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MICROSCOPIC FIDUCIAL MARKERS FOR INDUSTRIAL METROLOGY APPLICATIONS

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Abstract: Metrology and quality control are essential for advancing European manufacturing toward zero-defect and sustainable production. Integrating optical measurement with computer vision and digital twins enables real-time monitoring and precise process optimization. Accurate alignment of high-resolution 3D data is critical for automating workflows and reducing uncertainty in complex manufacturing environments. This paper explores a fiducial microscopical marker-based approach to improve 3D dataset alignment in optical metrology, particularly for focus variation systems. Two microscale marker designs - mechanical indentations and precision-milled crosses - were evaluated for use with Alicona Infinite Focus systems.

Key words: fiducial markers for microscopical metrology, industrial manufacturing, 3D dataset alignment

1. INTRODUCTION

In the past decades Industrial metrology has undergone a major transformation driven by the fast advances in electronics and computing power and the rising demand for higher precision, increased productivity and autonomous data collecting and evaluation. As European manufacturing industry pursues strategies towards zero defect manufacturing and digital transformation, the metrology role changes from isolated inspection to a central and intelligent decision-making process.

Optical metrology has become one of the core branches of modern quality assurance because of the fast, non-disruptive and highly accurate data-collecting [1].

At the same time, the capability of integration into automated production lines together with AI (Artificial Intelligence) driven image processing, pattern recognition and surface or features classification, is enabling real-time process monitoring, automated decision making and predictive quality control thus bridging the gap between measurement data and process optimization [2].

By optical measurement systems, a fundamental principle of data acquisition is the "what-you-

see-is-what-you-measure" paradigm. As a result, when inspecting components with complex geometries or occluding features, multiple measurements from various perspectives are often required to generate a comprehensive and coherent dataset that captures all necessary surface details for subsequent analysis.

2. PROBLEM DESCRIPTION

Evaluation of advanced optical systems such as the Alicona IF G5, Twip Consigno UL, and Keyence VK-X3000 reveals each of them has some common but significant limitations are prone to being influenced by factors such as illumination variability, steep surface transitions and other various errors cumulated on the moving axes of the microscope [4] [5].

Specifically, for components exhibiting intricate 3-dimensional geometries or exceeding the dimensions of the measurement platform, it becomes essential to acquire data from multiple orientations. However, most commercially available systems do not support fully automated multi-angle acquisition due to hardware constraints, particularly the lack of more than three controllable axes.

This limitation is sometimes addressed by incorporating robotic arms to manipulate the sample or sensor. While this approach expands measuring flexibility, it introduces additional challenges. Robotic systems are also subject to cumulative positioning errors across each axis of motion, which can degrade overall measurement accuracy, especially critical in high-resolution applications.

Alternatively, manual repositioning and measuring from various angles has as result multiple partial datasets. These must be accurately registered to reconstruct the complete geometry. While best-fit algorithms are commonly used for dataset alignment, their effectiveness is highly dependent on the presence of well-distributed and distinctive geometric features.

In practice, 3D microscopical dataset alignment presents the following major challenges:

A. Lack of Distinct Geometric Features:

Surfaces lacking well-defined or easily recognizable features limit the accuracy of best-fit alignment algorithms, often resulting in misaligned or imprecise registrations.

B. Cross-Instrument Alignment:

Different measurement systems use distinct coordinate frameworks and optical settings, and without shared features or uniform referencing, aligning their datasets accurately is challenging.

C. Alignment for Sequential Measurements:

When measuring the same component at different stages, such as before and after a manufacturing or wear process, precise alignment of the datasets is crucial. This ensures that true surface changes can be accurately identified and quantified, while minimizing the risk of errors caused by misregistration.

3. BACKGROUND

Correlating images using referencing points has been done since the beginning of the 20th

Century alongside the development of aerial photogrammetry.

The microscopical optical measuring systems are in general based on the same functioning principles as the ones used in classical surveying with the main difference being only the scale of the objects to be measured.

In the nanometer area microscopy (EM microscopes) fiducial markers are also already extensively used [6].

Despite this widespread use of markers in both macroscopic and nanoscopic measurement systems, there remains a notable research gap in the application of such techniques for micro-scale precision measurements. This study aims to address this gap by investigating and developing methodologies tailored specifically for high-accuracy measurements at the micrometer scale.

5. SOLUTION

The development of microscopic fiducial markers that can be either directly fabricated or fixed to the component under measurement eliminates the reliance on prominent surface details to be used as reference points during data alignment phase.

This advancement facilitates the automation of data acquisition and processing, while also enabling interoperability across various measurement instruments and software platforms. Consequently, the total time required to generate the final integrated dataset is significantly reduced.

6. DISCUSSION

Following a conceptual exploration and a critical review of existing use cases, including consideration of material properties, microscope compatibility and marker typologies encountered in related applications, several key criteria were identified to guide the design and fabrication of the fiducial markers as outlined below:

Size and Detectability:

Markers must be sufficiently large to be easily observable within the field of view of the measurement system. Simultaneously, their

dimensions must allow for high-resolution identification at magnified scales, thereby supporting precise spatial registration.

Unique Geometric Encoding:

The geometry of each marker should incorporate distinct features such as alphanumeric symbols or unique shapes to facilitate automatic recognition and differentiation by image processing algorithms. This enables robust marker tracking across multiple datasets.

Non-Invasiveness:

Markers should be designed to be non-intrusive, ensuring they do not alter the functional characteristics of the component under investigation. Their presence must not interfere with either the process performance or the structural integrity of the part.

Durability Under Process Conditions:

Markers must exhibit high resilience to the operational conditions of the fabrication process, including exposure to elevated temperatures, pressures, or chemical environments. This ensures that the same set of markers can be used throughout multiple measurement cycles without degradation.

Reusability and Cost-Efficiency:

Ideally, markers should be reusable or fabricated from materials and processes that are cost-effective. This consideration is essential for scalability and sustainable integration into industrial workflows.

7. METHODOLOGY

STEP 1. Fiducial micro-markers fabrication

Based on the above-mentioned criteria, several types of fiducial markers were conceptualized. However, for the purposes of this study, the experimental evaluation was limited to two variants that best met some of the selection criteria, despite each exhibiting certain limitations in terms of precision, manufacturing cost, or ease of implementation. Future research may also focus on exploring alternative types of markers that are more compatible with the

defined criteria, potentially enhancing the precision, robustness, and overall effectiveness of the proposed system.

Marker 1: Small-scale indentations with hemispherical geometry with diameter between 400 μm and 1 mm (**Fig. 1.**)

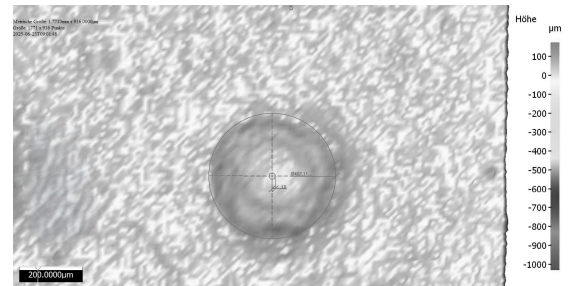


Fig. 1. Hemispherical indentation marker

These were manually fabricated by striking a metal plate with a nail, thereby producing the forementioned localized deformations. The geometric center of the resulting markers served as a reference point for initial alignment during data registration and was estimated to be between 10 μm and 50 μm precise.

Marker 2: Milling machine engraved cross with adjacent circles (**Fig. 2.**)

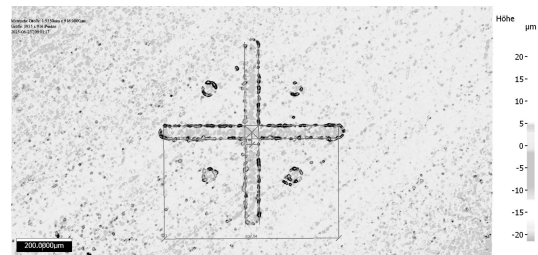


Fig. 2. Engraved cross with adjacent circles – marker

Using a Präzoplan Mauser milling machine, precision fiducial crosses were machined onto an aluminum component. Each fiducial consists of two orthogonal grooves, each measuring 600 μm in length. The intersection point of the cross can be manually identified with an accuracy of less than 2 μm . These crosses remain optically discernible under microscope objectives ranging from 5 $\times$ to 50 $\times$ magnification.

To facilitate automated identification, additional features were integrated into the design: each of the four quadrants surrounding the central cross

contains a 30 μm diameter milled circle as in Fig. 1. These circular markers serve as reference elements for a subsequent image recognition algorithm, enabling it to count the number of circles associated with each cross and thereby assign a unique identifier to each fiducial. Furthermore, standard image processing techniques, specifically the detection of pairs of parallel lines representing the arms of the cross, can be employed to determine the intersection of their midlines, thereby providing a reliable estimate of the geometric center of each fiducial.

STEP 2. Implementation of the proposed markers on actual measurable parts

PART A: Flat metal part with no distinguishable geometrical features.

The objective of this measurement campaign was to characterize the surface topology resulting from the water erosion process under varying operational parameters. The initial step involved acquiring a reference scan of the metal substrate prior to the onset of erosion. To facilitate precise spatial alignment post-process, six fiducial stamping markers (Marker 1) were introduced at the corners of the sample. These markers remained visible after machining, enabling consistent dataset registration.

Data acquisition was performed using the Laboratory Measurement Tool Software in conjunction with proprietary Alicona software. An initial coarse manual alignment of the pre- and post-process surface datasets was conducted, followed by a fine alignment using a best-fit algorithm to ensure optimal correspondence between the two surfaces.

Subsequently, differential surface analysis was carried out, enabling extraction of relevant geometric parameters such as erosion depth, feature length, and volumetric loss. The presence of the reference dataset and fiducial markers was critical for accurate feature extraction, as the substrate surface exhibited inherent curvature. This curvature would otherwise introduce significant errors in micron-scale volumetric evaluation due to misalignment.

An alternative strategy considered was to scan the entire surface area of the metal plate to

capture edge features for alignment. However, this approach was considered impractical due to the extensive data acquisition time associated with the high spatial resolution (1 μm), as well as the excessive volume of irrelevant data that would have been generated.

Part B: A milling cutter tool edge

The objective of this measurement was to evaluate wear through different milling process parameters and over a timespan. The Alicona Infinite Focus G5 System, equipped with additional A and B axes for rotation and tilting, was specially designed to collect detailed data from milling cutter tools. The system automatically combines data using recorded values from the moving axes, overlapping image correlation, and best-fitting algorithms. However, when measuring the same tool after multiple milling processes, the software sometimes cannot perfectly overlap datasets taken at different times, which complicates the evaluation of the geometric features of the wear. By using the proposed marker system along with its corresponding software algorithms, dataset registration can be simplified, enabling a quantitative evaluation of overall measurement accuracy and effectively achieving the wear evaluation objective.

Although the paper continues with two additional steps described, their implementation requires further investigation and substantial effort. These steps represent a potential direction for future work, but for now, they remain conceptual and will be considered for development in future research.

STEP 3. Developing a computer vision algorithm that can easily identify and use the targets by their geometries

Detecting the geometric center of cross-shaped fiducial markers in image data is a common task in precision metrology, microscopy, and automated alignment systems. Classical computer vision techniques, particularly those implemented in the Open Source Computer Vision Library (OpenCV), offer efficient and robust methods for this purpose. A widely used

approach involves applying edge detection (e.g., the Canny algorithm) followed by the Hough Line Transform to extract the linear components of the cross. Once the two main perpendicular lines would be identified, their intersection point can be computed analytically to determine the center of the marker with subpixel precision. This method is well suited for high contrast, structured patterns and provides a computationally efficient alternative to more complex machine learning in cases of noise or deformation, and additional filtering or contour-based techniques may be integrated to improve robustness [7].

STEP 4. Alignment of data sets using a suitable computational method

The Kabsch algorithm [8], a closed-form solution derived from the least squares method [9], can be used to perform an initial raw alignment of two sets of corresponding points by minimizing the root mean square deviation (RMSD) between them. This approach uses the optimal rotation matrix under the assumption of known point correspondences in Euclidean space. Following this coarse registration step, the Iterative Closest Point (ICP) algorithm [10] is applied to refine the alignment. ICP iteratively minimizes the distance between the source and target point clouds by updating point correspondences and computing the transformation that best aligns them. This two-stage process enables robust and precise 3D registration, with the ICP stage additionally providing a quantitative measure of registration quality.

8. CONCLUSION

The integration of microscale fiducial markers in optical metrology presents a robust and scalable solution to the persistent challenges of multi-angle and multi-instrument 3D dataset alignment, particularly in scenarios lacking distinctive geometric features. By using machined targets augmented with geometrically unique identifiers and classical computer vision techniques, accurate and automated detection of fiducial centers is achievable. This facilitates not

only reliable registration of data from complex geometries or high-resolution measurements but also ensures repeatability across temporal acquisition sessions. Furthermore, the combination of the Kabsch algorithm for initial rough alignment and the Iterative Closest Point (ICP) method for fine-tuning enables highly precise 3D point cloud registration. The proposed approach could effectively bridge the scale gap between macro and nanometrology, thereby enhancing measurement accuracy, reducing operator dependency, improving overall data acquisition and processing time and supporting automation in industrial inspection workflows. To comprehensively address the envisioned objectives and to advance the development of fully functional algorithms, further in-depth research and experimental validation are required.

9. REFERENCES

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MARCAJE MICROSCOPICE FIDUCIARE PENTRU APLICAȚII DE METROLOGIE INDUSTRIALĂ

Rezumat: Metrologia și controlul calității sunt esențiale pentru avansarea producției europene către producția durabilă și fără defecte. Integrarea măsurătorilor optice cu viziunea computerizată și gemenii digitale permite monitorizarea în timp real și optimizarea precisă a proceselor. Alinierea precisă a datelor 3D de înaltă rezoluție este esențială pentru automatizarea fluxurilor de lucru și reducerea incertitudinii în medii de producție complexe. Această lucrare explorează o abordare bazată pe markeri microscopici fiduciali pentru a îmbunătăți alinierea seturilor de date 3D în metrologia optică, în special pentru sistemele de variație a focalizării. Au fost evaluate două modele de markeri la scară microscopică - indentații mecanice și cruci frezate cu precizie - pentru utilizarea cu sistemele Alicona Infinite Focus.

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