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Scale-Dependent Point-Cloud Roughness Analysis for Image-Based 3D Road Surface Reconstruction

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Abstract: **Road surface roughness is an important indicator for transportation safety, ride comfort, and pavement maintenance planning. Image-based three-dimensional reconstruction provides a low-cost and non-contact approach for generating dense road surface point clouds that can be analyzed geometrically. However, roughness values derived from point clouds are strongly affected by the neighborhood radius used during local surface analysis. This study investigates the influence of neighborhood radius on point-to-plane roughness estimation for a reconstructed asphalt road surface. This study focuses on the computational influence of neighborhood-scale selection in point-cloud geometric analysis. A road segment was reconstructed from smartphone imagery using a Structure-from-Motion and Multi-View Stereo workflow, and the resulting point cloud was processed in CloudCompare. After alignment, cropping, and surface normal estimation, roughness was computed at three neighborhood radii: 0.2, 0.4, and 0.6 model units. The results show that radius selection substantially changes both the spatial scalar-field representation and the mean roughness values. At the smallest radius, roughness computation is highly sensitive to fine-scale texture and local point-level variation. At larger radii, isolated high-frequency variation becomes less fragmented, while broader geometric undulations become more dominant. The mean roughness increased from 0.0225 at radius 0.2 to 0.0411 at radius 0.4 and 0.0602 at radius 0.6, indicating that larger neighborhoods captured broader surface deviation rather than only smoothing local texture. These findings confirm that point-cloud roughness is scale-dependent and should always be interpreted together with the selected neighborhood radius. The study provides practical guidance for CloudCompare-based roughness analysis in image-based road monitoring applications.**

Keywords: **road surface roughness; point cloud; CloudCompare; point-to-plane distance; neighborhood radius; multi-scale analysis; Structure-from-Motion.**

I. INTRODUCTION

Road surface roughness is an important indicator of pavement condition because it affects traffic safety, ride comfort, vehicle operating cost, and maintenance planning [1]. Traditional roughness measurement systems, including profilometers, inertial profilers, laser scanners, and vehicle-mounted sensing platforms, can provide standardized and reliable measurements. However, these systems usually require specialized equipment, trained operators, and controlled survey conditions, which may limit frequent or low-cost road monitoring.

With the development of computer vision and photogrammetry, image-based three-dimensional reconstruction has become a practical alternative for road surface analysis. Structure-from-Motion and Multi-View Stereo techniques can generate dense point clouds from overlapping images, allowing geometric surface characteristics to be analyzed over a full road area rather than along a single longitudinal profile [2], [3]. Previous studies have shown that dense point clouds and UAV-based photogrammetry can support pavement roughness evaluation and road condition monitoring [4], [5], [12]. However, point-cloud roughness computation still depends strongly on methodological parameters, especially the neighborhood radius used for local surface analysis.

In point-cloud roughness analysis, a local neighborhood is defined around each point, a reference plane is fitted, and roughness is calculated from the deviation of the point from this local plane. Therefore, the selected neighborhood radius directly controls the scale of roughness interpretation. A smaller radius may capture fine texture and small local defects, but it can also be sensitive to point-level noise. A larger radius may reduce local fluctuations and reveal broader surface undulations, but it may also suppress small-scale irregularities. This creates a problem: roughness values computed from reconstructed road point clouds cannot be interpreted reliably without considering the analysis radius.

To address this issue, this paper investigates the influence of neighborhood radius on point-to-plane roughness estimation for a reconstructed asphalt road surface. A road-surface point cloud was generated using a Structure-from-Motion and Multi-View Stereo workflow and processed in CloudCompare. After alignment, cropping, and normal estimation, roughness was computed using three neighborhood radii: 0.2, 0.4, and 0.6 model units. From a computer vision and point-cloud processing perspective, the neighborhood radius functions as an algorithmic parameter that controls the scale of local geometric interpretation. The objective is to analyze how the selected radius affects scalar-field roughness patterns and mean roughness values, and to provide practical guidance for multi-scale roughness analysis in image-based road monitoring.

II. RELATED WORK

A. Road Surface Roughness Assessment

Road surface roughness has traditionally been assessed using profile-based measurement systems. These systems measure vertical displacement along a road profile and derive standardized indicators that support pavement management and maintenance decisions. Such methods are valuable because they provide repeatable and well-established outputs. However, profile-based measurements are usually limited to one-dimensional paths and may not fully represent localized defects, transverse variation, patching, rutting, or surface texture across the full road width [1].

Three-dimensional surface analysis provides a broader representation of road geometry. Dense point clouds allow roughness and local surface irregularities to be examined spatially across the road surface. This makes point-cloud-based analysis useful for observing localized pavement features that may not be captured by a single longitudinal profile. Recent work has shown that UAV-derived dense point clouds and image-based models can support road roughness assessment and pavement monitoring [2,4].

B. Image-Based 3D Reconstruction for Road Surfaces

Image-based reconstruction techniques generate three-dimensional geometry from overlapping two-dimensional images. In a typical SfM-MVS workflow, feature points are detected and matched across images, camera poses are estimated, and dense reconstruction is performed to generate a point cloud [3,5]. These methods have been widely used because they can produce detailed surface models using relatively accessible imaging equipment.

For road surface analysis, reconstructed point clouds offer several advantages. They allow local geometric variation to be inspected over the entire visible surface, and they enable scalar-field visualization of surface descriptors such as height, roughness, or deviation from a fitted plane. However, reconstructed point clouds may contain non-uniform density, local noise, and small geometric artifacts. These factors can affect neighborhood-based roughness computation, especially at small analysis radii.

C. Point-Cloud Roughness Computation

Point-cloud roughness computation evaluates the local geometric variability of a surface. A common approach is to define a neighborhood around each point, estimate a local reference plane, and calculate the orthogonal distance between the point and that plane. The resulting roughness values can be visualized as a scalar field, allowing spatial interpretation of surface irregularities.

Several local roughness descriptors may be used in point-cloud analysis, including height standard deviation, root mean square deviation, and mean or absolute point-to-plane deviation. Recent comparisons of roughness descriptors have also shown that different local roughness indices can produce different spatial roughness patterns, highlighting the importance of clearly defining the adopted metric [9]. Point-to-plane roughness is particularly useful because it provides a direct geometric interpretation: it measures how far a point deviates from a locally planar approximation of the surrounding surface.

In practical applications, the roughness result depends on neighborhood definition, point density, local plane stability, surface normal estimation, and the selected statistical descriptor. Therefore, the neighborhood radius must be reported clearly, especially when roughness values are used for engineering interpretation.

D. Neighborhood Radius and Scale Dependency

The neighborhood radius defines the spatial scale over which local surface variation is analyzed. When the radius is small, the fitted plane is based on a limited local region and the resulting roughness value is sensitive to fine texture, small defects, and local noise. When the radius is larger, the fitted plane is estimated from a wider region, which can reduce isolated noise effects but may also incorporate broader surface curvature or undulation.

This behavior means that roughness values computed at different neighborhood radii do not describe exactly the same surface characteristic. Small-radius roughness is closer to micro-scale texture and local irregularity, while larger-radius roughness reflects broader geometric deviation. Multi-scale roughness analysis is therefore useful because it reveals how surface variability changes as the analysis neighborhood expands. Scale-dependent point-cloud roughness analysis has also been emphasized in recent topographical studies, where neighborhood or moving-window size was shown to influence the interpretation of surface features [10].

III. MATERIALS AND METHODS

A. Road Surface Dataset and Point Cloud Generation

The experimental dataset consisted of smartphone images captured over an asphalt road segment under stable daylight conditions. The road surface contained visible texture, local defects, and broader surface irregularities, making it suitable for testing roughness behavior across multiple spatial scales.

A Structure-from-Motion and Multi-View Stereo workflow was used to reconstruct the road surface point cloud. COLMAP was selected for point cloud generation because it is an open-source reconstruction framework and is commonly used as a research-oriented SfM-MVS baseline [5]. In this paper, COLMAP is not evaluated against other reconstruction tools. It is used only to produce a representative reconstructed road-surface point cloud for studying neighborhood-radius effects in roughness computation. This design keeps the analysis focused on scale-dependent roughness behavior rather than reconstruction-pipeline comparison.

B. CloudCompare Preprocessing Workflow

The reconstructed point cloud was imported into CloudCompare for geometric preparation and roughness analysis. Before roughness computation, the point cloud was processed using a minimal preprocessing workflow shown in Fig. 1.:

1. Import the reconstructed road-surface point cloud.
2. Align the point cloud to a consistent top-view orientation.
3. Crop the road segment to isolate the region of interest.
4. Estimate surface normals using a local neighborhood-based approach.
5. Compute roughness using selected spherical neighborhood radii.
6. Visualize the resulting roughness values as scalar fields.

The preprocessing was intentionally limited to alignment, cropping, and normal estimation. No additional smoothing or filtering was applied before roughness computation. This was done to preserve the geometric characteristics of the reconstructed road surface and avoid artificially modifying micro-scale variation before analysis.

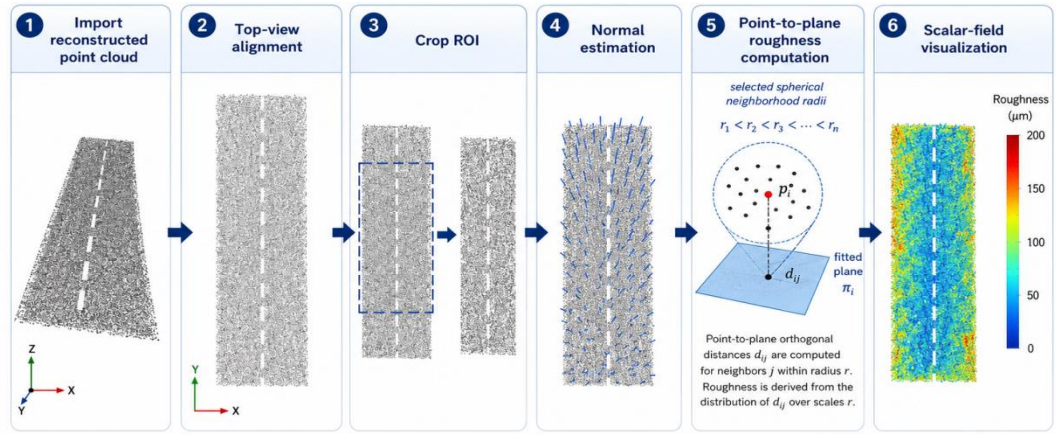

Fig. 1. Suggested workflow diagram for CloudCompare preprocessing and roughness analysis

C. Point-to-Plane Roughness Metric

As shown in Fig. 2, CloudCompare computes local roughness by fitting a local surface to the neighboring points around a target point and measuring the deviation from this local approximation. This follows the CloudCompare roughness definition, in which each point's roughness is calculated as its distance to the best-fitting plane computed from neighboring points [11]. In this study, roughness was interpreted using a point-to-plane formulation.

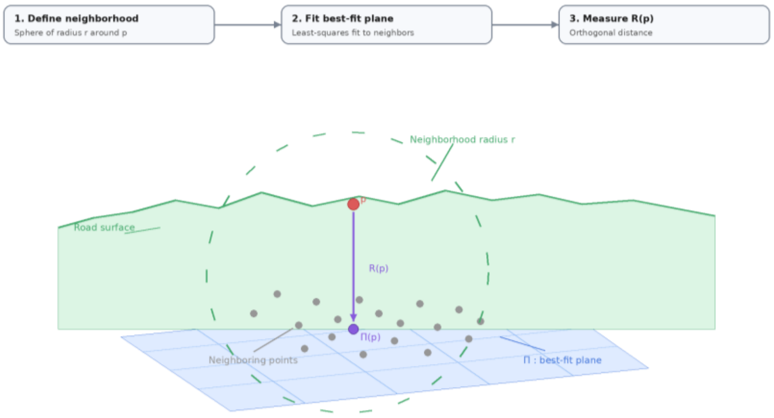

Fig. 2. Schematic illustration of point-to-plane roughness computation using a local best-fit plane.

For a given point p, a spherical neighborhood of radius r is defined. A best-fit plane is estimated from the neighboring points in that radius. The local roughness value is then computed as the orthogonal distance between the point and the fitted local plane:

$$R(p) = \mathrm{dist}(p, \Pi_p)$$

Where $R(p)$ is the local roughness value at point p, Π_p is the best-fit plane estimated from the neighboring points within radius r, and $\mathrm{dist}(p, \Pi_p)$is the orthogonal point-to-plane distance between point (p) and the fitted plane.The mean roughness over the region of interest is then computed as:

$$\bar{R} = \frac{1}{M}\sum_{j=1}^{M} R\,(p_j)$$

where M is the number of points in the region of interest and R(p_j) is the roughness value assigned to point j.

This metric describes the magnitude of local geometric deviation relative to a planar neighborhood approximation. It is suitable for road surface analysis because it can represent roughness spatially across the point cloud rather than along a single profile line.

D. Multi-Scale Radius Selection

Roughness was computed using three neighborhood radii:

- r = 0.2 model units: fine-scale roughness analysis
- r = 0.4 model units: intermediate-scale roughness analysis
- r = 0.6 model units: broader-scale roughness analysis

The three radii were selected to examine how roughness behavior changes as the local analysis neighborhood expands. The smallest radius was expected to emphasize micro-scale texture and local point-level variation. The intermediate radius was expected to reduce isolated noise while preserving meaningful surface structure. The largest radius was expected to emphasize broader surface undulation and macro-scale geometric behavior.

IV. RESULTS

Fig. 3, presents the scalar-field roughness maps obtained at the three neighborhood radii. The visual comparison provides a direct illustration of how increasing the neighborhood radius changes the spatial distribution of roughness values across the reconstructed road surface.

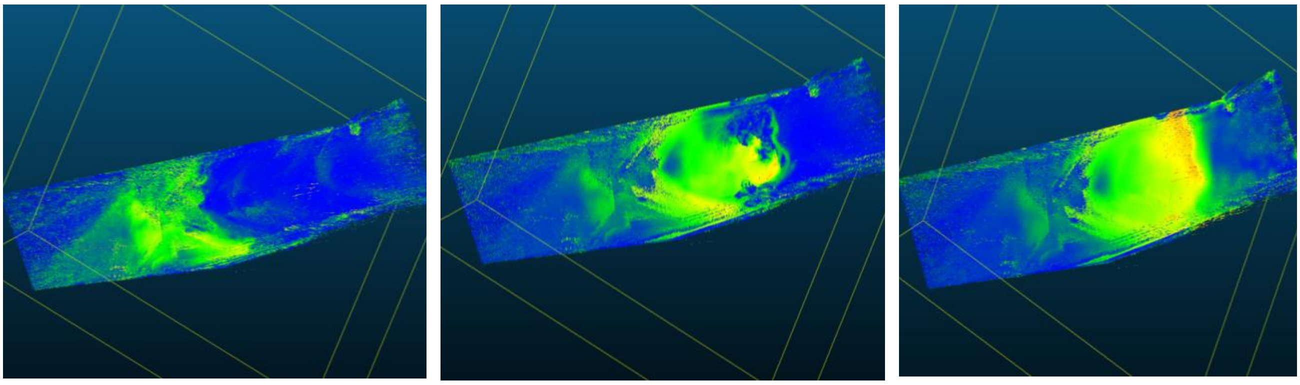

Fig. 3. Scalar-field visualization of the reconstructed road surface at different neighborhood radii: (a) r=0.2, (b) r=0.4, and (c) r=0.6 model units.

A. Scalar-Field Roughness at Radius 0.2

At radius 0.2, the roughness scalar field showed strong sensitivity to fine-scale surface variation. Localized high-roughness regions were clearly visible across the road surface, indicating that the small neighborhood radius preserved micro-scale texture and local geometric fluctuation.

However, scattered high-intensity regions were also visible in some areas. This suggests that roughness computation at a small radius may be sensitive not only to real surface texture but also to point-level noise or local reconstruction irregularities. As a result, radius 0.2 is useful for detecting fine surface details but should be interpreted carefully when the point cloud contains local instability or non-uniform point distribution.The mean roughness at radius 0.2 was 0.0225 model units.

B. Scalar-Field Roughness at Radius 0.4

At radius 0.4, the scalar-field representation became more spatially coherent. Compared with radius 0.2, isolated high-frequency variations were reduced and broader surface structures became more visible. The roughness pattern appeared less fragmented, suggesting that the larger neighborhood improved local plane-fitting stability.

The mean roughness increased to 0.0411 model units. This increase does not contradict the visual smoothing of isolated noise. Instead, it indicates that a larger neighborhood captured broader surface deviations and undulations that were not fully represented by the smaller local radius. Therefore, radius 0.4 provided an intermediate representation between micro-scale texture and broader geometric variation.

C. Scalar-Field Roughness at Radius 0.6

At radius 0.6, the scalar field became smoother and more dominated by macro-scale surface behavior. High-frequency local variation was less fragmented, while broad regions of elevated roughness became more apparent. This indicates that the largest radius shifted roughness interpretation from local texture toward larger-scale surface deviation.

The mean roughness increased further to 0.0602 model units. This result shows that increasing the radius can increase the average point-to-plane deviation when the road surface contains broader geometric undulation. Larger neighborhoods may therefore produce higher mean roughness values because the fitted plane spans a wider and less locally uniform surface area.

D. Summary of Mean Roughness Values

The results show a consistent increase in mean roughness as the neighborhood radius increased. This confirms that radius selection strongly affects the magnitude of the roughness value. The change in mean roughness also shows that the metric does not simply become smaller as the radius increases. Instead, the effect depends on the balance between local noise suppression and broader surface undulation captured by the expanded neighborhood.

TABLE I: Mean point-to-plane roughness values at different neighborhood radii

Neighborhood radius	Mean roughness	Interpretation
0.2	0.0225	Fine-scale texture and local variation
0.4	0.0411	Intermediate-scale surface structure
0.6	0.0602	Broader undulation and macro-scale behavior

V. DISCUSSION

A. Why Roughness Changes with Radius

The observed results demonstrate that neighborhood radius has a strong influence on point-cloud roughness computation. This occurs because the fitted local plane changes as the neighborhood size changes. At a small radius, the plane is estimated from a limited local area. It therefore follows small surface changes closely and captures micro-scale texture. At a larger radius, the plane is estimated from a wider surface region. This can reduce isolated point-level variation, but it also introduces sensitivity to broader surface shape.

In this study, the mean roughness increased from radius 0.2 to radius 0.6. This indicates that the road surface contains broader geometric undulations that become more visible when the local plane is fitted over a wider neighborhood. Therefore, larger radius values should not automatically be interpreted as smoothing in the numerical sense. They smooth isolated local fluctuations visually, but they may increase mean point-to-plane deviation if the surface is not locally planar over the larger radius.

B. Micro-Scale and Macro-Scale Interpretation

The three tested radii correspond to different levels of roughness interpretation. Radius 0.2 emphasizes micro-scale behavior, including fine pavement texture and point-level instability. Radius 0.4 provides an intermediate representation where isolated fluctuations are reduced but meaningful surface structure remains visible. Radius 0.6 emphasizes broader surface variation and larger undulations.

This scale dependency is important in road monitoring. If the objective is to identify fine texture, small cracks, or local defects, smaller radii may be more informative. If the objective is to evaluate broader surface deformation or undulation, larger radii may be more appropriate. A single radius cannot fully describe the complexity of road surface geometry.

C. Practical Implications for CloudCompare Analysis

The results suggest several practical recommendations for point-cloud roughness analysis in CloudCompare:

1. The neighborhood radius should always be reported together with roughness values.
2. Roughness values computed at different radii should not be compared as equivalent quantities.

3. Small radii are useful for fine-detail analysis but may be more sensitive to noise.
4. Larger radii reduce fragmented local variation but may emphasize broader geometric deviation.
5. Multi-scale analysis is preferable when the objective is to interpret both micro-scale texture and macro-scale surface behavior.

These recommendations are particularly relevant for reconstructed point clouds, where local point density and reconstruction noise may influence plane fitting. Reporting the neighborhood radius improves reproducibility and supports more reliable interpretation of roughness results.

D. Limitations

This study has several limitations. First, the analysis was conducted on a single reconstructed road segment. Additional datasets with different pavement materials, lighting conditions, and surface deterioration types would improve the generality of the findings. Second, the point cloud was reconstructed in normalized model units rather than metric-scaled units. Therefore, the roughness values should be interpreted comparatively within the same analysis framework rather than as absolute metric road roughness values. Third, no independent ground-truth reference such as a profilometer or laser scanner was used to validate absolute measurement error. Finally, the analysis focused on descriptive roughness behavior across radii; future work should include statistical testing and repeated datasets to quantify the robustness of the observed scale-dependent trends.

VI. CONCLUSION

This paper investigated the effect of neighborhood radius on point-to-plane roughness estimation for a reconstructed asphalt road surface. A COLMAP-derived road-surface point cloud was processed in CloudCompare, and roughness was computed at three neighborhood radii: 0.2, 0.4, and 0.6 model units.

The results show that neighborhood radius strongly affects both scalar-field appearance and mean roughness magnitude. At radius 0.2, the analysis was sensitive to fine-scale texture and local point-level variation. At radius 0.4, roughness patterns became more coherent while still preserving meaningful surface structure. At radius 0.6, the scalar field reflected broader surface undulation, and the mean roughness reached the highest value.

The findings confirm that point-cloud roughness should be interpreted as a scale-dependent descriptor rather than a fixed surface property. For image-based road monitoring, multi-scale roughness analysis provides a more complete understanding of surface geometry than single-radius evaluation. The study also highlights the need to report neighborhood radius clearly when using CloudCompare-based roughness computation for engineering applications.

Future work should apply the proposed analysis to additional road segments, metric-scaled reconstructions, ground-truth reference measurements, and statistical significance testing across repeated datasets.

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