Application of Simulation Software to Coordinate Measurement Uncertainty Evaluation

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

www.metrosage.com
Overview

- Introduction
- Influence Quantities on CMM Measurements
- Methods to Estimate Measurement Uncertainty
- The Simulation Method
- PUNDIT/CMM
  - Architecture
  - Walk Through
  - Applications
Task-Specific Uncertainty

- Specific to a particular measurand.
- Specific to a particular level of confidence.
- Sample Statement: “The uncertainty of the diameter of this nominally 3-inch diameter hole, measured under these specific conditions is ±0.0008 inches at 95% confidence.”
Traceability

“The property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.”

-ISO VIM 6.10 (emphasis added)
ISO 14253-1 Conformance

$U = \text{“Expanded Uncertainty”}$
The good news about CMMs: They are extremely versatile.

The bad news about CMMs: They are extremely versatile.

- Many different measurands
- Almost unlimited measurement conditions:
  - Workpiece location/orientation
  - Probe/stylus type & configuration
  - Environment
  - Sampling Strategy
CMM Measurement Influence Quantities

- CMM Errors
- Environmental Factors
- Probe System Errors
- Feature Form Errors
- Sampling Patterns
- Task-Specific Measurement Uncertainty
- Fitting Algorithms

\[ P = a^T \left( \sum w_{ij} \frac{\partial F}{\partial r} \left( \frac{\partial F}{\partial r} \right)^T + \sum w_{ij} \nabla^2 F \nabla^2 F^T \right) a \]
Methods to Estimate Measurement Uncertainty (ISO 15530 draft)

**Sensitivity Analysis** – Listing each uncertainty source, its magnitude, effect on the measurement result, correlation with other uncertainty sources, and combining appropriately. ("Uncertainty Budgeting")

\[
u_c^2 = \sum_{i=1}^{N} \left( \frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j)\]
Methods to Estimate Measurement Uncertainty (ISO 15530 draft)

**Expert Judgment** - may be the only possible method if a mathematical model or measurement data are not available. Its limitations in producing a defensible uncertainty value are evident.

**Substitution** – repeated measurement of a calibrated master part 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.
Methods to Estimate Measurement Uncertainty (ISO 15530 draft)

**Simulation** – Modeling and simulating the measurement process including the errors; examining the task-specific results yields estimates of both bias and measurement variability and hence uncertainty.

**Measurement History** – Large numbers of measurements over time can place an *upper bound* on measurement uncertainty. (This uncertainty includes both production & measurement variability, but ignores any measurement bias.)
## Uncertainty Method Scorecard for 3-Dimensional Metrology

<table>
<thead>
<tr>
<th>Method</th>
<th>Tractable</th>
<th>Comprehensive</th>
<th>Detector Mode Bias</th>
<th>Detector Mode Variability</th>
<th>Versatile</th>
<th>Predictive</th>
<th>Economical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity Analysis</td>
<td>?????</td>
<td>?????</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expert Judgment</td>
<td></td>
<td>?????</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>?????</td>
</tr>
<tr>
<td>Substitution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Computer Simulation</td>
<td></td>
<td>?????</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurement History</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>?????</td>
</tr>
</tbody>
</table>
Simulation Method

“The benefit of computer simulation is derived from repeated simulations of different measurement scenarios, where each scenario involves a specific set of measurement errors (as opposed to uncertainties). The use of specific measurement errors, together with the mathematical model, often allows a more complete description of the interactions, i.e. correlations, between sources than attempting to calculate sensitivity coefficients. (In some cases sensitivity coefficients are impossible to calculate analytically since the measurement process cannot be analytically described).” -ISO 15530
Discrete Point Coordinate Errors
PUNDIT/CMM Architecture

- 3D Geometric Modeler
  - Features
  - Tolerancing
  - 3D Geometric Modeler
    - Datum Reference
    - Frames
  - Simulation Engine
  - Analysis Algorithms
  - Results
  - Environmental Factors
  - Sampling Patterns
  - Mfg. Errors
  - CMM Model
  - Probe Model
  - 3D Geometric Modeler™
  - Features Tolerancing
  - Datum Reference Frames

MetroSage™
A Walk Through PUNDIT/CMM

- Workpiece Definition
- Manufacturing Parameters
- CMM Definition
- Sensor Definition
- Environmental Effects
- Measurement Plan
- Analysis and Results
Workpiece Definition

- ACIS import
- STEP import or create on line
- Define DRFs
- Define tolerances
- Verify tolerancing
Verifying Tolerancing
Manufacturing Parameters

Apply/ edit form

Errors:
- User Query
- Dense Data
- Manufacturing Process
CMM Definition

Choose CMM type:
- Geometry
- Working volume
- Operating parameters

Choose error model:
- Perfect CMM
- B89 test results
- Full parametric
Sensor Definition

Probe system:
- Fixed single tip
- Fixed multi-tip
- Articulated single tip

Error model:
- Perfect probe
- Piezoelectric
- Switching

Performance Test:
- ISO 10360
- ASME B89.4.1
- VDI/VDE
- User specified
Environmental Effects

- Current support or uniform, fixed, nonstandard temp. OR
- Uniform, time-varying, non-standard temp.
- Different temp. for machine & part
- Requires $C_T$, $\Delta C_T$, $T$, $\Delta T$, (& timing)
- Apply probing points to features
  - Manual selection
  - Automated regular patterns
  - “Optimized” patterns
- Regular patterns can be uniform or staggered, rows & columns or by point density
- Edge offsets can be specified
- Points falling into voids are discarded
Analysis and Results

- Choose number of simulations to run.
- For each tolerated characteristic, a histogram of results is produced.
- Range of results yields estimated uncertainty.
- Summary report generated.
Validating the Methods

• Physical Measurements
  
  Calibrated Artifacts Measured, Measurement Errors Noted & Compared with Uncertainties from Simulations.

• Reference Values
  
  Simulation of Simple Cases & Comparison with Anticipated Results
Uncertainties Bound Measurement Errors

<table>
<thead>
<tr>
<th>CMM &amp; Probe Performance</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>X linear accuracy (B89.4.1)</td>
<td>1.2 µm</td>
</tr>
<tr>
<td>Y linear accuracy (B89.4.1)</td>
<td>1.4 µm</td>
</tr>
<tr>
<td>Z linear accuracy (B89.4.1)</td>
<td>2.2 µm</td>
</tr>
<tr>
<td>Volumetric performance (B89.4.1)</td>
<td>3.9 µm</td>
</tr>
<tr>
<td>Offset probe performance (B89.4.1)</td>
<td>6.7 µm/m</td>
</tr>
<tr>
<td>Repeatability (B89.4.1)</td>
<td>0.34 µm</td>
</tr>
<tr>
<td>Probe ISO 10360-2 (25 points), 3 styli</td>
<td>0.82, 1.68, 1.82 µm</td>
</tr>
</tbody>
</table>
FOCUS on CMM ERRORS

Ball Step Gauge
25.4 mm Spheres
Step Length 100 mm

<table>
<thead>
<tr>
<th>ASME B89.4.1 CMM Performance Test</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Linear Accuracy</td>
<td>5.5 µm</td>
</tr>
<tr>
<td>Y Linear Accuracy</td>
<td>6.5 µm</td>
</tr>
<tr>
<td>Z Linear Accuracy</td>
<td>3.0 µm</td>
</tr>
<tr>
<td>Volumetric Performance</td>
<td>13.5 µm</td>
</tr>
<tr>
<td>Offset Volumetric Performance</td>
<td>50.0 µm/m</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.8 µm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sphere #</th>
<th>Z Location</th>
<th>XY Position</th>
<th>Sphericity</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.4</td>
<td>22.7</td>
<td>5.0</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>8.4</td>
<td>18.8</td>
<td>4.9</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>6.4</td>
<td>15.0</td>
<td>4.7</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>5.0</td>
<td>11.6</td>
<td>4.7</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>4.5</td>
<td>9.2</td>
<td>4.8</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>2.2</td>
<td>5.6</td>
<td>4.8</td>
<td>2.5</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>5.1</td>
<td>2.9</td>
</tr>
</tbody>
</table>
FORM ERRORS & SAMPLING

3-Lobe Radial Error of 10 \( \mu m \) Peak-to-Peak Amplitude
3 Equiangular Points about Circumference
100 Simulation Cycles

10.000dHole - Diameter
Mean Error = 0.000474 mm  Std Dev = 0.006763 mm
FORM ERRORS & SAMPLING

3-Lobe Radial Error of 10 µm Peak-to-Peak Amplitude
3 Equiangular Points about Circumference
100 Simulation Cycles
“What if … ?” Scenarios

When a simulation system is found to do a good job of representing actual physical conditions over a wide range of circumstances, it seems reasonable to expect that the simulation system can be used to carry out experiments which would be difficult, expense, or even impossible to conduct in the actual physical system.
FINDING the "WEAK LINK"
Cylindrical Hole in Rectangular Block
CMM, Probe & Thermal Conditions Modeled
Oscillating Uncertainties

Cylindricity: 2-Level Sampling Patterns with Pts Eclipsed (E) or Staggered (S)

Graph showing uncertainty vs. number of sample points for different sampling patterns.
PUNDIT/CMM helps you to:

- Meet New Measurement Traceability Requirements
- Show Product Conformance to Specifications
- Verify that Part Tolerancing is Complete, Consistent and Unambiguous
- Make the Right Choice when Purchasing a New CMM
- Find and Fix the “Weak Link” in your CMM System
- Use the Right CMM for a Specific Job
- Train Employees in Proper Measurement Procedures