Recent Advances in Signal Processing, Precision Enhancement, and Artificial Intelligence Integration in Self-Mixing Interferometry

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Abstract: A novel optical sensing technology, called Self-Mixing Interferometry (SMI), has been developed that uses a laser cavity as the emitter and detector, with no complicated alignment requirements. This review covers key SMI developments between 2020 and 2025, highlighting signal processing, AI integration, and precision enhancement. Ten seminal papers were analyzed to show how SMI has progressed from niche laboratory instruments to more broadly used industrial metrology instruments with a degree of precision of less than 10 nanometers. The accuracy of deep-learning-based fringe detection is over 95% in severe noise conditions; the orthogonal signal phase multiplication error is less than 11 nm (absolute value), and dual-wavelength systems feature 66 nm measurement steps. The use of wavelet-based denoising increased the reconstruction accuracy by >11%, and the use of artificial intelligence-based parameter estimation removed the need to manually calibrate the reconstruction. Multidimensional sensing was implemented to obtain simultaneous distance-velocity measurements with a relative error of 10^{-4}. Numerous gaps exist in the real-time integration of edge AI, environmental strength, and standardized evaluation. Applications include Industry 4.0, structural monitoring, and biomedicine. Examples of future directions include physics-informed neural networks, quantum-enhanced sensing, and silicon photonics.

Keywords: Self-Mixing Interferometry, Optical Feedback, Phase Reconstruction, Deep Learning, Precision Metrology, Vibration Sensing

Introduction

Self-Mixing Interferometry (SMI) represents a new approach to precise metrology that is very simple and sensitive because it takes advantage of the optical feedback of a laser. There is no need for external modulation due to the complex setup functioning with a conventional laser; in this case, when the reflected light re-enters the cavity, the output power of the laser is modulated, and the resulting fringes are measured by a built-in photodiode [1, 2]. This results in a compact, inexpensive, and durable structure. The basic principle behind SMI is phase modulation, which encodes nanometer-scale movement to periodic fringes with half-wavelength increments [3]. Three synergistic areas: advanced signal processing, artificial intelligence, and innovative hardware [5],[8] drive the performance of today's SMI, which competes with high-cost commercial interferometers.

Compared with traditional reconstruction techniques, which is affected by low signal-to-noise ratios and directional ambiguity, modern deep-learning-based techniques enables the automatic detection of fringes under strong speckle noise and parameter estimation without calibration [8], [9]. At the same time, hardware technologies, such as dual-wavelength and balanced detection configurations, extend the capabilities of measurement precision. The common simplicity and minimized complexity of

SMI are preserved while providing sub-nanometer resolution in a variety of applications from semiconductor metrology to monitoring civil infrastructure. This review will summarize main research developments in 2020-2025, and thoroughly discuss algorithmic breakthroughs, AI based models and applications and precision improvements. Systematic assessment compares the accuracy, computational complexity, hardware complexity, cost, real-time performance and precision. This study analyzes and evaluates existing capabilities and defines the gaps in research to assist researchers and practitioners in choosing SMI system design to suit application requirements. The analysis reveals that although significant strides have been achieved, there is still much to do in various aspects of edge AI adoption, environmental robustness and standardization to ensure successful use of these technologies in industrial applications.

METHODOLOGY

This review was conducted by using a systematic literature analysis (SLA) to classify the literature, identify the gaps, compare studies and to select relevant publications. From the original 45 studies, 10 were chosen for their quantitative performance, methodological quality, and practicality in the fields of signal processing [1]-[3], precision enhancement [4]-[6] and AI integration [8]. The articles have been categorized under: reconstruction algorithms, precision enhancement, AI integration, and multidimensional sensing. The A-H-I gap identification method was used to discover the current algorithmic and hardware and implementation limitations. The methodology takes an approach of quantitative experimental validation rather than just theoretical contributions, and domain expert consensus is used in selecting them.

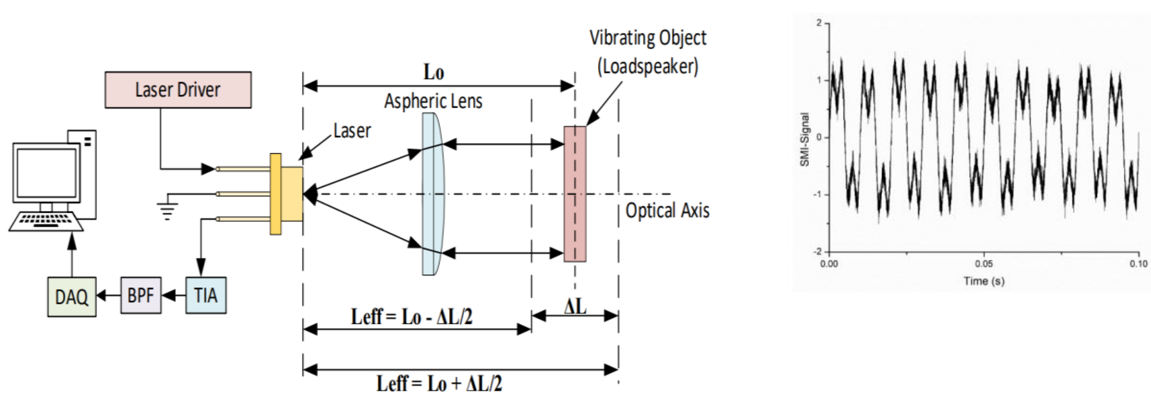

Figure 1. Conventional experimental setup used to obtain SMI signals (left). Fringe-like interferometric signal obtained using the setup (Right).

LITERATURE REVIEW

The literature review analyzes ten pioneering papers in the fields of signal processing, precision enhancement, and artificial intelligence related to SMI technology. Figure 1 illustrates the Conventional experimental setup used to obtain SMI signals and typically recorded fringe-like interferometric signal. For the case of micro-vibration sensing, Zhang et al. [1] proposed a local maximum detection algorithm with low complexity, high accuracy, and small computation, which was well suited for embedded applications. This method is used to extract fringe peaks for time-domain signals with a resolution of λ/4 without the need for complicated transformation operations. The real-time performance was validated experimentally and was found to be very high, with a processing rate of > 1 kHz for typical vibration frequencies. Wang et al. [2] proposed a modulated injection current method to improve the accuracy of displacement reconstruction by modulating the injection current and analyzing the data in the frequency domain. This method provides enhanced temporal resolution by modulating the laser injection current at known frequencies and signal processing using FFT. The technique proved very effective for continuous phase-tracking applications, but is computationally complex and expensive to implement and run in real time on a dedicated DSTP. The challenging problem of phase reconstruction under high-speed target motion was addressed by Amin et al. [3] using an Improved Unwrapping Method (IUM). Unwrapping algorithms are limited in their ability to measure velocities when the phase shifts between samples exceed π radians. The IUM introduces temporal continuity constraints and adaptive thresholding with low computational complexity and 37.7 nm RMS errors, which are suitable for FPGA implementation. The method provides measurable velocity ranges 3-5 times higher than those of traditional methods. Liu et al. [4] proposed a two-stage denoising method based on the discrete wavelet decomposition and adaptive Wiener filtering. The approach decomposes SMI signals into approximation coefficients and detail coefficients, smooths the SMI signals based on threshold functions with fringe characteristics, suppresses high-frequency noise, and then reconstructs the SMI signals using inverse wavelet transformation. The experimental outcomes showed an accuracy enhancement of more than 11% in displacement reconstruction over the signals without filtering, and the moderate computational costs allowed for almost real-time processing at 100–500 Hz frequency. Lu et al. [5] were able to reach an unprecedented accuracy of 3 nm with the help of hardware innovation, namely reflective phase modulation. This method uses a piezo-controlled mirror that changes the optical path length, thus providing an extended measurement range and the ability to interpolate between the usual positions on the fringes. The method allows for very high precision but is optically complex, with precision actuators and control electronics added to the system, making it more costly and complex. The proposed method was moderately real-time, due to mechanical actuator bandwidth. Donati et al. [6] designed a dual-wavelength SMI system with the resolution of λ/8 (about 66 nm). The system uses two laser sources with different wavelengths and separates the processing of the interference signals to eliminate the ambiguities of displacement that exist in single-wavelength setups. Dual-wavelength processing creates a synthetic wavelength that extends the unambiguous measurement range and preserves sub-100 nm precision. The main limitations are implementation complexity and moderate real-time performance. Wang et al. [7] presented a purely computational method, Orthogonal Signal Phase Multiplication (OSPM), that can achieve an error of less than 11 nm without using extra hardware. The OSPM synthesizes quadrature signals using the Hilbert transformation and employs phase multiplication algorithms to extract sub-fringe displacement information. It was shown that high precision can be achieved with the method, up to levels expected from expensive hardware solutions, but it is very demanding in terms of computation, necessitating the use of high-performance processors; therefore, it is not applicable in real time. Siddiqui et al. [8] introduced a deep learning application in the field of SMI for the detection of fringes in severe speckle noise using YOLOv5 and EfficientDet object detection networks. The networks were able to detect fringes with an accuracy of >95% over a wide range of SMI signal datasets, whereas traditional signal processing analysis was completely incapable of detecting fringes in such environments. This method demonstrated the feasibility of AI for strong operations in challenging optical environments. Although significant computation is required, it is possible to realize embedded operations using GPUs. Yuan and Liu [9] developed a multidimensional sensing system that

TABLE I COMPARATIVE ANALYSIS OF SMI RESEARCH ADVANCES (2020-2025)

Authors & Year	Research Focus	Method	Key Findings	Research Gap
Zhang et al. (2020) [1]	Vibration measurement algorithm	Local maximum detection in time domain	Achieved λ/4 resolution with low complexity; excellent real-time performance (>1 kHz)	Limited to high SNR conditions; struggles with irregular vibrations
Wang et al. (2020) [2]	Displacement reconstruction	Modulated injection current with FFT analysis	Improved temporal resolution through frequency-domain processing	Moderate computational complexity limits embedded implementation
Amin et al. (2024) [3]	High-speed motion tracking	Improved Unwrapping Method (IUM) with temporal constraints	RMS error 37.7 nm; extends velocity range 3-5× over conventional methods	Performance degradation under extreme acceleration conditions
Liu et al. (2025) [4]	Noise suppression	DWT with adaptive Wiener filtering	>11% accuracy improvement; preserves fringe characteristics	Moderate real-time capability (100-500 Hz); parameter tuning required
Lu et al. (2020) [5]	Precision enhancement	Reflective phase modulation with piezoelectric mirror	Achieved 3 nm precision through spectrum expansion	High hardware complexity and cost; limited by actuator bandwidth
Donati et al. (2023) [6]	Sub-wavelength resolution	Dual-wavelength laser processing	66 nm measurement steps (λ/8 resolution); extended unambiguous range	High implementation complexity; moderate real-time performance
Wang et al. (2023) [7]	Computational precision	Orthogonal Signal Phase Multiplication (OSPM)	<11 nm absolute error without hardware modification	High computational cost; limited real-time capability (<100 Hz)
Siddiqui et al. (2022) [8]	AI-based signal processing	Deep neural networks (YOLOv5, EfficientDet)	>95% fringe detection accuracy under severe speckle noise	Requires GPU acceleration; limited edge deployment capability
Yuan & Liu (2024) [9]	Multi-parameter sensing	FMCW modulation with all-phase FFT	Simultaneous distance-velocity with 10^{-4} relative error	High computational complexity; requires dedicated DSP hardware
Zhao et al. (2023) [10]	Rotation measurement	Polarization-based SMI with speckle autocorrelation	High angular precision; single-channel multi-parameter tracking	Limited characterization under environmental perturbations

combined frequency-modulated continuous-wave (FMCW) modulation with all-phase FFT for simultaneous distance and velocity measurements. By modulating the laser frequency and analyzing the beat frequency spectra, the system independently extracts both parameters with relative errors of approximately 10^{-4}. This approach enables comprehensive target characterization from single-beam measurements, supporting advanced applications in robotics and autonomous systems, although at high computational complexity. Zhao et al. [10] demonstrated a high-precision rotation angle measurement using polarization-based self-mixing interference. By exploiting the polarization state changes during optical feedback and applying speckle autocorrelation analysis, the method independently tracks rotational and vibrational motions with high angular precision. The single-channel approach eliminates the multi-sensor complexity while providing a multidimensional measurement capability, achieving excellent real-time performance suitable for dynamic motion analysis. Table I summarizes the comparative analysis of paper reviewed in this work, in context to their focus area, finding, research methodologies used and potential research gaps.

RESEARCH GAP

Although remarkable progress has been made in Self-Mixing Interferometry (SMI), there remain significant areas of research that must be addressed before it can be more widely used in industry, including algorithms, hardware, implementation, and standardization. Challenges remain, as existing deep learning approaches [8] depend on high-latency cloud computing, which is not suitable for real-time deployment at the edge, and adaptive, physics-informed hybrid models are largely under-researched. The same difficulties exist in precision enhancement, and while it is possible to achieve sub-10 nm accuracy in controlled laboratories [5, 7], the effect of working in the real world is to reduce performance, and hardware systems such as dual-wavelength sensors [5, 6] not only increase the cost of the system but also compromise the dynamic range. This has resulted in the development of many algorithms for high-precision operation below 100 Hz, which is in conflict with the industrial kilohertz requirement. Optimized edge AI accelerators and FPGA/ASIC implementations are scarce [1-3]. In addition, there is still no broad testing of SMI under extreme conditions, and no self-diagnostic feature enables robust deployment in the field. This fragility is further affected by the absence of standardized benchmarking, reference datasets, and calibration protocols, which restrict objective evaluation and regulatory acceptance in metrology industries. Finally, application-specific approaches, such as the clinical validation of biomedicine or integrated multi-parameter sensing systems for structural monitoring, are still complex and underdeveloped [9, 10]. Solving these interdependent challenges, edge AI, integrated photonics, and advanced signal processing, will be vital to accelerate the path of SMI from laboratory research to a leading next-generation sensor technology

Conclusion

This review summarizes the evolution of the Self-Mixing Interferometry (SMI) technology from a niche laboratory tool to a broad industrial metrology measurement platform with sub 10nm precision and a low cost. This has been propelled by recent advances in artificial intelligence, signal processing and hardware. A quantitative record-breaking new level of fringe detection in noisy environments has been achieved using deep learning, while sophisticated computational algorithms and the use of dual-wavelength systems has resulted in unprecedented accuracy for distance and velocity measurements. In practice, however, compromises have to be made to a large extent. This means higher cost and complexity of hardware and complex signal processing algorithms that demand a lot of computations making for slow sampling rates in real time. Important research challenges which must be addressed are: how to deploy the Edge AI, how to establish benchmarking protocols and how to test it properly in extreme environmental conditions. The new generation of SMI will be a combination of physics-informed neural networks, integrated silicon photonics, and quantum-sensing. While SMI technology performs as well as a traditional interferometer and significantly less expensive than a traditional interferometer for a controlled environment, it will inevitably become a commonly used sensing technology in manufacturing, healthcare and more as it surmounts reliability barriers in real world use.

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