Repeatability and Reproducibility Method of Hand-handle Laser Triangulation Profilometer

Repeatability and Reproducibility method of hand-handle laser triangulation profilometer

Guerino Gianfranco Paolini
Department of Industrial Engineering and Mathematical Sciences
Università Politecnica delle Marche
Ancona, Italy
g.g.paolini@pm.univpm.it

Matteo Nisi
U-Sense.IT Srl
Jesi, Italy
nisi@u-sense.it

Sara Casaccia
Department of Industrial Engineering and Mathematical Sciences
Università Politecnica delle Marche
Ancona, Italy
s.casaccia@staff.univpm.it

Federica Amicucci
Department of Industrial Engineering and Mathematical Sciences
Università Politecnica delle Marche
Ancona, Italy
S1109790@studenti.univpm.it

Cristina Cristalli
U-Sense.IT Srl
Jesi, Italy
cristalli@u-sense.it

Nicola Paone
Department of Industrial Engineering and Mathematical Sciences
Università Politecnica delle Marche
Ancona, Italy
n.paone@staff.univpm.it

***Abstract*— This paper explores the use of a hand-held laser triangulation-based measurement system for gap and flush measurements in the automotive industry, focusing on operator variability. In modern manufacturing, especially with Industry 5.0, precise measurements are essential for quality and efficiency. While laser triangulation technology offers high accuracy, when the device is portable human factors influence performance. The study evaluates the U-Sense.IT srl G3F laser profilometer in two modes: manual and with a magnetic holder. Using Measurement System Analysis (MSA), the research assesses repeatability (Equipment Variation, EV) and reproducibility (Appraiser Variation, AV), determining the Gauge Repeatability and Reproducibility (GRR). Data were collected from three operators measuring three cars, with repeated measurements for both gap and flush. Results show that the holder technique has lower variability in both repeatability and reproducibility compared to the manual method. The GRR for the holder was 2,22% for flush and 2,32% for gap, while the manual technique showed 3,13% for flush and 3,66% for gap. Both systems had GRR values below the acceptable 10% threshold, with the magnetic holder system demonstrating greater precision due to better sensor positioning. This research highlights the effectiveness of support systems in reducing human error, even if it reduces flexibility, showing that while both methods are valid, the magnetic holder system aligns better with Industry 5.0 principles by improving collaboration between humans and intelligent systems.**

Keywords*— *laser profilometer, gap and flush measurements, measurement system analysis

I. INTRODUCTION

In modern manufacturing processes, the integration of measurement systems plays a crucial role in ensuring quality, efficiency, and innovation. As industries evolve towards Industry 5.0, which emphasizes the integration of human-centric approaches alongside advanced technologies, the need for accurate measurement becomes even more critical. In this context, the ability to monitor and control various parameters, from material properties to machine performance, allows for greater flexibility and customization in production processes. Industry 5.0 focuses on the collaboration between humans and intelligent systems, where human expertise are combined with the innovative technologies [1]. Therefore, effective measurement techniques not only ensure optimal performance and safety but also enhance the ability to adapt processes to meet the unique needs of individual workers and customers, fostering a more personalized and sustainable approach to manufacturing. A clear example of how these advanced measurement systems are being applied is seen in the automotive industry. As the demand for high-quality, aesthetically pleasing vehicles has increased, so too has the need for precise gap and flush measurements [2].

Gap is the distance between two adjacent parts, measured along the tangent plane on the surfaces in exam. Flush is the step or offset between two parts, i.e. the distance between two adjacent surfaces measured in the orthogonal direction to the tangent plane on the surfaces in exam. Fig.1 represents two adjacent parts (solid lines) and the geometrical definition of gap and flush [3].

These measurements are essential for assessing the alignment and evenness of parts such as body panels, doors, and hoods, which significantly affect both the appearance and aerodynamics of the vehicle. Traditionally, these tasks were carried out manually, relying on physical tools and human inspectors to evaluate the alignment of parts. However, with the increasing complexity of manufacturing processes and the growing demand for precision and digitalization, manual methods are no longer sufficient [4]. These limitations have led to the adoption of advanced technologies such as laser triangulation, which provides highly accurate, repeatable, and non-contact measurement capabilities. By incorporating these technologies into the production process, automotive manufacturers can ensure the highest level of precision, reduce human error, and streamline production [5]. Several developments are presented in literature that propose the use of laser triangulation for gap and flush measurements in automotive production lines. In [3], [2], the authors presented for the first time a portable based laser triangulation sensor integrated to a smartphone, showing the potential of a portable IoT solution for measuring in line. The paper [6] presents another solution of a portable laser line triangulation system based on a smartphone; in this case the smartphone is used as camera system and a laser line projector is mounted on hand-held support fixture. Laser line triangulation system are also mounted on robots as presented in [4].

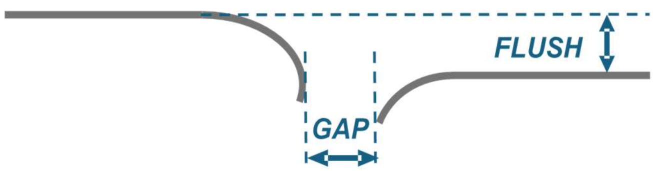

Fig. 1. Gap and Flush definition.

In recent years, the adoption of laser triangulation technology for gap and flush measurement has transformed quality control processes, offering superior accuracy and efficiency compared to traditional methods. However, while these advanced technologies can mitigate systematic errors, the influence of operator variability remains a critical factor when the sensor is manually operated. The growing focus on Industry 5.0, which emphasizes the synergy between human operators and intelligent systems, brings to light the need to quantify and address the variability introduced by human interaction with measurement tools [7]. This highlights a gap in the literature, as much of the existing research has focused on minimizing systematic errors in measurement systems, but has not fully explored how operator behaviour impacts precision in manual measurement modes.

In this context, this paper investigates the application of an innovative portable measurement system based on laser triangulation technology, specifically designed for gap and flush measurement within the automotive industry.

The primary focus of this study is on evaluating the system's performance when operated in manual mode and utilizing a magnetic holder, which facilitates the device's positioning during measurement. The goal of the research is to assess the degree to which operator variability influences the measurement process. By considering the interaction between the operator and the measurement system, this research aims to provide valuable insights into the potential sources of error and the level of precision achievable in real-world, operator-dependent conditions.

To ensure the reliability and robustness of the measurement system, the paper incorporates a comprehensive validation process. Specifically, it utilizes the Measurement System Analysis (MSA) methodology to assess the repeatability and reproducibility of the collected data. The purpose of MSA is to determine whether a measurement system is suitable for use in conformity assessment. To achieve this, the MSA methodology requires repeated measurements to be taken by different operators on different parts. The collected data is then statistically analyzed to estimate the variability attributable to the measurement equipment, the operators, and the overall system. In this paper, MSA is employed to quantify the consistency and accuracy of the measurements, accounting for both inherent system errors and variability introduced by the operator in using the two modalities of the system. This rigorous analysis allows for a deeper understanding of how human factors may impact the precision of gap and flush measurements and provides a framework for optimizing measurement techniques to reduce such influences [8].

Fig. 2. G3F profilometer

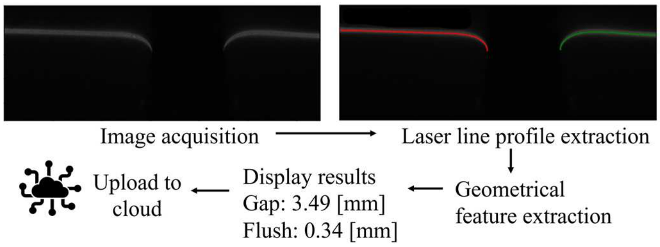

Fig. 3. G3F data stream mapping

Through this approach, the paper aims to bridge the gap between cutting-edge measurement technologies and human-centric industrial practices, ensuring that the integration of advanced systems in manufacturing processes can coexist harmoniously with the skills and variability of human operators.

The rest of this work is organized as follows. Section 2 reports the methodology used to acquire data by using the manual and magnetic holder systems and process the data by using the MSA. Section 3 presents the results of the MSA. Section 4 discusses the results, providing the insight of the measurement systems. In addition, Section 4 concludes the work.

II. MATERIALS AND METHODS

This study focuses on evaluating the performance of an innovative portable laser triangulation-based measurement system (laser profilometer) for gap and flush measurement in the automotive industry. Specifically, it examines the system's performance in manual mode and with a magnetic holder, which aids in device positioning during measurement. To do that, the measurement set-up has been explain and the measurement procedure to evaluate the systems' accuracy and reliability has been described.

A. Measurement set-up

The laser profilometer used for this study is the G3F sensor from U-Sense.IT srl (www.u-sense.it), Fig. 2, which is a smart portable laser profilometer, battery powered, fully compliant with a 5.0 industrial environment. One remarkable feature of the device is to be wireless, which allows manual use or fixed installation.

The profilometer features a laser line source that projects a line onto the target surface. A camera, aligned at an angle with respect to the laser axis, captures the laser line image and, through specialized algorithms, extracts the surface profile. The instrument automatically measures the gap and flush values on various surfaces, such as metallic painted or plastic surfaces. The measurement process is illustrated in Fig. 3. In the acquired image, the profile of the car illuminated by the laser line is shown in grey, while the colored lines, obtained after extracting the laser line, represent the reconstructed surface profiles. The analysis is provided to demonstrate the capability of the algorithm to extract the laser line even if the contrast is low. Particularly remarkable of this sensor is the capacity to process low contrast images as described in the patent [9]. The G3F sensor is calibrated to convert the camera image (in pixels) into a geometric profile, which accurately represents the target surface profile in millimeters. Finally, from this calibrated profile, various geometric features can be

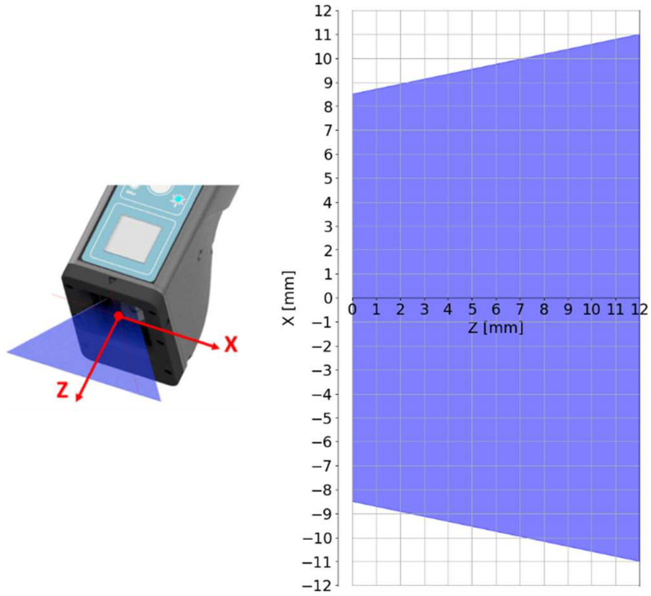

Fig. 4. G3F working range: the coordinate system z(x) (left) and the trapezoidal working range (right)

extracted. In this specific application, the gap and flush values are calculated and displayed on the instrument's screen.

Moreover, following the objectives from Industry 4.0, the G3F sensor is connected through Wi-Fi with the plant IT network, sharing the acquired data; indeed, it is an IoT device. The device has a working region reported in **Error! Reference source not found.** 4 which is specifically designed for gap measurements in the automotive sector. The working region covers the entire area in which the sensor can take measurements.

Finally, Table I reports the main characteristics of the G3F sensor.

During the operations in production line, the operator manually places the sensor in contact with the car surface in correspondence of the measurement target point. The sensor positioning is thus not precise as in the traditional automatic inspection procedure. However, sensor positioning precision can be increased by using a magnetic holder that facilitate the operator in sensor positioning and reduce unwanted movements.

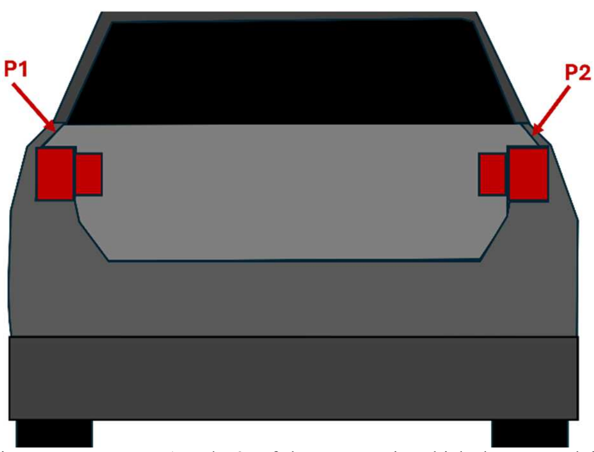

Fig. 5. Two parts, P1 and P2, of the car rear in which the gap and flush measurements have been acquired.

TABLE I. TECHNICAL CHARACTERISTICS OF G3F SENSOR

G3F specifications	
Laser wavelength	405 nm
Resolution X	7 µm (Z = 0 mm) 9 µm (Z = 12 mm)
Resolution Z	9 µm
Weight	350 g

The aim of this paper is indeed to quantify and compare from a metrological point of view, the performances of the G3F sensor in these two different operative modes: manual and with magnetic holder.

To perform the proposed analysis, data has been acquired in a production environment on three cars of the same model and year, representative of the production process variability. In the following paragraph, the measurement procedure is described.

B. Measurement procedure

Data of gap and flush were acquired from two parts, P1 and P2, of the car rear by three different operators (A, B, C) as illustrated in Fig. 5. For each part, three different cars were considered. Measurement procedure was repeated three times for a total of 18 measurement points collected for each operator for both gap and flush measurements. The measurement acquisition process was repeated twice: first by using the magnetic holder sensor and then by using the manual sensor without support.

The three operators have to carry out the measurements following these rules:

- Each operator has to measure all six parts (one point to the left side and one point to the right side in the rear of the three cars) in a random order;
- The measurements will be recorded in a dedicated file;
- After completing the initial round of measurements, the operators must repeat the process, again following a random order. This step helps verify the stability of the measurements over time and between different test cycles;
- To enhance practicality, the measurements may be organized in a way that allows the operator to complete all measurements on one side before moving to the other. If operators work in different shifts, each will perform all the measurements during their shift, ensuring the consistency and uniformity of the test across different work cycles.

C. Repeatability and reproducibility analysis

The Measurement System Analysis (MSA) [8], [10] was conducted on the analyzed samples to evaluate the precision and reliability of the measurement systems. This analysis focused on assessing both the variability between parts and the variability between operators, which are critical factors in understanding the overall measurement system performance. The analysis started from the average and range method that is a method for measurement system evaluation of continues scale. Each measure can be described with three subscipts as in (1)

$$x_{i,j,k}, \quad (1)$$

where:

- $i \in (1, \dots, N)$ is the part or the spot considered,
- $j \in (1, \dots, A)$ describes the operator,
- $k \in (1, \dots, T)$ describes the trial.

Then, the Repeatability – Equipment Variation (EV) and Reproducibility – Appraiser Variation (AV) were calculated, along with the Gauge Repeatability and Reproducibility (GRR).

EV reflects the variation in measurements that occurs when the same operator measures the same part multiple times, highlighting the consistency and reliability of the equipment during repeated measurements by the same individual. EV is calculated as in eq. (2)

$$EV = \bar{\bar{R}}\, K_1. \quad (2)$$

$\bar{\bar{R}}$ is the average range where each range is calculated as in eq. (3) and K_1 is a constant that depends on the number of trials:

$$R_{i,j} = \max(x_{i,j,k}) - \min(x_{i,j,k}). \quad (3)$$

AV reflects the variation in measurements when different operators measure the same part, highlighting the influence of human factors on the consistency of the results across multiple operators. Considering the average measure value for each operator (eq. (4))

$$operator\ average\ j-th = \bar{X_j} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{k=1}^{T} x_{i,j,k}, \quad (4)$$

AV is calculated as in eq. (5)

$$AV = \sqrt{\left(X_{diff}K_2\right)^2 - \frac{(EV)^2}{NT}}. \quad (5)$$

Where K_2 is a constant that depends on the number of operators and X_{diff} (6) is the range calculated as the maximum average operator value difference

$$X_{diff} = \max(\bar{X_j}) - \min(\bar{X_j}). \quad (6)$$

GRR represents the combined repeatability and reproducibility and it is calculated as in eq. (7)

$$GRR = \sqrt{EV^2 + AV^2}. \quad (7)$$

Then the TV (Total process Variability) must be evaluated to descibe repeatability, reproducibility and GRR behaviour in the part production. If the process variation is uknown, TV is estimated as (8)

$$TV = \sqrt{GRR^2 + PV^2}. \quad (8)$$

PV (9) is the part-to-part variation without measurement variation

$$PV = R_p K_3, \quad (9)$$

where K_3 is a constant that depends on the number of parts measured, while R_p (10) is the range of parts average (11):

$$R_p = \max(\bar{X_\iota}) - \min(\bar{X_\iota}), \quad (10)$$

$$part\ average\ i-th = \overline{X_{p,\iota}} = \frac{1}{AT}\sum_{j=1}^{N}\sum_{k=1}^{T} x_{i,j,k}. \quad (11)$$

The repeatability, reproducibility and GRR percentages are determined by calculating the proportion of total variability attributed to the variability of the study (EV% = 100*EV/TV; AV% = 100*AV/TV; GRR% = 100*GRR/TV). In conclusion, the GRR% provides an overall KPI of the measurement system's variation capability to describe the process. Based on the calculated GRR, the following criteria are used to evaluate the measurement system's acceptability:

- Acceptable Measurement system: GRR values less than 10% are considered acceptable; the measurement system provides reliable information about process changes.
- Conditionally acceptable: GRR values between 10% and 30% are acceptable for certain applications; it can be used for certain applications.
- Not acceptable measurement system: GRR values greater than 30% are considered unacceptable, indicating that the measurement system may need improvement to ensure reliable results.

III. Results

Results from the MSA, shown in Table II, provide an overview of the variability in terms of repeatability and reproducibility of the measurement system, both for manual and magnetic holder laser profilometer, for gap and flush measurements. Specifically, the table reports the EV that indicates the variability of the data introduced by the device, independently of variations introduces by the operator or process. Then, AV has been reported, that is the variation introduced by the operator. A low AV suggests that the operators are consistent in their measurements, minimizing the impact of human factors on the results. Finally, GRR has been reported that represents the total variability in the measurement system due to both the device (repeatability) and the operators (reproducibility).

TABLE II. EV %, AV% and GRR% for gap and flush measurements by using holder and manual laser profilometer

	EV%	AV%	GRR%
Holder Flush	2,15	0,56	2,22
Holder Gap	2,32	0,00	2,32
Manual Flush	2,99	0,92	3,13
Manual Gap	3,66	0,00	3,66

In particular, based on the results from the table, a clear distinction can be observed between the manual technique and the magnetic holder technique. The magnetic holder technique shows lower variability, with GRR values of 2,22 % for flush and 2,32 % for gap, compared to the manual technique, which has GRR values of 3,13 % for flush and 3,66 % for gap. Despite this difference, the GRR values for both systems are within acceptable limits, indicating that both techniques are capable of delivering reliable results. The lower variability in the magnetic holder system can be attributed to the support it provides to the operator during the measurement process, resulting in more consistent and precise measurements. In contrast, the manual technique is more prone to variability due to the greater influence of operator factors and the lack of additional support.

Based on results, repeatability (EV) is low for both techniques, with the holder technique showing lower values. This indicates that the holder technique introduces less variability compared to the manual technique, resulting in more consistent measurements. The EV values for the holder technique (2,15% for flush and 2,32% for gap) are lower than those for the manual technique (2,99% for flush and 3,66% for gap), highlighting that the support provided by the holder system contributes to reduced variability and improved repeatability.

Moreover, reproducibility (AV) shows minimal variability for the holder technique, with values of 0,56% for flush and 0,00 % for gap. This indicates that the operator has a limited impact on the measurements when using the holder system. On the other hand, the manual technique exhibits slightly higher reproducibility variability, with AV values of 0,92 % for flush and 0,00 % for gap. This suggests that operator differences play a larger role in influencing measurements during manual operation, particularly for flush measurements. Additionally, the results show that in terms of reproducibility, the flush is more sensitive than the gap to alignment issues, which is why the gap results show no appreciable variability.

IV. Discussions and conclusions

In conclusion, the analysis of the two laser profilometer modalities—manual and holder—has highlighted key differences in measurement variability. The results demonstrate that the holder system consistently offers lower variability across both repeatability (EV) and reproducibility (AV) compared to the manual sensor. The support provided by the holder system plays a crucial role in reducing variability by assisting the operator in positioning the sensor more consistently during measurements. This support system aligns with the vision of Industry 5.0, which emphasizes the collaboration between human operators and intelligent systems to enhance precision and reduce errors.

While the manual sensor exhibited higher variability, particularly in repeatability and reproducibility, it still yielded GRR values that are within acceptable limits, indicating that the system remains suitable for certain applications despite the greater impact of operator influence. In particular, the manual mode of operation offers maximum freedom of movement to the operator, which in a production line is doing a large variety of tasks; reducing any constraint is an advantage in terms of operator flexibility.

By incorporating support mechanisms like the holder system, the measurement process can effectively minimize human error while still leveraging the skills and adaptability of operators, which aligns with the principles of Industry 5.0. These findings emphasize the importance of developing systems that facilitate seamless interaction between human expertise and intelligent tools to optimize performance and reduce variability.

In this context, both sensor modalities, manual and magnetic holder, are valid and effective for their intended applications, also thanks to the wireless nature of the device. The magnetic holder system offers a marked advantage in terms of enhanced precision and a significant reduction in variability. On the other hand, while the manual method is slightly more variable, it remains functional and effective, providing acceptable performance for certain applications that do not require the extreme precision afforded by the magnetic holder system. The combination of these two approaches highlights the importance of choosing the right system based on the specific needs of the task, and demonstrates how technological advancements can complement human capabilities to achieve optimal results.

Acknowledgment

This work was partially supported by PR Marche Fondo Sociale Europeo Plus 2021/2027 and by the European project OPENZDM (Grant Agreement No. 101058673, call HORIZON-CL4-2021-TWINTRANSITION-01).

References

[1] O. Morales Matamoros, J. G. Takeo Nava, J. J. Moreno Escobar, e B. A. Ceballos Chávez, «Artificial Intelligence for Quality Defects in the Automotive Industry: A Systemic Review», *Sensors*, vol. 25, fasc. 5, Art. fasc. 5, gen. 2025, doi: 10.3390/s25051288.

[2] E. Minnetti *et al.*, «A Smartphone Integrated Hand-Held Gap and Flush Measurement System for in Line Quality Control of Car Body Assembly», *Sensors*, vol. 20, fasc. 11, Art. fasc. 11, gen. 2020, doi: 10.3390/s20113300.

[3] E. Minnetti *et al.*, «Smart portable laser triangulation system for assessing gap and flush in car body assembly line», in *2019 II Workshop on Metrology for Industry 4.0 and IoT (MetroInd4.0&IoT)*, giu. 2019, pp. 49–53. doi: 10.1109/METROI4.2019.8792858.

[4] J. Kholkhujaev, G. Maculotti, G. Genta, M. Galetto, e J. Inoyatkhodjaev, «Non-Contact Articulated Robot-Integrated Gap and Flushness Measurement System for Automobile Assembly», *IEEE Access*, vol. 10, pp. 86528–86541, 2022, doi: 10.1109/ACCESS.2022.3199066.

[5] G. D'Emilia, A. Gaspari, C. Iavicoli, e E. Natale, «Measurement uncertainty estimation of gap and profile in the automotive sector», *J. Phys.: Conf. Ser.*, vol. 1589, fasc. 1, p. 012017, lug. 2020, doi: 10.1088/1742-6596/1589/1/012017.

[6] L. H. Pham, D. N.-N. Tran, J. Y. Byun, C. H. Rhie, e J. W. Jeon, «A Smartphone-Based Laser Measuring System for Gap and Flush Assessment in Car Body», *IEEE Transactions on Industrial Electronics*, vol. 68, fasc. 7, pp. 6297–6307, lug. 2021, doi: 10.1109/TIE.2020.2992971.

[7] A. Baleani, P. Castellini, P. Chiariotti, N. Paone, e L. Violini, «Analysis of reproducibility and repeatability of a hand-held laser scanner for gap&flush measurement in car-assembly line», in *2020 IEEE International Workshop on Metrology for Industry 4.0 & IoT*, giu. 2020, pp. 648–653. doi: 10.1109/MetroInd4.0IoT48571.2020.9138222.

[8] L. Cepova, A. Kovacikova, R. Cep, P. Klaput, e O. Mizera, «Measurement System Analyses – Gauge Repeatability and Reproducibility Methods», *Measurement Science Review*, vol. 18, fasc. 1, pp. 20–27, feb. 2018, doi: 10.1515/msr-2018-0004.

[9] P. Chiariotti, N. Giulietti, N. Paone, e P. Castellini, «Apparatus, Method and Computer Program for Measuring a Space and / or an Alignment and / or an Angle of Misalignment Between a First Surface and a Second Surface», EP4341642A1, 27 marzo 2024

[10] EDITION, Fourth. Measurement Systems Analysis. 1990.