20th IMEKO TC10 Conference
"Measurement for Diagnostics, Optimization and Control to Support Competitiveness and Innovation"
Lisbon, Portugal, September 28–29, 2026

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 an italian Basilica 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].

The increasing availability of high-resolution point clouds from TLS has significantly improved the ability to characterize 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 is required [7, 8]. In addition, recent studies demonstrated the effectiveness of laser scanning techniques for identifying slope criticality in safety applications, with reference to roads and unstable terrains [9].

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 [10-13].

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 serves as a complementary descriptor, able to quantify local deviations from an ideal planar surface. Recent works have shown that TLS-based approaches can effectively detect and quantify flatness variations [14]. However, the potential of flatness as a safety assessment parameter in evacuation scenarios has not yet been fully explored.

The present work proposes a geometric

characterization of evacuation routes, based on the combined analysis of slope and flatness derived from TLS point clouds. In this framework slope represents a global parameter for surface inclination; flatness is used to capture local irregularities and surface quality.

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 [7-9]. This work proposes a unified framework that jointly considers slope and flatness 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 a Basilica in Central Italy, 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.

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.

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

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 preliminary 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.

To complement the slope analysis, the flatness of the surface will be evaluated by measuring how much the points deviate from a locally fitted plane, within a defined neighborhood.

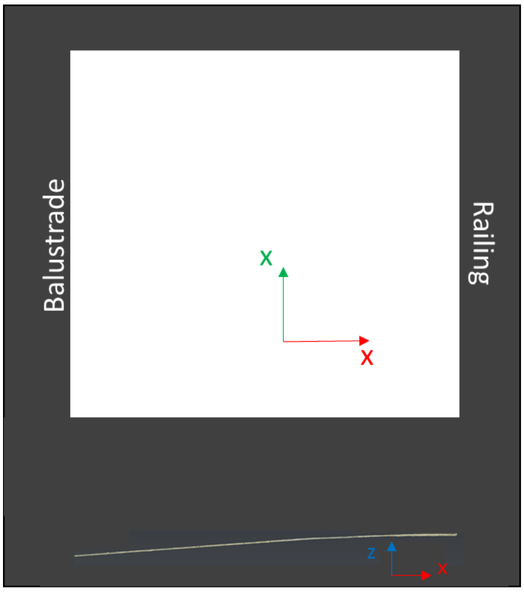

Fig. 1. In the figure above: top view of the selected rooftop portion (in white). In the figure below: section of the point cloud in the central zone of the selected rooftop portion.

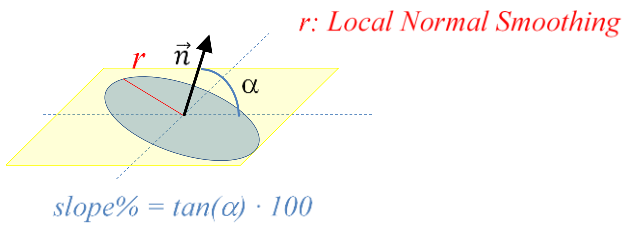

Fig. 2. Explanation of the meaning of slope and the "Local Normal Smoothing" parameter.

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 will be performed by considering the influence of different parameters, including:

- Point cloud density: the number of points used in the analysis will be varied to evaluate the effect of sampling resolution on the flatness assessment.
- Local neighborhood definition: the size of the local region used for computation will be varied in order to investigate its influence on the estimation of surface deviations.

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.

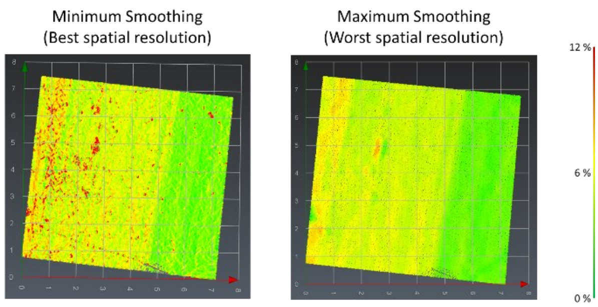

Fig. 3. Heatmap of the selected area obtained by setting the option: Min Smoothing (on the left); Max Smoothing (on the right)[11].

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.

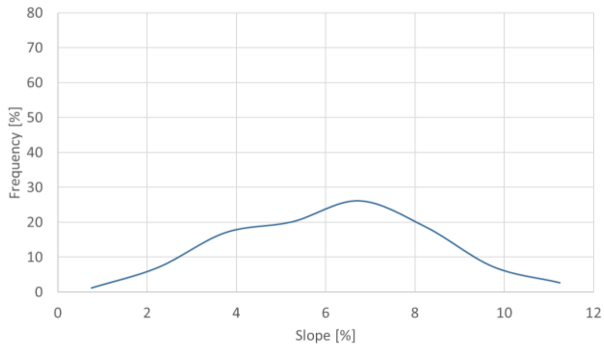

Fig. 4. Relative frequency distribution for the slope, corresponding to minimum smoothing selection.

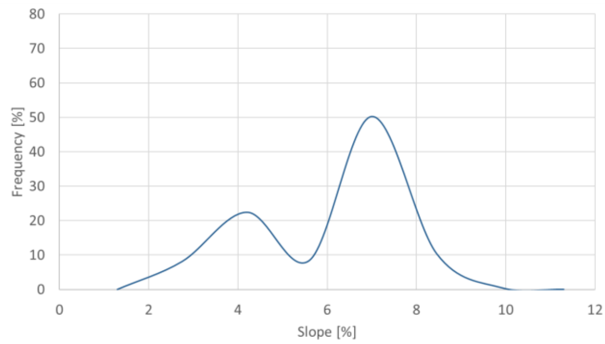

Fig. 5. Relative frequency distribution for the slope, corresponding to maximum smoothing selection.

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

A comparison between the slope results and those that will be obtained from a flatness analysis is expected to be very interesting, in order to assess whether the detected local slope irregularities correspond to variations in flatness, and to evaluate the consistency or complementarity between the two approaches.

In this perspective, the inclusion of flatness is expected to provide additional insight into the nature of the identified variations, distinguishing between actual geometric irregularities and artifacts related to scale or processing choices.

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 preliminary 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.

In this perspective, a comparison with flatness analysis is expected to provide further insight into the characterization of surface conditions. The continuation of the work will therefore focus on evaluating flatness and comparing slope and flatness estimates to assess their consistency and complementarity. Particular attention will also be devoted to assessing the uncertainty associated with the estimation of both slope and flatness 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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