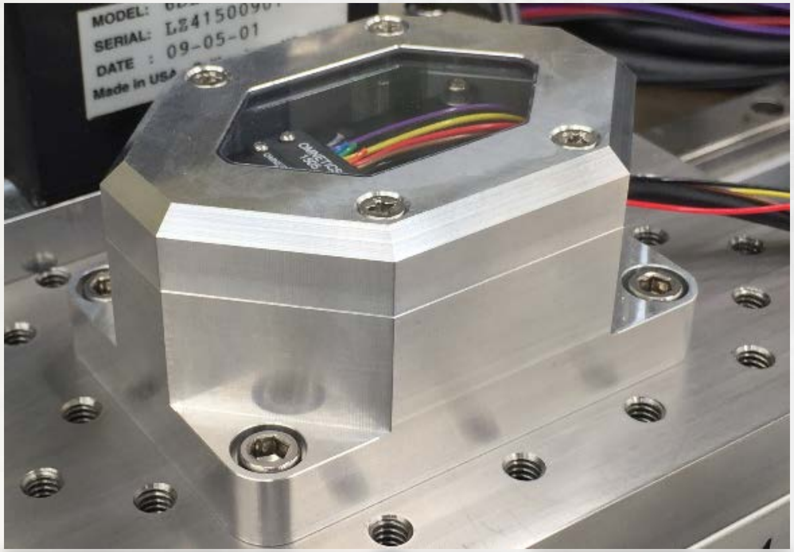
Determination of machine tool geometric performance using on-machine inertial measurements



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2nd 3D Metrology Conference – 3DMC, October 9-11, 2017 (Aachen, Germany)

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

Outline

- Motivation
- Method
- 1st Experiment
- 2nd Experiment
- Conclusion

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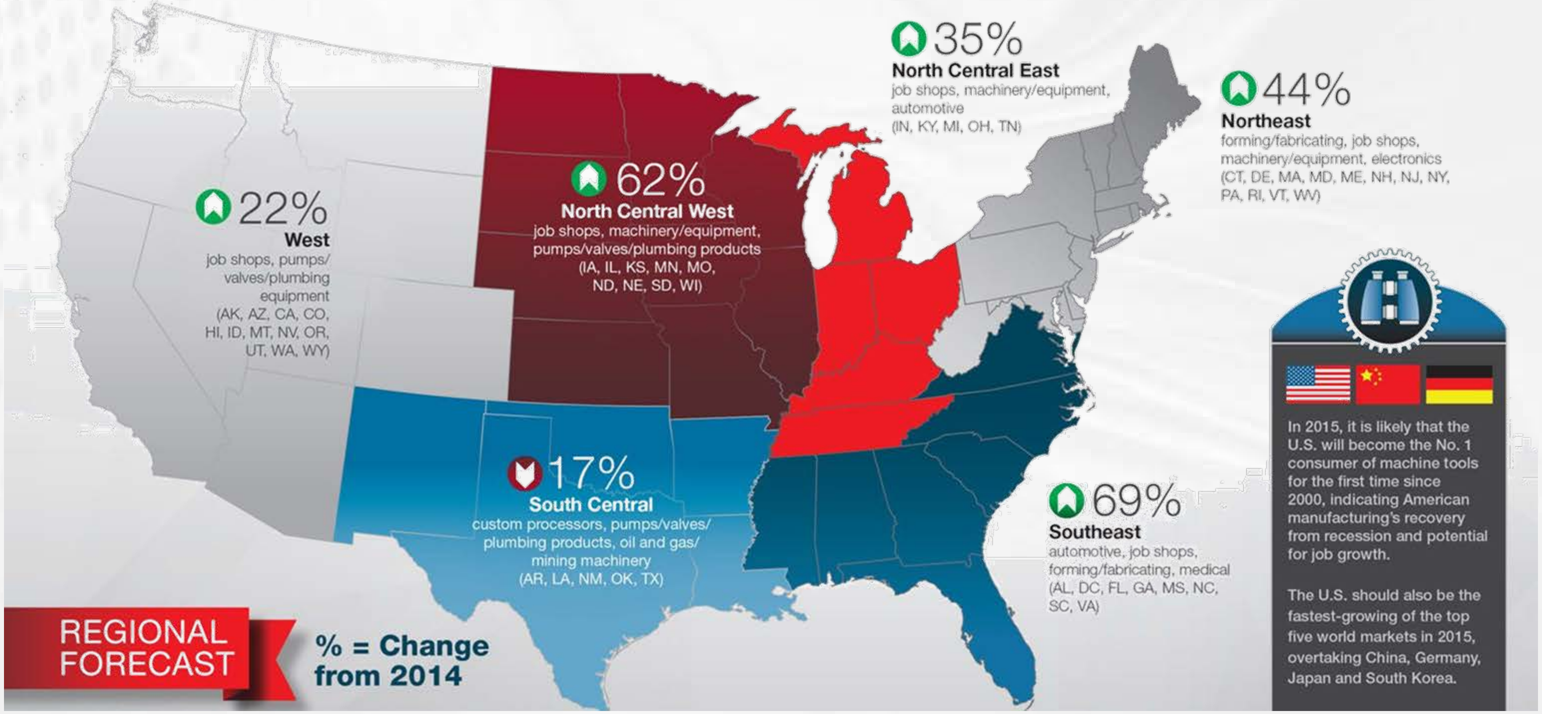
NIST → Economic Growth

- 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 ~1,300 manufacturing specialists through 400 manufacturing extensions

Manufacturing = Economic Growth

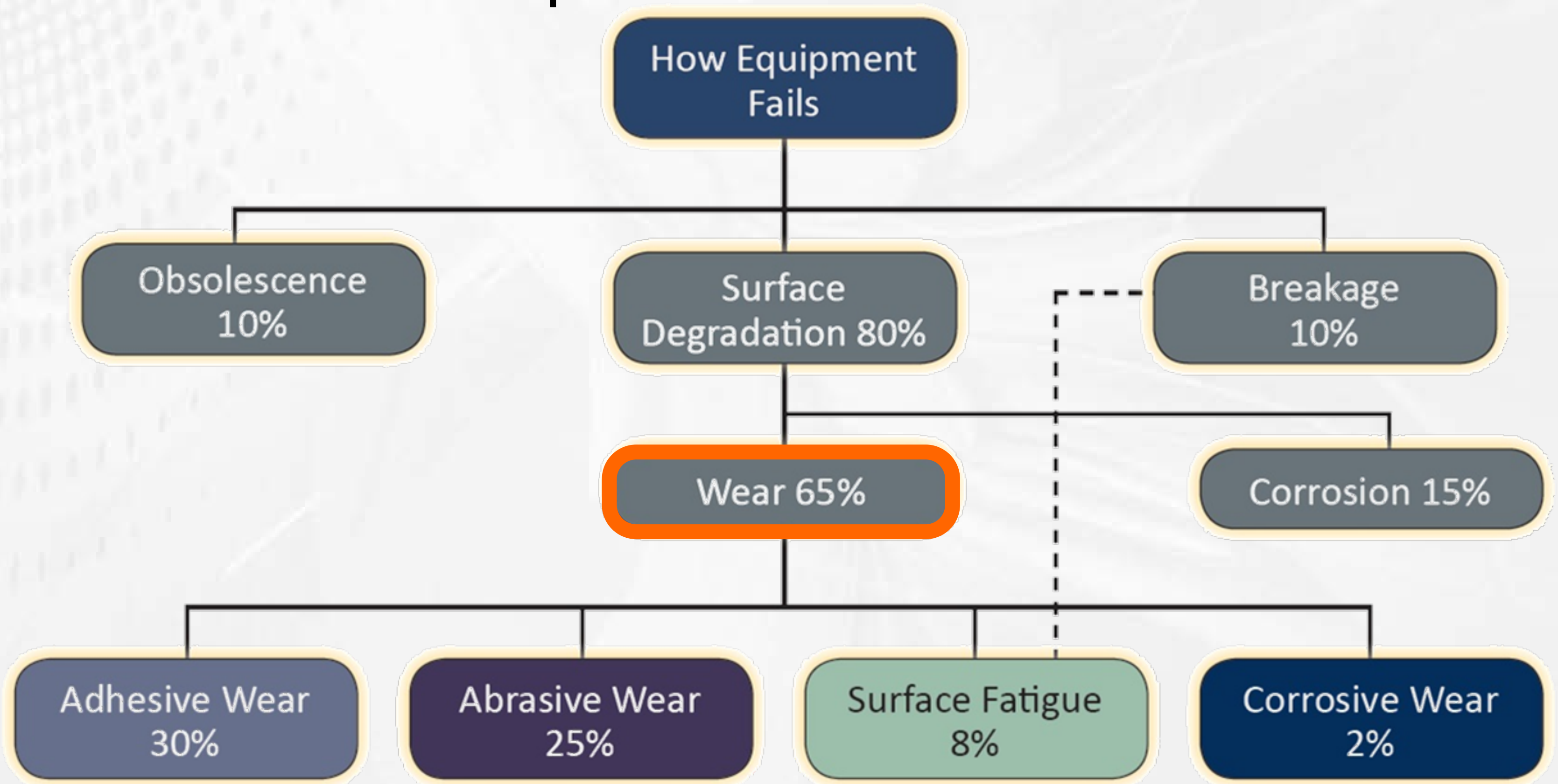
- Manufacturing = 12.1M U.S. jobs & 61% exports
- $8.8B forecasted spending in 2015 on metalcutting equipment, an <u>increase of 37% over 2014</u>



http://www.mmsonline.com/cdn/cms/1214-MMS-infogrfx-2014_x2-1_lowRes.jpg

Degradation Affects Production

- **Machine Tool Degradation** is unavoidable and causes faults & unplanned downtime



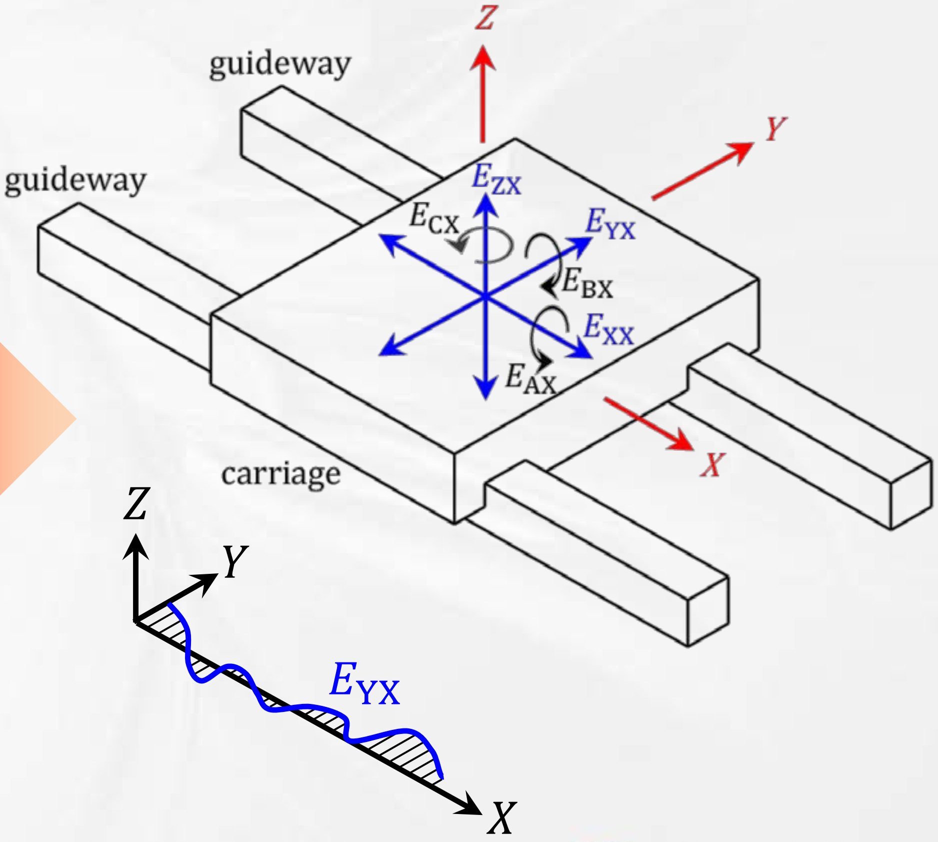
http://reliabilityweb.com/index.php/articles/lubrication_fmea_the_big_picture/

Wear Changes Performance

- Linear axis performance defined by error motions
- Tolerances = 20 μm & 60 μrad over 1 m of travel

Wear

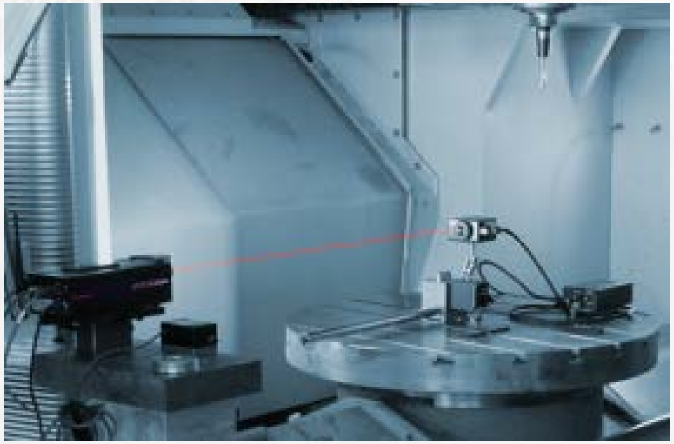
http://www.machinerylubrication.com/Read/664/wear-bearings-gears



How Is Performance Tracked?

- Faults/failures → 10s of $Billions (> new machines!)
- Routine tracking of performance can be expensive in time & equipment

1-2 days



http://www.apisensor.com/user-story-carter-ats/

30-60 minutes

http://www.renishaw.com/en/qc20-w-ballbar-system--11075

?

- Industry challenge: “Machine health in 5 min?”

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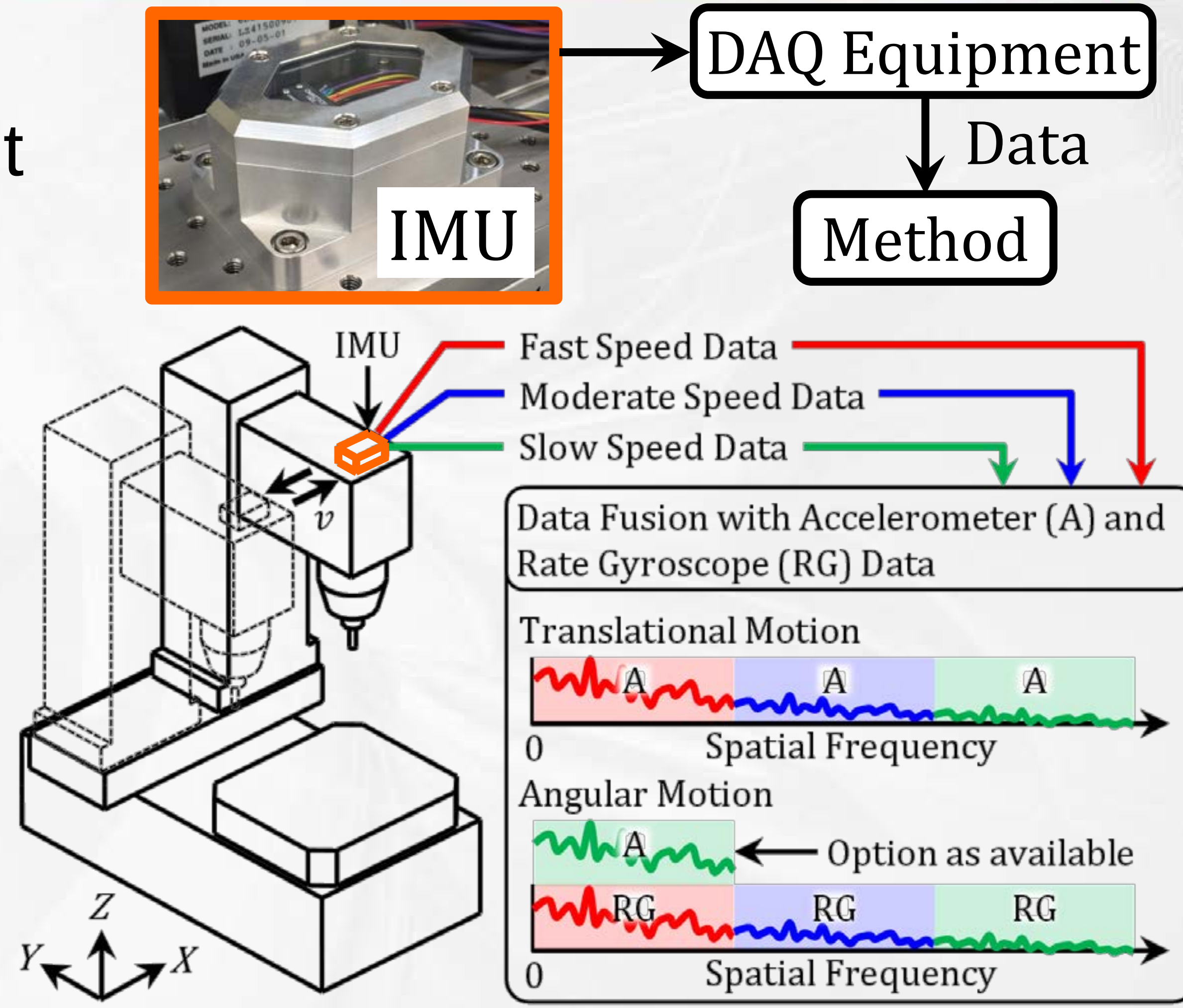
Technical Concept

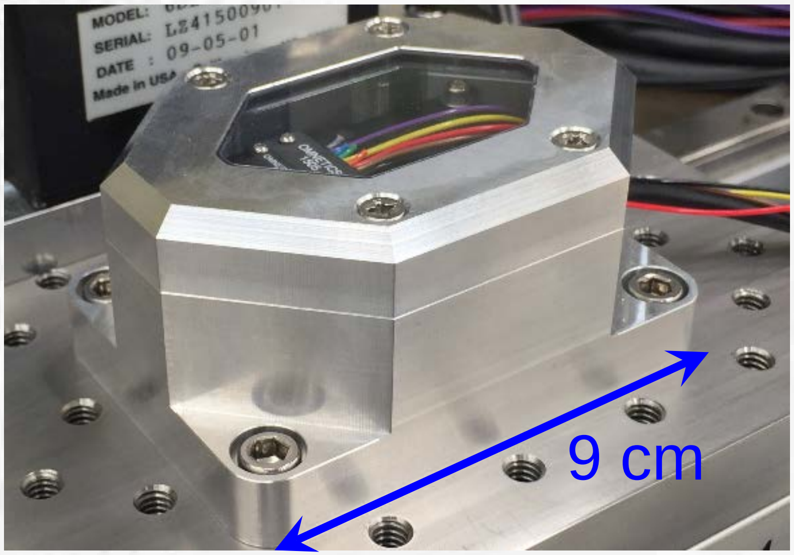
- Inertial measurement unit (IMU) measures <u>changes in error motions</u>
- 6-DOF
- IMU could answer industry challenge:
  - Non-intrusive
  - Quick

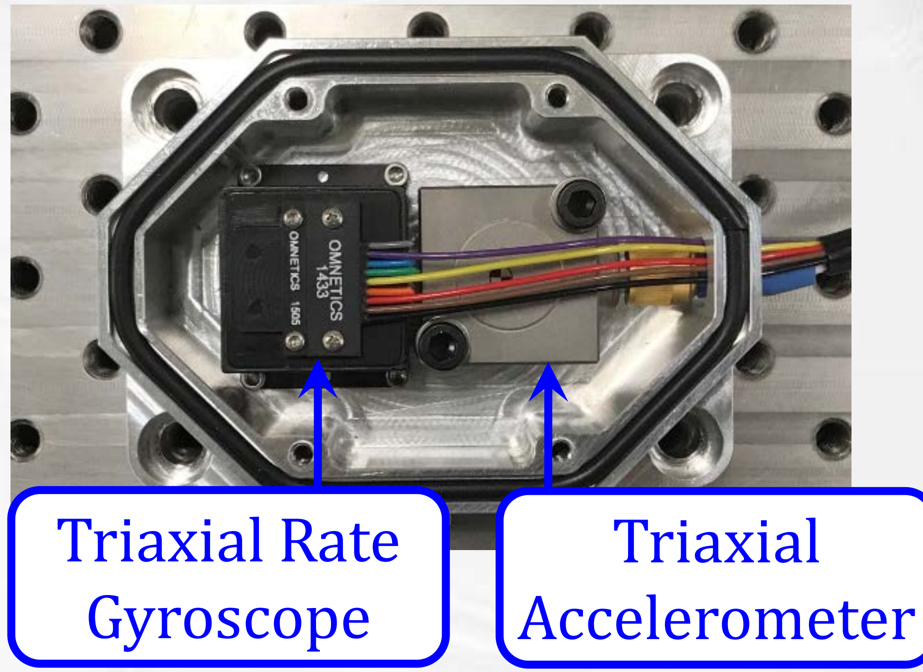


Ref: Vogl G.W., Donmez M.A., and Archenti A. (2016) Diagnostics for geometric performance of machine tool linear axes. *Annals of the CIRP* 65(1): 377-380.

IMU Sensors

- IMU uses precision MEMS inertial sensors



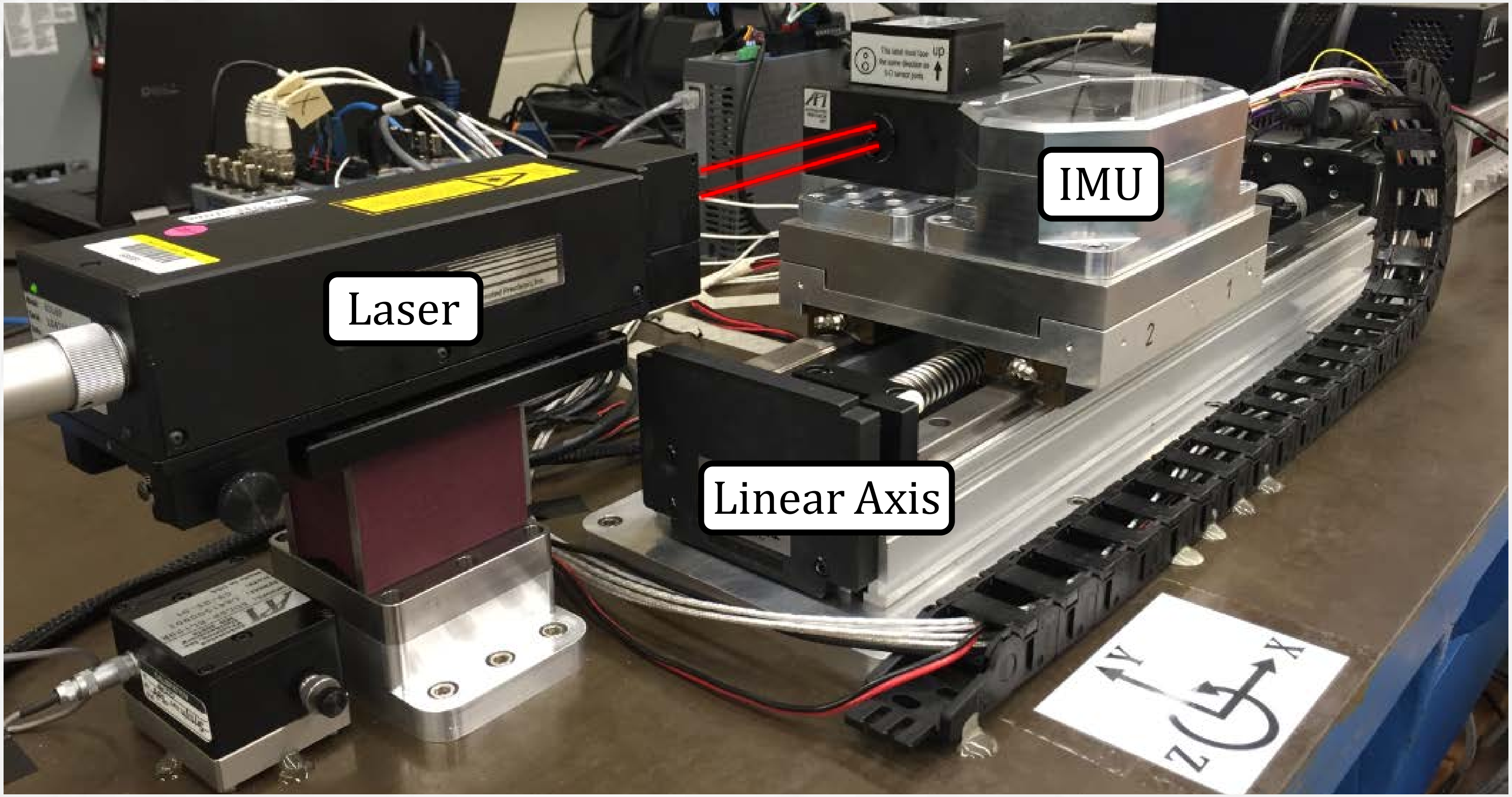


Sensor	Bandwidth[a]	Noise
Accelerometer	0 Hz to 400 Hz	69 (μm/s²)/$\sqrt{\text{Hz}}$
Rate Gyroscope	0 Hz to 200 Hz	35 (μrad/s)/$\sqrt{\text{Hz}}$

[a] frequencies correspond to half-power points, also known as 3 dB points

Linear Axis Testbed

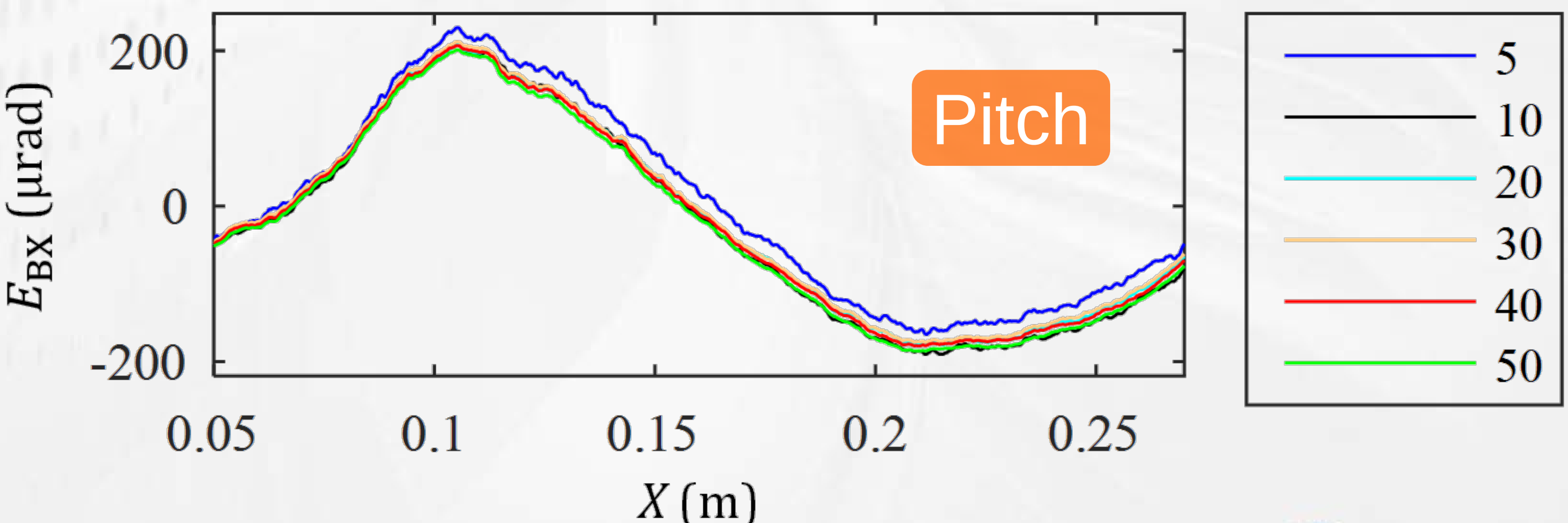
- Compare IMU-based results to laser-based results



Convergence via Averaging

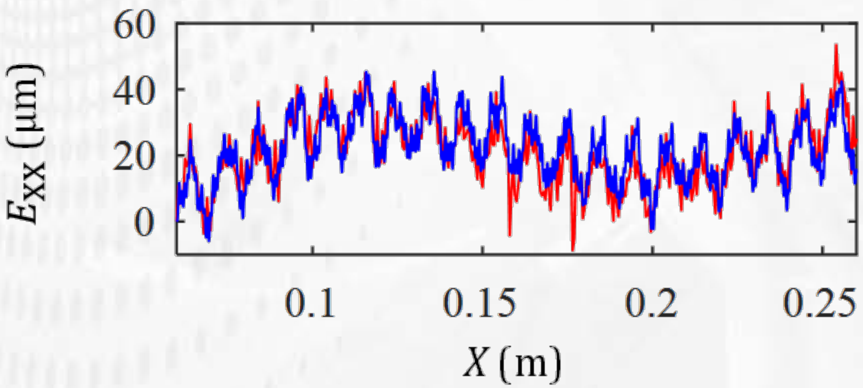
- Results are averaged across runs (5, 10, ..., or 50)
- Convergence within 5 µm or 15 µrad for < 10 runs

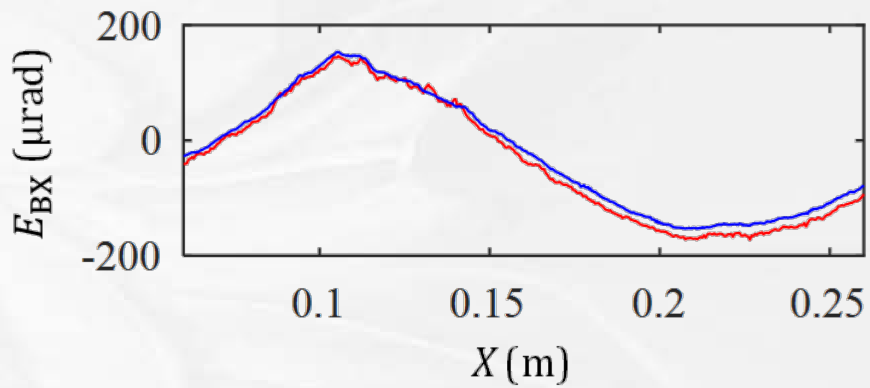
Data is collected over and over again for same path to achieve convergence

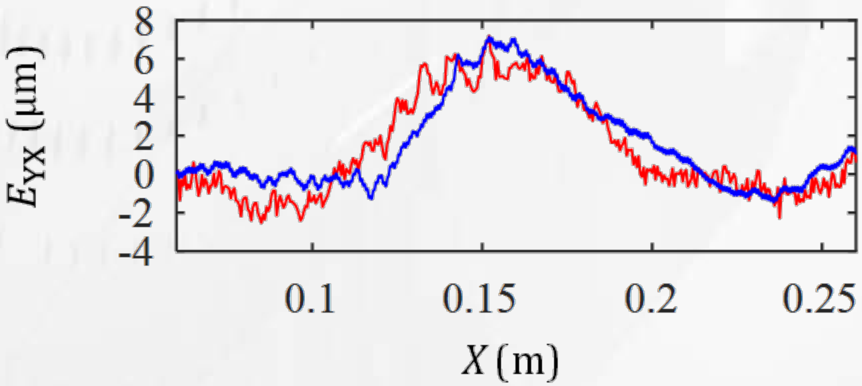


General Results

- Example: Converged error motions from IMU match those of laser-based system







Errors within ±11 µm, ±2.3 µm, and ±13 µrad (k = 1) for positioning, straightness, and angular error motions

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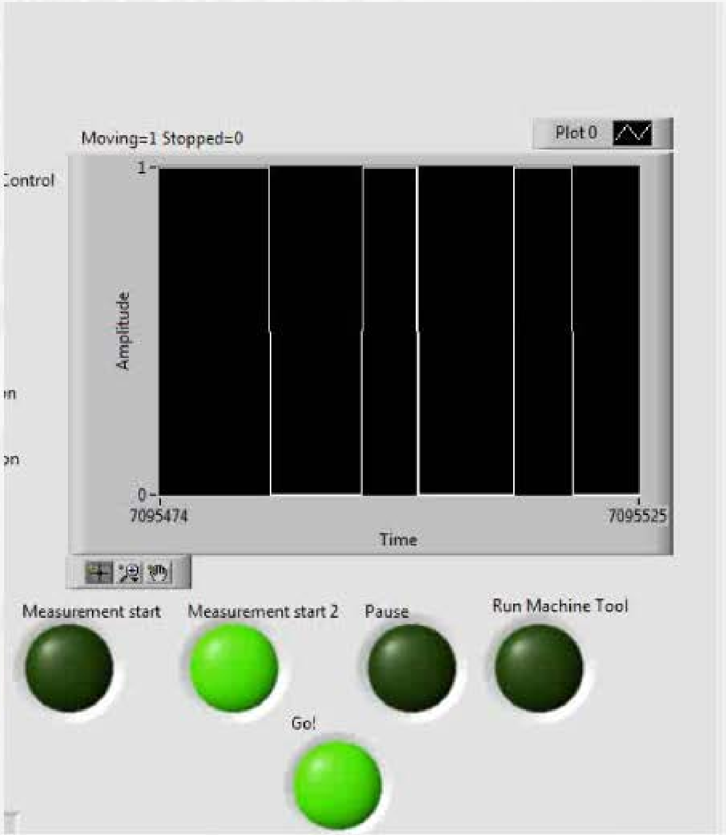
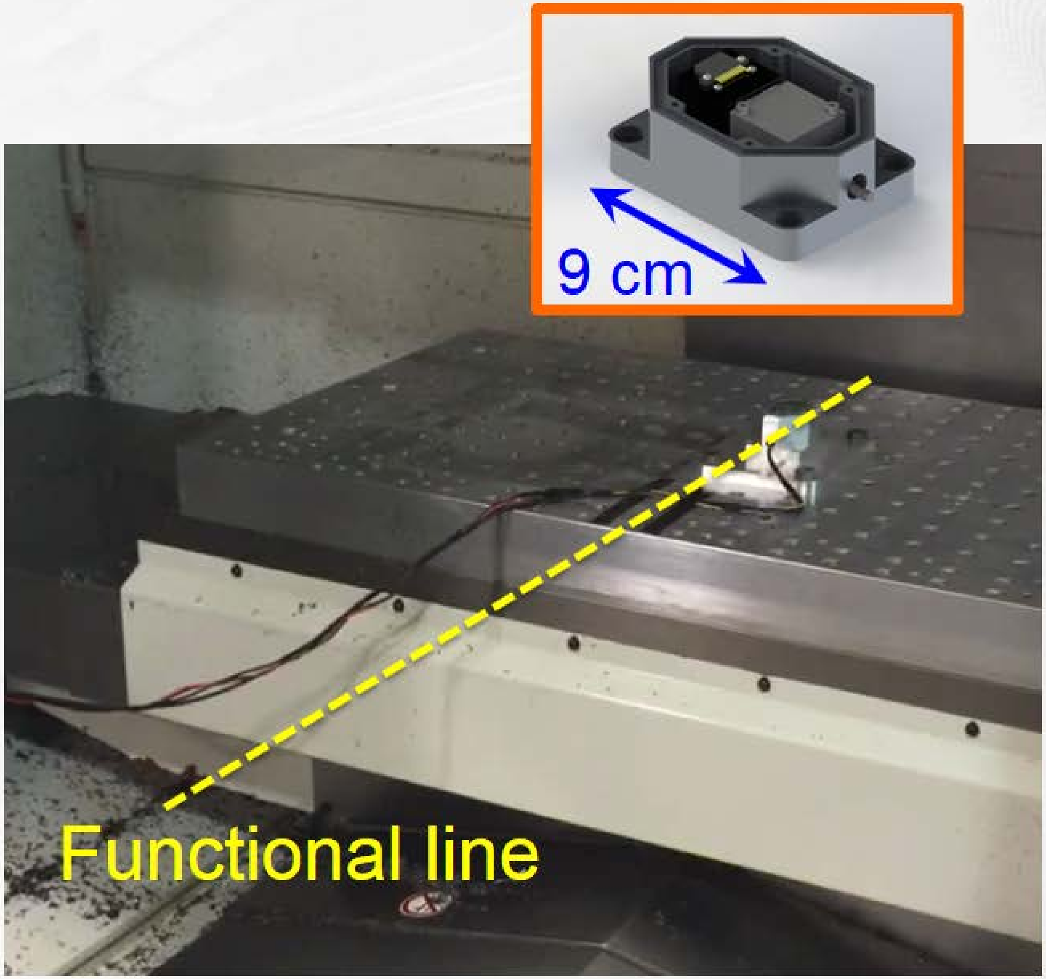
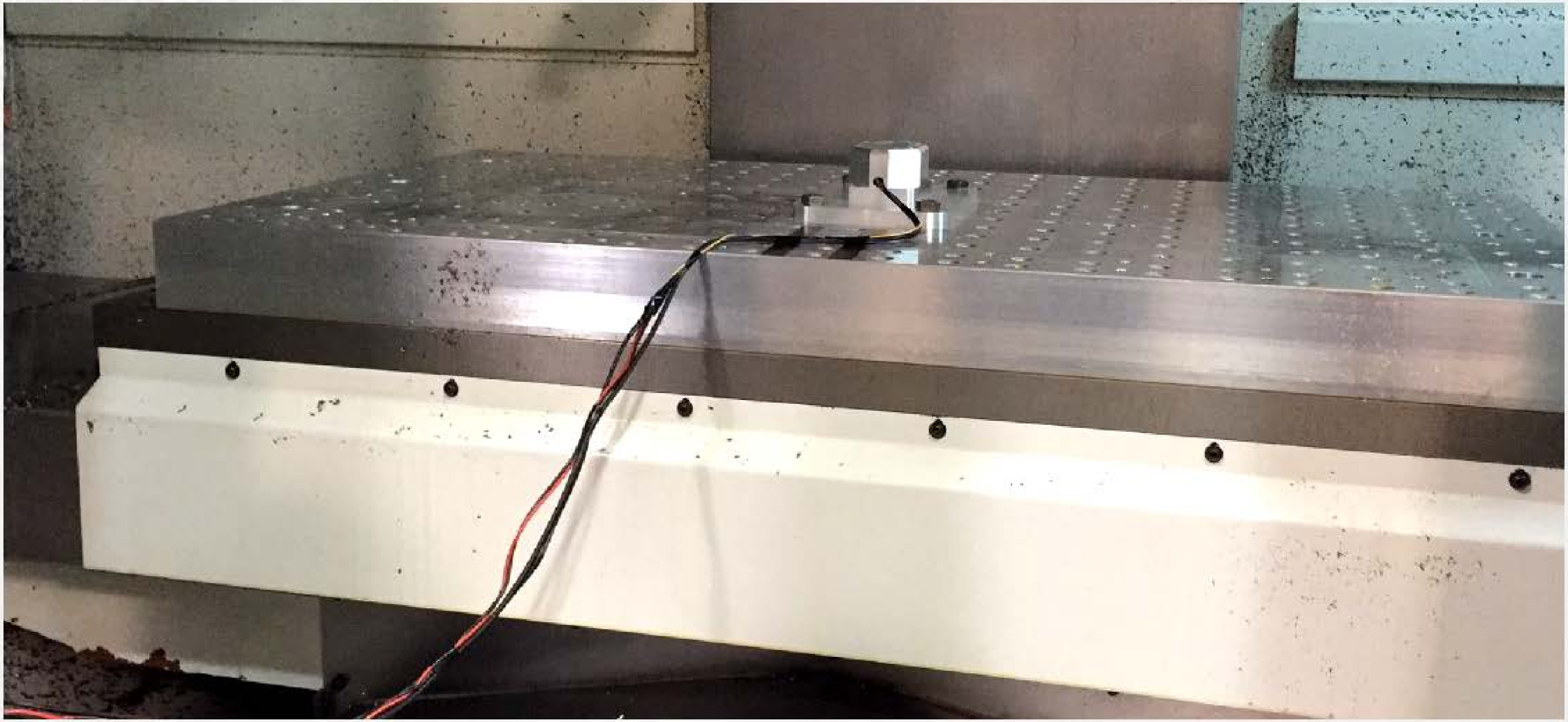
Small IMU on Machine Tool





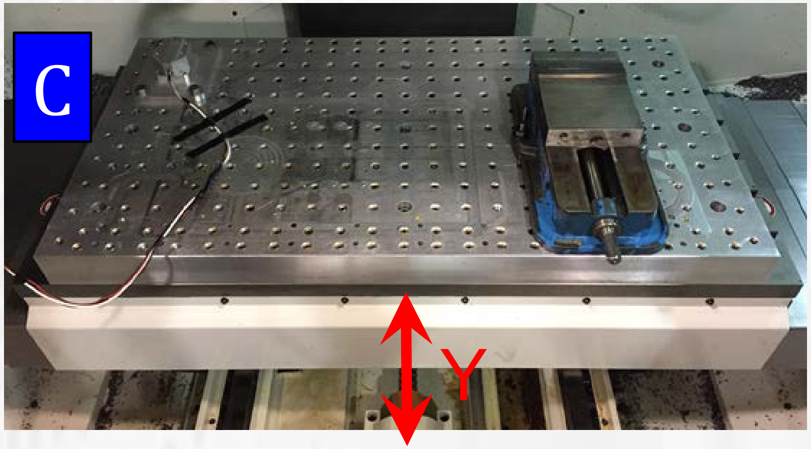
Data Collection

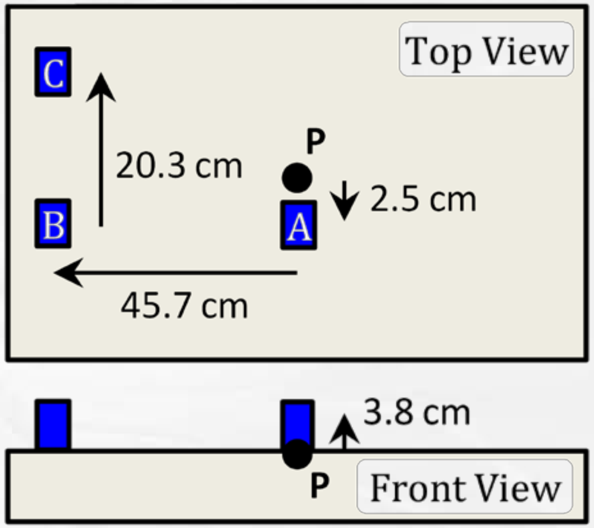
- Each run uses 3 different axis speeds
  - 0.02 m/s (‘Slow’), 0.1 m/s (‘Moderate’), 0.5 m/s (‘Fast’)

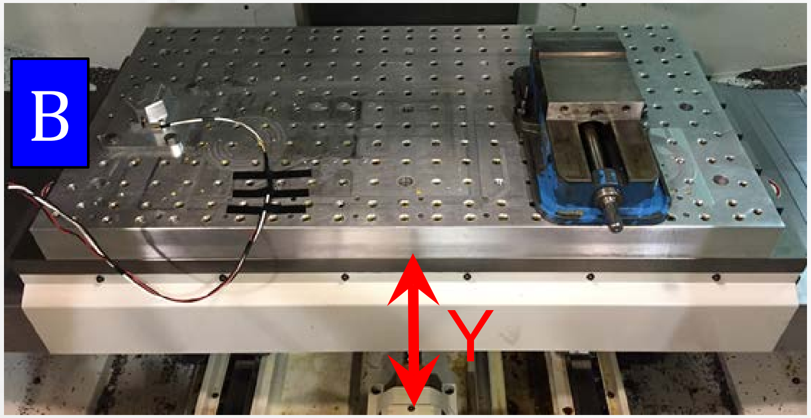


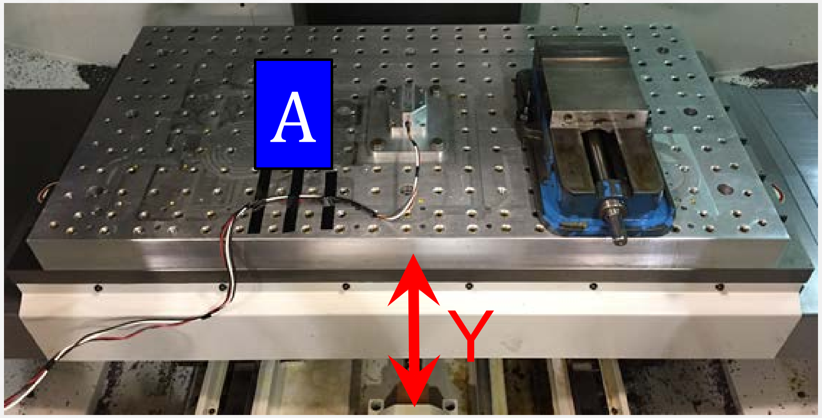
Small IMU on Machine Tool

- IMU on X-axis work subplate while Y travels

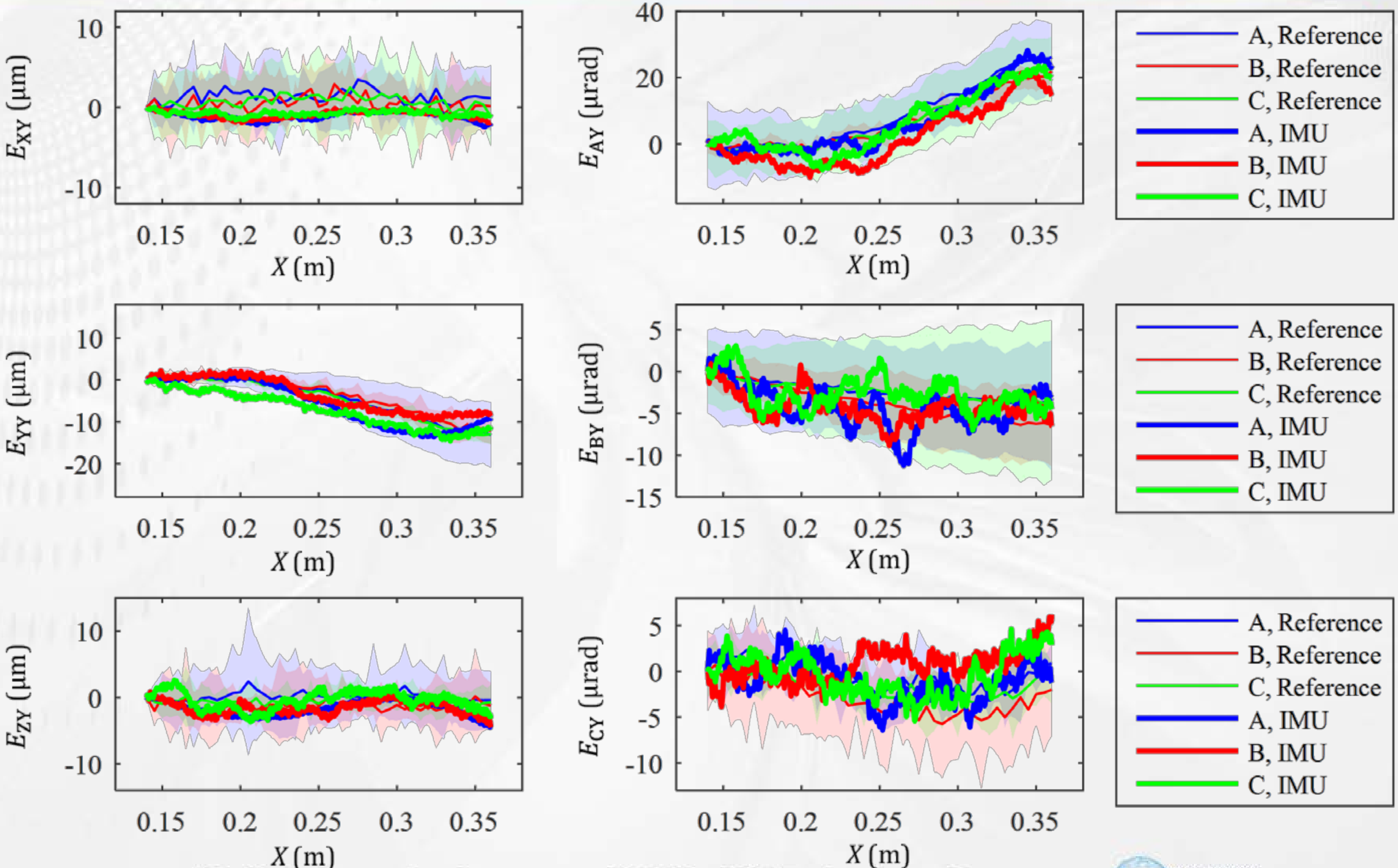






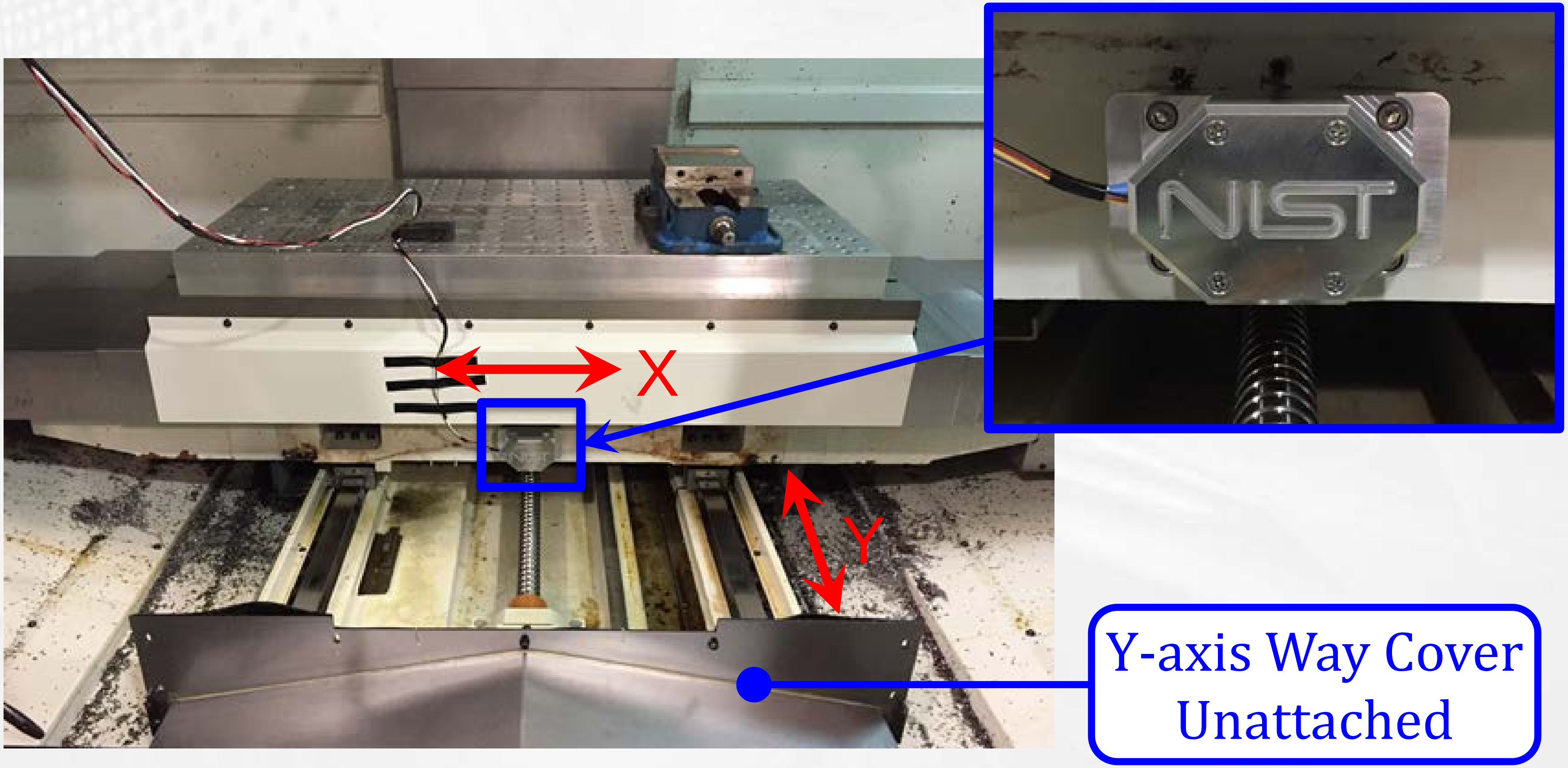


Error Motions – IMU vs. Reference



Small IMU on Machine Tool

- IMU can live within machine tool for seamless integration



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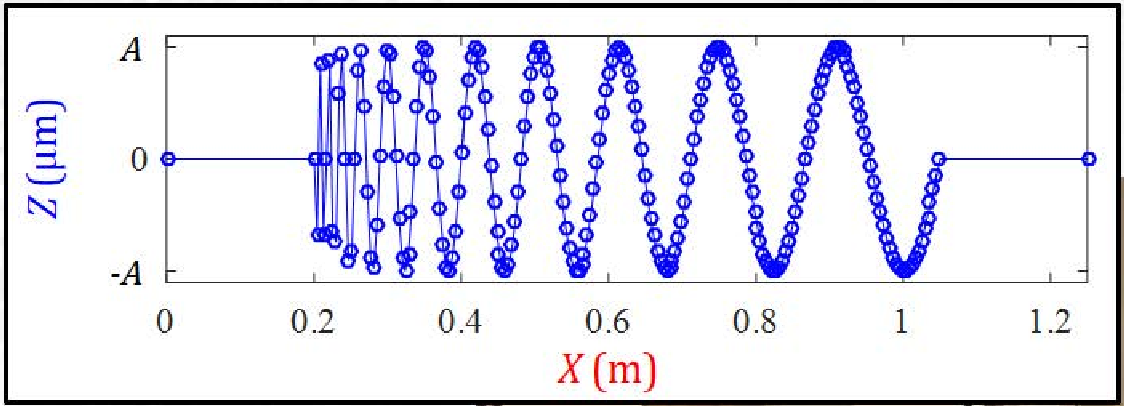
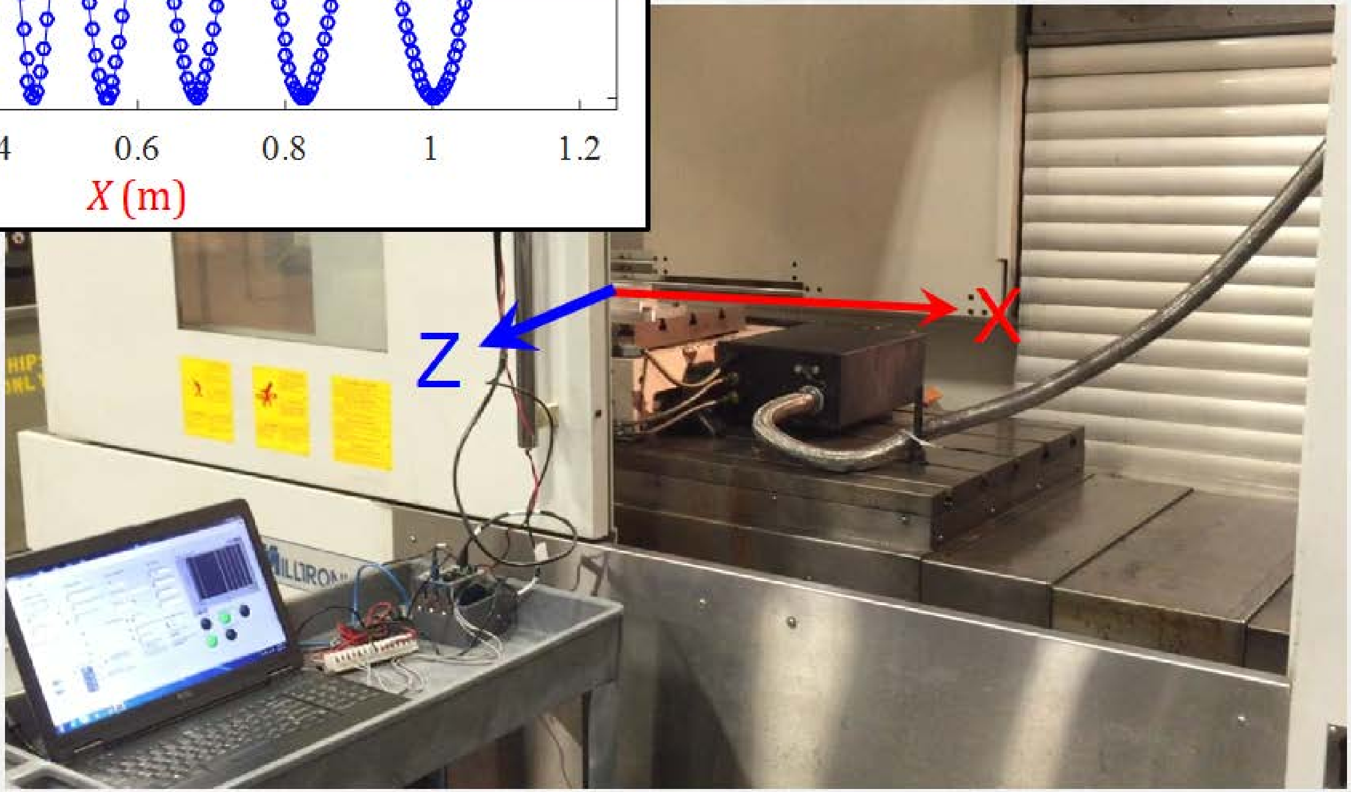
Small IMU on Machine Tool

- Mechanically simulate degradation via 2-axis motion



- *A* varies from 0 μm to 20 μm



Small IMU on Machine Tool

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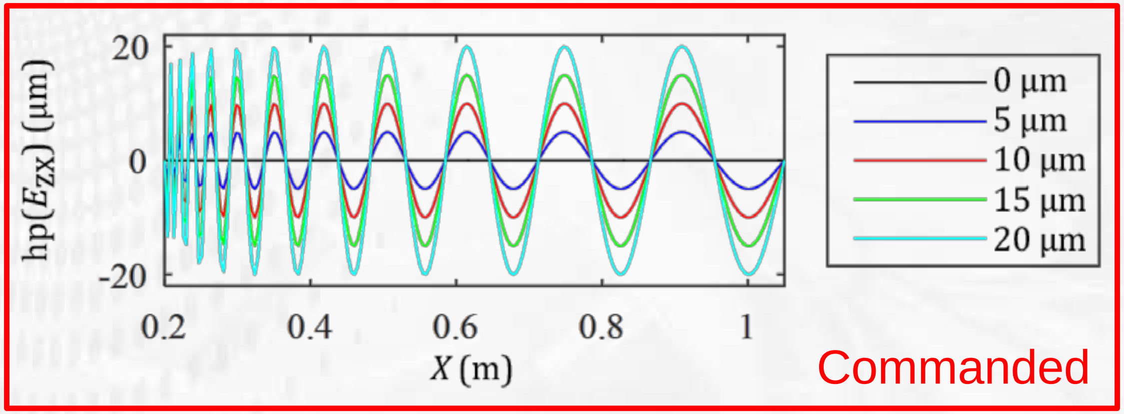
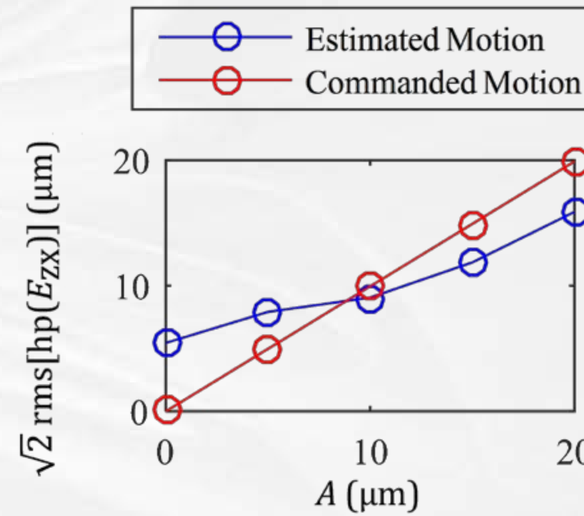
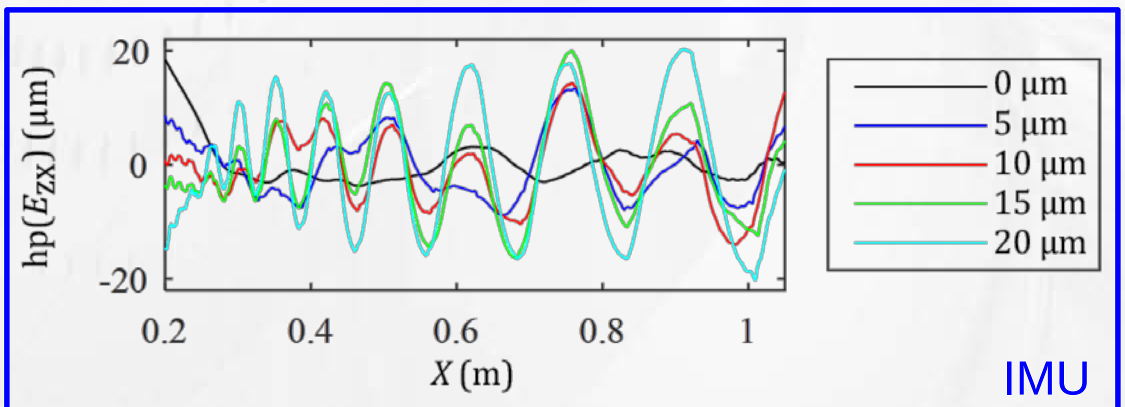


$\sqrt{2} * \text{rms}$





$\sqrt{2} * \text{rms}$

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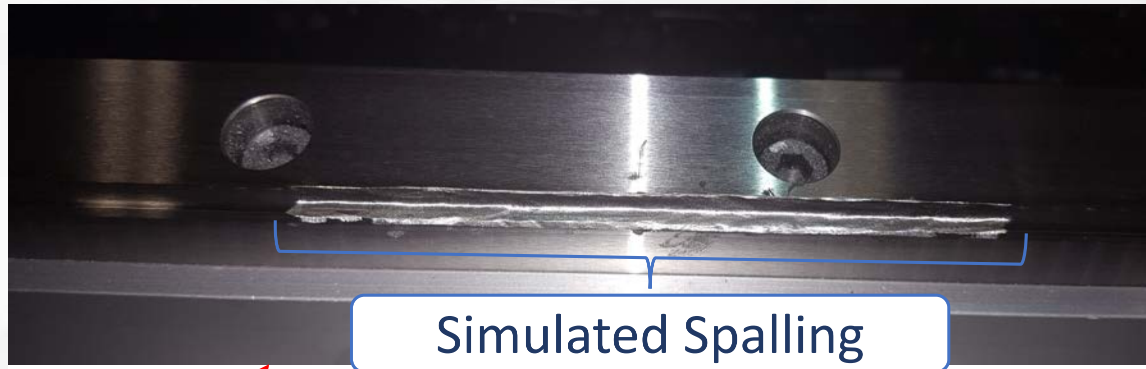
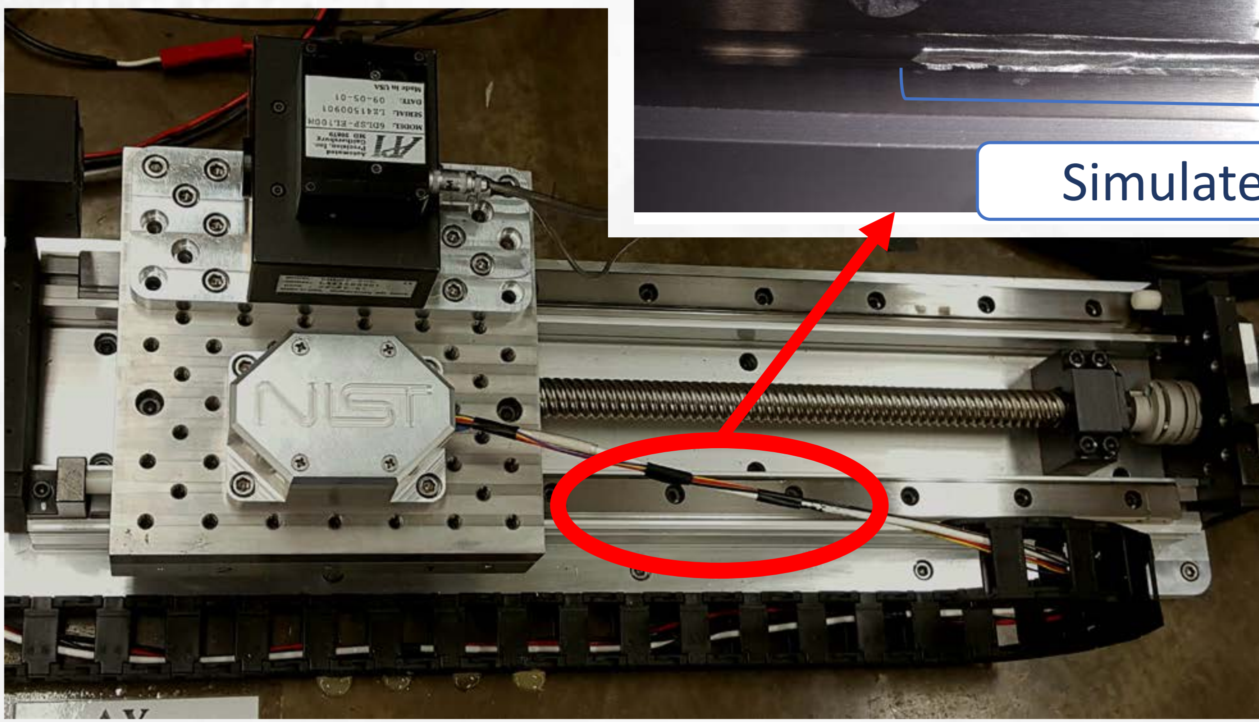
‘Spalling’ on Rail

- Rail was degraded to represent typical spalling





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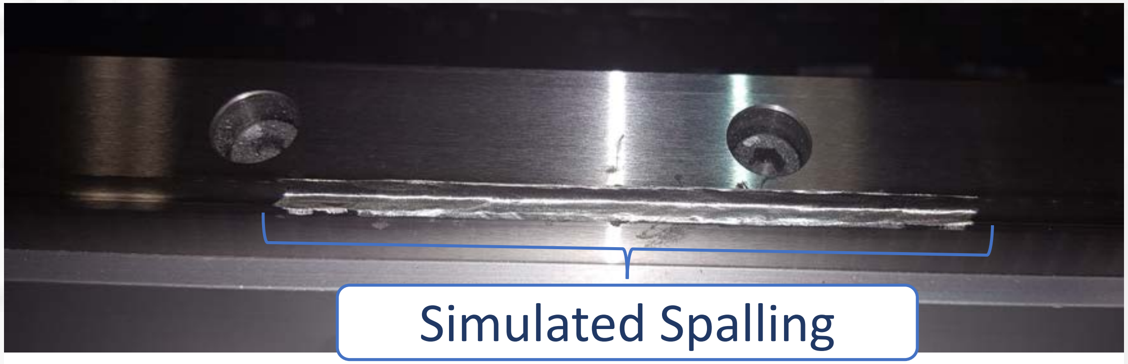
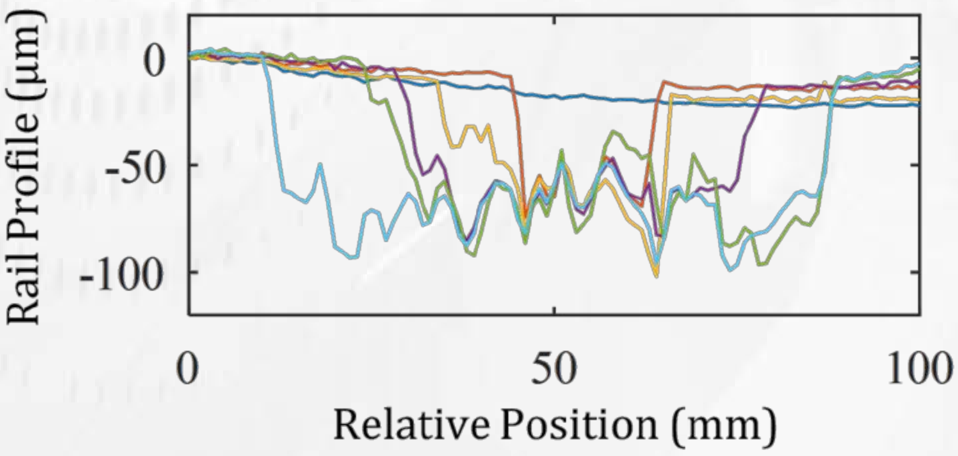
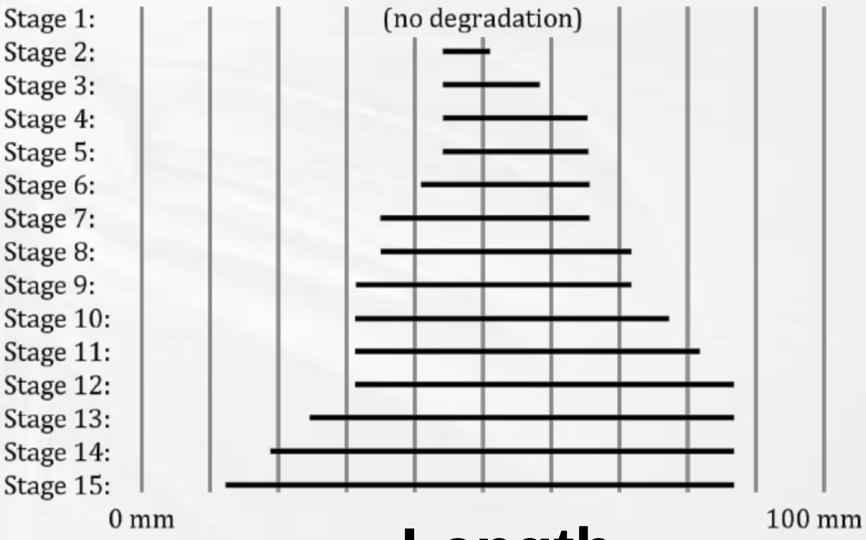




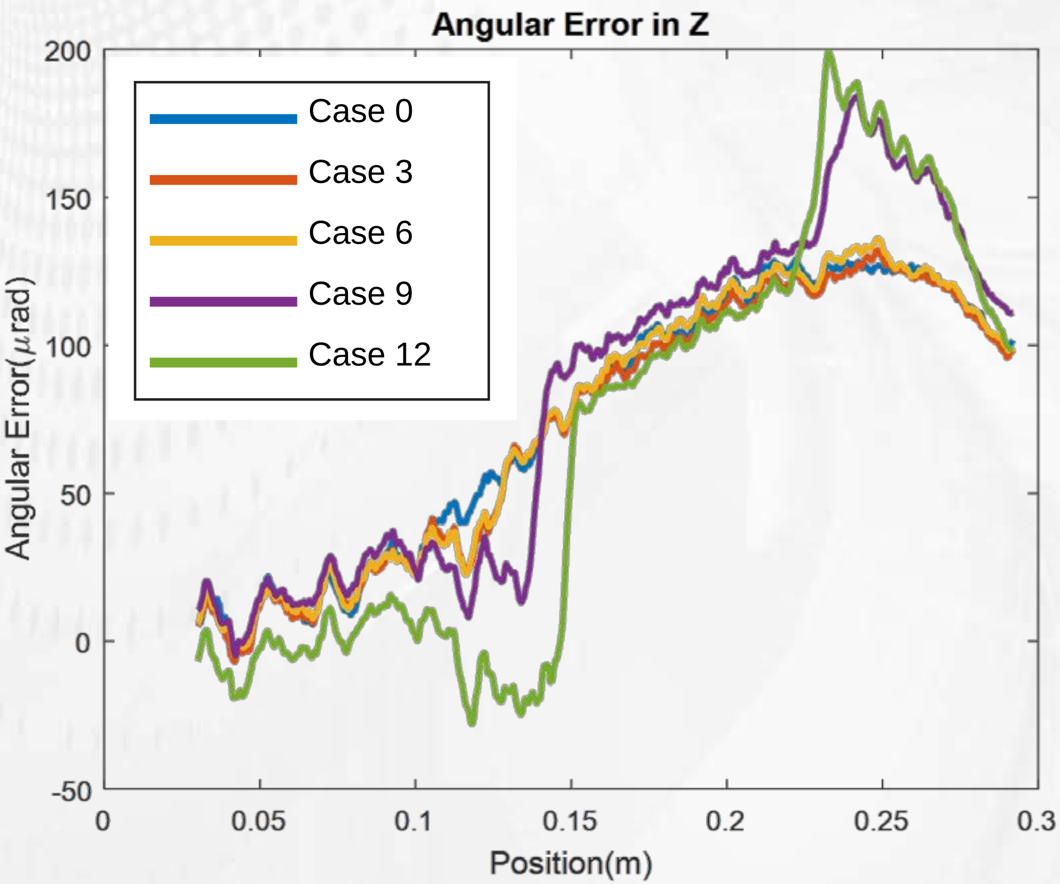
Depth

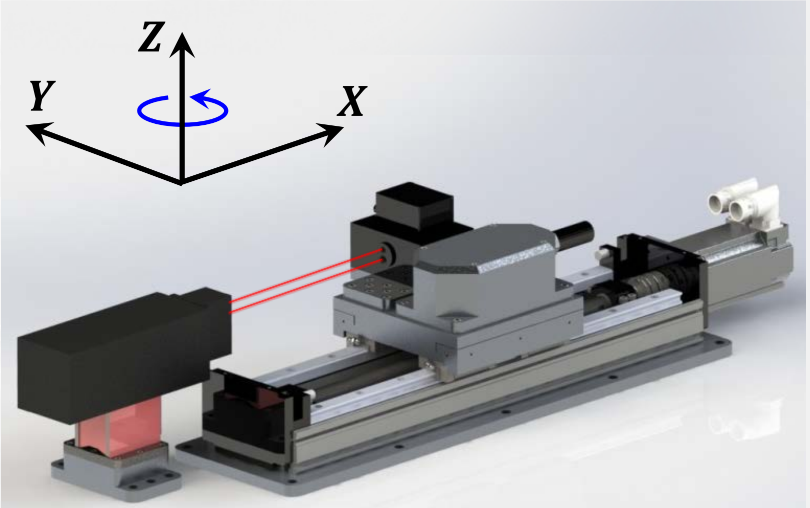


Length

Initial Diagnostics

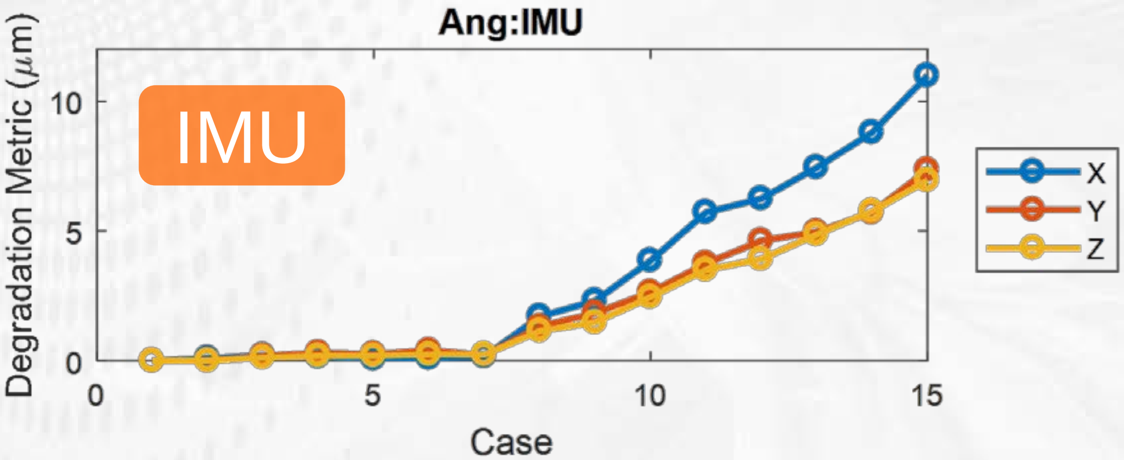
- Angular error motions show increasing “spalling”

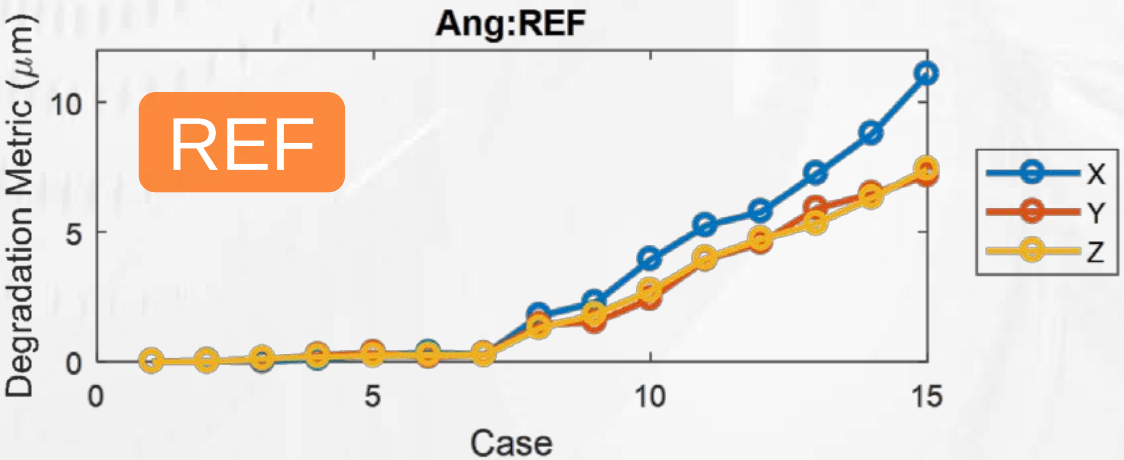


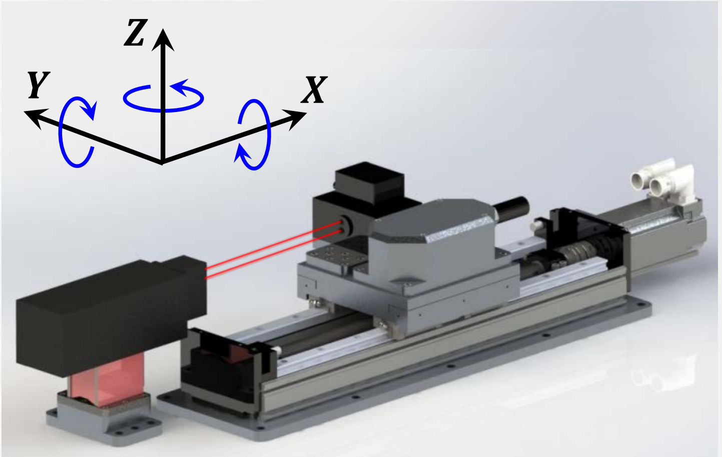


Initial Diagnostics

- Metric of angular errors shows increasing “spalling”

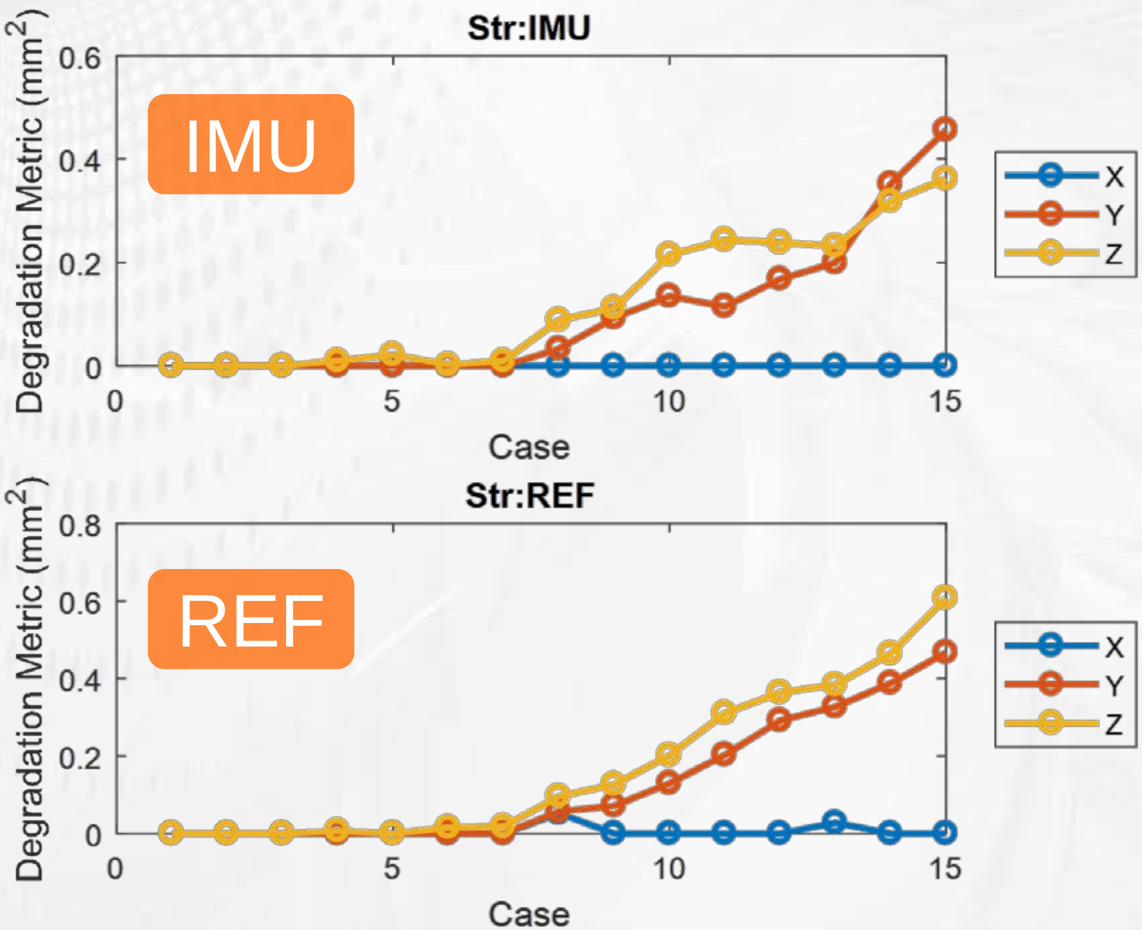


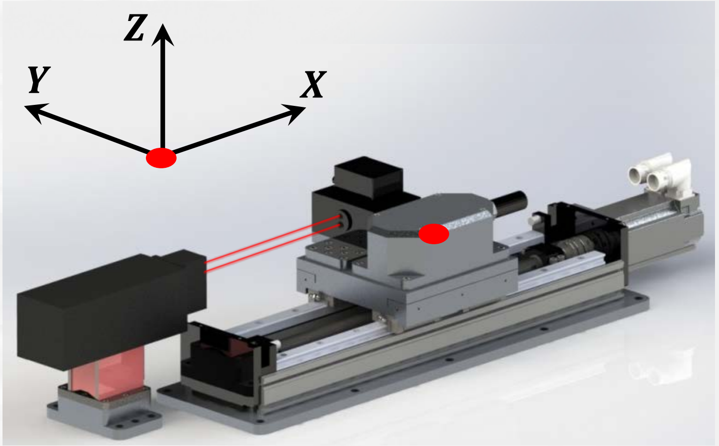




Initial Diagnostics

- Metric of translational errors also tracks "spalling"





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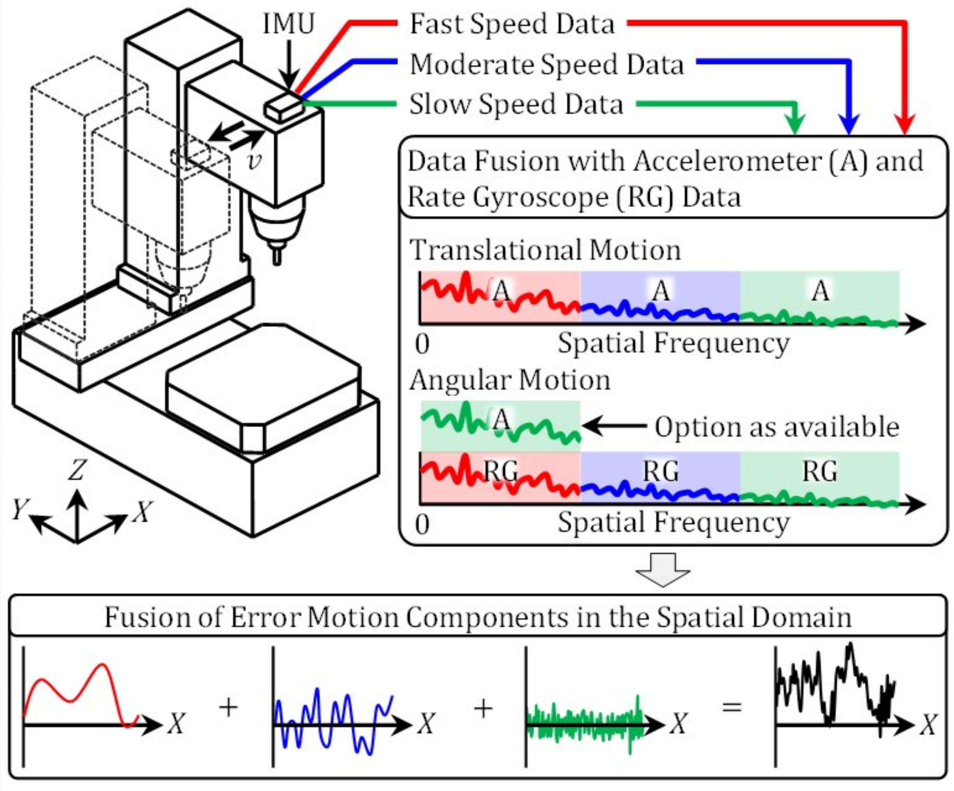
Conclusion

- Method is viable for “smart” machine tools

	Ballbar Systems	Laser-Based Systems	Vibration-Based Systems	IMU-based Method
Cost	~$20K	~$70K	~$5K	~$6K
Time	30 minutes	8 hours	< 1 minute	15 minutes
Accuracy	1 µm	1 µm / 5 µrad	N/A	5 µm / 15 µrad
6DOF	No	Yes	No	Yes
Setup change not required	No	No	Yes	Yes

Thank You



Questions?