DOI: 10.21062/mft.2025.014 http://www.journalmt.com

Optimization of Zero-Point Setting for Enhanced Measurement Accuracy

Miroslav Matuš (0009-0002-9214-8696)[1], Mário Drbúl (0000-0002-8036-1927)[1], Jaromír Markovič (0000-0002-5645-6715)[1], Michal Šajgalík (0000-0002-4908-1046)[1], Andrej Czán (0000-0002-8826-1832)[1], Miroslav Cedzo (0000-0002-1872-0925)[1], Richard Joch (0000-0002-9937-0057)[1], Martin Novák (0000-0002-2010-4398)[2], Jana Petru (0000-0002-2378-5678)[3*]
[1]Faculty of Mechanical Engineering, University of Zilina, Univerzitna 8215/1, 010 26 Zilina, Slovakia. E-mail: Miroslav.matus@fstroj.uniza.sk
[2]Faculty of Mechanical Engineering, J. E. Purkyne University in Usti nad Labem, Pasteurova 3334/7, 400 01 Ústí nad Labem, Czech Republic. E-mail: Martin.novak1@ujep.cz
[3]Faculty of Mechanical Engineering, VSB – Technical University of Ostrava, 17. listopadu 2172/15, 708 00 Ostrava, Czech Republic
[*]corresponding author: E-mail: jana.petru@vsb.cz

The precise setting of the zero point represents a critical factor in non-contact measurement of mechanical components, particularly in areas such as the engineering and automotive industries, where high accuracy is key to quality control. This study analyzes the impact of various alignment methods – specifically the best-fit method and the datum method (3–2–1) – on the measurement results of complex geometric shapes. Experimental measurements were conducted using a laser scanner and Polyworks 2015 software. The results indicate that the best-fit method achieves higher accuracy when measuring complex and freely oriented shapes, while the 3–2–1 method provides more consistent results for simply defined geometries. These findings confirm the importance of proper alignment method selection in optimizing non-contact measurement processes and offer new insights for improving efficiency in industrial quality control.

Keywords: Metrology, Best fit, Non-contact Measurement, Coordinate System

1 Introduction

Measurement of geometric properties of components is an integral part of production processes in modern engineering and automotive industries, where even small dimensional deviations can significantly affect the quality, safety, and functionality of final products. These industries require highly accurate and reliable measurement methods capable of capturing even minor dimensional differences, with speed and efficiency often being critical factors.

Modern metrology systems increasingly integrate optical measurement techniques, artificial intelligence (AI), and machine learning algorithms to enhance accuracy and reliability. Adaptive algorithms enable real-time data analysis, reducing errors and improving measurement robustness. The digital integration of these systems into production lines ensures immediate feedback, minimizing deviations and maintaining consistent product quality [1],[2],[3],[4].

In recent decades, non-contact measurement technologies, such as laser scanners and coordinate measuring machines (CMM), have gained widespread adoption. These technologies facilitate the measurement of complex shapes without physical contact with the object, reducing the risk of component damage and increasing productivity. However, the accuracy of non-contact measurements relies heavily on the efficient processing of point clouds. Advanced computational methods, including projection filtering and K-Means clustering, have proven effective in optimizing point cloud alignment and reducing measurement deviations. Furthermore, the integration of AI-driven algorithms has revolutionized dimensional metrology, allowing for automated anomaly detection and predictive analysis in real-time manufacturing environments. The growing reliance on intelligent measurement systems is paving the way for increased automation and enhanced efficiency in industrial metrology [2],[5].

Recent studies have highlighted the concept of Smart Manufacturing and Digitalization of Metrology, where AI and digital twins are used to simulate and optimize measurement processes, further increasing accuracy and efficiency [6]. The concept of the Digital Avatar of Metrology, which integrates virtual simulations with real-world measurement systems, has been explored as a method for improving automation and precision in industrial metrology [7]. These innovations provide a framework for reducing systematic errors, enhancing repeatability, and enabling real-time monitoring of measurement systems.

Laser scanners provide the ability to capture the surface of components with high precision, collecting millions of points in a very short time. These data are subsequently processed into detailed 3D models that allow for in-depth analysis of dimensional and shape deviations of components, thereby optimizing production processes. Studies comparing traditional and non-contact measurement systems have shown that laser scanners and coordinate measuring machines achieve higher accuracy and speed during scanning compared to traditional methods, especially for more complex geometric structures [8].

Christoph, in his study, demonstrated that the 3–2–1 method provides repeatable and consistent results for simpler geometric shapes, where ensuring a high degree of reproducibility is essential [9].

Kiraci and colleagues, in their study, compared the accuracy and efficiency of laser scanning and touch probes in measuring automotive parts. Their research examined the ability of both technologies to capture surface details and the geometry of complex parts. The study found that laser scanning offers high accuracy and speed that meets quality control requirements, particularly for complex surface shapes and geometries [10].

The aim of this study is to analyze the impact of zero-point setting and the selection of appropriate alignment methods on the accuracy of non-contact measurement for components with varying geometric complexities. Experiments were conducted using a laser scanner and Polyworks 2015 software, comparing the results obtained using the best fit and 3–2–1 method. The results of this study could contribute to the selection of optimal measurement methods in industrial practice and support the further development of measurement systems to improve the accuracy and efficiency of industrial control processes.

2 Best fit

The Best-Fit method is a key technique in metrology and 3D scanning, widely used to optimize the alignment of measured data with reference models. This method plays a crucial role in applications where a precise comparison between physical parts and their digital representations is required, allowing for the identification of deviations from nominal values. It is extensively utilized in manufacturing, quality control, reverse engineering, and even in architectural and artistic applications. The fundamental principle of the method lies in mathematical optimization, which ensures minimal deviations between the measured object's surface points and the reference model, often represented as CAD (Computer-Aided Design) data. At the core of the Best-Fit method is the process of aligning measured data with a reference surface. This begins with data acquisition using advanced 3D scanners, which capture coordinate points distributed across the object's surface. These points form a point cloud, representing the object's physical geometry. The next step is aligning the point cloud to the reference model through an iterative process, minimizing the total deviation between the scanned points and the nominal geometry. This optimization involves operations such as translation, rotation, and, in some cases, scaling of the measured object [11].

A key algorithm utilized in the Best-Fit method is the Iterative Closest Point (ICP) method. This algorithm iteratively determines the closest points between the point cloud and the reference model, continuously refining the alignment. Although ICP is highly accurate, its effectiveness is highly dependent on the quality of the initial positioning estimate of the object. If the initial estimate is incorrect, the algorithm may converge to a local minimum, leading to suboptimal alignment. Another commonly applied approach is the Least Squares Fitting method, which minimizes the sum of squared deviations between the measured points and the reference model. This technique is particularly suitable for geometries with well-defined surfaces, such as planes, cylinders, or spherical shapes. However, for more complex surfaces or irregular structures, hybrid approaches combining multiple algorithms are often used to enhance accuracy [12].

The Best-Fit method finds applications across various industrial and research fields. In quality control, it is one of the primary tools for comparing physical parts with their CAD models, enabling rapid identification of manufacturing defects and dimensional deviations. This capability significantly enhances the efficiency of production processes, ensuring compliance with design specifications. The method is also extensively applied in component certification, particularly in automotive, aerospace, and mechanical engineering industries, where adherence to strict dimensional tolerances is essential [13].

Moreover, reverse engineering heavily relies on this technique to generate highly accurate digital models from physical objects. These digital models serve multiple purposes, including the development of new products and the reproduction of spare parts, particularly in cases where original design documentation is unavailable [14].

In industrial metrology, the Best-Fit method is commonly used for precise data alignment from coordinate measuring machines (CMM), which is crucial for the analysis of geometric tolerances. The importance of this method continues to grow with advancements in modern technologies, including high-precision 3D scanners and increasingly powerful data processing software. These tools enable automation of the alignment process, significantly reducing processing time and increasing measurement accuracy. However, despite its many advantages, the method has certain limitations. Data quality is a critical factor, as noise, outliers, or inaccuracies in the scanned data can negatively impact alignment results. Additionally, for highly complex geometries, the computational complexity of the method can become a challenge, particularly when using iterative algorithms that require numerous iterations to achieve optimal alignment [15].

In summary, the Best-Fit method is an invaluable tool in metrology and 3D scanning, facilitating high-precision analysis, quality control, and optimization of manufacturing processes. Its versatility and accuracy make it a key technology in modern engineering, with ongoing improvements through new algorithmic developments and technological advancements. As new solutions emerge, the potential applications of Best-Fit methods are expected to expand, further enhancing efficiency and reliability in industrial measurement [16].

3 Alignment Method 3-2-1

The 3-2-1 method, also known as the fundamental alignment method or minimal reference system, is widely used in metrology for aligning and fixing objects in space. It serves to define a unique and stable coordinate system used for measuring the geometric characteristics of an object. This method is particularly popular in coordinate metrology (CMM) and in aligning data obtained through 3D scanning. It is based on the mathematical principle of defining a coordinate system using three fundamental reference elements: a plane, an edge, and a point. Together, these three elements ensure a unique and stable alignment of the object, eliminating all six degrees of freedom – three translations and three rotations. The principle of the method lies in the fact that the first reference element, the plane, is defined by three points on the surface of the object. This plane serves as the base to eliminate the movement of the object along the perpendicular direction to the plane, typically the Z-axis. The second reference element, the edge, is defined by two points on the surface of the object, restricting the object's movement in the plane, typically along the Y-axis. The third element, the point, fixes the remaining degree of freedom, determining the position of the object along the X-axis. Together, these three elements provide a stable and repeatable way to define the position and orientation of the object. The alignment process according to the 3-2-1 method involves several steps. First, three points on the surface of the object are selected to define the plane that serves as the primary reference. Next, two points are identified to form an edge and determine the object's orientation along the second axis. Finally, one point is used to fix the position of the object along the third axis. In this way, a unique alignment of the object is ensured, free from any remaining movements or rotations. This method is often used in quality control, enabling the alignment of parts and precise measurement of their geometric tolerances. In industrial processes, such as manufacturing and assembly, it is utilized for precise positioning of parts during machining or assembly. In the context of coordinate measuring machines (CMM), the 3-2-1 method is the standard way to create a stable coordinate system for measuring parts. In 3D scanning, it helps align scanned data with reference models or drawings, which is essential for analysis and quality control [17],[18],[21].

The main advantages of the 3-2-1 method include its simplicity and reliability. The method provides unambiguous alignment without the need for iterative calculations or optimization. It is ideal for applications where reference points are well-defined and easily accessible. On the other hand, its main drawback is its dependence on the quality of reference surfaces. If the surfaces are damaged or deformed, the alignment accuracy may decrease. Furthermore, for complex geometries, finding suitable reference points can be challenging, limiting the universality of this method.

4 Methodology

As part of the research, dimensional evaluation of a scanned component made of bent sheet metal, used in the automotive industry, was conducted. The study compared two methods: the best fit method and the 3-2-1 method, with the evaluations carried out in Polyworks 2015 software. To ensure complete data collection, it was necessary to scan the part from all sides without manipulation. To achieve this, the scanned part was secured in a fixation fixture (Fig. 1). Subsequently, due to the high gloss of the scanned surface, chalk powder was applied to reduce surface reflection. To enhance the accuracy of the evaluation, the fitting process was optimized by transforming the measurement data through variable adjustments. This approach significantly reduced measurement uncertainty and improved the stability of the applied algorithms. By refining the alignment process, deviations between the scanned model and the reference geometry were minimized, leading to a more reliable assessment of dimensional accuracy. The optimized transformation method provided greater consistency in measurement results, ensuring robust and repeatable analysis of the scanned component [19],[20].

During the scanning of the part, it was necessary to properly set its position. An important factor was ensuring that the red target (marker) directly intersected the scanning line (Fig. 2). If the position was not correctly adjusted, the scanning process would become inefficient, resulting in an extended overall process and measurement time. Additionally, the scanning had to be performed under stable temperature and humidity conditions.

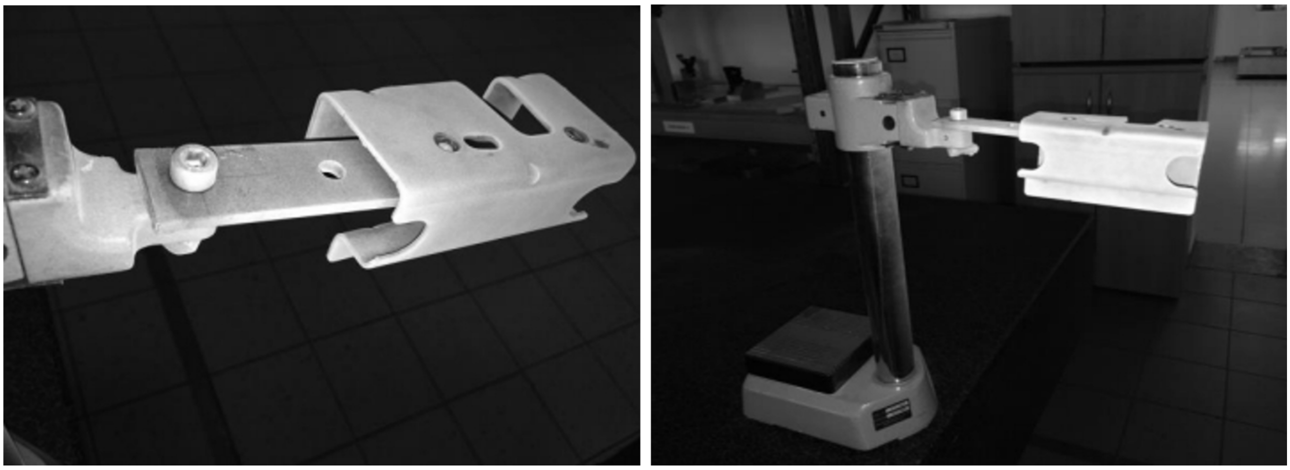

***Fig. 1** Mounting fixture*

***Fig. 2** Correct scanning (left) and incorrect scanning (right)*

Before the evaluation, it was necessary to process the scanned point clouds. During the scanning process, surfaces that were not relevant to the evaluation were captured, including parts of the stand to which the part was clamped. The adjustment involved removing all unnecessary sections.

5 Results

The first method analyzed in the research was the best fit method. Initially, the data from the 3D model of the part were entered into the software, followed by the loading of the scanned data (Fig. 3).

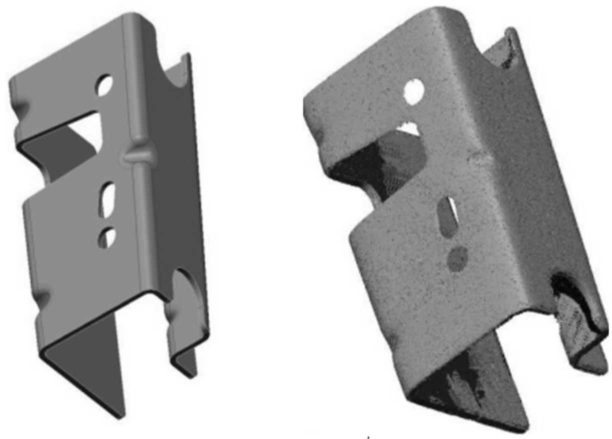

***Fig. 3** Loaded model (left) and loaded scan (right)*

Since the 3D model and the scanned model have different coordinate systems, it was necessary to configure them (Fig. 4).

First, the views were aligned, and subsequently, identical points were defined on both the scanned part and the model to achieve alignment. As shown in the image (Fig. 5), the alignment is not entirely perfect. The aligned model is incomplete and requires adjustments to ensure that the edges and boundaries align properly.

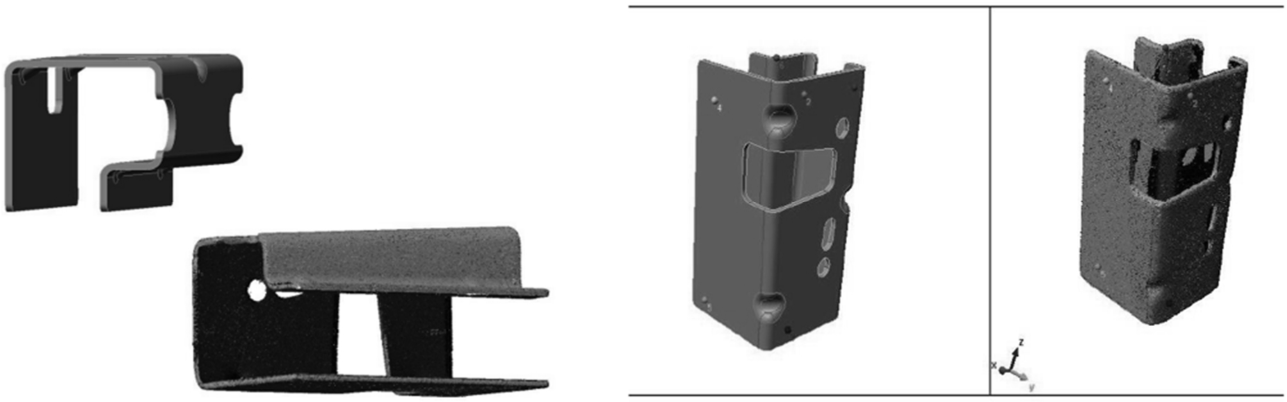

***Fig. 4** Different coordinate systems of the scan and the model*

Fig. 5 *Rough alignment - brown for the scan, green for the model*

Therefore, the best fit function in the software was utilized (Fig. 6). The noise tolerance, which the program commonly operates with based on the measurement strategy, was then selected. In our case, the noise tolerance was set to 4 mm.

Based on the technical drawing documentation, a dimension for measurement was selected. Deviations in the general tolerance of the slot position at SC004 were analyzed, which were specified in the drawing as ±1 mm. The measured value was 0.614 mm. For comparison, the measured value for auxiliary alignment using points was 5.472 mm.

The second method used was the 3-2-1 method. This alignment method is based on the selection of a point, a line or axis, and a plane. Therefore, when aligning the scan with the CAD model using this method, the best fit function was used as a supplementary adjustment. In the image (Fig. 7), alignment using the best fit method (left) and auxiliary alignment (right) can be seen.

The next step involves selecting surfaces on the model. The first surface chosen was surface A, followed by the center and axis of the holes as surfaces B and C (Fig. 8). In the software, the "Datum Reference Frame – Align" option was selected. Lastly, the alignment was defined based on the established datums A, B, and C.

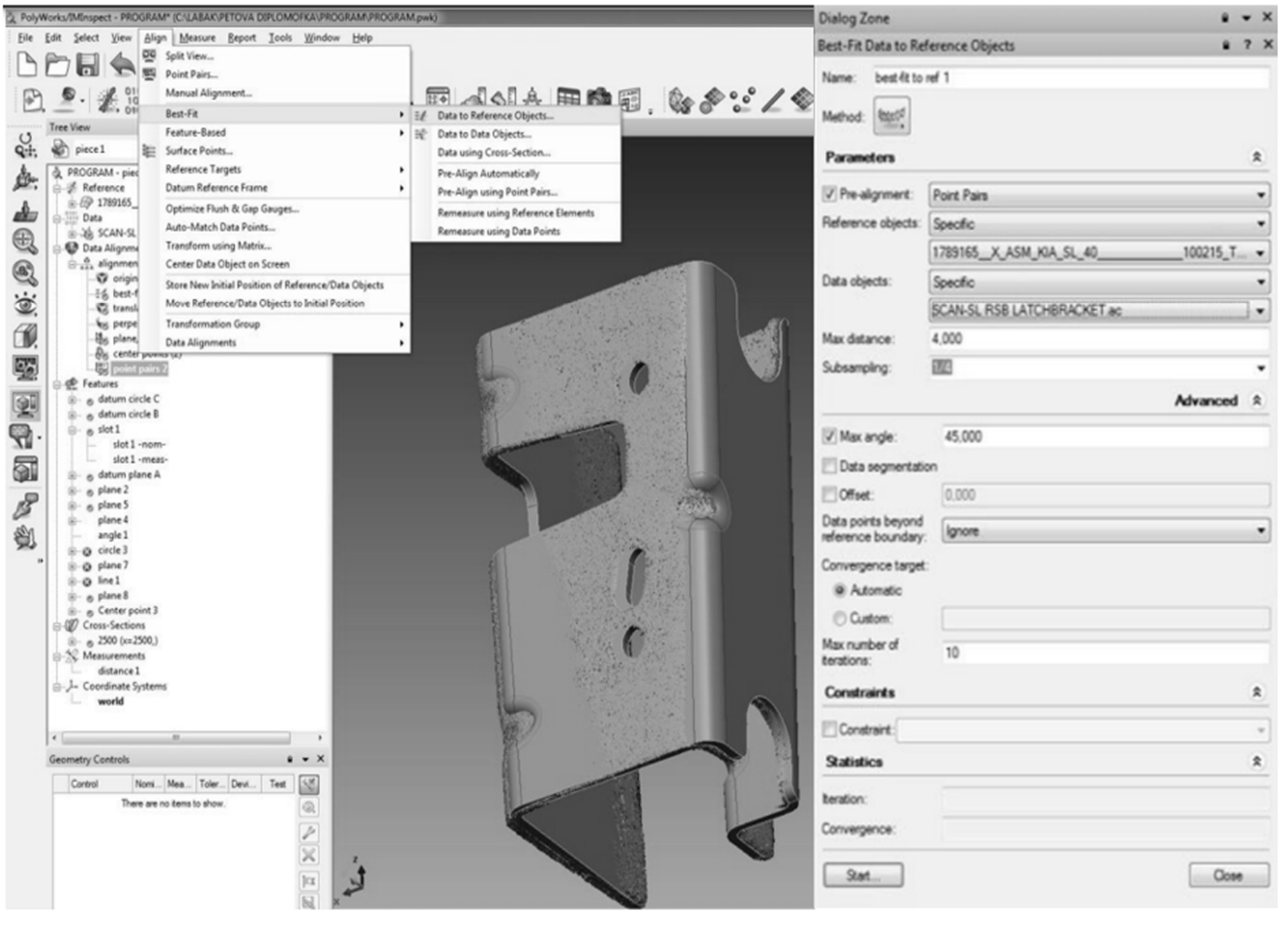

Fig. 6 *Best fit alignment with 4 mm noise*

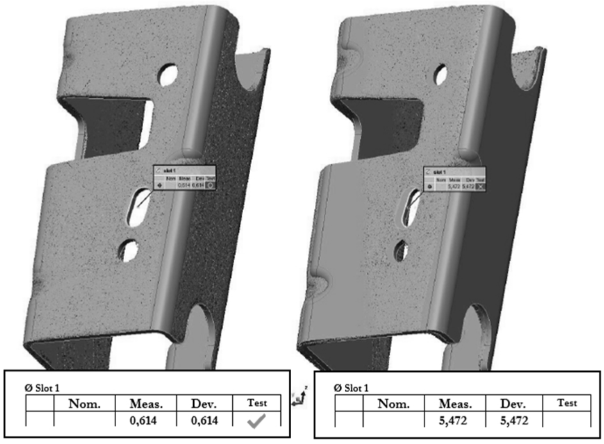

Fig. 7 *Best fit alignment (left) and auxiliary alignment (right)*

The final step in this setup was the selection of the alignment based on the previously defined datums A, B, and C. This resulted in a measured value of 0.138 mm, which is the most accurate compared to other auxiliary alignments (Fig. 9).

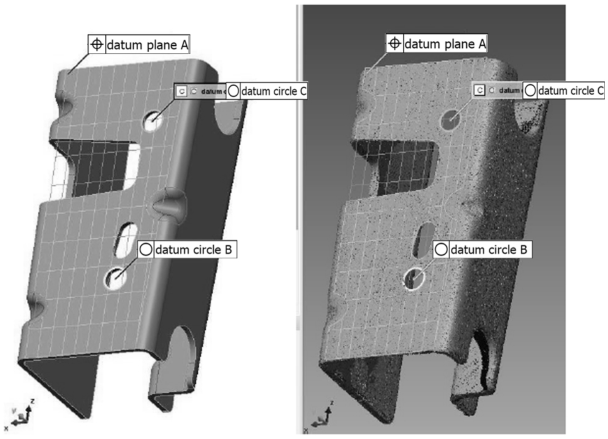

Fig. 8 *Selected elements of points, lines, and planes on the CAD model and scan*

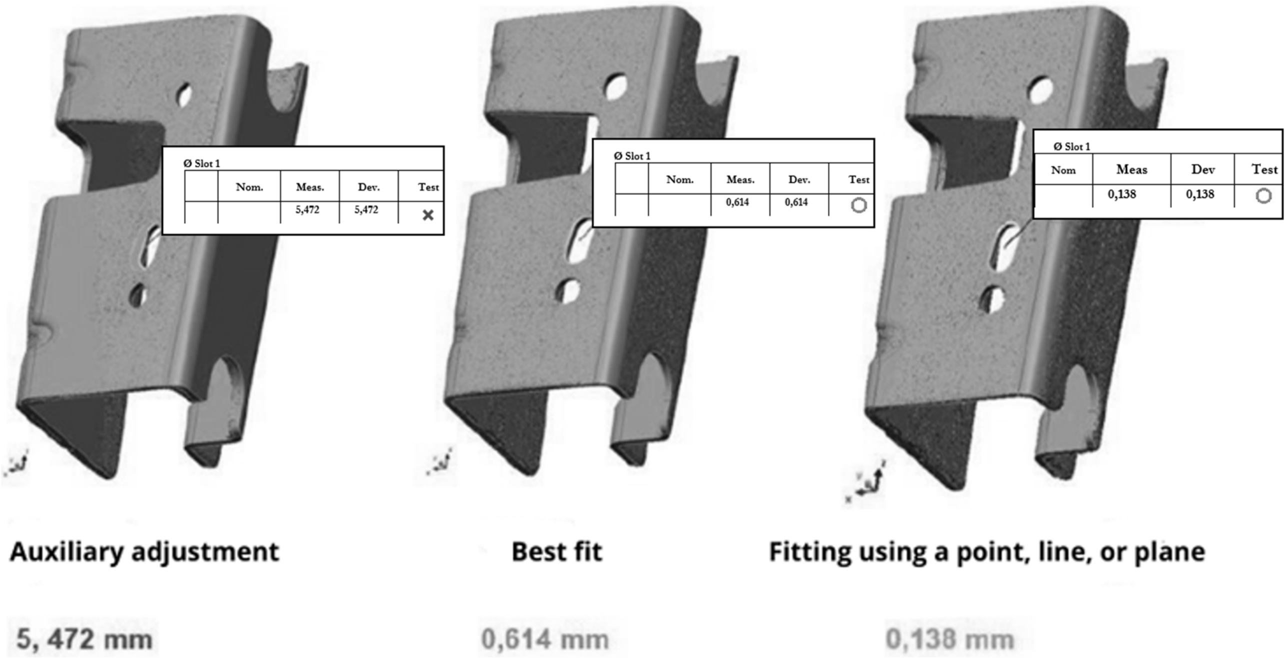

Fig. 9 *Comparison of the accuracy of applied methods*

6 Discussion

Continuous development, particularly in the aerospace and automotive industries, brings increasing demands for the quality and accuracy of components used. Emphasis on manufacturing quality is closely linked to the need for verification and prevention. This study addressed the importance of correctly aligning data with the reference CAD model of a component to ensure accurate and reliable measurements.

Based on the comparison of measured deviations using different alignment methods, it was confirmed that relying solely on auxiliary methods, such as point pair alignment or the best fit method, can lead to inaccurate interpretation of measurement results. Such deviations can create a misleading view of the component's quality, potentially affecting not only the metrologist's reputation but also customer-supplier relationships. For this reason, these methods should primarily be used as auxiliary or rough alignments.

On the other hand, primary methods such as 3–2–1 or alignment through a point, line, and plane provide more precise and reliable results. For components with complex shape features, the method of reference point systems (RPS) is preferable. However, the component analyzed in this study does not contain such features but has clearly identifiable geometric shapes, such as a plane, a line, or a longitudinal slot. Therefore, it can be assumed that the results achieved using the RPS method and the 3–2–1 method would be comparable.

The practical contribution of this study lies in clarifying the impact of individual alignment methods on the accuracy and reliability of measurements, serving as a basic guide for metrologists and quality control professionals in selecting an appropriate approach to component alignment. The results can directly help improve the accuracy of processes in real industrial environments, thereby eliminating the risk of inaccurate results that could lead to incorrect quality assessments and costly errors.

7 Conclusion

This study provided an in-depth insight into the importance of selecting and applying proper alignment methods in non-contact measurements. By comparing the best fit and 3–2–1 method on various geometric shapes, it was confirmed that each method has its specific applications. The best fit method, using a noise tolerance of 4 mm, achieved a measured deviation of 0.614 mm, which falls within the general tolerance of ±1 mm. On the other hand, auxiliary alignment using points resulted in a larger deviation of 5.472 mm, indicating lower accuracy for this method. The 3–2–1 method achieved the highest accuracy with a deviation of 0.138 mm, clearly demonstrating its reliability for simply defined geometries.

These findings underscore the need for a thorough analysis of measurement requirements before selecting the optimal alignment method. The best fit method is ideal for complex geometries and irregular shapes, whereas the 3–2–1 method provides more precise and consistent results for simply defined geometries.

The practical contribution of this study lies in clarifying the impact of different methods on measurement accuracy, serving as a valuable guide for metrologists and quality assurance professionals. The results are directly applicable in industrial practice, helping to improve quality control processes and reduce costs associated with measurement errors.

Future research could explore the application of these methods to more complex geometric shapes and integrate advanced technologies, such as machine learning algorithms, to automate and optimize the alignment process. These approaches could further enhance the accuracy and efficiency of metrological processes, supporting innovation and quality in industrial manufacturing.

Acknowledgement

This research was funded by the University of Žilina project APVV-22-0328: " Design of a Methodology and its Verification for the Measurement of Selected Parameters of Ti Implants in the Manufacturing Process", APVV-23-0366: " Research on the Reference Benchmark and Measurement Methods Ensuring the Determination of the Relationship between Geometric Specifications and Qualitative Indicators of 3D Objects Manufactured by Additive Technologies", Kega project 028ŽU-4/2022: " Implementation of innovative approaches to student education in the field of 3D metrology", KEGA 025STU-4/2024: " Development of soft skills of university students in technically oriented subjects", and KEGA 017/ZU-4/2022: "Implementation of digital technologies and simulations into the teaching process of machining technology"

References

[1] SALEH, H. R., AHMAD REZA. (2024). An improved iterative closest point algorithm based on the particle filter and K-means clustering for fine model matching. *The Visual Computer*, pp. 7589–7607. DOI: https://doi.org/10.1007/s00371-023-03195-0.

[2] ZHANG, X., WANG, J., & WANG, Y. (2024). Precision Optical Metrology and Smart Sensing. *Sensors*, 24(21), pp. 6816. DOI: https://doi.org/10.3390/s24216816.

[3] SAMELOVÁ, V., MAREK, T., JELÍNEK, A., JANKOVYCH, R., MARADOVÁ, K., & HOLUB, M. (2024). A Case Study on Assessing the Capability and Applicability of an Articulated Arm Coordinate Measuring Machine and a Touch-Trigger Probe for On-Machine Measurement. *Machines*, 12(12), 841. https://doi.org/10.3390/machines12120841

[4] ADELEKE, A. K., ANI, E. C., OLU-LAWAL, K. A., OLAJIGA, O. K., PORTILLO MONTERO, D. J. (2024). Future of precision manufacturing: Integrating advanced metrology and intelligent monitoring for process optimization. *International Journal of Science and Research Archive*, 11(01), pp. 2346–2355. DOI: https://doi.org/10.30574/ijsra.2024.11.1.0335
.

[5] WANG, Z., HU, J., SHI, Y., CAI, J., PI, L. (2024). Target Fitting Method for Spherical Point Clouds Based on Projection Filtering and K-Means Clustered Voxelization. *Sensors*, 24(17), pp. 5762. DOI: https://doi.org/10.3390/s24175762.

[6] ZHANG, Y., LIU, J., & LAI, T. (2024). Smart Manufacturing and Digitalization of Metrology. *Journal of Advanced Metrology*, 18(3), pp. 251–267. DOI: https://doi.org/10.1016/j.jam.2024.03.005

[7] WANG, H., ZHOU, X., & CHEN, B. (2024). Digital Avatar of Metrology: Enhancing Measurement Accuracy and Automation. *International Journal of Precision Engineering*, 29(7), pp. 1125–1140. DOI: https://doi.org/10.1016/j.ijpe.2024.07.010

[8] BENATTIA, B., B. A. (2024). Automation of three-dimensional inspection using the iterative closest point algorithm: application to a gas turbine blade. *The International Journal of Advanced Manufacturing Technology*, pp. 4703–4713. DOI: https://doi.org/10.1007/s00170-024-13866-4.

[9] CHRISTOPH, M. (2008). Alignment and stability in industrial measurement using 3-2-1 technique. *Metrology Journal*, pp. 411–417.

[10] KIRACI, E., G. A. (2016). Evaluating the capability of laser scanning to measure an automotive artefact: a comparison study of touch trigger probe and laser-scanning. *International Journal of Productivity and Quality Management (IJPQM)*. DOI: https://doi.org/10.1504/IJPQM.2016.077776

[11] WANG, Z., HU, J., SHI, Y., CAI, J., PI, L. (2024). Target Fitting Method for Spherical Point Clouds Based on Projection Filtering and K-Means Clustered Voxelization. *Sensors*, 24(17), pp. 5762. DOI: https://doi.org/10.3390/s24175762.

[12] EL-MELEGY, M. T. (2007). Non-iterative approach to best fit matching for exact calibration in coordinate metrology. *Computer-Aided Design*, pp. 789–796.

[13] FAN, K. C. (2000). *Measurement accuracy enhancement in three-dimensional coordinate metrology using best-fit algorithms*. pp. 128–137.

[14] LI, S., KANG, H., LI, Z., ZHOU, Y., ZHANG, Y., LIU, J., & LAI, T. (2024). Development of a Large-Aperture Coordinate Precision Measurement Instrument Using Differential Geometric Error Weighting. *Applied Sciences,* 14(22), pp. 10125. DOI: https://doi.org/10.3390/app142210125.

[15] RIKARDO, M., A. A. (2014). Framework for verification of positional tolerances with a 3D non-contact measurement method. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, pp. 85–93. DOI: https://doi.org/10.1007/s12008-014-0214-7.

[16] MINETOLA, P. (2012). The Importance of a Correct Alignment in Contactless. I*nternational Journal of Precision Engineering and Manufacturing*, pp. 211–218. DOI: https://doi.org/10.1007/s12541-012-0026-2

[17] PEARN, B. S. (1993). Alignment metrology. *Optical Methods in Engineering Metrology*, pp. 87–112. DOI: https://doi.org/10.1007/978-94-011-1564-3_3.

[18] RAINER, M., M. V.-S. (2019). Best-fit method for the calibration of 3D objects using a laser line sensor mounted on the flange of an articulated robot. Tagungsband des 4. *Kongresses Montage Handhabung Industrieroboter*, pp. 207–216. DOI: https://doi.org/10.1007/978-3-662-59317-2_21.

[19] WARSZA, Z. L., PUCHALSKI, J., WIĘCEK, T. (2024). Novel Method of Fitting a Nonlinear Function to Data of Measurement Based on Linearization by Change Variables, Examples and Uncertainty. M*etrology*, 4(4), pp. 718–735. DOI: https://doi.org/10.3390/metrology4040042.

[20] ANASIEWICZ, K., JÓZWIK, J., LELEŃ, M., PIEŚKO, P., LEGUTKO, S., TOMCZAK, J., PATER, Z., BULZAK, T. (2024). Identification of Internal Defects in Forged Shafts by Measurement of Residual Stresses Using X-Ray Method. *Manufacturing Technology*, 24(5), pp. 711–720. DOI: 10.21062/mft.2024.086.

[21] SAŁAMACHA, D., JÓZWIK, J. (2023). Evaluation of Measurement Uncertainty Obtained with a Tool Probe on a CNC Machine Tool. *Manufacturing Technology*, 23(4), pp. 513–524. DOI: 10.21062/mft.2023.051.