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Artificial Intelligence in Metrology

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Annotation: *This article explores the applications of artificial intelligence (AI) technologies in metrology, particularly in the field of optical measurement. The study analyzes the early-stage use of artificial intelligence, machine learning, and deep learning algorithms in quality control tasks such as image segmentation and classification. The use of AI in optical measuring instruments for detecting abrasive grains on the surface of grinding tools—evaluating their distribution, size, and height—is examined as a practical example. Additionally, the article discusses future scenarios in which AI could not only detect defects but also identify production deficiencies, provide feedback, and even autonomously trigger corrective actions. The findings demonstrate that AI in metrology holds strong potential not only to reduce human workload but also to support complex decision-making processes in industrial environments.*

Keywords: *Artificial intelligence, metrology, optical measurement, image processing, segmentation, classification, deep learning, machine learning, abrasive grains, quality control, production automation, digital metrology.*

Introduction.

Optical measurement systems have notably outpaced tactile methods in terms of artificial intelligence integration. Much like humans, AI systems learn from experience, assist in daily activities, and simultaneously evoke both fascination and concern. As AI steadily becomes embedded in industrial processes, questions arise regarding its role in quality control. To what extent can artificial intelligence currently contribute? Which capabilities remain within the realm of future potential? And importantly, how much trust and responsibility are we prepared to delegate to such systems?

The development of AI.

Modern artificial neurons utilize sophisticated algorithms to replicate the function of human brain cells. These intricate interconnections—collectively referred to as neural networks—empower machines to tackle a wide range of tasks across various domains. Neural networks possess the capability to learn autonomously and refine their own performance over time[1]. At the core of artificial intelligence lies this self-improving algorithm. Yet, before such learning can occur, certain prerequisites must be fulfilled: high-performance computing systems and vast datasets are essential for enabling effective machine learning.

The training

Training and Specialization of AI

The process of training artificial intelligence is highly data-intensive. Initially, AI systems lack any inherent knowledge or capability. Unlike human beings—who naturally perceive and distinguish attributes like color or size even as infants—AI requires meticulous instruction to recognize such features[2]. Every function must be explicitly taught. However, AI's strength lies in its specialization: when applied to repetitive and narrowly defined tasks, it performs exceptionally well, particularly in areas that demand high levels of concentration from humans. As a result, properly trained AI not only operates with greater precision but also processes information significantly faster than a human can, and is less prone to making errors.

Artificial Intelligence, Machine Learning, and Deep Learning

Artificial intelligence encompasses all technologies that allow machines to operate based on logical rules and decision-making processes. Within this broad category, machine learning refers to systems that improve their performance through data-driven experiences—learning patterns, making predictions, and adapting to new inputs. A more advanced branch of this is deep learning, which involves neural networks composed of multiple hidden layers[3]. These layers process diverse inputs and stimuli, gradually extracting and transforming them into a defined output. Deep learning enables AI to handle more complex cognitive tasks by mimicking certain structures of the human brain[4].

Current Capabilities of AI in Measurement Technology.

Despite its rapid development in other sectors, artificial intelligence remains at an early stage within the field of metrology. At present, its primary application lies in the area of image analysis. Within this scope, AI is mainly tasked with two key functions: segmentation and classification. These functions form the foundation of how AI contributes to the evaluation of visual measurement data, although the broader integration of AI into measurement processes is still under exploration and development[5].

Segmentation and Classification in AI-Based Measurement

Segmentation involves dividing an image into specific regions that are relevant for quality control purposes. The AI system isolates these areas to focus analysis only where it's necessary, improving accuracy and efficiency.

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Classification, on the other hand, refers to assigning identified features into predefined categories based on their characteristics. For instance, AI can determine the laser class of a component that has undergone laser processing or distinguish and label different object types within a dataset[5].

How AI Learns: Example from Metrology

The training process for both segmentation and classification tasks follows the same principle: the AI is provided with labeled datasets. In the context of metrology, this could involve marking visual data with labels such as "dot" or "scratch." By repeatedly analyzing this annotated data, the AI learns to distinguish between these features. Over time, the system becomes capable of making independent assessments — for example, identifying a defect and determining: "This is a scratch."[6].

Risks of Using AI in Metrology

The potential risks associated with AI in measurement technology are similar to those present in other fields where AI is applied. Although we can observe and understand how input data affects the neurons in the neural network and track the output it generates, the internal decision-making process—the part in between—remains largely opaque[7]. This phenomenon, often referred to as the "black box" problem, poses a challenge in terms of transparency and interpretability.

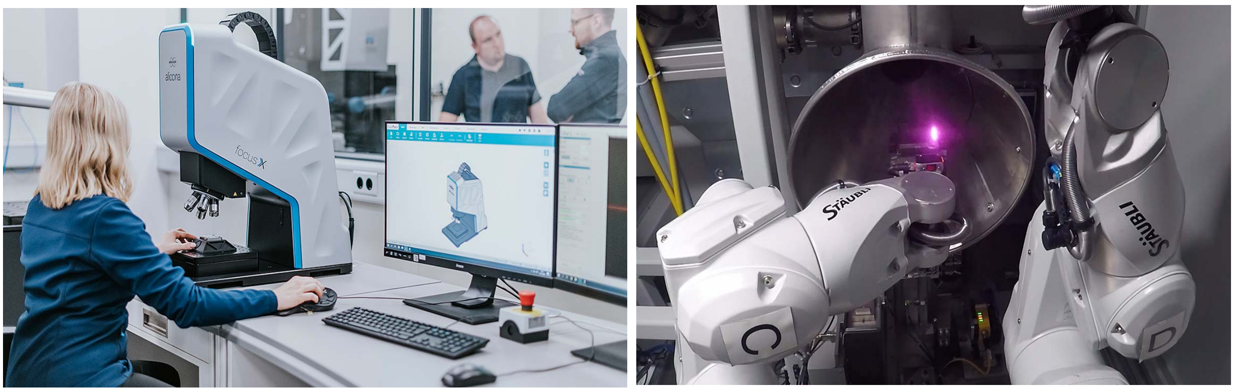
In the specific context of metrology — especially in tasks such as segmentation and classification — this limitation requires users to place considerable trust in the system's internal logic. While AI systems may show high levels of accuracy and reduced error rates, this underlying opacity must be carefully considered when evaluating reliability and accountability in quality assurance processes.

Will AI Replace Human Workers in Quality Assurance?

Given that artificial intelligence has the potential to ease the workload of measurement technicians, a valid question arises: Will AI eventually replace human roles in quality assurance? From today's perspective, such a scenario appears unlikely. One of the most pressing issues currently facing the industry is a widespread shortage of skilled professionals — a challenge that also affects the field of quality control.

Even seemingly simple tasks demand a high degree of precision and expertise. In this context, AI is not so much replacing people as it is addressing gaps in workforce availability. Furthermore, by automating tedious and repetitive detail work, AI enables human workers to focus their time and energy on more complex and high-value responsibilities.

Thus, instead of viewing AI as a threat to employment, it should be seen as a tool for enhancing human effectiveness, allowing existing personnel to be deployed where their skills are needed most.



AI Applications in Optical Metrology: A Closer Look

Laser-treated components offer a clear illustration of how artificial intelligence is being successfully applied within the field of metrology. In the realm of optical measurement technology, several manufacturers have already begun utilizing AI across three primary areas:

Internal Technological Optimization:

AI is being used to enhance and refine the company's own technologies. For example, machine learning algorithms are employed to better determine focal points, reduce measurement noise, and improve image clarity — ultimately enhancing measurement precision.

Customer-Side Data Utilization:

Clients are given access to large-scale measurement datasets that can be used to train their own AI models. Given the enormous data volume required for training accurate algorithms, this service adds significant value.

Custom AI Solutions via Deep Learning:

Tailor-made AI applications are developed for individual customer needs. This typically involves programming specialized deep learning software that addresses specific measurement challenges or component types.

Why Optical Technology Leads in AI Integration

Compared to traditional tactile systems, optical measurement technologies are significantly ahead in integrating AI[8]. This is particularly evident in areal surface measurements, which can only be performed using optical methods. These measurements provide exceptionally detailed data — a valuable asset when training and applying AI. However, as with much of AI, the technology still holds untapped potential, and many applications are only in their early stages.

Use Cases of AI in Measurement Technology

AI is currently being applied in various specific tasks within metrology, including:

Defect Detection: Automated identification of surface flaws.

Laser Class Segmentation: Differentiation of surface treatments based on laser type.

Grinding Grain Analysis: Recognition and categorization of abrasive particles.

Position and Orientation Detection: Accurate spatial alignment of components.

Shot Peening Evaluation: Assessment of treated surfaces for structural integrity.

Contour Recognition: Shape and edge detection for dimensional analysis.

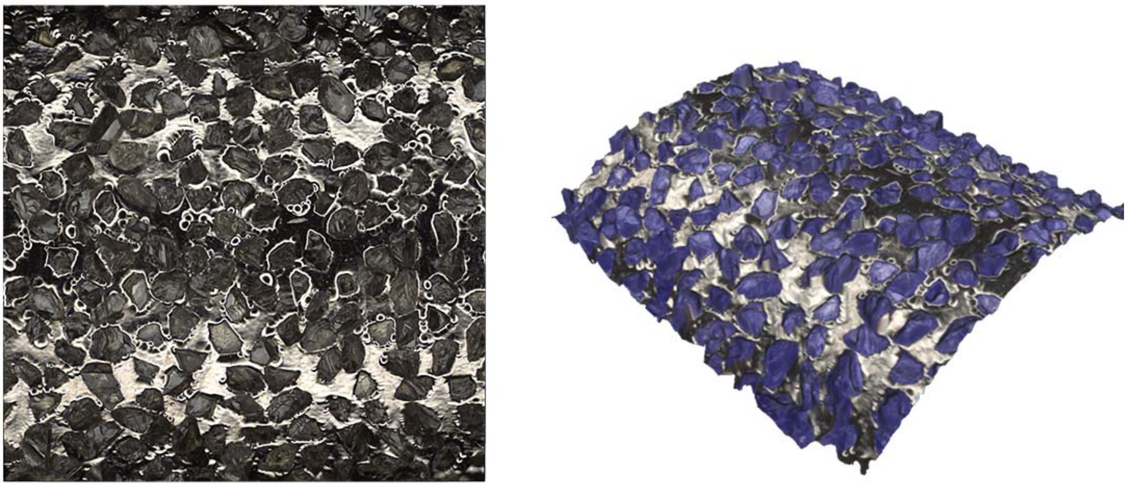


Figure 1: Grinding grains as detected and evaluated by AI.

Practical Example: Surface Analysis of a Grinding Pin

An excellent real-world application of AI in metrology can be seen in the surface evaluation of grinding tools. In Figure 1, all fine abrasive grains on the tool surface are visible. Traditionally, human operators estimate their characteristics—such as size, depth, width, and distribution—based on visual assessment. However, this process is subjective and prone to error[9].

AI, by contrast, can perform this task with high precision and consistency. At the top of the image, we see the surface as perceived by the human eye; below it, the blue dots indicate abrasive grains automatically detected by the AI. Once trained with labeled data to distinguish true abrasive grains from background elements, the AI is capable of quantitatively assessing not only the number of grains, but also their distribution, dimensions, and spatial arrangement (as shown in Figures 2 and 3).

Conventional image processing methods often fall short due to the diversity of materials, bonding agents, and geometries, which create complex lighting conditions and make consistent detection challenging. AI, on the other hand, offers greater robustness and adaptability in such varied scenarios.

The Future of AI in Measurement Technology

There is ongoing debate about the ultimate role of AI in metrology. Some industry experts maintain that AI will remain limited to image processing tasks, such as segmentation and classification[10]. Others foresee a broader transformation, where AI becomes an integral part of autonomous decision-making in production and quality control.

Future Scenarios and Possibilities

To understand where AI might be headed, it is essential to move beyond concepts like the digital twin and consider AI's integration across entire process chains. One possible development is the intelligent generation of measurement plans based on CAD models and PMI (Product Manufacturing Information). Though some professionals remain skeptical, this could significantly simplify the work of measurement technicians.

Going further, AI could take on a supervisory or intermediary role, bridging metrology and production. In this scenario, the AI would not just detect anomalies — it could also identify root causes within the production process, provide feedback, or even trigger corrective actions automatically. Such closed-loop systems could enhance process reliability and efficiency [10].

While all of this lies within the realm of possibility, the timeline for such advancements remains uncertain. The pace of development will depend on technological progress, data quality, industry readiness, and regulatory considerations.

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