Towards Smart Machine Tools

A NIST Perspective of Research Opportunities

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NIST → Economic Growth

- NIST within U.S. Department of Commerce
- NIST promotes U.S. innovation by advancing measurement science, standards, and technology
- 6,100 Employees/Associates
- NIST partners with about 1,300 manufacturing specialists through 400 manufacturing extensions
Manufacturing = Economic Growth

- Manufacturing = 12.5M U.S. jobs & about 60% exports
- World machine tool consumption ↓4% in 2016, but U.S. machine tool spending ↑18% in 2016 (to $8.7B) over 2015

Modern Machine Shop, 2015 Capital Spending Survey & Forecast

U.S. Manufacturing Jobs Per Year

U.S. Bureau of Labor Statistics
Machine Tools are Vital for Production

• 100s of machine tools used in plants to mill precision parts
• 3+ axis motion
Problem = Unplanned Downtime

- Faults/failures → 10s of $Billions per year (> new machines!)
- Machine tool degradation causes performance changes and unplanned downtime

Machinery Lubrication (2004), Wear in Rolling Element Bearings and Gears

Reliabilityweb.com (2018), Lubrication FMEA: The Big Picture
Why Not Measure Health?

• Major manufacturers say routine tracking of performance is **too expensive**

• Accuracy a pro, but setup and operation time/cost a con
  
  • Offline
  • Lack of periodic data
  • Expensive

Laser $\rightarrow$ 1-2 days

Ballbar $\rightarrow$ 1 hour

Cap probes $\rightarrow$ hours

IBS Precision Engineering

Renishaw

API
GOAL: Smart Machine Tools

- **Industry challenge:** “Machine health in 5 min?”
- On-machine measurement science to diagnose performance and root-causes
  - **Offline** Online
  - Lack of periodic data Data-rich
  - Expensive Inexpensive

Linear Axis Health Tracking

[How?]

Spindle Health Tracking

[How?]
GOAL: **Smart Machine Tools**

- Make machine tools **self-aware** with diagnostics of performance & root causes
- Predict part errors based on health tracking & optimize asset management

**Machine #1**
- Axis 1
  - 15 µm range
  - Spalling detected
- Spindle
- Axis 2
  - 70 µrad range

**Optimum Machine: #5**
IMU for Linear Axis Monitoring

Data Fusion with Accelerometer (A) and Rate Gyroscope (RG) Data

Translational Motion

Angular Motion

IMU Data Collection

- Each run uses 3 different axis speeds
- IMU can live within machine tool for usage with no setup
NIST Linear Axis Testbed

- Testbed to study IMU-based method & diagnostics / root-cause analysis
NIST Linear Axis Testbed

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Metric vs. degradation stage

- IMU
- REF
Root-Cause Analysis for Rail Wear

• Find root cause of changing error motions
• 4 possible physical causes: inner/outer raceway damage on Rail 1 or 2
• Root-cause analysis correctly identified spalling on inner raceway of Rail 1
IMU for Linear Axis Health Tracking

- Research Opportunities to use IMU for Comprehensive Root-Cause Analysis

- Error Motion Metrics vs. Time
- Error Motion Changes
  - Locations and Magnitudes of Degradation
- Root-Cause Analysis
  - Sources of Error → Trucks, Rails, Lead Screw, Ball Nut, and/or Controlled Motor
GOAL: Smart Machine Tools

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Linear Axis Health Tracking

[How?] IMU

Spindle Health Tracking

[How?] TBD

Squareness Health Tracking

[How?] IMU
Lesson #1 – Smart & Metrological

• Traceable – Data is traceable to NIST
  • Sensors calibrated along “measurement chain” to NIST

• Dimensional – Results are physical quantities
  • Inspired by international machining standards
  • Tracking Δ error motion > 2 μm and > 6 μrad
  • Physical quantities can be measured

• Verify and validate – If possible!
  • Compare results to those from traceable independent reference
  • Even complicated diagnostics can be shown to be correct
Lesson #2 – Smart & Simple

• Simple analytics
  • Can be explained and standardized
  • More robust because tested more easily
  • Easier to implement for great adoption
  • Goal- or physics-based thresholds

• Simple user setup
  • Plug and play solutions
  • Vendor neutral for flexibility
Lesson #3 – Future Directions

• Make smart machine tools with online, data-rich, and inexpensive diagnostics & prognostics of performance & root causes of faults/failures

• Predict part errors based on health tracking & optimize asset management

• Manufacturers also need...

MTConnect/Industry 4.0 – networked factories, to enable actionable intelligence about system interactions/relationships

“Close-the-Loop” Solutions – from process to part using subsystem performance at each level (machine tools & robots ↔ final part inspection)
Prognostics, Health Management, and Control

www.nist.gov/el/isd/ks/phmc.cfm