

Editorial

Closing Editorial: Applied Industrial Metrology: Methods, Uncertainties, and Challenges

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Abstract

This closing editorial summarizes and introduces the Special Issue, Applied Industrial Metrology: Methods, Uncertainties, and Challenges, highlighting recent advances in traceability, uncertainty evaluation, intelligent metrology, sensor technologies, flow measurement, and standardization. The collected contributions demonstrate how digitalization, artificial intelligence, and advanced sensing are transforming industrial measurement while reinforcing the enduring importance of measurement traceability, comparability, and uncertainty for reliable, sustainable industrial applications.

1. Introduction

Metrology provides the foundation for confidence in measurements, enabling scientific discovery, industrial innovation, international trade, and regulatory compliance. While the International System of Units (SI) ensures worldwide consistency and is based on international comparisons [1], industrial metrology [2–5] extends these principles into practical environments where measurement systems must operate under constraints related to cost, speed, robustness, traceability, and uncertainty [6]. As manufacturing technologies become increasingly digitalized and autonomous, the demand for reliable, traceable, and intelligent measurement solutions continues to grow.

The Special Issue, Applied Industrial Metrology: Methods, Uncertainties, and Challenges, was conceived to provide a forum for researchers and practitioners working at the interface between fundamental metrology and industrial applications. The objective was to highlight recent advances in measurement methods, uncertainty evaluation, calibration, traceability, sensor development, and data-driven metrology across diverse industrial sectors. This Special Issue presents nine high-quality contributions originating from different countries and covering a broad spectrum of industrial metrology topics. Together, these articles illustrate the diversity of modern measurement science, ranging from dimensional and optical metrology to flow metering, dielectric characterization, acoustic sensing, machine learning, and the standardization of emerging materials.



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2. Overview of Published Articles

Although addressing different application domains, the contributions naturally cluster around several complementary themes that characterize current developments in industrial metrology.

2.1. Traceability, Standardization, and Measurement Comparability and Intercomparison

Reliable measurements depend not only on accurate instruments but also on internationally recognized traceability chains and harmonized measurement procedures [7,8]. The review article on international comparisons published at the beginning of this Special Issue highlights the fundamental role of the CIPM Mutual Recognition Arrangement in ensuring worldwide confidence in measurement capabilities. It emphasizes how international comparisons establish equivalence among national metrology institutes and support global trade, regulation, and scientific collaboration. Complementing this perspective, Ono proposes a novel framework for the dual-mode standardization of emerging material specifications. Rather than focusing solely on technical standards, the work integrates measurement-based information with market-oriented decision-making, illustrating how metrology can facilitate the industrial adoption of innovative materials while preserving comparability and reliability. This contribution demonstrates that standardization and traceability remain essential pillars for transferring measurement confidence from laboratories to industrial applications. Cetinkaya et al. present an interlaboratory comparison of RF power measurements using automatic measurement software across European metrology laboratories. Measurements at multiple frequencies and power levels were evaluated using GUM and Monte Carlo uncertainty methods. Results showed strong agreement, validating the software's reliability and suitability for accurate, consistent RF power comparisons.

2.2. Measurement Uncertainty and Industrial Verification

Quantifying measurement uncertainty remains one of the defining characteristics of modern metrology. Industrial users increasingly require uncertainty budgets that realistically reflect measurement conditions while remaining practical for routine inspection. This challenge is illustrated by the investigation of uncertainty associated with coordinate measuring machines (CMMs) and optical 3D scanning for centrifugal rotor inspection. By comparing tactile and optical approaches, the authors demonstrate how complementary measurement technologies can be evaluated within a common uncertainty framework, allowing informed decisions according to the functional requirements of complex industrial components. The emphasis on uncertainty evaluation reflects an important trend in industrial metrology: moving beyond measurement accuracy alone toward comprehensive confidence assessment.

2.3. Intelligent Metrology and Artificial Intelligence

Artificial intelligence is rapidly transforming industrial measurement systems by improving feature extraction, prediction, and process optimization. Two contributions exemplify this evolution. One article presents a flexible wheel alignment measurement method combining semantic segmentation based on APCS-SwinUnet with point-cloud registration to achieve low-cost three-dimensional measurements suitable for automotive applications. Another investigates the prediction of deposited bead geometry in wire-arc additive manufacturing using artificial neural networks and support vector machines [9]. Accurate prediction of deposited geometry contributes to improved process control, reduced waste, and enhanced manufacturing quality. These studies demonstrate how machine learning is becoming an integral component of industrial metrology, complementing traditional measurement science with advanced data analysis and predictive capabilities.

2.4. Advanced Sensors and Measurement Instrumentation

Industrial measurements increasingly rely on compact, robust, and application-specific sensing technologies capable of operating in challenging environments.

A novel cylindrical capacitive sensor is introduced for characterizing the dielectric properties of liquids over the frequency range from 1 to 30 MHz. The proposed design offers a cost-effective alternative while maintaining satisfactory measurement performance, illustrating how sensor innovation can broaden access to reliable electrical characterization.

Another contribution presents a high-frequency coupled-resonator capacitive micro-machined ultrasonic transducer (CMUT) designed for acoustic emission monitoring during additive manufacturing. By combining enhanced bandwidth and sensitivity with compact dimensions, the proposed sensor addresses the growing need for real-time structural health monitoring in advanced manufacturing processes.

Together, these papers illustrate the continuous development of measurement instrumentation that balances performance, affordability, and industrial applicability.

2.5. Flow Metrology and Sustainability

Accurate flow measurement plays a critical role in emerging energy and environmental technologies [10,11]. This is particularly true for carbon capture [12], utilization, and storage (CCUS), where reliable quantification of gaseous carbon dioxide is essential throughout the process chain [13].

The reported interlaboratory comparison of SI-traceable calibration facilities for gaseous CO₂ flow metering represents an important contribution to establishing international consistency in this strategically important field. By comparing calibration capabilities across laboratories, the study reinforces confidence in flow measurements supporting future low-carbon technologies.

This contribution illustrates the growing role of metrology in addressing global sustainability challenges. One additional challenge consists of measuring it for nanoparticles [14].

3. Emerging Trends and Future Perspectives

Several important trends emerge collectively from the contributions published in this Special Issue.

- First, industrial metrology is becoming increasingly data-driven [15]. Artificial intelligence, machine learning, and advanced computational methods are no longer peripheral tools but are progressively integrated into measurement systems themselves.
- Second, uncertainty evaluation continues to evolve beyond laboratory environments. Future developments will require uncertainty methodologies capable of supporting autonomous production systems, digital twins [16], and real-time decision making.
- Third, sensor innovation remains a key driver of industrial metrology [17]. Miniaturized, application-specific sensors with improved sensitivity and broader operating ranges will continue expanding measurement capabilities across manufacturing, materials science, and environmental monitoring.

Finally, traceability and standardization [18,19] remain indispensable despite rapid technological evolution. Whether measurements concern advanced materials, additive manufacturing, environmental monitoring, or intelligent production systems, confidence ultimately depends on internationally recognized measurement infrastructures.

These directions clearly illustrate that future industrial metrology will combine rigorous measurement science with digital technologies while maintaining the fundamental principles of traceability, comparability, and uncertainty evaluation.

4. Conclusions

The Special Issue *Applied Industrial Metrology: Methods, Uncertainties, and Challenges*, successfully brings together contributions illustrating both the diversity and the

evolution of contemporary industrial measurement science. The published papers span topics ranging from international metrology infrastructure and standardization to intelligent sensing, additive manufacturing, dimensional metrology, dielectric characterization, flow measurement, and machine-learning-assisted measurement systems. Collectively, these contributions demonstrate that industrial metrology is undergoing significant transformation driven by digitalization, advanced sensing technologies, artificial intelligence, and increasing societal demands for sustainable and reliable industrial processes. At the same time, the Special Issue reaffirms that the fundamental principles of traceability, uncertainty evaluation, and international comparability remain central to all measurement activities.

I would like to express my sincere gratitude to all authors for submitting their valuable contributions, and to the reviewers for their careful evaluations and constructive comments.

It is hoped that the articles collected here will serve as useful references for researchers, engineers, and industrial practitioners, while stimulating further developments in applied industrial metrology and strengthening the links between measurement science and industrial innovation.

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