

# Macro Texture Detection Method for Road Surface Based on Machine Vision

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**Abstract**— Road surface macro texture, characterized by surface irregularities with wavelengths ranging from 0.5 mm to 50 mm, plays a vital role in determining pavement performance and overall roadway safety. It significantly affects key functional aspects such as skid resistance, drainage capability, tire–pavement interaction, and noise emission. Conventional measurement techniques, including the sand patch test and laser profilometry, although precise, are limited by high operational costs, intensive labor requirements, and restricted spatial coverage. To address these limitations, this study investigates the application of machine vision as a non-contact and fully automated approach for quantitative macro texture evaluation. The proposed framework combines high-resolution imaging, advanced preprocessing methods, and machine learning algorithms, particularly convolutional neural networks (CNNs), to enable reliable extraction and classification of texture features from both two-dimensional and three-dimensional data sources. The integration of LiDAR and inertial measurement sensors further enhances measurement precision and system stability under varying environmental conditions. The results highlight the potential of such systems for real-time, vehicle-mounted surface inspection, offering superior scalability and cost-effectiveness compared to traditional methods. Despite persistent challenges related to environmental variability, data annotation, and computational complexity, machine vision–based solutions represent a promising advancement toward intelligent, data-driven, and sustainable management of road infrastructure.

**Keywords**— Macro texture, Machine vision, Road surface analysis, Cost-Effectiveness, Detection

## I. INTRODUCTION

Macro texture, defined as the surface roughness of pavement within a wavelength range of approximately 0.5 mm to 50 mm, plays a critical role in determining road safety and pavement performance. This texture directly influences essential factors such as water drainage, skid resistance, tire–pavement interaction, and overall driving safety. Conventional methods for evaluating macro texture, including the sand patch test and laser profilometry, provide reliable measurements; however, they are often constrained by high operational costs, labor-intensive procedures, and the requirement for direct contact with the pavement surface [1]. These limitations have prompted growing interest in alternative, non-contact assessment techniques. Machine vision, which integrates camera-based

imaging and advanced image-processing algorithms to analyze pavement surfaces, has emerged as a promising approach for automated macro texture evaluation. By capturing high-resolution surface images, machine vision systems enable rapid and extensive assessment of texture characteristics across large road networks, supporting efficient and continuous monitoring [2]. The integration of modern machine learning methods, particularly convolutional neural networks (CNNs), has further enhanced the precision and robustness of these analyses. Such systems offer adaptability, scalability, and real-time processing capabilities, making them highly suitable for large-scale infrastructure management. This study examines the evolution of machine vision as a transformative technology for macro texture detection, emphasizing its potential to advance road safety and infrastructure management through efficient, data-driven pavement assessment.

## II. LITERATURE REVIEW

Road surface texture, particularly macro texture, is a fundamental parameter in evaluating pavement performance, safety, and maintenance requirements. Macro texture characterizes the surface roughness at the millimeter scale, which directly affects water drainage efficiency, skid resistance, and the overall durability of the pavement. Recent advancements in machine vision technology have facilitated the emergence of automated, non-destructive techniques for detecting and analyzing road surface macro texture. This literature review examines the evolution of macro texture assessment methods, with an emphasis on machine vision–based approaches, their underlying methodologies, and the technical challenges that continue to shape this field.

### A. Overview of Macro Texture and Its Importance

Macro texture, generally ranging from 0.5 mm to 50 mm, plays a crucial role in both vehicle safety and pavement maintenance [1]. Previous research has demonstrated that macro texture characteristics directly influence tire–pavement interaction, thereby affecting parameters such as skid resistance, rolling resistance, and tire–pavement noise generation. Conventional measurement approaches, including the sand patch method and laser profilometry, have been widely used to quantify pavement macro texture. Although the sand patch method is simple and

cost-effective, it remains labor-intensive, operator-dependent, and susceptible to variability. In contrast, laser-based profilometers offer higher accuracy and repeatability but are constrained by high operational costs and limited spatial coverage, which reduces their practicality for large-scale assessments. These limitations have encouraged researchers to investigate machine vision-based techniques as a promising alternative for automated, accurate, and efficient macro texture characterization.

### B. Machine Vision in Pavement Texture Detection

Machine vision technology, which integrates cameras, image processing software, and advanced computational algorithms, has emerged as a promising alternative to traditional methods for texture measurement. Its fundamental principle lies in capturing high-resolution images of the pavement surface and subsequently applying image analysis algorithms to identify and quantify surface characteristics [3]. Recent studies have highlighted the capability of machine vision systems to detect and measure pavement macro texture with notable precision and efficiency.

#### 1. Early Development in Machine Vision for Road Texture:

The earliest applications of machine vision in pavement evaluation primarily centered on the detection and classification of cracks [4].

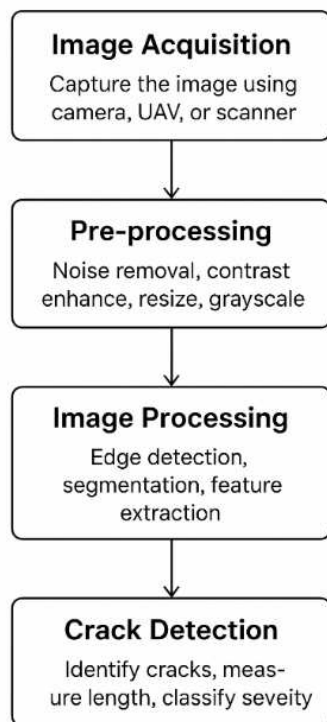


Figure 1. The architecture of image processing-based crack detection.

With subsequent advancements in camera resolution and image processing algorithms, researchers extended its use to the assessment of pavement macro texture. Initial methods typically employed grayscale imagery in conjunction with edge

detection techniques, most notably the Canny and Sobel operators, to extract surface texture characteristics.

**The Canny operator:** The Canny edge detection algorithm, introduced by John F. Canny in 1986, is widely regarded as one of the most effective methods for edge detection. Compared to earlier techniques, the Canny operator offers superior performance in identifying edges with high accuracy and minimal noise [5]. This algorithm utilizes a pair of  $3 \times 3$  convolution kernels, as illustrated in Figure 2.

|    |    |    |    |   |    |
|----|----|----|----|---|----|
| 1  | 2  | +1 | -1 | 0 | +1 |
| 0  | 0  | 0  | -1 | 0 | +1 |
| -1 | -2 | -1 | -1 | 0 | +1 |

Figure 2. The kernels of Canny operator

**The Sobel operator:** The Sobel operator, first introduced by Sobel in 1970, is a widely used edge detection technique that assigns greater weight to image pixels located closer to the center of the convolution mask [6]. This algorithm identifies edges at points where the intensity gradient reaches its maximum, following a defined criterion to determine the edge pixels within an image [7]. The Sobel method employs two  $3 \times 3$  convolution kernels to detect edges in both horizontal and vertical directions. To implement this algorithm, the image undergoes a filtering process using the designated kernels, beginning with the left kernel [8]. As a gradient-based operator, the Sobel method relies on the magnitude of intensity changes to identify edge features. Figure 3 illustrates the convolution kernels utilized in the Sobel edge detection algorithm.

|    |    |    |    |   |   |
|----|----|----|----|---|---|
| -1 | -1 | -1 | -1 | 0 | 1 |
| 0  | 0  | 0  | -2 | 0 | 2 |
| +1 | +1 | +1 | -1 | 0 | 1 |

Figure 3. The kernels of Sobel.

These approaches depended largely on the contrast generated by shadows and highlights formed by surface irregularities. Although they demonstrated a certain level of effectiveness, their performance was constrained by fluctuations in lighting conditions and the inherent difficulty of interpreting grayscale texture patterns.

#### 2. Advanced Imaging Techniques

The shift from traditional grayscale imaging to three-dimensional (3D) imaging represents a pivotal advancement in the field of macro texture detection. The introduction of techniques such as stereo vision and laser triangulation has

made it possible to accurately capture detailed 3D surface profiles of pavements [9].

Stereo vision systems, typically composed of two cameras positioned at distinct viewpoints, generate depth maps by analyzing disparities between the paired images. For instance, [10] utilized stereo vision technology to construct 3D surface models and compute key macro texture parameters, including Mean Profile Depth (MPD) and Mean Texture Depth (MTD) [11].

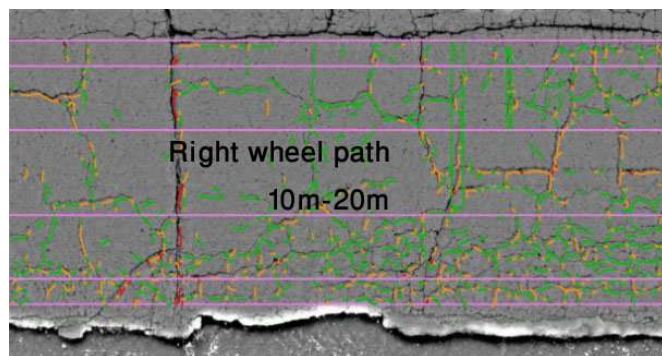


Figure 4. Example of an MPD outlier texture measurement caused by the presence of cracks.

Alternatively, laser triangulation methods employ a laser projector in conjunction with a camera to detect deformations in the projected laser line caused by surface irregularities. This technique enables highly precise texture quantification [12]. Despite their superior measurement accuracy, 3D imaging approaches remain expensive and technically demanding for large-scale or high-speed road surface monitoring. Requirements such as frequent calibration, specialized hardware, and controlled environmental conditions continue to limit their practical deployment on a broader scale.

### C. Machine Learning and Deep Learning Approaches

The convergence of machine learning (ML) and deep learning (DL) techniques with machine vision has significantly advanced the analysis of road surface conditions, enabling more accurate and adaptive texture characterization. Recent studies have demonstrated that ML algorithms, including support vector machines (SVMs) and decision trees, are effective in classifying pavement texture types and estimating macro-texture parameters derived from image-based features [13]. By training these algorithms on labeled datasets, it becomes possible to recognize intricate texture patterns and extract valuable insights from complex visual data.

#### 1. Deep Learning and Convolutional Neural Networks (CNNs)

Deep learning methodologies, particularly convolutional neural networks (CNNs), have achieved remarkable progress in the analysis of road surface textures owing to their capability to capture and learn hierarchical image features. A CNN, composed of multiple convolutional and pooling layers, is capable of discerning intricate texture details while maintaining robustness against noise and illumination variations. [14] proposed a CNN-based approach for road surface texture

classification that demonstrated high accuracy in differentiating various levels of macro texture. By training the model on a comprehensive and diverse collection of road imagery, their method exhibited strong generalization to real-world conditions, effectively overcoming several constraints associated with conventional image processing techniques.

#### 2. Hybrid Models and Data Fusion

Recent research has increasingly focused on hybrid approaches that integrate convolutional neural networks (CNNs) with auxiliary sensing technologies [15], such as laser scanners and inertial measurement units (IMUs), to enhance the accuracy and robustness of texture detection. The fusion of visual and complementary sensor data enables a more holistic understanding of road surface conditions. For instance, combining 3D laser scanning with 2D imagery has been demonstrated to significantly improve macro texture estimation, as the former offers precise depth information while the latter provides rich surface detail. By capitalizing on the unique advantages of each sensing modality, hybrid models achieve superior accuracy and reliability in macro texture detection compared to single-sensor approaches.

### D. Challenges in Machine Vision-Based Texture Detection

Despite advancements in technology, several challenges remain in deploying machine vision for macro texture detection on a large scale. These challenges include:

#### 1. Lighting and Environmental Conditions

Lighting conditions play a crucial role in determining the quality and reliability of image-based texture detection systems. Variations in illumination caused by factors such as sunlight intensity, shadow distribution, and atmospheric conditions can introduce inconsistencies in image quality, thereby reducing the accuracy of texture analysis. To address these challenges, researchers have developed various lighting normalization approaches, including adaptive histogram equalization and multi-exposure imaging [16]. More recently, advances in deep learning have led to the development of models trained on datasets encompassing a wide range of lighting conditions, resulting in improved robustness and generalization in real-world applications.

#### 2. Speed and Real-Time Processing

Another major challenge lies in achieving high-speed, real-time processing for road surface monitoring within dynamic traffic conditions. The use of high-speed cameras, coupled with optimized image-processing algorithms, is crucial to capture and analyze visual data without introducing motion blur or latency [17]. However, attaining true real-time performance remains difficult for deep learning models due to their substantial computational demands. To address this limitation, recent studies have explored edge computing and GPU acceleration as promising approaches for enhancing processing efficiency.

#### 3. Data Labeling and Model Generalization

Machine learning and deep learning models typically require substantial amounts of labeled data for effective training. The

process of collecting and annotating such data is often time-consuming and labor-intensive. Furthermore, the considerable variability in road surface types and conditions poses challenges for models to generalize effectively across diverse environments. To mitigate these issues, approaches such as synthetic data generation and transfer learning have been investigated. Transfer learning, in particular, enables models to be fine-tuned on specific datasets, thereby enhancing performance without necessitating extensive retraining.

### ***E. Future Directions and Emerging Trends***

Recent research on machine vision-based macro texture detection is increasingly focusing on the development of integrated, multimodal systems that leverage visual, depth, and additional sensor data. The combined use of LiDAR and infrared cameras, alongside conventional RGB imaging, provides a more comprehensive characterization of road surface conditions [18]. Furthermore, the emergence of autonomous and connected vehicle technologies offers the potential for large-scale, continuous monitoring of road infrastructure through vehicle-mounted machine vision systems. Advances in artificial intelligence (AI) further enhance texture detection, with federated learning approaches enabling models to be trained across multiple devices or vehicles. This decentralized training strategy improves model performance while preserving data privacy, thereby facilitating real-time, large-scale road monitoring and supporting the development of safer and more efficient transportation networks.

## **III. METHODOLOGY**

The methodology for assessing macro-texture on road surfaces through machine vision encompasses a systematic sequence of procedures, integrating image acquisition, preprocessing, and analytical techniques to obtain precise texture measurements. This non-contact, automated approach facilitates efficient evaluation of pavement conditions and is readily scalable for monitoring extensive infrastructure networks. The process typically involves three principal stages: data acquisition, image preprocessing, and subsequent texture analysis with feature extraction.

### ***A. Data Acquisition***

Data acquisition constitutes the initial stage of the process, wherein images of the road surface are captured using high-resolution cameras. These cameras are typically mounted on a vehicle to facilitate efficient data collection over extended distances and are strategically positioned to maintain a stable view of the pavement texture.

The deployment of high-speed or high-frame-rate cameras allows data acquisition at driving speeds, thereby minimizing motion blur and ensuring the capture of detailed surface textures. For enhanced depth measurement accuracy, certain systems employ stereo vision configurations, which utilize two cameras to capture images from distinct perspectives, or laser triangulation methods. Stereo vision systems generate three-dimensional surface profiles by analyzing the parallax between

images obtained from different viewpoints, whereas laser triangulation relies on projecting a laser line onto the surface and detecting its deformation with a camera to map surface irregularities. Both methodologies enable the computation of key texture parameters, such as Mean Profile Depth (MPD) and Mean Texture Depth (MTD), thereby providing precise three-dimensional representations of the pavement surface.

### ***B. Image Preprocessing***

Image preprocessing plays a critical role in standardizing and enhancing acquired images, thereby highlighting texture features and mitigating the influence of environmental factors such as variable lighting. Typical preprocessing approaches include the application of noise-reduction filters, such as Gaussian or median filters, which suppress high-frequency noise while preserving important edge information [19]. Edge detection algorithms, including Sobel and Canny operators, are commonly employed to delineate texture elements, such as aggregate particles and voids, which serve as key indicators of macro-texture. Additionally, contrast enhancement techniques, such as adaptive histogram equalization, are frequently utilized to improve the visibility of surface features under diverse illumination conditions. To further address lighting inconsistencies arising from sunlight or vehicle shadows, shadow removal and normalization procedures may be applied, ensuring that the images provide a uniform representation of the road surface.

### ***C. Texture Analysis and Feature Extraction***

Texture analysis represents a critical stage in pavement evaluation, wherein texture characteristics are quantitatively assessed to determine macro texture quality. Conventional approaches typically involve the measurement of Mean Profile Depth (MPD) and Mean Texture Depth (MTD), which serve as standardized indicators of road surface texture, providing insights into pavement roughness and water drainage capacity. For three-dimensional data obtained via stereo vision or laser triangulation, MPD and MTD are derived by analyzing surface profiles in each image frame [20]. In contrast, for two-dimensional image data, alternative metrics such as grayscale variance, fractal dimensions, or other statistical measures are often employed to approximate surface roughness.

Recent advances have seen the integration of machine learning and deep learning techniques to improve the precision of texture analysis. Convolutional Neural Networks (CNNs) are particularly effective in this context, as they can automatically extract complex features pertinent to macro texture classification and quantification. By training CNNs on extensive datasets of labeled road surface images, these models can identify patterns in texture and categorize surfaces according to roughness levels, such as high or low. When supported by large and diverse training datasets, CNNs demonstrate strong generalization capabilities across varying pavement types and environmental conditions, thereby enhancing robustness [21].

Moreover, emerging methodologies increasingly leverage data fusion approaches, integrating information from multiple

sensors to achieve more comprehensive texture assessment. For instance, LiDAR can provide detailed three-dimensional surface profiles, which, when combined with visual data from cameras, yield a more precise characterization of macro texture. Inertial measurement units (IMUs) offer complementary information by capturing vibrations associated with pavement roughness, further enriching the analysis. Such hybrid strategies improve detection accuracy, reduce dependence on any single data source, and increase resilience to varying environmental conditions.

#### IV. EXPECTED RESULTS

**High-Resolution Texture Measurement:** The system is required to accurately quantify road macro-texture characteristics, including Mean Profile Depth (MPD) and Mean Texture Depth (MTD), based on captured images. By analyzing these parameters, the system can assess surface roughness, providing a comprehensive understanding of texture variations that influence skid resistance and water drainage factors that are critical for vehicle safety.

**Automated Detection and Classification:** By leveraging advanced machine learning techniques, particularly convolutional neural networks (CNNs), the proposed system can automatically identify and classify road surface textures. When trained on diverse and representative datasets, CNNs are capable of distinguishing between various texture types and surface roughness levels. This automated classification facilitates the identification of pavement sections that require maintenance, thereby reducing the need for manual inspection and significantly shortening assessment time.

**Real-Time Processing and High-Speed Operation:** The system must be capable of processing images in real time, facilitating deployment on moving vehicles at typical road inspection speeds. This functionality allows for continuous monitoring of extensive road networks without disrupting traffic or necessitating road closures, representing a substantial improvement over conventional contact-based inspection methods.

**Adaptability to Varying Conditions:** Machine vision systems frequently encounter performance limitations due to environmental variations, including changes in lighting and adverse weather conditions. To address these challenges, robust operation under diverse conditions can be achieved through adaptive preprocessing strategies, such as contrast enhancement and illumination normalization. Moreover, incorporating data fusion techniques that integrate supplementary sensor information, for example, from LiDAR or inertial measurement units (IMUs), has been shown to enhance detection accuracy and increase system resilience to external disturbances.

**Scalability and Cost-Effectiveness:** Ultimately, the system must demonstrate both scalability and cost-effectiveness to facilitate extensive deployment across large-scale infrastructure networks. By minimizing the need for direct physical contact with the pavement and leveraging rapid data processing capabilities, the system can substantially reduce

operational costs, thereby enabling practical implementation for routine road maintenance and safety evaluations.

#### V. CONCLUSION

This study underscores the transformative potential of machine vision for the quantitative assessment of road surface macro texture. By integrating high-resolution imaging techniques, advanced preprocessing algorithms, and deep learning frameworks, particularly convolutional neural networks (CNNs), the proposed approach provides a non-contact, efficient, and scalable alternative to conventional texture evaluation methods. The synergistic fusion of visual data with LiDAR and inertial sensor inputs enhances measurement accuracy and facilitates real-time analysis suitable for vehicle-mounted inspection systems. Beyond improving cost and labor efficiency, this framework supports proactive infrastructure maintenance and promotes road safety through continuous, data-driven monitoring. Nonetheless, challenges remain in addressing variations in lighting and environmental conditions, as well as the extensive data requirements associated with deep learning model training. Future research should focus on multi-sensor data fusion, the application of edge computing for rapid on-site processing, and the development of adaptive learning models capable of generalizing across diverse pavement conditions. Overall, machine vision constitutes a critical step toward intelligent, sustainable, and fully automated road management systems.

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