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DETECTION OF VEHICLE BODY AND GEOMETRIC DEVIATIONS USING CORRECTED OPTICAL MEASUREMENTS IN AUTOMOTIVE SERVICE ENVIRONMENTS

Evgeny Popov [1]

[1] Researcher in Optical Metrology and Automotive Diagnostic Systems, LLC "Meid 2000", Moscow, Russia

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Abstract

Reliable detection of vehicle body and geometric deviations in automotive service environments remains a challenging task due to unstable measurement conditions and heterogeneous surface properties. While optical diagnostic systems are widely used for non-contact inspection, their accuracy strongly depends on the quality and stability of primary measurements. In this paper, I present methods for detecting vehicle body geometry deviations based on optically measured data obtained after adaptive geometric and photometric correction. The proposed approach operates on stabilized optical measurements and focuses on identifying geometric inconsistencies in body panels and aerodynamic components, including vehicles with modified or non-standard geometry. Experimental results demonstrate that the use of corrected optical measurements significantly improves detection accuracy, repeatability, and robustness compared to uncorrected measurements. The presented methods enable consistent geometric diagnostics under real service conditions and provide a practical basis for subsequent feature-level analysis and decision-making systems in automotive cyber-physical architectures.

Keywords: *Optical diagnostics; vehicle geometry; body deviation detection; measurement correction; automotive service; computer vision*

1. Introduction

Accurate assessment of vehicle body geometry is a critical task in automotive service diagnostics, directly affecting safety, aerodynamic performance, and long-term structural integrity. Optical measurement systems are increasingly employed for this purpose due to their non-contact nature and ability to capture complex surface geometry at high spatial resolution. However, in real service environments, optical diagnostics are subject to variable illumination, sensor repositioning, and surface heterogeneity. These factors introduce measurement instability that limits the reliability of geometric deviation detection across repeated inspections. As a result, small but diagnostically significant deviations may be masked by measurement noise or falsely detected due to environmental artifacts. Recent advances in adaptive calibration and distortion correction address the stability of primary optical measurements under non-structured conditions. Building on these developments, this work focuses on the next stage of the diagnostic pipeline: reliable detection of geometric deviations using corrected and uncertainty-aware optical data.

2. Problem Definition and Measurement Model

I represent the corrected optical measurement as a set of spatial points describing the observed vehicle surface. The diagnostic task consists of identifying deviations between the measured geometry and an expected reference representation. In automotive service conditions, reference geometry may correspond to nominal factory geometry, pre-repair or baseline measurements, or a statistically derived reference model obtained from multiple observations. The primary challenge lies in distinguishing true geometric deviations from residual measurement uncertainty, particularly for vehicles with modified body panels, aftermarket components, or altered aerodynamic configurations. To formalize this task, I define the deviation field D as the Mahalanobis-like distance between the corrected point cloud C and the reference manifold M, constrained by the local uncertainty covariance Σ estimated during the correction stage. For any measured point $c \in C$, the local deviation is expressed as:

$$D(c, M) = \min_{m \in M} (c - m)^T \Sigma^{-1} (c - m)$$

This formulation ensures that the detection process accounts for heteroscedastic noise patterns inherent in optical scanning.

3. Optical Measurement After Adaptive Correction

The methods presented in this study assume that primary optical measurements have undergone adaptive geometric and photometric correction. This correction stabilizes spatial relationships and suppresses illumination-induced artifacts, providing a consistent basis for geometric analysis. Corrected measurements exhibit improved spatial coherence across repeated scans, reduced sensitivity to changes in illumination and viewing angle, and explicitly controlled measurement uncertainty. These properties are essential for reliable deviation detection, especially when the magnitude of geometric deviations is small relative to overall vehicle dimensions. By establishing a virtual metrological frame, the system ensures that measured coordinates remain invariant even when the sensor undergoes minor repositioning or micro-movements during the scanning process. This stability is particularly critical when analyzing high-gloss surfaces or dark paints, where photometric artifacts typically degrade the signal-to-noise ratio of geometric features.

4. Detection of Geometric Deviations

4.1 Deviation Representation

Geometric deviations are represented as spatial differences between the corrected measured surface and a reference geometry. Depending on the diagnostic task, deviations may be evaluated locally at the level of individual body panels or globally at the level of overall body alignment. Local deviations are critical for identifying impact damage, deformation, or assembly defects, while global deviations indicate structural warping, chassis misalignment, or cumulative effects of repairs and modifications.

4.2 Comparison Strategy

Deviation detection is performed using spatial alignment followed by point-to-surface distance evaluation. I employ a robust Iterative Closest Point (R-ICP) algorithm with uncertainty-aware and photometric weighting to ensure that high-glare or low-confidence regions do not distort the alignment process. Non-rigid alignment is applied when reference geometry does not correspond to the current configuration of the vehicle, such as in vehicles with modified suspension systems or non-standard aerodynamic components.

4.3 Thresholding and Significance Assessment

Detected deviations are evaluated against uncertainty-aware thresholds derived from the local metrological stability index. This approach prevents false detections caused by residual measurement noise and ensures that only diagnostically meaningful deviations are reported.

5. Experimental Evaluation

I evaluated the proposed methods under real automotive service conditions using vehicles with standard geometry as well as vehicles equipped with modified body components. The experimental setup involved multiple scanning cycles under varying ambient light levels ranging from 200 to 1500 lux. The results indicate that corrected measurements substantially reduce false-positive deviation detection by filtering out ghost geometries induced by specular reflections. Repeatability across measurement sessions is significantly improved, with a standard deviation of geometric residuals reduced by a factor of three compared to raw optical data. Quantitatively, the system demonstrated the ability to resolve deviations as small as 0.35 mm on high-gloss surfaces, whereas uncorrected optical measurements failed to reliably distinguish deviations below 1.2 mm.

6. Discussion

The results demonstrate that reliable detection of vehicle body deviations is achievable only when geometric analysis is performed on stabilized and uncertainty-aware optical measurements. Adaptive correction does not merely improve measurement quality; it fundamentally enables consistent geometric diagnostics in non-structured service environments. By incorporating the uncertainty covariance into the deviation model, the system bridges the gap between raw computer vision data and metrological standards.

7. Conclusion

This paper presents methods for detecting vehicle body and geometric deviations using corrected optical measurements in automotive service environments. By operating on stabilized and uncertainty-aware data, the proposed approach achieves improved accuracy, repeatability, and robustness compared to traditional optical diagnostics. The results confirm that adaptive correction is a prerequisite for reliable geometric deviation detection and establish a foundation for subsequent diagnostic stages, including feature-level analysis and decision-support systems within automotive cyber-physical frameworks.

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Contact: evgpopov.msk@gmail.com