

Continuous Attitude Measurement and Digital Twin Modeling of High-Speed Circular Test Tracks Based on Tightly Coupled RTK-GNSS/IMU

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Abstract: To overcome the difficulty of traditional methods in achieving continuous geometric state inspection of curved and transition sections on high-speed circular test tracks in automotive proving grounds, this paper proposes a vehicle-borne continuous kinematic attitude measurement method based on tightly coupled Real-Time Kinematic Global Navigation Satellite System and Inertial Measurement Unit integration. With four circular test tracks at the Beijing Automotive Reliability Standard Proving Ground as a case study, a mean three-axis attitude digital twin model for each track was constructed via adaptive extended Kalman filtering and 0.2 m spatial resampling. The digital twin accurately records the geometric state of each track and can be automatically updated with each inspection, enabling dynamic monitoring of track geometry. Results show that the roll angle amplitudes of the four tracks follow a power-law relationship with the median design speeds, consistent with superelevation design principles. The pitch angle standard deviation increases from 0.057° on the innermost track to 0.394° on the outermost, indicating stronger longitudinal profile excitation at higher speeds. Complementary International Roughness Index and Riding Quality Index measurements, independently acquired by a laser profilometer, characterize pavement conditions from dimensions beyond the digital twin's attitude output. Over a total driving time of approximately 15 minutes across the four tracks, the proposed method captured over 72000 valid spatial attitude measurement points, providing a feasible solution for rapid periodic inspection of test track geometric states.

Keywords: Digital Twin; Continuous Kinematic Attitude Measurement; Adaptive Extended Kalman Filter; Circular Test Track, International Roughness Index

1. Introduction

The circular high-speed lanes in automotive reliability standard proving grounds serve as critical sites for vehicle durability testing, tire evaluation, and active safety system calibration. Geometric parameters such as superelevation, longitudinal slope, and pavement roughness must be regularly inspected and compared with design values [1]. Compared with ordinary highways, circular test tracks exhibit more extreme geometric characteristics, including smaller curve radii, larger superelevation slopes ($\geq 30^\circ$), and continuously curved and transition sections. Traditional inspection methods cannot effectively characterize the full geometric state of such tracks: total stations provide high accuracy but rely on discrete points, making continuous geometric description of curved and transition sections difficult; laser profilometers and survey vehicles can capture longitudinal profile data but are insensitive to curve superelevation and involve high equipment costs [2].

Digital twin (DT) technology maps the real-time state of physical objects to digital models, enabling structural state awareness and prediction. In recent years, it has been widely applied in infrastructure monitoring of bridges [3], tunnels [4], and pavement management [5]. Tao et al. [6] summarized the functional structure of digital twins as a closed-loop framework of “perception, analysis, decision, execution,” which informs the methodology of this study. In the field of road infrastructure,

Talaghat et al. [7] proposed a complete conceptual framework and blueprint for road pavement digital twins and validated it on real roads. Kaewunruen et al. [8] extended digital twins to the full lifecycle of bridge infrastructure, including operation, maintenance, and demolition decisions. Yin et al. [9] designed a distributed twin framework for highway systems to address data fragmentation across systems. However, digital twin modeling of standard proving ground circular tracks remains unexplored. The strong curvature and large superelevation of such tracks not only limit the application of conventional measurement methods but also pose great challenges to digital modeling and evaluation [10,11].

In recent years, vehicle-borne tightly coupled RTK-GNSS/IMU systems have become a basic sensor configuration for intelligent connected vehicles, enabling continuous three-axis attitude and three-dimensional trajectory measurement and output under normal driving conditions. For attitude estimation, Crassidis et al. [12] systematically reviewed nonlinear attitude estimation theory; Sun et al. [13] compared extended Kalman filter (EKF), unscented Kalman filter (UKF), and particle filter methods for GNSS/IMU integration; Zheng et al. [14] proposed an LSTM-assisted adaptive Kalman filter to improve positioning accuracy under complex maneuvers. At the engineering application level, Sun et al. [15] combined GA-BP neural networks with tightly coupled GNSS RTK/IMU integration to handle challenging urban navigation scenarios. Cheng et al. [16] proposed a multi-sensor interactive multi-model error-state Kalman filter fusion scheme for ADAS test platform vehicles, achieving good attitude estimation accuracy in proving ground tests. For pavement geometric inspection, Alatoom and Smadi [17] used IMU-pulsed coherent radar sensor fusion for low-cost pavement roughness evaluation; Alessandrini et al. [18] demonstrated smartphone-based crowdsensing for road surface condition monitoring. Mobile laser scanning has become an important tool for fine-scale pavement geometry inspection owing to its high-resolution 3D point cloud acquisition. Tri Saksena and Adikusuma [19] compared the consistency of International Roughness Index (IRI) measurements between mobile laser scanner (Leica Pegasus TRK 700 Evo) and the Dipstick method; Yadav et al. [20] proposed a mobile

solid-state LiDAR-based pavement roughness analysis method for economical large-area periodic inspection. Nevertheless, a method for continuous geometric state description of standard proving ground circular tracks is still missing.

This study addresses the following question: can a vehicle-borne RTK-GNSS/IMU system be used during regular driving and testing to simultaneously construct a three-axis attitude digital twin model of standard proving ground circular tracks, enabling low-cost, high-frequency periodic inspection of track geometric state? The main contributions are: (1) a continuous linear measurement scheme for curved and transition sections of circular tracks is proposed, integrating tightly coupled RTK-GNSS/IMU with 0.2 m spatial resampling to build a three-axis attitude mean-field digital twin model; (2) based on field data from four service tracks of a standard proving ground, a power-law relationship between roll angle amplitude A_ϕ and design speed v is quantitatively revealed ($R^2=0.998$), providing a data basis for superelevation consistency inspection; (3) the complementarity between the continuous attitude field and laser profilometer IRI data is analyzed, clarifying the applicable scenarios and information dimensions of the two measurement approaches.

2. Study Site and Equipment

2.1 Overview of the Standard Proving Ground and Track Parameters

The research object is four concentric circular test tracks (Road 1-4) in the Beijing Daxing District automotive reliability standard proving ground, with design speeds increasing from inner to outer tracks. Key geometric parameters of each track - curve radius, superelevation value, and spiral curve length - were precisely controlled during design and construction [21]. The basic parameters of each track (design speed range, effective test mileage, and data scale) are shown in Table 1. For Road 4, the representative design speed is taken as the lower bound of the stated range (160 km/h) for calculation purpose. The effective mileage of Road 4 is only 40% - 50% of the other three tracks because the outer track straight section exceeded the mileage cutoff range for this data acquisition. The four tracks together yield 72540 effective data points, covering the complete design condition spectrum

from inner low-speed to outer high-speed tracks.

Table 1. Basic Parameters and Data Acquisition Scale of Each Circular Track

Track	Design speed (km/h)	Median of speed interval (km/h)	Effective mileage (m)	Effective data (0.2 m spacing)	Number of runs
Road 1:inner	60~95	77.5	4017	20085	10
Road 2:middle-inner	90~110	100.0	4339	21695	8
Road 3:middle-outer	120~155	137.5	4219	21095	9
Road 4:outer	≥160	160.0	1933	9665	4

2.2 Data Acquisition Equipment

The data acquisition equipment uses a vehicle-borne RTK-GNSS/IMU integrated navigation system. The main sensor parameters are as follows: GNSS receiver supports BeiDou B1/B2/B3, GPS L1/L2/L5, and GLONASS L1/L2 multi-constellation signals, with horizontal positioning accuracy better than 20 mm + 1 ppm in fixed solution mode; IMU is a tactical-grade fiber optic gyro inertial navigation unit with gyro bias stability better than 0.02 °/h and accelerometer bias stability better than 50 μg, with attitude update rate of 100 Hz. The system adopts a tightly coupled RTK-GNSS/IMU configuration [22], enabling simultaneous estimation of navigation parameter errors and sensor systematic errors.

Test vehicles started from designated starting points of each track and drove clockwise at the corresponding design speeds. The same track was tested multiple times on different dates. During testing, GNSS signal quality was high, with fixed solution ratio exceeding 95% throughout. Brief signal losses occurred no more than three times (high-voltage line occlusion, each lasting no more than 2s), and data from loss periods were removed in post-processing.

IRI and Riding Quality Index (RQI) data for each track were independently collected by a professional laser profilometer survey vehicle. IRI was calculated with 10 m as the calculation unit [23]; RQI was converted from IRI according to the relevant evaluation standard [24] and summarized every 100 m. Laser profilometer data provide independent comparison for high-precision calibration information, serving as an external verification reference for the attitude output of the digital twin model.

3. Research Methodology

3.1 Adaptive Extended Kalman Filter

The original 100 Hz RTK-GNSS/IMU data undergo adaptive extended Kalman filter (AEKF) post-processing to improve attitude solution

accuracy. A standard 15-dimensional error state vector is adopted [22], including attitude error, velocity error, position error, gyroscope three-axis bias, and accelerometer three-axis bias, each with three components:

$$\mathbf{x}_k = [\varphi^T, \delta \mathbf{v}^T, \delta \mathbf{r}^T, \mathbf{b}_g^T, \mathbf{b}_a^T]^T \in \mathbb{R}^{15} \quad (1)$$

where φ is the three-dimensional attitude error vector, $\delta \mathbf{v}$ the three-dimensional velocity error vector, $\delta \mathbf{r}$ the three-dimensional position error vector, $\mathbf{b}_g$ and $\mathbf{b}_a$ the gyroscope and accelerometer three-axis bias vectors respectively, and superscript T denotes transpose. The constructed tightly coupled GNSS/IMU configuration allows simultaneous estimation of navigation parameter errors and sensor systematic errors.

AEKF maintains a sliding window on the innovation sequence to adaptively adjust the process noise covariance matrix $\mathbf{Q}_k$, addressing non-stationary noise during testing. The innovation covariance matrix $\mathbf{C}_k$ is calculated using a sliding window of length N:

$$\mathbf{C}_k = \frac{1}{N} \sum_{i=k-N+1}^k \mathbf{e}_i \mathbf{e}_i^T \quad (2)$$

where $\mathbf{e}_i$ is the innovation vector at step i . The adaptive scaling factor γ_k is determined by the ratio of the trace of the actual innovation covariance to the theoretical innovation covariance $\mathbf{S}_k$:

$$\mathbf{Q}_k = \gamma_k \cdot \mathbf{Q}_0 \quad (3)$$

$$\gamma_k = \max \left(1, \frac{\text{tr}(\mathbf{C}_k)}{\text{tr}(\mathbf{S}_k)} \right) \quad (4)$$

$$\mathbf{S}_k = \mathbf{H}_k \mathbf{P}_k^* \mathbf{H}_k^T + \mathbf{R}_k \quad (5)$$

Here, $\mathbf{Q}_0$ is the initial process noise covariance matrix, $\mathbf{H}_k$ the measurement matrix, $\mathbf{P}_k^*$ the prior state estimate covariance matrix, and $\mathbf{R}_k$ the measurement noise covariance matrix. The lower bound of γ_k is set to 1, ensuring the filter does not reduce process noise estimation accuracy under normal conditions; when external disturbances cause actual innovation to exceed theoretical expectations, γ_k automatically increases to enhance the weight of recent measurements. In practice, the peak value of γ_k during brief GNSS signal occlusion is approximately 3-5, while $\gamma_k \approx 1$ during

constant-speed driving.

3.2 Spatial Resampling and Mean-Field Construction

The AEKF-filtered attitude time series are smoothed by a 1s moving average to remove high-frequency jitter caused by vehicle vibrations. Because the vehicle speed varies among different runs, the spatial spacing of the original time series is non-uniform (approximately 20-50 mm). Resampling is performed along the travel distance direction with a step size of 0.2 m. For each target distance position, the sample point with the nearest distance deviation is selected from all available runs, and the mean value is taken as the representative attitude value at that position.

The step size is selected based on the following considerations: (1) it is much larger than the GNSS single-point positioning uncertainty, ensuring no overlap or confusion between adjacent sampling points; (2) it is smaller than the minimum characteristic wavelength of spiral curve sections, thus sufficient to capture the geometric variation patterns of superelevation transition sections; (3) multi-run averaging compresses single-run random errors to the order of $1/\sqrt{n}$ (where n is the number of runs). The inter-run standard deviation of multi-run attitude values at the same position is less than 5% (see Section 4.4), verifying the effectiveness of the resampling strategy.

3.3 Power-Law Relationship Fitting

Using the median value of the design speed interval of each track as the independent variable and the roll angle amplitude A_ϕ as the dependent variable, a double-logarithmic linear regression (i.e., least-squares straight line fitting in log-log space) is performed on the four data points, which is equivalent to estimating the parameters of the power function:

$$A_\phi = a \cdot v^b \quad (6)$$

The fitting yields $a=8.23 \times 10^{-8}$, $b=3.82$, $R^2=0.998$. Here A_ϕ is in degrees, v in km/h, a is the scaling coefficient, and b the power exponent. The coefficient of determination R^2 is calculated in log-log space, indicating that the power-law model explains 99.8% of the logarithmic variation of the four data points. With only four sample points, the extrapolation capability of the fitted curve is constrained to the sample range; the fitting is based on the median design speeds

of the test tracks (77.5, 100.0, 137.5, 160.0 km/h), and the regression curve provides good interpolation accuracy within this interval.

4. Results

4.1 Roll Angle Distribution of Each Circular Track

The roll angle mean-field profiles along travel distance for the four tracks are shown in Figure 1. Through aggregation of multi-run data at 0.2 m spatial nodes, the physical track superelevation distribution is mapped to a quantifiable digital geometric reference profile.

The inner track Road 1 has a roll angle ranging from -1.76° to -0.92° , with $\sigma_\phi=0.14^\circ$, indicating a nearly horizontal road surface and a weak superelevation effect. Road 2 expands to -5.98° to -1.00° with $\sigma_\phi=1.90^\circ$; the difference between curved and straight sections is already clearly distinguishable. Road 3 exhibits a range of -23.29° to -0.89° with $\sigma_\phi=9.38^\circ$, showing a very significant superelevation effect. Road 4 reaches a maximum roll angle of 33.96° and $\sigma_\phi=13.66^\circ$, far exceeding ordinary highway superelevation limits ($\leq 8\%$), reflecting the special requirements of high-performance testing in proving grounds. The mean roll angles of the four tracks are negative, indicating that the tracks are inclined toward the inside of the circle (positive superelevation), consistent with engineering design for curve-driving stability.

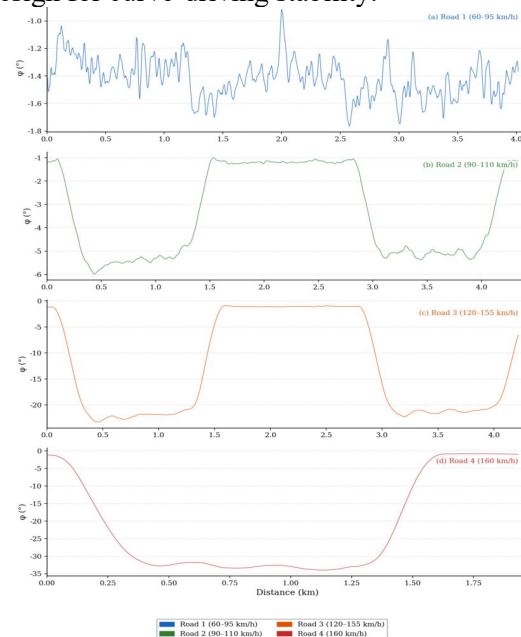


Figure 1. Mean-Mield Roll Angle Profiles of the Four Circular Tracks: (a) Road 1, (b) Road 2, (c) Road 3, (d) Road 4

From a mechanical perspective, the centrifugal force balance equation for curve driving is:

$$F_c = \frac{mv^2}{R} = mg \tan \phi \quad (7)$$

The maximum roll angle of Road 4 corresponds to $\tan(33.96^\circ) \approx 0.674$, meaning that about 67% of the gravitational component provides centripetal force, meeting the extreme requirement of 160 km/h high-speed driving on the outer track.

4.2 Three-Axis Attitude Profiles

Taking Road 2 as a representative, the complete profiles of three-axis attitude (roll angle ϕ , pitch angle θ , heading angle ψ) versus travel distance are shown in Figure 2. These illustrate the multi-dimensional geometric information contained in the digital twin model: roll angle records the spatial distribution of curve superelevation, pitch angle reflects low-frequency geometric features of the longitudinal profile, and heading angle encodes track curvature. Together they provide a three-dimensional geometric description of the track, which is not attainable from single-axis inspection.

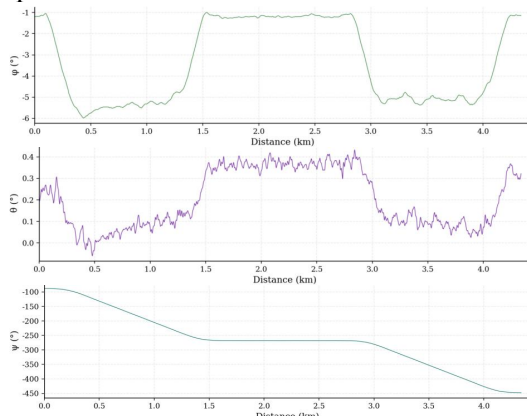


Figure 2. Three-Axis Attitude Mean-Field Profiles for Road 2: (a) Roll Angle, (b) Pitch Angle, (c) Heading Angle

The roll angle profile exhibits periodic fluctuations synchronized with curve curvature changes: the angle increases in curved sections and returns to near zero in straight sections. The pitch profile amplitude is smaller than that of the roll angle, fluctuating in the range of -0.06° to 0.43° , indicating relatively gentle longitudinal slope variations with an overall gentle uphill trend. The heading angle profile is a continuously accumulated heading angle, monotonically decreasing from approximately -88° at the start to approximately -448° at the end, with a total rotation of approximately 360° , consistent with one lap of the circular track. The

absolute angular rate of the heading angle is proportional to the theoretical curvature $1/R$ of the track - higher in curved sections and lower in straight sections - validating the reliability of the navigation solution.

4.3 Power-Law Relationship between Roll Angle Amplitude and Design Speed

The scatter relationship between the roll angle amplitude A_ϕ of each track and the median design speed v , together with the power-law curve fitted according to Equation (6), is shown in Figure 3. The four data points ($v=77.5, 100.0, 137.5, 160.0$ km/h; $A_\phi=1.41, 3.37, 12.81, 21.50^\circ$) fall on a straight line in log-log coordinates, with $R^2=0.998$.

Equation (6) describes an empirical relationship between measured vehicle body roll angle amplitude and design speed, rather than a mechanical prediction of the pavement superelevation angle. It is composed of three superimposed contributions: (1) the pavement design superelevation angle, which follows the centrifugal force balance law v^2/R ; (2) additional body roll angle induced by the suspension system under large lateral acceleration, which increases nonlinearly with speed; (3) trajectory offset effects due to tire lateral slip. The curve radii of the four tracks increase from the inner to the outer track, so the design superelevation angles do not simply increase in the same proportion – larger radii require smaller superelevation for a given speed. This geometric factor further enhances the nonlinear variation of A_ϕ with track order. Therefore, the exponent $b=3.82$ serves as a comprehensive fitting index reflecting the coupled effects of pavement superelevation, suspension dynamics, and track geometry on body roll, providing a baseline reference for multi-track superelevation consistency inspection.

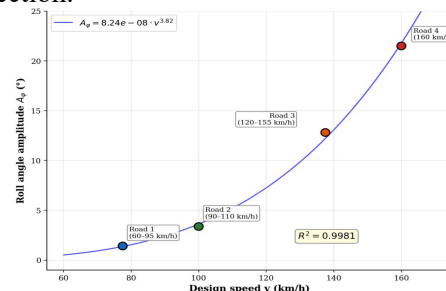


Figure 3. Power-Law Relationship between Roll Angle Amplitude A_ϕ and Design Speed V (Log-Log Coordinates)

4.4 Inter-Track Variation of Pitch Angle Standard Deviation

Table 2. Attitude Characteristics of the Digital Twin Model and Measured IRI/RQI for Each Track

Track	$\varphi_{\text{range}} (^{\circ})$	$\sigma_{\varphi} (^{\circ})$	$A_{\varphi} (^{\circ})$	$\sigma_{\theta} (^{\circ})$	IRI mean (m/km)	σ_{IRI} (m/km)	RQI mean
Road 1	-1.76~-0.92	0.14	0.42	0.057	1.58	0.54	92.87
Road 2	-5.98~-1.00	1.90	3.37	0.135	3.02	0.85	83.07
Road 3	-23.29~-0.89	9.38	12.81	0.394	3.24	1.13	80.19
Road 4	-33.96~-0.77	13.66	21.50	0.389	3.03	0.96	82.58

The pitch angle standard deviation σ_{θ} increases monotonically from 0.057° on Road 1 to 0.394° on Road 3, and remains at 0.389° on Road 4, indicating that the longitudinal profiles of Road 3 and Road 4 excite the vehicle body to a similar degree. This trend partially corresponds to the variation pattern of IRI, but the consistency is not complete. The IRI of Road 4 is lower than that of Road 3, while σ_{θ} is close to that of Road 3, suggesting that σ_{θ} cannot directly replace IRI as a quantitative indicator of pavement roughness. Instead, the two reflect pavement conditions from different physical mechanisms (σ_{θ} represents low-frequency vehicle body vibration response, while IRI represents the displacement integral of a standard quarter-car model). Their combined use provides complementary information.

4.5. Spatial Frequency Spectrum Analysis

To separate systematic design components from local random disturbances in the track geometric features, a spatial frequency domain decomposition method is applied, a mean-removed fast Fourier transform (FFT) analysis of the roll angle profiles. This analysis decouples the original angle signal into two parts: low-frequency components mainly corresponding to systematic geometric forms such as curve superelevation design, and medium-high frequency components attributed to random deviations from local pavement unevenness. The spatial frequency spectrum characteristics of the mean-field profiles are shown in Figure 4.

The spatial power spectra show that the main peaks of all four tracks are located in the low-frequency band, and the power decays rapidly as frequency increases, reflecting the low-frequency spatial periodic nature of the roll angle signal dominated by curve superelevation. For Roads 2-4, the main peak height accounts for more than 99.9 % of the total power spectrum, with a drop of more than three orders of magnitude between the main peak and the

The main attitude statistics of the digital twin model, together with the measured IRI and RQI data for each track, are summarized in Table 2.

mid-frequency band; local bulges in the mid-frequency band do not constitute significant spatial periodic components. Road 1 exhibits a distinct spectral shape: the main peak power ratio drops to 70.8 %, while the mid-frequency band (0.01-0.05 cycle/m) contributes 16.5 % of the power, and the spectrum shows a broadened shape instead of a sharp convergence. This difference arises because the inner track has shorter curved sections and more frequent superelevation changes, superimposing additional fluctuation components onto the roll angle profile at spatial scales of 20-100 m. For all four tracks, the power in the high-frequency band (above 0.1 cycle/m) approaches zero, indicating that the 1s moving average smoothing effectively filtered out short-wavelength high-frequency vibrations.

4.6. IRI/RQI Distribution Characteristics

The measured IRI distributions of each track obtained by the laser profilometer are shown as histograms in Figure 5. The IRI distributions of the four tracks show clear gradient differences. Road 1 has a mean IRI of 1.58 m/km, with the histogram concentrated below 1.5m/km; only 0.7 % of the segments exceed 3.5 m/km, indicating the best pavement smoothness and high spatial uniformity. Roads 2-4 have mean IRI values in the range of 3.02-3.24 m/km, approximately twice that of Road 1. Their histograms are obviously shifted to the right, with the proportions of segments exceeding 3.5 m/km being 24.0 % for Road 2, 27.8 % for Road 4, and 32.8 % for Road 3. Road 3 shows the widest histogram distribution, with a maximum IRI of 7.94 m/km and a standard deviation of 1.13 m/km, which is higher than those of Road 2 and Road 4, indicating that the spatial variability of pavement smoothness is largest on Road 3, with alternating sections of relatively good and poor smoothness. Road 4 has a standard deviation of 0.96 m/km, between those of Road 2 and Road 3, suggesting a moderate level of

spatial heterogeneity in the high-speed outer track.

The RQI values follow the same general trend as IRI: Road 1 (92.87) is the highest, Road 3 (80.19) the lowest, and Road 4 (82.58) is higher than Road 3. This is because RQI is converted from

IRI using a nonlinear formula according to the relevant evaluation standard [24]; the conversion slope is steeper in the 3.0-3.5 m/km range, so small differences in IRI are amplified into more pronounced differences in RQI.

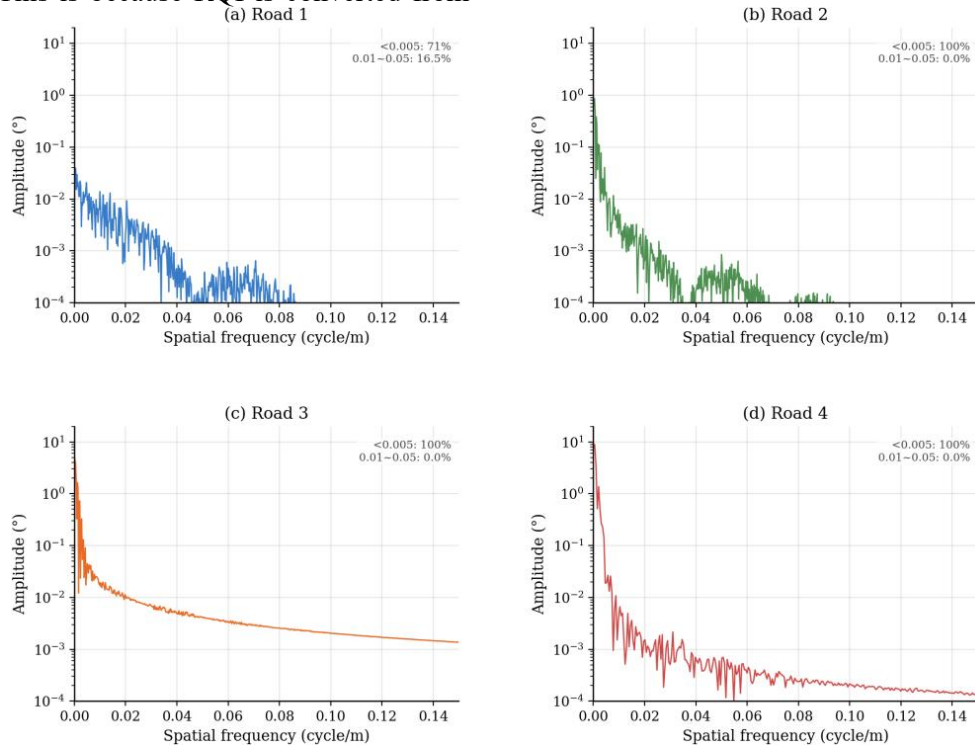


Figure 4. Spatial Power Spectra of Roll Angle for Each Track: (a) Road 1, (b) Road 2, (c) Road 3, (d) Road 4

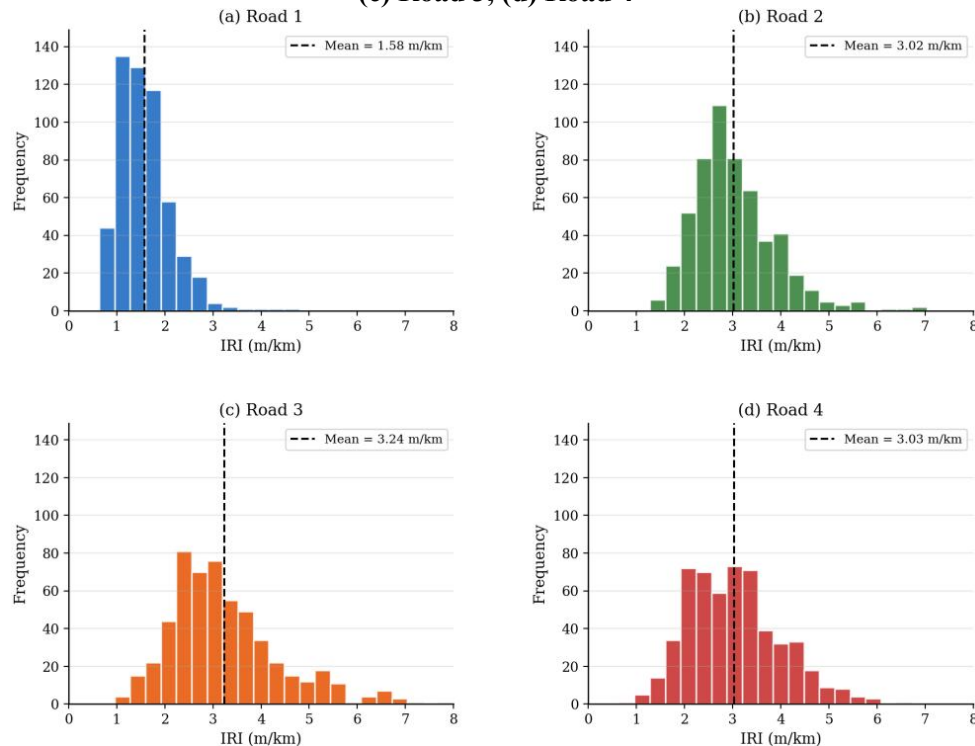


Figure 5 Histograms of Measured IRI for Each Track: (a) Road 1, (b) Road 2, (c) Road 3, (d) Road 4

5. Discussion

5.1 Complementarity between the Continuous Attitude Field and Traditional Inspection Methods

The proposed method and existing mainstream inspection methods characterize the state of circular tracks from different dimensions, forming a complementary rather than a substitutive relationship, as summarized in Table 3.

Mobile laser scanning, as an emerging pavement geometric inspection technique, lies between the laser profilometer and the proposed method in terms of spatial resolution and geometric information dimension. Mobile laser scanning can obtain millimeter-level point clouds with full-lane lateral coverage, but data post-processing is complex, equipment cost is high, and it mainly targets pavement surface topography rather than vehicle body attitude [19]. The proposed method takes vehicle body attitude as the core inspected object, directly reflecting the influence of macro-geometric parameters

such as superelevation and longitudinal slope on vehicle dynamic response, thus complementing mobile laser scanning in information dimension. The unique value of the continuous attitude field lies in its systematic geometric description of curve superelevation. The roll angle field directly reflects the spatial distribution of the superelevation angle, which can be used to verify whether construction superelevation is consistent with design values and whether geometric transitions (e.g., in spiral curves) are smooth. The laser profilometer excels at capturing short-wavelength unevenness in the longitudinal profile and is the legal measurement tool for standardized indicators such as IRI/RQI, but it cannot directly obtain curve superelevation information. The total station provides millimeter-level absolute positioning accuracy, suitable for control point layout and cross-section coordinate verification, but its low efficiency makes continuous measurement of curved sections difficult. The three methods cover the track geometric features from different dimensions and scales; their combined use forms a complete inspection system.

Table 3. Performance Comparison of Three Inspection Methods

Method	Spatial resolution	Geometric information dimension	Measured object	Continuity	Equipment cost	Typical efficiency
Total station	Discrete points (10-20 m)	3D coordinates	Marker point displacement	Discontinuous	Medium	~2 days for full track
Laser profilometer	10 mm (longitudinal)	Longitudinal profile elevation	IRI/RQI	Longitudinal continuous	High	~1 day for full track
This work	0.2 m (3D continuous)	Three-axis attitude + position	Superelevation / longitudinal slope / heading	3D continuous	Low (standard on-board sensors)	~15 min for full track

5.2 Digital Twin Model and Multi-Source Data Fusion Applications

The digital twin model constructed in this paper uses the three-axis attitude mean field as its carrier, covering the full length of the four tracks (14508 m in total) with a spatial resolution of 0.2 m, totaling 72540 attitude data points. It accurately records the geometric state of each track; successive inspection runs replace the stored mean field, keeping the twin synchronized with the evolving physical track geometry.

To further enhance the information dimension of the digital twin model, multi-source data fusion is a natural extension. Three-dimensional laser scanning point clouds can provide millimeter-level 3D geometric reference in limited sections, effectively complementing the continuous full-track attitude field of the digital twin model.

Yadav et al. [20] imported high-resolution 3D point cloud data from mobile laser scanning into a BIM environment to construct a road digital twin containing both geometric and semantic information, validating the feasibility of mobile laser scanning for pavement condition assessment and lifecycle management. Following a similar idea, laser point clouds can serve as local high-precision calibration references to establish a transformation coefficient from IMU attitude angles to pavement elevation, and then apply the calibrated coefficient to the full-track continuous attitude data, generating an enhanced digital twin that balances accuracy and coverage. This fusion approach is already feasible in engineering practice; the core challenge is the precise spatial-temporal registration between laser scanning and on-board sensors.

In addition, the digital twin model constructed in this paper is primarily oriented toward periodic inspection of track geometric state and does not yet involve real-time interaction with vehicle dynamic testing. Huang et al. [25] proposed a vehicle-in-the-loop testing method based on a digital twin proving ground, where real-time vehicle attitude and position are obtained via GNSS/INS, and test scenarios are injected into a high-precision map-based virtual proving ground, forming a closed-loop interaction between the virtual and real worlds. This provides a reference path for evolving the proving ground digital twin from static geometric description to dynamic test support.

A typical 3D point cloud sample of the proving ground circular track pavement (100 m single-lane segment) is shown in Figure 6, illustrating the usable information density of laser point cloud data. Wheel-track wear traces are clearly distinguishable in the point cloud, indicating that laser point cloud data can be used for high-precision identification of local pavement distresses, effectively complementing the macro-geometric state description of the digital twin model. As data accumulate, the fused enhanced digital twin will simultaneously possess both a macroscopic full-track attitude field and local millimeter-scale 3D topography, achieving comprehensive inspection capability that combines global monitoring and local detailed examination.

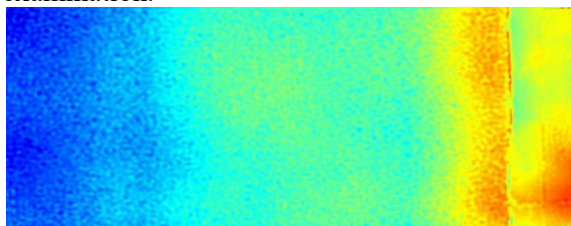


Figure 6. Typical 3D Point Cloud Sample of the Proving Ground Circular Track Pavement

5.3 Complementary Mechanism between the Continuous Attitude Field and IRI/RQI

The three-axis attitude field of the digital twin model and IRI/RQI each encode different physical dimensions of pavement state. IRI is calculated by filtering and integrating the longitudinal profile elevation using a standard quarter-car model, and it is most sensitive to longitudinal profile undulations with wavelengths of 1.3-30 m. The attitude field of the digital twin model, after 1s moving average

smoothing, effectively captures low-frequency geometric components such as curve superelevation and long gentle slopes; the high-frequency cutoff is determined by the smoothing window and the 0.2m resampling step. The two types of indicators extract pavement information from different wavelength ranges and physical mechanisms, and their combined use provides a more complete characterization of pavement conditions.

From the perspective of the digital twin model, the ϕ field directly describes the spatial distribution of curve superelevation, serving as a quantitative tool for evaluating design consistency and construction deviations of circular tracks. The θ field reflects low-frequency geometric features of the longitudinal profile and is sensitive to long-wavelength undulations (>10m). IRI/RQI provide a standardized pavement smoothness metric and are the legal basis for pavement maintenance decisions. Molinero-Pérez et al. [26] proposed a dual-model (classification and regression) framework for IRI estimation, demonstrating that IRI prediction can benefit from multi-source sensor data fusion. The three types of indicators form a gradient complementarity in wavelength coverage: the ϕ field focuses on systematic macro-geometry, the θ field covers low-frequency longitudinal information, and IRI captures medium-frequency unevenness. Integrating these three indicators within the digital twin framework enables a more comprehensive representation of the track geometric state.

5.4 Measurement Uncertainty

The attitude measurement uncertainty of the digital twin model is composed of three levels: sensor accuracy, filtering estimation, and spatial sampling. At the sensor accuracy level, the horizontal positioning error in GNSS fixed solution mode is approximately 20 mm + 1 ppm, contributing about 22 mm to a single point on a 4339 m perimeter track. The IMU attitude accuracy is constrained by the gyro bias stability (0.02 °/h); the single-point attitude uncertainty after AEKF post-processing is estimated to be 0.01°-0.05°.

At the filtering estimation level, the 15-dimensional error state model is well suited to the constant-speed circular track scenario. The sliding window length $N=50$ was experimentally verified to balance convergence speed and

innovation statistical sufficiency. γ_k is close to 1 during normal driving and briefly rises to 3-5 during signal occlusion, demonstrating the algorithm's robustness to non-ideal conditions. At the spatial sampling level, the 0.2 m resampling step filters out high-frequency information with wavelengths shorter than 0.4 m. This has a limited effect on macro-geometric parameters such as superelevation, curvature, and long gentle slopes, but it cannot identify short-wavelength local defects (e.g., potholes or expansion joints). After multi-run averaging, the inter-run standard deviation at the same position is less than 5 %, indicating good measurement repeatability of the spatial resampling strategy. Multi-run averaging reduces random errors to the order of $1/\sqrt{n}$ (where n is the number of effective runs).

6. Conclusions

This paper has proposed a continuous linear measurement method for circular test tracks based on tightly coupled RTK-GNSS/IMU fusion. Taking four circular tracks of the Beijing Automotive Reliability Standard Proving Ground as the research object, a three-axis attitude mean-field digital twin model with a spatial resolution of 0.2 m and covering a total track length of 14508 m was constructed. This digital twin encodes the as-built geometric state of each track into a queryable mean-field representation that is refreshed by each successive inspection run. The following conclusions are drawn:

AEKF and 0.2 m spatial resampling achieved continuous three-dimensional attitude measurement of curved and transition sections. A total of 72540 spatial attitude data points were obtained for all tracks, with a total driving time of approximately 15 minutes. Compared with traditional methods, the proposed approach greatly improves inspection efficiency and spatial continuity. The inter-run standard deviation at the same position is less than 5%, indicating good measurement repeatability. The roll angle amplitude of the circular tracks follows a power-law relationship with the median value of the design speed interval: $A_\phi \sim v^{3.82}$ ($R^2=0.998$). The power exponent of 3.82 is larger than the theoretical value derived from the centrifugal force balance equation, reflecting the nonlinear enhancement of body roll angle due to tire lateral slip and suspension roll under high-speed driving conditions. This relationship

can serve as a quantitative reference for superelevation consistency inspection of circular tracks.

The continuous attitude field of the digital twin model and the IRI/RQI from the laser profilometer characterize pavement conditions from different dimensions. The former is suitable for continuous full-track description of macro-geometric parameters such as superelevation and longitudinal slope; the latter provides standardized smoothness indicators suitable for pavement maintenance decisions. The two data types form effective complements in measurement scale, sensitive wavelength, and information dimension, and their combined use supports a more comprehensive pavement state evaluation.

Future work includes: extending comparative experiments with multiple vehicle types and weather conditions to evaluate the vehicle-type dependency and environmental robustness of the attitude response; establishing a complete measurement uncertainty evaluation system based on the ISO GUM framework; exploring spatiotemporal registration and fusion methods for RTK-GNSS/IMU continuous attitude data and local laser point clouds to construct a hybrid digital twin that balances accuracy and coverage; and designing an adaptive band-pass filter to separate different wavelength components from the ϕ and θ profiles, enabling quantitative assessment of the correlation between attitude signals at different frequency bands and IRI/RQI.

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