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Experimental evaluation of software estimates of task specific measurement uncertainty for CMMs

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ABSTRACT

Estimation of the uncertainty of Coordinate Measuring Machine (CMM) measurements for real, imperfect parts is a very complex undertaking. Not only are there many contributors to the uncertainty that may interact in a non-linear fashion, making it difficult to mathematically determine an uncertainty estimate, but it is also difficult to predict the long-term variation of these parameters. Our work seeks to provide experimental validation of the uncertainties predicted by two different commercial software packages that purport to predict the task-specific measuring uncertainty of CMM measurement results. The validation procedure uses repeated measurements of calibrated artifacts to experimentally determine measurement uncertainties. These measurements can then be simulated in the commercial software packages. The comparison will allow the software to be tested to see if it appropriately accounts for the influences of the operator, environment, and part placement. This paper reports the results of actual part measurements and the predicted uncertainty provided by commercial simulation packages. Differences between experimental and simulated uncertainties are highlighted, and their causes examined.

1. Introduction

There are different recognized methods for determining the uncertainty of measurements made with CMMs. These include the use of reversal techniques, the substitution method, computer simulation, and expert judgment (all covered in the ISO 15530 series of standards [1]). The evaluation of task specific uncertainty for CMMs using the substitution method is not often performed due to the difficulty or expense of developing a calibrated artifact with which to compare the workpiece, although research has been done on specific cases [2]. The *Vocabulaire International des Termes Fondamentaux et Généraux de Métrologie* (VIM) [3] defines traceability in terms of an unbroken chain of comparisons, each with an associated uncertainty. From this, we may infer that a proper uncertainty statement for a CMM measurement must also be traceable: the uncertainty for a specific measurand will rely, in turn, on other uncertainties such as scale errors, the choice of reference standards, and the machine calibration procedures.

One major difficulty in establishing traceability for CMM measurements of specific geometries using the substitution method is that the operating conditions and the positioning of the part geometry may vary from case to case, and thus from measurand to measurand. Unless the situation has an identical, calibrated reference geometry of the same dimension measured under similar conditions, the uncertainty determined by experimentally measuring the artifact cannot be guaranteed to accurately predict the workpiece measurement uncertainty. In the case of an artifact accurately mimicking the workpiece geometry and placement, repeated measurement of the artifact provides a sampling of measurement error produced by the CMM which is traceable to standards. This is a limitation for most practical purposes since producing and calibrating such an artifact is expensive or impossible. To alleviate this problem, commercial software packages have been developed that provide a way to simulate the CMM task specific uncertainties in a virtual environment.

The method of determining task specific measurement uncertainty by software simulation is implemented by performing a series of repeated measurements using a simulated, or virtual, CMM [4–7]. These repeated measurements each have a slightly different set of inputs (the influence quantities) and the results are tabulated to determine the variation of the measurand for these input quantities. If the input quantities adequately represent the conditions of the actual CMM in question (and its environment) and if the sensitivity of the measurand to these quantities is correctly determined by the software, it is possible that the output from the software will represent the variability that will occur with actual CMM measurements.

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The two main methods of simulation are either to develop a single CMM model by measuring one or more artifacts, or to develop a series of CMM models that will meet some user-specified criteria (such as CMM performance test values). The model is usually comprised of two components: the geometric errors of the CMM structure, and the random errors of the probing system. If a model is built from actual artifact measurements, each simulated measurement will superimpose a set of small random errors on the model. If a set of randomly developed CMM models is used, then each measurement will be performed once for every CMM model in the set. In either case, a population of measurement data is generated that is representative of actual CMM measurements. Two commercial packages are investigated in this paper. The first, PUNDIT/CMM v2.10, is a stand-alone package that will estimate uncertainties for each of the features identified on a solid model by the user. The second, Virtual CMM (VCMM), is integrated with the CMM's native measuring software to use existing measuring programs as a source of feature selection and relies in part on determination of geometric errors of the CMM using a calibrated ball plate artifact and KALKOM 4.0 software to analyze the errors.

The experiments described in this paper are a direct comparison of two uncertainty estimation techniques: the measurement of calibrated artifacts (the basis for the substitution method), and the use of simulation software.

2. Experimental procedure

In order to evaluate software models of task specific uncertainties, measurements of artifacts with calibrated dimensions were taken using a Leitz 654 PMM – a 3-axis overhead bridge configuration with movable table (600 mm × 500 mm × 400 mm measuring volume) and LVDT probe. The measuring software used to evaluate the features was Quindos 6. All features were evaluated utilizing the Least Squares fitting algorithm. Repeated measurements were taken at different locations within the machine volume. Different artifact orientations were used in order to observe the differing values that may arise as a result of varied machine behavior throughout the measuring volume.

Two master rings were measured using a sampling of 5 positions in the CMM measurement volume, and 6 orientations at each position were tested. The rings were fixtured with their central axes either along a CMM motion axis or diagonal relative to the CMM measuring volume. Ten repeated measurements were made at each orientation/position. The rings had nominal inner diameters of 112 mm and 25 mm and were Federal XX and XXX rings, respectively. Fig. 1 shows the two master ring artifacts as fixtured (diagonally) on the CMM for the experimental testing, and Fig. 2 shows some of the different ring orientations used in the testing, and the different locations in the machine measuring volume used in both the experimental and simulation tests.

The results of the measurements are compared to software evaluations of the same measurement scenarios to the extent the software inputs allowed. Each software model uses particular inputs to develop an estimation of the measurement uncertainty. In general, the inputs include part geometry, part location, environmental conditions, measurement strategy, part form errors, probing performance, and elements of the machine geometry errors.

It is assumed the quality of these input values will have a strong influence on the reliability of the software results, and the user must also decide whether the values should attempt to capture the CMM and its environment at a particular point in time or if the inputs should be representative values for a longer time scale. For the experimental comparisons discussed in this paper, the input

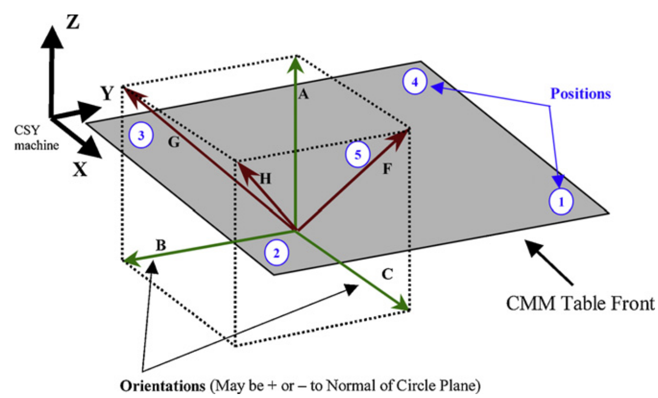


Fig. 2. Positions (1–5) and orientations (A, B, C, F, G, H) used in the measurements.

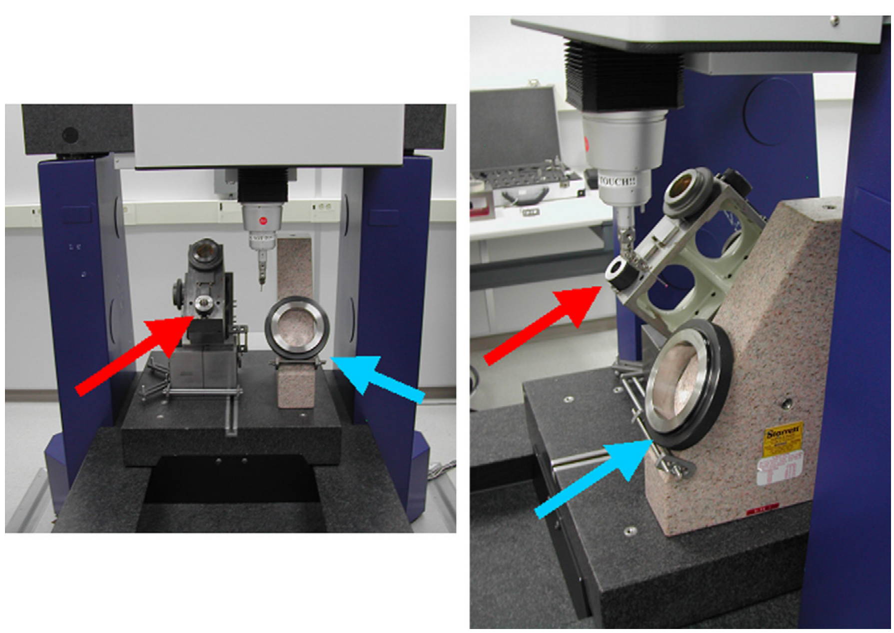


Fig. 1. Examples of fixturing for master rings. 25 mm ring shown by the left arrow and 112 mm ring shown by the right arrow.

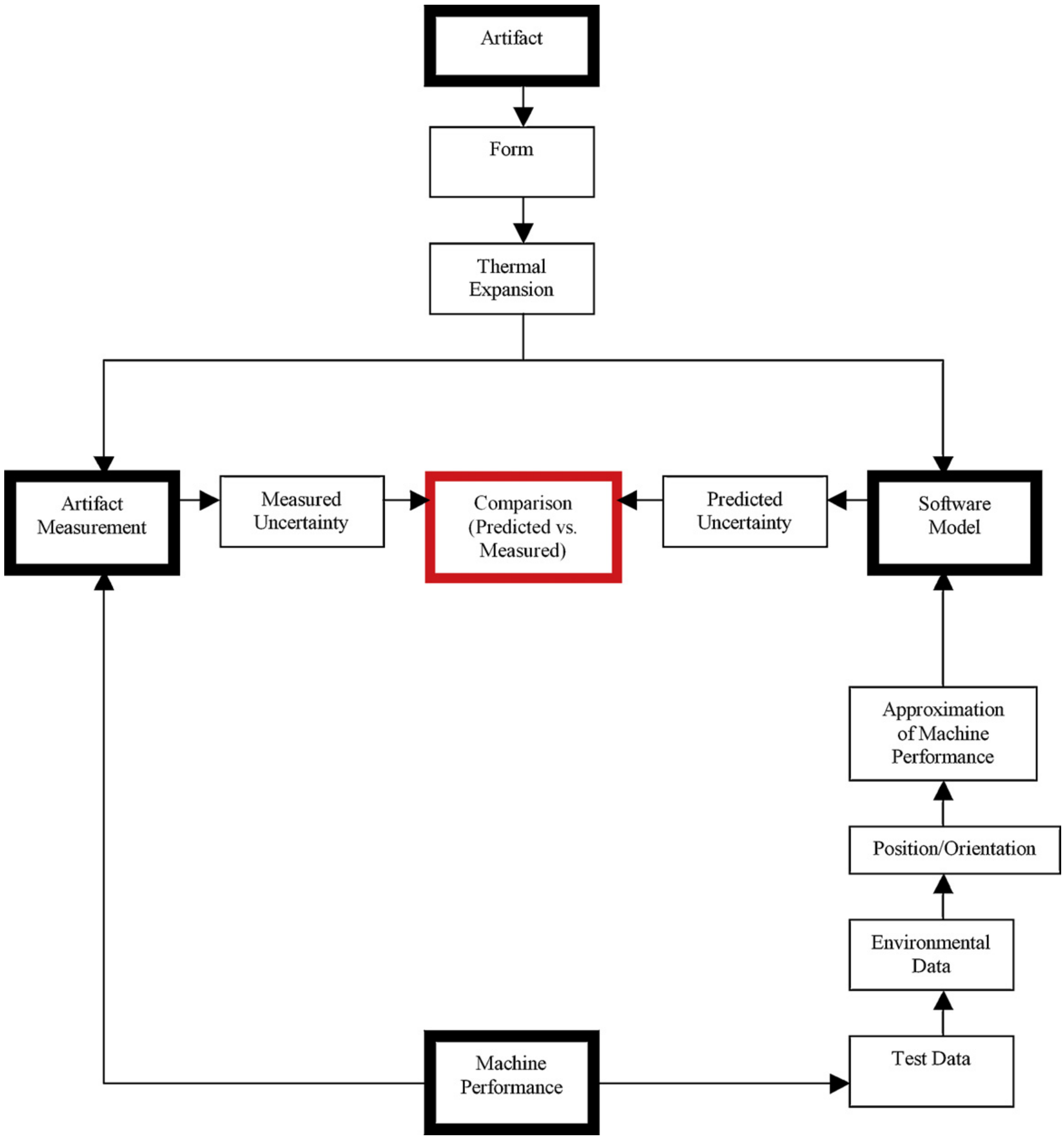


Fig. 3. Flow chart for the comparison of experimental and simulated measurements.

values are related to the conditions that existed during the measurements.

The flowchart shown in Fig. 3 describes graphically the contribution of the artifact, the environment, and the measuring machine to the measurement uncertainty. If the influence factors that contribute to the uncertainty are well understood by the user, and the software has the ability to manipulate these data properly, close correlation is to be expected between the measured data and the predicted uncertainty.

The calculation of uncertainty based on the measured data is performed using the method described in ISO TS 15530-3 and outlined in Table 1. This method accounts for both observed variability in the artifact measurements, the uncertainty of the artifact calibration, and the effect of bias that may exist in the measured data.

3. Results

As discussed in Section 2, the input quantities used in the software simulations are a strong contributor to the reliability of the final estimates of uncertainty. The conditions that existed during the experimental measurement scenarios and the corresponding input variables for the software simulations are shown in Table 2.

The primary results reported here are a comparison of the software predictions for the measurement uncertainty for diameter and form for the two ring masters – 112 mm and 25 mm inside diameters – with calculations of uncertainty from actual measurement results. For the experimental measurements, the rings are measured in each of the orientations at the five positions on the machine (see Fig. 2). The rings were measured over two 4–5-day stretches, separated by a period of 2 months.

A comparison is shown in Fig. 4 for the VCMM uncertainty simulations for diameter and form for each ring size, 112 mm on the left and 25 mm on the right. VCMM shows similar uncertainties for the diameter measurements, but a large difference in form error uncertainty in the comparison of the two rings. The larger gage had form errors that are larger than those for the smaller gage, while the diameter uncertainties were comparable.

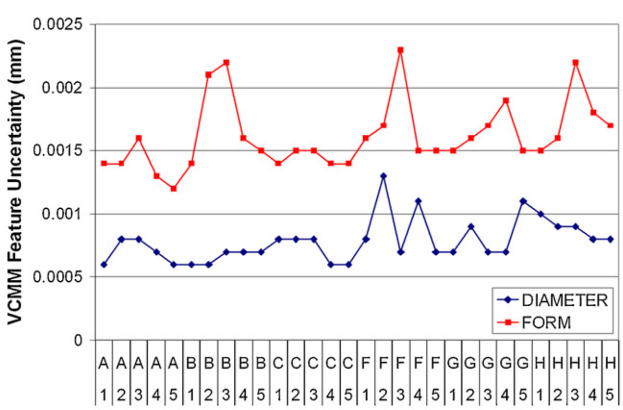
Since the VCMM data relied primarily on calibrated plate data, it is likely that the errors revealed during the plate measurement

Table 1
Uncertainty calculation for artifact measurement from ISO TS 15530-3.

$U = k \times \sqrt{u_{cal}^2 + u_p^2 + u_w^2} + \lvert b \rvert$	Expanded uncertainty calculation with k-coverage factor ($k=2$ used for 95% probability).
Components:	
$u_{cal} = U_{cal}/k$	Standard uncertainty from the artifact calibration certificate (here k is the coverage factor indicated by the certificate).
$u_p = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2}$	Standard uncertainty of measurement procedure, i.e. standard deviation of measurement results.
$u_w = (T - 20\,^\circ\mathrm{C}) \times u_\alpha \times l$	Standard uncertainty due to the manufacturing process and workpiece. In this case only thermal uncertainty is included. u_α is the standard uncertainty for the coefficient of thermal expansion and l is the *measured dimension*.
$b = \bar{y} - x_{cal}$	Systematic uncertainty, or *bias* component.

Table 2
Measuring conditions and software inputs.

	Experiment	PUNDIT	VCMM
Temperature	20.0–20.7 °C	20.5 °C	Not used
Artifact	Ring gages: 25 mm, 112mm	CAD models of ring gages	Nominal geometries of 2D circles created in measurement software
Probe	Single tip with knuckle, 3 × 50 mm stylus	Single tip	Probe element defined in measurement software, used in 'real' measurements
Uncertainty in thermal expansion coefficient	1.18 ppm/°C	1.18 ppm/°C	Not used
CMM performance data	N/A	ISO 10360-2 ($E = \mathbf{A} \pm \mathbf{B} \cdot L$)	Ball plate measurement defines systematic and random errors



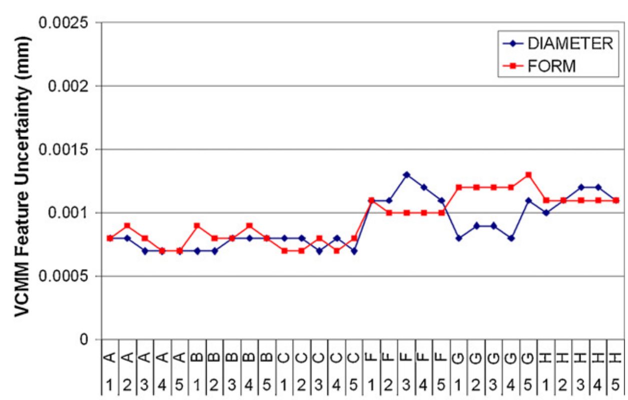


Fig. 4. Summary of form and diameter simulations using VCMM.

are reflected in these results. The ball plate measurements indicated that there were roll errors about the Z and Y axes of the CMM. These roll errors are amplified by the probe lengths used in measuring the rings. This may explain the increase in form errors with the increased dimension of the gage, as the roll of the axes would make the ring appear to have an "oval" shape.

Fig. 5 shows the PUNDIT uncertainty simulations for diameter and form for each ring size. Based on the input of overall performance criteria, the PUNDIT uncertainties were not as strongly dependent on the position or orientation of the part. Furthermore, the diameter of the artifact appears to have a stronger influence on the uncertainty estimates than in the case of VCMM. The form uncertainties from PUNDIT appear to be independent of size (diameter) of the feature, and related to the probing uncertainty and the uncertainty in the environmental conditions. The uncertainty in the diameter measurement appears to change depending on the size of the feature, and is probably also linked to the (thermal) environment.

Figs. 6 and 7 show the comparison of the simulated uncertainties from PUNDIT and VCMM, along with the experimentally determined uncertainties. Fig. 6 shows the data for the uncertainty in determining the ring diameter, while Fig. 7 shows the uncertainty in determining the form of the rings. The first impression from these graphs is that there is fairly good agreement between the methods. Table 3 summarizes the deviations of software estimates for uncertainty from experimental values.

Table 3
Summary of software uncertainty estimate deviations from experimental values.

	112 mm gage		25 mm gage	
	Diameter (μm)	Form (μm)	Diameter (μm)	Form (μm)
Experimental uncertainty values	1.1	1.5	1.2	1.1
VCMM deviation	−0.3	0.2	−0.3	−0.2
PUNDIT deviation	0.2	0.2	−0.7	0.2
VCMM % difference	25.9	−10.3	23.1	13.7
PUNDIT % difference	−18.7	−10.9	62.4	−17.8

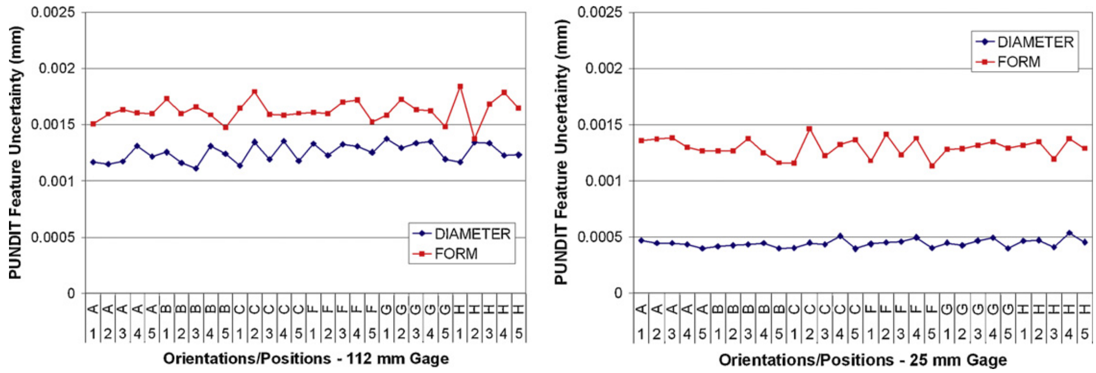


Fig. 5. Summary of form and diameter simulations using PUNDIT.

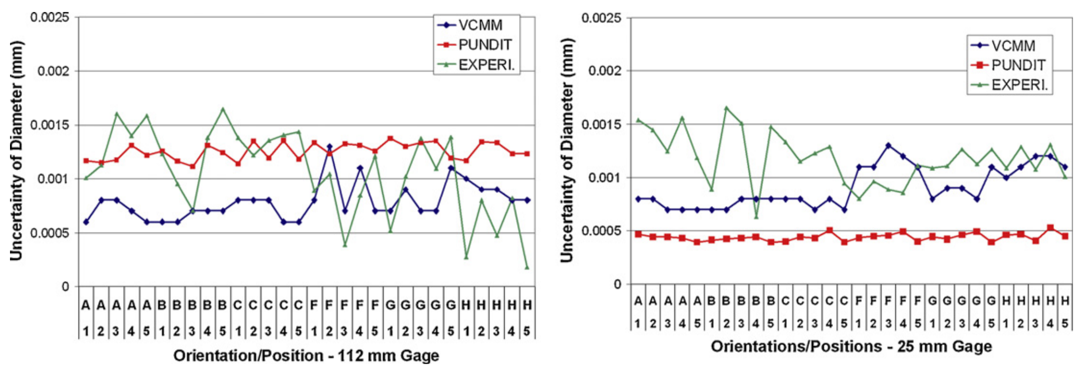


Fig. 6. Graphical comparisons between experiment and simulation for diameter measurement of the 112 mm and 25 mm rings.

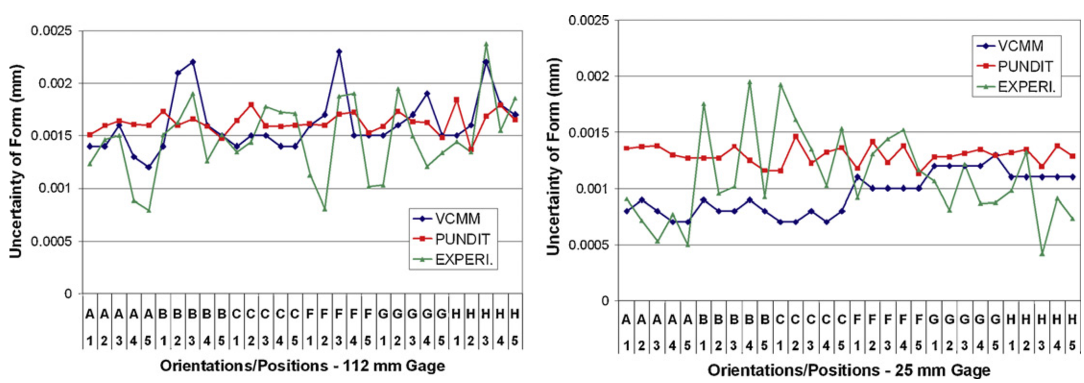


Fig. 7. Graphical comparisons between experiment and simulation for form measurement of the 112 mm and 25 mm rings.

4. Conclusion and future work

The results indicate that the comparison strategy, as implemented in these experiments, can reach general agreement with the software predictions. Each software package had different operating modes, and in these experiments just one method was used for each software. For VCMM, the machine geometry data were obtained through the measurement of a calibrated ball plate, and the errors revealed in those tests were used for the simulations. For PUNDIT, an overall performance value (MPE_E) was used to limit the types of virtual machines used in the simulation. The result of these choices is that the VCMM software has a more precise picture of the actual CMM geometry errors, while the PUNDIT product can produce estimates for an entire class of machines that meet a specific testing requirement. The ability of these simulation packages to predict long term effects is not clear, as the primary inputs to the error model are based on past, short-term performance of the machine. The accurate characterization of long-term changes in the CMM and its environment is needed to see how well the software can handle these data. It is hoped that the continuation of the current experiments will provide useful information in this regard.

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