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Automation of the matting process for improved accuracy in optical coordinate measurements

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ABSTRACT

Optical coordinate measurements provide numerous benefits, such as high speed and non-contact operation; however, they are highly sensitive to the surface properties of the object being measured. Surfaces that are highly reflective or transparent, in particular, present significant challenges for optical measurement systems. In such cases, specialized matting sprays are commonly employed to ensure reliable data acquisition. As indicated by previous studies, manually applying these sprays can result in uneven coating thickness and streak formation, which are especially problematic for high-precision coordinate measurements and may negatively affect the accuracy of the results. This research tackles this challenge by aiming to improve the precision of optical coordinate measurements for applications requiring surface matting. A concept for an automated matting process is proposed, implemented using a robot designed and manufactured through 3D printing technology. The system enables controlled and repeatable application of spray, with a regulated force applied to the atomizer. The study details the mechanical design of the robot, the control components integrated into the system, and the methods used to regulate both the atomizer's position and the applied force. To assess the effectiveness of the approach, comparative experiments were conducted. These experiments analyzed changes in the measured diameter of a reference sphere after applying the spray manually and via the robotic system. Measurements were performed using a Hexagon Absolute Arm RA-7320 in combination with PolyWorks software, and the force exerted on the atomizer was recorded in both cases. The findings demonstrate that automation allows the matting agent to be applied more evenly and in thinner layers, significantly enhancing measurement repeatability compared to manual application. Overall, the study confirms the advantages of automating surface preparation and highlights potential avenues for further development.

Keywords: CMM (coordinate measuring machine), accuracy, automation, optical measurements, reflective surfaces, matting process.

INTRODUCTION

With the development of Industry 4.0 [1] and Industry 5.0 concepts [2,3], all stages of the manufacturing process are undergoing dynamic transformation. This industrial evolution is characterized by the automation of individual production stages, the implementation of machine learning-based systems [4,5], the use of simulation tools [6,7], and the development of advanced solutions supporting the planning of both machining processes and inspection activities [8,9].

Dimensional and geometric inspection is increasingly based on advanced metrological machines and systems, which themselves are experiencing significant technological progress. Study [10] presents a coordinate measuring machine (CMM)-based inspection planning system oriented toward integration with the Industry 4.0 concept, enabling more efficient coordination of measurement processes. In [11], smart optical metrology systems are discussed, combining coordinate and surface measurements to enhance automation and efficiency. A growing trend toward integrating multiple measurement approaches can also be observed; for example, [12] introduces a hybrid measurement system designed for large-scale workpieces, including uncertainty analysis and the integration of various measurement technologies.

Coordinate measuring systems are gradually becoming an integral part of production lines, while optical systems are increasingly adopted due to their speed and non-contact nature [13]. In [14], the authors emphasize the role of optical coordinate metrology and propose a database-driven approach to uncertainty estimation. This represents a rapidly developing global trend, strongly supported by artificial intelligence methods. Simulation-based approaches to uncertainty evaluation are also being explored, as shown in [15]. Currently, the Laboratory of Coordinate Metrology is conducting the project "An Expert system based on machine learning as a new tool for modeling the uncertainty of coordinate measurement," supported by the National Centre for Research and Development under the LIDER program (LIDER15/0306/2024). The project focuses on developing a tool for rapid and straightforward estimation of measurement uncertainty based on archival data, which is expected to promote wider adoption of uncertainty evaluation and improve the quality of conformity assessment decisions with respect to specification limits, both for optical and contact measurement systems. The research also aims to identify factors influencing measurement results and associated uncertainty, which remains an insufficiently explored area, particularly in the case of optical coordinate measurement systems.

Despite the clear advantages of optical systems, numerous studies have shown that certain surfaces – especially highly reflective or transparent ones – still pose significant challenges for light-based measurements. In [16], the authors present an accurate 3D reconstruction method for highly reflective mechanical surfaces using structured light combined with phase-shifting and Gray code techniques, reducing errors caused by reflections. Study [17] investigates the influence of surface material and object preparation on the accuracy of optical coordinate measurements, highlighting the critical role of surface conditions. In [18], the focus is on optical measurement of surface topographies with transparent coatings, emphasizing challenges related to light refraction and signal distortion.

To mitigate undesired optical effects on such surfaces, dedicated matting agents are commonly used. However, studies such as [19,20] indicate that these agents are not entirely neutral, as they introduce unintended material accumulation on the surface, typically ranging from a few to several tens of micrometers [17]. While this effect may be negligible in less demanding applications, in ultra-precision coordinate metrology even minimal material deposition can significantly influence results. Although spray manufacturers recommend applying coatings from a specified distance, studies conducted at the Laboratory of Coordinate Metrology at PK Krakow University of Technology have shown that the quality of the applied layer strongly depends on the operator's experience [21].

Previous studies on matting coatings in optical measurements have mainly focused on analyzing the influence of coating type and thickness on measurement accuracy [20], optimizing application parameters to obtain the thinnest and most homogeneous coating possible [22,23], as well as comparing different matting agents in terms of coating thickness and resulting scan quality [19,24]. The important role of the object preparation stage has also been emphasized, indicating that both the matting strategy and coating properties may significantly affect the accuracy of optical coordinate measurements [21,25]. However, the automation of the matting layer application process itself remains relatively underexplored.

Maintaining this distance consistently during manual application is challenging, and deviations may result in excessive coating, streak formation, or other undesired effects. The difficulty of preserving a uniform distance, particularly for less experienced operators, motivated the development of the Bocio I robot. Its purpose is to automatically apply a consistent matting layer to the object by exerting a controlled and constant force on the spray atomizer. The robot allows the spray to be positioned in the gripper so that the recommended spacing from the reference sphere is maintained. Once connected to a power source, the robot executes the programmed sequence of operations autonomously, following the order defined in its control code.

Considering the ongoing automation trends and the challenges associated with applying matting layers in ultra-precision measurements, this study proposes automating the deposition process using a dedicated robotic system. This approach addresses a fundamental stage of any measurement procedure, namely the proper preparation of the measured object. A review of the literature indicates that no comparable attempts to automate this process have been reported so far. Although research on automated coating deposition exists, it is primarily focused on paint or protective coatings. Most scientific efforts are directed toward improving measurement accuracy through optimization of machine settings, proper calibration, and the selection of appropriate measurement procedures. These include methods for assessing the accuracy of optical systems, e.g., [26], virtual models of coordinate measuring machines [27], and metrological digital twins [28]. Other works address calibration of measurement systems using multi-position methods [29], the application of camera calibration techniques and deep learning to enhance machine vision-based inspection systems [30], as well as sensor calibration and environmental condition control [31]. However, relatively little attention has been paid to the object preparation stage [32], despite its critical importance; inadequate preparation can lead to significant errors even when advanced equipment and validated methods are employed.

This paper presents the concept of a robot designed to automate the application of matting layers and describes the experiments conducted to verify the effectiveness of the proposed solution. The study explores a relatively new research area, combining metrological measurement results with an analysis of the controlled actuation force applied during matting agent deposition. The final section outlines directions for further development of the proposed system and identifies potential avenues for future research.

METHODS AND MATERIALS

Concept of automating the matting process

To address the need for controlling the matting layer, a concept for automating the matting process (Figure 1) was proposed using a dedicated robot (named Bocio I) (Table 1). The robot model has also been presented in [33]. Its primary function is to perform matting of the measured object under controlled and repeatable conditions, particularly through the application of a constant force to the atomizer. This approach enables the generation of uniform matting layers and improves control over the surface preparation process before measurement.

Investigations were conducted to evaluate the effect of the force applied to the atomizer on the matting process, and the results were subsequently correlated with the accuracy of the measurements obtained.

The robot was designed based on defined assumptions regarding the maximum dimensions and allowable load of the gripper. It is capable of handling spray containers with capacities ranging from 300 to 500 ml (the most commonly available on the market), which are mounted in a dedicated

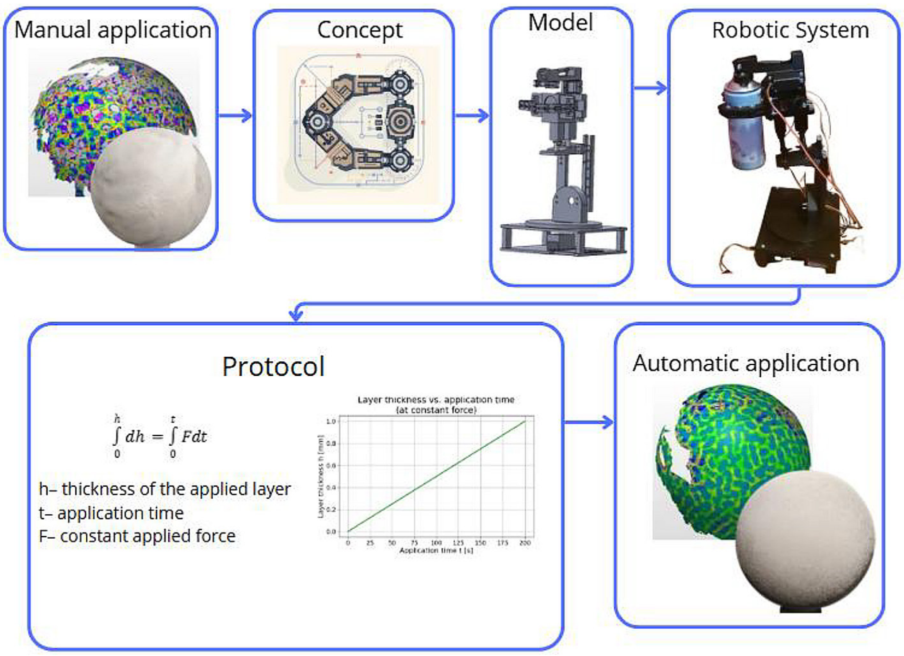

Figure 1. Concept of automating the matting process

holder. The mechanical design was developed using SolidWorks software.

The base of the robot houses an Arduino UNO R3 control board, a prototyping board, and an MG996R servo motor, enabling smooth rotation of the robot arm over a full 360° range. This range of motion makes it possible to matte spherical components with diameters larger than the robot itself, including their internal surfaces. The height and tilt angle of the gripper can be adjusted by the operator using two screws driven by servomechanisms. The gripper, inspired by the human hand, is composed of two stabilizing "fingers" and a third element that actuates the spray atomizer.

The physical prototype of the robot was produced using additive manufacturing on an Artillery Sidewinder X4 Plus 3D printer. The three-dimensional printing process was carried out according to the design specifications using OrcaSlicer software, which also defined the maximum worktable temperature and the primary printing parameters. Table 1 presents the robot parameters, while its main modules are shown in Figure 2. The Bocio I robot is controlled via the integrated Arduino IDE software. Following the programmed instructions, the robot positions the atomizer, mounted in its holder, at the designated angle and applies a uniform layer of matting agent to the measured object, effectively matting its surface. The measurements collected during the robot's operation enable the assessment of the repeatability of the applied force, recorded as analog signals from the FSR 402 force sensor.

Surface preparation – manual matting spray application

Prior to performing measurements on the reference sphere, its surface was prepared in accordance with procedures commonly applied in accredited laboratories. In particular, the object was continuously stored in a climate-controlled room maintained at 20 ± 0.5 °C; therefore, no additional thermal stabilization was required. Before matting, the surface was cleaned using a dedicated lint-free cloth soaked in alcohol to remove any contaminants. Next, surface whitening of the sphere was achieved through the application of a matting spray, following standard laboratory practice: a single application was performed while maintaining the manufacturer-recommended distance of 20 cm between the object and the spray nozzle to ensure optimal application conditions, with an atomizer pressing time of approximately 2 seconds. Figure 3 presents the scheme of applying the matting layer using a robot.

The Helling 3D scanning spray was employed, belonging to a group of commonly used matting agents, including products such as Aesub, Attblime, and Helling 3D. These sprays are available in white, transparent, or self-sublimating variants, as well as in versions requiring manual removal. The Helling 3D spray is characterized by a coating thickness in the range of 8–15 µm (representing an intermediate range between sprays capable of producing coatings of approximately 1 µm and about 30 µm, which motivated its selection) and a white color. Based on discussions with industry representatives, this product is known to be widely used in industrial practice. The prepared object was then placed on a rotary table, where it remained awaiting measurement.

Determination of sphere diameters via coordinate measurements

Coordinate measurements were conducted in the accredited Laboratory of Coordinate Metrology at PK Krakow University of Technology, in an environment maintained at

Table 1. Main characteristics of the robot

	Characteristic	Value/ description
	Base dimensions	190 × 160 mm
	Robot height (base configuration)	361 mm
	Vertical adjustment range	±30 mm along the Z-axis for the gripper
	Maximum gripper finger span	135 mm
	Container diameter range	40–120 mm
	Compatible containers	Standard aerosol cans (300–500 ml)
	Spray activation time (duration of pressure applied to the matting spray nozzle)	Software-controlled

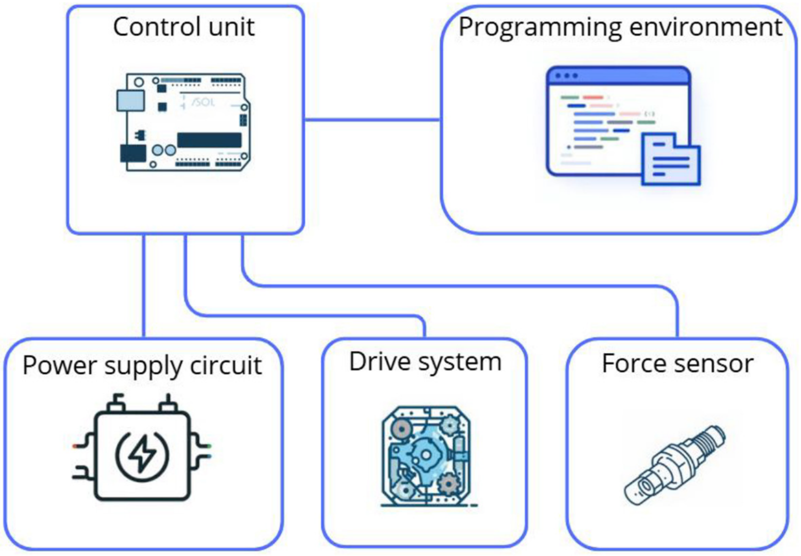

Figure 2. The main modules of the robot

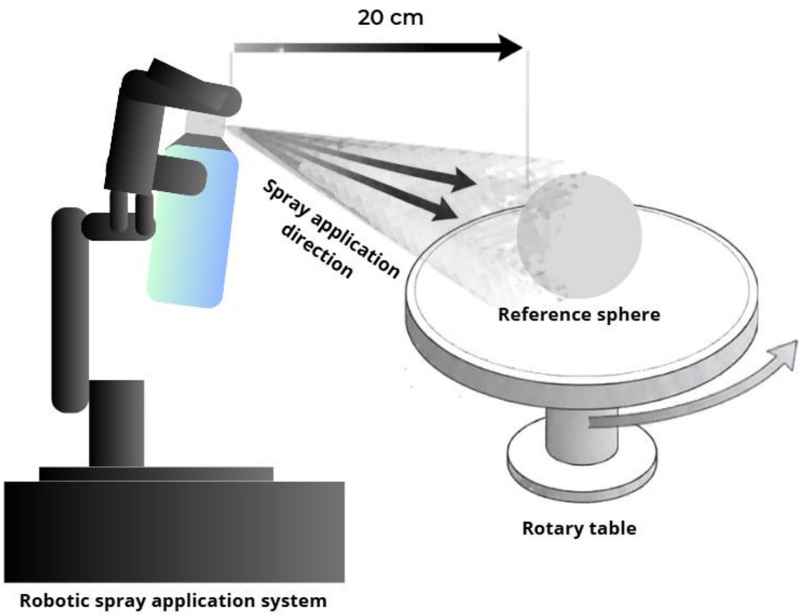

Figure 3. Scheme of applying the matting layer using a robot Bocio I

a stable temperature of 20 ± 0.5 °C. The measurements employed a Hexagon Absolute Arm 7320RI Articulated Arm Coordinate Measuring Machine (AACMM) fitted with an RS2 laser scanner head (Figure 4a, Table 2).

The Maximum Permissible Error of the RS2 scanner head is 0.065 mm, determined in the Laboratory in accordance with ISO 10360-8:2013 [34]. The information regarding probing errors is provided in Table 3. The white coating (matting) study was carried out using spheres; therefore, the verification of the probing head was performed only to a limited extent, focusing on the part of the standard related to sphere-based tests. The system accuracy was evaluated using a reference sphere without a matting layer. The main tests were then conducted on a different sphere covered with the matting coating. The standard also includes additional tests involving a flat artefact and a stylus articulation test; however, these were omitted as such geometries and test scenarios were not considered within the scope of this study.

The object measured was a ceramic sphere with a diameter of ϕ30.0005 mm (Figure 4b). This sphere was used as a reference standard

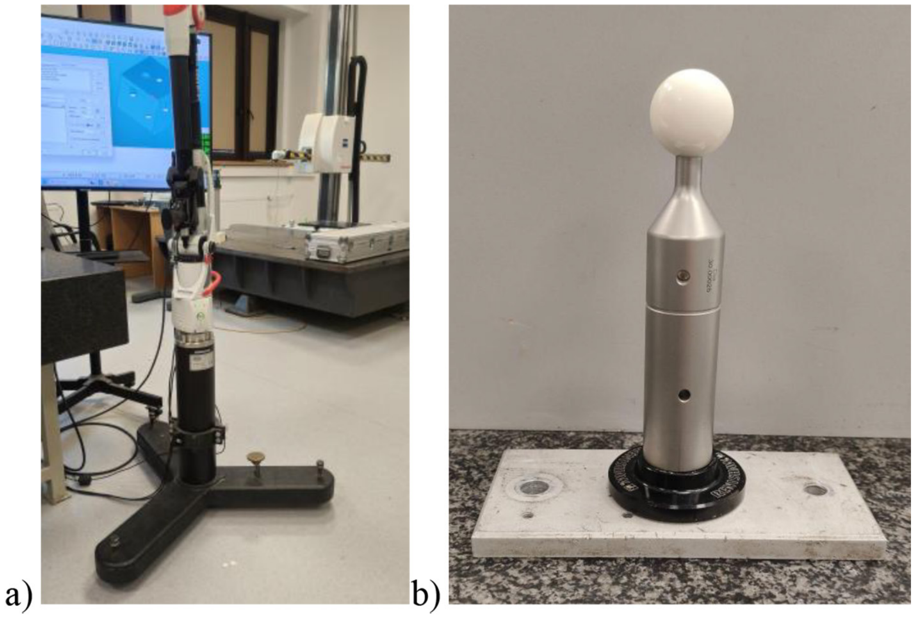

Figure 4. a) Hexagon Absolute Arm 7320RI AACMM; b) Ceramic reference sphere

and had been calibrated on a Leitz PMM 12106 coordinate measuring machine, for which the Maximum Permissible Error ($E_{0,MPE}$) of length measurements is defined by the equation: $E_{0,MPE} = 0.0008 + 0.0025/1000 \cdot L$ mm. The uncertainty in determining the sphere's diameter, calculated via the least squares method, was 0.12 µm [36].

The measurement procedure for the investigated object comprised six series (four series were conducted in automatic mode and two in manual mode), each consisting of five repetitions of scanning the sphere coated with matting spray. The articulated arm was moved in four directions (with rotations of approximately 90 degrees) to acquire data from all surfaces of the sphere, resulting in dense point clouds containing approximately one million points. The point clouds were subsequently processed using the PolyWorks software. Points generated by reflections (e.g., from the rotary table, which is part of the experimental setup and shown in Figure 3) were removed by manually indicating the regions to be deleted. The spheres were then reconstructed using the best-fit method - the least squares fitting method with a 3-sigma filter, and their diameters were subsequently determined.

Atomizer actuation force measurements

The force exerted on the scanning spray atomizer, both by the operator and by Robot Bocio I, was measured using an FSR 402 force sensor connected to an Arduino Uno R3 microcontroller and controlled through the Arduino IDE software. This resistive sensor changes its resistance according to the applied force. With a diameter of 18 mm, the chosen sensor allows real-time force readings. It was mounted within the robot's gripper in a way that enables detection of even minimal forces during the measurement process. The recorded data were obtained as analogue values. In total, six tests were performed, including two with manual spray application and four using the robotic system. 8 force measurements were performed, with 4 measurements conducted for each method. The main sources of uncertainty included the nonlinearity and hysteresis of the FSR sensor, as well as the limited repeatability of the matting spray application process, associated, among others, with changes in the mass and pressure of the spray can during application. The measurements were carried out under the controlled conditions of the accredited laboratory.

Table 2. Technical specifications of the Hexagon Absolute Arm 7320SI [35]

Measuring range, m	2.0
Probing point repeatability, mm	0.044
Probing volumetric accuracy, mm	±0.061
Scanning system accuracy SI, mm	0.079

Table 3. Probing errors for RS2 scanner head

Parameter	Permissible (MPE/MPL) μm	Measured (P/L) μm	Uncertainty (U) μm
MPE(P[Size.Sph.1×25:Art:ODS]) Maximum Permissible Error of size sampling	65.0	-45.0	1.2
MPE(P[Form.Sph.1×25:Art:ODS]) Maximum Permissible Error of form sampling	65.0	43.0	1.2
MPE(P[Size.Sph.All:Art:ODS]) Maximum Permissible Error of size sampling (all points)	65.0	-32.0	1.2
MPL(P[Form.Sph.D95%:Art:ODS]) Maximum Permissible Limit of sampling dispersion	65.0	62.0	1.2

RESULTS

Analysis of accuracy of coordinate measurements with manual and automated surface matting

Tests performed on the reference sphere, first with a manual application of Helling 3D scanning spray by the operator and then with automated application by the robot, showed a clear difference in the distribution of the matting agent across the surface, noticeable to the naked eye. The layer applied manually appeared thicker and exhibited multiple imperfections, whereas the layer applied by the robot was much thinner [37].

Table 4 shows the single measurement results acquired with the Hexagon Absolute Arm RA-7320 AACMM. The first four series correspond to measurements taken after the scanning spray was applied by Robot Bocio I, while the last two series present the results obtained following manual application of the spray.

Overall, most of the measured sphere diameters obtained from the AACMM tests exceed the reference value (Figure 5). In the series with automated spray application, the largest deviation from the reference value is 0.0237 mm (no. 2), while for manual application, the deviation reaches 0.2275 mm (no. 5). Regarding the smallest deviations, automatic application shows 0.0023 mm (no. 4), whereas manual application shows 0.1319 mm (no. 6). These results, presented in Figure 4, highlight the improved accuracy and repeatability achieved through automated application.

Differences between manual and automated spray application are mainly related to the uniformity and thickness of the matting layer. Manual application leads to non-uniform surface coverage, which affects local optical properties and may introduce measurement disturbances. In contrast, an automated application provides greater control over the coating process, resulting in a more uniform layer and lower measurement result dispersion. The results confirm that automating the surface preparation process improves the accuracy of coordinate measurements.

Analysis of force stability

As shown in Figure 6, during manual matting, the recorded signal values ranged from 0 to 303. These values are expressed in arbitrary units (a.u.), reflecting the raw output of the FSR 402 sensor, which was not calibrated to provide absolute force measurements in newtons. Due to the non-linear response and application-dependent characteristics of the FSR 402, the analysis was based on the raw sensor signal to allow a relative comparison between measurements.

Manual application of the scanning spray by the operator exhibited significant variability in the applied force, leading to larger amplitude fluctuations than those observed with the automated method. In contrast, during automated measurements, signal values ranged from 9 to 71. Robot Bocio I applied a stable force to the spray atomizer for approximately 5.5 to 10 seconds. Once the atomizer was engaged, the force remained constant and changed only when the robot released the gripper. For manual application, however, the applied force fluctuated depending on factors such as hand movement or adjustments to the grip on the can, which directly influenced the amount of scanning material released. Since both manual and automated measurements were performed using the same sensor and measurement setup,

Table 4. Measurement results of the reference sphere following manual and automated matting application

Reference sphere diameter, mm	Measured sphere diameter, mm					
	Robot application				Manual application	
	1	2	3	4	5	6
30.0005	30.025	30.033	30.052	29.998	30.352	30.227
30.0005	30.028	30.031	30.031	30.008	30.109	30.125
30.0005	30.018	30.003	30.008	29.999	30.312	29.950
30.0005	30.018	30.140	29.969	30.033	30.157	30.185
30.0005	30.029	30.040	30.047	29.976	30.210	30.175
Mean value	30.024	30.024	30.021	30.003	30.228	30.132
Standard deviation	0.005	0.015	0.034	0.021	0.102	0.108
Difference from the reference sphere	0.023	0.024	0.021	0.002	0.227	0.132
Type A evaluation of uncertainty	0.0024	0.0068	0.0152	0.0092	0.0458	0.0484

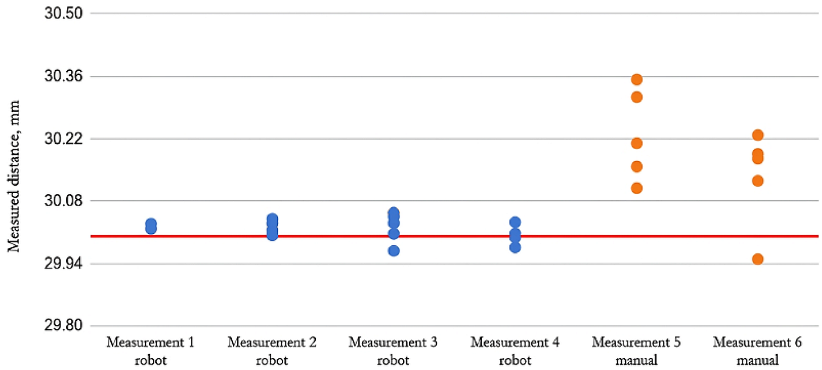

Figure 5. Comparison of measurement results for the reference sphere manual and automated surface coating

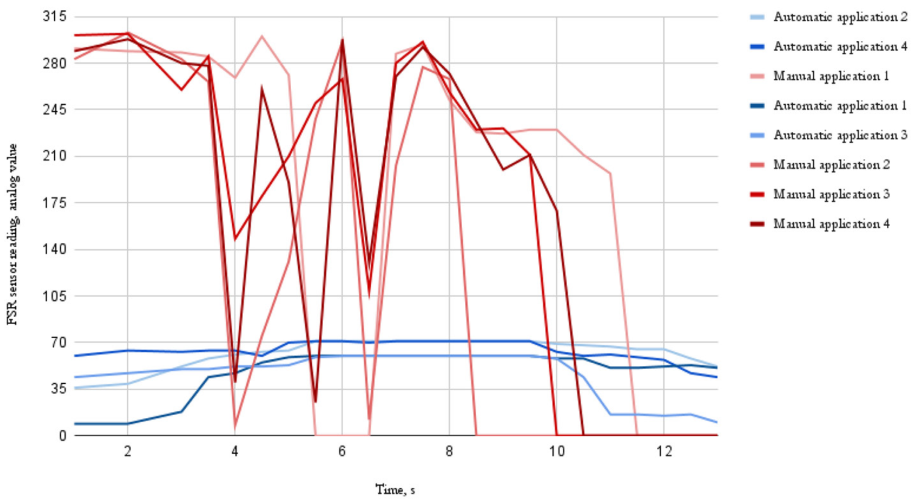

Figure 6. Comparison of the actuation force operator and robot

the nonlinear response of the sensor affected both conditions similarly, thereby preserving the validity of the relative comparisons.

Based on the obtained FSR sensor signal profiles, the mean signal values, standard deviations (Table 5), and Type A uncertainties associated with signal variability over time were determined. The average Type A uncertainty determined for manual application was 26.08, whereas for automated application it was 2.69. This confirms the greater stability and repeatability of the automated application process.

Table 5. Statistical characteristics of sensor signals

No. Manual application	Mean signal values	Standard deviations
Manual application 1	180.39	125.17
Manual application 2	114.91	130.74
Manual application 3	166.04	121.45
Manual application 4	162.52	123.04
Automatic application 1	50	16
Automatic application 2	63	10
Automatic application 3	46	18
Automatic application 4	64	8

CONCLUSIONS

The studies and analyses carried out confirm the feasibility and benefits of automating the matting process in ultra-precision optical coordinate measurements. Marked differences were observed when comparing the diameters of a reference sphere coated manually with those obtained using the Bocio I robot. The automated procedure consistently resulted in smaller deviations from the reference value, highlighting the advantage of controlled application. The lowest standard deviation for standard sphere measurements was achieved with automated application, at 0.005 mm, while the highest value, 0.108 mm, was recorded for manual application. This indicates that the variability of results is more than twenty times greater than with manual application, and the difference between the averaged standard deviation values for the methods described above is 0.087 mm. A similar trend was observed for Type A uncertainty. The maximum uncertainty value for the automated process was 0.0152 mm and was more than three times lower than the minimum value obtained for the manual application, 0.0458 mm. The average type A uncertainty for the automatic process was lower than the average uncertainty for the manual process by 0.0387 mm. By applying a constant actuation force and maintaining precise motion, the robot produced thinner, more uniform matting layers than manual spraying. A more homogeneous matting layer improves the accuracy of optical scanning by providing more uniform light scattering and reducing local variations in surface reflectivity. As a result, the influence of specular reflections and signal fluctuations is minimized, leading to more accurate point determination and, consequently, more accurate 3D reconstruction of the object. This improvement was clearly reflected in the coordinate measurement results, demonstrating enhanced accuracy and repeatability. The results support the adoption of automated matting in measurement processes.

Regarding the robotic system, it should be noted that 3D printing technology enabled rapid fabrication of the structural components, offering both cost efficiency and the flexibility of in-house production. Such attributes can facilitate broader implementation of this approach in laboratory practice both in research and industrial settings.

The authors have planned further work, recognizing the potential of the developed solution to significantly improve the accuracy of the measurement preparation stage. A further series of tests has been planned, involving several matting products as well as a change of the measured object to a gauge block, in order to provide a broader validation of the developed solution in the context of applying different products to various surfaces.

In the context of the Robot itself, future research will focus on improving its design and developing standardized procedures for surface preparation prior to measurements using the device, in order to achieve an even higher level of control and repeatability. It is assumed that the accuracy of the system may depend, among others, on the load applied to the gripper and the characteristics of the employed servo drives. Therefore, calibration of the positioning system has been planned to assess the stability of operating conditions.

The obtained results confirm the crucial importance of the specimen preparation stage, indicating that even when a world-class measuring machine is used, insufficient care at this stage can significantly affect the final measurement results. Researchers from the Laboratory of Coordinate Metrology plan further work aimed at improving this stage and developing procedures that will enable enhanced measurement accuracy not only in laboratory conditions but also in industrial environments.

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