EXPERIMENTAL ANALYSIS OF INDUSTRIAL COORDINATE MEASURING SYSTEMS USING A CALIBRATED PRODUCTION WORKPIECE

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Abstract: The measurement of a part on a coordinate measuring machine may be affected by many factors such as the machine accuracy itself, the measuring environment, the probe configuration, and the measuring strategy. In order to understand the effect of some of those factors on industrial-grade machines, a master production workpiece has been circulated in Brazilian industries for measuring particular GPS features according to a predefined master measuring protocol. Conclusions could be drawn about the behaviour of each machine under varying conditions, the measurement divergences from one similar machine to another operating under distinct conditions, the complexity of measurements with CMMs, and the need for good measurement practices in the productive sector.

Keywords: Coordinate Metrology, Good Measurement Practices, GPS Characteristics.

1. INTRODUCTION

Conventional coordinate measuring machines (CMMs) have been widely used in industries to characterize parts stemming from the production floor for many years. The result of a given characterization may be affected by many factors such as machine accuracy itself, probe configuration, measuring environment, and measurement strategy. In order to observe the effect of influence factors in measurements, a master calibrated production part has been chosen and sent to some industries in Brazil for collecting data points of the calibrated part features on their CMMs in accordance with a predefined master measuring protocol.

From the comparative study, the following matters are to be highlighted: (a) to discern how standard industrial CMMs operating under different conditions behave when measuring the same objects using predefined measurement procedures; (b) to evaluate the influence on the measurement result of uncertainty sources deriving from the machine itself, e.g. machine geometry, probe repeatability, indexing probe head reproducibility, as well as from its surrounding conditions like site temperature and vibrations; (c) to provide valuable information for the intercomparison participants in order to optimize the capability and quality of their measurements; (d) to evidence how complex CMM measurements might be given the intricate way the uncertainty sources interact with themselves; and (e) to promote good metrology practices in industrial CMM measurements.

2. COMPARATIVE STUDY DESIGN

2.1. Definition of the master workpiece

The choice of the master part, an off-the-shelf cast-iron steering case, was made based on factors like variety of dimensional and geometrical characteristics, quality of the machined surfaces, probe accessibility, easiness of shipping and handling. The workpiece GPS characteristics to be measured are illustrated in Fig. 1 and labeled as GPS.XXX. Datum feature indications are filled in blue, toleranced feature callouts are filled in green (location, orientation, run-out), theoretically exact dimensions are filled in yellow.
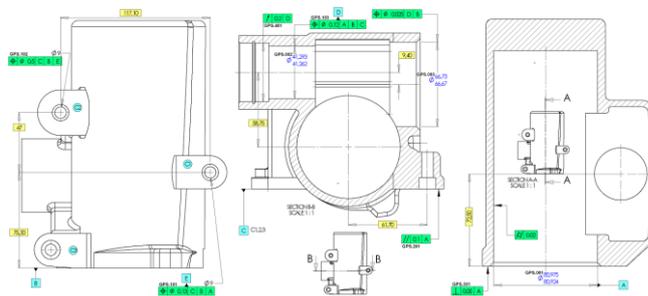

Fig. 1. Drawing of the workpiece used for the experimental analysis of industrial CMMs (dimensional and geometrical tolerances under scrutiny labeled as GPS.XXX)

2.2. Calibration of the GPS characteristics

The master part was calibrated on a high-accuracy CMM installed on a temperature-controlled reference laboratory to (20.0 ± 0.3) °C in accordance with the method proposed in ISO/TS 15530-2 [1], which is based on multiple orientation measurements of the part. For features of size and position tolerances, the technique also claims for measurements on calibrated length standards such as gauge blocks and rings.

The sampling strategy was not functionality-oriented defined, because the comparative study was designed to be as far as possible insensitive to intrinsic part imperfections. The basic assumption here was that the calibration sampling strategy mirrored the actual one. Hence, both the measured points and the fitting algorithm were chosen to be nearly the same during workpiece calibration and measurements on each CMM. Differences however may arise due to software divergences.

The estimated calibration uncertainty therefore accounts for CMM geometry and scale effects, probe qualification residuals, machine repeatability, and temperature influences on workpiece, machine scales, and length standards. In table 1 the measurement strategies employed for the realization of each measurand defined in Fig. 1 are briefly described and the corresponding calibration result displayed.

Table 1. Short description of the measurands under scrutiny and the corresponding reference values (expanded uncertainty stated)

Label	Measurement Strategy Summary	Reference Value
GPS.001	Diameter of a least-squares cylinder obtained from five evenly-distributed points sampled on each of the three circular cross-sections	80.9440 ± 0.0012
GPS.002	Diameter of a least-squares cylinder obtained from five evenly-distributed points sampled on each of the three circular cross-sections	41.2783 ± 0.0011
GPS.003	Diameter of a least-squares cylinder obtained from five evenly-distributed points sampled on each of the three circular cross-sections	66.7187 ± 0.0010
GPS.101	Position of a cylinder axis measured as three circle cross-sections (five point on each), which define three least-squares circle centres, related to a datum system (primary datum: least-squares plane defined by nine points; secondary datum: least-squares plane defined by ten points; tertiary datum: least-squares cylinder axis obtained from five points sampled on each of the three circular cross-sections)	0.0589 ± 0.0014
GPS.102	Position of a cylinder axis measured as three circle cross-sections (five point on each), which define three least-squares circle centres, related to a datum system (primary datum: least-squares plane defined by nine points; secondary datum: least-squares plane defined by ten points; tertiary datum: least-squares cylinder axis obtained from five points sampled on each of the three circular cross-sections)	0.3121 ± 0.0030
GPS.103	Position of a cylinder axis measured as three circle cross-sections (five point on each), which define three least-squares circle centres, related to a datum system (primary datum: least-squares cylinder axis obtained from five points sampled on each of the three circular cross-sections; secondary datum: least-squares plane defined by ten points; tertiary datum: least-squares plane defined by nine points)	0.1226 ± 0.0023
GPS.201	Parallelism of a least-squares plane measured with nine points related to a datum axis (least-squares cylinder axis obtained from five points sampled on each of the three circular cross-sections)	0.0442 ± 0.0018
GPS.301	Perpendicularity of a least-squares plane measured with ten points related to a datum axis (least-squares cylinder axis obtained from five points sampled on each of the three circular cross-sections)	0.0054 ± 0.0011
GPS.401	Circular run-out in the radial direction (twenty-five evenly-spaced points) related to a datum axis (least-squares cylinder axis obtained from five points sampled on each of the three circular cross-sections)	0.0252 ± 0.0020

2.3. Workpiece measurement setup

The participants have been instructed to measure the part in two different locations within the machine envelope (i.e., near and far from the machine origin) and at two different orientations (i.e., aligned with X- and Y-axes), as illustrated in Fig. 2. For each location/orientation arrangement, four measuring cycles have to be carried out under repeatability conditions. In order to check daily laboratory temperature variation effects on measurements, the experimental setup just described has to be repeated on two distinct work shifts.

Fig. 2. Picture of the workpiece selected for the experiments on the clamping device (in the centre) and the position / orientation on the CMM table (left: near machine zero; right: far from machine zero)

For sake of simplicity, thus far all analyses have been restricted to machines of the same manufacturer outfitted with similar touch probes and indexing heads, as well as measuring/evaluation software. For this reason, execution efforts has been tremendously reduced, as the same master measurement protocol and basic probe configurations have been used in all cases. The experimental approach therefore is sensitive to influence factors like CMM geometry errors, spatial and temporal temperature variations, indexing probe head reproducibility, probe qualification residuals, etc. It is not sensitive to operator-induced errors or part imperfections.

2.4. Data analysis

In order to analyze the measurement bias and the sources of variability proposed in this work, the analysis of variance (ANOVA) statistical technique has been employed. In the ANOVA method, the variance can be decomposed into three main categories (in addition to shift-location interaction):
- measuring repeatability, which may include probing and indexing head variation;
- between-shift variation, which may include thermal variation over time;
- part-location and -orientation variation, which may include machine scale and geometry errors, as well as thermally induced errors.

Based on the master workpiece calibration results and on the ANOVA components of variation, the metric normalized error (En-value) has been calculated for each evaluated GPS characteristic. An En-value in the range [0,1] indicates that there is a good agreement between the two results, and an En-value out of that range, that the results are not identical. It is worthy of attention that large measurement uncertainty values may also result in small En-values, and then the En-value may give an erroneous picture of the situation.

3. CMM STUDY RESULTS

Up to now, the master part has been measured on five industrial-grade CMMs of similar specification as per ISO 10360-2 [2]. All machines are enclosed in metrology rooms with some kind of temperature control, and checked by the manufacturer on a periodic basis. Interim checks of CMM geometry errors are not carried out by the operators on any machine under analysis.

3.1. Overall analysis and results

Fig. 3 gives an overall picture of the variation sources derived from the analysis of variance for each GPS characteristic on a given CMM (coded as co.0X). The gray part of each error bar illustrates the repeatability component; the diagonal line part, the between-shift variation, the white part, the shift-location interaction, and the horizontal line part, the workpiece-location variation.

The workpiece-location variation source reflects errors e.g. resulting from the machine geometry imperfections and from temperature effects. In general, the workpiece-location variation was the dominant contribution to the measurement variation. That means, first, the need for good metrology practices in routine measurements, such as restricting the access of people in the measuring lab and allowing the parts to be measured to reach a reasonable thermal equilibrium; and, second, the careful consideration of the temporal and spatial temperature fluctuations in the mechanical and/or computational correction in the routine calibration.

Fig. 3. Contribution of each variation component for each measured GPS characteristic on all machines

From the graph shown in Fig. 3 one could notice that by changing the part location/orientation on the machine table or by measuring the part in different shifts, uncertainties larger than 0.02 mm (1σ) could be reasonably attributed to the measurement result. The pure measuring repeatability is normally the least contribution to the total variation, and the uncertainties found are normally much greater than machine specifications.

Since the analysis of variance method does not consider measurement bias, i.e., deviation from the reference value, the En-values were calculated for all situations (machine and GPS characteristic). The En-values are shown in Fig. 4. For most of the cases there is a good agreement between the two results, i.e., average of all measurements on each machine / GPS characteristic and the respective reference value, even though uncertainties based on the decomposed variation components may artificially improve En-values.

Fig. 4. En-value chart for each measured GPS characteristic on all machines

In the particular case of machine co.02, the En-values were greater than the unity for the features of size and for the position and perpendicularity characteristics. The reason is the poor probe qualification strategy, which is especially important for the standard touch-trigger probe mounted on that particular CMM. Task-specific qualification should be preferred when evaluating features of size in order to reduce uncertainties.

3.2. Detailed analysis and results

The overall analysis and results described in the previous section showed how difficult could be the task of estimating the uncertainty attributed to the measurement result of GPS characteristics commonly found on industrial parts. CMMs of similar accuracy classes may produce different results by varying some measuring conditions.

To detail the influence of each variation component on a particular CMM, which could assist the user in improving the measurement process, bias and range control charts has been used to illustrate systematic and random effects on the measurement. Fig. 5 shows the control charts for the feature of size labelled GPS.001, which was sampled and evaluated as the diameter of a least-squares cylinder obtained from five evenly-spaced points sampled on each of the three circular cross-sections. The range chart indicates that the pure repeatability is under control (i.e., consistent).

The bias chart illustrates that variation caused by daily variation (lines b1 and b2 in the graph) is not as much relevant as the variation due to workpiece location and/or orientation, which is beyond the pure repeatability limits. There is a significant difference, of approximately = 2 μm, between readings taken at distinct locations/orientations, which might be caused by thermally-induced position errors or CMM calibration residuals.
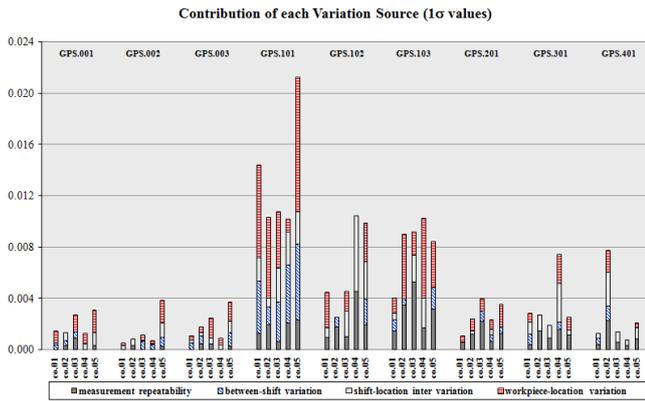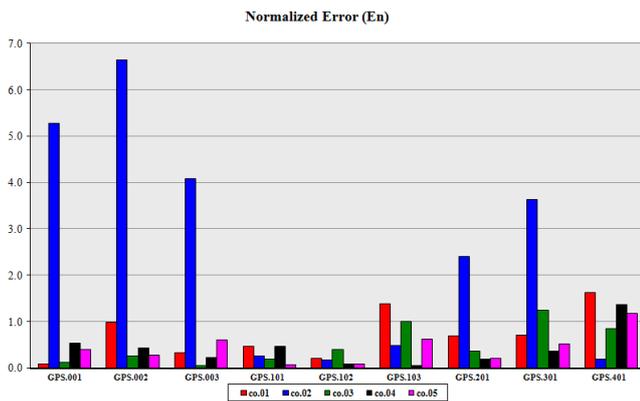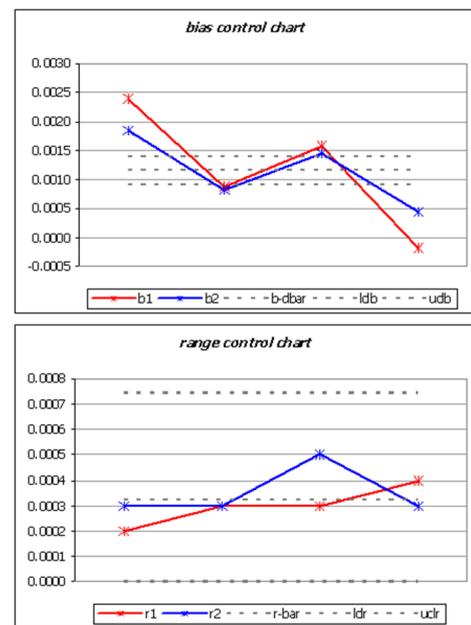

Fig. 5. Bias and range control charts for GPS.001 (measurement of a feature of size)

The charts for the position tolerance labeled GPS.101 are shown in Fig. 6, which was sampled and evaluated as the position of a cylinder axis measured as three circle cross-sections, which define three least-squares circle centres, related to a datum system. The range chart presents an outlier likely caused by dust on the part. In fact, good metrology practices are usually not observed in industrial measurements. As a nested GPS characteristic, the pure repeatability observed for the position tolerance is about ten times larger than that for a feature of size. That is also

because the measurement of the position tolerance GPS.101 requires several probe orientations (effect of indexing head positioning reproducibility).

The bias chart clearly indicates a difference between measurements taken at distinct shifts (difference of about 2 μm; lines b1 and b2 in the graph). That is likely to be a consequence of temperature variations over a working day and their effects, such as thermally-induced machine scale errors combined with part growing/shrinking and thermally-induced machine geometry errors.
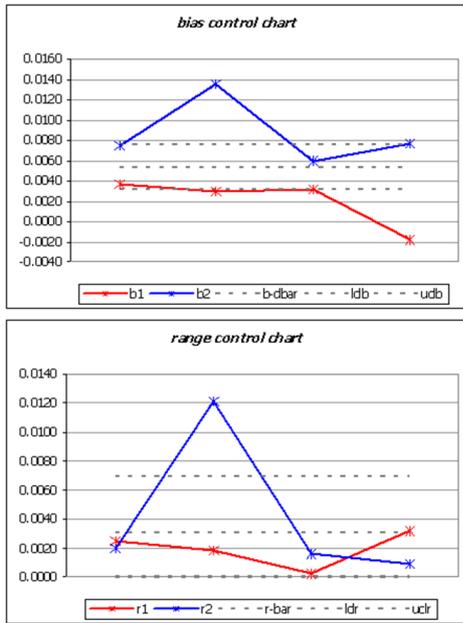

Fig. 6. Bias and range control charts for GPS.101 (measurement of a position tolerance)
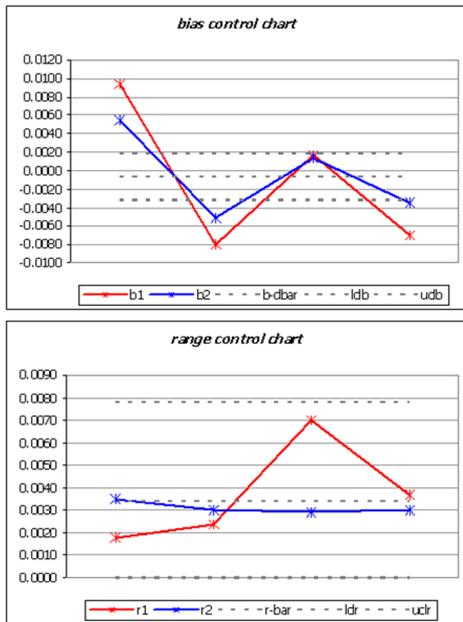

Fig. 7. Bias and range control charts for GPS.103 (measurement of a position tolerance)

For the position tolerance labeled GPS.103, i.e., position of a cylinder axis measured as three circle cross-sections,

which define three least-squares circle centres, related to a datum system; one can extend the considerations drawn to GPS.101. Fig. 7 illustrates the range and bias charts.

3.3. Direct comparison of two CMM results

The comparison of two similar CMMs when measuring the same workpiece characteristic (GPS.101) is shown in Fig. 8. The range chart of CMM.B displays a mean range about four times greater than that for CMM.A. Regarding the bias chart, neither the error pattern nor the magnitude of the error for each workpiece orientation and location present any similarity. That just ratifies how difficult is to estimate uncertainties in CMM measurements, and how important is to periodically check the measurement process as a whole.
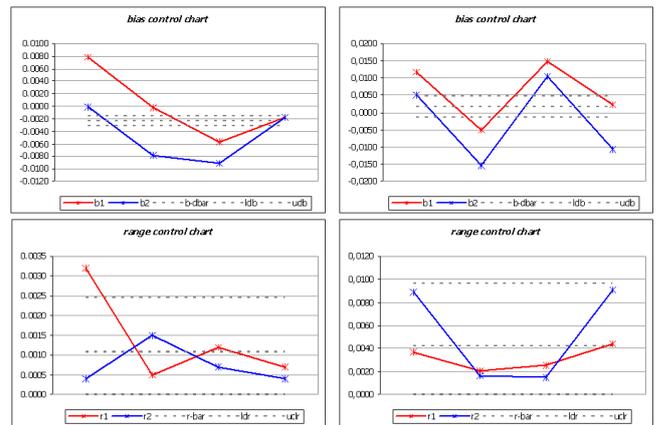

Fig. 8. Bias and range control charts for GPS.101 (measurement of a position tolerance) on two similar CMMs (CMM.A: left; CMM.B: right)

4. CONCLUDING REMARKS AND DISCUSSION

The bar chart of discriminated variation sources showed that contributions other than the measurement repeatability may considerably inflate the uncertainty of the measurement result. The relevance of a temperature control for metrology purposes could be inferred from the experimental analysis. The major variation contribution for most cases was due to thermally-induced effects on the machine structure (scales, guides) and on the part.

The evaluation of nested characteristics like the position of a line related to a datum system evidenced how important is to make rational use of indexing probe heads. The more probe orientations one uses, the larger the expected variation will be. That is because not only the probe head positioning variation, but also the geometry machine errors excited by the use of many probe orientation could definitively affect any decision-making process.

5. REFERENCES

[1] Draft ISO/TS 15530-2 2005: GPS - CMM: Techniques for Determining the Uncertainty of Measurement - Part 2: Use of Multiple Measurement Strategies in Calibration of Artefacts.
[2] ISO 10360-2:2001, GPS - Acceptance and Reverification Tests for Coordinate Measuring Machines (CMM) – Part 2: CMMs Used for Measuring Size.