Metrol. Meas. Syst., Vol. 29 (2022), No. 1
DOI: 10.24425/mms.2022.138546

METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.wat.edu.pl

DEVICE FOR INTERIM CHECK OF COORDINATE MEASURING MACHINES

Rodrigo Schons Arenhart1), Morgana Pizzolato1), Fernanda Hänsch Beuren2), Adriano Mendonça Souza3), Leandro Cantorski da Rosa1)

1) *Federal University of Santa Maria, Department of Production Engineering and Systems, Roraima avenue, 1000, Santa Maria, Brazil* (✉ *rodrigo.schons@acad.ufsm.br*, +55 55 99608 1406, *morgana.pizzolato@gmail.com*, *leski78@hotmail.com*)
2) *State University of Santa Catarina, Department of Industrial Technology, Fernando Hastreiter street, São Bento do Sul, Brazil* (*fernanda.beuren@udesc.br*)
3) *Federal University of Santa Maria, Statistics Department, Roraima avenue, 1000, Santa Maria, Brazil* (*amsouza.sm@gmail.com*)

Abstract

This paper presents a new interim check device for coordinate measuring machines (CMMs) built from an AISI 1020 carbon steel bar with the incorporation of calibrated spheres. This artifact's construction was made to make the interim checks of machine's type faster and cheaper. Three devices were designed based on the ISO 10360-2 standard, the good practice guide No. 42 (NPL), and prominent authors' research on the subject. The three options are presented in detail, but only one was built due to budget, size, and adaptability restrictions. An exploratory study was conducted to verify the device's usability in two CMMs and concluded that the differences between the measurements are not significant. However, one machine had absolute variation values and a total standard deviation higher than the other, generating a larger expanded uncertainty.

Keywords: coordinate measuring machine, device, interim check.

1. Introduction

Metrology started to support the humanity's economic activities and is still an important quality control factor [1]. Dimensional metrology had a significant growth due to the demand generated by automobiles, accelerating the incorporation of *coordinate measuring machines* (CMMs) in this industry [2]. These machines are measuring instruments for checking the quality of production and are particularly used for measuring parts with complex geometries due to their high efficiency and dimensional accuracy [3] [4].

To guarantee the reliability of the measurements made with the CMMs, these must be periodically checked and calibrated, to evaluate the performance and to optimize the measuring process [5]-[7]. Calibration is done by comparing measurement values and uncertainties of a reference with values established by standards under specified conditions [8]. The interim check [7] aims to maintain confidence in equipment performance, observing occurrence or not of significant variations between calibrations. Interim checks must be performed according to a standardized procedure [5] - [7], in the case of volumetric performance periodic verification of the CMMs used in linear measurements, the ISO 10360-2: 2009 [9] standard provides the necessary support [3].

Some factors complicate establishing of an interim check technique for all CMMs, such as the maximum measuring volume of the machines and the manufacture of artifacts with good thermal stability, easy to calibrate, and low cost [4]. Still, some artifacts are recommended for interim checks, such as devices of typical measurement forms, ball plates, hole plates, ball bars, bars with holes, circular patterns, and rotational kinematic bars. There is also recommended

Article history: received June 9, 2021; revised August 25, 2021; accepted October 11, 2021; available online November 9, 2021.

that the material of the artifact should have a thermal constant like the parts typically measured with the CMM [9], [10].

This paper aims to build an adequate and low-cost device for CMMs interim check. The solution is presented through the construction and verification of the usability of a device. To verify the state of the art on the subject, data from a *systematic review* (SR) of the literature on interim check devices of CMMs are used [11]. To assist in the elaboration of the device's designs, we used the SR [11], the ISO 10360-2: 2009 [9] standard, and the NPL good practice guide No. 42 [10]. To verify the usability of the device in the measurement volume of CMMs, we conducted an exploratory study, with the *analysis of variance* (ANOVA) [12]. Acceptance, reverification, and interim check results can be used to estimate measurement uncertainty of coordinate measurements based on information about the CMM's accuracy [13] - [15]. This study uses the *uncertainty R&R* (UR&R) method proposed by [16] to define the expanded uncertainty.

2. Interim check: standardization and previous studies

2.1. Standardization

Usually, after periodic machine maintenance, it is recommended to perform a verification test, according to a standard procedure, to assess operational compliance according to criteria informed by the manufacturer [17]. In an organization's quality assurance, simplified performance monitoring can be used periodically to demonstrate the probability that the CMM will meet specified requirements. The user must determine the frequency of interim checks according to the required measurement performance, the environmental operating conditions, and the use of the machine. The CMM should also be checked immediately after any significant event that may affect its performance [9], [10].

The choice of a standard device for interim tests depends on the institution's quality system's requirements [15]. Among the artifacts recommended for this procedure, Devices with typical measurement forms have the advantage of testing the capabilities of the measurement software more severely, on the other hand, a new device may be required in the event of a change in CMM measurement tasks. The advantages of a ball bar are its low cost, size, lightness, and the use of a stable and robust metal bar. The disadvantages are that the calibration is not directly traceable as it is based on computed surface and that it duplicates a measurement task rarely practice [10]. In addition, the use of KOBA ball-bar rod standards is not usual anymore because of the wearing of mounting sockets. The simple tube and L-shaped tube standards are also rarely used [15].

Rotational kinematic bars have bars of different lengths, and among its advantages is the vast volume of measurement provided, even though it is a portable device. These devices are developed with stable and lightweight materials and are easy to use. Its main disadvantages are the use only in CMMs that can vectorize in a circle and not be as robust as other devices presented by ISO 10360-2:2009. Ball plate devices are robust and stable; on average, they have a low construction cost, but they are heavy. Hole plates are lighter than ball plates and have the advantage of measuring any side of the structure [10]. *Physikalisch-Technische Bundesanstalt* (PTB) and Federal Institute for Materials Research and Testing (BAM) developed the plate standard with spherical reference elements in the form of internal spheres for computed tomography checking. The standard is made of Zerodur, has an expansion coefficient very low ($\alpha = 0 \pm 0.1\text{x}10^{-6}\,\text{K}^{-1}$), and the sphere forms errors do not exceed 2.5 µm, but it is an expensive material for specific measurements [15], [18].

2.2. Previous studies

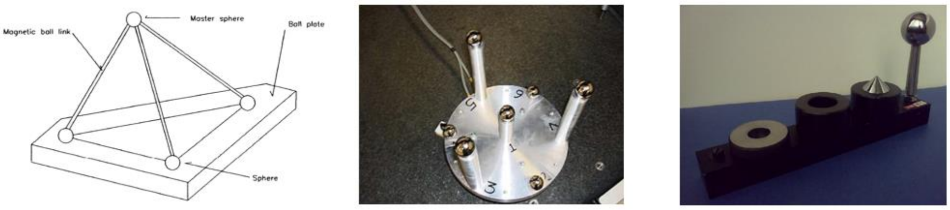
Three studies were highlighted in the systematic review [11] for contributing with new devices for checking CMMs. The first device verified was a modular structure [5] that has the shape of a tetrahedron with a high precision sphere at each apex and can be configured in different directions on the CMM volume. The modular structure is explained in Fig. 1a.

The base structure contains a frame for fixing the tetrahedron where three spheres of 20 mm diameter are fixed. The structure has three magnetic bars; each one connects the spheres of the base to a fourth sphere, positioned above the base, called the master sphere. The artifact is suitable for small and medium-sized CMMs, which, according to manufacturers' catalogues, have a measuring volume between 0.08 m^3 and 7.68 m^3. Six bars of different lengths were used in the study. Therefore, depending on the size of the bars and how they are assembled, different tetrahedron configurations can be obtained. The authors claim that measurements can be carried out in 33 different ways in 40 minutes.

The second device examined is the spatial structure [4], which has a cylindrical base with seven spheres of 19 mm in diameter, with high precision and accuracy, as can be seen in the Fig. 1b. Three spheres are attached to the surface of a cylindrical base, one is in a centralized position, and the other three are fixed to the tallest steel rods. The main requirements of this project are that the spheres have a sphericity of less than 0.1 μm and that a material resistant to damage and corrosion be used, such as chromium steel.

The experimental procedure for performing the check with this device is to measure the seven spheres a first time and then rotate the structure by 15 degrees, from the point where the angle is equal to zero to the point where the angle is equal to 360. In this manner, 175 points are collected, capable of generating the measurement of 15,225 distances between them. The necessary measurement time, according to the authors, is 45 minutes.

The device with several calibrated workpieces measurement standards [19] was also verified, which must be permanently fixed on the measurement surface of the CMM to continually develop the procedure. The artifact is recommended for daily verification of the accuracy of CMMs, must be small to allow measurements without restrictions on machine's volume. The device must have calibrated and traceable standards, being able to provide a continuous test for plane, sphere, circle, cone, and cylinder measurements. Figure 1c shows the artifact with fundamental geometries.



(a) (b) (c)

Fig. 1. Devices: a) modular structure; b) spatial structure; c) artifact with fundamental geometries.

The three devices presented in the systematic review [11] have structural and application usage differences. The first presents construction and methodology that can be used mainly in calibrations; the second is indicated for interim checks, rechecks, and acceptance tests; and the third is used regularly as a daily accuracy test. Consequently, to choose or build a device, the user must consider the form of use and the concepts presented by the standardization and studies already developed.

3. Analysis of variance (ANOVA)

Experiment planning techniques are important in engineering to solve problems in the development of new products, processes and in improving them [20]. These procedures are basic to determine which products or services will be successful in the market as they are a convincing way to show cause and effect relationships, manipulating attributes and observing the consequences [21].

Generally, the difference between the expected results and the reference value are well represented through *gage repeatability and reproducibility* (GRR) study, from that, when a hypothesis must be tested experimentally, one of the most robust and reliable methods used is ANOVA [22]. This method is recommended to assess the occurrence of interactions, being suitable for the GRR study as it provides more accurate parameters estimates involved in the *measurement systems analysis* (MSA) [23].

The GRR study is a planned factorial experiment in which traditionally the different factors are part and operator [24]. Repeatability refers to variation in measurements made with a measuring instrument, used several times by a single operator measuring the same characteristic of the same part. Reproducibility is variation in measurements average made by different operators, using the same instrument, measuring the same characteristic of same part [12].

GRR using ANOVA decomposes variability into four sources: parts, operators, the interaction between part and operator, and repetition error due to the measuring instrument. A sample of at least five equal parts is used, measured by three different operators, where each operator performs three measurements on each part. Measurements are random, both for the part and for the operator [12]. Figure 2 shows a typical structure of sources of variance in a traditional GRR study.

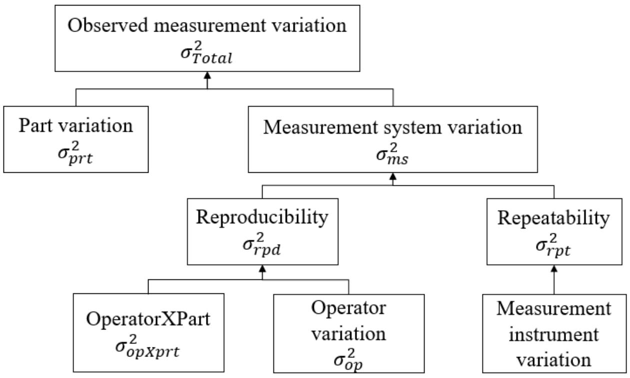


Fig. 2. Typical structure of the sources of variance in a traditional GRR study.

The variation components´ are presented in equations (1)-(3), where σ^2 represents variance of a component of variance. The subscripts "prt", "ms", "rpt", "rpd", "op" and "opXprt" respectively represent "part", "measurement system", "repeatability", "reproducibility", "operator", "operator x part interaction”. The equations are based on the sum of variance laws [21], [24], [25]:

$$\sigma^2_{\mathrm{Total}} = \sigma^2_{\mathrm{prt}} + \sigma^2_{\mathrm{ms}}, \tag{1}$$

$$\sigma^2_{\mathrm{ms}} = \sigma^2_{\mathrm{rpt}} + \sigma^2_{\mathrm{rpd}}, \tag{2}$$

$$\sigma^2_{\mathrm{rpd}} = \sigma^2_{\mathrm{op}} + \sigma^2_{\mathrm{opXprt}}. \tag{3}$$

4. Method

4.1. Development of the device

The device development begins with particularities identification of the measurement systems to be used in the research, information such as operating conditions, physical and environmental restrictions, maximum measurement capacity, among other technical aspects of the CMM operation. This survey is carried out with the study of the technical characteristics available in the CMMs operating manuals, in addition to other aspects incorporated by the laboratories that are responsible for the machines.

The interim checks device is designed with adherence to the SR, ISO 10360-2: 2009, and NPL guide nº 42 as its main references [11], [9], [10]. In parallel, commercial models found in the dimensional metrology market are highlighted as a form of additional references and cost comparison. The projects are developed using CAD/CAM software, while the construction and assembly of the device are carried out with the aid of a mechanical automation laboratory.

4.2. Device usability

This step verifies the interim check device usability over the CMMs measurement volumes. It is desired to define in which positions/orientations in measuring volume of each machine it can be placed so that the check can be conducted. Thus, this stage presents an exploratory study of variability through a gage R&R test with different factors ANOVA.

Unlike traditional GRR, only one operator is used in this study because as [26], [27] evidenced, operator criterion is not significant for this measurement instrument type. This is because when the part measured by the CMM is changed, different operators remain measurement in the range, without significantly variance interfering. However, it should be noted that the operator must be trained in the operation of this equipment since the lack of training can generate differences between measurements.

From this, the machines general variability exploratory study can be done with a GRR study, using a two-way ANOVA: (i) measurement quadrants; and (ii) device orientation. This experiment is carried out to check if the machine has variability in measurements along its volume according to device orientation. The measurements variability is evaluated in three different quadrants of each machine, with five device orientations in each quadrant. Figure 3 shows a configuration of the exploratory GRR study.

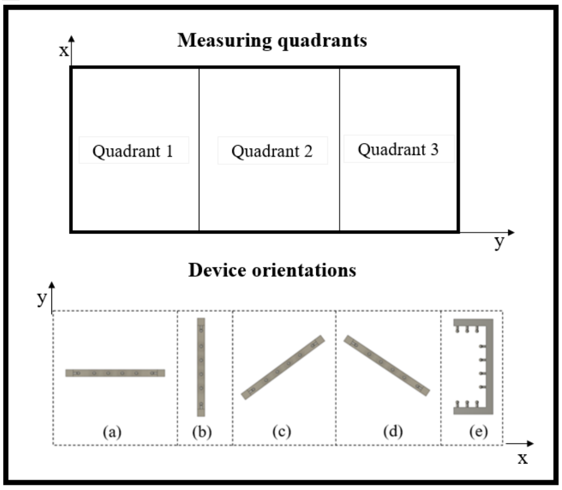


Fig. 3. Configuration of the exploratory GRR study.

The variation components´ in exploratory GRR study is presented in equations (4)-(6), where σ^2 represents the variance of a component of variance. The subscripts "ort", "ms", "rpt", "rpd", "mq" and "mqXort" respectively represent "device orientation", "measurement system", "repeatability", "reproducibility", "measuring quadrant", "measuring quadrant x device orientation interaction”. The equations are based on the sum of variance laws [21], [24], [25]:

$$\sigma^2_{\mathrm{Total}} = \sigma^2_{\mathrm{ort}} + \sigma^2_{\mathrm{ms}}, \quad (4)$$

$$\sigma^2_{\mathrm{ms}} = \sigma^2_{\mathrm{rpt}} + \sigma^2_{\mathrm{rpd}}, \quad (5)$$

$$\sigma^2_{\mathrm{rpd}} = \sigma^2_{\mathrm{mq}} + \sigma^2_{\mathrm{mqXort}}. \quad (6)$$

To assess the variability, the measuring procedure uses the distance between the two upper spheres of the device. These calibrated spheres have diametric values of 20.0014 mm and 20.0020 mm, with an uncertainty of 0.0005 mm (k=2). The distance between the two upper spheres is measured in the five orientations and the three quadrants of each machine, as proposed in Fig. 3. Thus, it is expected that the device's usability can be verified to develop a checking procedure involving the other calibrated spheres.

During measurements, each sphere is measured with five probing points, the first is on the upper surface and the others on the middle line. The measurement configuration with a fixed probe head is conducted with one tip "from the top". In a machine with a motorized probe, the orientation of the measuring tip changes in two angles (0° and 90°). The object temperature correction is applied in the measurements and the test room and standards must be stabilized after as least two hours in a temperature range between 19 and 21 °C.

For the statistical analysis of the results, the UR&R method proposed by [16] is used to estimate the expanded uncertainty for both MSs. This hybrid method uses experiments to estimate uncertainty's sources and the GUM [28] is used to evaluate influences that cannot be measured directly. The sources are from the generic uncertainty budget for dimensional calibrations: master gage uncertainty, R&R, thermal factors, measuring machine scale uncertainty, elastic deformation, instrument geometry, and customer gage geometry.

5. Results

5.1. Device construction

The step begins with coordinate measuring machines particularities identification. We used two CMMs with different characteristics and measurement volumes identified as *CMM Measurement System 1* (CMM-MS 1) and *CMM Measurement System 2* (CMM-MS 2). The CMM-MS 1 is operated only by trained technicians. The CMM-MS 1 performs measurements with a touch-trigger probe and with two optical cameras, touch measurements are made with a fixed probe-type, with a length of 20 mm, and a probe tip with a diameter of 3 mm. Optical measurements are carried out with two cameras; the first inserted next to the probe support (surface measurements) and the second located on the axis of the lower part of the measurement table (profile measurements). The comparison between measurement systems particularities is shown in Table 1.

Table 1. Comparison between the particularities of the measurement systems

Item	**Measurement System 1**	**Measurement System 2**
Measurement type	Touch/Optical	Touch
Type of the probe head	Fixed	Motorized
Probe length (mm)	20	20
Probe tip diameter (mm)	3	2
Measurement volume (m^3)	0.144	0.576
XYZ Travels (mm)	640x900x250	800x1200x600
$E_{L,MPE}$ (µm)	2.4+4.0L/1000	2.9+4.0L/1000
Type of measurement table	Tempered Glass	Granite
Maximum weight supported	75 kg	Indefined
Measurement Resolution (mm)	0.0005	0.001
Maximum drive speed (mm/s)	330	510
Operation temperature (°C)	0 to 40	10 to 40
Operation Humidity (%)	30 to 80	20 to 90

The CMM-MS 1 has a measuring volume of 0.144 m^3 (640 x 900 x 250 mm), supporting a maximum weight of 75 kg on its measuring surface (tempered glass table). Its measurement resolution is 0.0005 mm, and the camera settings are 2048 x 1590 pixels. The maximum drive speed is 330 mm/s. The operating temperature range varies between 0 and 40 °C, while the humidity range varies between 30 and 80%. However, despite the operation range in the environmental conditions, the laboratory defines the use of the machine in a temperature range between 19 and 21 °C and maximum humidity of 70%.

The CMM-MS 2 machine performs touch measurements with a motorized head with a touch-trigger probe (length of 20 mm and probe tip with a diameter of 2 mm). The measuring volume is 0.576 m^3 (800 x 1200 x 600 mm) on a granite surface. Its measurement resolution is 0.001 mm, and maximum handling speed is 510 mm/s. The operating temperature range varies between 10 and 40 °C, while the humidity range varies between 20 and 90%. However, the machine is used in a temperature range between 18 and 22 °C.

In device development, we seek to select an interim check device compatible with expectations required for research MSs; three options were designed. The first alternative is based mainly on SR [11], where we projected a virtual spatial structure variation, proposed by Silva *et al*. (2009). This device is specifically indicated for CMM interim check and was developed by a reference in the area, so it was redesigned to compose the list of options. This project was given the name of a cylindrical ball plate device (shown in Fig. 4a).

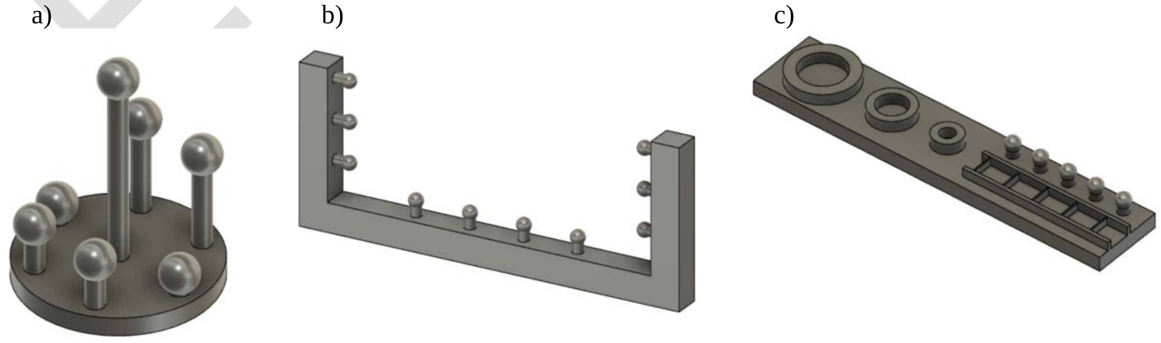


Fig. 4. Projects: a) cylindrical ball plate; b) ball ruler; c) device of basic geometric forms.

The cylindrical ball plate device has a cylindrical base with a 100 mm diameter; a central rod welded to base with 100 mm height; two 50 mm rods; two with 25 mm; and two with 10 mm. On each rod surface, a standard sphere 20 mm diameter is fixed using neodymium magnets. We suggested using two magnetic supports to optimize device stability since the measurement surface can be glass or granite.

The second project was developed according to the methodology proposed by [4], [5], and related standards. However, the design was developed to better adapt to machines measuring volume and the MSA methodology to optimize device usability. We named the device a ball ruler device (Fig. 4b). This device aims to cover the majority machine measuring surface to facilitate a simple and agile interim check and provide stability, bias, linearity, and GRR studies.

The ball ruler device was projected with a steel bar, 40 mm wide by 40 mm high, divided into three sections. The horizontal section is 540 mm long, while the other two vertical sections are 180 mm each. In the device's internal base, ten cylindrical steel rods are used to fix ten chrome steel spheres through neodymium magnets. The rods are 15 mm in diameter and 20 mm high, and the spheres are 20 mm in diameter.

The third device was designed according to the previous guidelines but with a focus on the devices found in the market like ball-bar, plate standard, spherical references, and hole plate standards. This project has a larger surface when compared to the devices in the market and has three basic measurement geometric shapes through length patterns (blocks, rings, and spheres). This device is shown in the Fig. 4c.

The last device's base is 500 mm long, 100 mm wide, and 20 mm high. It also has five cylindrical rods 10 mm high and diameter of 15 mm, for the incorporation of five 20 mm spheres. Next to the spheres, close to the base, are positioned five-gauge blocks (2 mm each). Three-gauge rings are fixed on the other device half, with diameters 20, 40, and 60 mm.

The main restrictions for the device's choice are the adequacy in the machines measuring volume, the usability evaluating possibility through experimental studies, and the cost. Therefore, we consulted commercial options that were outside acquiring equipment reality of the laboratories. We made an analysis to identify the best cost-benefit among the projects developed in the research. The budgeted costs of building/purchasing devices are presented in Table 2 (in united states dollars).

Table 2. The budgeted costs of building/purchasing devices (in united states dollars)

Device	Base	Standards	Labour	Calibration	Total Cost
Cylindrical ball plate device	$ 73.36	$ 13.54	$ 22.57	$ 112.87	$ 222.34
Ball ruler device	$ 46.28	$ 13.54	$ 33.86	$ 112.87	$ 206.55
Device of basic geometric forms	$ 34.99	$ 209.93	$ 45.15	$ 158.00	$ 448.07
Comercial product (Ball-bar)	$ 0.00	$ 0.00	$ 0.00	$ 0.00	$ 4,995.00

From identifying the costs linked to each project, a discrepancy is noted between the product sold and the elaborated projects. Thus, we selected the ball ruler device. The reasons for this choice were: (i) the ruler occupies a large part of MSs measurement volume; (ii) the device can carry experimental MSA studies; (iii) the ball ruler has major potential for checking errors of distances measurements; (iv) the project has the lowest total budgeted manufacturing cost among all projects.

The device construction was made by a mechanical automation laboratory, where cutting and welding services were carried out, in addition to device parts fixing. The main structure was built from a 40x40 mm AISI 1020 square carbon steel tube with a 1.2 mm wall thickness. The carbon steel was used too in the rods for fixing the spheres in a 16 mm round carbon steel bar. Ten neodymium magnets were used to fix spheres in the device.

The device's total construction cost was US$ 198.00 in February 2021, of which US$ 31.40 for the square tube and round bar, US$ 35.40 for spheres, US$ 8.90 to purchase a set of ten neodymium magnets, and US$ 14.00 with different materials (screws, sandpaper, spray paint).

The construction cost was charged by the exchange of materials. The spheres' calibration cost was US$ 108.30. The ball ruler device final total cost was 4% lower than the budget. Figure 5 shows the built-in interim check device.

Fig. 5. The built-in interim check device.

5.2. Device usability

The exploratory study to evaluate the device usability in the measurement systems used in the project was done with a modified GRR study (conducted with action 2.7 software) in machine measuring surfaces. This evaluation sought to identify variations between measurements over CMM volume. According to the method in section 4.2, we defined three measurement quadrants that encompass the volume of the measurement systems and five device orientations Fig. 3, in section 4.2, shows exploratory GRR study configuration.

CMM-MS 1 results showed that there is a relation between the three measurement quadrants and the orientations of the device. This indicates that the MS was not able to categorize the variations between the orientations of the device in each quadrant, inferring that the MS cannot verify a significant difference in the measurement of the device in the CMM volume. The experiment results indicate that the variations presented relate to a total standard deviation that represents the orientations' variability of the measuring device within the machine's volume. Therefore, the study considers that the variation relates to the measurement system itself, which registered measurements with variability over its measurement range but was unable to categorize them.

It can be concluded that as the differences among the measurements in the three quadrants are not significant, the CMM cannot identify these differences, indicating that there is no significant variability over the machine's measurement volume. The study showed that the central quadrant had a higher average than the other two quadrants (397.284 mm in quadrant 2 and 397.283 mm in quadrants 1 and 3). The orientations standard deviation was equal to zero, this may be due to the material's stability, but is an unlikely situation for measurements made with CMM. Table 3 presents the contribution of variation in CMM-MS 1.

Table 3. The CMM-MS 1 contribution variation

Item	**Standard Deviation**
Repeatability	0.00212
Reproducibility	0.00011
Quadrants	0.00011
Orientations	0.00000

Figure 6 shows the GRR graphs for CMM-MS 1, where the “c” and “d” orientations presented greater ranges of variation between the measurements collected (range graph in Fig. 6). This behaviour is due to the difficulty of measuring with the device inserted diagonally to the “X” axis (generating a series of attempts until a valid measurement is achieved). The graph of interactions in Fig. 6 shows the existence of erratic behaviour of the averages in comparison with the analysed quadrants, which reinforces MS's inability to categorize the real measurement of the distance in the device.

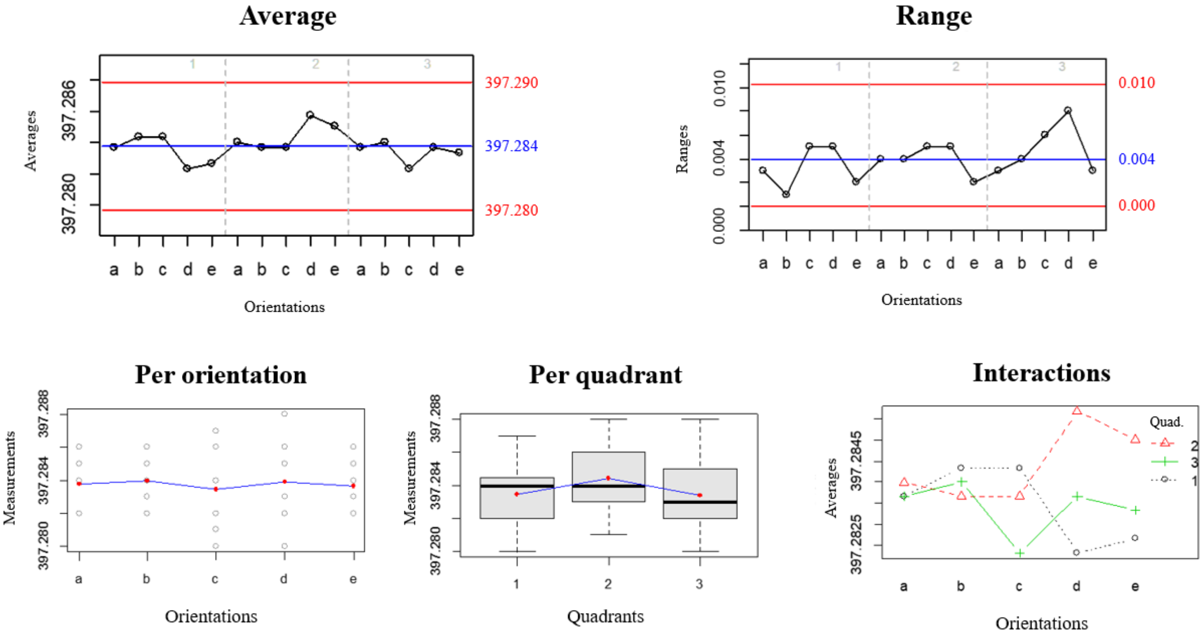


Fig. 6. The GRR graphs for CMM-MS 1.

The results of the GRR study in the CMM-MS 1 demonstrate that although the averages were close to 397.284 mm and did not have significant variability between the quadrants, there were variations confirmed both in the analysis of the contribution of variation in Table 3 and in the graphs of Fig. 6. There is also the difficulty of measuring in the diagonal orientation to the “X” axis, which must be avoided due to the delay in collecting the data and the possibility of measurement error.

The same experiment was carried out on CMM-MS 2, in which a relation between the measurement quadrants and the device's orientations was also verified. One orientation of the device recorded values above the measurements of the other ones (orientation “c” in Fig. 3). Table 4 presents the contribution of variation in CMM-MS 2, is find that the standard deviation value of the orientations was higher in CMM-MS 2 than CMM-MS 1 and that the contribution value of the quadrants was lower in CMM-MS 2. This demonstrates that the orientations had a significant contribution to the measurement error in this machine, while the quadrants did not contribute to the variation.

Table 4. The contribution of variation in CMM-MS 2.

Item	Standard Deviation
Repeatability	0.00259
Reproducibility	0.00363
Quadrants	0.00000
Orientations	0.00543

The finding verified in CMM-MS 1 was not found in CMM-MS 2 because measurements with the device diagonally to the "X" axis of the machine did not result in more measurement range and did not increase the measurement time. This can be assigned to the CMM-MS2 motorized probe head, improving the collect data time, and granted efficient measurements. Thus, the result of the variation in CMM-MS 2 considers that, as in CMM-MS 1, measures with variability were recorded throughout its measurement range, but without being able to categorize the measures.

Figure 7 presents the GRR graphs for CMM-MS 2, in which it can be verified that seven measurements are not contained in the control limits in the average graph. The range graph showed a greater variation in the first measurement quadrant, in addition to having a greater amplitude than that seen in CMM-MS 1. This can also be seen in the graph per orientation, which unlike the CMM-MS 1, showed variations. The measurements average in quadrants one, two, and three, respectively, were: 397.302 mm, 397.304 mm, and 397.303 mm. This generated a graph of interactions with crossings between the averages and the quadrants, which contributes to finding that the CMM-MS 2 is also unable to categorize the device measurements in different quadrants and orientations.

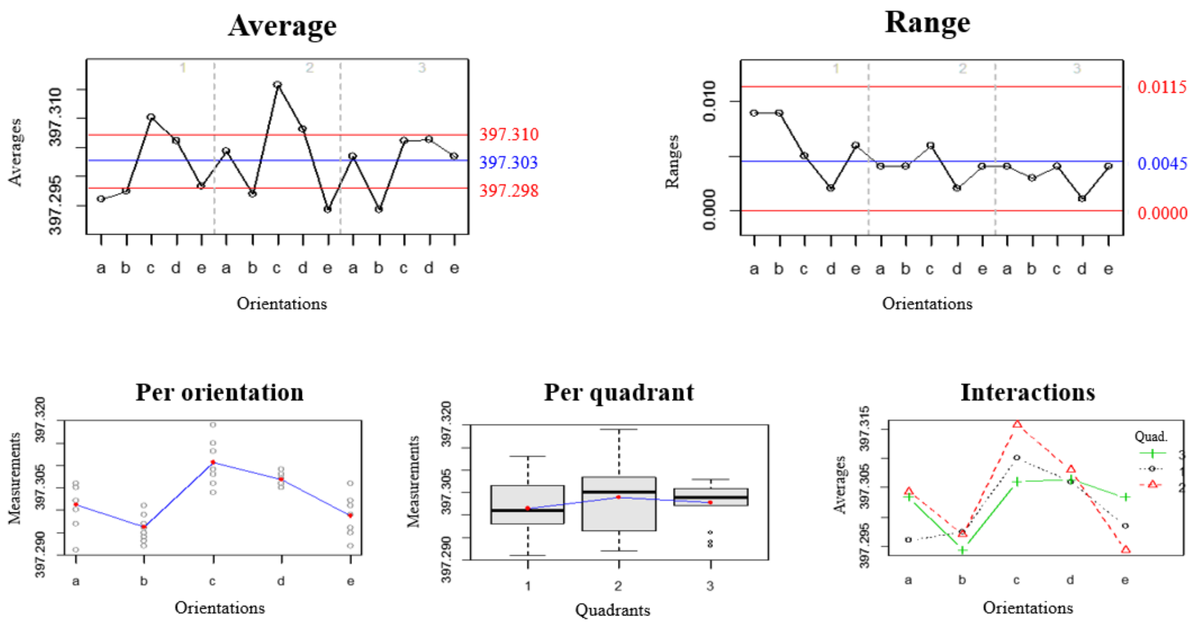


Fig. 7. The GRR graphs for CMM-MS 2.

A greater range of variation was observed in CMM-MS 2 compared to CMM-MS 1 (standard deviation of CMM-MS 1 = 0.00213, while CMM-MS 2 = 0.00703), in addition to greater values of averages in CMM-MS 2 (Average CMM-MS 1 = 397.284 mm, while CMM-MS 2 = 397.303 mm). These differences can be caused: (i) by the device itself; (ii) by the measurement system; (iii) by variations in environmental conditions; (iv) for the improper use or behaviour of the machine; and/or (v) by probe head rotation errors. Both experiments were carried out in the temperature range of 20 ± 1 °C and with relative humidity below 70%.

Table 5 shows the comparison between the results of the experimental study of GRR in the measurement systems. It is confirmed that CMM-MS 2 had a greater standard deviation than CMM-MS 1, which was verified by the dispersion of the collected measurements. The absolute values of variation were lower in CMM-MS 1, and both measurement systems generated relation between quadrants and orientations. Therefore, it is concluded that the analysed MSs did not maintain the same variability in all their volumes, but that it demonstrated a random behaviour.

Table 5. The comparison between the results of the experimental study off GRR in the measurement systems.

Item	CMM-MS 1	CMM-MS 2
Total Standard Deviation	0.00213	0.00703
Repeatability	0.00212	0.00259
Reproducibility	0.00011	0.00363

As the standard deviation of measurements in CMM-MS 1 was smaller than in CMM-MS 2, there was also a lower uncertainty for this measurement system. Other factors that contributed to this result were a greater variation from the reference temperature in the CMM-MS 2 and the smaller measuring scale of the CMM-MS 1. Thus, the mean values of the distance between the two upper spheres of the device in the GRR study were: CMM-MS 1 = 397.284 ± 0.003 mm and CMM-MS 2 = 397.303 ± 0.004 mm. Table 6 presents the uncertainty budgets for the two measurement systems.

Table 6. Uncertainty budgets for the two measurement systems

Uncertainty source	CMM-MS 1 (mm)	CMM-MS 2 (mm)
Calibrated spheres	0.00025	0.00025
Repeatability	0.00086	0.00106
Scale measuring	0.00014	0.00029
Temperature variability	0.00069	0.00092
Device Cte variability	0.00028	0.00028
Spheres geometry	0.00098	0.00098
Combined standard uncertainty	0.00153	0.00177
v_{eff} (k)	49.1 (2.05)	39.6 (2.07)
Expanded uncertainty	0.003	0.004

6. Conclusions

This paper presented a new interim check device for CMMs built from a steel bar with the incorporation of calibrated spheres. The objective was achieved from the elaboration of three projects (cylindrical ball plate, ball ruler, and device of basic geometric forms) based on the ISO 10360-2, in the NPL guide nº 42 and works presented in a systematic review.

The Ball Ruler was the device selected to be built because it has major potential for checking errors of distances measurements, occupies a large part of the measurement volume of the machines, can conduct experimental studies of MSA and still have the lowest total budgeted cost of manufacture and calibration among all projects. It is important to note that the cost of construction of this device is less than 5% of the purchase price of a commercial one and that the total cost of construction and the calibration of the spheres was approximately 4% less than the budgeted amount.

The usability of the device was verified through an exploratory study with an ANOVA of different factors. This experiment was carried out to verify whether the machines showed variability in measurements over their volumes due to the orientation of the device. Variability was assessed in three quadrants of the CMMs using five different device orientations in each quadrant.

The results of ANOVA in the two MSs showed that measurements with variability were recorded throughout their measurement range, but without being able to categorize them. Thus, it is concluded that as the differences between the measurements in the three quadrants are not significant, the machines are unable to identify these differences, indicating that there is no significant variability over the measurement volume of the machines. However, CMM-MS 2 had absolute values of variation and a total standard deviation higher than CMM-MS 1. This, combined with issues of variations in the reference temperature and measuring scale, generated a larger expanded uncertainty in the CMM-MS 2.

The differences between the two machines can be caused: (i) by the device itself; (ii) by the measurement system; (iii) by variations in environmental conditions; (iv) for the inappropriate use or behaviour of the machine; and/or (v) probe head rotation errors. From the uncertainty budgets, it is noticed that the standard deviation generated by the two machines presented a high contribution of uncertainty, so a new study after the CMMs' calibration may be conducted to obtain a smaller expanded uncertainty. Therefore, it is recommended for future research: (i) conduct a full MSA study with an experimental check of the stability and reproducibility of the device; (ii) calibrate the standard device in an accredited laboratory and conduct comparative tests to assess measuring accuracy of machines and standards; (iii) the device's gravitational deformability can be investigated, and support points must be provided to ensure minimal deformation. Besides, the possibility of producing another interim check device, such as the cylindrical ball plate device, is mentioned to verify which model is most suitable for this purpose.

Acknowledgements

This work was supported by the Brazilian National Research and Development Council (CNPq) and the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES). We are grateful for the comments and suggestions of three anonymous referees that increased the quality of the work and indicated possible paths for further research.

References

[1] Fanton, J. P. (2019). A brief history of metrology: past, present, and future. International Journal of Metrology and Quality Engineering, *10*, 5. https://doi.org/10.1051/ijmqe/2019005

[2] Hocken, R. J., & Pereira, P. H. (Eds.). (2016). *Coordinate measuring machines and systems*. CRC Press, Taylor & Francis Group.

[3] Cuesta, E., Alvarez, B., Sanchez-Lasheras, F., & Gonzalez-Madruga, D. (2015). A statistical approach to prediction of the CMM drift behaviour using a calibrated mechanical artefact. *Metrology and Measurement Systems*, *22*(3), 417–428. https://doi.org/10.1515/mms-2015-0033

[4] De Aquino Silva, J. B., Hocken, R. J., Miller, J. A., Caskey, G. W., & Ramu, P. (2009). Approach for uncertainty analysis and error evaluation of four-axis co-ordinate measuring machines. *The International Journal of Advanced Manufacturing Technology*, *41*, 1130–1139. https://doi.org/10.1007/s00170-008-1552-z

[5] De Aquino Silva, J. B., & Burdekin, M. (2002). A modular space frame for assessing the performance of co-ordinate measuring machines (CMMs). *Precision Engineering*, *26*(1), 37–48. https://doi.org/10.1016/S0141-6359(01)00096-4

[6] Wozniak, A., & Mayer, J. R. R. (2012). A robust method for probe tip radius correction in coordinate metrology. *Measurement Science and Technology*, *23*(2), 025001. https://doi.org/10.1088/0957-0233/23/2/025001

[7] International Organization for Standardization and International Electrotechnical Commission. (2017). *General requirements for the competence of testing and calibration laboratories* (ISO/IEC 17025:2017). https://www.iso.org/standard/66912.html

[8] International Organization of Legal Metrology. *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)* (JCGM 200:2008).

[9] International Organization for Standardization. (2009). *Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 2: CMMs used for measuring linear dimensions* (ISO 10360-2:2009). https://www.iso.org/standard/40954.html

[10] Flack, D. (2011). *Measurement Good Practice Guide No. 42. CMM Verification.* National Physical Laboratory.

[11] Arenhart, R. S., Pizzolato, M., Menin, P. L., & Hoch, L. (2021). Devices for interim check of coordinate measuring machines: a systematic review. *MAPAN - Journal of Metrology Society of India*, *36*(1), 157-173. https://doi.org/10.1007/s12647-020-00406-0

[12] Automotive Industry Action Group (AIAG). 2010. *Measurament Systems Analysis (MSA)* - Reference Manual.

[13] Płowucha, W. (2018). Uncertainty of coordinate measurement of geometrical deviations. *Procedia CIRP*, *75*, 361-366. https://doi.org/10.1016/j.procir.2018.04.071

[14] Płowucha, W. (2019). Point-straight line distance as model for uncertainty evaluation of coordinate measurement. *Measurement*, *135*, 83-95. https://doi.org/10.1016/j.measurement.2018.11.008

[15] Sładek J. A. (2016). *Coordinate metrology: accuracy of systems and measurements*. Springer-Verlag, 55-382.

[16] Doiron, T. (2016). Dimensional measurement uncertainty from Data, part 2: uncertainty R&R. *International Journal of Metrology*. *23*(3), 22-29.

[17] Koteras, R., Wieczorowski, M., & Znaniecki, P. (2018). Acceptance and reverification of CMM in industrial conditions. *Advances in Science and Technology. Research Journal*, *12*(1), 80–88. https://doi.org/10.12913/22998624/80987

[18] Bartscher, M., Hilpert, U., Goebbles, J., & Weidemann, G. (2007). Enhancement and proof of accuracy of industrial computed tomography (CT) measurements. *CIRP Annals. 56*(1), 495–498. https://doi.org/10.1016/j.cirp.2007.05.118

[19] Swornowski, P. J. (2014). A new concept of continuous measurement and error correction in Coordinate Measuring Technique using a PC. *Measurement*, *50*, 99–105. https://doi.org/10.1016/j.measurement.2013.12.032

[20] Montgomery, D. C., & Runger, G. C. (2018). *Applied statistics and probability for engineers*. John Wiley & Sons, Inc.

[21] Sharpe, N., De Veux, R., & Velleman, P. (2010). *Business Statistics*. Pearson Education, Inc.

[22] Cywiak, M., Cywiak, D., & Yáñez, E. (2020). Two-way ANOVA gage R&R working example applied to speckle intensity statistics due to different random vertical surface roughness characteristics using the Fresnel diffraction integral. *Metrology and Measurement Systems*, *27*(1), 103–117. https://doi.org/10.24425/mms.2020.131715

[23] Beckert, S. F., Paim, & W. S. (2017). Critical analysis of the acceptance criteria used in measurement systems evaluation. *International Journal of Metrology and Quality Engineering*, *8*(23), 1-9. https://doi.org/10.1051/ijmqe/2017016

[24] Montgomery, D. C. (2013). *Introduction to statistical quality control*. John Wiley & Sons, Inc.

[25] Jing, G. G. (2018). How to measure test repeatability when stability and constant variance are not observed. *International Journal of Metrology and Quality Engineering*, *9*(10), 1-9. https://doi.org/10.1051/ijmqe/2018007

[26] Arenhart, R. S., Pizzolato, M. (2020). Análise de Sistemas de Medição em uma Máquina de Medir por Coordenadas / Measurement System Analysis on a Coordinate Measuring Machine. *Revista FSA*, *17*(6), 182–203.

[27] Jurkowski, S. (2019). Application of the R&R method to determine the operator's influence on measurements made with a coordinate measuring arm. *Archive of Mechanical Engineering*, *66*(1), 73–81. https://doi.org/10.24425/ame.2019.126372

[28] International Organization for Standardization and International Electrotechnical Commission. (2008). *Uncertainty of measurement. Part 3: guide to the expression of uncertainty in measurement (GUM:1995)* (ISO/IEC GUIDE 98-3:2008). https://www.iso.org/standard/50461.html

Rodrigo Schons Arenhart obtained his B.Sc. degree and his M.Sc. degree in Production Engineering from Federal University of Santa Maria (UFSM). Between 2015 and 2017, he was Metrologist at the LADIPP, a laboratory providing calibration and testing services, from UFSM. From 2018 to 2021 he was a researcher at LADIPP in the dimensional metrology area, with a focus on coordinate measuring machines. He is currently pursuing a Ph.D. degree in Production Engineering at UFSM; besides he is a researcher at the Laboratory of Statistical Analysis and Modeling (LAME) and collaborates with advisors for LADIPP. Subjects of interest are quality control, scientific and industrial metrology, cost management, economic engineering, and statistics.

Morgana Pizzolato graduated in Mathematics and Mechanical Engineering from Passo Fundo University in 1984 and 1990, respectively. After years of experience in the metal-mechanical industry, she completed her master's and her doctorate in production engineering at the Federal University of Rio Grande do Sul in 2001 and 2006, respectively. She is currently a professor at the Federal University of Santa Maria, coordinating LADIPP, an accredited laboratory. Her main research interests are statistical applied in metrology methods.

Fernanda Hänsch Beuren holds a doctorate (2013) and a master's degree (2011) in Production Engineering: Product and Process, from the Federal University of Santa Catarina (UFSC), specialization (2006) in Furniture Design, from the Federal Technological University of Paraná (UTFPR) and a degree in Mechanical Technology: Industrial Production of Furniture, by the University of the State of Santa Catarina (UDESC). She has experience working in the furniture industry for domestic and foreign markets in Product Research and Development (R&D) and Process Management. She is an adjunct professor (since 2014) of the Mechanical Production Engineering course at the State University of Santa Catarina (UDESC), where she is currently the director of Research and Graduate Studies.

Adriano Mendonça Souza got a degree in Mathematics (FIC - Faculdade Imaculada Conceição - Santa Maria), Specialization in Statistics and Quantitative Modeling (UFSM - Federal University of Santa Maria - Santa Maria) and Master in Industrial Engineering (UFSM). He is doctor in Industrial Engineering (UFSC-Universidade Federal de Santa Catarina - Florianópolis) and, in this period he researcher at Texas A & M University (TX - USA). He researcher at ISCTE - Business School - Lisbon Institute - Portugal. He is currently full professor at the Statistics Department (UFSM). The areas of interest are applied statistics, quality control, time series analysis, multivariate analysis, operational research, production management and public policy evaluations by means of econometric models.

Leandro Cantorski da Rosa graduated in Mechanical Engineering from Santa Maria Federal University (1978), Master´s degree in Production Engineering from Santa Maria Federal University (1984) and Doctorate in Production Engineering from Santa Catarina Federal University (2000). Currently he is Professor at Santa Maria Federal University. In 2015, he published the book Introduction to Statistical Process Control in its second revised and expanded edition. He has experience in the area of Production Engineering, with an emphasis on quality and productivity, working mainly on the following topics: process management with a focus on quality improvement, environmental aspects and safety at work.