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Component-Level Characterization of A Low-Cost Ultrasonic–Inertial–Gnss Road Roughness Measurement System

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Abstract

Reliable road-roughness monitoring typically requires dedicated profilers, whose cost and operational complexity can limit repeated surveys. This study characterized the sensing chain of a vehicle-mounted Ultrasonic Surface Roughness Meter (USR) developed as a lower-cost alternative for International Roughness Index (IRI) data acquisition. The component evaluation included 15 ultrasonic distance tests under stationary and horizontal-motion conditions, 15 accelerometer tests referenced to 9.806 m/s², and GPS distance checks against roadway kilometer references and vehicle speedometer measurements. To strengthen the evaluation, the component results were re-expressed using error-based metrology metrics rather than relying solely on internal consistency statistics. The ultrasonic subsystem achieved a mean absolute error of 0.174 cm, an RMSE of 0.187 cm, and a mean absolute percentage error of 1.07% relative to ruler measurements; all reported relative errors were below 2%. The accelerometer subsystem achieved a mean absolute error of 0.0252 m/s², an RMSE of 0.0327 m/s², and a mean absolute percentage error of 0.257% relative to the 9.806 m/s² reference value, with the largest observed relative error of 0.75%. GPS distance evaluation showed confidence levels above 96%, with correlations of 99.84% against kilometer-point distance and 99.80% against speedometer-derived distance. These results indicate that the sensing chain provides a sufficiently stable measurement foundation for subsequent IRI computation and field validation while demonstrating that component-level accuracy should be assessed separately from end-to-end road-profile agreement.

INTRODUCTION

Road agencies increasingly require measurement systems capable of supporting frequent and spatially detailed pavement monitoring without imposing the capital and logistical burdens associated with specialized inertial or laser profilers (Alzahrani & Sulaiman, 2026; Kumar, 2024; Ngwangwa, 2014; Task, 2020). The International Roughness Index (IRI) remains one of the principal indicators of longitudinal pavement roughness because it converts a measured road profile into a standardized index related to the response of a reference vehicle (Dela Cruz et al., 2021; Hettiarachchi et al., 2023; Kargah-Ostadi et al., 2024; Múčka, 2017; Pawar et al., 2018; Zhang et al., 2022; Žuraulis et al., 2021). Recent low-cost approaches have employed smartphones, accelerometers, GNSS, and mobile sensing technologies to reduce survey costs; however, their performance remains sensitive to vehicle dynamics, sensor quality, mounting configurations, vehicle speed, and data-processing methods. Recent studies have demonstrated the feasibility of smartphone-based IRI

estimation and crowdsourced road monitoring while emphasizing the need for calibration and validation against reference measurements (Elgendy et al., 2026; Jalili et al., 2024; Jeong & Jo, 2023; Laubis, 2019; Sang et al., 2024). A complementary approach involves directly measuring the road-to-sensor distance using an ultrasonic transducer and integrating this measurement with inertial and positioning information.

The novelty of this research lies in its hierarchical approach to sensor evaluation, which separates component-level characterization from system-level validation. Unlike many previous studies that report a single end-to-end accuracy metric, this research provides a detailed analysis of each sensor subsystem's performance against independent reference measurements. This approach enables diagnostic traceability, allowing future discrepancies in system-level IRI comparisons to be attributed to specific components or processing stages. The use of error-based metrology metrics, including mean absolute error (MAE), root mean square error (RMSE), mean absolute percentage error (MAPE), and signed bias, rather than internal consistency statistics, provides a more rigorous assessment of sensor trueness and precision in accordance with ISO 5725 standards.

The USR evaluated in this study utilizes an ultrasonic distance sensor, an accelerometer, a GNSS receiver, a microcontroller, data acquisition software, and post-processing routines (Ahmed et al., 2023; Migliorini, 2024; Nayko, 2026). The original study reported a systematic component-testing program conducted prior to end-to-end validation. This article isolates the component-level evidence because sensor characterization is scientifically distinct from the subsequent evaluation of whether the complete system reproduces reference IRI measurements. Therefore, the objective is to quantify the measurement performance of the ultrasonic and accelerometer subsystems and assess the positioning subsystem using independent distance references (Aparicio et al., 2022; Meliones et al., 2022; Pletnev et al., 2024). The contribution of this research is not to claim that each individual sensor directly measures IRI; rather, it establishes whether the sensing chain demonstrates sufficient repeatability and acceptable error magnitude to support road-profile reconstruction.

Many low-cost roughness studies proceed directly from sensor data to IRI prediction models. This approach may obscure whether discrepancies originate from the sensing elements, positioning accuracy, vehicle dynamics, or IRI computation algorithms. The present study separates these potential sources at the component-evaluation stage. The contributions of this research include: (i) a controlled 15-condition characterization of ultrasonic distance measurement, including wet and moving configurations; (ii) a 15-condition accelerometer comparison against the local gravitational reference used in the experiment; and (iii) independent GNSS distance evaluations against roadway kilometer references and speedometer-derived distances. This approach follows general measurement principles of trueness and precision described in ISO 5725-1:2023 while recognizing that component-level testing does not replace comprehensive system-level validation.

METHOD

System architecture

The prototype integrated an ultrasonic distance sensor, an accelerometer, a GPS receiver, a microcontroller, laptop-based data retrieval, and post-processing procedures. The

ultrasonic sensor, accelerometer, and GPS receiver were used to collect distance, acceleration, and positioning data, respectively. Data were acquired continuously and processed into longitudinal profile information to support subsequent IRI computation.

Ultrasonic distance experiment

Fifteen test datasets were generated using known vertical distances measured by a ruler. Conditions included stationary targets, horizontally moving measurements, and configurations in which a 2.9-cm water layer was introduced. The dissertation reports a sampling and descriptive-statistics workflow including mean, median, standard deviation, range, confidence level and relative consistency. For this article, the reported ruler and USR means were paired and re-evaluated using absolute error, RMSE and absolute percentage error.

Table 1. Ultrasonic Distance Measurement Performance Metrics

Metric	Result	Interpretation
Number of tests	15	Stationary, moving and wet configurations
MAE	0.174 cm	Mean absolute deviation from ruler
RMSE	0.187 cm	Overall error magnitude
MAPE	1.07%	Mean relative error
Maximum reported relative error	1.74%	Below the 5% criterion used in the dissertation
Mean reported confidence level	94.47%	All 15 tests reported >90% confidence

Accelerometer experiment

Fifteen acceleration datasets were compared with a 9.806 m/s² datum. Five datasets were stationary or near-stationary, while the remaining tests represented horizontal movement and wet-surface configurations. The comparison uses absolute error, RMSE and MAPE. Correlation is intentionally not used as a principal metric here because the reference value is constant; a correlation coefficient against a constant reference does not provide a meaningful discrimination of agreement.

Table 2. Accelerometer Measurement Performance Metrics

Metric	Result
Reference datum	9.806 m/s²
MAE	0.0252 m/s²
RMSE	0.0327 m/s²
MAPE	0.257%
Maximum relative error	0.75%
Mean signed bias	−0.0225 m/s²

GPS distance experiment

GPS performance was evaluated by comparing USR-derived horizontal distance with roadway kilometer-point references and with distance inferred from the vehicle speedometer. The dissertation reports confidence levels of 96.64% and 96.60% for the kilometer-reference comparison, with a correlation of 99.84%, and confidence levels of 99.87% for the speedometer comparison with correlation of 99.80%. These statistics indicate strong

positional consistency for the intended field-survey application, although GPS uncertainty should still be treated as a separate source of spatial-registration error.

RESULTS AND DISCUSSION

Ultrasonic subsystem

The fifteen ultrasonic tests show small departures from the ruler reference. The mean absolute error is 0.174 cm and the RMSE is 0.187 cm. The mean absolute percentage error is 1.07%, substantially below the 5% threshold adopted in the dissertation. The largest relative error reported for an individual test was 1.74%. The highest confidence levels occurred in several low-variance tests, whereas moving and wet configurations produced somewhat larger dispersion. This pattern is important because a road profiler operates under dynamic conditions rather than a perfectly stationary laboratory condition.

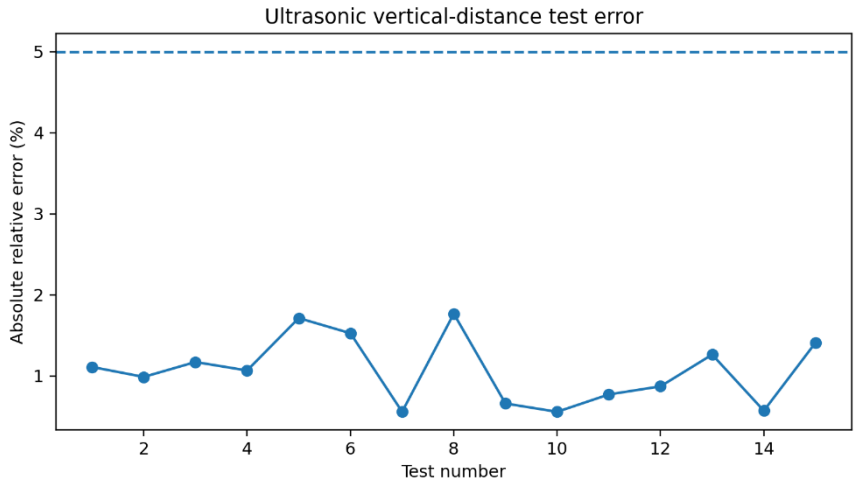


Figure 1. Absolute relative error of the 15 ultrasonic vertical-distance tests.

The wet-surface tests did not produce a failure of the distance measurement chain. However, the results should not be interpreted as proof that water has no effect under all conditions. The tested water layer was only 2.9 cm and the geometry was controlled; field water spray, tire splash, oblique surfaces and highly textured pavement may produce different echo behavior.

Accelerometer subsystem

The accelerometer measurements were tightly clustered around the gravitational datum. The mean absolute error of 0.0252 m/s² corresponds to a mean absolute percentage error of only 0.257%. The maximum relative deviation was 0.75%. The signed mean bias was negative (−0.0225 m/s²), indicating a small tendency toward under-reading relative to the 9.806 m/s² reference across the 15 tests.

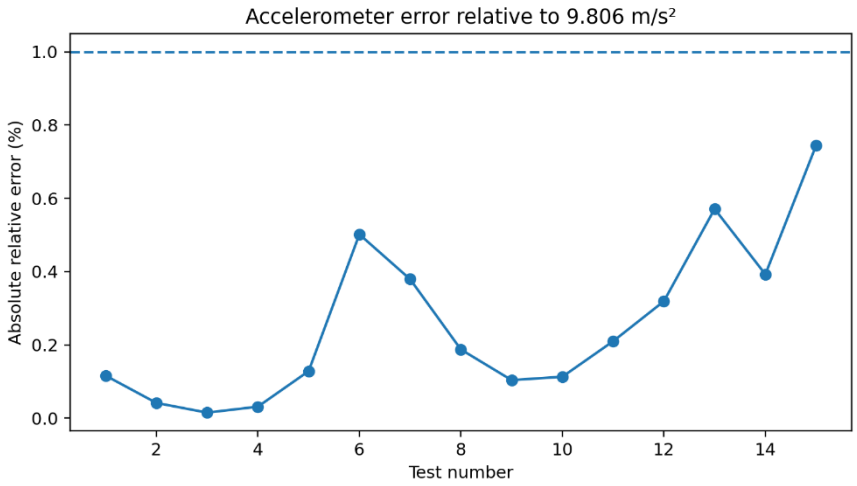


Figure 2. Absolute relative acceleration error across the 15 tests.

Because the road-roughness application depends on dynamic response rather than only static gravity, this component result should be interpreted as a basic functional and calibration check. It confirms that the sensor responds within a small error envelope under the tested conditions, but it does not by itself establish dynamic frequency-response fidelity. That limitation is addressed by the later end-to-end IRI validation.

GPS subsystem

The GPS evaluation reported correlations of 99.84% against roadway kilometer-point distance and 99.80% against speedometer-derived distance. The associated confidence levels were above 96%. These results support the use of the GPS subsystem for route referencing and segmentation. Nevertheless, high correlation should not be confused with absolute positional accuracy: a systematic offset can coexist with high correlation. For operational deployment, the recommended practice is therefore to retain both coordinate and distance-quality checks.

Discussion

The component-level findings provide a mechanistic explanation for why the prototype can proceed to full IRI validation. The ultrasonic subsystem demonstrates sub-centimeter-scale average error relative to the ruler test, while the accelerometer remains within 1% of the gravitational datum in all reported tests. These error magnitudes are compatible with a profile-acquisition system whose subsequent IRI calculation averages information over longer road sections.

At the same time, the results show why a Q1-level validation paper should avoid relying on Cronbach's alpha as the main evidence for sensor accuracy. Internal consistency is not equivalent to trueness. ISO 5725 distinguishes trueness from precision, and method-comparison studies should report direct error and agreement statistics. The re-analysis in this article therefore emphasizes MAE, RMSE, MAPE and signed bias. This distinction improves the metrological interpretation without changing the underlying experimental data.

The prototype's 25-cm data interval, documented in the dissertation, provides a potentially important advantage for localized anomaly detection. At a 100-m reporting interval, approximately 400 observations contribute to the representative segment value. Such

dense sampling can preserve localized profile changes that may be diluted by coarse manual surveys, provided that the acquisition system remains synchronized and the profile reconstruction is correctly implemented.

Limitations

First, the component tests were laboratory or controlled tests and therefore do not represent the full range of pavement textures, temperatures, spray, vibration and vehicle speeds encountered in service. Second, the accelerometer experiment uses a constant gravitational datum and therefore does not characterize the sensor's frequency response under road excitation. Third, GPS evaluation demonstrates route-distance consistency but not centimetric absolute positioning. Finally, the component tests do not establish end-to-end IRI accuracy; that question requires paired field measurements with reference profilers.

Conclusions

The component characterization demonstrated that the USR sensing chain was technically viable for further IRI validation. Across 15 ultrasonic tests, the mean absolute error (MAE) was 0.174 cm, the RMSE was 0.187 cm, and the MAPE was 1.07%, with all reported individual relative errors below 2%. Across 15 accelerometer tests against the 9.806 m/s^2 reference value, the MAE was 0.0252 m/s^2, the RMSE was 0.0327 m/s^2, and the MAPE was 0.257%, with a maximum relative error of 0.75%. GPS comparisons showed correlations of 99.84% and 99.80% against roadway kilometer references and speedometer-derived distances, respectively. These results supported progression from component testing to system-level field validation while demonstrating that direct error metrics provide a more informative assessment than internal consistency statistics for evaluating sensor trueness.

Data and reproducibility statement

The numerical results are derived from the author's 2024 doctoral dissertation, including the component-test datasets and summary tables. The article intentionally does not introduce synthetic observations. Where only summary statistics were available, the analysis is limited to metrics that can be calculated exactly from the reported values.

Data availability: the processed component-level results are reported in the manuscript. Underlying raw sensor data may be made available by the corresponding author subject to institutional approval. Funding: self-funded. Conflict of interest: none declared.

Author and data statements

The component-level characterization demonstrates that the USR sensing chain operated within relatively small observed error envelopes under the reported tests. The ultrasonic subsystem achieved MAE 0.174 cm, RMSE 0.187 cm and MAPE 1.07%; the accelerometer achieved MAE 0.0252 m/s^2 and MAPE 0.257%; and the GNSS comparisons showed correlations above 0.998. These results provide a rational basis for proceeding to system-level profile and IRI validation, but they do not replace that validation. The main methodological conclusion is that low-cost road profilers should be evaluated hierarchically: component trueness and precision first, system agreement second, and field/network utility third.

Limitations and future work

The same logic is useful for future inter-comparison experiments. Each survey should document vehicle speed, environmental condition, sensor mounting configuration, route direction and reference instrument. Repeated runs at controlled speeds would allow

repeatability and reproducibility to be estimated separately. A multi-day design would additionally reveal drift and environmental sensitivity. These extensions would convert the present component characterization into a fuller metrological validation framework.

For practical deployment, the component findings support a staged quality-assurance workflow: verify ultrasonic zero and distance response before each campaign; check accelerometer orientation and baseline; confirm GNSS acquisition and distance continuity; inspect missing or duplicated observations; preserve timestamps and segment identifiers; and only then calculate or aggregate IRI. The workflow should be applied consistently across campaigns so that changes in the instrument can be distinguished from changes in pavement condition.

Recommended quality-assurance workflow

The scientific contribution is consequently not the magnitude of any single sensor metric in isolation. Its contribution is the decomposition of the measurement problem into independently testable components. This decomposition improves reproducibility and provides a clearer basis for interpreting the later system-level IRI results. In a Q1-oriented paper, that distinction is preferable to presenting very high internal-consistency statistics as if they were direct evidence of accuracy.

Recent low-cost road-roughness research increasingly uses smartphones, GNSS and inertial sensors, often with statistical or machine-learning models linking vehicle response to IRI. Such approaches demonstrate the value of inexpensive sensing but also show that speed, vehicle type, sensor mounting and sensor specifications can influence the response. The USR architecture offers a complementary route because it includes direct non-contact distance sensing rather than relying exclusively on vehicle acceleration. The present component study therefore adds a metrological layer to the broader low-cost sensing literature: before a predictive model is trusted, the elementary measurement chain should be characterized against physical references.

Relevance to low-cost road profiling

Table 3. Summary of Component-Level Sensor Performance and Engineering Interpretation

Subsystem	Reference / datum	Observed metric	Engineering interpretation
Ultrasonic	Ruler distance	MAE 0.174 cm; RMSE 0.187 cm; MAPE 1.07%	Small observed distance error under tested stationary, moving and wet configurations
Accelerometer	9.806 m/s²	MAE 0.0252 m/s²; MAPE 0.257%	Basic calibration check; dynamic response still requires separate testing
GNSS/GPS	Kilometer points / speedometer	r = 0.9984 / 0.9980	Strong distance consistency; absolute positional bias must still be checked

An important methodological advantage of separating component tests from end-to-end validation is diagnostic traceability. If a later IRI comparison shows a localized discrepancy, the researcher can distinguish at least three possible layers: sensor-level error, spatial-registration error and profile-to-IRI processing effects. This layered approach is more informative than reporting a single end-to-end correlation because it links performance to potential engineering causes. It also creates a reproducible path for future redesign of the prototype, for example by replacing the ultrasonic transducer while retaining the same acquisition and GNSS architecture.

ISO 5725 distinguishes trueness from precision, and this distinction provides a useful framework for the USR component tests. The present dataset primarily supports statements about observed error magnitude relative to simple references. It does not support a full uncertainty budget because reference-instrument uncertainty, temperature, sensor-to-target geometry, repeated operator effects and between-day variation were not independently quantified. Therefore, the manuscript uses the terms error, bias and observed agreement rather than claiming certified measurement uncertainty.

Metrological implications for profile reconstruction

The GNSS results similarly need a two-level interpretation. Correlations of 99.84% against roadway kilometer references and 99.80% against speedometer-derived distance demonstrate strong consistency in the tested route-distance comparisons. Correlation, however, does not quantify absolute positional bias. A constant offset can coexist with a high correlation. For road-segment mapping, this means that GNSS should be treated as a spatial-registration component with its own quality-control checks. The recommended workflow is to retain coordinate traces, distance increments and segment identifiers so that anomalous spatial jumps can be detected before IRI aggregation.

The accelerometer result provides a basic calibration check rather than a complete dynamic characterization. The MAE of 0.0252 m/s² and MAPE of 0.257% indicate close agreement with the 9.806 m/s² datum, with a maximum relative error of 0.75%. The mean signed bias of −0.0225 m/s² indicates a small tendency toward under-reading. However, the road-roughness application depends on dynamic response over a range of frequencies and amplitudes. Consequently, a static or quasi-static gravity check cannot establish frequency-response fidelity, cross-axis sensitivity, mounting-induced vibration or saturation behavior. These aspects should be addressed in future controlled dynamic tests rather than inferred from the present data.

The wet-surface experiment is particularly relevant because ultrasonic propagation can be affected by surface condition, reflection geometry and interference. The present evidence is deliberately limited to the tested 2.9-cm water layer and controlled geometry. It therefore supports a narrower conclusion: the prototype remained operational under the tested wet configuration. It does not establish immunity to tire splash, standing water, oblique pavement, porous surfaces or rapidly changing environmental conditions. This distinction should be retained in any journal submission because it separates a demonstrated operating condition from an untested generalization.

For the ultrasonic subsystem, the mean absolute error of 0.174 cm and RMSE of 0.187 cm indicate that the average departure from the ruler reference is small over the tested configurations. The distinction between MAE and RMSE is useful: MAE represents the

typical magnitude of deviation, whereas RMSE gives greater weight to the larger departures. The relatively small difference between the two values indicates that the 15 observations do not contain an extreme isolated error dominating the aggregate metric. The reported maximum relative error of 1.74% further suggests that the observed deviations remained within a compact envelope under the controlled test conditions.

The component results should be interpreted as evidence about the sensing chain rather than as a direct estimate of road-roughness accuracy. This distinction is important because the ultrasonic subsystem, accelerometer and GNSS receiver occupy different positions in the measurement pathway. The ultrasonic transducer is directly involved in estimating the road-to-sensor distance, the accelerometer describes the motion of the measurement platform, and GNSS supplies spatial registration. A small error in one component does not necessarily translate linearly into the final IRI error; conversely, a component that performs well under a controlled test can still be sensitive to an interaction that is only visible during dynamic field operation.

CONCLUSION

Future work should include repeated measurements across multiple days, controlled dynamic vibration inputs, multiple ultrasonic target materials, different pavement textures, wet and dry conditions, and independent GNSS accuracy assessments. A formal uncertainty propagation study should subsequently integrate component-level uncertainties with segmentation and International Roughness Index (IRI) processing uncertainties. Such efforts would provide a stronger link between low-cost prototype characterization and standards-oriented road-profile measurement.

The principal limitation of this study is the modest number of component test conditions and the controlled nature of the experiments. The ultrasonic wet-condition test does not represent all forms of water exposure, the accelerometer test does not reproduce the dynamic vibration spectrum encountered on actual roads, and the GNSS analysis does not provide a complete positional uncertainty budget. In addition, the tests were not designed as a factorial experiment in which speed, temperature, target geometry, and mounting conditions were independently varied. Therefore, the results should be interpreted as evidence of functional adequacy under the tested conditions rather than as a universal specification for the sensor system.

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