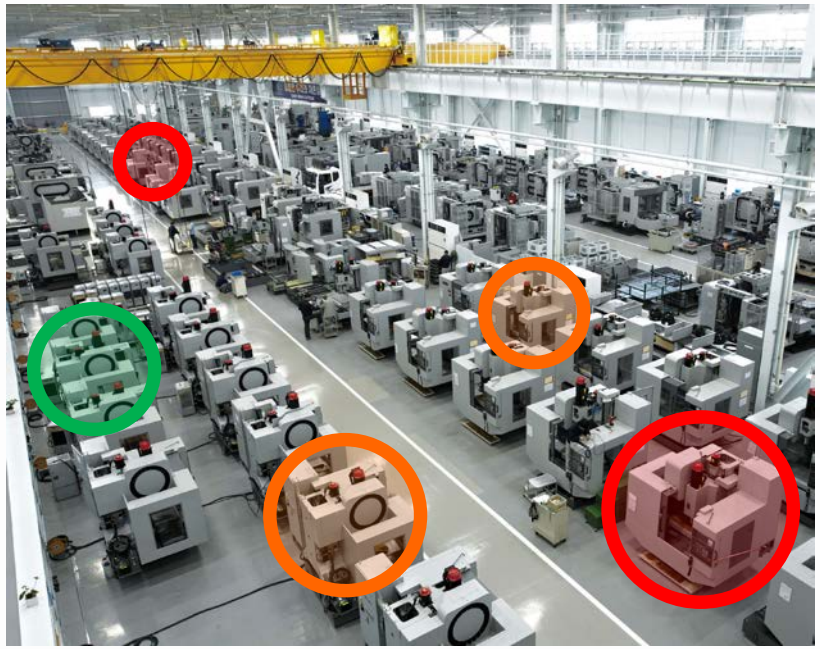
Emerging Sensing Technologies Towards Smart Machine Tools



Greg Vogl

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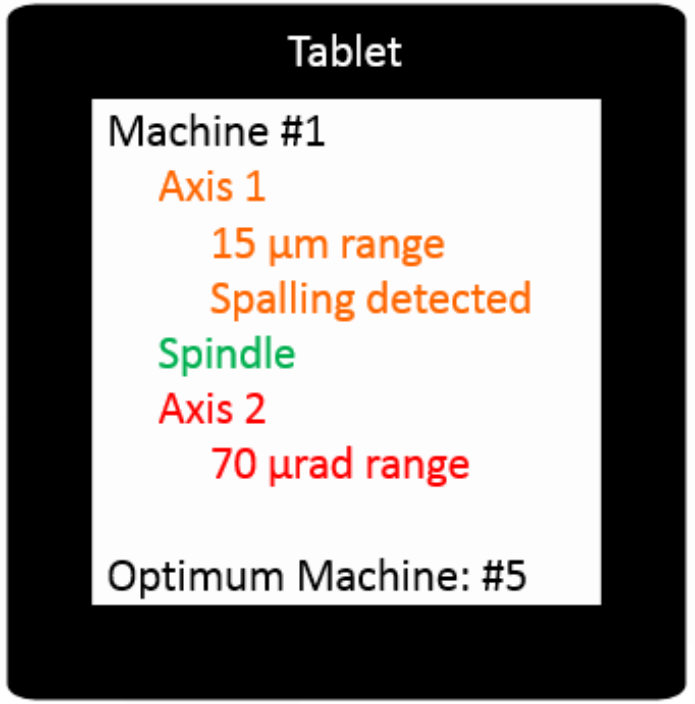
Standards and Technology
(NIST)

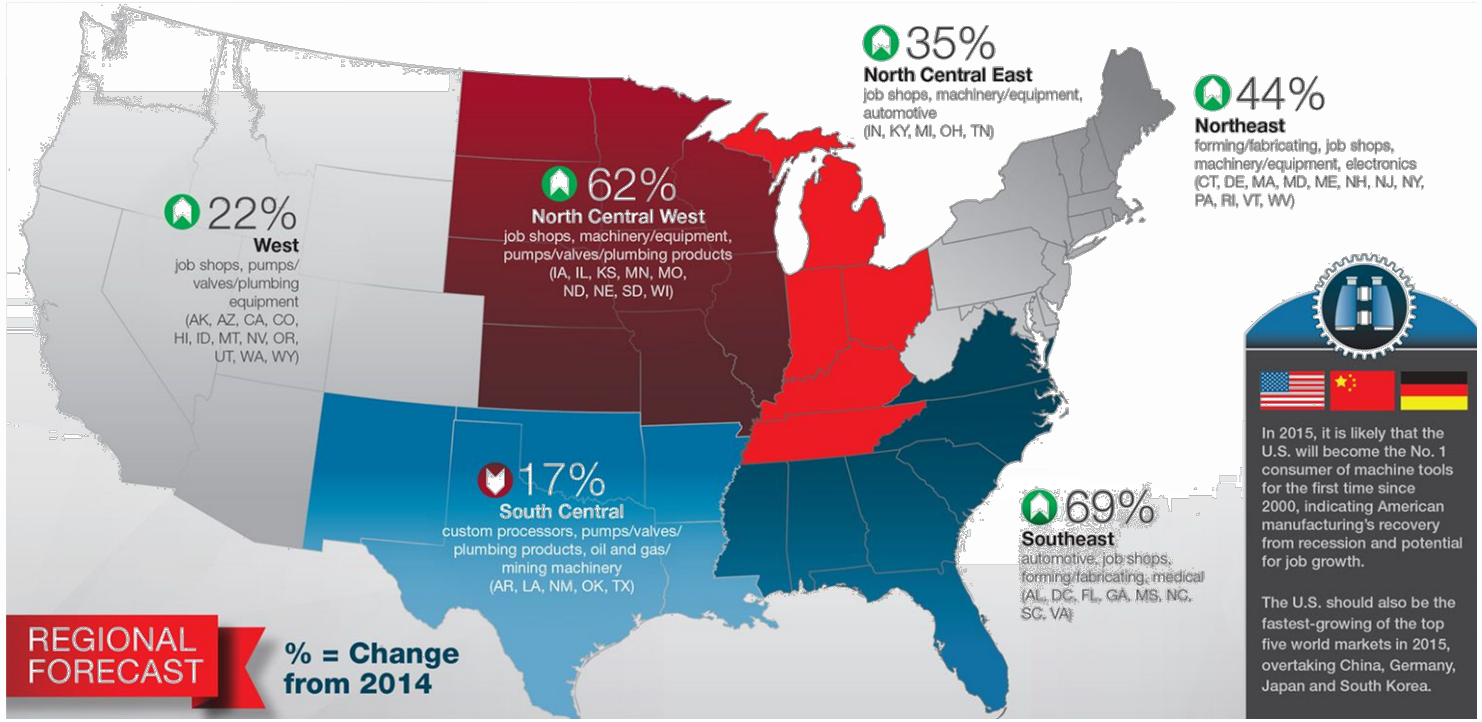


NIST → Economic Growth

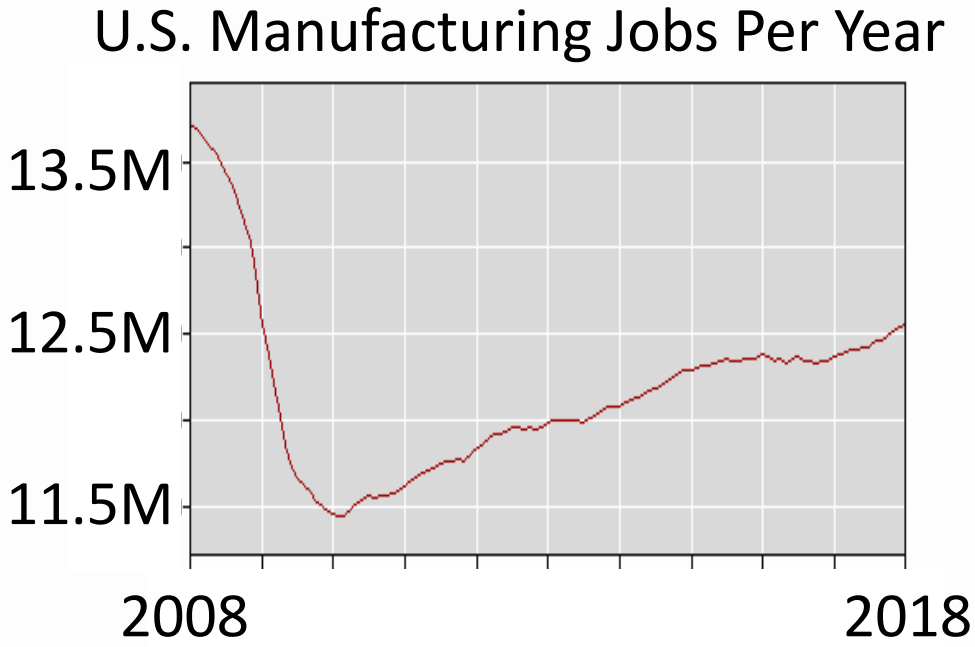
- NIST within U.S. Department of Commerce
- NIST promotes U.S. innovation by advancing measurement science, standards, and technology
- 6,500 Employees/Associates
- NIST partners with about 1,200 manufacturing specialists through manufacturing extensions

Manufacturing = Economic Growth

- Manufacturing = 12.5M U.S. jobs & about 60% exports
- 2.8% economic growth for U.S. machine tool orders [Oxford Economics]



Modern Machine Shop, 2015 Capital Spending Survey & Forecast



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

Hyundai Wia Plant

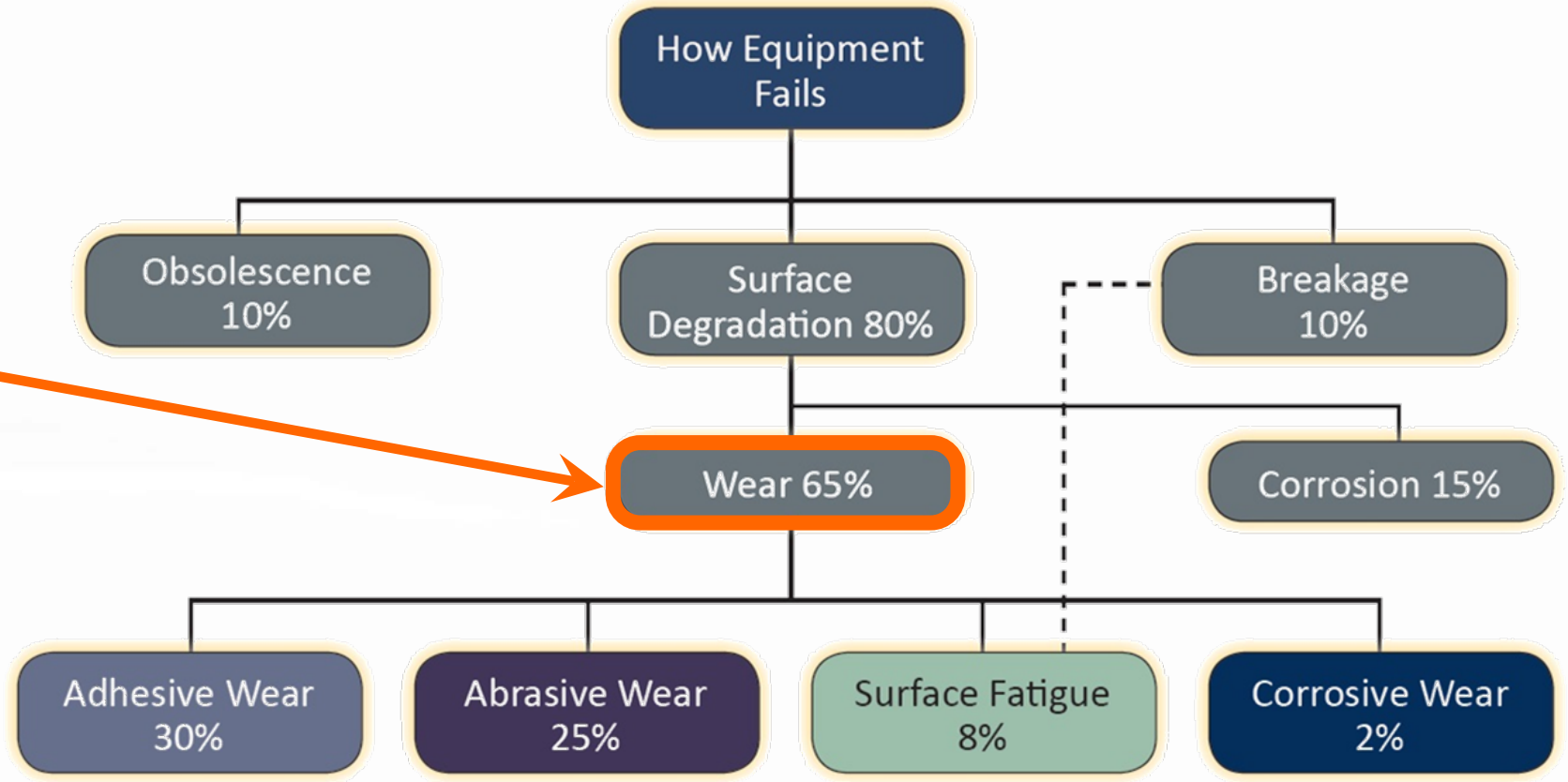
5-Axis Machine Cutting of Helmet (Daishin Seiki Corporation)

Problem = Unplanned Downtime

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

Wear

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

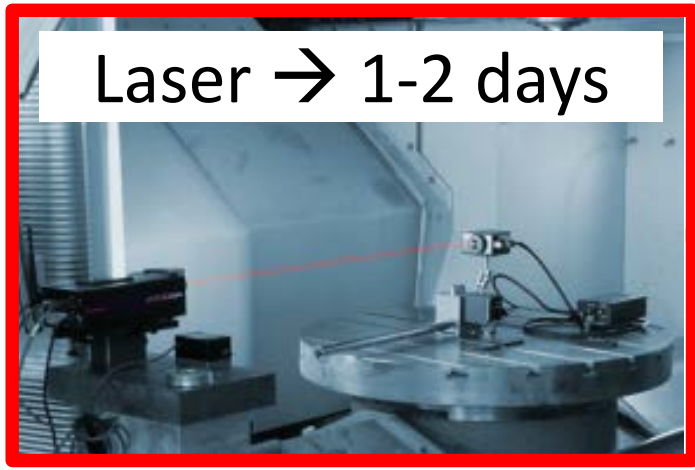


Reliabilityweb.com (2018), *Lubrication FMEA: The Big Picture*

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 → 1-2 days



API

Cap probes → hours

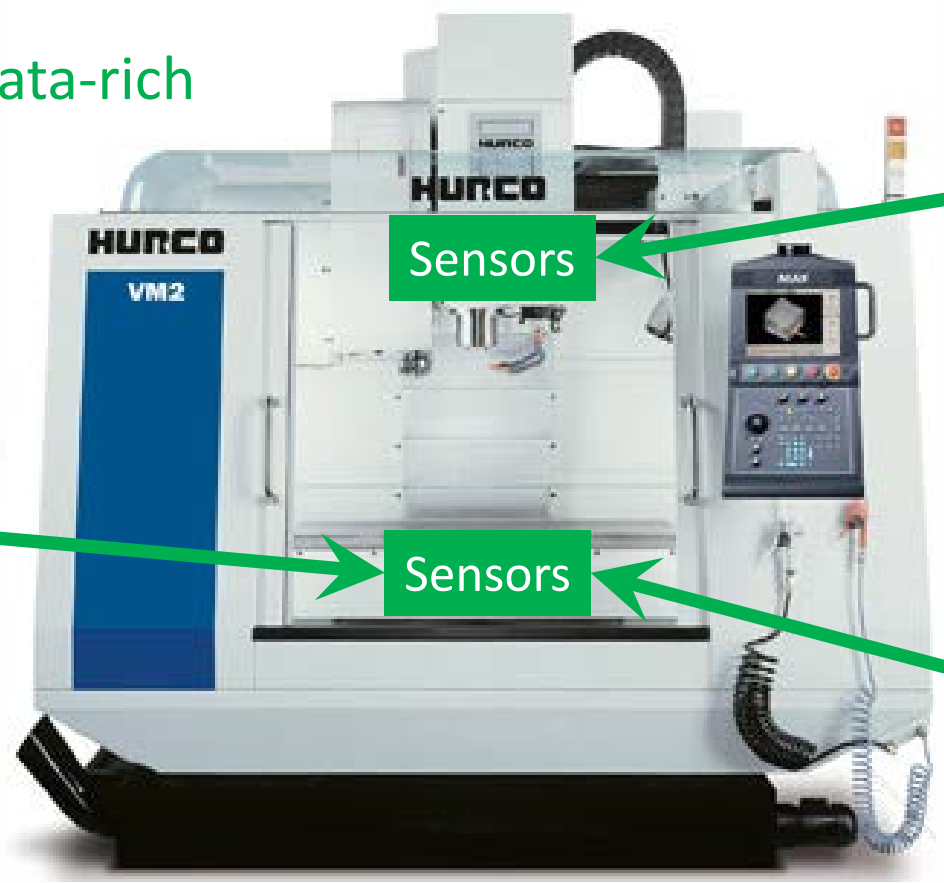
IBS Precision Engineering

Ballbar → 1 hour

Renishaw

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

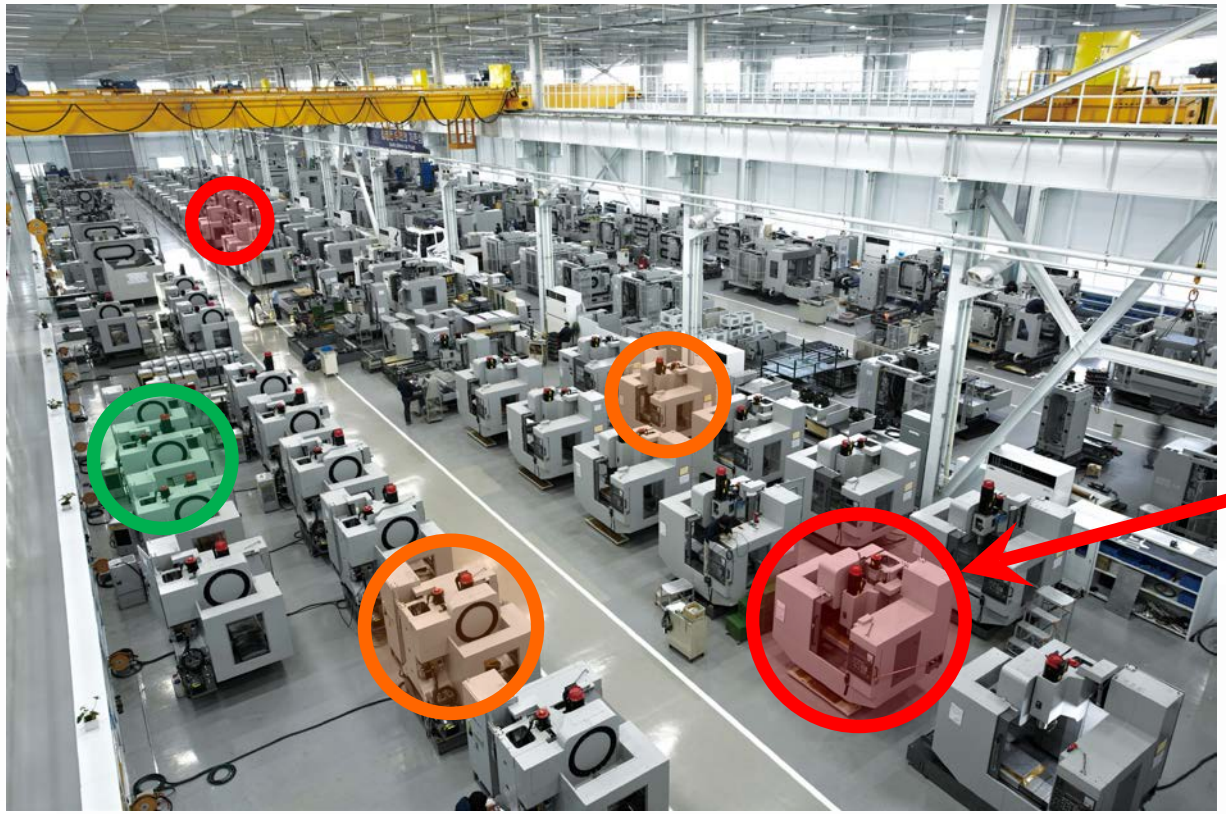
[How?]

Squareness 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



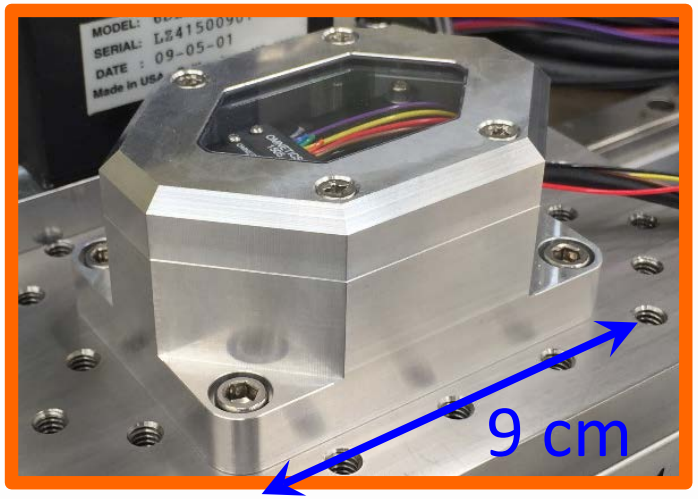
Hyundai Wia Plant

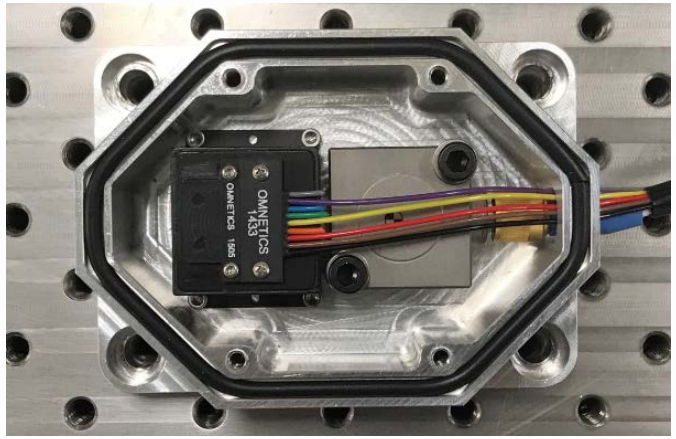
Tablet

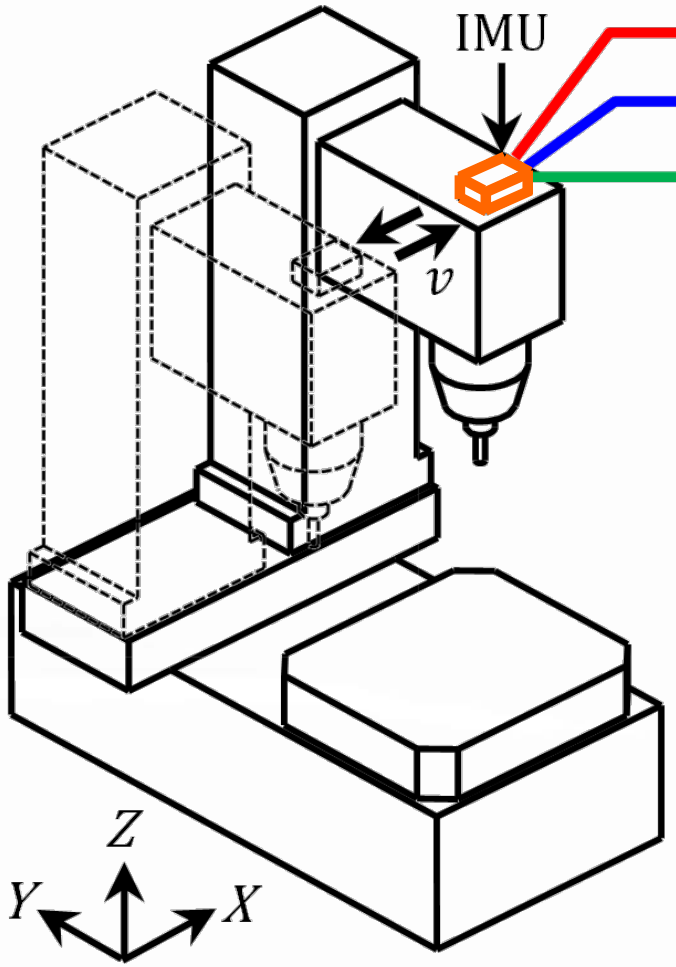
Machine #1
- Axis 1
  - 15 µm range
  - Spalling detected
- Spindle
- Axis 2
  - 70 µrad range

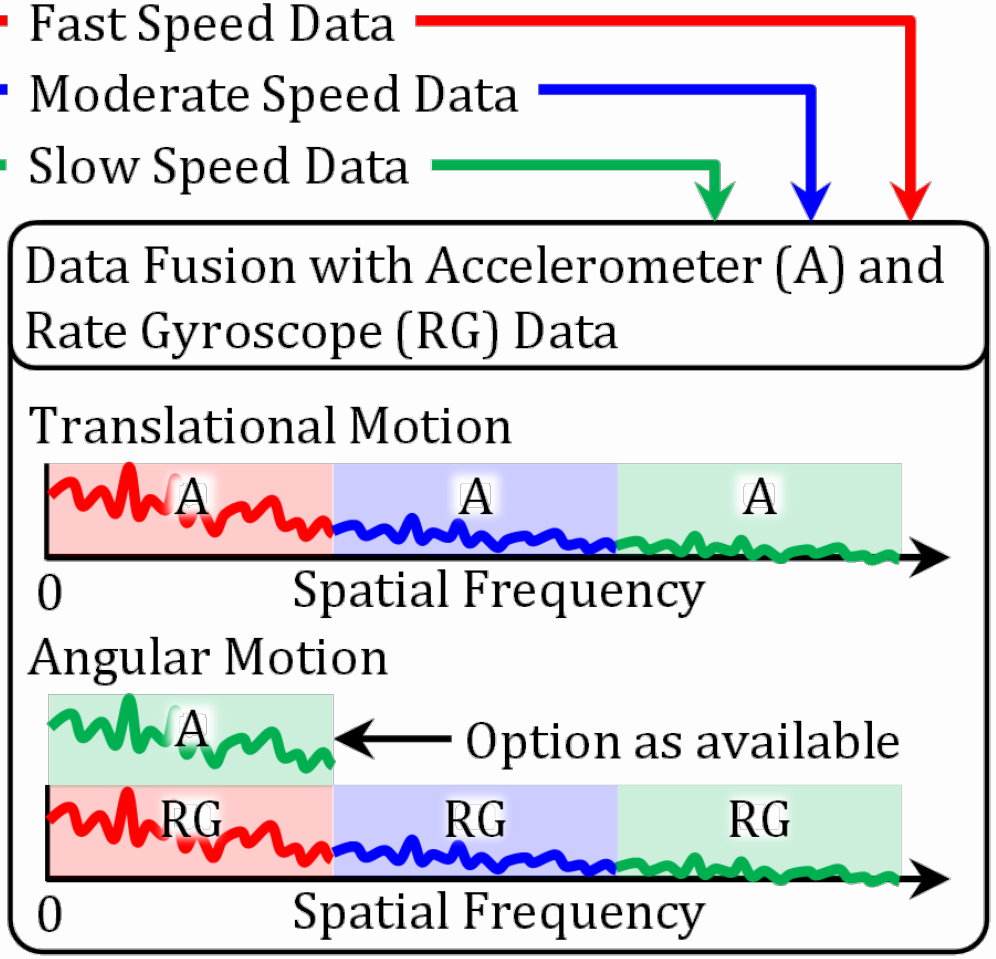
Optimum Machine: #5

IMU for Linear Axis Monitoring





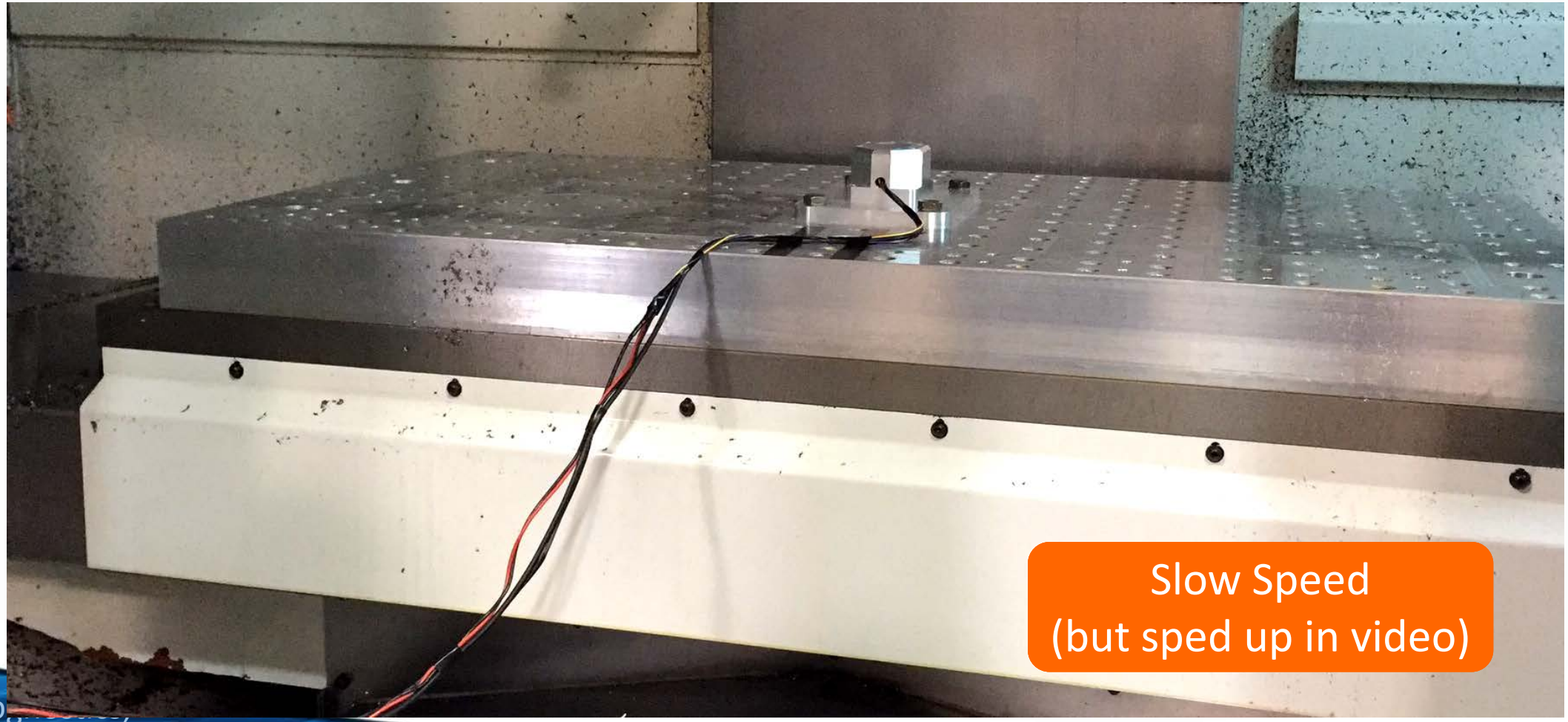




Vogl G.W., Donmez M.A., and Archenti A. (2016) Diagnostics for geometric performance of machine tool linear axes. *Annals of the CIRP* 65(1): 377-380.

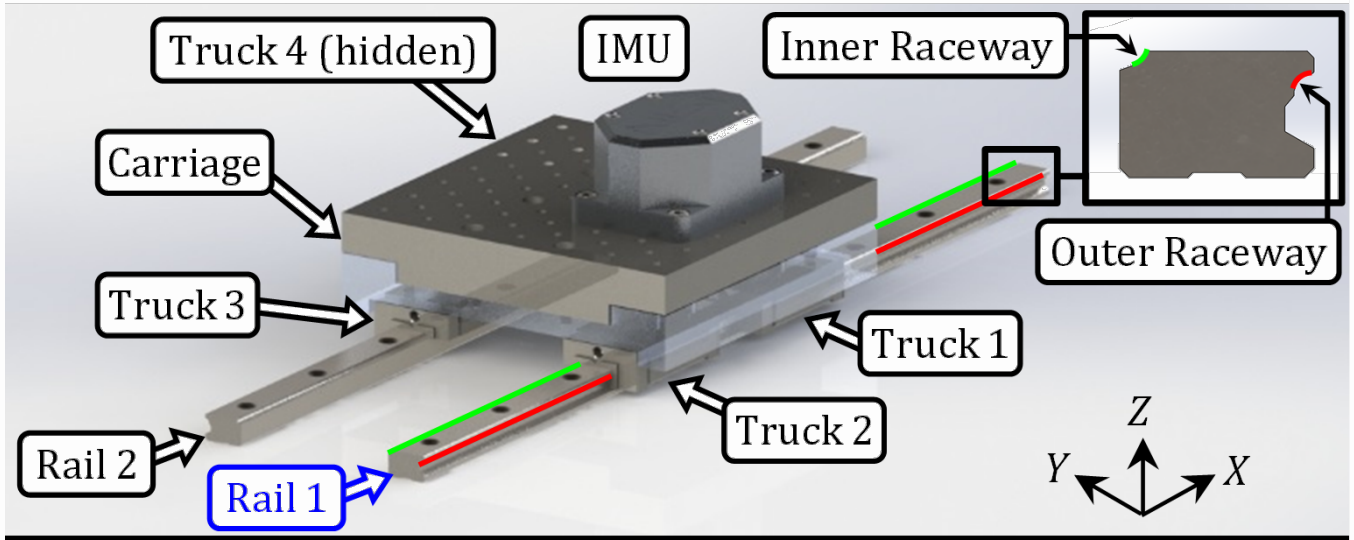
IMU Data Collection

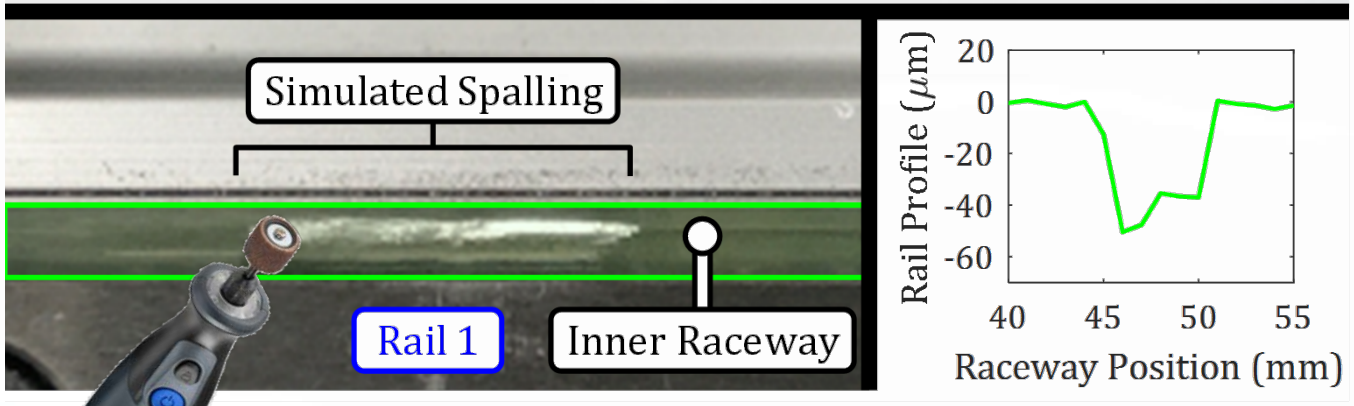
- Each run uses 3 different axis speeds
- IMU can live within machine tool for usage with no setup



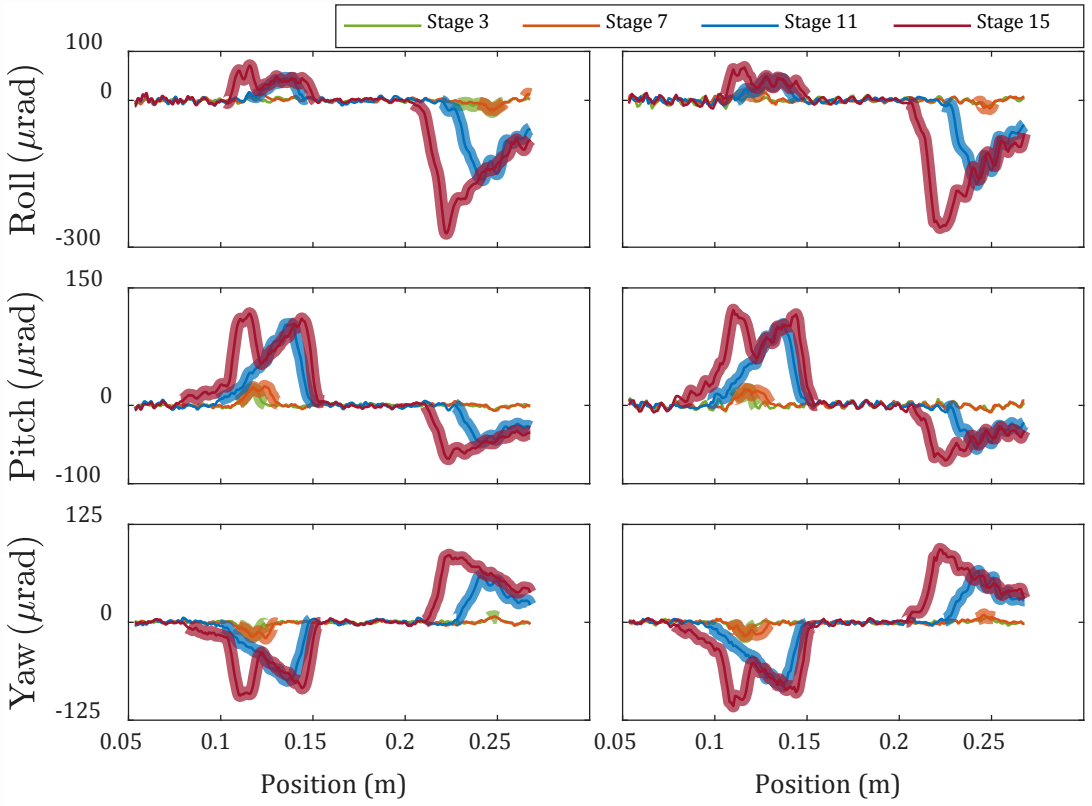
NIST Linear Axis Testbed

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





ΔError vs. Position



IMU

REF

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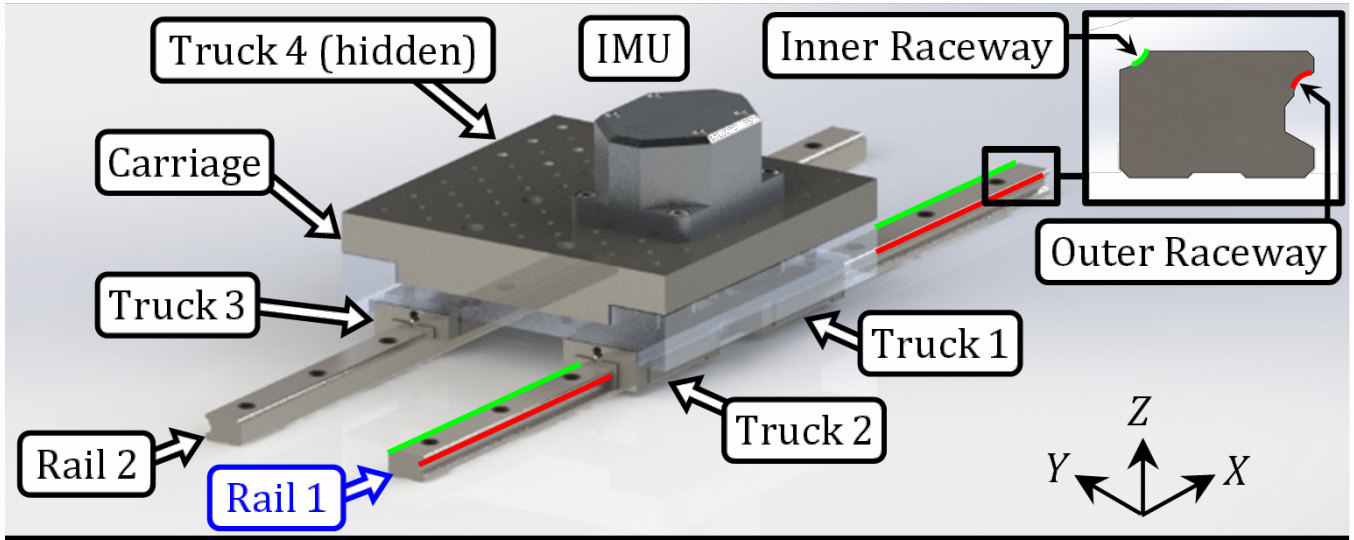
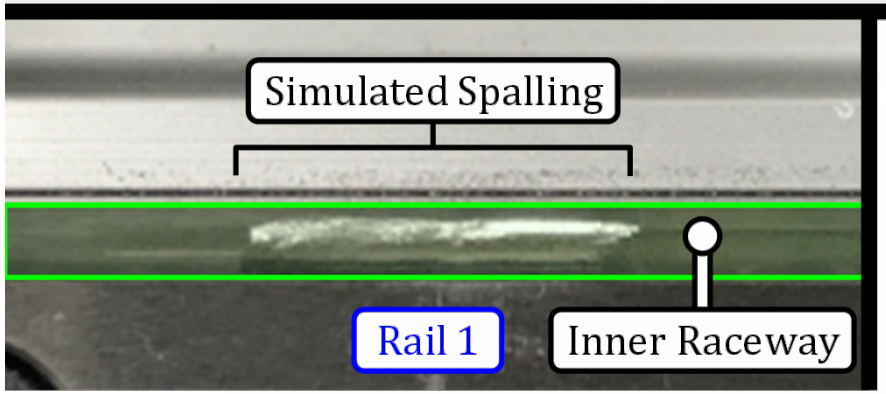
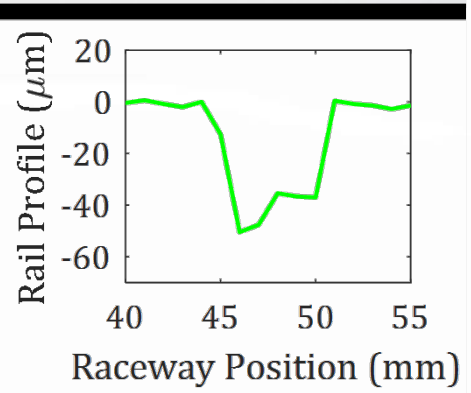
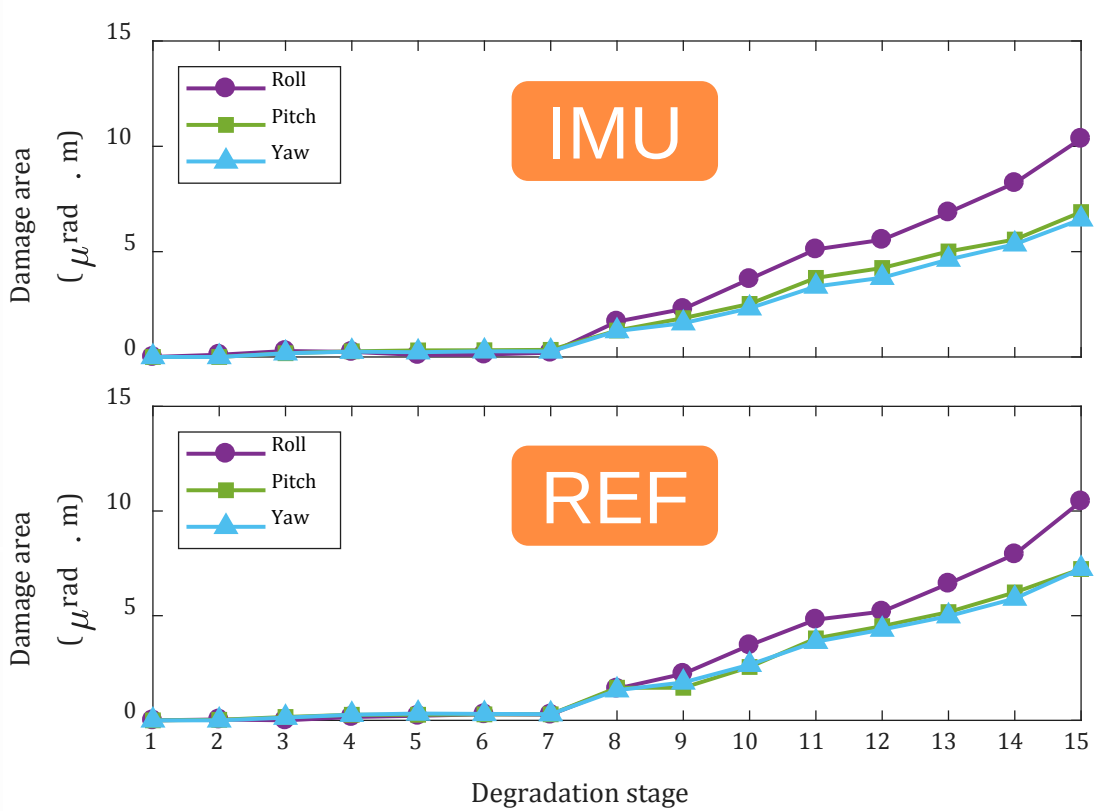




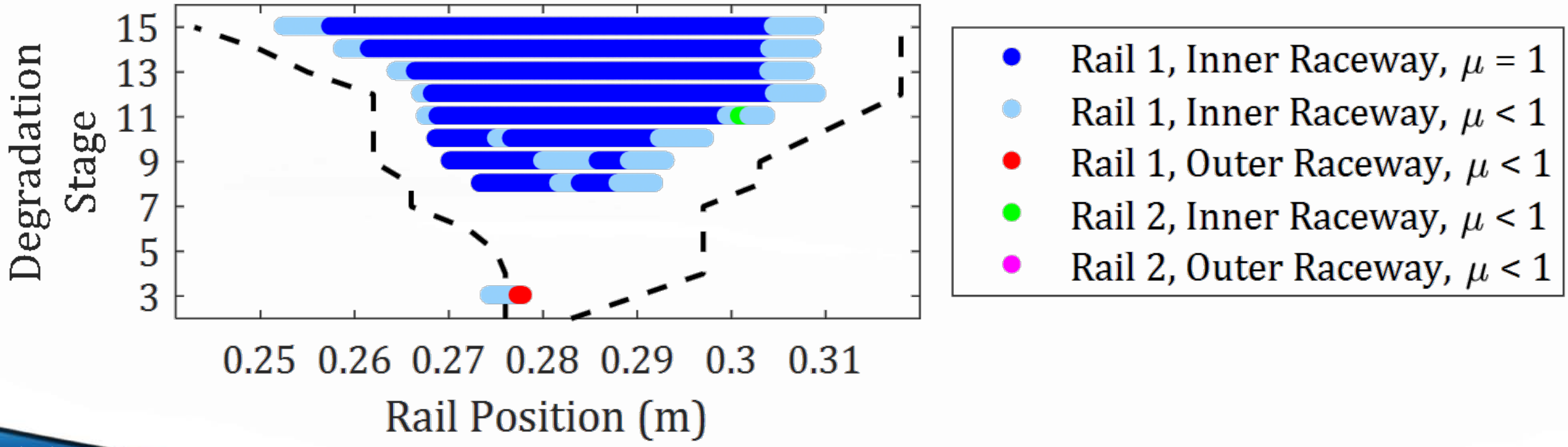


Metric vs. degradation stage



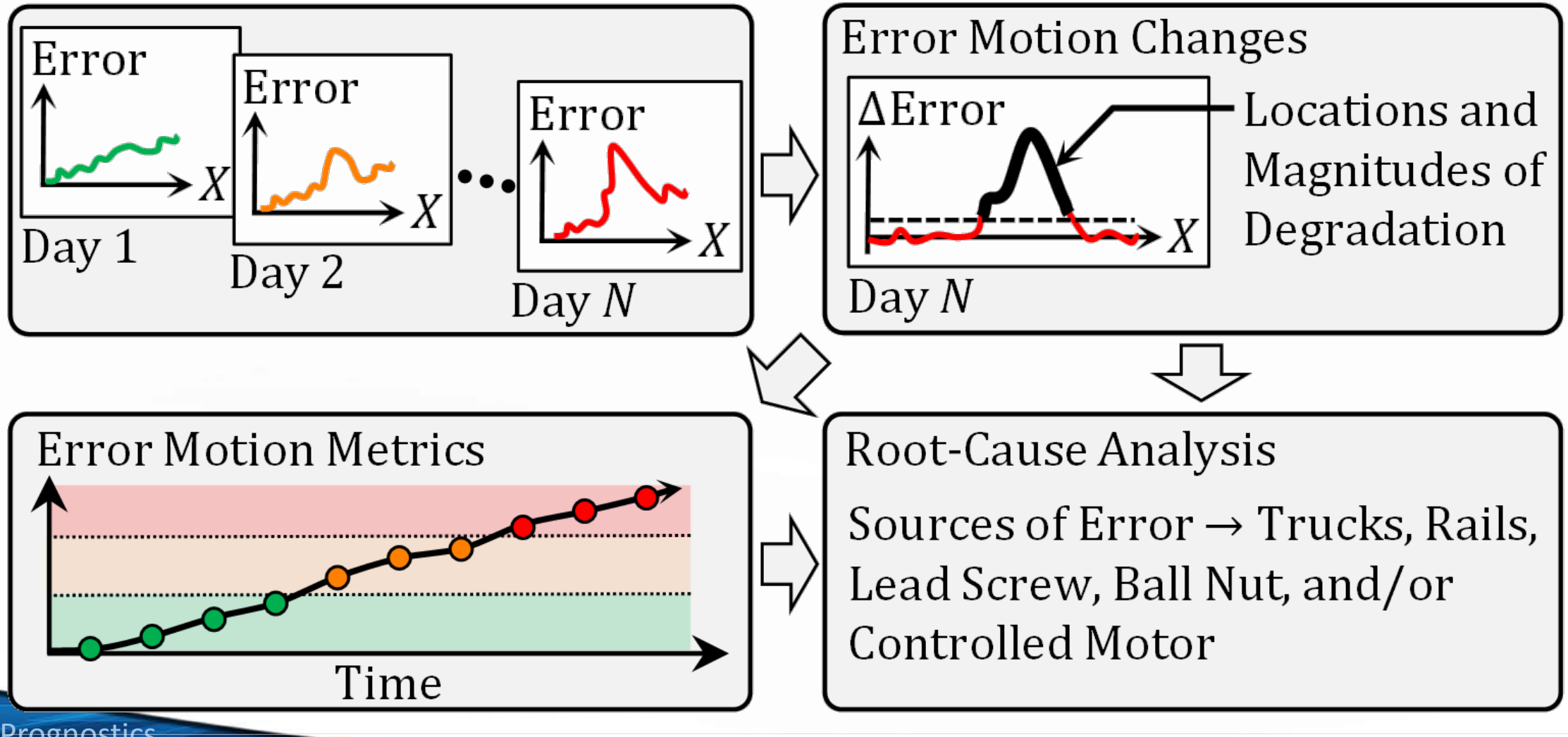
Root-Cause Analysis for Rail Wear

- 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



GOAL: Smart Machine Tools

- Industry challenge: "Machine health in 5 min?"
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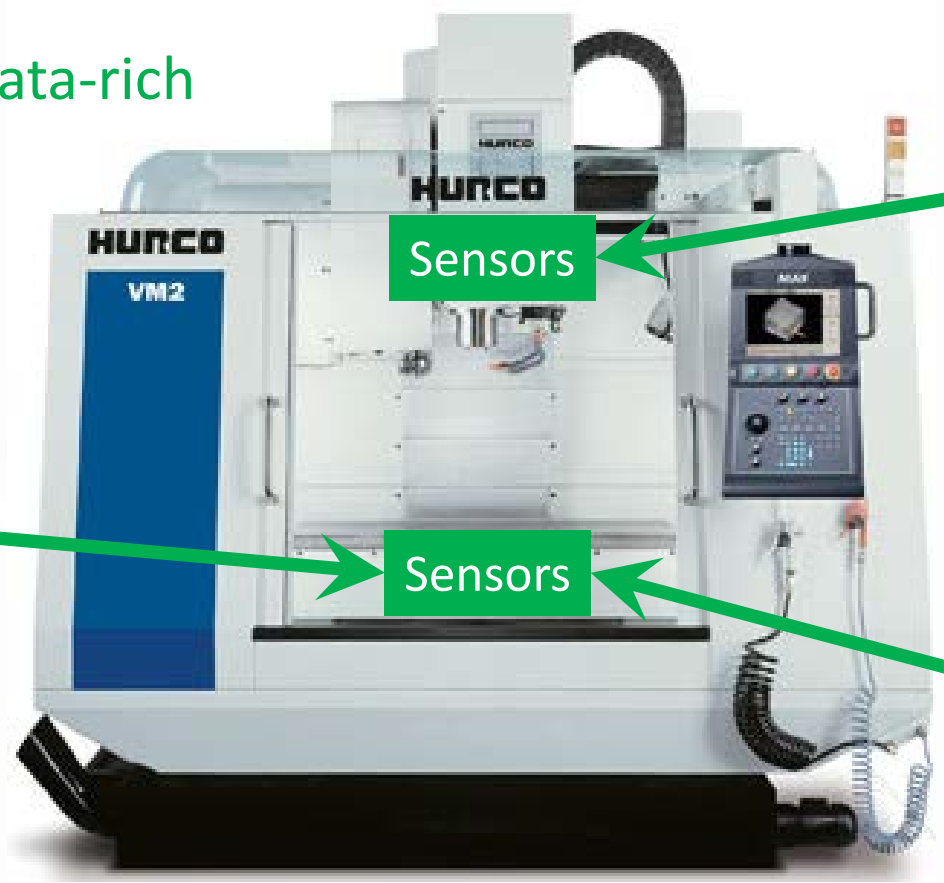


Spindle Health Tracking

~~[How?]~~ TBD

Linear Axis Health Tracking

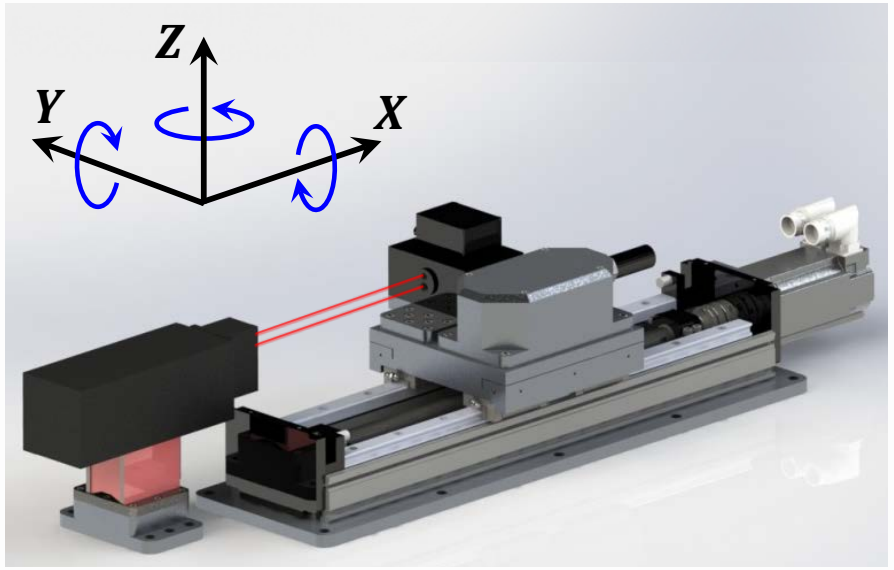
~~[How?]~~ IMU

Squareness Health Tracking

~~[How?]~~ IMU

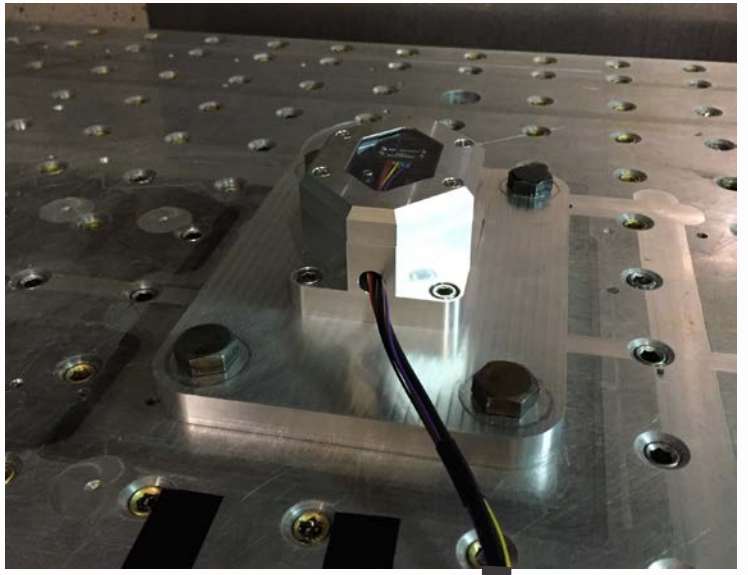
Lesson #1 – Smart & Metrological

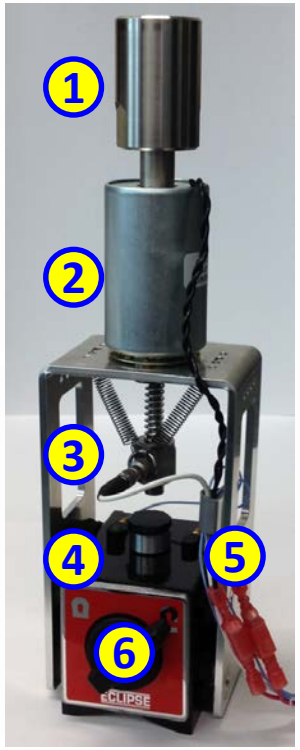
- **Traceable – Data is traceable to NIST**
  - Sensors calibrated along “measurement chain” to NIST
- **Dimensional – Results are physical quantities**
  - Inspired by international machining standards
  - Tracking Δ error motion > 2 µm and > 6 µrad
  - Physical quantities can be measured
- **Verify and validate – If possible!**
  - Compare results to those from traceable independent reference
  - Even complicated diagnostics can be shown to be correct

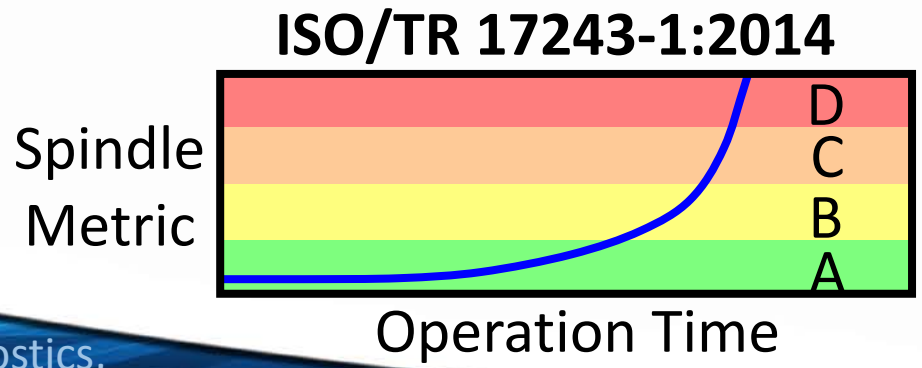


Lesson #2 – Smart & Simple

- **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

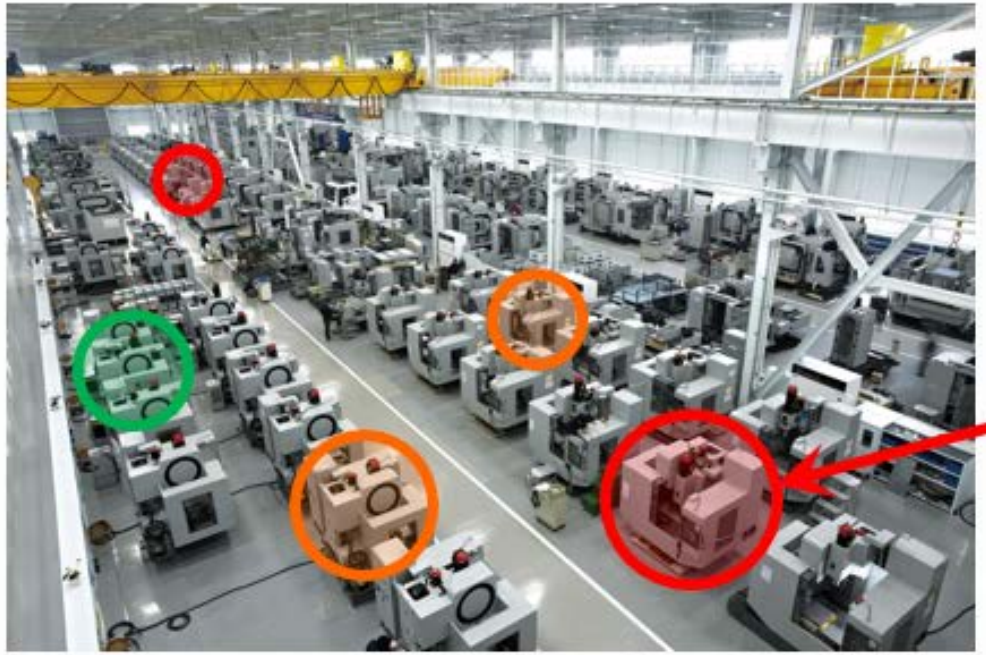




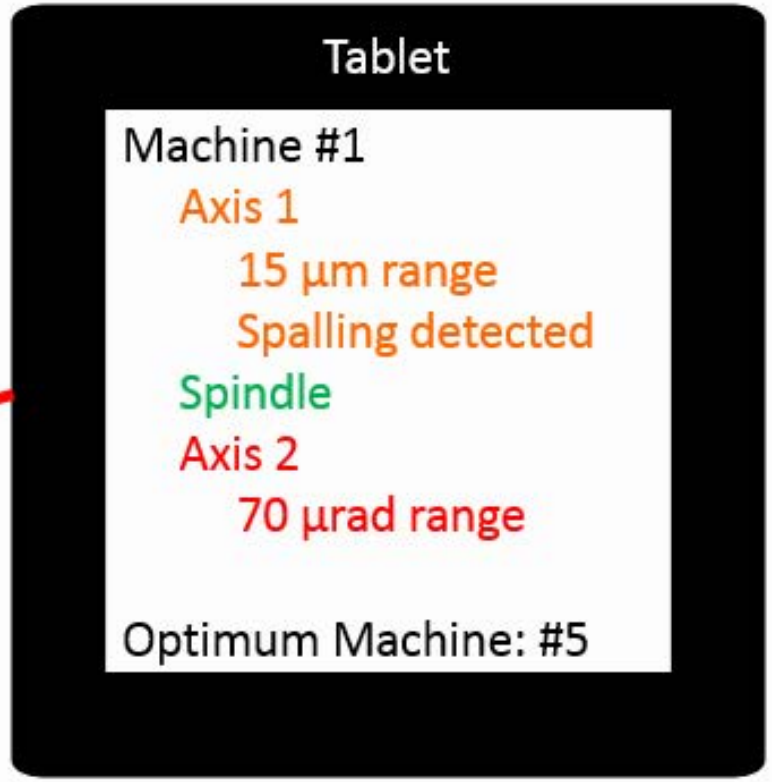


Lesson #3 – Future Directions

- 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



Hyundai Wia Plant



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What's the Prognosis? New Research Roadmap Aims for Fault-Free Manufacturing Processes

From NIST Tech Beat: August 26, 2015

Contact: Mark Bello
301-975-3776

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In today's increasingly complex manufacturing operations, Murphy's Law is only an unexpected hiccup away—anything from a data error to an errant vibration to a dulled cutting tool can undermine production. But in a future with fully effective sensing and information technologies that anticipate and avert potentially harmful process spasms, everything that might go wrong, simply could not.

Measurement Science Roadmap for Prognostics and Health Management for Smart Manufacturing Systems,* a new report generated for the National Institute of Standards and Technology (NIST), charts a course toward this ideal. The new roadmap is based on input received during a 2014 workshop of industry, university and government experts on prognostics and health management (PHM) technologies, systems and practices.

Prognostics—the estimation of the remaining life of an equipment item, subsystem, or system—and health management methods aim to maintain breakdown-free manufacturing production at top efficiency. Using a range of sensing technologies, these methods monitor the performance and operating conditions of equipment and systems, assess their health, and predict how long an operation can continue to perform as intended. Knowing when faults are likely to occur permits equipment to be repaired or replaced with little to no interruption. Should faults occur, however, PHM can be used to diagnose the root cause.

"Overall, the objective of PHM is to provide timely actionable information to enable intelligent decision making for improved performance, safety, reliability and maintainability," explains mechanical engineer Brian Weiss, who leads NIST research on PHM for smart manufacturing systems.

PHM techniques are used effectively in several industries, including automotive, aeronautics and heavy equipment. And NASA employs PHM in managing the International Space Station.

Prognostics, Health Management, and Control

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