# Application of Simulation Software to Coordinate Measurement Uncertainty Evaluations

**Jon M. Baldwin, Kim D. Summerhays, Daniel A. Campbell and Richard P. Henke**

**Abstract:** Uncertainty evaluations for coordinate measuring machine (CMM) metrology are problematic due to the number, ranges, interactions and generally unknown sensitivity coefficients of the parameters that can influence the measurement result. The situation is particularly difficult when a task-specific uncertainty is required and poses problems for both auditors and metrology practitioners. Auditors often lack satisfactory tools for a comprehensive assessment of a client's claims of traceability. Measurement professionals, similarly, have difficulty demonstrating compliance with measurement traceability requirements and, in addition, can find themselves at a real economic disadvantage if reliable measurement uncertainties are not known. In this paper, the historical perspective of, the motivations for, and the necessity of task-specific uncertainty evaluations are briefly discussed. This is followed by a presentation of the requirements and desirable features of a credible method for task-specific CMM uncertainty evaluation. Next, a description of the major design features of a practical software application for evaluating uncertainties of CMM measurements are presented. This is concluded by presenting several application examples and case studies which demonstrate that, in the arena of task-specific CMM uncertainty evaluation, simulation methods exhibit notable strength and versatility.

## 1. Introduction

One of the significant developments in coordinate metrology over the last dozen or so years has been a growing interest in evaluating the uncertainty of results produced by three dimensional (3D) measuring systems, particularly coordinate measuring machines (CMMs). Several motivations underlie this developing concern. Principal drivers of this activity include the steadily increasing employment of CMMs as tools for product and process assessment, a generally increased concern for product quality, greater globalization of trade, increased competition in the manufacturing environment and increasingly tighter tolerances for manufactured goods. Two reflections of this interest have been a growing body of research on the topic and the recent appearance of national and international standards dealing with or requiring the evaluation of measurement uncertainty.

In this paper, the motivations and available methods for evaluating task-specific uncertainties (i.e. an uncertainty applicable to a specific geometric dimensioning and tolerancing (GD&T) parameter of a designated part feature, under particular conditions of manufacture and measurement) in complex systems, such as CMMs, are discussed, pointing out the strengths and weaknesses of each. Then, simulation methods as applied to this problem, with an emphasis on the necessary and desirable features for a software application for CMM uncertainty evaluation are presented. Next, an implementation of software that embodies these features is described. Finally, a small set of application

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examples and case studies are presented that demonstrate the validity and utility of simulation methods for task-specific uncertainty evaluation of coordinate measurement systems.

## 2. Task-Specific Uncertainty: Historical Perspective and Motivation

There has been an interest on the part of researchers, going back at least to the early 1990s [1], in methods to derive task-specific measurement uncertainty evaluations from more general CMM performance parameters, and this effort has since been carried forward by workers in several countries. [2-6]

Generic CMM performance indices have been available for some time, the most prominent being those issued by the International Organization for Standardization (ISO) [7] and by the American Society of Mechanical Engineers (ASME). [8] While generic CMM performance tests such as these are valuable in comparative assessments of coordinate measurement systems, they are incapable of evaluating task-specific measurement uncertainty.

Meanwhile, task-specific uncertainty evaluation has become firmly established as a necessary component process in demonstrating measurement traceability to national and international standards. ISO 17025 [9] emphasizes the importance of uncertainty evaluation and, most importantly, states that traceability is achieved by means of an unbroken chain of calibrations or comparisons which include the measurement uncertainty of each step. Similarly, ANSI/NCSL Z540 [10] states, "Calibration certificates and/or reports shall…state the traceability to…standards of measurement and shall provide the measurement results and associated uncertainty of measurement …" ASME B89.7.5 [11] sets out in explicit detail the requirements for traceability of dimensional measurements.

The economic importance of uncertainty evaluation has been further emphasized in recent standards, notably ISO 14253-1 [12] and ASME B89.7.3.1 [13], which create guidance for the formulation of decision rules to govern the acceptance or rejection of articles of commerce. These standards provide for possible economic penalties for greater measurement uncertainty.

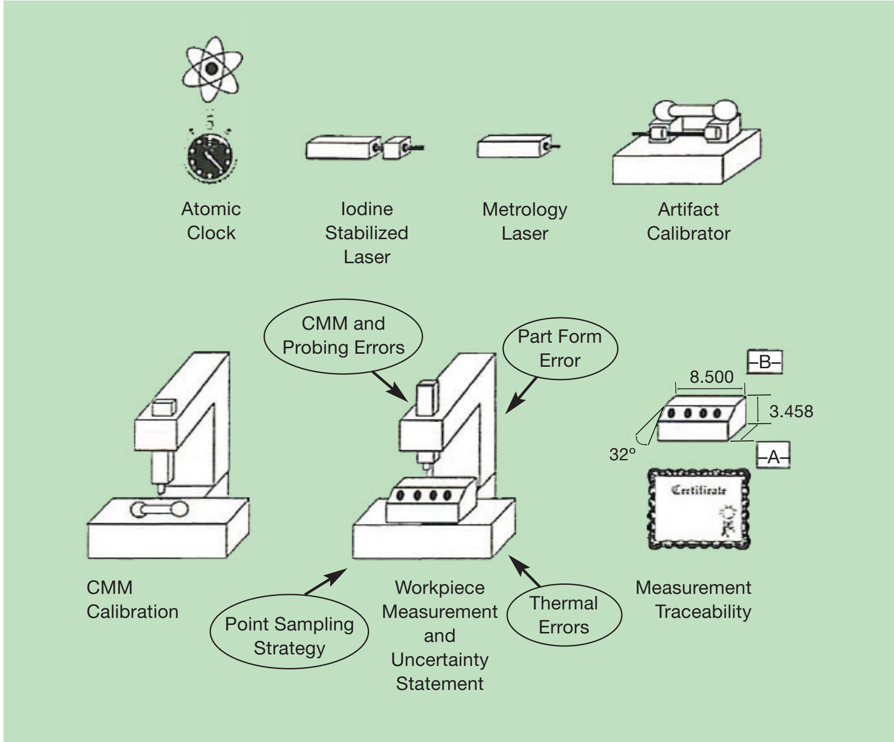


**Figure 1.** Sources of uncertainty in the CMM traceability chain.

## 3. CMMs and Methods for Evaluating Task-Specific Uncertainty

The major factor that inspires the widespread application of CMMs in industrial dimensional metrology is their extreme versatility; no other dimensional measuring device is capable of determining such a large variety of parameters on as large a range of workpiece types and sizes. Unfortunately, this same versatility leads to difficulty when it is necessary to state measurement uncertainty. In addition to the many different measurands that are evaluated in a typical CMM measurement session, one is confronted with almost unlimited sources of variability in the conditions of measurement: workpiece location and orientation, sensor type(s) and configuration(s), environment, sampling strategy and computational considerations, to name just a few. It is this tremendous variability that is at the heart of the fact that typical CMM calibrations and performance tests cannot directly produce task-specific measurement uncertainties.

This complexity can be further appreciated by referring to Fig. 1, which shows the CMM measurement traceability chain in its entirety. Traceability is established in a multi-step process, going all the way back in an unbroken sequence to national or international standards. Each step contributes an uncertainty that must be considered in developing the final, task-specific uncertainty and traceability statements. Some of these steps are relatively straightforward. Some information may be available to the CMM user with little required effort. For example, the uncertainties of the steps through the artifact calibration are likely assessed by national or international measurement institutions and/or qualified calibration sources, and should be captured on the artifact calibration certificate. Others, notably the CMM calibration and workpiece measurement, are complicated and are of necessity left in the hands of the CMM user, who might not be well equipped for their evaluation.

The available methods for CMM uncertainty evaluation have been summarized in a draft ISO technical report. [14] They are:

| Evaluation Method | Tractable | Comprehensive | Detects Measurement Bias | Detects Measurement Variability | Versatile | Predictive | Economical |
|---|---|---|---|---|---|---|---|
| | Desireable Attributes of an Uncertainty Evaluation Method | | | | | | |
| Sensitivity Analysis | ????? | ????? | Strong | Strong | Weak | Strong | Weak |
| Expert Judgment | Strong | ????? | ????? | ????? | Weak | Strong | ????? |
| Substitution | Strong | Strong | Strong | Strong | Weak | Weak | Weak |
| Computer Simulation | Strong | ????? | Strong | Strong | Strong | Strong | ????? |
| Measurement History | Strong | Strong | Weak | ????? | Weak | Weak | Weak |

**Table 1.** Uncertainty method scorecard for 3D metrology.

1. *Sensitivity Analysis,* which involves listing each uncertainty source, its magnitude, effect on the measurement result and its correlation with other uncertainty sources, then combining them in a manner that accounts for the sensitivity factor of each source and the interactions between sources. This is the approach described in the ISO Guide to Uncertainty in Measurements (GUM) [15] and is particularly useful if a mathematical model of the measuring process can be had, because direct computation of the sensitivity coefficients is possible.
2. *Expert Judgment,* which may be the only available method if a mathematical model or measurement data are not available. Its limitations in producing a defendable uncertainty statement are evident.
3. *Substitution,* wherein repeated measurement of a calibrated master workpiece yields a range of errors and thus the uncertainty. This is a powerful method of capturing the relevant error sources and their interactions. Its major disadvantages are expense (need for multiple master parts) and a reduction of the range of utility of the CMM.
4. *Computer Simulation,* where virtual models of the CMM, the workpiece and the measurement process are created, and estimates of the individual error sources are provided. These data are then applied in repeated virtual measurements. The distributions of the task-specific results yield estimates of both bias and measurement variability and hence uncertainty. Simulation methods are discussed in a new supplement to the GUM. [16]
5. *Measurement History,* which is useful if large numbers of measurements over time are available. This method can place an upper bound on measurement uncertainty. It fails to detect measurement bias.

Regardless of the method chosen to evaluate CMM uncertainty, there are a few requirements for a credible method. A minimum set of requirements is:

1. The chosen method must be comprehensive, i.e., all the major influence variables must be considered.
2. All necessary GD&T parameters must be supported.
3. The evaluations of those parameters must conform to the definitions established by the appropriate national and international standards.
4. It must produce accurate and reliable results.

Several other qualities are highly desirable. They include:

1. The method should be versatile by supporting a useful variety of CMM and probing system error models, and workpiece and CMM thermal models.
2. It should demonstrate fidelity by allowing realistic construction of measurement scenarios and metrology hardware configurations, and correct choice of geometric fitting algorithms.
3. It should be interoperable by accepting data from legacy sources, e.g. existing workpiece designs and inspection programs, and should provide a defined interface for communicating uncertainty information with other applications.
4. It should be flexible, offering a spectrum of tradeoffs between cost of system characterization and quality of the resulting uncertainty evaluations.

Table 1 presents a comparison of the five techniques as they apply to evaluation of task-specific uncertainty of CMM measurements, comparing them according to seven important properties.

*Sensitivity analysis* is rated questionable as regards tractability and comprehensiveness, due to the need for explicit information on the standard deviation and sensitivity factor for every uncertainty source and on the correlation between every pair of uncertainty sources. In some cases sensitivity coefficient calculation is impossible, since the measuring process cannot always be analytically described. Sensitivity analysis is rated as poor in regards to cost, due to the labor-intensive nature of the process,

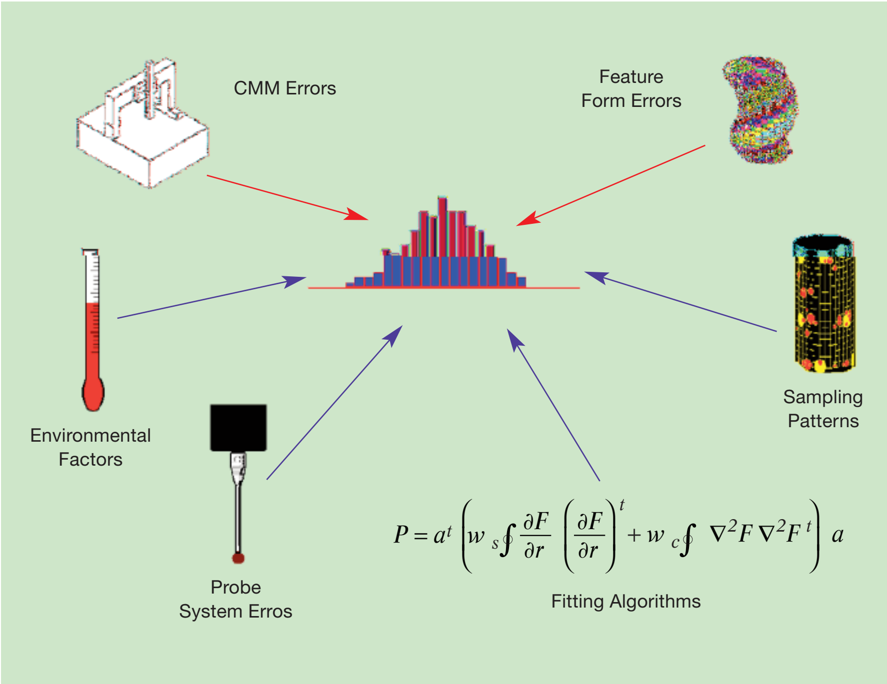


**Figure 2.** General categories of CMM measurement influence quantities.

and poor from a versatility perspective since much of the analysis is unique for each individual application. Its strength is that, properly conducted, sensitivity analysis does a thorough job of detecting both bias and variability.

The strength of *expert judgment* is its tractability; it can be applied to any situation where the "expert" is confident. Conversely, the comprehensiveness of expert judgment is difficult to evaluate and open to question. Cost can vary widely. The versatility of the method is not great; a separate consultation may be required for each and every application. The ability to detect bias and variability is a strong function of the quality of the expert; coverage of these issues is difficult to document and defend.

*Substitution* performs well except in the areas of cost and versatility, which are weaknesses of the method. Since calibration of the artifact is required and, in typical CMM applications, a wide variety of parts must be measured, this method is generally uneconomical. Similarly, the requirement of an artifact reasonably similar, if not identical, to the workpiece means that the method lacks versatility.

*Measurement history* is by definition tractable and comprehensive. There are ongoing costs associated with maintaining and preserving the measurement database. Its scope is limited to a particular workpiece. Measurement bias is undetected. The method detects measurement variability but cannot distinguish it from production process variability.

*Computer simulation* is easily applied to a wide range of problems; generally, all the information required to set up a simulation is available from the workpiece and measurement process designs. It can be variable in comprehensiveness; the result is only as complete as the model. This is primarily a concern to be dealt with during initial selection of the simulation software. Versatility and tractability of simulation methods go hand in hand; both depend on the same information sources. Finally, simulation methods easily capture both bias and variability of the measurement process. Simulation shares the strengths of sensitivity analysis but often allows a more complete assessment of interactions between error sources.

## 4. Influence Quantities on CMM Measurements

Earlier, it was mentioned that one of the principal sources of difficulty in evaluating measurement variability is the number and interactions of variables that can affect a CMM measurement. It is now necessary to visit this topic more explicitly and in its full complexity. CMM measurement influence quantities can reasonably be categorized as illustrated in Fig. 2. Within this categorization there are further levels of complexity as detailed in Table 2. It is important to note that this table may not be comprehensive, nor are all the influence variables listed likely to be important in every instance. The significant point is that in any CMM measurement the sources of variation will be many and their interactions will frequently be complex and beyond the reach of analytical treatment. It is likely that in most cases a few of these errors will predominate.

Due to wide variations in measurement systems, environments and measurement objectives, and to the prevalence of interactions between many of these influence variables, it is not practical to offer extensive generalizations concerning their relative importance. Thermal effects are commonly significant, as can be uncompensated geometric errors in the CMM. Dynamic geometric effects become more significant as measuring speed is increased. Simple examples of the interaction between workpiece form errors and sampling strategies are well known. [17, 18]

## 5. Levels of CMM Uncertainty

It is necessary also to deal with the fact that our knowledge of an uncertainty source is often incomplete. This can be illustrated by one example, CMM rigid body geometric errors, frequently one of the most important error sources. For each axis, six functions of axis position are needed: position error along the axis, straightness in the two orthogonal directions, roll, pitch, and yaw, as well as three scalar parameters, the out-of-squareness values for each axis pair, giving a total of 21 items in all for a three axis Cartesian CMM. Introduction of a rotary axis would require a similar set of six functions plus two additional squareness parameters. The discussion and examples cited in this paper will address the most common case of three axis Cartesian CMMs, but is extendable in principle to other CMM geometries.

| Influence Category | Influence Factor | Typical Source(s) |
|---|---|---|
| CMM Geometry | Rigid Body Errors | CMM Design/Construction, Maintenance |
| | Quasi-static Errors | Workpiece Loading |
| | Dynamic Errors | CMM Design, Operating Parameters |
| | Scale Resolution | CMM Design |
| Sensor System | Probe Type | Availability, Operator/Programmer Judgment |
| | Stylus Configuration | Operator/Programmer Judgement |
| | Calibration Strategy | Control Software, Operator/Programmer Judgment |
| | Stylus Bending | Probe Selection |
| | Approach Velocity | Control Hardware |
| | Probe Repeatability | Probe Selection, Adjustment |
| | Lobing | Probe Design, Selection |
| | Indexable Head Repeatability | Design, Maintenance |
| | Scanning Force and Speed | Control Hardware, Operator/Programmer Judgment |
| | Filtering | Hardware, Software Design |
| Environment | Thermal Effects | CMM, Workpiece |
| | External Vibration | Facility Design |
| | Humidity | Facility Design, Weather |
| | Atmospheric Pressure | Facility Design, Weather |
| | Power, Other Utility Variations | Facility Design |
| | Lighting, Ventilation System | Facility Design |
| Workpiece Factors | Systematic Form Error | Manufacturing Method |
| | Distortion by Fixturing | Operator Practice |
| Sampling Strategy | Numbers and Locations of Sampling Points | Operator/Programmer Judgment |
| Data Analysis | Fitting Algorithm Choice | Availability in Software, Operator/Programmer Judgment |

**Table 2.** Potential CMM measurement influence variables.

While all these parameters can be determined, the calibration process is time consuming, on the order of a week or more, and requires calibrated artifact(s). Often, particularly in production metrology facilities, much less is typically known. For example, the commonly used B89 test suite characterizes CMM performance by six scalar parameters: a repeatability parameter, three linear displacement accuracy values, volumetric performance and offset volumetric performance. The only calibrated artifact required is a length standard. Obviously, the B89 results provide far too little information to characterize fully the rigid body errors of the CMM but the test can be performed in about one to 1½ days.

There is a continuum of tradeoff choices available, where greater effort and expense will produce higher quality data and smaller estimates for the uncertainties. It is reasonable to expect results based on a full parametric characterization to lie toward the high cost, higher quality end of this range and that an uncertainty evaluation based on a simpler CMM performance test would produce higher uncertainty values at lower cost.

It should be noted that performance test suites other than the B89 tests are available and are sometimes cited by CMM users and vendors. For example, the ISO 10360-2 tests are commonly cited by CMM vendors. Although the system described here will produce uncertainty evaluations based on a variety of such tests, including all of the above-mentioned options, the examples and discussion in this paper will focus on the B89 tests. While either of these test suites offer substantial time saving as compared to a full parametric characterization, it was observed that the B89 tests generally result in uncertainty estimates that correspond more closely to those derived from a full knowledge of the rigid body errors. Generally, the observed order of the uncertainty estimates is full parametric specification < B89 < ISO 10360.

The reasons observed for this are:

1. The B89 tests provide six parameters to characterize CMM perform-

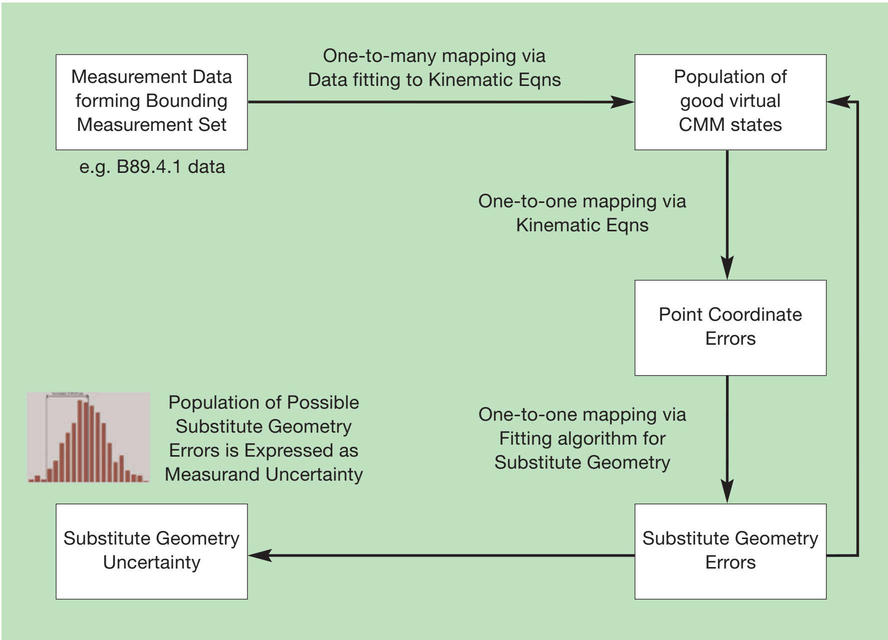


**Figure 3.** Principles of uncertainty evaluation by simulation by constraints, using CMM kinematic errors as an illustration.

ance while the 10360 tests, depending on how they are performed, provide one, two or three parameters. Thus the CMM model is significantly more completely determined by the B89 tests.

2. The B89 volumetric performance test explicitly specifies the locations and orientations in the CMM working volume of the test artifact, while the ISO 10360 protocol leaves this matter to the user's judgment.

Whatever the basis for the CMM performance evaluation, the result is an estimate of the uncertainty of a single point measurement and is an insufficient metric for demonstrating traceability or assessing conformance to a specification. Ordinarily the value will vary throughout the CMM working volume. At each point in the working volume, there will be a distribution of measured values. Each time a point is measured some value will be drawn from the distribution of values for that region of the work space. This value must be combined with the other error sources to give the overall point uncertainty and those point uncertainties propagated through the measurement process to give a complete uncertainty statement.

## 6. Description of the Method

At the heart of our implementation is a National Institute of Standards and Technology (NIST) developed method called Simulation by Constraints (SBC). [3] The choice of method was based largely on the desire for flexibility to the user in cost/benefit tradeoffs, as mentioned earlier. SBC provides this by allowing simulations to be set up and executed in the face of incomplete information. This can be seen by reference to Fig. 3 where, for the purpose of illustration, it focuses on just one aspect of CMM uncertainty evaluation, the effect of rigid body mechanical errors. The method begins with the recognition that the information available to define the uncertainty source may be incomplete; in this case, using a CMM performance test that does not completely define the CMM geometry. For example, there usually will be many sets of 21 rigid body parameters that would result in the same discovered set of six B89 parameters, the Bounding Measurement Set (BMS). The SBC method would begin with the generation of an adequate number (typically hundreds) of rigid body parameter sets that result in B89 numbers near the BMS values. Each of these sets of 21 parameters (3 scalars and 18 functions) can be thought of as a virtual CMM. For each virtual CMM the error of each individual point measured on the workpiece is computed. These points (with their errors) are submitted to the CMM data processing algorithms to obtain the corresponding substitute geometries for all the measurement features of concern. The substitute geometries are used to evaluate all the GD&T parameters of interest and the bias and range of the distribution of the results for each parameter provides its measurement uncertainty. The extension of the SBC concept to other error sources is straightforward.

## 7. System Architecture

The software architecture that was developed for task-specific uncertainty evaluation is shown in Fig. 4. One of the objectives of this architecture is to leverage, as much as possible, commercial, off the shelf software capabilities. An implementation of this architecture (PUNDIT/CMM™) has been created. Central to the implementation is the definition of the workpiece, represented in the context of a 3D geometric modeling kernel. This kernel supplies geometric modeling services. The current implementation is based on the ACIS® solid modeler,[1] although another geometry kernel could be substituted. Surrounding this kernel is the dimensioning and tolerancing layer which provides the essential services of identification, assignment and checking of tolerance features, datum reference frames and tolerances. This functionality is provided by FBTol®.[2] The services provided by the dimensioning and tolerancing layer fulfill many of the metrology-related functions currently neglected or inadequately provided by all known computer-aided design (CAD) geometry kernels; specifically the abilities to associate the raw geometry with the workpiece features to be toleranced and measured, to unambiguously assign tolerances to those features, and to create and associate datum reference frames. Finally, the outermost

[1] ACIS is a registered trademark of Spatial Technologies, Inc.

[2] FBTol is a registered trademark of Honeywell Federal Manufacturing & Technologies.

 

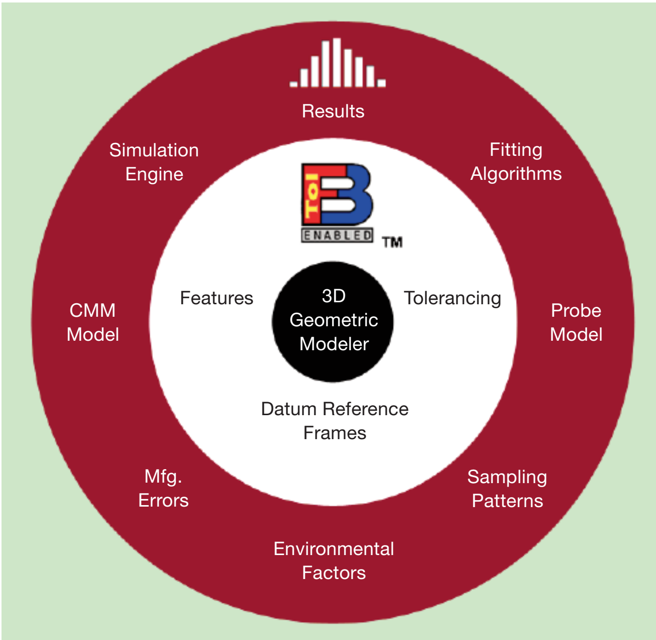


**Figure 4.** Uncertainty evaluation system architecture.

software, or interface and special services, layer provides CMM metrology-specific functions, such as the simulation engine, the geometric fitting and tolerance evaluation algorithms, the models of the various components of the CMM metrology process, and the user interface which allows parameterization of the measurement process.

The operation of this architecture in a typical simulation run might be as follows. As mentioned above, the outer software (interface and services) layer provides most user interface functions; for conciseness, this involvement is not always specifically identified. A workpiece model is imported by the interface layer and is passed to the geometry kernel. The dimensioning and tolerancing layer operates on the model, generally using a combination of tolerancing "wizards" and user interaction, to identify tolerance features, supply datum information and tolerances. This is an essential first step, after which most of the remaining operations may be performed in any convenient sequence. The interface and services layer creates the CMM and probing system models, and the environment model. The dimensioning and tolerancing layer provides services for creating the measurement plan, i.e., how the features are to be probed, fitting algorithm selections, etc. The interface and services layer is used to supply the manufacturing information, i.e., the shape and amplitude of the form errors for each feature. Finally, the interface and services layer provides the simulation engine, drives the simulation run, and presents the results.

## 8. User Interface Design

The user interface is crucial to the usability of the uncertainty evaluation system, in that a careful and logical presentation of the measurement process greatly facilitates straightforward and natural-seeming development of measurement scenarios. At the highest level, the user interface is organized into seven "tabbed" activities, each representing a distinct aspect of the measurement process. These tabs are presented at the bottom of the display screen (see Fig. 5) and, with the exception of the workpiece tab, may be visited in any desired order.

Examples of each of the tabbed pages are presented in Fig. 6. From left to right and top to bottom, these are:

a. *The Workpiece Tab.* Here, the as-designed workpiece geometry and the associated tolerance requirements are defined. Generally, the workpiece model will be created in and, imported from, an independent CAD system, although a rudimentary facility, suitable for modeling workpieces of simple geometry, is provided. A graphical view of the model occupies the right-hand pane of the tab. Once the model has been imported or created, tolerancing is applied. This may be done automatically using built-in software wizards, interactively by the operator, or with a combination of these methods. If a legacy inspection program is available in the *Dimensional Measuring Interface Standard* (DMIS) [19] format, the feature, datum and tolerance information can be extracted and automatically imported. In any case the tolerance information, including tolerance features, datum reference frames, material condition modifiers and applied tolerances, is displayed in lists in the left-hand pane. Also in this tab, the tolerance scheme applied to the workpiece can be verified. A suite of tools is available that can be used to automatically determine if any aspect of the part design is over or under constrained and if tolerance definition is complete. This capability, although not essential for uncertainty evaluation, has value from the very beginning of the workpiece design and tends to encourage concurrent development of the design and the measurement.

b. *The Manufacturing Information Tab.* The previous tab was concerned with the part as designed; this one deals with the part as manufactured. Specifically, it accounts for the fact that no manufacturing process creates features of ideal shape. Many of the shape errors are systematic and characteristic of the manufacturing methods and parameters. [20] It is well established that the interaction of shape (form) errors and the sampling pattern used in the CMM measurement can be a significant source of uncertainty. [21] PUNDIT/CMM has available several ways of applying form errors to each feature; one of them is shown in Fig. 6. The available methods are:
   1. User Query, where someone sufficiently knowledgeable about the manufacturing process can apply combinations of specific functional shapes, e.g. lobing, taper, bellmouth, twist, etc., and random error.
   2. Dense Data, where, if one or more samples of the actual production have been carefully and completely measured, the discovered form errors can be applied in the uncertainty evaluation.
   3. Manufacturing Process, where a library of form errors can be assembled and reused as needed.

   It is also worth noting the pair of radio buttons near the top center of the screen. These allow perfect workpiece form to be temporarily applied, and are useful in doing "what if?" types of analysis, in this case determining how

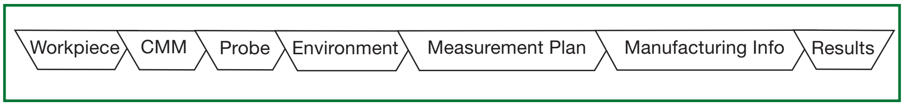


**Figure 5.** Highest level user interface.

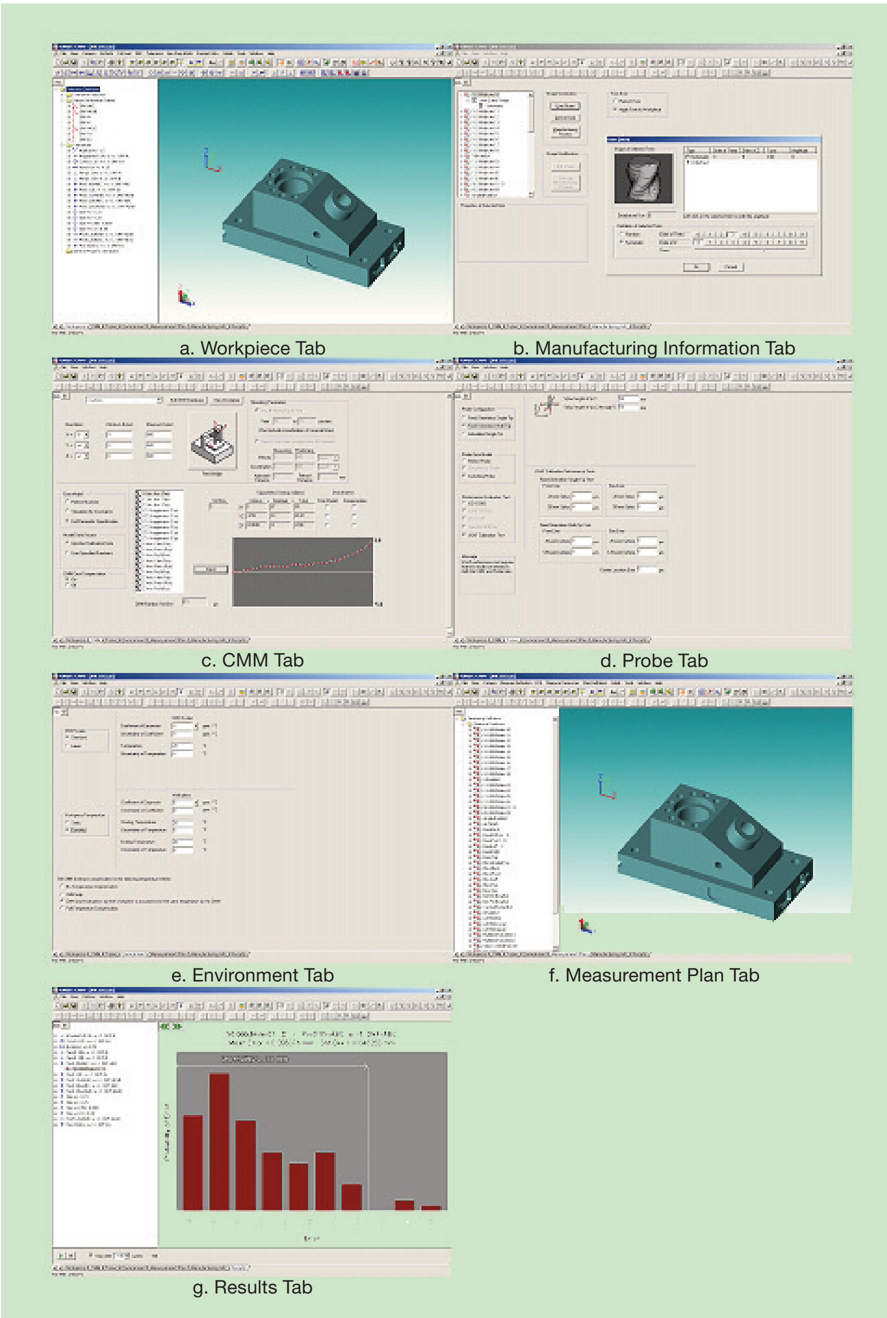


**Figure 6.** User interface illustrations.

much form error contributes to the total uncertainty. Similar capabilities will be seen for other influence quantities.

c. *The CMM Tab.* Here, the CMM model is defined. The CMM design (e.g. bridge, cantilever, etc.) and axis stacking are designated, along with the working volume and home location. A CMM performance model is chosen. Currently available are perfect machine, B89 model, full parametric model, the ISO 10360 model and an extended version of the latter, currently under consideration for ISO adoption. A database of CMM performance parameters is provided and initially is populated with selected manufacturer-published information. The database can be updated to include new machines and user-determined performance parameters for specific CMMs. There is also a dialog for entering measuring velocities, accelerations, etc. These are required when the transient thermal model is invoked, as will be described in a following section.

d. *The Probe Tab.* PUNDIT/CMM currently accommodates contact probes. There are models for switching and piezo probes, as well as a perfect probe option. Allowed probe configurations are fixed single tip, fixed multitip, and articulated single tip. The probe performance test is also chosen here, the options being the ASME B89.4.1, ISO 10360, and VDI/VDE [22] tests as well as an extended version of the ISO tests.

e. *The Environment Tab.* Thermal effects are almost always the predominant environmental source of error in CMM measurements. Two basic thermal models are supported: a static model where temperature is constant throughout the measurement and one which allows the workpiece temperature to change in the course of the measurement. Within each of these models, a selection is available that allows for several levels of temperature compensation: none, compensation for CMM temperature only, compensation for CMM and workpiece temperature where both are assumed to be at the same temperature, and full compensation when part and CMM may be at different temperatures. In recognition of the fact that some highly accurate CMMs employ laser interferometry to determine CMM position, environmental effects on interferometric scales can be modeled, as well.

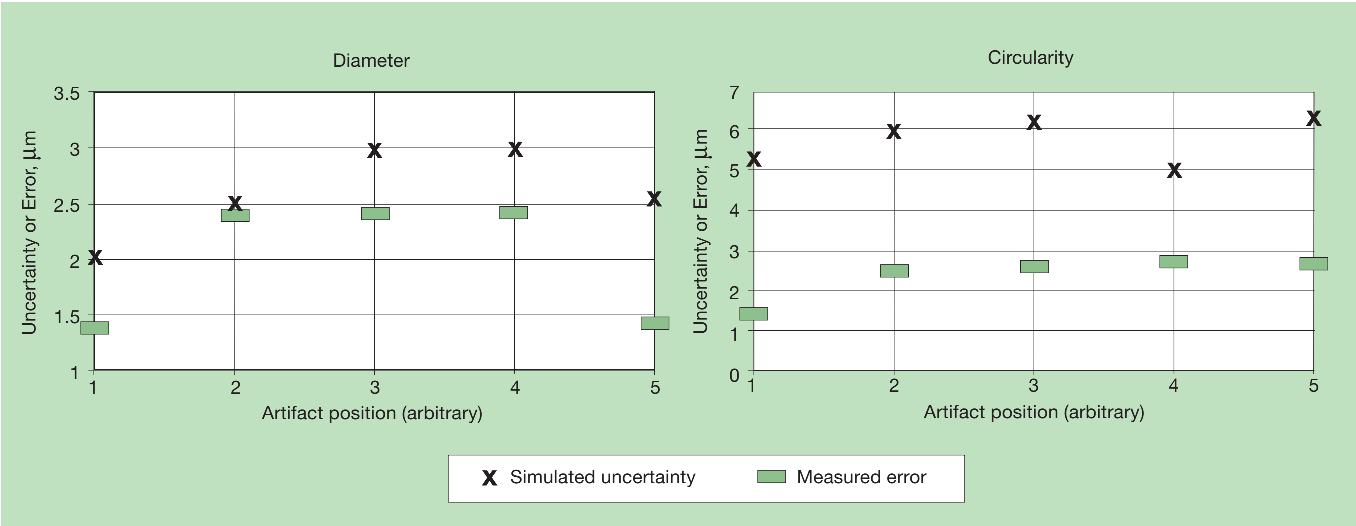


**Figure 7.** Comparison of simulated uncertainty and measurement error.

f. *The Measurement Plan Tab.* In this tab, the numbers and distributions of measurement points, the order of measurement, the position of the workpiece in the CMM measurement volume, the fitting algorithm and the probe selection are specified. Point placement on a feature can be specified in a variety of ways: points can be placed manually, a variety of regular patterns can be applied by automated routines, and optimized patterns [21] designed to give the best results in the face of feature form errors can be imported as can point patterns from existing DMIS measurement programs. Edge offsets can be specified for the automated pattern routines, and points falling into voids on the model are automatically rejected. If needed, DMIS code for measurement of each feature can be produced here.
g. *The Results Tab.* Here, the uncertainty evaluation analysis is conducted and the results displayed. Along the left side of the window is a tree that lists the tolerances that have been applied and the features to which they belong. To the right is a pane which will display a histogram of the errors for whatever feature/tolerance combination is chosen on the left. Along the bottom are controls for selecting the number of simulations to be run, and displaying the progress of the run. For a part of moderate complexity, a series of a few hundred simulations can be run in 60 seconds or so. All of the feature/tolerance pairs are analyzed in each simulation run, so all the results are immediately viewable by selecting the appropriate combination from the tree. A text output of the analysis and "screen grabs" of the histograms are also available.

## 9. Applications and Case Studies

Presented here are some simple but useful application case studies produced with the uncertainty evaluation system.

### 9.1 Validation of the Method

Simulation software for evaluating CMM task-specific measurement uncertainty is complex and comprehensive testing for validation is similarly so. Validation methodologies have been the subject of recent research [23] and have begun to be codified. [24] Considered here are some examples of these methods as applied to PUNDT/CMM.

#### 9.1.1 Physical Measurements

The effectiveness of uncertainty evaluation software can be gauged by showing that for calibrated parts, the observed measurement errors are reasonably bounded by the computed uncertainties. A study of this sort, using PUNDIT/CMM, was conducted by metrologists at the National Institute of Standards and Technology and at the Oak Ridge Metrology Center, using various artifacts and CMMs. [23] A typical example from that study is presented here. A calibrated 300-mm diameter disk was positioned in a variety of locations and orientations in the measuring volume of a high accuracy CMM and, using a fixed sampling pattern, measured for diameter and circularity thus providing a set of known measurement errors. The B89.4.1 performance test suite and ISO probe tests were also conducted on this same CMM and used to define the CMM performance to PUNDIT/CMM. Some of the results are presented in Fig. 7. The errors at all positions and locations are bounded by the uncertainties predicted by the software. It is not surprising that the uncertainties provide somewhat loose bounds, considering that the CMM performance was specified by only the six B89 parameters. Better information on the CMM, e.g. a full parametric specification of the rigid body errors, would be expected to yield a tighter bounding, as can be illustrated using virtual calibrated artifacts. An example is presented in Figs. 8 and 9. Figure 8 shows the part and the set of five representative GD&T parameters used for comparison. Figure 9 compares the full parametric specification results (FPS) to the corresponding values deduced from only (B89) performance test data. The calculations here were based on deactivating all error sources other than the CMM itself. The simulation results based on B89 performance testing bound those based on the full parametric specification by the same order as they bound the actual measurement results in Fig. 7.

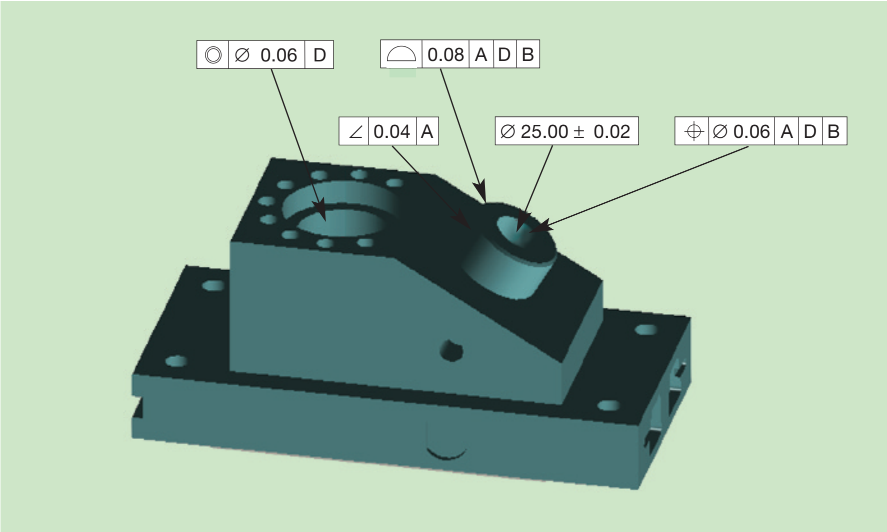


**Figure 8.** Workpiece and tolerances used in case study discussed in Section 9.1.1.

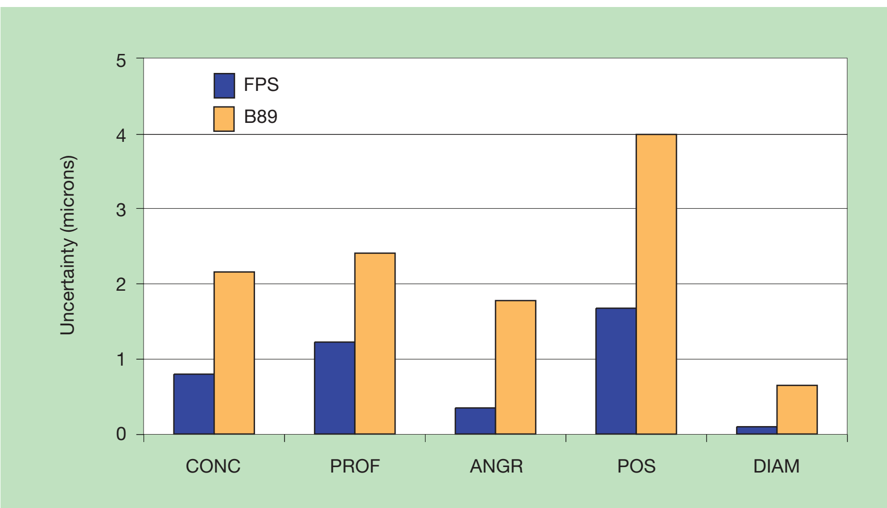


**Figure 9.** Relative estimated uncertainties for FPS and B89 CMM models.

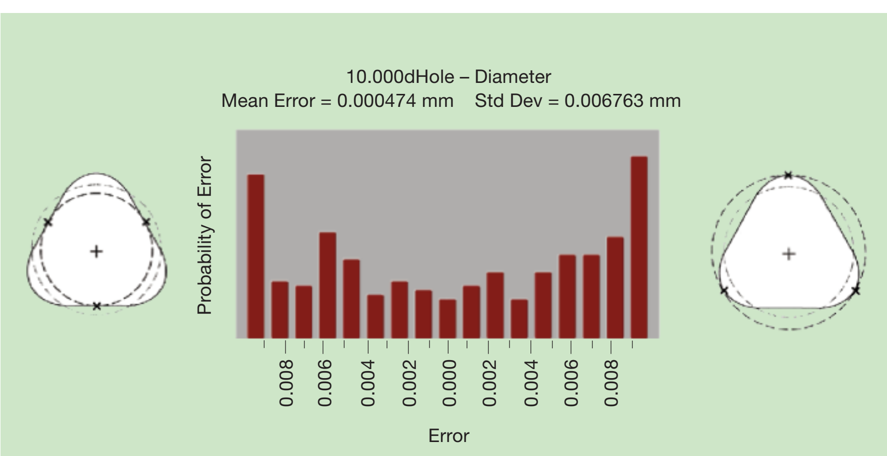


**Figure 10.** Distribution of diameter errors for cylinder with three lobes, sampled at three equiangular positions at each of three levels.

### 9.1.2 Reference Values and Component Testing

A reference value is a special case result that has a known value, which can be tested for in simulation. PUNDIT/CMM incorporates two features that allow component testing for reference values within the integrated software environment. The first of these is the fact that a model of the geometrically-perfect workpiece of interest is available. This means that, in effect, the software can be tested using a nearly infinite set of virtual calibrated parts. The second feature is the ability to temporarily deactivate entire classes of influence quantity. This allows a focus on particular contributors to uncertainty, where it is relatively easy to develop test cases and to verify that computed results are compatible with anticipations. Described here are just two examples, one nearly trivial and the other somewhat more complicated, both involving use of reference values.

In the first instance a 500-mm step gage part was measured by simulation under conditions where all error sources other than thermal ones were turned off. The step gage was stipulated to have a coefficient of thermal expansion of precisely 10 ppm/ºC and a temperature of exactly 21 ºC. The simulations showed systematic length errors of 1 µm at 100 mm, 2 µm at 200 mm, etc., just as anticipated.

As a second example of focus on specific error sources, consider a 10 mm inside diameter cylinder sampled at three equiangular points at each of three levels along its length (the points at each level eclipse those of other levels when the cylinder is viewed end-on). The cylinder surface was specified to have a 3-lobe (sinusoidal) form error (i.e., cylindricity) of peak-to-peak amplitude 10µm. The CMM, probe and thermal conditions are set to "perfect." PUNDIT/CMM then predicts a cylindricity bias (mean error in measurement) of the (negative) full amplitude (– 10 µm) and no variability around this. To see why this is so, note that in simulation, the phasing of the form error to that of the sampling pattern is randomized on each cycle. But because the form error here is entirely systematic, and the number of sample

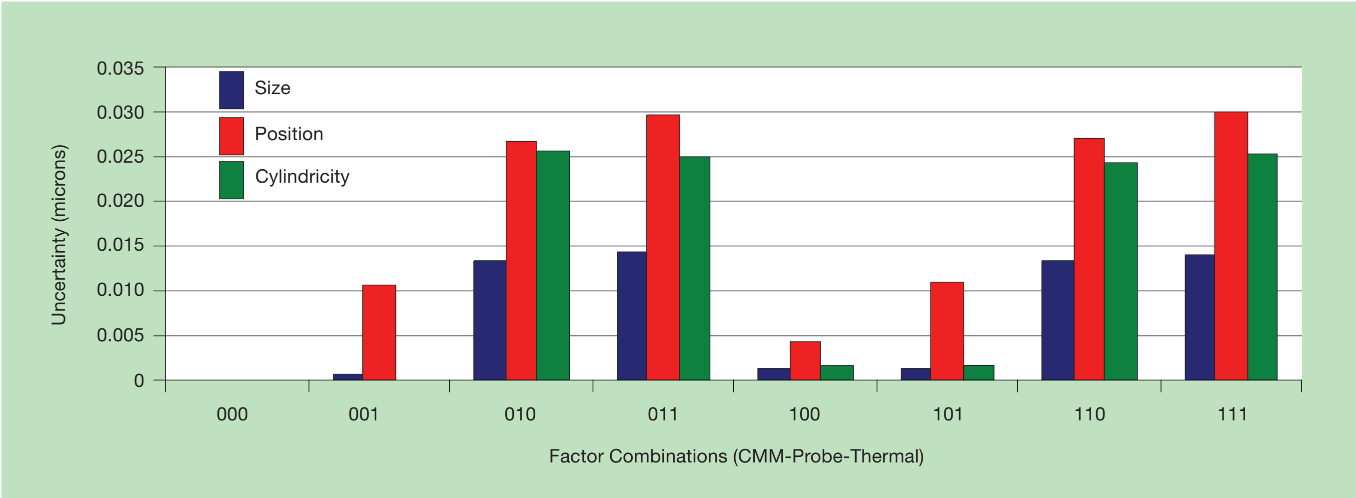


**Figure 11.** Contributions of several influence variables to overall uncertainty.

points at each level is equal to the number of lobes, the cylindricity obtained in the simulated measurements is *always zero* regardless of the phasing. Thus on each cycle, the bias [= (measured cylindricity) – (true cylindricity)] is the full – 10µm. Whatever the phasing of the lobing to the points, the measured cylinder *center* location should remain fixed and PUNDIT/CMM predicts zero bias and zero variability in measured position. Finally, the measured cylinder radius can be expected to range above and below its nominal value by half of the cylindricity, depending upon the phasing of the lobing to the sampling. The measured *diameter* would thus range over the full cylindricity (10 µm). Furthermore, the distribution of the diameters can be expected to be quite non-Gaussian, since the sinusoidal lobing form error yields a notably higher sampling rate at its extrema than at intermediate values. This is just what PUNDIT/CMM shows in its error histogram (Fig. 10). Several of the examples that follow may be considered as instances of validation by component testing, as well as demonstrations of the importance of specific error sources.

### 9.2 Relative Importance of Error Sources

This example illustrates the relative contributions of several error sources to overall uncertainty. The effects of CMM geometry errors, probe errors and thermal nonidealities were considered. The CMM linear accuracies were 3.0 µm, 2.1 µm and 2.5 µm for the x, y and z axes, respectively. The volumetric performance was 7.2 µm. Offset volumetric performance was 7.1 µm/m and the repeatability was 1 µm. The piezoelectric probe was modeled with a random error ($\sigma$) of 5 µm. The CMM scales were considered to be temperature insensitive; the workpiece was aluminum, temperature compensated with an expansion coefficient of 22 ± 2 ppm/°C and a temperature of 25 ± 3 °C. There was no form error added to either the measured cylindrical feature nor to the datum features, and the datum features were assumed to be perfectly measured. These last points are important since, generally, errors in the datum features will propagate into the uncertainty of the position and orientation of the feature under consideration.

The computed uncertainty is shown separately in Fig. 11 for size, location and form, and for every possible combination of error sources. The notation "101" signifies, for example, that CMM and thermal errors were considered in that particular experiment, but not probe error. In each case 300 simulated inspections were performed. While the interrelationships of the error sources were not treated explicitly, their relative independence can be seen from the fact that the uncertainty values from treatment of two error sources at once are approximately equal to the root-sum-of-squares of the uncertainties from the error sources treated singly.

### 9.3 Form Error/Sampling Pattern Interactions

This example illustrates the interaction between feature form errors and sampling strategy. Again, the measurement of a cylindrical hole has been simulated, but it is now assumed that the part is measured with a perfect CMM and probe and that there are no thermal effects. A three lobe form error of 0.4 µm amplitude was assumed in one experiment and a combination of three lobe error and random error, each of 0.2 µm maximum amplitude was used in another. The sampling patterns all used even numbers of points arranged at two levels near the ends of the cylinder and evenly spaced at each level. The "eclipsed" patterns (labeled "E" in Fig. 12) have the points at each level placed at the same angular positions while in the "staggered" patterns (labeled "S") the point positions on one level are rotated by half the angular spacing relative to the other level. Notice the oscillatory behavior with maxima when the number of points at each level is an integer multiple of the lobing frequency. The staggered pattern helps to damp the effect but even then it persists to fairly large numbers of sampled points and can be seen even in the "mixed" cases where the random error is as large as the systematic.

### 9.4 Effect of Errors in Datum Measurement

It is generally understood that errors in the measurement of datum surfaces will be reflected in measurements made relative to those datums. CMM users may appreciate less well the magnitude of the effect. This example provides a simple illustration. The workpiece is a rectangular block; the feature of interest is a cylindrical hole centrally located in one face of the block. The

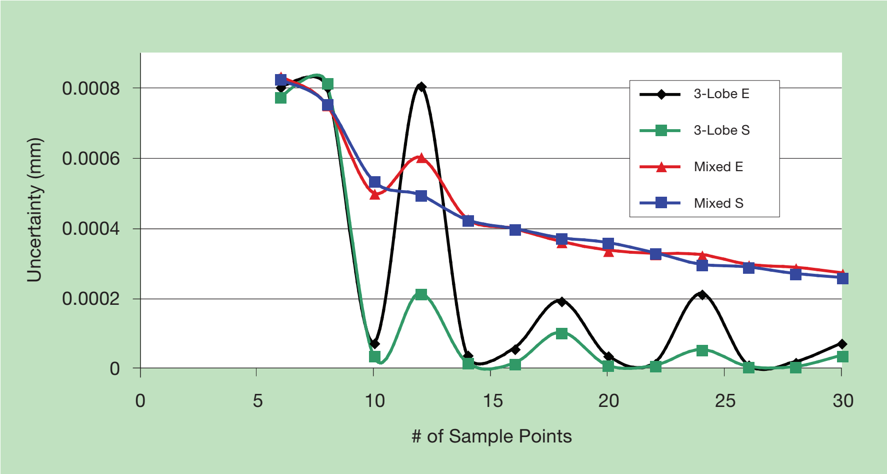


**Figure 12.** Interaction of sampling strategy with feature form.

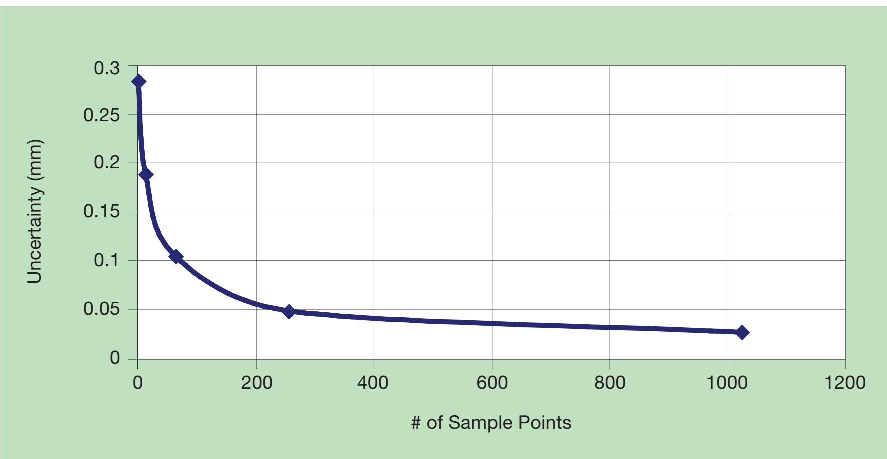


**Figure 13.** Effect of datum form error on probe point density required to achieve a specified positional uncertainty for a dependant feature.

hole is toleranced positionally relative to three planar datum surfaces, each of which is considered to have been manufactured with 100 µm of random form error. All else about the measurement is considered perfect. Figure 13 shows the relation of positional uncertainty of the hole as a function of sampling density of the datum surfaces. Suppose, for example, that the hole is assigned a positional tolerance of 0.5 mm. Remembering that in a real measurement there will be other sources of error, it might be considered wise to keep the error from this particular source to 10 % or less of the tolerance. This requires a minimum of about 250 probing points per datum surface.

## 10. Conclusions

The design of a comprehensive system for evaluating the task-specific uncertainty of measurements made with CMMs has been described, and examples of its application have been shown. With replacement of some of the CMM-specific models, it could be adapted to other 3D metrology systems, for example, articulated arm CMMs and laser theodolites. The software has been shown to be robust and versatile. It can be of use both to auditors and measurement professionals when demonstrated traceability of CMM results is required. Measurement practitioners will also find the system of value in identifying and reducing the sources of uncertainty in their measurements, resulting in economic benefit. The software also can be beneficial in a variety of subsidiary functions, including:

a. Verifying that tolerance applications are complete, consistent and unambiguous;
b. Making the right choice when purchasing a CMM;
c. Finding and fixing the "weak link" in a CMM system;
d. Choosing the best CMM for a specific job; and
e. Training users in proper CMM measuring procedures.

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