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Geometrical characterization of evacuation routes from Terrestrial Laser Scanner point clouds

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***Abstract* – In emergency evacuation analysis, the geometric characterization of walking surfaces is a key factor influencing safety conditions and pedestrian behavior. While floor inclination is commonly evaluated from point cloud data, this parameter alone may not adequately reflect a surface's actual walkability, particularly in the presence of local irregularities. This work introduces a metrological approach that combines slope estimation and flatness evaluation using point clouds acquired by a Terrestrial Laser Scanning (TLS). Slope is derived from the orientation of locally estimated surface normals, whereas flatness is quantified through deviations from locally approximated planes. The analysis deepens understanding of factors that can affect measurement uncertainty, including the choice of algorithm, the setting of hyperparameters, and the study strategies for the floor surface. In particular, both quantities are evaluated at different spatial scales by modifying the size of the "neighbourhood" used in the calculations. The methodology is applied to a point cloud dataset acquired on the rooftop of the Papal Basilica of Saint Peter in the Vatican, which is open to the public. Preliminary findings indicate that areas with similar inclinations may differ significantly in surface regularity, highlighting the importance of adding flatness into the analysis. The proposed work provides a framework for a more complete geometric characterization of evacuation paths.**

Keywords* – Terrestrial Laser Scanner, point cloud processing, slope, flatness, measurement uncertainty, spatial resolution, evacuation planning, emergency.

I. INTRODUCTION

In analyzing emergency scenarios, evaluating building accessibility and safety conditions requires reliable and quantitative information. Among the geometric features influencing evacuation dynamics, the inclination of walking surfaces is commonly considered a key parameter, as it directly affects pedestrian speed, stability, and overall evacuation efficiency [1-6].

For these reasons, the entire problem should be addressed from a metrological perspective, where the influence of the complete measurement chain on the final results is explicitly evaluated [7–8]. This includes the whole workflow, from data acquisition to preprocessing, feature extraction, and the computation of the final descriptors.

The increasing availability of high-resolution point clouds from TLS has significantly improved the ability to characterize as-built environments in detail for evacuation planning. These technologies are widely used in structural monitoring and damage analysis, particularly in post-disaster contexts, where rapid, non-contact data acquisition are required [9, 10]. In addition, recent studies demonstrated the effectiveness of laser scanning techniques for identifying slope-related critical areas in safety applications, with reference to roads and unstable terrains [11]. Other works integrate the data from TLS with Building Information Modeling (BIM) models to control the surfaces flatness [12].

However, extracting reliable geometric descriptors from point clouds remains greatly dependent on data processing strategies. The assessment of slope, for instance, is influenced by factors such as point density and neighborhood definition. More generally, the entire processing pipeline, from point cloud registration to feature extraction, introduces variability that must be carefully considered [13-16].

Moreover, focusing exclusively on slope may lead to an incomplete characterization of walking surfaces. Real floors, especially in historical or complex architectural contexts, often exhibit local irregularities: surface roughness, small height variations, and geometric discontinuities can significantly affect pedestrian behavior, particularly under the stress conditions typical of emergency evacuations.

In this perspective, flatness and levelness serve as complementary descriptors, able to quantify local deviations from an ideal planar surface. Floor flatness represents the smoothness and the regularity of a surface. On the other hand, levelness relates to the floor's conformity to the horizontal plane and indicates the changes in elevation. Recent works have shown that TLS-based approaches can effectively detect and quantify flatness variations [17]. However, the potential of floor flatness and levelness as safety assessment parameters in evacuation scenarios has not yet been fully explored.

Floor flatness and levelness assessment is mostly applied to concrete floors or slabs and several different specifications exist. In these standards, the straightedge method is the reference. This is traditional and commonly used. In this procedure, the surveyor positions a straightedge at various points on the surface and records the maximum deviation under it with a stainless-steel slip gauge. The measured deviation is then compared with the required tolerance to determine whether the surface flatness is acceptable or rejected. This is a labor-intensive and time-consuming process that relies on limited samples measurements, and it is prone to errors.

The standard tolerances are provided by different standards. For instance, EN 13670 [18] considers the straightedge method placed directly on the concrete surface to identify local variations, dips, or undulations and specifies local and global flatness tolerances for different types of concrete surfaces. Moreover, floor regularity is more relevant in case of industrial concrete structures. For example, Italian national standard UNI 11146 [19] gives different limits depending on the straightedge length. Another standard used is ASTM E1155 [20]. This describes how to evaluate the surface of a concrete floor and how to determine its flatness and levelness. It is regarded as an improvement over the traditional straight-edge method and has been adopted by the American Concrete Institute as the standard system for measuring concrete finish quality. However, all these standards are applied to newly constructed concrete floors. To the authors knowledge, there are no specifications for floor flatness and levelness for escape routes but only for slopes. According to the Italian Ministerial Decree of 3 August 2015, evacuation routes whose slope is $\leq 5\%$ may be considered horizontal. In addition, all walking surfaces along the escape routes must provide safe foot passage: they must be non-slippery and free from dangerous depressions or protruding irregularities, and they must remain in a condition that ensures safe movement and egress for occupants.

Considering the design of escape paths in cultural heritage buildings, these can present sloped floors not suitable for the evacuation of a great number of people. Moreover, the floors can be built using bricks, paving or cobble stones that have a less regular surface compared to concrete slabs and can represent a potential danger. For these reasons, it is important to assess the geometrical features of the floors considering the as-build structure.

The present work proposes a geometric characterization of evacuation routes, based on the combined analysis of slope, flatness, and levelness derived from TLS point clouds. In this framework slope captures global inclination, whereas flatness quantifies local deviations from an ideal plane and thus surface quality; levelness captures deviations relative to the horizontal plane, reflecting elevation changes that may affect walking stability.

Particular attention is devoted to the role of spatial scale and hyperparameter setting, which influence both descriptors and their interpretation. The objective is also to investigate their complementarity in describing conditions that may affect walkability and safety.

In fact, slope and surface quality are typically examined independently [9-11]. This work proposes a unified framework that jointly considers slope, flatness, and levelness to analyze the global and local characteristics of evacuation paths. By integrating these aspects, the proposed approach aims to provide a more comprehensive representation of floor geometry, suitable for emergency planning applications. The metrological implications of this approach, including the influence of processing and setting choices on the measurement uncertainty, are also discussed.

II. DESCRIPTION OF THE METHOD

The considered test case is the rooftop of the Papal Basilica of Saint Peter in the Vatican, which is visited by numerous tourists and requires an accurate emergency response. In particular, the church's rooftop has been considered because it is partially open to the public, and the floor features different slopes to drain rainwater. Some of these areas are selected as escape routes in case of emergency.

A Leica RTC 360 TLS has been used to acquire the point cloud, and the processing has been carried out using the Leica software suite. The laser scanner has been positioned on a tripod at a height of 1.7 m. In the acquisition phase, Leica Register360 has been used to join the point clouds acquired from 846 setups used to scan the whole Basilica. The resulting point cloud contains 25.300 million points and has been analyzed using Leica Cyclone 3DR software. To better align the different acquisitions, the instrument uses a Visual Inertial System (VIS), which tracks the unit's movement relative to the previous scan position. Because the site remained open to the public during the acquisition campaign, the laser scanner's "Double Scan" function was used at each setup. This removes any objects and visitors that moved between consecutive scans.

A portion of the rooftop of approximately 8 m x 8 m has been selected, characterized by varying slopes (Fig. 1).

All the geometrical features of the floor are calculated using Leica Cyclone 3DR version 2025.1. Specifically, the used functions are slope analysis, surface flatness and levelness.

The Leica software calculates a percentage slope for each point based on the angle between the local surface normal and the horizontal. This function requires setting a Local Normal Smoothing parameter, which represents the radius of the circular area used to calculate the local normal (Fig. 2).

In this analysis, the slope has been calculated using the maximum and minimum values of the Local Normal Smoothing parameter, corresponding to radii of 213 mm and 42 mm, respectively.

Floor flatness quantifies the micro-waviness of a surface, and it is assessed using the build-in function "Surface Flatness". In this procedure, the flatness attributed to each sampled point is determined using the neighboring points. These are located within a maximum radial distance equal to half the ruler dimension. Specifically, the algorithm translates a cylinder aligned with the Z axis across a regular grid that covers the object surface. At each cylinder position, a best-fit local plane is computed from the points contained within the cylinder. The algorithm then evaluates the flatness of the corresponding surface area by comparing the cylinder-contained points against this local plane and determining whether the deviations satisfy a specified tolerance.

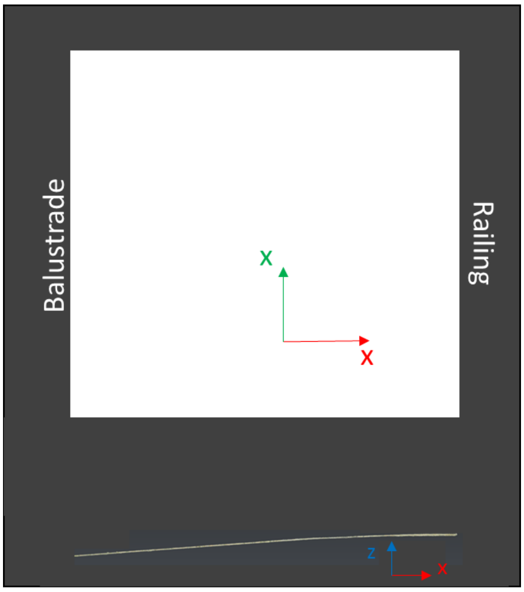

Fig. 1. In the figure above: top view of the selected rooftop portion (in white). In the figure below: section of the point cloud in the central zone of the selected rooftop portion.

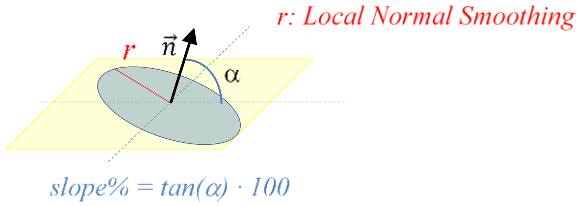

Fig. 2. Explanation of the meaning of slope and the "Local Normal Smoothing" parameter.

The introduction of flatness aims to identify irregularities that are not detectable from slope evaluation alone, providing additional information on the quality of the walking surface.

The flatness analysis has been performed considering the influence of the selection of the radius of the cylinder for the surface fitting. In particular, the selected radii values are the same as for the slope analysis. In both cases, the considered tolerance value is equal to 3.00 mm.

III. RESULTS AND DISCUSSIONS

The first analysis of the selected surface consists of creating a heat map of the slopes obtained by setting the Local Normal Smoothing parameter to its minimum and maximum values, corresponding to minimum and maximum smoothing.

It should be noted that the choice of the lowest spatial resolution allows for the clear identification of two areas with a prevailing and distinct slope: an area on the left, with a slope greater than 5% and the remaining part with a slope lower than 5%, which can be approximated to a horizontal plane according to the Italian standard.

In fact, according to the Italian Ministerial Decree of 3 August 2015, evacuation paths with a slope ≤ 5% can be considered horizontal. Slopes above 8% are generally not accessible to occupants with mobility impairments, and slopes exceeding 12% should only be used in exceptional evacuation conditions.

Furthermore, based on the slope maps shown in Fig. 3, it can be observed that the use of minimum smoothing allows local surface irregularities to be clearly identified. These small-scale variations are otherwise less evident when higher levels of smoothing are applied.

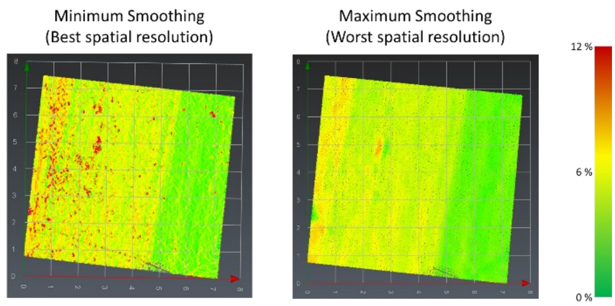

Fig. 3. Heatmap of the selected area obtained by setting the option: Min Smoothing (on the left); Max Smoothing (on the

right)[11].

This is even more manifest when analyzing the relative frequency distributions. Graphs in Fig. 4 and Fig. 5 refer to the distribution of the slopes in the area considered. The figures show that:

- the distribution obtained using the "maximum smoothing" option, that is the worst spatial resolution, appears to be clearly bimodal;
- the distribution obtained with the "minimum smoothing" option, which provides better spatial resolution, shows a much less pronounced bimodal behavior.

These observations can be explained by referring to the previously shown heatmap, which shows that the portion of the terrace considered comprises two macro areas with different slope levels. The bimodality is less evident in the case of "minimum smoothing", since the better spatial resolution produces greater variability in the calculated slope values, making the two peaks wider and, therefore, less distinct.

Therefore, to identify macro areas with different slopes, the minimum spatial resolution is the most suitable choice for quantifying these slopes; however, it does not allow us to identify local irregularities.

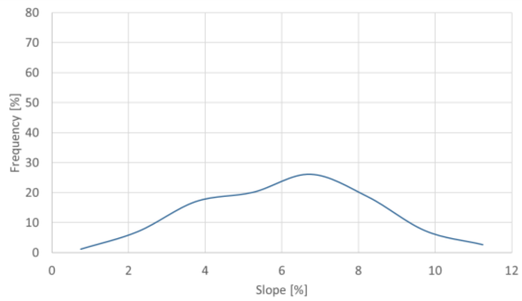

Fig. 4. Relative frequency distribution for the slope, corresponding to minimum smoothing selection.

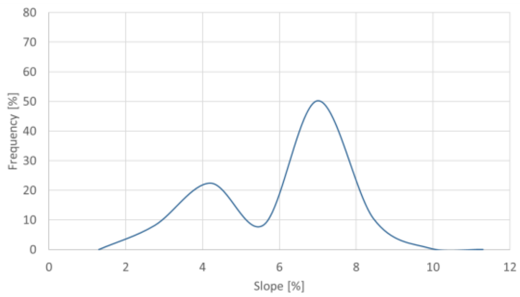

Fig. 5. Relative frequency distribution for the slope, corresponding to maximum smoothing selection.

These findings highlight a scale-dependent interpretation of slope, suggesting that different spatial resolutions may be required depending on the specific safety assessment objective.

The second analysis is the floor flatness evaluated using two cylinder radii. This kind of evaluation is of interest since the Italian Ministerial Decree of 3 August 2015 suggests that all the walking surfaces along the escape routes must not be slippery, nor must they have dangerous depressions or protrusions, and they must be in such condition as to ensure the safe movement and passage of occupants.

As for the slope evaluation, the surface is represented as an heatmap where the green points are within the selected tolerance limits. Red indicates points located above the fitted plane while the blue ones are below it. The floor flatness heatmaps of the surface are represented in Fig. 6.

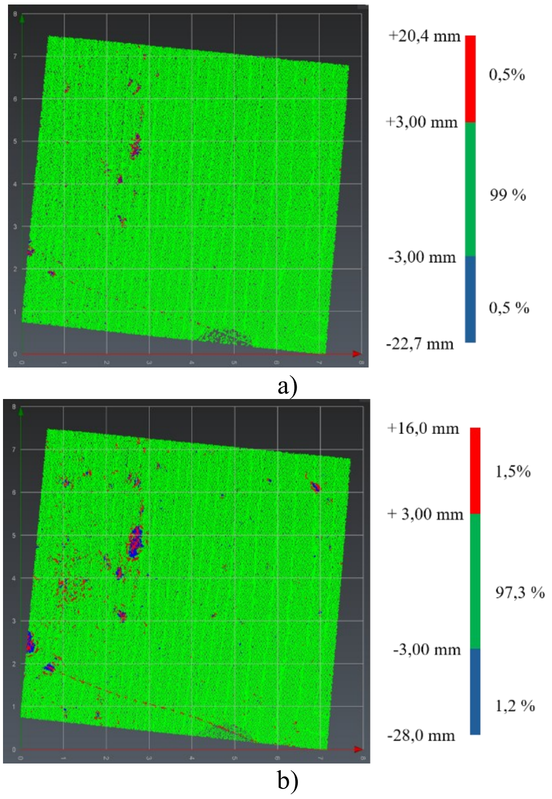

Fig. 6. Heatmaps of the floor flatness on the considered surface by setting the minimum (a) and the maximum cylinder radius (b).

Fig. 6 also reports the relative frequency of the point cloud that are above, below and inside the tolerance limits.

From the heatmaps in Fig. 6, most of the floor appears to be within the near-flat range represented in green while there are some localized defects with small clusters of red and blue points. These suggest local bumps and voids.

Using the 240 mm cylinder radius, local irregularities are more pronounced than with the 42 mm radius. This trend is also confirmed by the distribution of points inside the selected tolerance limits. With the smaller radius (42 mm), 99% of the points are within tolerance. For the 240 mm radius, the percentage of points considered flat decreases to 97.3%.

With a smaller radius, localized unevenness is absorbed into the fitted plane and therefore is not detected.

The last analysis that has been carried out is the floor levelness. In Fig. 7, the heatmap of the surface represents the variation in height of the point cloud.

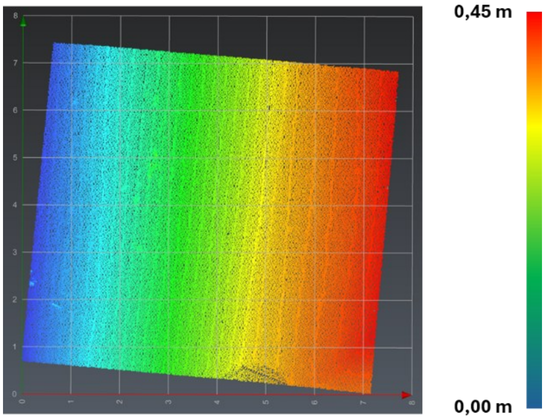

Fig. 7. Heatmap of the floor levelness on the considered surface.

As shown in Fig. 7, the blue points are positioned lower on the cloud while the red ones are higher. In this case, to measure the variation in height, an offset equal to the lowest point is used. From Fig. 7, it is possible to assess that the floor is largely planar since there are smooth color changes. This passage presents three main levels and most of its variation is gradual with a maximum height variation equal to 0.45 m.

IV. CONCLUSIONS AND OUTLOOK

This work presents a metrological approach for the geometric characterization of walking surfaces from TLS point clouds, with particular attention to the influence of processing parameters such as spatial resolution, smoothing level, and analysis scale, on the slope and flatness evaluation. Slope alone may not be sufficient to fully describe the geometric and functional conditions of walking surfaces: surfaces with similar slope values may exhibit different local behaviors, which can significantly impact accessibility and safety.

The results relative to the slope evaluation show that the choice of hyperparameters plays a crucial role in characterizing surface geometry, as it directly affects the ability to detect local irregularities. In particular, the use of minimum smoothing allows small-scale variations in slope to be identified, which are not visible when higher levels of smoothing are applied. This confirms the importance of considering the spatial scale of the analysis when interpreting slope maps, especially in the context of evacuation route assessment. A similar dependency is observed for floor flatness. Using small areas for evaluating the surface regularity may reduce sensitivity and lead to not detecting localized unevenness since these are incorporated into the fitted plane.

The continuation of the work will therefore focus on comparing slope, flatness, and levelness estimates to assess their consistency and complementarity. Particular attention will also be devoted to assessing the uncertainty associated with the estimation of both slope, flatness, and levelness parameters.

The proposed approach represents a contribution towards a more comprehensive geometric characterization of evacuation routes, supporting the development of more reliable and informative assessment methodologies and aiding decision-making in emergency planning.

Future developments will also explore the integration of these geometric indicators into evacuation simulation models, enabling a direct assessment of their impact on pedestrian flow and safety conditions.

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