3-Dimensional Shop Floor Measurements To Improve Yield

Dr. Erik Novak
Good Metrology Saves Significant Money

- According to Quality Digest, poor quality control costs an average of $2M/year over the 100 companies they surveyed.

- NIST performed 16 economic studies since 2000, showing average benefit of metrology investment is 47:1
Consequences of Poor Quality Control Are Severe

Internal Failure Costs
- Waste
- Scrap
- Rework
- Additional failure analysis
- Reinspecton
- Downgrading
- Shortages

External Failure Costs
- Repair and service
- Warranty claims
- Complaints
- Returns
- Travel and Return time
- Throughput
- Downtime
- Post-warranty costs
- Dissatisfaction
- Customer perception
The Modern Take on ‘An Ounce of Prevention…’
Effects on Measurement Capability Are Interrelated
Micro-Scale Defects Are Critical To Understand

• Performance
  – Pitting/porosity, scratches, affect efficiency
  – Nicks and dents can cause leaks
  – Burrs can cause damage to other parts

• Longevity
  – Defects can lead to excessive wear
  – Imperfections can initiate corrosion
  – Structural integrity is compromised by voids

• Perception
  – The human eye is excellent at seeing small flaws
  – The human eye is terrible at estimating their size
  – Customers will reject parts they suspect
Metrology Tradeoffs Must Be Balanced

- **Major Goals:**
  - Quantify anything an operator can readily see
  - Quantify anything a scribe gauge or ‘calibrated fingernail’ can feel
  - Meet current and next-gen part spec drawings
  - Instant results
  - Future Proof – Automation Capability, Customizable, Cloud-enabled…
Traditional Shop-Floor Inspection Methods Are Insufficient

Visual / Finger Test
- Operator dependent
- Non-gage capable

Replication combined with surface profiler
- High material costs
- 30+ mins/measurement
- Operator and material dependent

***When in doubt – reject or rework… Expensive!!!
Test: Which Pit Is Deepest?
Test: Which Pit Is Deepest?

- 25 um (.001”)
- 80 um (.0032”)
- 150 um (.006”)
- < 5 um (<.0002”)
- 20 um (.0008”)
- 150 um (.006”)

10/2/2018 10
Most Portable Tools Are 2D and Lack Resolution

Laser Scanners and Stereosopes
- Limited lateral resolution >2mil (50um)
- Non-gage capable for micro-defects <10mils
- Single line doesn’t capture full defect (i.e. deepest point)
- Sensitive to material finish, reflectivity and slope

2D Stylus Profilers
- Limited vertical range
- Give PV value only
- Can’t measure edges, corners across steps

***Portable and convenient but not capable of measuring micro-defects
Pit Measurement Using 2D Trace Varies

.0030”
(76 um)
Pit Measurement Using 2D Trace Varies

0.0025”
(63 um)
Pit Measurement Using 2D Trace Varies

.0022”
(56 um)
Automated 3D Results Eliminate Uncertainty

0.0028” (71 um)

<table>
<thead>
<tr>
<th>Color</th>
<th>Max Height (in)</th>
<th>% Weighted Height (in)</th>
<th>Area (mi²)</th>
<th>Area [%]</th>
<th>Volume (mi³)</th>
<th>Feature Width (in)</th>
<th>Feature Length (in)</th>
<th>Lateral Aspect Ratio</th>
<th>Depth Aspect Ratio</th>
<th>Location</th>
<th>Distance To Closest Feature (in)</th>
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<tr>
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<td>-0.0028</td>
<td>-0.0027</td>
<td>92</td>
<td>0.83%</td>
<td>-150</td>
<td>0.010</td>
<td>0.014</td>
<td>2.1:1</td>
<td>4.0:1</td>
<td>(0.035,0.064)</td>
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</table>

Total (1) -- -- 92 0.83% -150 -- -- -- --
Maximum -0.0028 -0.0027 92 0.83% -150 0.010 0.014 -- --
Average -- -- -- 0.00% -- -- -- -- --
Large Defects Are Even Harder To Assess

.0023”
(58 um)
Large Defects Are Even Harder To Assess

.0009”
(23 um)
Large Defects Are Even Harder To Assess

.0017”
(43 um)
Large Defects Are Even Harder To Assess

.0013”
(33 um)
Analysis of Entire Defect Eliminates Uncertainty

0.0029” (74 um)
**3D Lab-Based Metrology Is Impractical**

3D Optical Profilers
- $75-200K
- Limited to small parts
- Requires dedicated, trained operator
- Slow feedback due to measurement turnaround time

3D Stylus Profilers
- $25-150K
- Limited to small parts
- Limited to single trace – can’t measure full feature
- Measurements take several minutes
- Slow feedback due to measurement turnaround time

***Lab-based metrology provides adequate resolution but is not practical for shop-floor inspection***
What Are Critical Criteria For Success?

- Easy To Use
- Non-Destructive
- Sufficient Resolution
- Sufficient Range
- Field of View
- Correlation
  - Between Units
  - With other techniques
- Robustness
- Extensible
3D Shop Floor Measurements Provide Instant Feature Analysis
Interferometry/Structured Light/Fringe Projection: Scalable Surface Metrology

Resolution depends primarily on the wavelength of fringes

Laser Interferometry: Optic Shape
White Light Interferometry: Micro-Roughness
Fringe Projection: Large Irregular Shape

Optical Coherence Tomography: Retina
Phase Contrast Microscopy (DIC): Spyrogyra Cell
Polarization Combined With Structured Light Allows Fast 3D Measurements

Array of color filters matched to detector
- Uses 4 pixels to reconstruct color
- Color image in one frame
- Slight loss in lateral resolution

Array of micro-polarizers matched to detector
- Uses 4 pixels to reconstruct phase
- 3D image in one frame
- Slight loss in lateral resolution

US Patent 7,230,719
Polarized Structured Light (PSL) Enables Precision Hand-Held Metrology

- Structured light uses the bending of projected lines to compute 3D shape
- Generally requires multiple patterns, colors, or angles so is not vibration-immune
- High-resolution difficult to achieve, especially on metal surfaces
- Polarization enables both single-frame and high-resolution measurements
# 4D InSpec Designed Specifically for Shop Floor Metrology

<table>
<thead>
<tr>
<th>Specification</th>
<th>4D InSpec</th>
<th>4D InSpec XL</th>
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<tbody>
<tr>
<td>Vertical Resolution</td>
<td>2.5 um (0.0001”)</td>
<td>2.5 um (0.0001”)</td>
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<tr>
<td>Depth Range</td>
<td>2.5mm (0.1000”)</td>
<td>9mm (0.35”)</td>
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<td>Standoff distance</td>
<td>35mm (1.3”)</td>
<td>60mm (2.3”)</td>
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<td>Field of View</td>
<td>8 x 8mm (0.3”x0.3”)</td>
<td>15x15mm (0.6”x0.6”)</td>
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<td>Lateral Sampling</td>
<td>3.5 um (0.00015”)</td>
<td>7.0 um (0.0003”)</td>
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<td>Meas+Analysis time</td>
<td>&lt;1sec</td>
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PSL Measures Many Materials and Finishes

- Carbon Fiber
- Composites
- Glass
- Plastics
- Cast Iron
- Metals
- Silicon
- Rubber
- Paper
- Textiles
- Semi-transparent/cloudy Surfaces

- Ultra-finish
- Matte
- Rough
- Flat
- Curved
- Corners

Ultra-finished Blades

Paint Layer Thickness

Spline Gear
PSL Provides High Repeatability

- Measured 0.00075” (19um) defect 30 times
- Results Shown Below
- Standard deviation = .00002” (0.5um)
Cross Platform Correlation Is Important

- Range of pit depths observed on field hardware (25-75 um, 0.001 to 0.003”) 
- Results are within $\pm 2.5$um (0.0001”) on average 
- FRT white light profilometer and 4D InSpec are statistically indistinguishable
3 System Correlation Data Shows Excellent Agreement

- Feature range from .0008 to .014” (20 um to 355 um)
- Offset <.00009” (2 um)
- Slope <1.2% different
- $R^2 > .996$

\[
\text{IS171104 vs. IS161201} = 1.0125x + 9E-05 \\
R^2 = 0.9961
\]

\[
\text{IS171104 vs. Demo} = 0.9986x - 6E-05 \\
R^2 = 0.9973
\]

\[
\text{IS161201 vs. Demo} = 0.9989x - 6E-05 \\
R^2 = 0.9975
\]
InSpec Vs. 3D Microscope Shows Excellent Correlation on Shot Peened Roughness

\[ y = 1.0048x + 0.5809 \]

\[ R^2 = 0.9978 \]
Reliability Can Matter as Much as Capability
Optics Allow Fold Mirror To Access Tight Spaces
Custom Fixturing Makes Specific Part Measurements Simple

Corner | Flat | Blade Edge | 45°
Key Shop Floor Measurement Applications

- **Part Types**
  - Turbine blades
  - Pipes
  - Shafts
  - Gears and transmissions
  - Solder joints and connectors
  - Rivets and fasteners
  - Solar panels
  - 3D printed metals and plastics

- **Types of Measurements**:
  - Porosity
  - Corrosion depth, volume, areal coverage
  - Rivet depth and planarity
  - Radius of curvature
  - Pit and scratch depth, area, aspect ratios, volume
  - Die peen, laser mark depth, uniformity, and planarity
  - Cooling hole geometry
Intuitive, Touchscreen Interface Provides Instant Results

Live Video

Results

Analyses
Rapid Return on Investment Possible With Appropriate Metrology

- **Reduced rework** rate by 30% on a critical engine component with ability to measure corrosion and wear
- **Reduced measurement time** of pitting on a large aerospace component from 3 days to 2 hours
- **Increased yield** by 20% at a new-make machine shop after quantifying visually ID’d defects as merely cosmetic
- **Reduced labor** by 1 week in service through elimination of disassembly/assembly prior to inspection of a critical component
Good Metrology Enables Integration and Customization

- Remote Interface option allows control of InSpec from 3rd party applications for easy of use with robotics and automated staging

- Full surface can be exported into XYZ point cloud for outside analysis, storage, or CAD integration

- Defect results stored in simple CSV format for interface with factory QC systems

- IronPython Scripting allows user-customized analyses
Applications: 3D Sintered Printing
Applications: 3D Polymer Printing: Layer Height, Periodic Errors

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10/2/2018
Applications: 3D Polymer Printing – Process Variations
Rivet Depth And Planarity

- Large depth of focus and field of view allows snapshot measurement of fasteners
- Quantify
  - Recession
  - Tilt
  - Uniformity

Measurement 48
Applications: Cooling Hole Geometries

benefit of large depth of focus

- Angle of hole is about 20 degrees with respect to surface
- Depth of hole is about 20 mils
- Geometry can be checked without bright-field uncertainties
Dot Peen, Laser Marking Depths Are Easily Quantified

- Structures too deep can lead to corrosion
- Markings too shallow can wear prematurely and cause loss of serialization
- InSpec quantifies each individual feature automatically
Applications: Defects on Radiused Surfaces

- User defined size thresholds for identifying features of interest
- Finds all defects that meet criteria
- Reports depth, volume, area, slope, location and more

*** Auto Feature Analysis removes all uncertainty
Applications: Scratch Severity

• No need to guess at maximum depth

• InSpec calculates 2 point maximum depth and weighted depth (average of user set % of deepest points)
Applications: Corrosion Tracking
Applications: Robotic Inspection

- Vibration immunity allows measurement without isolation
- Defects automatically reported as they are found
- 100% Inspection possible
Shop Floor 3D Measurements Saves Money

- Measure components prior to disassembly
- Avoid delays from using metrology lab
- Halt reliance on human’s ‘calibrated fingernail’ or ‘calibrated eye’
- Eliminate errors from replicast/cross sectioning
- Measure at any angle
- Measure without line of sight
- Accurate, repeatable results
- **Improve Yields Dramatically!**
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Questions?

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