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An approach to improve accuracy and productivity of industrial CMM measurements at high scanning speed

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Abstract
Coordinate measuring machines (CMM) allow the geometrical characterization of parts relying on different probing principles. Contact scanning mode represents an important solution at industrial level as it allows reducing measurement time cycle and increasing productivity. Scanning may introduce dynamic effects contributing to measurement uncertainty, and in most cases measurement errors have a significant systematic component. Considering the scanning speed as leading factor, this paper presents a task-specific approach for the correction of CMM measurements on industrial parts at high-scanning speed, for assuring reliable results and comprehensive uncertainty evaluation. The approach is illustrated using a connecting rod as a case study in the context of an ongoing research project.

Coordinate measuring machine; measurement uncertainty; contact scanning probing mode

1. Introduction

Coordinate Measuring Machines (CMM) represent the most comprehensive solution for dimensional and geometrical analysis of parts in industry [1]. Beside the consolidated performances of discrete point probing systems, developments in the mechanics, electronics and control components enabled high reliability of continuous scanning acquisition. Compared to discrete points measurements, scanning allows faster measurement cycles and higher density of points, enabling e.g. a more comprehensive characterisation of free-form shaped parts. Furthermore, scanning can be especially beneficial for large parts measurements because the speed compensates for the drift effects typical of long measuring times related to slower discrete point probing mode [2]. However, a measurement point acquired by scanning does not represent a zero-force contact point and it is affected by e.g. dynamic errors, major contributions from probe shaft bending and variations in the probe head sensitivity. Many studies highlight that the scanning speed is the leading factor of these negative effects, demonstrating increasing deviations from discrete-points results at higher scanning speeds [3]. Indeed, despite not being a recognized performance indicator, CMM manufacturers usually define a range of recommended speeds to assure reliable measurements. These depend on the part geometry, feature size, verified specification and probing system configuration. Measurements performed at slow scanning speeds (e.g. 1-3 mm/s) are quite comparable to discrete-points mode in terms of accuracy, and it has been recently documented that scanning measurements are now preferred for high-accuracy calibrations of complex shaped parts e.g. gears [2].
Unfortunately, scanning speed values in the order of few mm/s are somewhat limiting the productivity in industrial measurements for the inspection of parts in manufacturing, where strong focus is on number of inspected features and cycle time [3]. Nevertheless, it is worth noticing that by increasing the scanning speed, the deviation from the reference discrete-points value prove to be task-specific and systematic [4]. Furthermore, the single effects of scanning are only partially recognizable as specific contributors to the measurement uncertainty [5], while the scanning speed can be considered as the main indicator to evaluate a comprehensive uncertainty contributor. Therefore, considering the common industrial requirement of increasing the scanning speed while assuring reliable results, the possibility of accounting a speed-related compensation represents an important goal.
The result of a CMM measurement may be corrected as follows

$$y_{corr} = y + \sum E_i \quad (1)$$

where E_i represents any known systematic error (e.g. scale, probing, thermal). The task-specific expanded uncertainty U (with k as coverage factor for 95% confidence level) is generally computed as

$$U = k \cdot \sqrt{\sum u_i^2} \qquad (2)$$

where u_i represents the typical uncertainty contributors linked to e.g. scale errors, probing errors, repeatability, thermal effects among others. The u_i elements may be evaluated using different methods [6], some of which are standardised or being standardised within the ISO 15530 series of standards. Regardless the uncertainty assessment technique, the effects of scanning speed can be accounted for adding to (1) a correction E_S for the known systematic error due to scanning speed and to (2) the related uncertainty contributor u_s.
This work presents a practical approach using a case study for the correction of CMM measurements performed at relatively high scanning speed (5-20 mm/s) and the evaluation of its contribution to measurement uncertainty.

2. Evaluation of CMM scanning speed effect: a case study

An industrial case was studied to propose a quantification method for scanning speed effects and their contribution to the measurement results and uncertainty. In particular, a methodology relying on multiple measurements was applied, currently under development within the European project "Evaluating Uncertainty in Coordinate Measurement" (*http://eucom-empir.eu/*). It is an experimental technique and includes the randomization of systematic errors by repeating measurements in four different orientations of the part in the measuring volume. The first orientation is defined as a typical orientation of the part; then, by rotating the part by 90° around each axis of the CMM, 3 more orientations are defined. The errors are reduced by averaging the repeated measurement results and the uncertainty is determined based on the variance of results. Additional contributors (e.g. scale, probing and thermal effects) are evaluated separately.

The identified specimen is an aluminium alloy connecting rod for automotive application, featuring form errors in the range 5-10 µm. The measurands here presented are the diameters of the two holes, acquired at the median section with 0.2 mm step width. The measurements were carried out using a cartesian CMM (Zeiss Prismo Vast 7; Vast active head; MPE = (2.2 + *L*/300) µm, *L* = length in mm). The acquisitions were performed at four different scanning speeds. The speed suggested by the CMM manufacturer to users (5 mm/s) was taken as starting value to identify the other relevant speeds. A value equal to half of the recommended speed (2.5 mm/s) was selected to simulate part calibration conditions, and the related results have been considered as reference values. The two additional speeds (10 mm/s and 20 mm/s), twice and four times the recommended speed, represent the target scanning conditions for industrial applications. For each of the four speeds, the measurements were carried out in four different orientations of the connecting rod in the CMM measuring volume, repeating the measurement five times. Figure 1 shows the values obtained for the small end hole diameter. It can be noticed that, for all the orientations of the part, the results are characterized by high repeatability even at the highest speeds (0.1 µm std.dev.). An increasing shift from the reference value is observed at increasing speeds, quite independently from the part orientation. The evidence is a much larger effect of the scanning speed, in comparison to other contributors e.g. the geometrical errors of the CMM. This systematic behaviour opens to the possibility of high-speed results compensation based on the lower speed measurements.

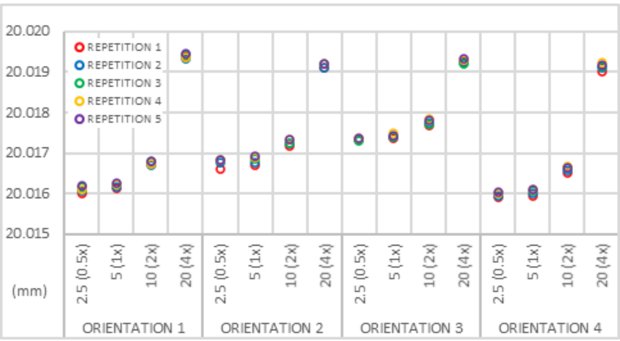

Figure 1. Case study results: repeatability of diameter measurements in different part orientations and at different scanning speeds (mm/s).

3. CMM scanning speed in task-specific uncertainty evaluation

For each tested scanning speed, the average of the complete measurement dataset (i.e. 5 repetitions on 4 orientations) was considered as measurement result. In order to further highlight the effects of scanning speed and the possibility to correct its systematic component, only the contributors referring to geometrical errors and repeatability have been considered in the uncertainty budget i.e. ignoring other effects such as scale, probing and thermal errors. To compare results, the normalized error E_N [7] was computed, considering the measurement at 2.5 mm/s as reference. The analysis shows a significant underestimation of the measurement uncertainty at 20 mm/s, due to two aspects: at that speed, the deviation from the reference heavily increases; additionally, in this specific experiment, the variance of results at 20 mm/s considering all orientations turns out to be even lower than those at lower speeds; further experiments are planned to investigate this unexpected result. The correction for the systematic effect E_S is computed, using data from Orientation 1 only, as the difference between the mean value of the results at a target speed and the mean value of the results at half of that speed. In case the correction is applied, the uncertainty contributor u_s is evaluated as the standard deviation of the average of the dataset at half of the target speed.

Figure 2 presents the final result for each scanning speed. The first element represents the reference value. The second dataset shows the results without the proposed E_S correction, confirming the increasing E_N at higher speeds. The last dataset includes the correction E_S, highlighting full compatibility of results with a significant drop of E_N at 20 mm/s.

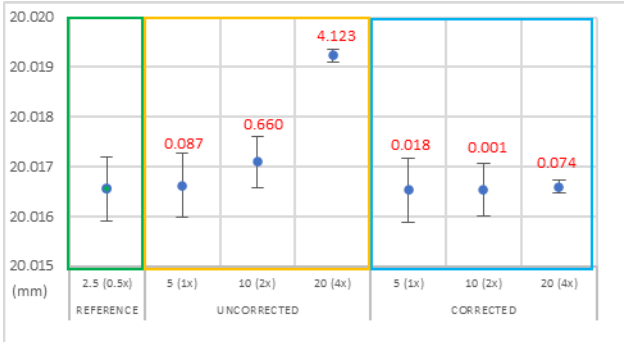

Figure 2. Comparison between corrected and uncorrected results at the different scanning speeds (mm/s). In red, the value of E_N. Error bars represent only the uncertainty contributors referring to scanning speed, geometrical errors and repeatability.

4. Conclusions and further developments

A methodology for the correction of CMM measurement results on industrial parts at high scanning speed has been illustrated using a connecting rod as case study. The procedure relies on repeated measurements at two scanning speeds: the selected value for production and half of it. Experiments performed at three different target speeds and with four different part orientations delivered results that are consistent with the reference value. A more extensive validation is being planned on different and more complex parts and related measurands.

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