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A HYBRID APPROACH TO THE UNCERTAINTY ANALYSIS OF COORDINATE MEASUREMENTS

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Abstract: In this paper, a new methodology for the uncertainty analysis of coordinate measurements is presented. The methodology can be applied on any kind of measurements performed by a CMM, and it is intended to be especially useful when performing reference measurements of geometrical and dimensional characteristics of workpieces. Master parts calibrated using this approach can be used in connection with ISO/TS 15530-3 for the uncertainty assessment of other CMMs, when measuring similar parts. Consistent measurement strategies and the real measurand definition according to the technical drawing are the foundations of this methodology, generally based in high-density measurement points. Assessment of uncertainties is performed using models in complete agreement with the measurement procedure, considering all major uncertainty contributions. Resources from artificial intelligence were applied to accelerate the development of adequate measurement procedures, simplifying the work of the CMM operator. To validate the proposed methodology, a cast iron steering case was calibrated and compared to simulation results obtained with PUNDIT/CMM, a software solution for task-specific uncertainty evaluation of coordinate measurements.

Keywords: CMM, measurement uncertainty, master part.

1. INTRODUCTION

Coordinate measuring machines (CMM) have become essential for industrial measuring technology. The potential and versatility of CMMs to measuring several geometrical and dimensional features is one of the main reasons for its acceptance in calibration laboratories and production.

Ironically, the benefits lead to one of the most significant implementations problems: the uncertainty evaluation of the CMM measurement process. Uncertainty evaluation is a fundamental requisite to establish traceability as an integral part of quality assurance according to the ISO 9000 series of standards. However, uncertainty evaluation of coordinate measurements in the industrial environment remains a problem, mainly because of the complexity of the measurement task. In this area, some effort was made in 2004 by the International Organization for Standardization (ISO) in publishing the ISO/TS 15530-3 [1], technique for determining the uncertainty of measurement using calibrated workpieces or standards. Nevertheless, this technique requires a calibrated object, measured in a reference coordinate machine and the methodology for calibrating these objects is still subject to discussion in the ISO/TC 213 committee. The parts 2, 4 and 5 of this standard will address this problem in the future. Meanwhile, the problem of assessing uncertainties for calibrated objects or master parts remains.

Today, very few laboratories in the world can afford a computational solution as the Virtual CMM (VCMM) developed by the PTB in 1996. "Basically, the virtual CMM performs point-by-point simulation of measurements, emulating the measurement strategy and the physical behavior of the CMM, with the dominating uncertainty contributions disturbing the measurement" [2]. Most other laboratories use sensitivity analysis, expert judgment, Monte Carlo simulations, simple uncertainty budgets, or do nothing to assess measurement uncertainty [3].

In any case, there is a lack of knowledge regarding the combined influence of measurement strategy, the actual measurand and the workpiece form error. Many researchers become aware of this problem and addressed some partial solutions, generally by means of simulation techniques, historical data or expert opinion [3]. One of the most comprehensive and flexible software software solutions is the PUNDIT/CMM package, which performs Monte Carlo simulations regarding probe error and sampling patterns, part form errors, fitting algorithms, CMM error and environmental effects [4].

In this paper we introduce a hybrid methodology to calibrate master parts using coordinate measuring machines and expressing the related measurement uncertainties. The methodology is intended to be especially useful in middle-level laboratories, such as those who provide calibration services for the industry. The focus is on developing consistent measurement procedures, high number of probing points and functionally oriented fitting of geometrical features, fully understanding of the measurand definition and task-specific uncertainty budgets. Finally, a study case will be presented concerning the calibration of a cast iron steering case and a comparison of the uncertainty results with outcomes from PUNDIT/CMM software.

2. GPS IN COORDINATE METROLOGY

Dimensional metrology is based fundamentally on physical standards as gage blocks, step gages, calibrated rings and so on. One basic hypothesis is that these parts have low form errors and good surface finishing. However, assumptions like that are only valid in some special cases, and cannot be applied as a general rule. In the production floor, definitions of sizes and distances are not very well established because of the presence of form and geometrical deviations.

Historically, international standards on uncertainty were developed around Taylor's principle and conventional instruments. Only in the last two decades, primary because of the growing of computized measurement systems, have geometrical product specifications become the center of attention for many dimensional metrologists. Measurement results from instruments that collect coordinate points from parts surfaces are strongly influenced by the probing technology, point sampling, digital filters and evaluation criteria of geometrical features.

Today, as CMMs become more accurate, the question of how exactly a diameter or a circularity deviation can be measured will depend strongly on how well the diameter and the circularity statements were defined previously. For that reason, the knowledge of the GPS (Geometrical Product Specifications) standards developed by the International Organization for Standardization (ISO) is a fundamental requisite for the personnel involved in coordinate measurements of production parts. Familiarity with the American standard ASME Y14.5M-1994 [5] and the differences with GPS must be regarded as well.

As previously mentioned, evaluation criteria is one of the reasons of misinterpretation and, in consequence, measurement error in coordinate measurement. According to the international standards, substitute geometrical elements must be always calculated by means of Tchebysheff algorithms. Least squares evaluation can only be used in one exceptional case (estimating circularity according to ISO 4291 [6]).

Sampling of measurement points is another source of errors, since large quantity of probing points cannot be taken because obvious economical reasons. From the mathematical point of view, there is a minimal quantity of points that must be acquired so the geometrical elements can be defined. However, such a low quantity of points will not allow a proper realization of the measurand, as defined in the technical drawing. In the special case of datum elements, the minimum quantity of points is allowed only if reference fixtures with low form error as plates, angle plates, master cylinders, etc, are attached to the datum, reproducing the contacting element needed to create the reference [7].

Meanwhile, the complexity of the sampling problem considering the diversity of geometrical elements, the multiplicity of form errors present in real parts, the correlation between evaluation criteria and the need for traceability, allow us to assert that no universal recommendation can be established for any specific measurand. Consequently, it is important to recognize that in the absence of any prior information about the characteristics to measure, it is not possible to plan a probing strategy or measurement procedure that actually provides realistic results.

The best approach is to "learn" as much as we can about the measurement task, by using all practical and economical resources at our disposal. The learning curve will set a boundary to what can and what cannot be accomplished in real problems. It is here where artificial intelligence (AI) can help us to accelerate the training process and systematically document all the important data regarding the measurement process. The methodology presented in the next section takes advantage of AI techniques, allowing us to solve real problems by recycling and adapting solutions from the past.

3. A NEW APPROACH: THE HYBRID METHOD

Many reasons can lead to the need of calibrating a master part. One of these reasons can be, as previously mentioned, the uncertainty evaluation of production coordinate measurements. Thus, a solid link within the traceability chain can be established, be means of substitution measurements with the reference part.

Another reason can be the need of performing stability analysis of the CMM. Interim checks should be performed periodically to assure that all statements made during calibration remain valid. Therefore, it is possible to declare that the CMM has not change its characteristics and, in consequence, its influence on the measurement uncertainty.

Finally, there is the need for providing physical standards for inspection equipments in the industry. In these cases, master parts work as zero setting during the initial setup of dedicated measurement instruments. Any systematic error present in the reference part will be introduced all along the subsequent measurements, reducing the production process capability observed by the final client.

Each one of these three types of calibration needs requires a specific approach for the measurement strategy and uncertainty analysis. In this work, only the first type of calibration will be assessed, primarily because its inherit complexity. However, it is possible to make analogies to the other two types of calibration needs, as long as the main assumption of task-specific measurement procedure and uncertainty analysis remains valid.

3.1 The approach

The approach presented in this paper, named as Hybrid Method, take advantage of several techniques well known to coordinate metrologists, as reversal techniques, point wise averaging and others. These techniques, together with substitution methods and a proper measurement and probing strategy, in total agreement with the technical specifications, lead to a clear and efficient methodology.

Thus, for a specific geometrical or dimensional tolerance, a specific model for uncertainty assessment and a specific measurement strategy was developed, inspired by a previous work of Salsbury [8]. The basic idea is that every geometrical or dimensional tolerance measured in a selected workpiece is a special case, and a general approach will only lead to a very conservative uncertainty budget, or in some cases, to systematic errors not fully corrected.

The GUM approach for the evaluation of measurement uncertainty is the base of the proposed method. Monte Carlo simulations are applied when necessary, to confirm that all the hypotheses in GUM were sustained. Very simple simulation tools for some complicated error sources were developed too, as well as previous knowledge of the production and measurement procedure from the client.

The methodology considers five major uncertainty contributions to uncertainty and six general groups of tolerances as shown in Table 1:

Table 1. Uncertainty contributions and tolerances.

Uncertainty components	Tolerances
Repeatability	Size
Machine	Form
Probing	Orientation
Workpiece	Position
Temperature	Run-Out
	Profiles

For each of the six tolerance groups, an uncertainty model was developed, containing all five uncertainty contributions. However, some uncertainty contributions could apply or not depending on the tolerance and the measurement procedure. Consequently, sensitivity coefficients "calls outs" when a specific uncertainty contribution must be applied, or not, in every case.

3.2 The methodology in action

In practice, the Hybrid Method is based on a growing database, constantly updated with inputs from the operators who are carrying out the calibrations of parts. The database is composed by highly detailed measurement procedures developed in previous calibrations of some other master parts. Operators will be aided by a software which has access to the database, and performs a complete Case-Based Reasoning (CBR) cycle. It is possible to define CBR, as the process of solving new problems based on the solutions of similar past problems. It has been argued that CBR is not only a powerful method for computer reasoning, but also a pervasive behavior in everyday human problem solving [9].

The CBR cycles begins by introducing a few cases already tested on the Case Base (CB). Then, when a new calibration task arrives, the operator is asked to search on the database for a similar measurement task carried out previously in the calibration laboratory. The search through the database is performed by the Nearest Neighbor Algorithm (NNA). The goal of the NNA is to find out which procedure stored on the database is the most applicable to the actual measurement problem. To do so, the NNA calculates distances in a N-dimensional space between the data stored and the actual needs. Thus, NNA works right on the "Retrieving" phase of CBR. The distances are calculated by means of the Pythagoras's Theorem, and using proper scales for comparisons. Each scale has levels that can be easily quantified by scalars through a proper parameterization, allowing the computation of the distances (Table 2). This means that the number of levels within it divides every factor, so dimensions could be numerically assessed.

Clearly, the actual measurement task will not be exactly the same as that retrieved from the database, so the operator must perform some modifications in the measurement procedure. Recommendations and good practice guides were developed to aid the user to realize these adjustments, including a general procedure with uncertainty analysis.

Table 2. Uncertainty contributions and tolerances.

Selection Parameters	Levels					
CMM used	CMM 1	CMM 2	CMM 3			
Workpiece positions over the CMM	Just one setup	Two positions (reversal)	Four positions (ISO 15530-2)	"N" positions		
Probe	Standard	Multiple styli	Motorized probe head	Scanning		
Type of calibration	Type 1 (CMM uncertainty evaluation)	Type 2 (CMM monitoring)	Type 3 (Master part for dedicated instruments)			
Additional standards	Step-gage, block gage	Ring gage	Calibrated sphere	All previous	No additional standards	
GPS characteristic	Size	Form	Orientation	Position	Run -Out	Profiles
Cycles	Three	Five	"N" cycles			

Finally, when all the adaptations are made and the measurement executed and evaluated, the new procedure is stored in the database, for future access and consideration. (Fig 1).

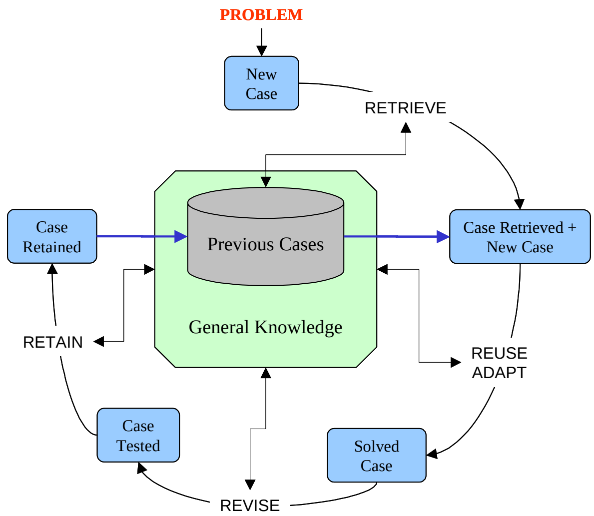

Fig 1. General Case-Based Reasoning (CBR) algorithm.

As a result, the computer program will aid the user in solving the problem of planning, executing and evaluating the coordinate measurement process.

The detailed procedures contain all the information needed by the operator to perform a proper calibration, including the uncertainty budgets according to the Hybrid Method. Table 3 shows the structure of a typical measurement procedure (not fully detailed). Multimedia information, as pictures, films of the part being measured and other relevant data are also stored on the database.

3.3 Case study: calibration of a cast iron steering case

The proposed methodology has been put into practice by means of a case study. The workpiece subject to calibration was taken from the production line of a manufacturing company, which produces finished components for the automotive sector. The selected part is a cast iron, recirculating ball nut, steering gear case, presenting eleven geometrical and dimensional characteristics: parallelism, perpendicularity, cylindricity total run-out, three diameters and four positions. All characteristics are critical and 100 % inspected on the production floor using a dedicated CMM. Thus, traceability is needed to assure parts are always within specifications.

Table 3. Structure of a detailed measurement procedure.

Main Data	Detailed Information
Client	➢ Client name ➢ Serial number of the part ➢ Uncertainty required ➢ Etc.
Analysis of the measurement task	➢ Identification of the tolerance to be measured ➢ Technical drawing of the part ➢ Pictures of the part
Workpiece Fixture	➢ Design of the fixture for the part ➢ Picture of the part mounted in the fixture on the CMM
……	…………………………
Probe	➢ Probe qualification ➢ Probe configuration ➢ Stylus size and tip size ➢ Picture of styli mounted
CNC Parameters	➢ Scanning speed ➢ Approaching speed ➢ Approaching vector ➢ Measurement force ➢ Film of 1 cycle of the measurement
Features measured	➢ Kind of features measured (circle, plane, cylinder, etc) ➢ Number of points measured ➢ Probing points distribution ➢ Fitting ➢ Filtering
Evaluation of results	➢ Graphic results ➢ Tables and uncertainty evaluation according to the Hybrid Method

For reasons of comparison, results obtained from the Hybrid Method were contrasted with outcomes from the PUNDIT/CMM software. To do so, the part was 3D modeled with dedicated CAD software, along with all the information needed from the measurement process (Fig 2).

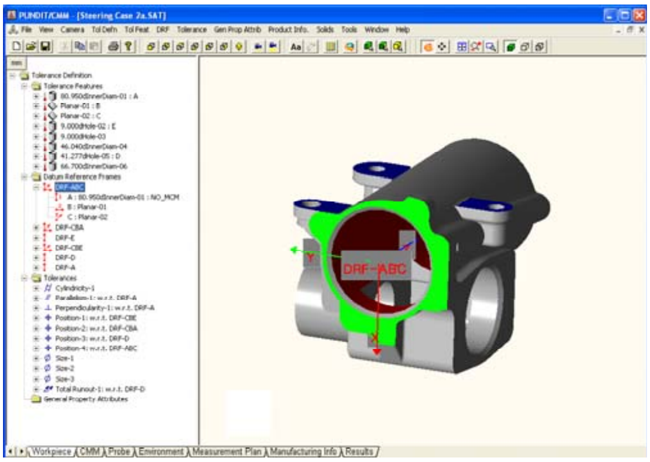

Fig 2. CAD model of a cast iron steering gear case, commonly used in light trucks (from the PUNDIT/CMM interface).

This case study can be considered as the first case introduced on the CB, and reflects an adequate diversity of characteristics, allowing the CBR system to retrieve solutions for future problems. However, only when more solutions were introduced on the CB, the overall effectiveness of the CBR system will increase.

In this particular case, general knowledge from coordinate metrology was used to aid the user planning the measurement procedure. As general knowledge we refer to all books, recommendations, standards, papers, etc, available by the user. Thus, to smooth the progress of developing a proper procedure, many data, quick tips, tables, graphics and all the equations needed for the Hybrid Method were systematically introduced on a General Procedure. The General Procedure was thus developed for those cases where no similar cases exist from past calibrations.

As a result of the analysis of all available information, a measurement procedure was developed and then executed on a reference CMM from an accredited laboratory. After the measurement, uncertainty budgets for all eleven characteristics were evaluated. Data from the measurement process, including part model and specifications, CMM errors, probe definition, environmental conditions, probe strategy, part positioning and all other information needed by PUNDIT/CMM was then summarized, and the simulations performed. Results for both approaches are presented in Table 4.

Table 4. Uncertainty results for measurements according to the Hybrid Method and the PUNDIT/CMM simulation

Characteristic measured	U_{95} [mm] Hybrid Method	U_{95} [mm] PUNDIT/CMM
C Parallel to A	0,0198	0,0020
B Perpend to A	0,0035	0,0011
Cylindricity	0,0021	0,0026
Position CAE	0,0125	0,0186
Position CBA	0,0120	0,0143
Position ABC	0,0128	0,0075
Position D	0,0055	0,0061
Total Runout	0,0028	0,0043
Diameter 41,293	0,0021	0,0022
Diameter 66,73	0,0021	0,0019
Diameter 80,975	0,0021	0,0030

A first conclusion from Table 4 is that uncertainty values spread from 2 µm to 20 µm, depending on the characteristic measured. The range of values observed could not be explained by simply comparing with uncertainties from the CMM calibration results (estimated at 3,1 µm for distances up to 500 mm). Results could better be clarified if the part form error and the probing strategy were analyzed. Certainly, parts from the production floor present form error that should not be neglected in coordinate measurements. However, quantifying this source of uncertainty is not a simple task. The Hybrid Method by itself does not allow us to assess the individual effect of part form error combined with the specific probing strategy. On the other hand, it is possible to simulate different scenarios on PUNDIT/CMM, isolating each source of uncertainty and rerunning for each case. Doing so, the relative effect of Probe Error, Part Form, Thermal Effects and CMM could be assessed and compared for all eleven characteristics, as presented in Fig 3.

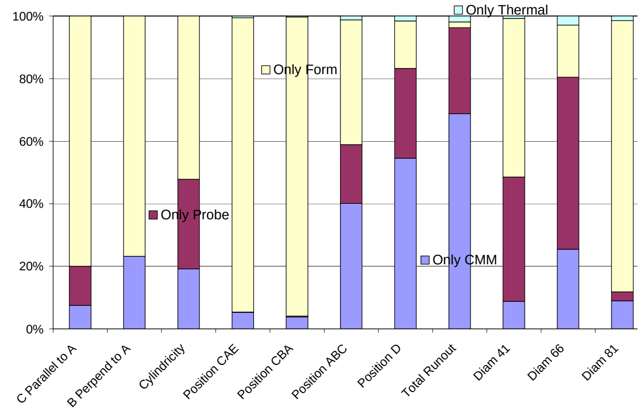

Fig 3. 100 % Stacked Bar Chart comparing percentage contribution of each source of uncertainty for all eleven tolerances.

Clearly, by simply observing the previous figure, we conclude that form error for the specific probing strategy (in this case: 50 points equally distributed for all geometrical features) is the leading source of uncertainty for most characteristics. In particular, positional deviations are largely influenced by this source, because of its effect on datuming of the reference frame. Thermal effects remained almost negligible for every case, because of the excellent environmental control in the laboratory facilities.

4. CONCLUSION

In this paper, a hybrid methodology for uncertainty analysis of coordinate measurements has been described. It can be applied for all the principal tolerances found in actual technical drawings.

Master parts calibrated using this approach can be used in connection with ISO/TS 15530-3 for the uncertainty assessment of other CMMs, when measuring similar parts. The methodology proposed applies the real measurand definition according to the technical drawing, and gives recommendations and good practices guides to the final user of the coordinate measuring technique. Consistent measurement strategies are the foundation of this methodology, generally based in high density of measured points. Assessment of uncertainties is performed using models in complete agreement with the measurement procedure, considering all major uncertainty contributions. Resources from artificial intelligence were applied to accelerate the development of adequate measurement procedures, simplifying the work of the CMM operator. Uncertainty results from the measurement of a steering case were compared between the Hybrid Method and PUNDIT/CMM, confirming the assumptions made regarding all sources of uncertainty.

Future work will be carried on to fully validate the proposed approach, including testing the entirely CBR cycle, upgrading of the programming software to a web based application, studying the CMM operator reception of the method, developing a better NNA search algorithm and providing comparison with the ISO/TS 15530-2 draft standard, when it is published in its final form.

5. ACKNOWLEDGMENTS

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