- Human error?, faulty sensing?
- Urgent issue or something to put on the 'to-do' list?

- Information overload or insufficient data?

We have a long way to go in
Monitoring, Diagnostics, Prognostics, and Decision-making…

Developing Measurement Science to Advance Monitoring, Diagnostics, and Prognostics in Manufacturing Operations

Brian A. Weiss, *Project Leader*
Greg Vogl, Helen Qiao

Prognostics and Health Management for Reliable Operations in Smart Manufacturing

Intelligent Systems Division

Engineering Laboratory

National Institute of Standards and Technology

Images Courtesy of Fotolia

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Agenda

NIST and Smart Manufacturing

Outreach

Research Focus

Use Case Development

Solution transfer to industry

Engineering Lab's Mission…

- *…promote U.S. innovation and competitiveness by advancing **measurement science, standards, and technology** for engineered systems in ways that enhance economic security and improve quality of life*
- *Carry out mission related activities in…*
  - *Engineering and manufacturing products, processes, equipment, technical data, and standards*
  - *Manufacturing enterprise integration*
  - ***Intelligent systems and control***
  - ***Robotics and automation***
  - *Cyber-physical systems*

Courtesy: Fotolia

Above content from: www.nist.gov/el/about-el

More on Measurement Science…

Used in the context of creating **critical-solution enabling tools** – metrics, models, and knowledge – for U.S. manufacturers. This includes:

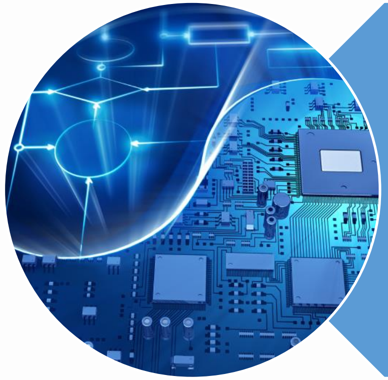
- Development of…
  - Performance metrics
  - Measurement and testing methods
  - Predictive modeling and simulation tools
  - Reference materials (e.g. data sets)

  - Artifacts
  - Protocols
  - Technical data
  - Knowledge modeling
- Conduct inter-comparison studies and calibrations
- Evaluation of technologies, systems, and practices
- Development of the technical basis for standards, codes, guidelines, and/or practices

Why Smart Manufacturing?

- Enable manufacturers to…
  - make what you want, where you want it, and when you want it.
  - **respond in real time to meet changing demands and conditions**
  - easily and rapidly reconfigure factory production and supply networks to optimize system performance
  - **deal effectively with uncertainty and abnormal events and learn from past experience to enable continuous improvement**
  - maintain seamless interoperability between factory processes and supply networks and between large manufacturers and small manufacturers

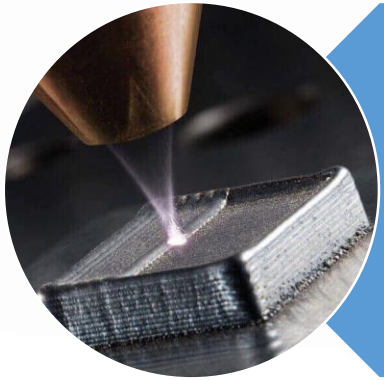
Smart Manufacturing Programs



Model-Based Engineering

Trustworthy Systems, Components, and Data

Robotic Systems



Additive Manufacturing

Trustworthy Systems, Components, and Data

Cybersecurity for Smart Manufacturing

High Performance Wireless Systems for Smart Manufacturing

Prognostics and Health Management for Reliable Operations in Smart Manufacturing

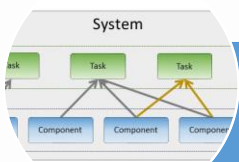
Supply Chain Traceability for Agri-Food Manufactuiring

Research Objective and Deliverables

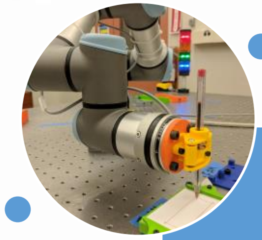
To develop and deploy **measurement science** to promote the implementation, verification, and validation of advanced monitoring, diagnostic, and prognostic technologies to increase reliability and decrease downtime in smart manufacturing systems

Standards and Guidelines

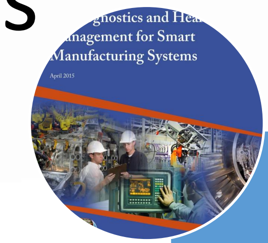
Reference Datasets and Software Tools



Test Methods and Performance Metrics



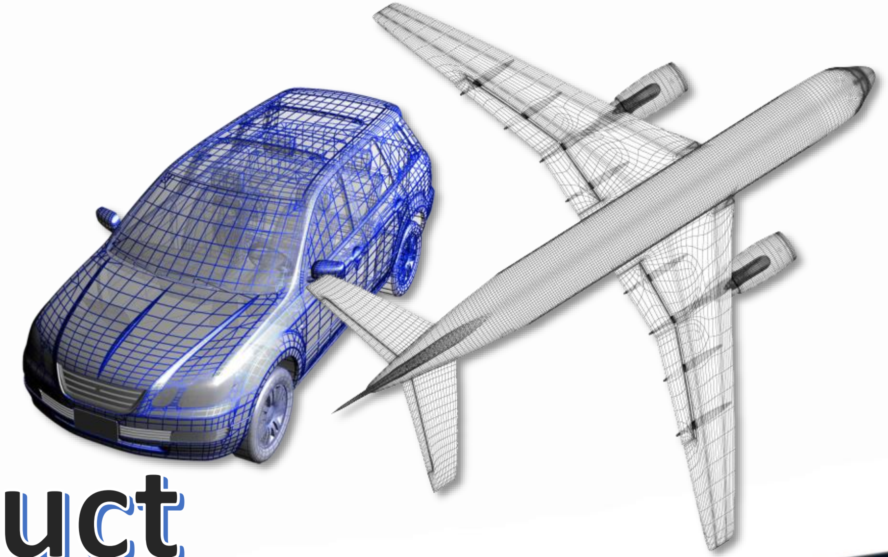
Use Cases and Test Scenarios



Roadmaps and Case Studies

- Range from very simple to very complex
  - Few to many moving parts
  - Few to many relationships among components, sub-processes, etc.
- Both consist of physical components that work together to produce one or more capabilities
- Physical components (and therefore, functional capabilities) will degrade over time
- Maintenance may or may not be required throughout its life

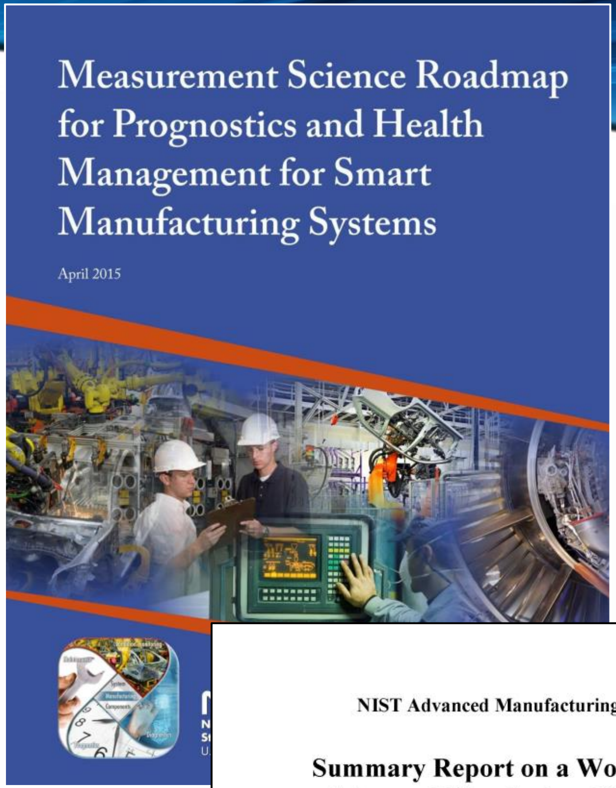
Process

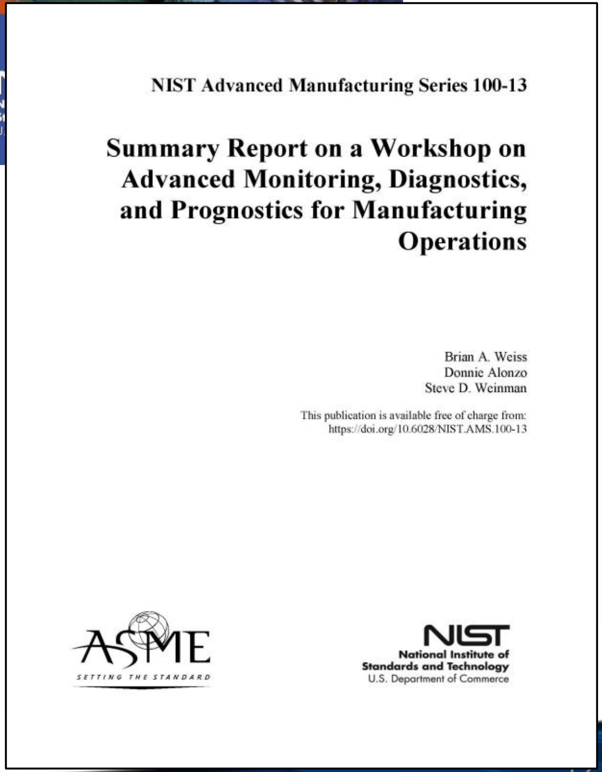


Product

How do we know this is Important?

- Measurement Science Roadmapping Workshop
- Manufacturing Standards Requirements Gathering Workshop
- Collaborative studies with university and industry partners
- Interactions with various technical organizations





NIST Advanced Manufacturing Series 100-13

Summary Report on a Workshop on Advanced Monitoring, Diagnostics, and Prognostics for Manufacturing Operations

Brian A. Weiss
Donnie Alonzo
Steve D. Weinman

This publication is available free of charge from:
https://doi.org/10.6028/NIST.AMS.100-13

ASME SETTING THE STANDARD

NIST National Institute of Standards and Technology U.S. Department of Commerce

UNIVERSITY OF Cincinnati

THE UNIVERSITY OF MICHIGAN ARTES SCIENTIA VERITAS 1817

TechSolve

ASME SETTING THE STANDARD

phmsociety

Outreach: Roadmapping Workshop and Report

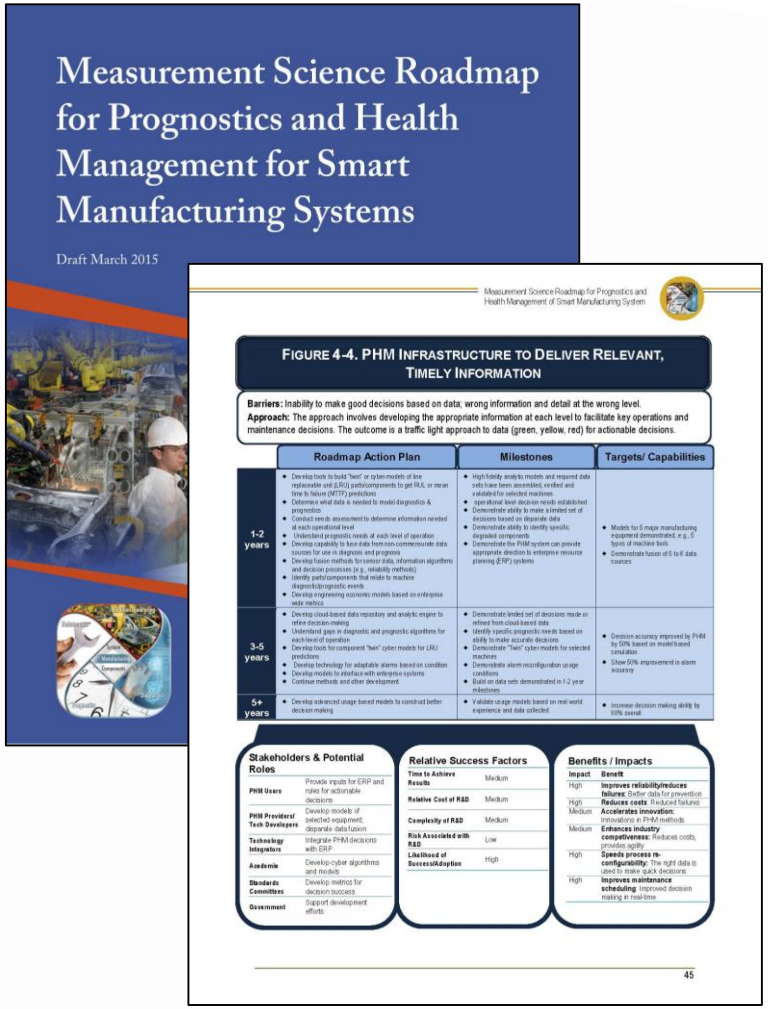
Goal: Identify goals, desired capabilities, and challenges to develop necessary measurement science

The Workshop

- Featured over 70 people from 35 organizations including manufacturers, technology vendors, academia, standards development organizations, and other government agencies

The Report

- Extensively documents breakout groups' efforts to identify goals, desired capabilities, challenges and barriers, and priority roadmap topics relating to three critical PHM topic areas
- http://www.nist.gov/el/isd/phm4sms-workshop.cfm



- B. A. Weiss, G. Vogl, M. Helu, G. Qiao, J. Pellegrino, M. Justiniano, and A. Raghunathan, "Measurement Science for Prognostics and Health Management for Smart Manufacturing Systems: Key Findings from a Roadmapping Workshop," *Annual Conference of The Prognostics and Health Management Society,* 2015.
- J. Pellegrino, M. Justiniano, A. Raghunathan, and B.A. Weiss, "Measurement Science Roadmap for Prognostics and Health Management for Smart Manufacturing Systems," *NIST Advanced Manufacturing Series,* 100-2, September 2016.

Workshop Roadmap Action Plans

PHM Manufacturing Process Techniques and Metrics

- **Advanced Sensors for PHM in Smart Manufacturing**
- **PHM Data Format, Taxonomy, and Architecture**
- Enterprise-wide PHM for Maintenance Planning

PHM Performance Assessment

- **Overarching Architecture Framework for PHM with Standards and KPIs**
- **Identification of PHM Performance Metrics**
- **Failure Data for Prognostics and Diagnostics**
- **Determination of PHM Data and Information Needs**
- Cost model for PHM Performance
- Taxonomy for Applications

PHM Infrastructure – Hardware, Software, and System Integration

- **Open-Source Community for PHM**
- **PHM Infrastructure to Deliver Relevant, Timely Information**
- Embedded Sensors for PHM of Emerging Manufacturing Technologies
- PHM as an Equipment Design Feature

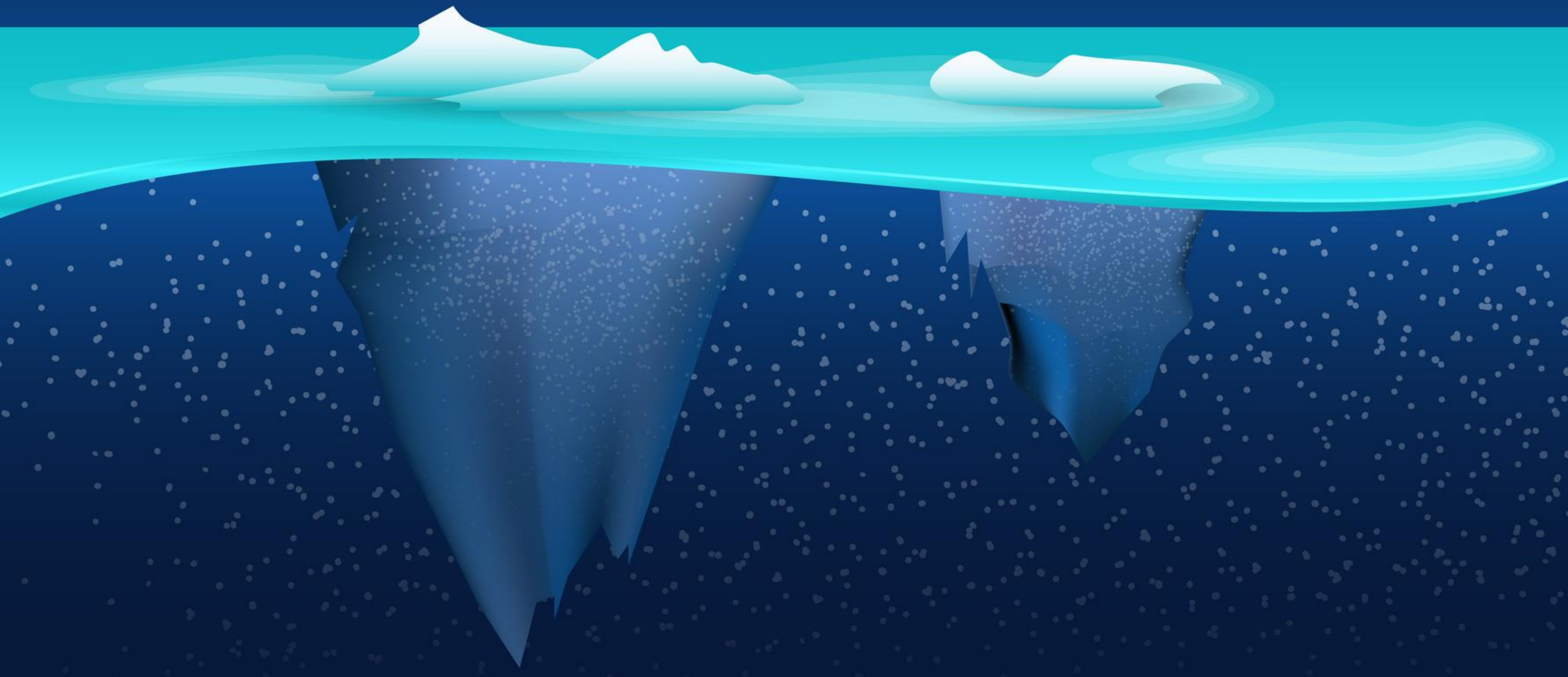
Outreach: Sensing, Diagnosis, and Prognosis in Manufacturing

- Goal: Identify industry needs and priorities
- Approach: Industrial case studies
  - SMEs versus Large Manufacturers
  - Collaboration with UC/UM IMS
- Key findings:
  - Real data illuminates actual performance
  - Initial area of interest is equipment utilization, but interest quickly shifts to diagnosis, prognosis, and dynamic scheduling
  - Large barriers include systems integration and lack of sufficient data to support analysis

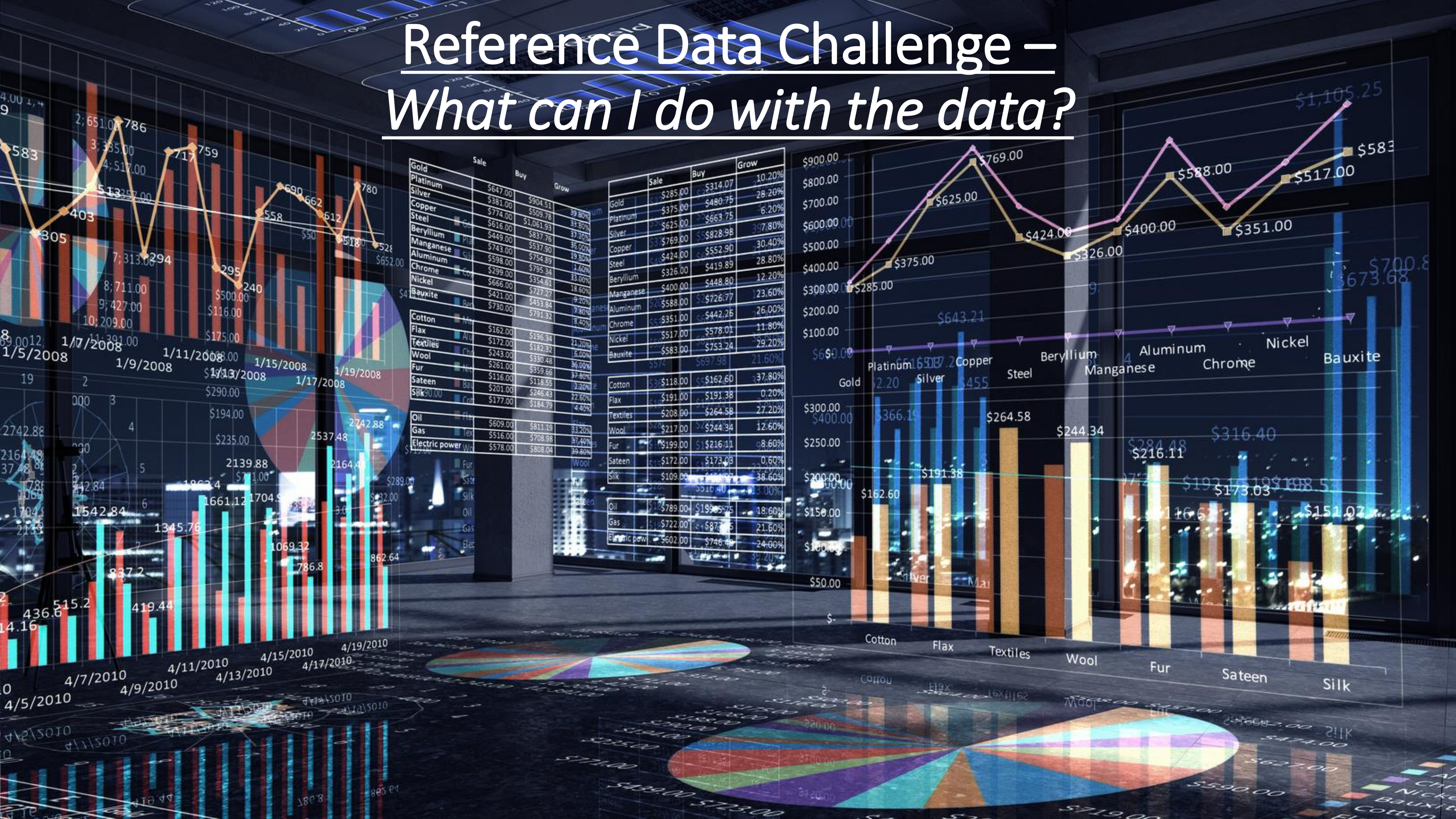
- X. Jin, B.A. Weiss, D. Siegel, J. Lee, and J. Ni, "Present Status and Future Growth of Advanced Maintenance Technology and Strategy in US Manufacturing," *Special Issue: PHM for Smart Manufacturing Systems*, vol. 7 Special Issue, pp. 17-34, September, 2016.
- X. Jin, D. Siegel, B.A. Weiss, E. Gamel, W. Wang, and J. Ni, "The Present Status and Future Growth of Maintenance in U.S. Manufacturing: Results from a Pilot Survey," *Manufacturing Review*, vol. 3, June, 2016.
- M. Helu and B.A. Weiss, "The Current State of Sensing, Health Management, and Control for Small-to-Medium-Sized Manufacturers," *ASME 2016 Manufacturing Science and Engineering Conference (MSEC2016)*, 2016.
- G. Vogl, B.A. Weiss, and M. Helu, "A Review of Diagnostics and Prognostic Capabilities and Best Practices for Manufacturing," *Journal of Intelligent Manufacturing*, pp. 1-17, June, 2016.

Reference Data Challenge – *How much is enough?*

<u>Reference Data Challenge –</u>
Do I truly understand my data?

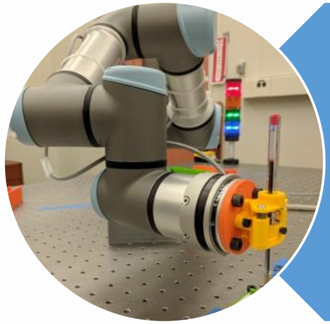


Reference Data Challenge – *What can I do with the data?*



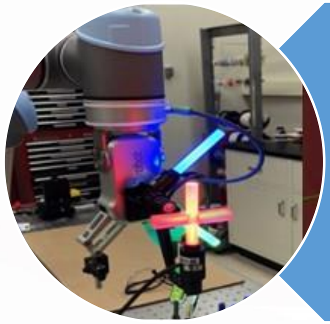
Reference Data Challenge – *How do I quantify the human impact?*

Research Levels and Testbeds



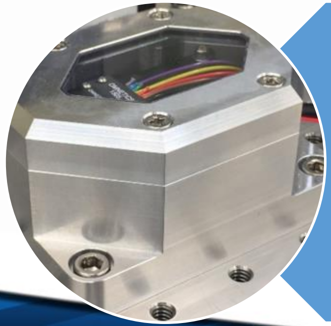
Identification of Robot Workcell Degradation

- Work Cell-Level Research
- PHM for Robot Systems Lab/Testbed



Assessment of Robot Accuracy Degradation

- Robot-Level Research
- PHM for Robot Systems Lab/Testbed



Machine Tool Linear Axes Diagnostics and Prognostics

- Component-Level Research
- Linear Axis Test bed & ‘Shops’ Machine Tools

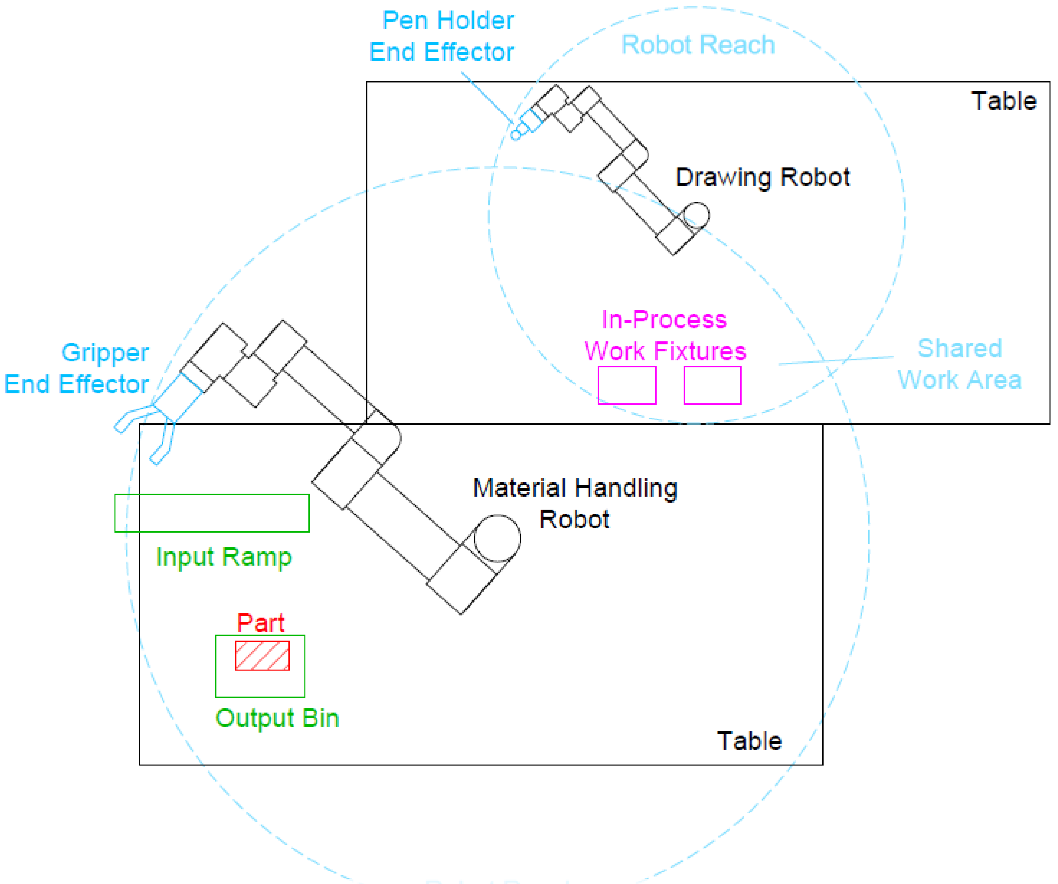
Research Focus and Plan

Verification & Validation of Equipment and Process Health Tech…

- Identify sources throughout the workcell that influence performance on positioning tasks using an artifact-based approach
- Enhance capability to measure end-of-robot-arm positional accuracy through development of active smart targets and corresponding test procedures
- Extend single-axis diagnostics to multi-axis prognostics of machine tool linear stages
- Generate datasets from NIST testbeds and external pilot sites
- Contribute to development of guidelines within an ASME Standards subcommittee on Advanced Monitoring, Diagnostics, and Prognostics

NIST PHMC Robotics Testbed

- 2 robots
  - Material Handling
  - Path Following
- End Effectors
  - Electric Parallel Finger Gripper
  - Pen holder
- Fixtures
- Parts



- A. Klinger and B.A. Weiss, “Robotic Work Cell Test Bed to Support Measurement Science for Monitoring, Diagnostics, and Prognostics,” *ASME 2018 International Manufacturing Science and Engineering Conference (MSEC2018)*, June 2018
- B.A. Weiss and A. Klinger, “Identification of Industrial Robot Arm Work Cell Use Cases and a Test Bed to Promote Monitoring, Diagnostic, and Prognostic Technologies,” *Annual Conference of the Prognostics and Health Management Society 2017*, October 2017.
- B.A. Weiss, M. Helu, G. Vogl, and G. Qiao, “Use Case Development to Advance Monitoring, Diagnostics, and Prognostics in Manufacturing Operations,” *12th International Federation of Automatic Control (IFAC) Workshop on Intelligent Manufacturing Systems IMS 2016*, December 2016.

Kinematic Breakdown to Assess Workcell Health

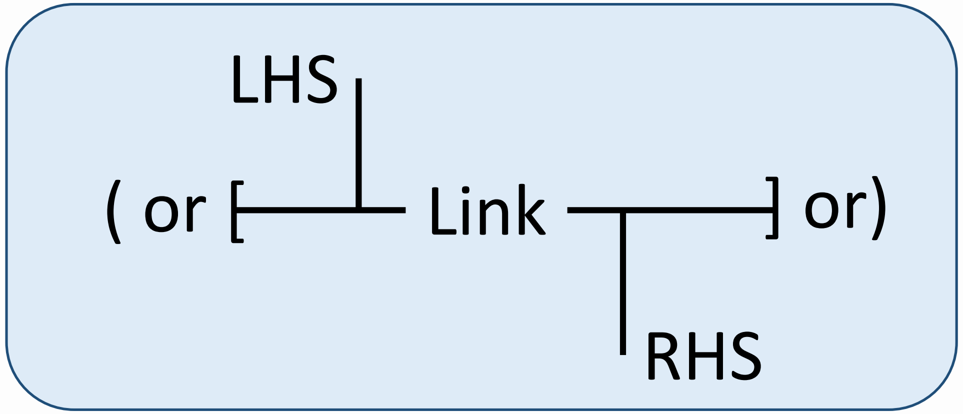
- Flexible method to identify sources of positioning repeatability degradation within a robotic workcell beyond the robot
  - Robots
  - End effectors
  - Fixtures
  - Etc.
- Low Cost, Minimally Invasive, In-Process Test
- Identify degradation before fault or failure
- Measure rate of degradation before fault or failure

- A. Klinger and B.A. Weiss, "Examining Workcell Kinematic Chains to Identify Sources of Position Degradation," *Annual Conference of the Prognostics and Health Management Society 2018*, September 2018.

Kinematic Links

- Links can be defined at any level of detail
  - Component
  - Sub-system
  - Physical mechanical link
- Each link has a left-hand-side (LHS) and a right-hand-side interface (RHS)
- Intermittent and non-intermittent interfaces can be represented with "()" and "[]" respectively
- Textual representation

Graphic Representation



Textual Representation

(or [LHS, Link, RHS] or)

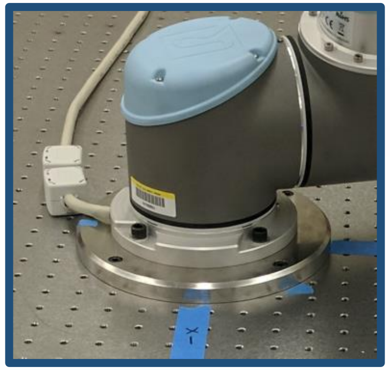
Material Handling Robot Kinematic Chain

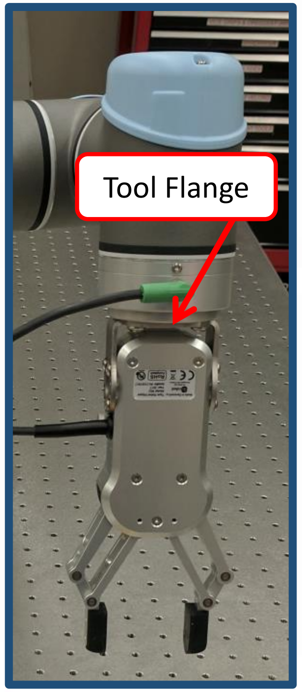
Graphic Representation

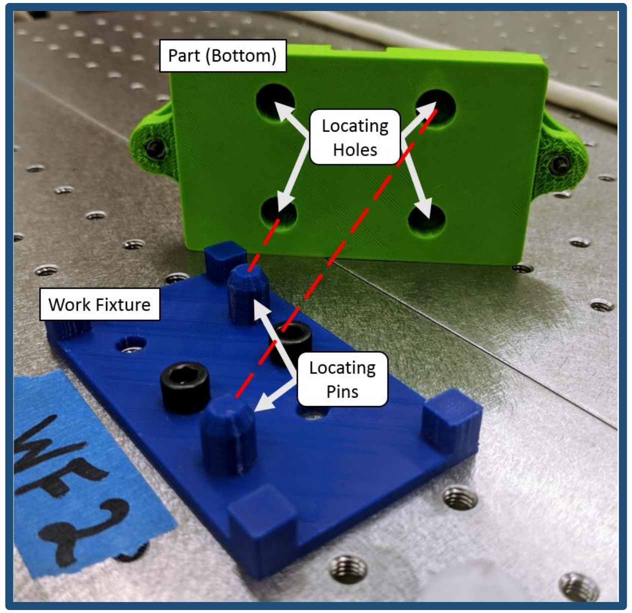
Robot Base | Gripper Mounting | Part Geometry | Fixture Geometry

World Frame][— Robot —][— Gripper —)(— Part —)(— Fixture —][World Frame

Tool Flange | Gripper Fingers | Part Geometry | Fixture Mounting







Use Case Degradation Modes

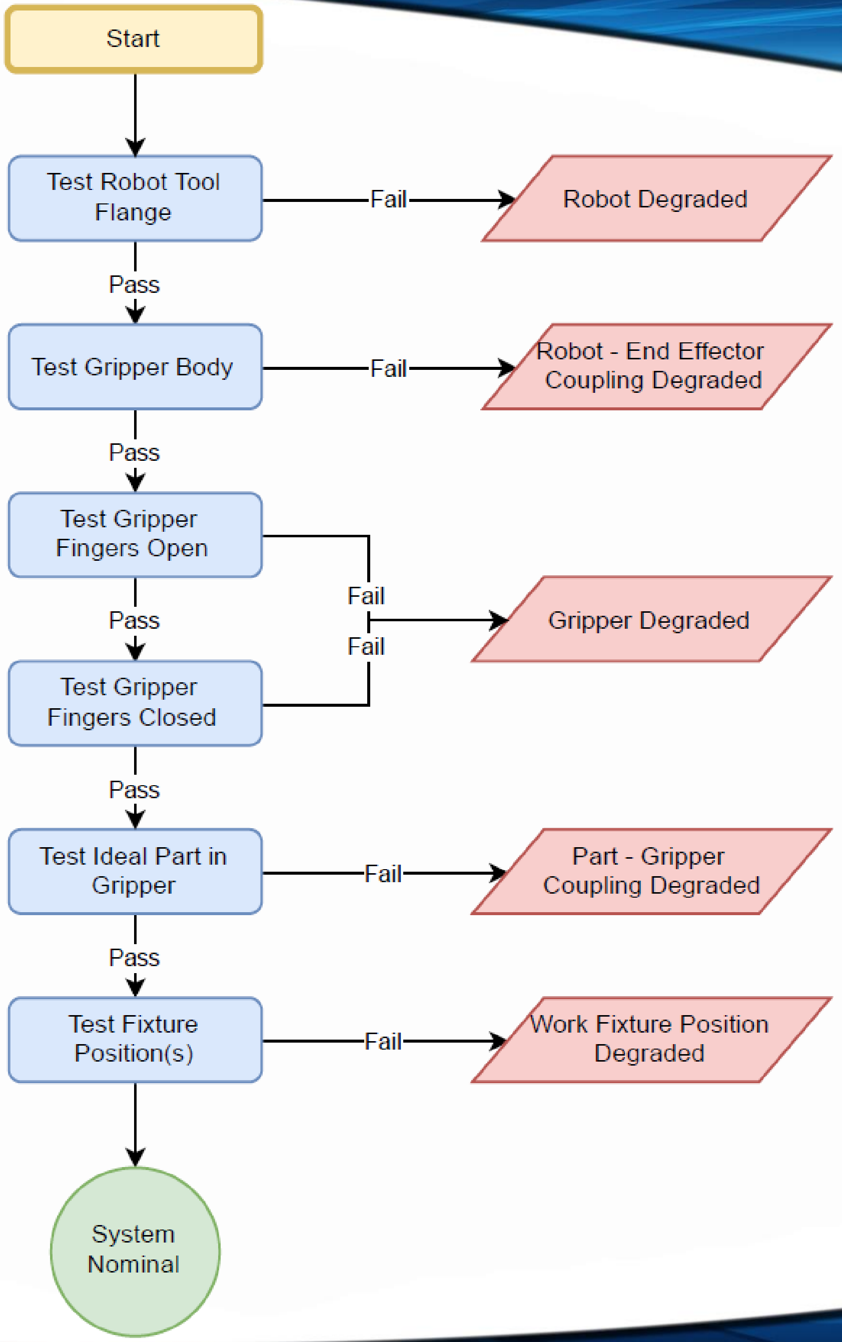
- Assume each link can cause positioning degradation due to deformation
- List relationships between links
- Identify positioning degradation modes which may be present during operation

Kinematic Chain Section	Degradation Mode(s)
World Frame][Robot Base	Loose Connection
[Robot Base, Robot, Robot Tool Flange]	Robot Wear
Robot Tool Flange][Gripper Mounting	Loose Connection
[Gripper Mounting, Gripper, Gripper Fingers]	Gripper Wear
Gripper Fingers)(Part Geometry	Finger Positioning, Bad Part*
[Part]	Bad Part*
Part Geometry)(Fixture Geometry	Bad Part*, Bad Fixture**
[Fixture Geometry, Fixture, Fixture Mounting]	Bad Fixture**
Fixture Mounting][World Frame	Loose Connection

*From either part inaccuracy or damage
**From either fixture positioning inaccuracy or fixture wear/damage

Test Decision Tree

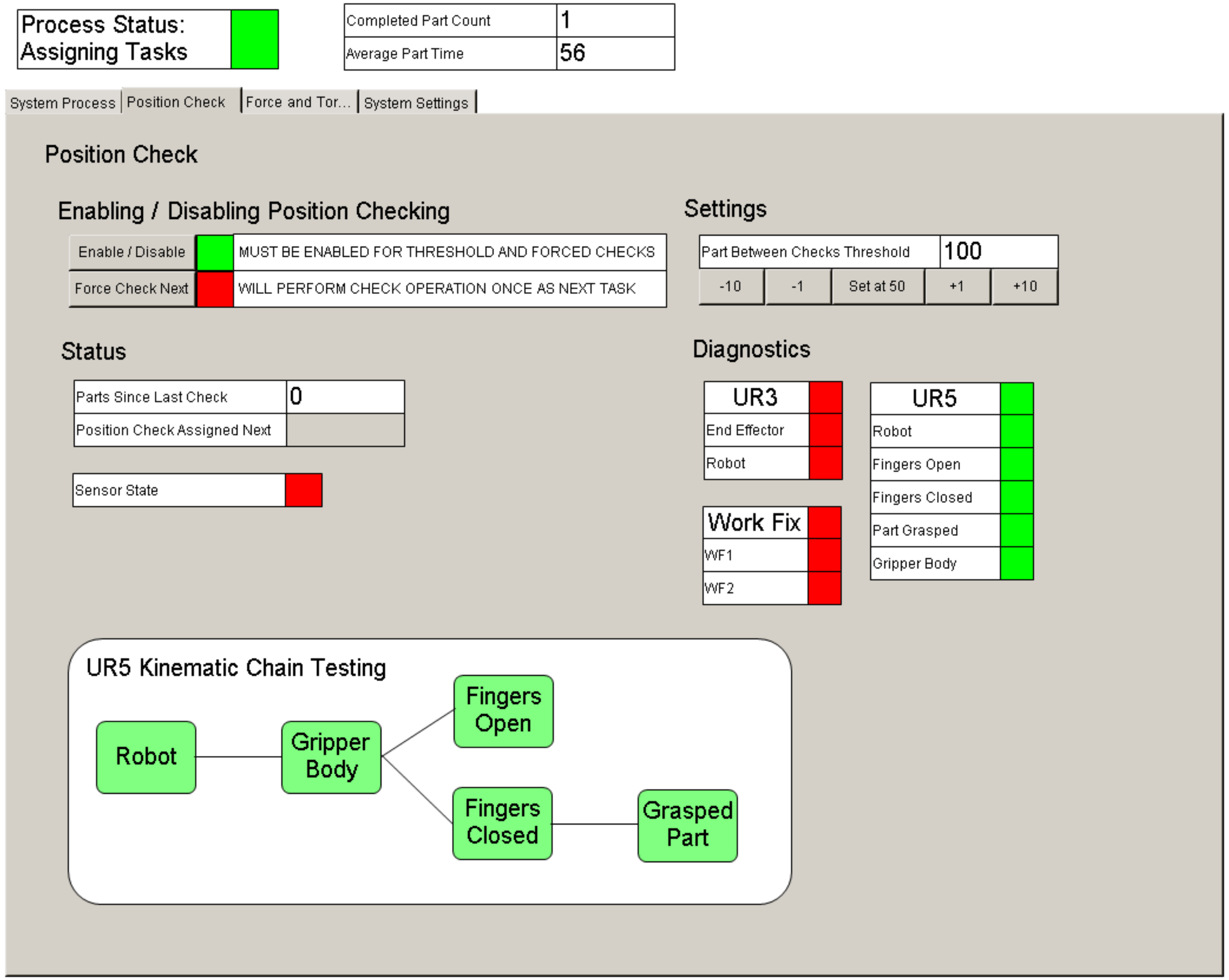
Test in order working away from the reference frame / measurement device



engineering laboratory PHM4SM

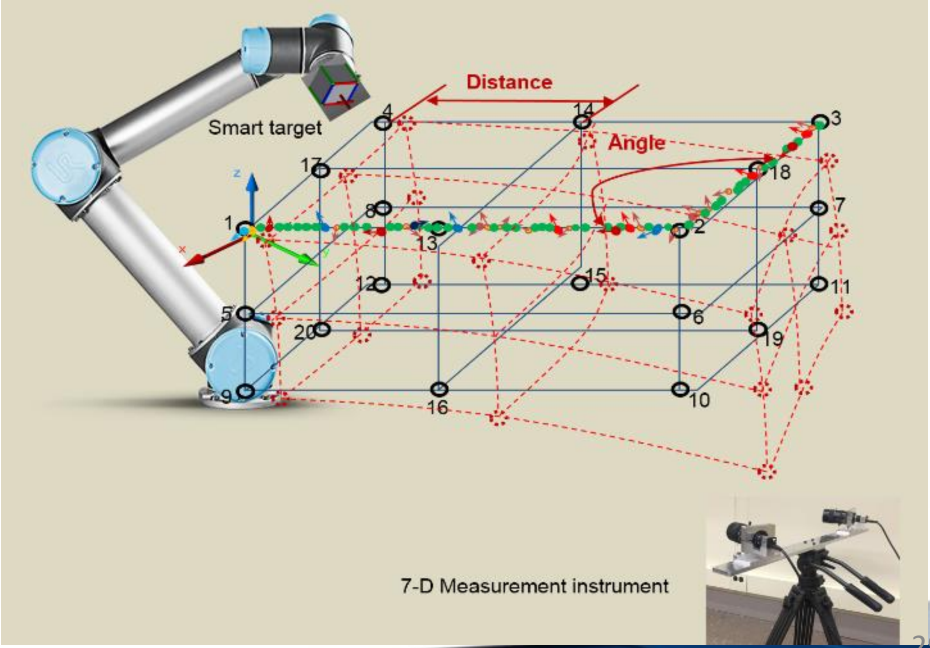
Testbed Application Example

- Implemented on testbed with inhouse designed sensor
- Measurement points:
  - Robot tool flange
  - Gripper Body
  - Fingers, Open
  - Fingers, Closed
  - Grasped Ideal Part
  - TODO - Fixtures

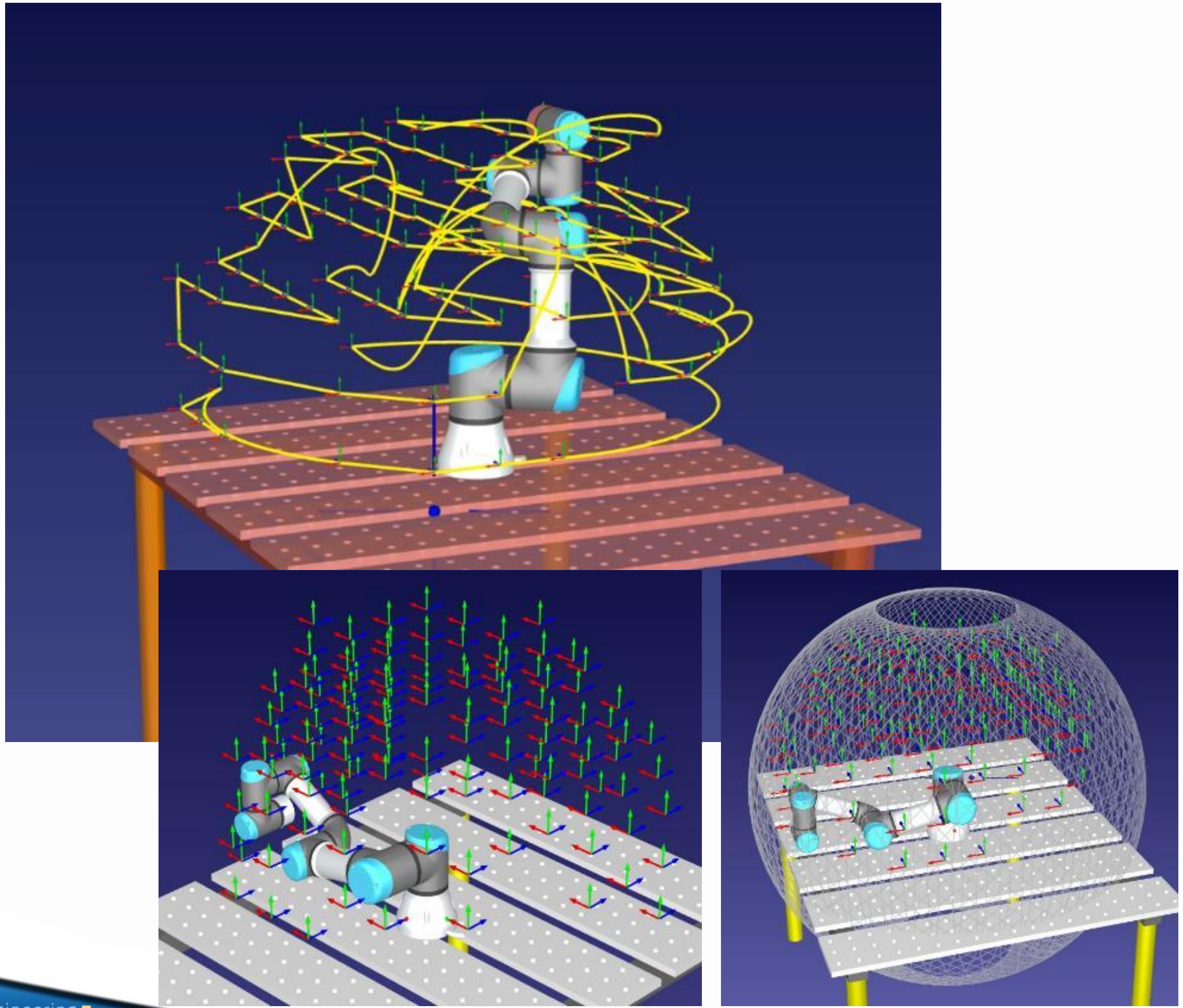


Robot Level Research – Assessment of Robot Accuracy Degradation

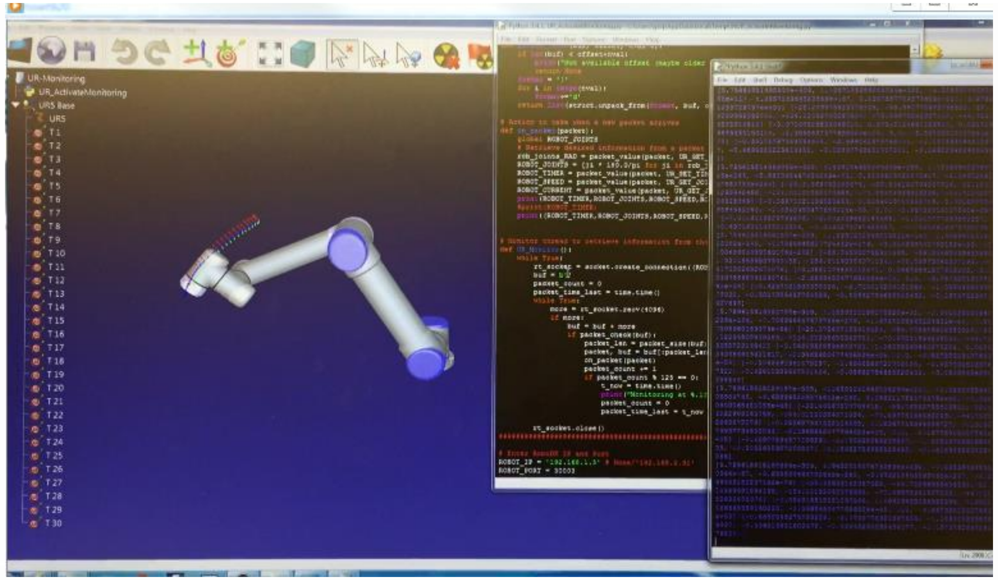
- **Research Objective**: Develop a quick health assessment methodology to enable manufacturers to assess the health of their robot arms by monitoring accuracy degradation
- **Key Output to Date:**
  - Algorithms and test method for quick robot position and orientation accuracy assessment
  - Advance sensing - 7-D measurement system
  - Innovative target – smart target
- **Impact:** Reference test methods will educate and guide manufacturers in deploying PHM to quickly assess robot health promoting greater employment of predictive maintenance strategies (e.g. robot system calibration, joint and gear box replacement etc.) that will increase efficiency and productivity while decreasing downtime.



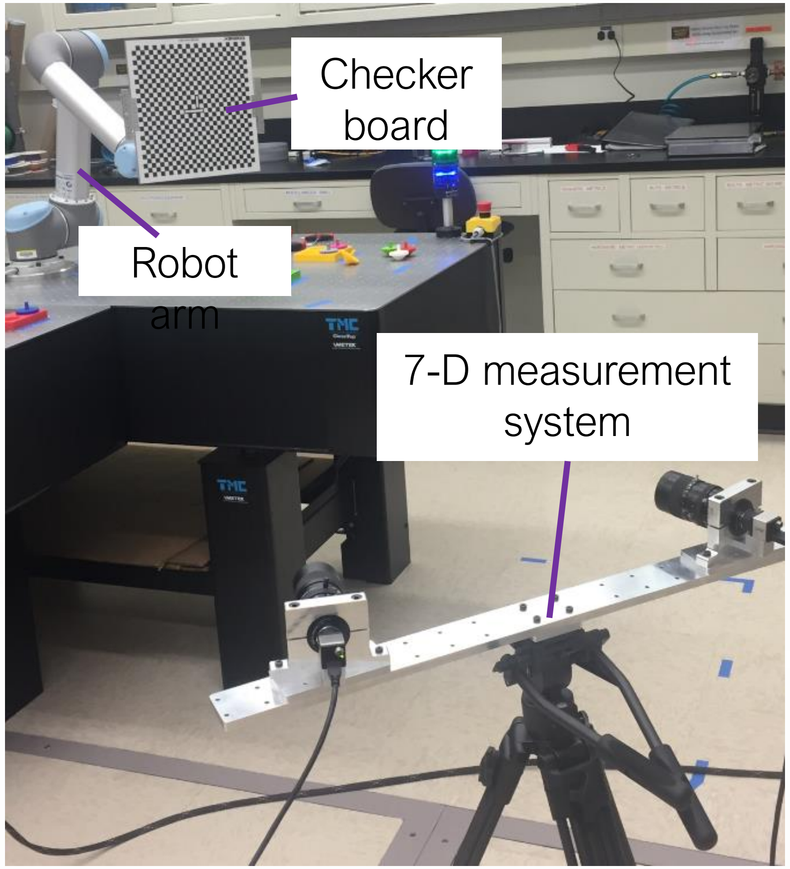
Test Method Development and Reference Data Collection

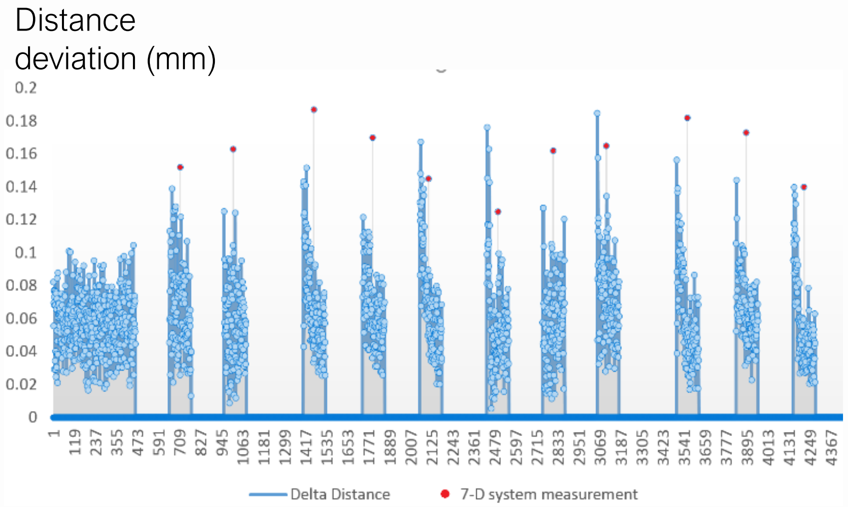


Real-time controller data collection



Robot – Reference Data Sets



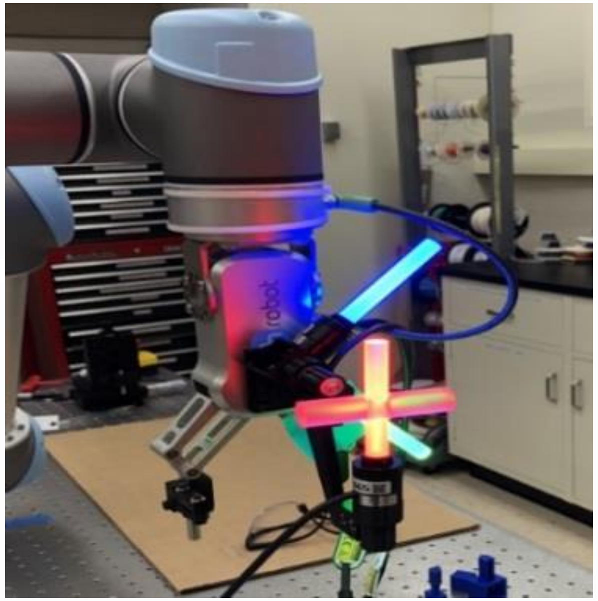


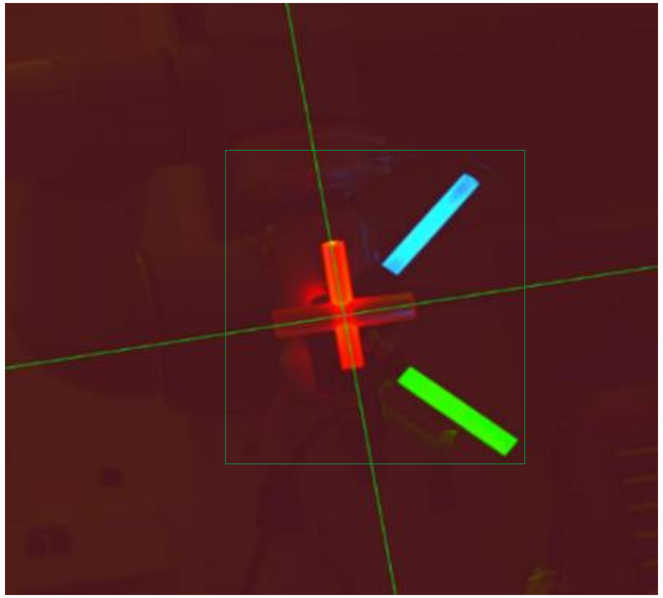
TCP deviations: 7-D system measured vs. calculated deviations from controller actual joint positions minus target joint positions

Reference data set URL:
https://www.nist.gov/el/intelligent-systems-division-73500/cognition-and-collaboration-systems/degradation-measurement

6-D Smart Target for Vision-based Measurement

- **What is it?** – A smart target (patent pending) that can be integrated with vision-based measurement instruments to acquire six-dimensional (6-D) information (x, y, z, pitch, yaw, and roll) of a moving object with high accuracy (accuracy down to 50µm).





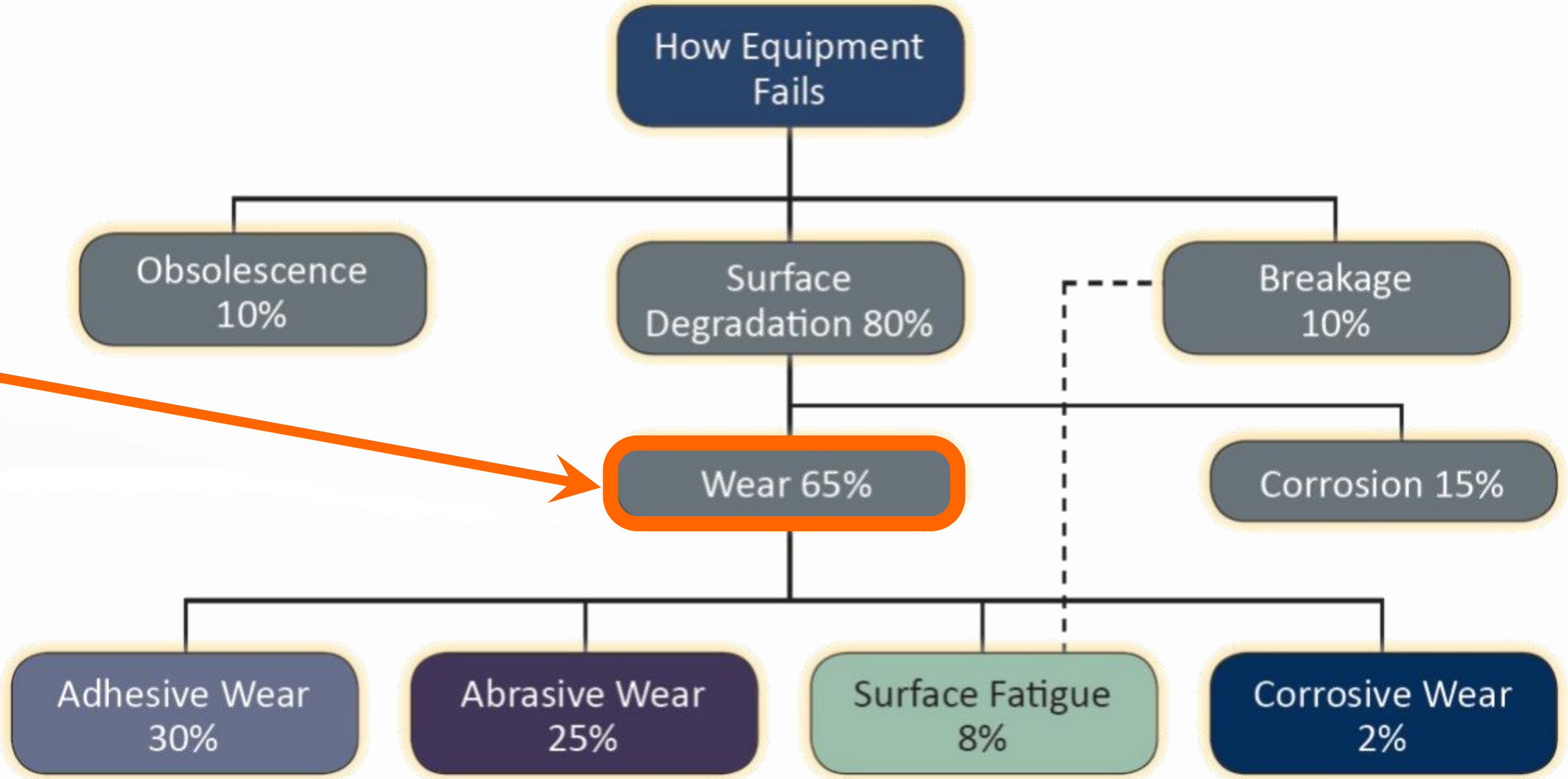
- Qiao, G., "Dynamic High Accuracy 6-D Measurement System with a Vision Agnostic Non-Blocking Smart Target," U.S. Provisional Patent Application serial number 62/672,270 filed on May 16, 2018

Problem = Unplanned Downtime

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

Wear

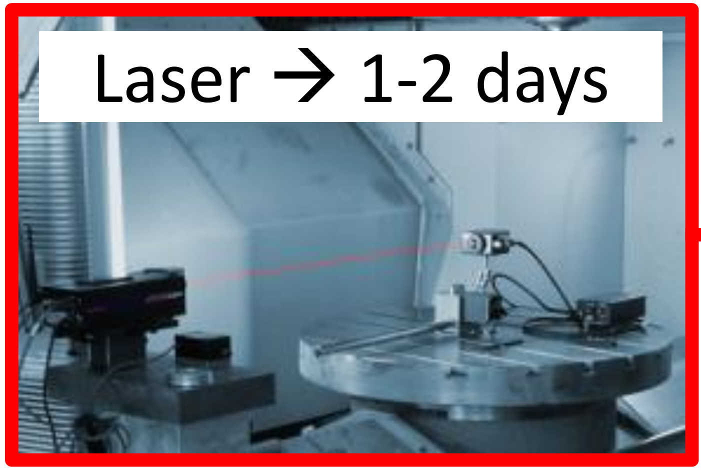
Machinery Lubrication (2004), *Wear in Rolling Element Bearings and Gears*



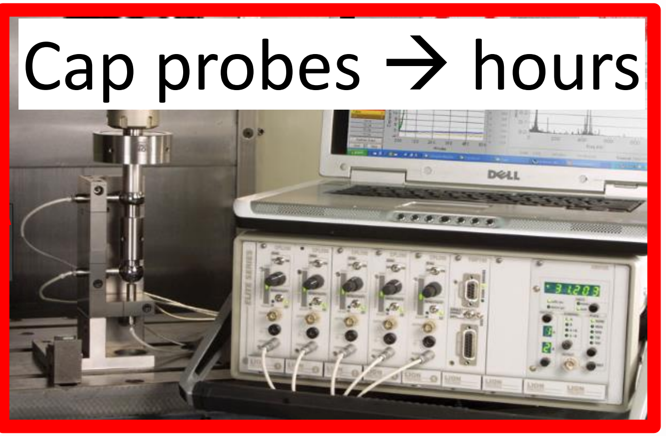
Reliabilityweb.com (2018), *Lubrication FMEA: The Big Picture*

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



API

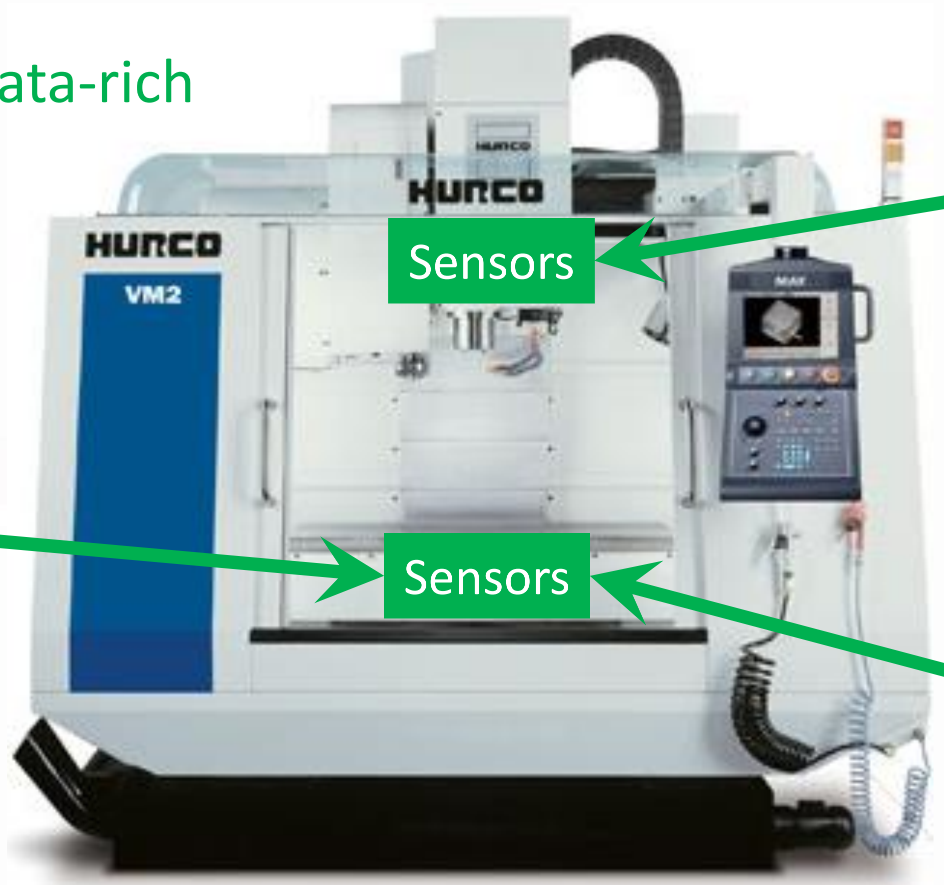


IBS Precision Engineering

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



Spindle Health Tracking

[How?]

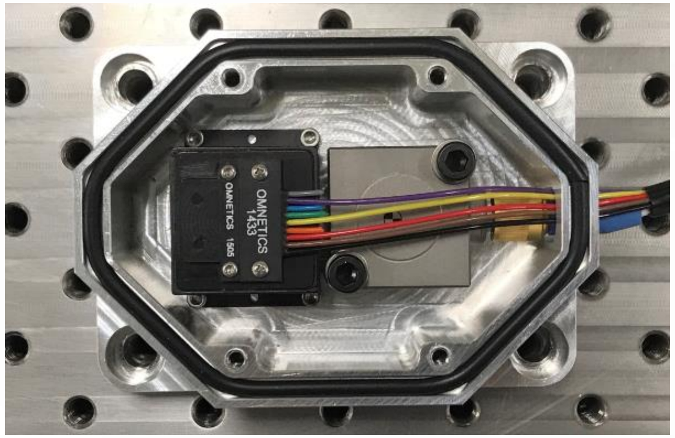
Linear Axis Health Tracking

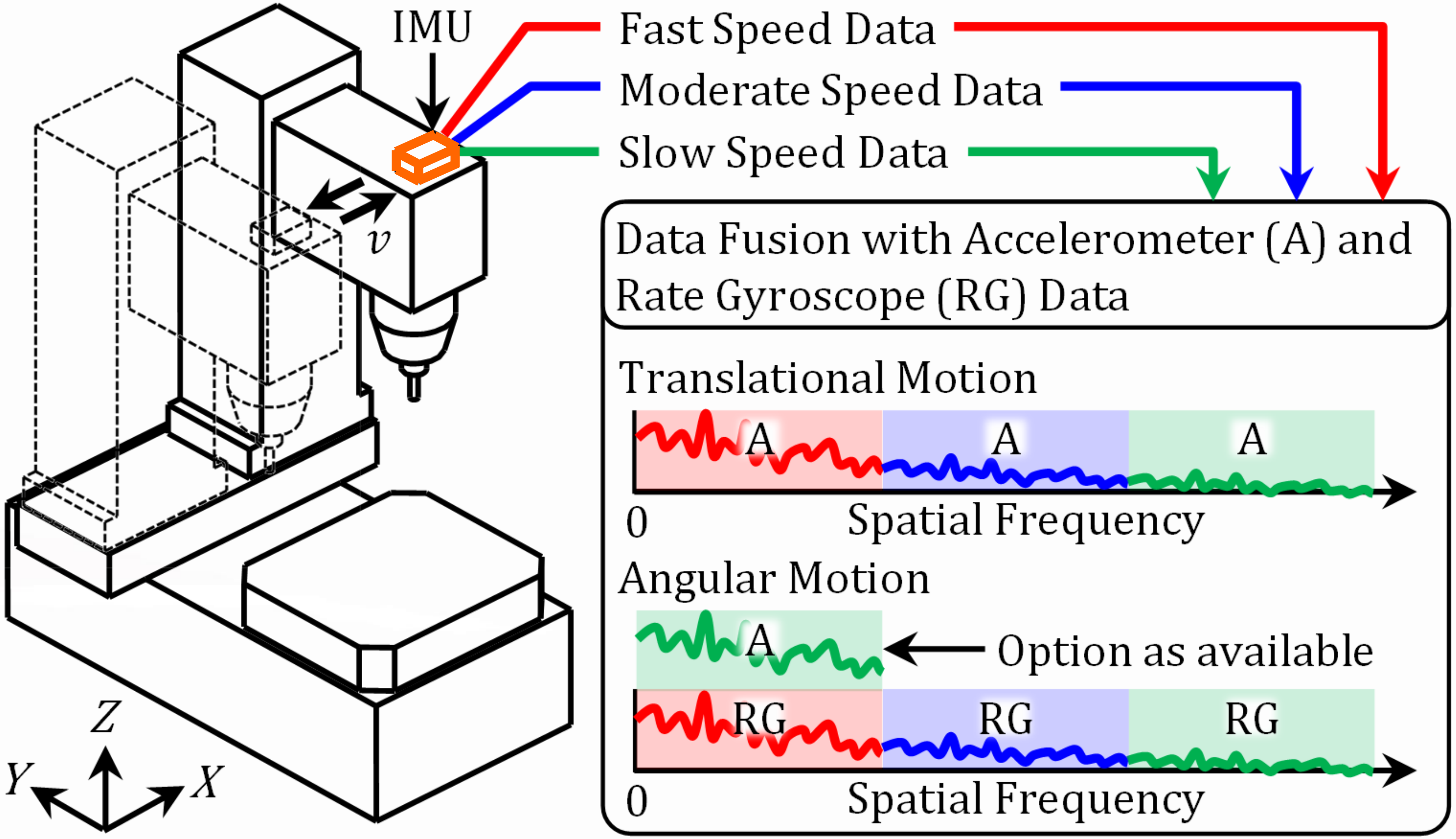
[How?]

Squareness Health Tracking

[How?]

IMU for Linear Axis Monitoring

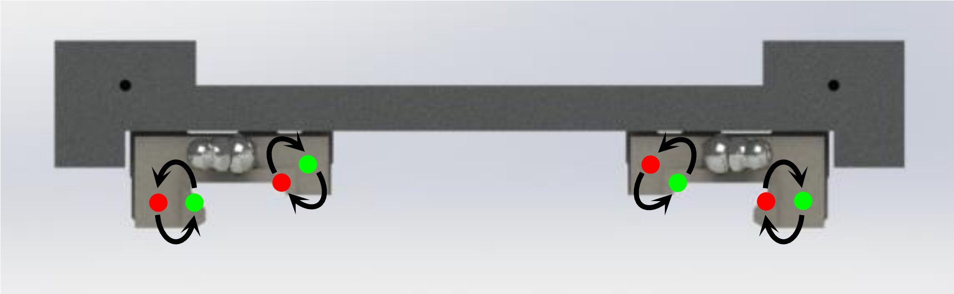


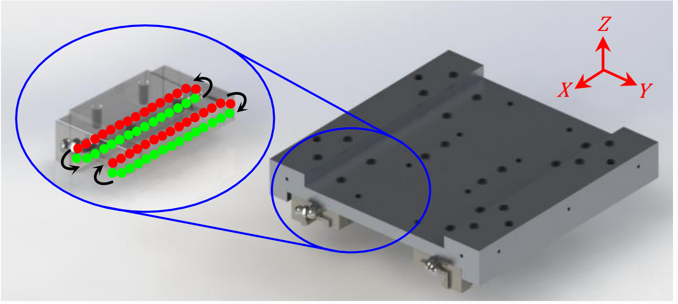


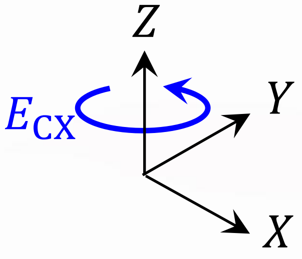
- G. Vogl, R. Pavel, A. Archenti, T. Winnard, M. Mennu, B.A. Weiss, and M.A. Donmez, "Identification of machine tool geometric performance using on-machine inertial measurements," *6th International Conference on Virtual Machining Process Technology (VMPT 2017)*, May 2017.
- G. Vogl, M.A. Donmez, A. Archenti, and B.A. Weiss, "Inertial Measurement Unit for On-Machine Diagnostics of Machine Tool Linear Axes," *Annual Conference of the Prognostics and Health Management Society*, October 2016.

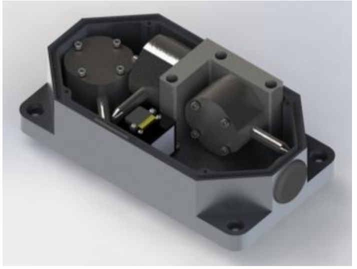
Performance Tracking to Diagnostics

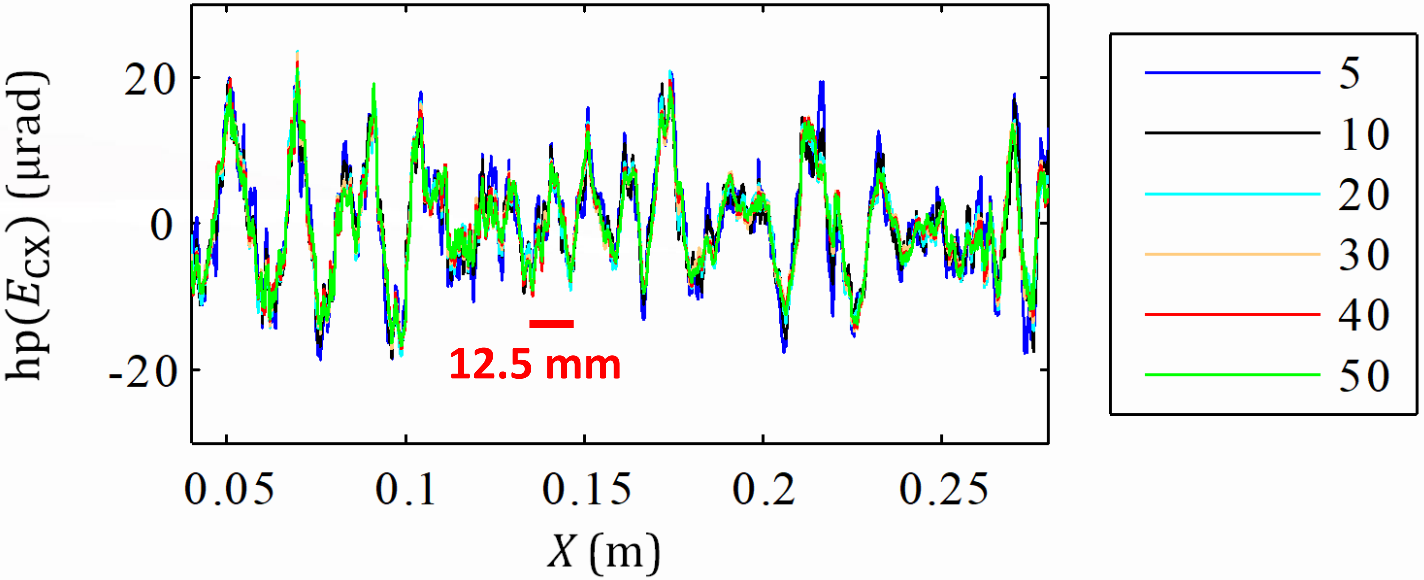
- 3.97 mm DIA $\xrightarrow{\times \pi}$ 12.5 mm ball-passing distance





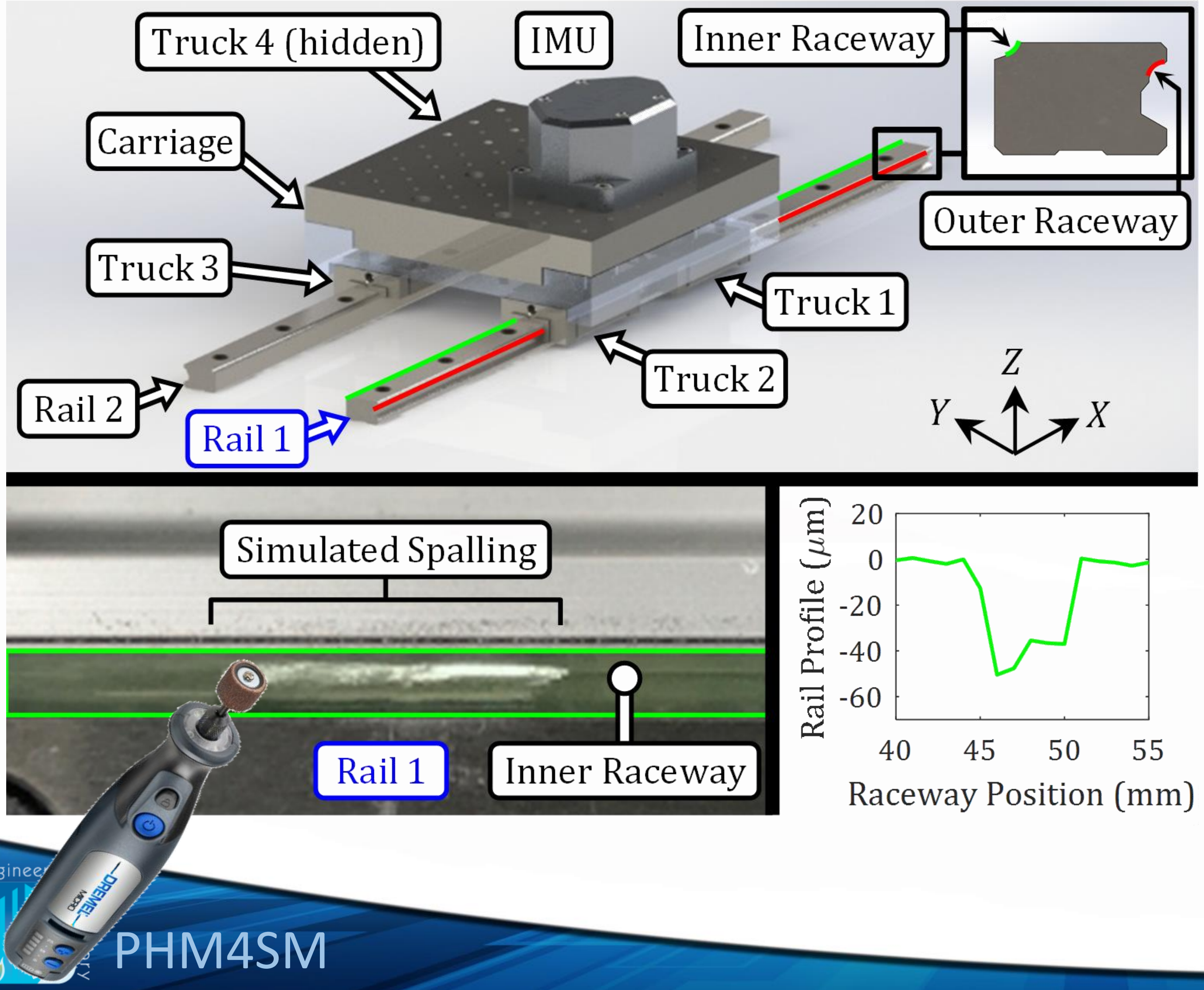




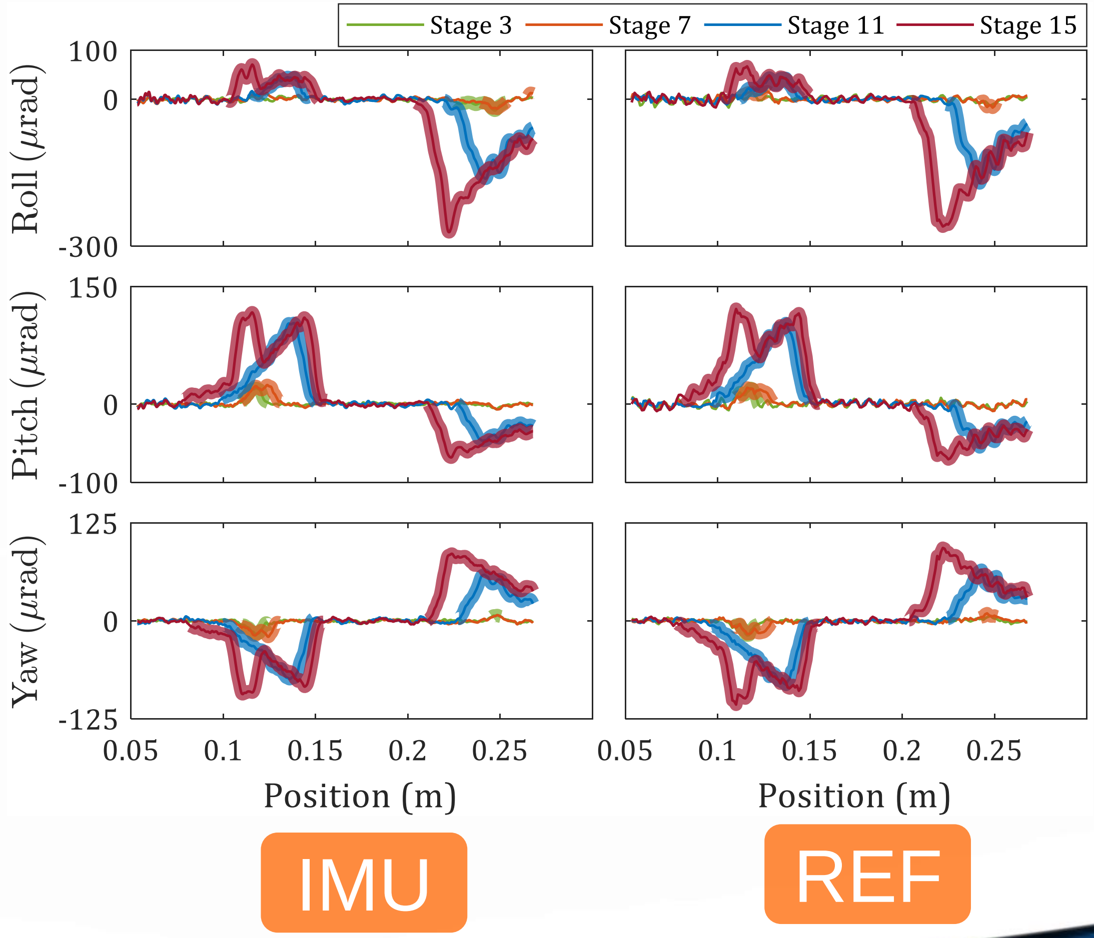


NIST Linear Axis Testbed

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



ΔError vs. Position



Further Enabling PHM…

- Aid manufacturers in designing, deploying, verifying, and validating PHMC strategies within their manufacturing operations

Questions to Answer During PHM Design & Deployment

- What physical or task degradation has the potential to impact the metrics I care about most in my process?
  What health degradations can impact my quality, productivity, scrap, etc.?
- What data, leading to intelligence, do I need about my process to determine where and when health degradation will occur?
  What can be monitored and how?
- How do I prioritize the risk of faults and failures in my system and process?
  Where should I deploy PHM since I can't put it everywhere?
- How does the health of my physical system, and its constituent elements, influence the health of my process?
  How can I map the relationships between the physical and functional to better understand my process?

engineering laboratory

Next Steps

- Continue research in the machine tool and robotics domains
- Output additional reference datasets
- Pilot test methods and protocols in manufacturing environments
- Contribute to standards development
- Be responsive to the manufacturing community's needs

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

From NIST *Tech Beat*: August 26, 2015

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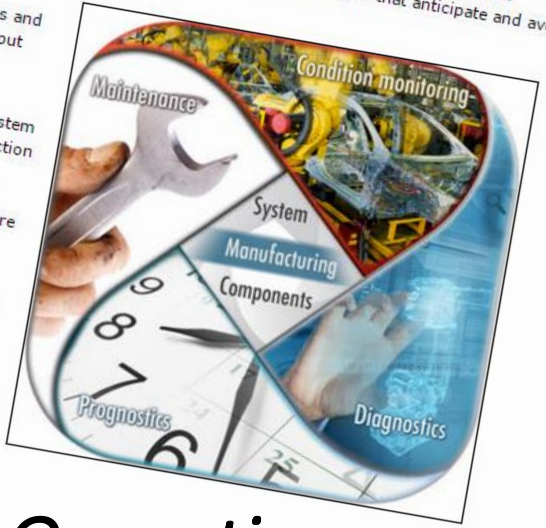
In today's increasingly complex manufacturing operations, Murphy's Law is only an unexpected hiccup away—anything from a data error to an errant vibration to a dulled cutting tool can undermine production. But in a future with fully effective sensing and information technologies that anticipate and avert 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 and Health Management for Reliable Operations in Smart Manufacturing

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