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Integration of Vision Systems and CMM Inspection in Precision Manufacturing

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Abstract

The article is dedicated to the transformation of dimensional inspection in precision manufacturing through the integration of machine vision systems and coordinate measuring machines. Relevance is determined by increasing geometric complexity of components and the need to maintain micron-level accuracy under high production rates. The work describes the structural reorganization of inspection processes into distributed measurement systems where sensing, validation, and control are interconnected. Special attention is paid to data fusion mechanisms, calibration strategies, and the redistribution of measurement uncertainty across heterogeneous sensing layers. The work sets itself the task of explaining how integrated inspection architectures improve both efficiency and measurement reliability. Analytical review and conceptual interpretation of recent scientific studies are used to solve it. Such sources have been studied in terms of measurement architectures, in-line metrology, optical coordinate systems, and uncertainty propagation models. The conclusion shows that integration does not merge technologies into a single method but restructures them into a hierarchical measurement infrastructure combining speed, coverage, and traceable accuracy. The article will be useful for researchers and engineers working with advanced inspection systems in precision manufacturing environments.

Keywords: precision manufacturing, machine vision, coordinate measuring machine, data fusion, in-line inspection.

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Introduction

Dimensional verification in precision manufacturing increasingly operates under conditions where geometric tolerances approach micrometre scales while production systems demand continuous throughput. Under such constraints, inspection cannot remain isolated from production processes. It becomes embedded within them. Traditional measurement approaches, based on sequential verification using coordinate measuring machines, provide high accuracy but introduce temporal discontinuities. Measurement interrupts production. This limitation becomes critical when component geometries are complex and production cycles are compressed.

At the same time, vision-based inspection systems extend measurement capabilities by enabling rapid, non-contact data acquisition.They acquire extensive volumes of geometric data without disrupting the continuity of manufacturing processes, yet their performance shows strong dependence on surrounding conditions and material surface characteristics, which generates a structural imbalance where speed increases while measurement stability becomes conditional, and the coexistence of these properties drives a transformation in inspection logic so that measurement is no longer associated with a single device but instead emerges from the interaction among multiple interconnected systems.

The purpose of this study is to develop a conceptual framework for integrated vision–CMM inspection systems and to clarify how their interaction reorganizes dimensional control into coordinated measurement infrastructures.

To accomplish this aim, three research objectives are established, where the first focuses on identifying the internal architecture of integrated inspection systems and determining the distribution of measurement functions between sensing and validation layers, the second addresses the analysis of mechanisms through which heterogeneous data sources are combined and interpreted including calibration procedures and data fusion strategies, and the third examines how such integration influences temporal dynamics and operational efficiency of inspection processes within production environments.

The hypothesis assumes that measurement accuracy in integrated systems is not determined by individual sensor performance but emerges from the interaction between optical and coordinate measurement layers through structured data exchange and uncertainty redistribution.

Novelty is defined by the reinterpretation of inspection not as a sequence of measurement operations but as an interconnected system of data flows, computational transformations, and control feedback. Existing studies describe optical and coordinate metrology separately or compare their performance, while insufficient attention is given to the mechanisms through which they interact as parts of a single measurement infrastructure.

Methods and materials

The literature base was assembled through targeted searches in international scientific databases, including Scopus, Web of Science, and IEEE Xplore, focusing on publications from the last five years. Search queries combined domain-neutral keyword clusters such as “optical metrology AND coordinate measurement,” “machine vision AND inspection systems,” and “data fusion OR in-line measurement,” allowing identification of studies addressing both individual measurement technologies and their interaction within production environments.

The initial retrieval produced approximately forty publications, which were subsequently narrowed to a focused set of studies through selective comparison. The selection emphasized works that described operational structures, data processing mechanisms, and implementation-level interactions between measurement systems rather than isolated performance metrics. Studies confined to single-sensor assessment without accounting for system-level integration were excluded from consideration.

The reviewed body of literature demonstrated several recurring structural patterns, where measurement systems were commonly described as layered configurations in which sensing, processing, and validation function as interconnected elements, while the relationships among these elements were articulated through calibration models, data fusion algorithms, and feedback mechanisms linking measurement outputs with production control, and the observed outcomes reflected expanded measurement coverage, enhanced temporal efficiency, along with condition-dependent improvement in accuracy under the combination of heterogeneous data sources. At the same time, the analysis exposed fragmentation in existing descriptions. Optical and coordinate measurement processes were often examined independently, with limited explanation of how their interaction reshapes system behavior.

The sources varied in analytical depth, ranging from experimental studies focused on calibration accuracy to system-level analyses of in-line metrology and digital manufacturing environments. This heterogeneity revealed a gap. Individual elements of inspection systems are described in detail, yet their interdependence remains insufficiently clarified.

Comparison of these studies led to the need to interpret integrated inspection not as a combination of technologies but as a unified process in which measurement, computation, and control form a continuous operational structure. The analysis is limited by variability in experimental configurations, sensor types, and calibration approaches described in the reviewed studies, which restricts direct quantitative comparison.

Results

The inspection process in precision manufacturing increasingly behaves as a distributed measurement system rather than a single-stage verification procedure.

Measurement no longer occurs at one point in the production chain. It is decomposed into interacting layers where data are captured, transformed, and validated across multiple sensing modalities. Within such a configuration, vision systems and coordinate measuring machines form complementary subsystems, each occupying a distinct functional position in the overall metrological architecture.

Table 1. Functional roles of vision systems and CMM within integrated metrological architecture (compiled by the author based on Catalucci et al., 2022; Castro-Martin et al., 2021; Stojadinovic et al., 2021)

System Component	Primary Function	Operational Position	Data Characteristics	Limiting Factors
Vision Systems	Rapid geometric data acquisition	In-line / near-process	Dense, continuous, high-frequency	Sensitivity to surface, lighting, occlusion
CMM Systems	High-precision validation	Post-process / selective	Sparse, high-accuracy, traceable	Limited accessibility, slower operation
Data Fusion Layer	Integration of heterogeneous datasets	Computational layer	Hybrid, reconstructed geometry	Model dependency, data quality
Calibration Layer	Alignment of coordinate systems	Cross-system interface	Parameterized transformations	Environmental stability
Control Interface	Feedback to manufacturing system	Process integration	Corrective signals	Latency, uncertainty propagation

A persistent observation emerges when inspection is examined at the level of data flow rather than equipment type. Optical systems tend to operate as high-frequency acquisition layers, capturing dense spatial information under real-time constraints, while coordinate measurement systems operate as stabilizing layers that impose geometric rigor and traceability. This separation is not arbitrary. It reflects fundamental differences in how measurement uncertainty propagates through contact and non-contact modalities. Optical acquisition introduces variability at the level of surface interaction, lighting conditions, and feature detectability, whereas CMM measurement concentrates uncertainty in probe positioning, accessibility, and path planning. When these systems are integrated, uncertainty is redistributed rather than eliminated.

Calibration procedures illustrate this redistribution explicitly. In camera-based inspection pipelines, geometric calibration requires alignment between image space and physical coordinates through intrinsic and extrinsic parameter estimation. Under machine learning-assisted calibration, reprojection errors can be reduced below 0.05 pixels, with experimental comparisons against optical CMM references confirming stability of parameter estimation across multiple poses (El Ghazouali et al., 2022). At the same time, average dimensional errors below 12 µm and sub-micrometre repeatability have been demonstrated for large-scale vision-based inspection scenarios, indicating that properly calibrated optical systems approach coordinate-level accuracy under controlled conditions (El Ghazouali et al., 2022). The implication is not equivalence between systems, but conditional convergence: optical measurement approaches coordinate metrology only when calibration, environmental control, and feature detectability remain stable.

A different mechanism appears when measurement is embedded directly into production flow. In-line metrology systems reorganize inspection by relocating measurement to the point of manufacturing. In such configurations, dimensional verification occurs within cycle times constrained by production throughput, typically requiring measurement operations within 20–25 s windows while maintaining target precision on the order of 0.040 mm for critical features (Castro-Martin et al., 2021). This temporal constraint reshapes system architecture. Measurement devices must prioritize speed and robustness, often relying on non-contact sensors combined with high-speed positioning systems reaching velocities of 6 m/s and resolutions of 0.001 mm. Under these conditions, measurement accuracy is no longer a static property of the instrument but a dynamic outcome of synchronization between sensing, motion, and data processing layers.

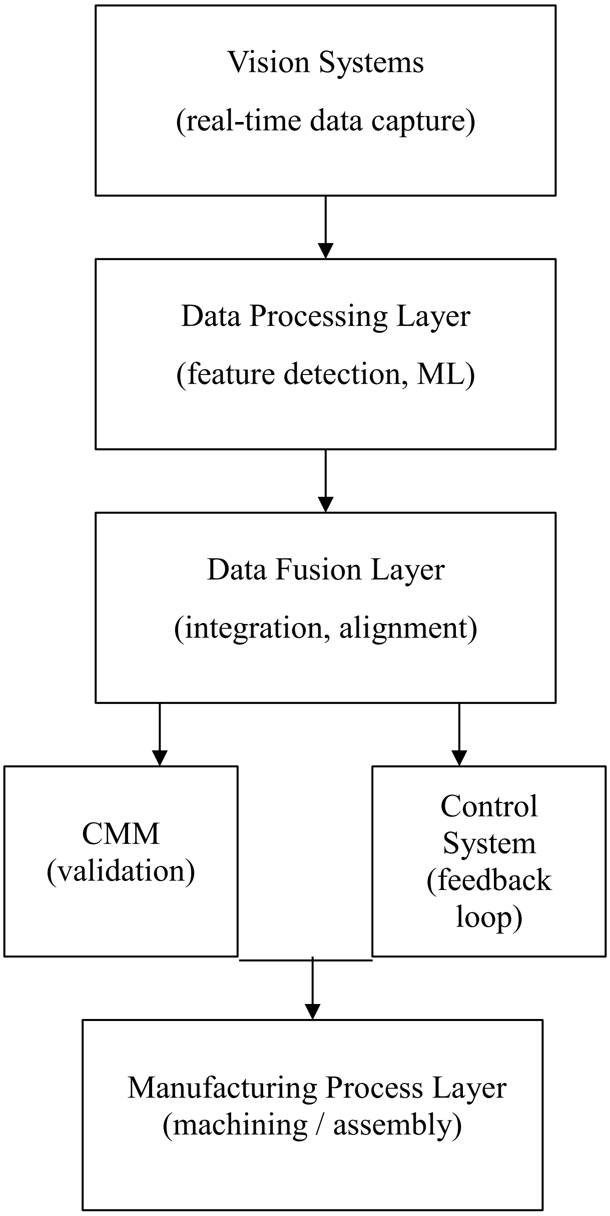
The integration with coordinate metrology introduces a second transformation. CMM systems extend the measurement chain by providing reference-grade verification and structured inspection planning. When inspection planning is formalized through algorithmic models, the measurement process itself becomes computationally optimized. For example, optimization of probe trajectories using ant colony algorithms reduces total measurement path length by 12.81–30.11% relative to conventional programming strategies and by 3.71–15.16% relative to automated STEP-NC generation, directly decreasing inspection time without altering measurement fidelity (Stojadinovic et al., 2021). This reduction reflects a deeper mechanism: efficiency gains are achieved not by faster measurement execution, but by restructuring the spatial sequence of measurement points. Time is redistributed across the path rather than compressed within individual measurements.

Such restructuring becomes critical when integrating vision-derived data. Optical systems generate dense point clouds with incomplete coverage due to occlusion, surface reflectivity, and material properties. Intricate geometrical forms, especially those characteristic of additive manufacturing processes, generate inaccessible zones and line-of-sight discontinuities that reduce the completeness of measurement coverage. In these cases, the function of CMM inspection shifts from primary measurement to selective validation. Contact probing is applied to geometrically critical features where optical uncertainty exceeds acceptable thresholds. The measurement system effectively partitions the geometry into regions of optical sufficiency and regions requiring coordinate verification.

The interaction between these regions is governed by data fusion mechanisms. Combining datasets from multiple sensors increases measurement coverage and improves estimation accuracy beyond what can be achieved by a single modality. Data fusion algorithms, including Gaussian process models and weighted least-squares approaches, enable reconstruction of geometric features from heterogeneous inputs, while machine learning methods extend this capability to complex geometries without predefined models (Zhang et al., 2023). In practice, this results in hybrid measurement fields where sparse high-accuracy CMM points anchor dense but less certain optical data. The geometry is reconstructed through statistical reconciliation rather than direct measurement alone.

An additional layer emerges when measurement is performed in-process. Vision-based systems embedded into machining environments capture dimensional deviations during production rather than after completion. This alters the temporal structure of quality control. Deviations are detected before they accumulate into defects. Feature-based vision models enable measurement of machining precision directly on the machine tool, linking geometric interpretation with process parameters and enabling corrective actions without interrupting production (Li et al., 2024). The measurement system becomes part of the control loop.

Figure 1. Integrated measurement-control architecture for vision systems and CMM inspection (compiled by the author based on Zhang et al., 2023; Li et al., 2024; Zhou et al., 2025)



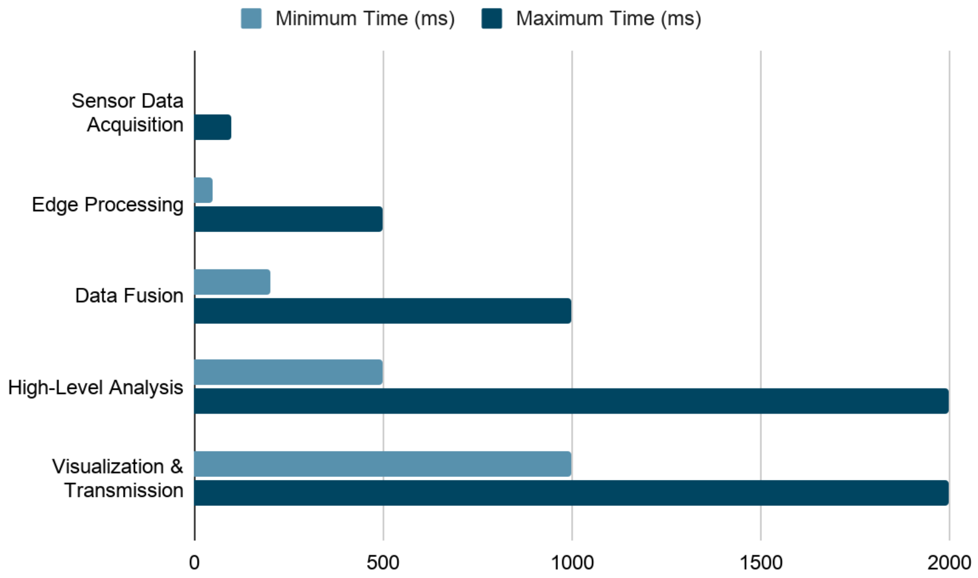
The behavior of integrated systems under uncertainty reveals further structural properties. In multi-camera or monocular vision-guided configurations, uncertainty propagates through kinematic chains linking sensor observations to actuator movements. When this propagation is explicitly modeled, system-level accuracy can be restored through compensation algorithms that map visual deviations to mechanical corrections. Such mappings have been successfully applied in complex assemblies, including aircraft structures, where multi-camera inputs are transformed into actuator adjustments across multi-axis systems, enabling successful assembly under high precision requirements (Zhou et al., 2025). Here, measurement is inseparable from motion control.

Optical coordinate measurement systems provide an intermediate case between pure vision and classical CMM inspection. Optical CMM platforms combine non-contact sensing with coordinate frameworks, allowing high-density measurement while preserving traceability. Their application to edge wear and surface evaluation demonstrates the ability to capture detailed geometric variations while maintaining compatibility with coordinate-based quality assessment procedures (Rzepka et al., 2024). The resulting datasets bridge the gap between surface characterization and dimensional metrology, particularly in applications where contact probing is impractical.

A distinct configuration arises in vision-based coordinate metrology using structured artefacts. Multi-sphere artefacts encoded with spatial patterns enable vision systems to reconstruct coordinate frames with high precision, effectively transforming image-based measurements into coordinate measurements. This approach demonstrates that coordinate metrology can be achieved without physical probing when geometric constraints are embedded into the measurement object itself (Isa et al., 2024). The measurement system shifts part of its functionality into the artefact.

At the system level, integration requires coordination across heterogeneous computational layers. Measurement data originate at the sensor level, are processed at edge devices within milliseconds, and are aggregated at higher computational levels for analysis and decision-making. Typical response times range from 1 to 100 ms at the sensor level, while higher-level processing may require up to 2 s for visualization and data transmission (Castro-Martin et al., 2021).

Figure 2. Temporal distribution of processing stages in integrated inspection systems (compiled by the author based on Castro-Martin et al., 2021; El Ghazouali et al., 2022)



This hierarchy ensures that rapid local responses coexist with slower global analysis. The measurement system operates simultaneously in real-time and analytical modes. Several limitations should be acknowledged. Differences in measurement principles complicate direct comparison between optical and contact systems, particularly in relation to surface-dependent errors and traceability. Optical measurements are sensitive to material properties such as reflectivity and translucency, while contact measurements are constrained by probe accessibility and interaction forces. Data fusion mitigates these limitations but introduces its own dependencies on model selection and data quality.

Integration does not eliminate the distinction between vision systems and CMM inspection. It reorganizes their interaction.

Measurement becomes a coordinated process rather than a single operation.

Discussion

A shift becomes visible when inspection is examined as an operational system rather than a sequence of verification steps. Measurement begins to behave as a distributed infrastructure embedded into production flow, where sensing, computation, and validation no longer operate independently. The interaction between vision systems and coordinate measuring machines reorganizes this infrastructure into layered configurations. Each layer performs a distinct function. None operates in isolation.

Within this configuration, vision subsystems continuously capture geometric information at high frequency, forming dense spatial representations that evolve alongside the manufacturing process. Their behaviour depends on interaction with physical surfaces. Reflectivity alters signal intensity. Occlusions fragment datasets. Noise accumulates. The mechanism of data acquisition therefore remains inherently unstable. Accuracy fluctuates.

CMM subsystems intervene at a different stage of this process. Their function emerges not as repetition of measurement but as imposition of geometric discipline. Sparse probing sequences introduce reference points that stabilize spatial interpretation. These points do not increase data density. They constrain it. The measurement field becomes anchored.

Accuracy, under such conditions, develops through reconciliation rather than direct observation. Dense optical data provide coverage. Sparse coordinate measurements imposes structure. The system negotiates between them. Measurement ceases to be a property of a device. It becomes a property of interaction.

This interaction extends into the computational layer where data fusion mechanisms operate. Combined datasets do not simply accumulate. They undergo transformation through statistical alignment, regression models, and learning-based reconstruction. Geometry is inferred. Not fully measured. The reconstruction depends on model assumptions, parameter tuning, and data consistency. Stability emerges conditionally.

In practice, this introduces a secondary dependency. Measurement reliability becomes tied not only to sensor behaviour but to computational interpretation. When datasets remain consistent, reconstruction converges. When variability increases, deviations propagate through the model. The system responds by redistributing uncertainty across layers. It does not remove it.

Temporal organisation reveals another structural transformation. Measurement no longer interrupts production cycles. It synchronizes with them. In-process vision systems capture deviations during machining, while coordinate verification operates selectively. The inspection process unfolds in parallel with manufacturing. Time is no longer segmented. It becomes continuous.

This continuity alters control logic. Measurement outputs begin to influence production parameters directly. Deviations trigger corrective actions. Feedback loops form. Inspection integrates into control infrastructure. The boundary between measurement and manufacturing weakens.

At the same time, synchronization introduces constraints. Data acquisition operates within milliseconds. Interpretation requires longer intervals. Processing delays accumulate, particularly when dense point clouds are reconstructed or multi-view data are aligned. The system experiences imbalance. Sensing accelerates. computation lags. Responsiveness depends on managing this disparity.

Uncertainty propagation further complicates system behaviour. Optical systems translate image data into spatial coordinates through calibration models. Coordinate systems rely on kinematic precision. Their uncertainties differ in origin and structure. When combined, they interact non-linearly. Errors do not sum directly. They reshape each other.

This interaction becomes critical when measurement drives mechanical action. In vision-guided assembly or adaptive machining, deviations detected in image space must be translated into actuator adjustments. Without explicit modeling of error propagation, corrections introduce instability. Control becomes sensitive to measurement noise.

An alternative trajectory emerges in approaches where measurement capability shifts toward the environment itself. Encoded artefacts and structured geometries embed spatial reference into objects. Vision systems reconstruct coordinate frames using these embedded constraints. Calibration dependence decreases. The measurement system extends beyond instruments.

Several limitations remain visible. The analysis relies on studies employing heterogeneous configurations, including variations in sensor types, calibration procedures, and environmental conditions. Direct comparison of accuracy metrics remains restricted. Optical measurements demonstrate sensitivity to lighting, vibration, and material properties, while coordinate measurements depend on accessibility and probing strategy.

Another constraint relates to computational models used in data fusion. Machine learning approaches require representative training data and controlled conditions.

When operational environments deviate, performance degrades. Interpretability remains limited. Decision processes become partially opaque.

Integrated inspection does not collapse measurement technologies into a single method. It reorganizes their interaction into a coordinated system where sensing, computation, and validation operate as interdependent layers. Measurement shifts position inside the production process. It operates from within.

Conclusion

Inspection systems reveal a structural transformation when analysed as coordinated infrastructures rather than isolated instruments. Measurement functions distribute across sensing and validation layers, where vision systems generate continuous geometric information and coordinate systems impose reference constraints that stabilize interpretation.

Interaction between heterogeneous datasets unfolds through calibration and fusion mechanisms that convert fragmented observations into coherent spatial representations. These mechanisms redistribute uncertainty across the system, allowing stable operation under variable conditions without eliminating variability at the source.

Temporal organisation changes as measurement aligns with production flow. Inspection no longer interrupts manufacturing cycles. It develops in parallel with them, combining rapid acquisition with selective verification. Synchronization replaces sequential operation.

Accuracy emerges from interaction. Not from devices.

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