. https://unctad.org/system/files/information-document/cstd2024-2025_issues02_tfta_en.pdf (30/08/2025).

Urban, R., Štroner, M., Braun, J., Suk, T., Kovanič, Ľ., Blistan, P., 2024. Determination of Accuracy and Usability of a SLAM Scanner GeoSLAM Zeb Horizon: A Bridge Structure Case Study. *App. Sci.*, 14(12), 5258, doi: 10.3390/app14125258.

Verykokou, S., Ioannidis, C., 2025. Image Matching: A Comprehensive Overview of Conventional and Learning-Based Methods. *Encyclopedia*, *5*(1), 4.

Vosselman, G.V., Maas, H.-G., 2010. *Airborne and Terrestrial Laser Scanning*. Whittles Publishing, Caithness (UK).

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., Reynolds, J.M., 2012. 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorph.*, 179, 300-314.

Winiwarter, K. Anders, B. Höfle, 2021. M3C2-EP: Pushing the limits of 3D topographic point cloud change detection by error propagation. *ISPRS J. Photogramm. Remote Sens*, 178, 240-258.

Wujanz, D., Burger, M., Tschirschwitz, F., Nietzschmann, T., Neitzel, F., Kersten, T.P., 2018. Determination of Intensity-Based Stochastic Models for Terrestrial Laser Scanners Utilising 3D-Point Clouds. *Sensors*, 18(7), 2187, doi: 10.3390/s18072187.

Wujanz, D., Barazzetti, L., Previtali, M., Scaioni, M., 2019. A Comparative Study Among Three Registration Algorithms: Performance, Quality Assurance and Accuracy. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 42-2/W9, 779-786.

Xu, H., 2025. *Evaluation of Terrestrial and Mobile Laser Scanning Systems: A Manufacturer-Based Comparative Study*. MSc thesis on Civil Engineering for Risk Management (CERM), Politecnico Milano, Lecco Campus, Italy.

Zhang, Y., Shi, P., Li, J., 2024. 3D LiDAR SLAM: A survey. *Photogramm. Record*, 39, 457-517, doi:10.1111/ phor.12497.

Zealquest, 2025. Zealquest Official Website. https://www.zealquest.com (29/08/2025).

Zoller+Fröhlich, 2025. Zoller+Fröhlich Official Website. https://www.zf-laser.com (26/08/2025).