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Interlaboratory Comparison of a physical and a virtual assembly measured by CT

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Abstract

In a comparison including 20 laboratories, a physical as well as a virtual assembly provided as two data sets were used to investigate measuring and post-processing approaches in Computed Tomography, CT. Different procedures were used in the comparison including one simulating in-line measurement. The comparison demonstrated that: (i) a tangible improvement in the use of CT compared to previous comparisons; (ii) most of the participants were able to reduce their scanning time by more than 70% without increasing the length measurement errors; and (iii) most of the participants can further reduce their uncertainties, thereby reducing the tolerance size that can be inspected using CT in industry.

Keywords: Computed Tomography (CT); Measurement uncertainty; Assemblies

1. Introduction

X-ray Computed Tomography, CT, is recognised as a game-changing technology in the field of quality control of assemblies [1] [2]. It is known that dimensions may differ between non-assembled and assembled components, explaining why assemblies may fail, even if all non-assembled components are within specifications. Assembly inspection based on CT measurements ensures more reliable information than any destructive testing method, which irretrievably deforms the assembly. Despite the growing interest in the use of CT for assembly inspection in industry, only a small body of literature is available on this matter. This paper reports on the results of the InteraqCT comparison representing the first comparison focused on CT inspection of assemblies. Two assemblies reflecting parts commonly inspected in industry in terms of materials and measurands were selected for the comparison. In contrast to previous comparisons that only focused on physical items [3] [4], the present comparison has introduced a virtual item as a scan produced and reconstructed by the coordinator, and then distributed electronically to all participants. The virtual item represents an evolution of the concept of softgauge used in the measurement of surface texture [5].

2. InteraqCT comparison: items and measurands

The InteraqCT interlaboratory comparison on CT of assemblies was organised by the Department of Mechanical Engineering, Technical University of Denmark (DTU) and carried out as an activity within the Marie Curie ESR Project INTERAQCT. The comparison was carried out with a parallel circulation in the period from June 2015 to September 2016, involving 20 laboratories from 7 countries: Austria, Belgium, Denmark, Germany, Italy, Singapore, and the UK. National metrology institutes, equipment manufacturers, universities, research centres, and industrial companies were all represented in the comparison. All the end-user participants have a keen interest in using CT for quality control of assemblies. The assemblies used in the comparison are shown in Figure 1. The physical assembly is a two-component item comprising a 56-mm miniature cylindrical step gauge, machined from an aluminium rod, and a tube made of

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borosilicate glass. The tube presents an inner diameter of 17.5 mm and an outer diameter of 19.4 mm. The physical assembly is designed to avoid the contact between the step gauge and the glass in the areas used for defining the measurands, ensuring that any post-assembly deformation is minimised. The physical assembly comprises two kinds of measurands: the gauge measurands and a gauge-tube measurand, making it the first of its kind. The gauge measurands are the lengths defined as the distances between two flanks of the step gauge. The gauge-tube measurand is the length defined as the gap distance between the top of the first tooth of the gauge and the inner diameter of the tube. The measurands selected on the physical assembly are shown in Figure 2. $L1$ and $L4$ are two unidirectional lengths [6] with nominal sizes of 3.5 and 14 mm, respectively. $L2$ and $L3$ are two bidirectional lengths [6] with nominal sizes of 3.5 mm and 10.5 mm, respectively. T is a gauge-tube measurand with a size of 3.5 mm. The measurands were selected to compare the measurement error and measurement uncertainty estimation between gauge and gauge-tube measurands as well as between unidirectional and bidirectional measurands. It is known that a unidirectional measurand is very robust against any potential local error of CT, e.g. surface determination, beam hardening, noise, etc., whereas a bidirectional measurand is not [1][2][6]. 20 samples were manufactured, imaged and their absorption coefficient values were compared using the Beer–Lambert law [1]. The maximum variation in the absorption coefficient value among the samples was quantified to be less than 15%, leading to the conclusion that the samples were adequately homogeneous for use in this comparison. The imaging of the samples was conducted on a Nikon XT H 225 ST CT (Voltage = 150 KV, Current = 175 μ A, voxel size = 40 μ m, and exposure time = 1 s).

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Figure 1 (top) the physical assembly and (bottom) the industrial assembly used to produce the virtual assembly.

Virtual assembly is based on imaging of a subassembly of an insulin injection device. The industrial item includes an inner component, made of polyoxymethylene, and an outer component, made of ABS-polycarbonate. The generation of the virtual assembly was carried out using two set of scanning parameters in order to obtain data sets with two different image quality levels. The measurands selected on the virtual assembly are shown in Figure 3. The measurands were all selected on the outer component. $D1$ and $D2$ are two Gaussian diameters with nominal sizes of 3.3 mm and 5.5 mm, respectively. $D1$ is an inner diameter, while $D2$ is an outer diameter. $R1$ is unfiltered roundness of $D1$. $C1$ is coaxiality of $D2$. The measurands were chosen to provide an increasing level of difficulty for the participants. The use of a virtual item yields the following advantages over a physical one: (i) it enables determination of whether CT post-processing has an effect on the accuracy of CT measurements by uncoupling scanning and post-processing; (ii) it allows a parallel circulation based on a same item, thereby avoiding problems associated with the sample homogeneity; (iii) it gives significant cost savings associated with manufacturing, calibration, and shipping; (iv) it reduces the workload of participants as no scan is required for this item.

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Figure 2 The overview of measurands of the physical assembly: $L1$, $L2$, $L3$, $L4$, and T .

Figure 3 The overview of measurands of the virtual assembly: $D1$, $D2$, $R1$, and $C1$. The measurands were all selected on the outer component.

3. Measurement Procedures

Two scanning procedures were defined for the physical assembly. The first approach, coded as “Own Choice”, does not apply any scanning restrictions on any of the scanning parameters. The second one, coded as “Fast Scan”, introduced a series of limitations such as scanning time less than 1 hour, including preliminary corrections, no image averaging, and no measurement replication. The Own Choice approach was meant to identify the performance limit of CT systems because it allowed the participants to use any software and hardware corrections. The Fast Scan approach was meant to investigate whether CT can be used for in-line metrology. The fast scan procedure was suggested by the industrial partners of the comparison due to their interest of accelerating the CT measurement process. No constraints on the X-ray current and voltage were set because CT systems with different nominal powers were used in this comparison. The procedures for the virtual assembly involve post-processing of two sets of reconstructed datasets having two different image quality levels (LIQ, low image quality, and HIQ, high image quality). The different image quality levels were used to investigate how participants adapt their post-scanning approaches as the image quality varies. It is known that the noise has an important effect on the error of CT measurements because it increases surface outliers and impairs the surface determination method performance [7]. The two image quality levels were obtained by scanning the two-component item using two sets of scanning parameters. The signal-to-noise ratio [1][2] of LIQ datasets was quantified to be 35% lower than the one of HIQ datasets. All the procedures prescribed the location and distribution of sampling points as well as the datum system for each measurand. These very restrictive procedures were meant to allow comparable results between the coordinator and participants. The results collected in the comparison are kept confidential.

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4. Reference measurements

The use of assemblies originated a number of challenges such as documentation of the dimensional stability after assembly and of the thermal stability during shipping for the physical assembly. 20 samples of the physical assembly and a single sample of the virtual assembly were measured using a tactile Coordinate Measuring Machine, CMM, before and after circulation, as shown in Figure 4. Due to the design constraints, $L1$, $L2$, $L3$, and $L4$ were calibrated before assembly (see Figure 4a) while T (see Figure 4b) was calibrated after assembly.

Figure 4 Measurement setup for calibration of (a and b) the physical assembly and of (c) the virtual assembly.

The uncertainty for the CMM measurements was based on the ISO 14253-2 [8], as a simplification of the GUM approach [9]. The following influence factors were considered in the uncertainty assessment: uncertainty from the calibration artefact certificate, measurement repeatability, temperature, geometric errors of the equipment, and relocation of sample. Details of the measurement uncertainty are described in [10]. Ten repeated measurements were conducted for each measurand. Three probing forces, 0.05 N, 0.10 N, and 0.15 N, were used to compensate for the sample deformation. The sample deformation was found to be a relevant source of systematic errors for the measurements of T (the physical assembly) and of $D1$ and $D2$ (the virtual assembly). The status of all the samples of the physical assembly was monitored three times (December 2015, May 2016, and August 2016). In order to judge the agreement between sets of CMM reference measurements, E_n numbers [11] were calculated for all the selected measurands according to the following equation

$$E_n = \frac{X_{after} - X_{before}}{\sqrt{U(X_{after})^2 + U(X_{before})^2}}. \quad (1)$$

Where X_{after} is the reference value of the considered measurand after circulation (May and August 2016), X_{before} is the reference value of the same measurand before circulation (December 2015), $U(X_{after})$ and $U(X_{before})$ are the corresponding expanded measurement uncertainties. If $|E_n| < 1$ the two sets of CMM measurements are in agreement, while they are not if $|E_n| > 1$. The three measurement rounds agreed well for all five measurands (all $|E_n| < 1$), ensuring that all the samples were dimensionally stable during the circulation period. Figure 5 shows the reference values for T taken at two different times, before and after circulation. The calibration equipment and environment were also monitored without observing any departures from the standard operating conditions. The status of the virtual assembly was not monitored because of the absence of a physical circulation. The average reference expanded measurement uncertainties (k

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= 2) were estimated in the range of 1.1-2.6 μm , depending on the sample and measurand. Further details on the reference measurements can be found in [10].

Figure 5 Reference values for the gauge-tube measurand T before and after circulation. The results are reported without expanded measurement uncertainties, being in the range of 0.002-0.004 mm, in order to improve readability.

5. Physical assembly

The results of the single participants were analysed and compared with reference values obtained by the coordinator and found to fit into two groups. An example of results is shown in Figure 6, while the remaining results can be found in [7]. 60% of the participants were able to provide measurement results with deviations in the range of 1-35 μm for all measurands. The extent of measurement deviations yielded the measurement-deviations-to-voxel-size ratios [1][3] far below 1. Three participants were also able to reduce the measurement-deviations-to-voxel-sizes ratio down to 0.1, representing the limit of the surface determination accuracy [2]. It is believed that the small measurement errors are a direct consequence of a small extent of imaging artefacts, as observed by looking at the material greyscale distribution according to [12]. The greyscale distributions for those participants presented negligible distortions, yielding a good contrast of inner and outer edges of the physical assembly, as shown in Figure 7a. The image noise of those participants was also found to be small, typically in the range of 3-5% of the

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greyscale distributions. 20% the participants provided measurement results with large deviations, with a maximum deviation of 145 μm , resulting in the measurement-deviations-to-voxel-size ratios being far above 1. The greyscale distributions for those participants presented visible distortions, as shown in Figure 7b. The possible causes of such image distortions can be the X-ray scatter and beam hardening [1][2][7][12] and the limitation of the reconstruction algorithms occurring at high magnification levels [1][7]. After checking the CT data sets provided by those participants, encoder offset, temperature variation, software beam hardening correction, and misalignment of X-ray tube filament were identified as influence factors. Encoder offsets change the voxel size, magnifying the size of the physical assembly in an unpredictable and unrepeatable way. Encoder offsets were observed in CT systems with and without high accuracy moving system, suggesting that the users should not completely rely on the CT moving system. Temperature variations impair the response of the detector and the dimensional stability of item being scanned. The majority of the participants, who presented larger deviations, carried out measurements at a temperature of 22 °C or above. Software beam hardening corrections lead to overcorrection of the CT data sets, when an improper correction course is selected [13]. In this present comparison, the participants who used software based beam hardening generally ended with larger measurement errors than those participants who used hardware based beam hardening correction (physical filter on the X-ray tube). The misalignment of X-ray tube filament produces sharp discontinuity in the distribution of the greyscales across the X-ray projections, modifying the voxel size locally. The misalignment of X-ray tube filament was observed for two participants using the open-tube X-ray sources. The image noise of those participants was found to be in the range of 15-20% of the greyscale distributions, being up to 6 times bigger than the noise of the participants of the first group.

Figure 6 Measurement values for *L2* conducted according to the Own Choice approach. The expanded uncertainties for the reference measurements being in the range of 1.4-2.0 μm .

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Figure 7 Two oriented slices of two samples of the physical assembly showing different extent of image artefacts. Figure 7a shows a uniform greyscale distribution, giving evidence that the most important influence factors were well minimised. Figure 7b shows a non-uniform greyscale distribution along the slice. X-ray scatter and beam hardening made the slice blurry, while the limitations of reconstruction algorithm generated the streaks being visible at the bottom and at the top of the slice.

Figure 8 shows that an appreciable percentage of the participants provided comparable measurement results for both scanning approaches even though they used up to 70% shorter scanning time in the Fast Scan approach. The fastest participant was able to carry out a CT scan in 7 minutes. The measurement deviations between two scanning approaches were found to be in the range of 2-5 μm , depending on the measurand. Two approaches were used to reduce the scanning time in this comparison. The first one aimed at achieving a good image contrast using higher X-ray current values, reducing in the detector integration time. The second one was based on a strong reduction of the number of X-ray projections. Better results were achieved by the participants who adopted the first approach because a strong reduction of X-ray projections yields

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aliasing artefacts [1] [7] [14], which intensify the geometrical errors of the rotary table because faster movements are required. As a general conclusion, the CT measurement time can be reduced down to 7-10 minutes without generating additional length measurement errors. Faster CT measurements are still a mirage using the current CT systems.

Figure 8 The deviations between two scanning approaches used for scanning the physical assembly.

X-ray powers in the range of 5-90 W were used in the present comparison because of the different types of X-ray sources and scanning philosophies. Some participants selected a power level ensuring a focal spot size as small as possible as a scanning approach, while others used higher X-ray power in order to yield better contrast, with the final aim of making surface determination more efficient. By conducting a statistical analysis, it was observed that the two scanning philosophies lead to similar results for lengths measurements. The voxel size used for the physical assembly was found to be in the range of 30-100 μm . No clear impact of the voxel size on the error of measurement was observed for any measurand as shown in Figure 9. It can be seen from the figure that the length measurement error did not increase as the voxel size increased for all measurands used in this comparison. This result can be due to the following three reasons. Firstly, the selected measurands did not suffer from a loss of imaging resolution because their size was larger than the imaging resolution. Secondly, all the participants used surface determination approaches with sub-voxel resolution, reducing the effect of the decreasing imaging resolution at increasing voxel sizes. Thirdly, the measurands were all defined as a distance between two flanks with very low flatness (2-3 μm), ensuring that any change in the imaging resolution does not modify the measurements in a significant way. The dependency between the dispersion of CT measurements and the voxel size was not evaluated because the majority of the participants did not provide the coordinator with a standard

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deviation value. A future CT comparison should investigate such topic further. Finally, no relation between the model year of a CT and accuracy was observed in this comparison, leading to a general conclusion that no substantial hardware advancement has been made since the first comparison carried out in 2011 [3].

The participants provided the following comments that can be used as a starting point for future CT comparisons involving physical assemblies. Firstly, assemblies with larger differences in the X-ray absorption between the components should be taken into account, e.g., an assembly including a steel and a polymer component. Secondly, the size of the measurands should be increased in order to make visible residual geometrical errors as well as to better reflect the size of the measurands inspected in industry. Finally, a fast scan procedure with a measuring cycle below 2 minutes needs to be involved in order to better comply with industrial requirements.

Figure 9 The deviation from the reference values with respect to the voxel size for the physical assembly scanned according to the Own Choice approach.

6. Measurement uncertainty for physical assembly

Measurement uncertainty has a direct an economic impact in industry because it influences the zone of conformance, which is defined as the stated tolerance reduced by the measurement uncertainty [15]. The larger measurement uncertainty, the smaller the zone of conformance, resulting in increasing the probability of having non-conforming parts. The quantification of CT measurement uncertainty represents a major problem in industry because of the large variety of active influence factors and the absence of international standard dealing with this topic [16]. Consequently, measurement uncertainties are often not well representative of the measurement process. In this comparison, three factors were investigated in connection with the measurement uncertainty: number of participants stating a measurement uncertainty, measurement uncertainty size and reliability and measurement uncertainty methods. 90% of the participants stated at least one measurement uncertainty compared to the previous comparisons [3][4], where the percentage

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was 80%. The measurement uncertainties provided by the participants can be clustered in 5 groups, with the majority of the participants below 10 μm (see Figure 10). In order to evaluate the agreement between participant values and reference values, E_n numbers [11] was used according to the following equation

$$E_n = \frac{X_{part} - X_{ref}}{\sqrt{U(X_{part})^2 + U(X_{ref})^2}}. \quad (2)$$

Here, X_{part} is the participant's result, X_{ref} is the reference value, $U(X_{part})$ and $U(X_{ref})$ are the corresponding expanded measurement uncertainties. Although E_n numbers show some limitations when uncertainty estimations are not stated in a uniform way [17], it was decided to use E_n numbers in order to be consistent with the previous comparisons [3][4]. By using E_n numbers, it was found that 70% of the 80 measurement results conducted using the Own Choice approach are in agreement with the reference measurements ($|E_n| < 1$). 60% of the 80 measurement results carried out using the Fast Scan approach are in agreement with the reference measurements ($|E_n| < 1$). The percentage of participant results being in agreement with the reference values appeared to be up to 20% larger than the previous comparisons [3][4]. Subsequently, a recalculation of measurement uncertainties ensuring $|E_n| = 0.99$ was carried out in order to understand the extent to which the participants overestimated the uncertainties. Note that, such a recalculation only involved the 14 participants who were in agreement with the reference values ($|E_n| < 1$). The recalculated values evidenced that all the 14 participants could have reduced the measurement uncertainties by up to 50%, resulting in the best cases in uncertainties in the range of 2-4 μm for unidirectional measurands and in the range of 3-8 μm for bidirectional measurands.

The last point of interest is to review the methods used by the participants to quantify the measurement uncertainty. 10 of the 20 participants stated their measurement uncertainties according to one of the following approaches: GUM [9], ISO 14253-2 [8], ISO 15530-3 [18], and ISO 23165 [19]. The reference object calibration certificates, environment temperature, CT repeatability, voxel size, CT probing error, detector deformations, rotary table errors, and surface texture of the physical assembly represented the typical standard measurement uncertainties considered by the participants in the present comparison. Figure 11 shows the measurement uncertainty of $L1$ and $L3$ with respect to the voxel size used by the participants. It can be seen from the figure that no dependency relationship can be identified, giving evidences that the voxel size did not represent the major standard measurement uncertainty in this comparison. None of the participants who stated a measurement uncertainty according to ISO 15530-3 complied with the condition of similarity in terms of materials and measurands. 8 of the 20 participants based the measurement uncertainties on the manufacturer specifications, namely either the Maximum Permissible Error for sphere centre point measurement, MPE_{SD} [20], or the Maximum Permissible Error for length measurement, MPE_E , [20]. None of those participants however converted the MPE value into a Type B standard measurement uncertainty.

According to the reported results, it can be concluded that the uncertainties were found to be consistent for more than 60% of the performed measurements but generally overestimated by up to 50%. Finally, the participants showed some confusion regarding the different methods to estimate the measurement uncertainty, which may have contributed to overestimation measurement uncertainties.

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Figure 10 The histogram of expanded measurement uncertainties for the physical assembly stated by the participants. The presented measurement uncertainties refer to the Fast Scan approach.

Figure 11 The expanded measurement uncertainties of $L1$ and $L3$ with respect to the voxel size used by the participants. The presented measurement uncertainties refer to the Fast Scan approach.

7. Virtual assembly

Figure 12 reports the results for all measurands on the virtual assembly. From the measurements of the diameters $D1$ and $D2$, it can be extracted that all the participants inspected those measurands without problems. The standard deviations for those measurands were found to be $0.5 \mu\text{m}$ for $D1$ and $D2$. The image quality did not play a role in this inspection because the selected diameters were defined as Gaussian ones. The ease of inspecting of diameters confirms what was reported in the previous comparisons [3][4]. A good agreement among the participants was also recorded for the measurements of $R1$. The standard deviation of $R1$ was found to be approximately $2 \mu\text{m}$ for all data sets. Such a good agreement may suggest that the large deviations for roundness measurement reported in [4] were mainly caused by errors in the scanning approaches rather than in post processing approaches. Larger deviations between all participants and the reference value were instead observed as the image quality decreased. On average, the roundness measurement deviations of the LIQ datasets increased by 20% with respect to the ones of the HIQ datasets. The measurement results of $C1$ instead show the worst agreement among the participants. The standard deviations were found to be approximately $10 \mu\text{m}$ and $16 \mu\text{m}$ for the measurements conducted on HIQ datasets and LIQ datasets, respectively. The principal cause of such a large variability was believed to be the datum system. Many

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participants established a datum system whose axes were not perpendicular to each other, while others did not use any datum system for the evaluation. The impact of the image quality was assumed to be negligible in this specific evaluation because the coaxiality represents a unidirectional measurand [6].

By using the results of the virtual assembly, the influence of the number of fitting points on the measurement result error was also investigated. It can be reported that the participants who used 70, 100, 500, 1000, or 10000 points provided results within a range of variability of 1 μm . As a consequence, no influence of the number of fitting points on the accuracy of the measurement results was recognised for any of the four measurands in the present comparison. Moreover, no differences were observed among different inspection software packages using different fitting point patterns for the diameter measurements, whereas some differences were observed for roundness and coaxiality measurements. Such differences may reflect the ways of managing the surface outliers and datum systems in different software packages. Finally, none of the participants was able to state a measurement uncertainty for this task due to the lack of scientific literature enabling a-priori quantification of the measurement uncertainty.

Based on the presented results, it can be deduced that the participants used robust inspection strategies to cope with different levels of image quality. Furthermore, the results pointed out that among the post-processing activities, the definition of a datum system played a major role, resulting in very large measurement errors.

The participants also gave a series of suggestions for a new comparison involving virtual assemblies. Firstly, the number of measurands and fitting methods should be larger in order to give a profound understanding of CT post processing. Two or more industrial assemblies involving different materials should be selected to investigate the connection between inspection strategies and assembly materials. Secondly, the impact of the reconstruction of X-ray projections should be considered because such a topic is not well covered in literature. Thirdly, filtering of form measurements should be taken into account in order to produce a practical guide for end users.

(a)

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Figure 12 Results for the virtual assembly based on (a) HIQ and (b) LIQ data sets. The calibration value for *D1* is 3.001 ± 0.0010 mm, for *D2* is 5.543 ± 0.001 mm, for *R1* is 0.007 ± 0.001 , and *C1* is 0.009 ± 0.002 mm. The measurement uncertainties are reported at 95% confidence level.

8. Summary

The main conclusions of this comparison are:

- The InteraqCT comparison on Computed Tomography of assemblies involved a physical step-gauge-in-tube and a virtual assembly.
- 20 participants from 7 countries participated in the comparison. National metrology institutes, equipment manufacturers, universities, research centres, and industrial companies are represented within the comparison.
- Reference measurements were obtained using a tactile CMM for all items, resulting in expanded reference measurement uncertainties in the range of 1.1-2.6 μm .
- Out of a total of 200 measurement results collected in this comparison, up to 70% of the results yielded $|E_n| < 1$, indicating a good agreement with reference measurements.
- 18 of the 20 participants stated a measurement uncertainty within this comparison, with the majority of the participants reporting uncertainty values below 10 μm . The recalculated

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measurement uncertainties, ensuring $|E_n| = 0.99$, evidenced that an appreciable percentage of participants can further reduce their measurement uncertainties by up to 50%.

- Most of the participants were able to reduce their scanning time by more than 70% without increasing the length measurement errors. Nevertheless, a measurement faster than 7 minutes was not achieved.
- Measurements on the virtual assembly showed that increasing the complexity of the measurand increases the range of variation among the participants. The definition of datum system appeared as a major source of measurement errors.

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