Accurate Robotic Machining: Challenges and Solution Approaches

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NIST Workshop on Robot Absolute Accuracy, March 11-12, 2025
Rockville, MD

Georgia Tech
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Accurate Industrial Robotics for Manufacturing

- Automation of large parts manufacturing dominated by monumental gantry systems
- Serial manipulators present an attractive alternative:
  - Cheaper
  - More flexible (reconfigurable)
  - More compliant
  - Less accurate
- <2% of industrial robots used for material removal (Verl et al. 2019)

Source: https://www.electroimpact.com/Products/Composites/Overview.aspx

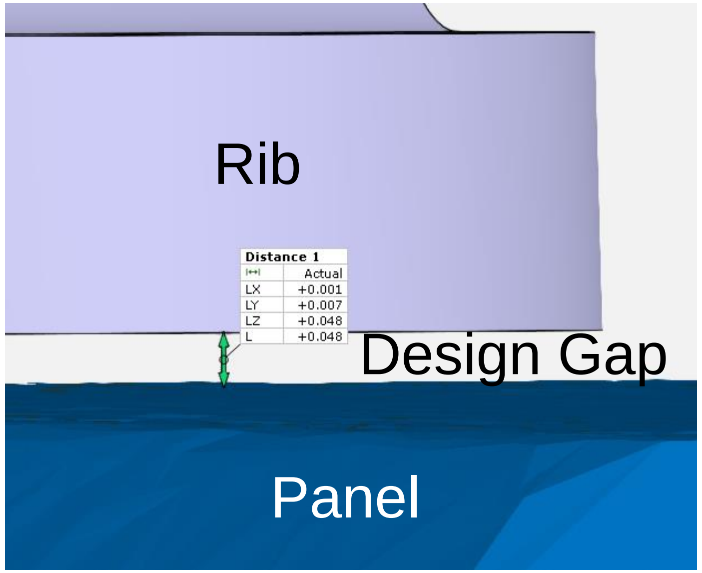
Source: https://www.postandcourier.com/business/new-robots-to-help-boeing-s-c-meet-production-hike/article_b42c9b5b-3a40-5326-bcf4-ed3bacb83a06.html

Example Application

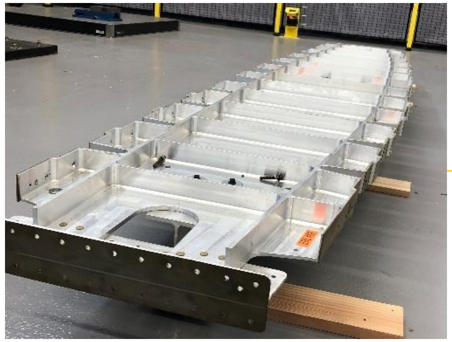
Aircraft Assembly

Major structural joins for aerospace have tolerances on the order of <.125 mm

Current process is performed by hand which is time consuming, iterative, and causes inefficient production flow



Wing Skin



Wing Rib

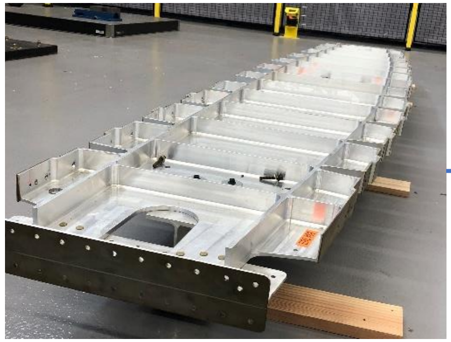
Temporarily Join → Measure Gaps → Disassemble / Manufacture Shims → Align with Shims → Permanently Join

Potential Solution

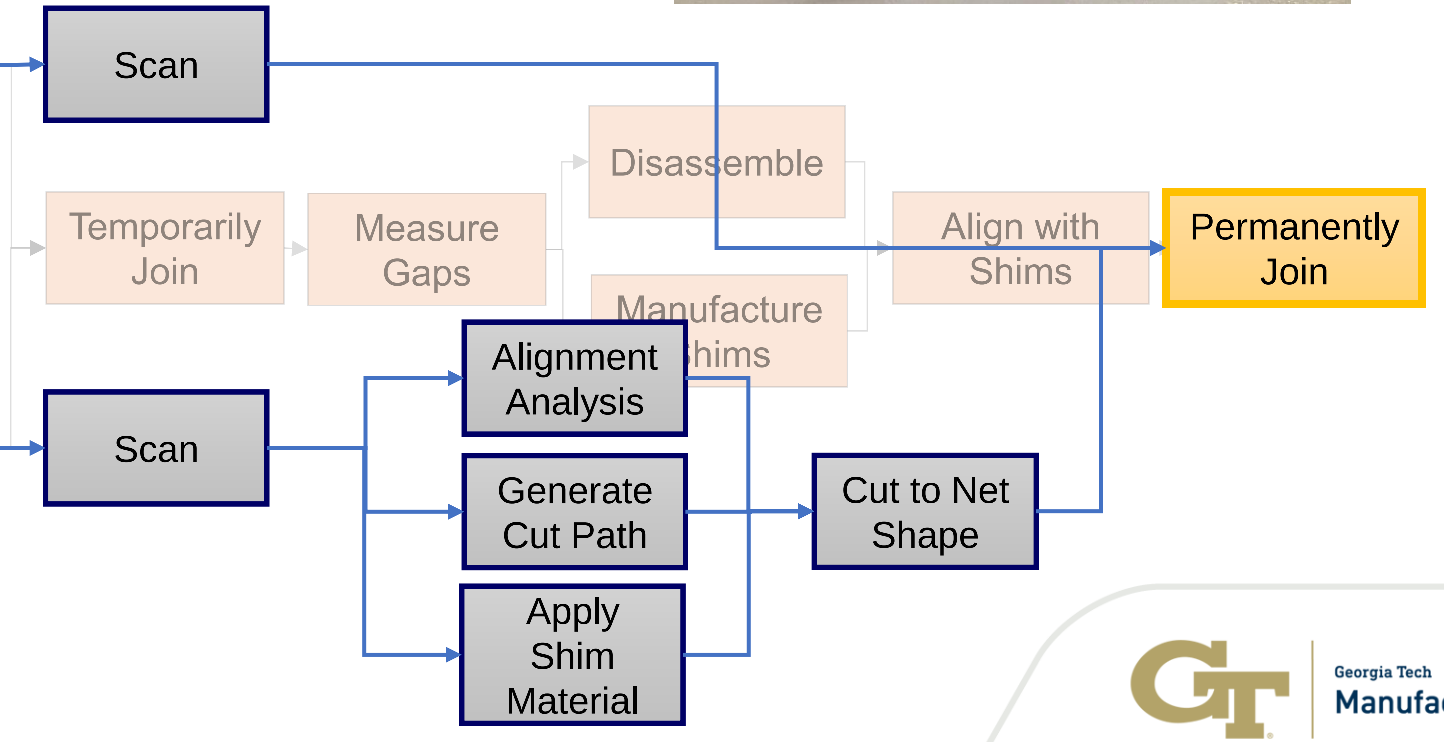
Shim-Less Aircraft Assembly

Automate shim assembly using low-cost, accurate articulated arms to scan mating surfaces and machine joining surface to net shape

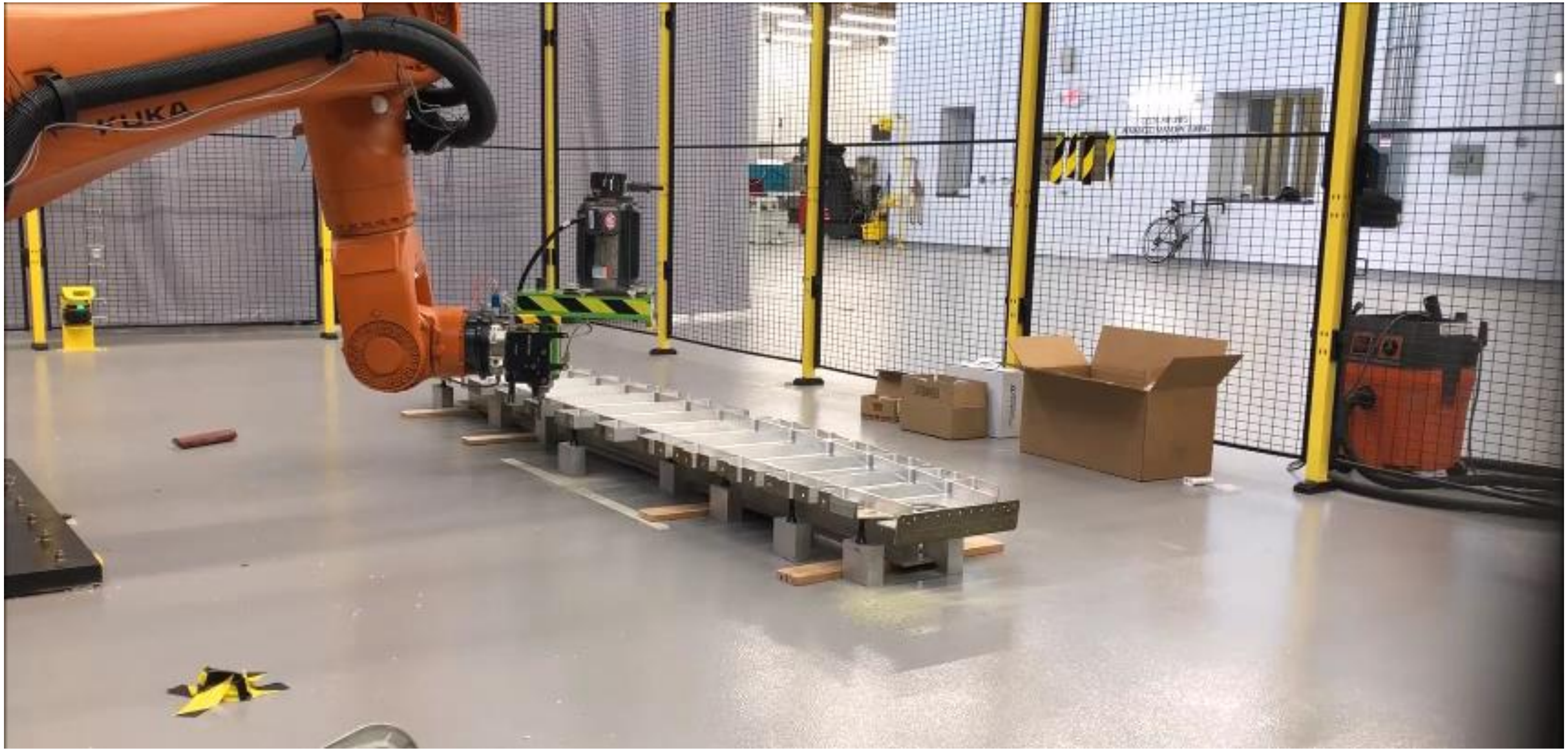
Wing Skin



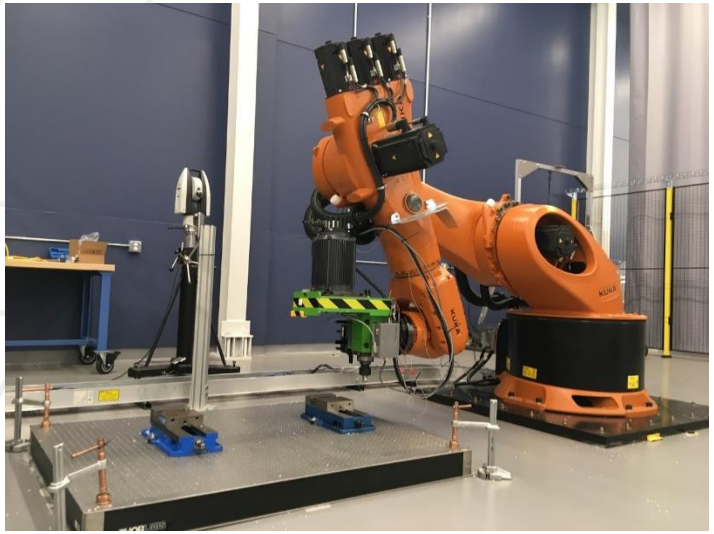
Wing Rib

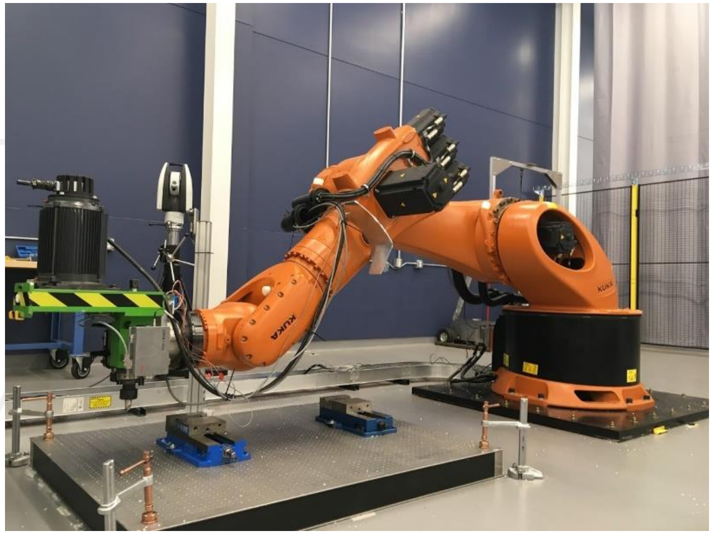


Wing Rib Shim Machining



Factors Contributing to Machining Accuracy





Robots have much lower kinematic accuracy than CNC machines

Low kinematic accuracy → Part inaccuracy

Robots are more compliant than CNC machines

Large compliance → Part inaccuracy

Modal properties of robot arms change with configuration

Pose dependent FRF → Dynamic path errors

Interaction between robot and workpiece

Time-varying process forces and part compliance → Part inaccuracy

Accurate Robotic Machining Research @ GT

Research on redundancy resolution in robotic machining began

Transition to TwinCat

Velocity Control

Milling Tests on small Wing Rib

Full Size Wing Rib Milling

Sensor Fusion Models Developed

Global Calibration

6 DoF Control

Standardization

Part + Fixturing Error Reduction

2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022+

BMDC Opens

Single Pose Static Stiffness Optimization

3 DoF Closed Loop Control in RSI

Break Up Normal and Tangential Commands

Established Benchmark Test for Different Control Strategies

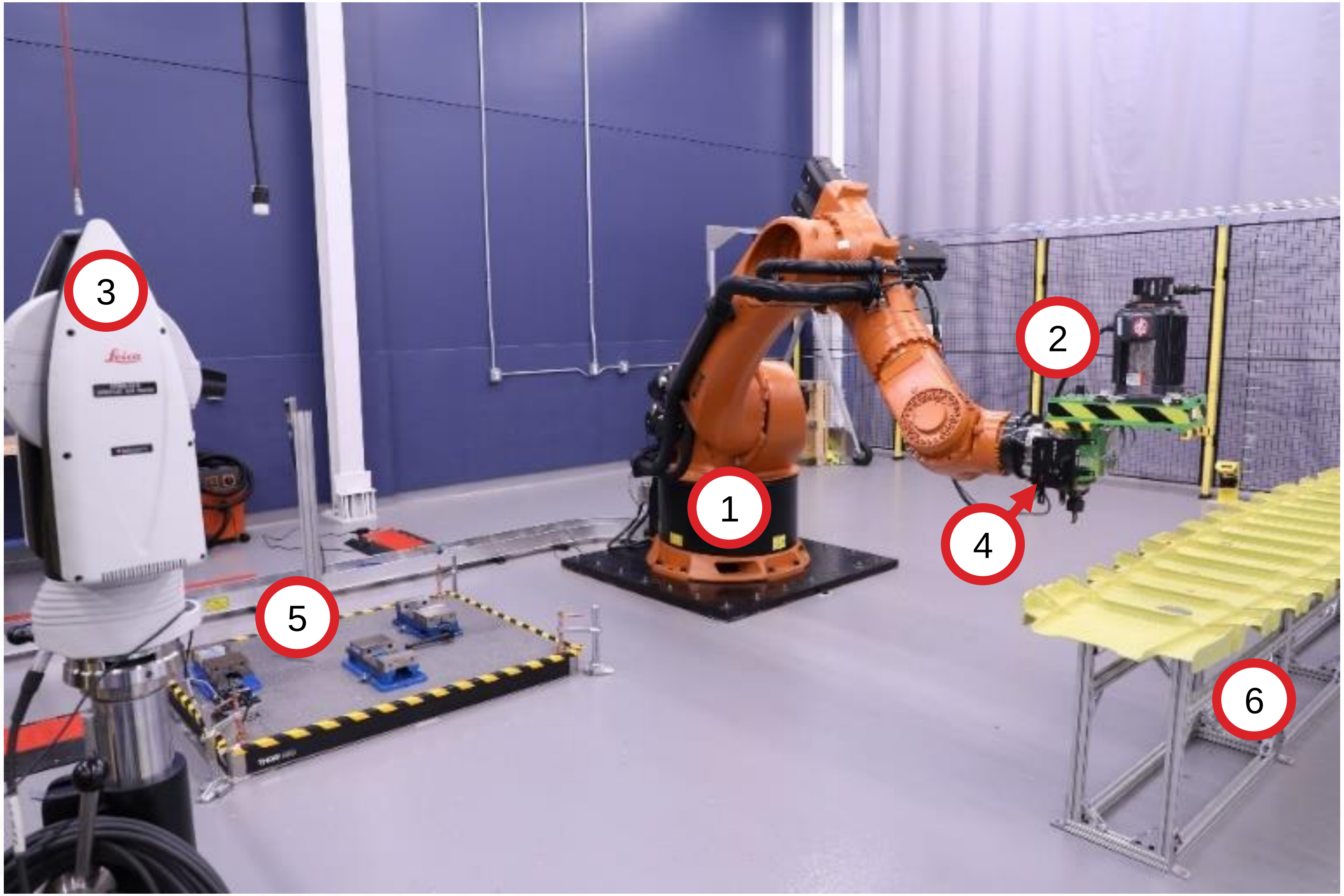
Fully Operational Real Time Controller

Adaptive Gain Tuning

Process-Dependent Trajectory Planning

Industrial Scale Evaluation Methods

Work Cell



1. KUKA KR500-3 Robot
2. Mill
3. Leica AT960 Laser Tracker
4. Leica T-Mac Tracker Target
5. Vices
6. Wing rib

Control Architecture

Sensors

- Leica AT960 laser tracker and Leica T-Mac
- Leica T-Scan
- Gladiator Technologies LandMark™60 IMU
- ATI Force Sensor

Processing Nodes

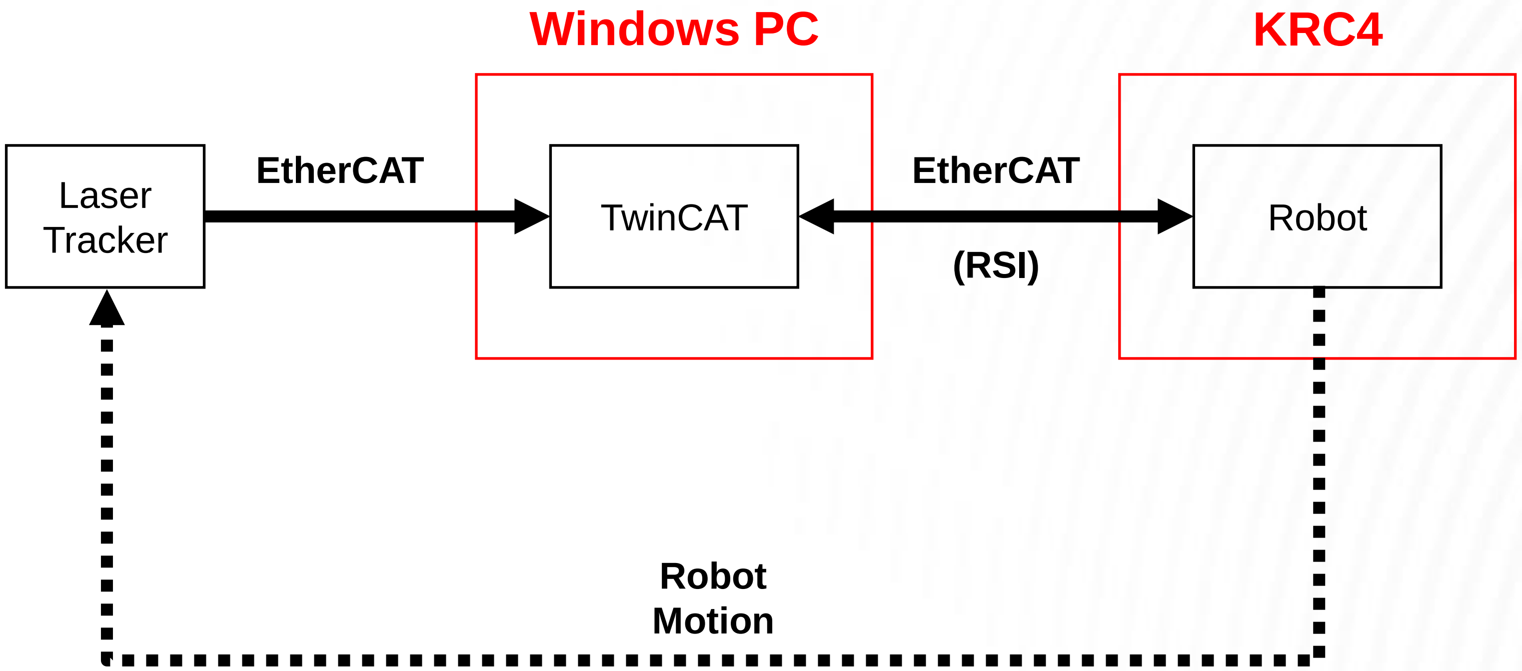
- KUKA KRC4 robot controller
- Windows workstation

Network

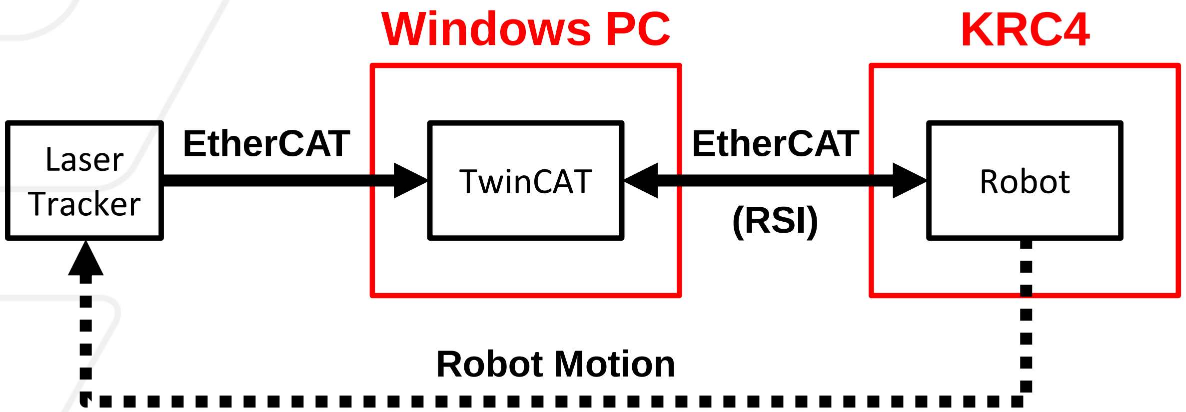
- EtherCAT

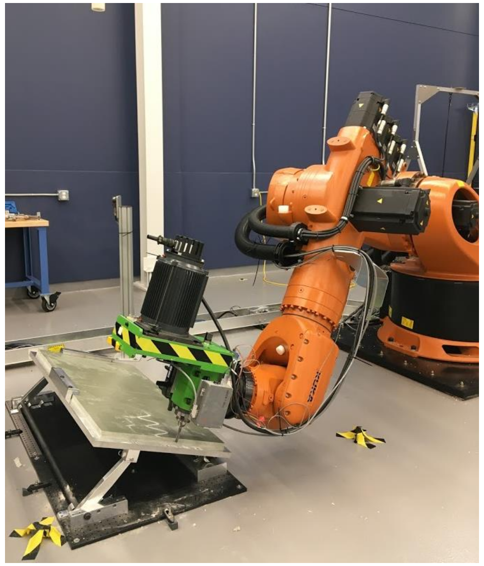
Plant

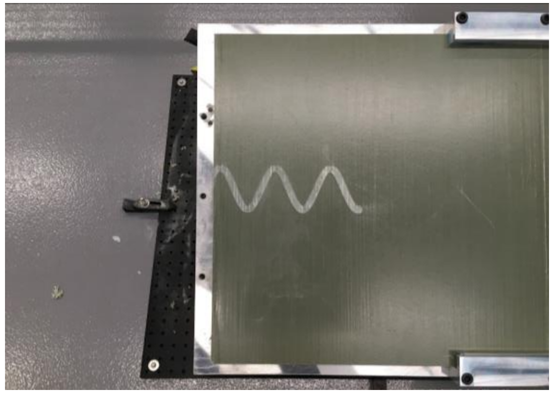
- KUKA KR 500-3 Robot
- KUKA smartPAD Teach Pendant



Real-Time Feedback Control





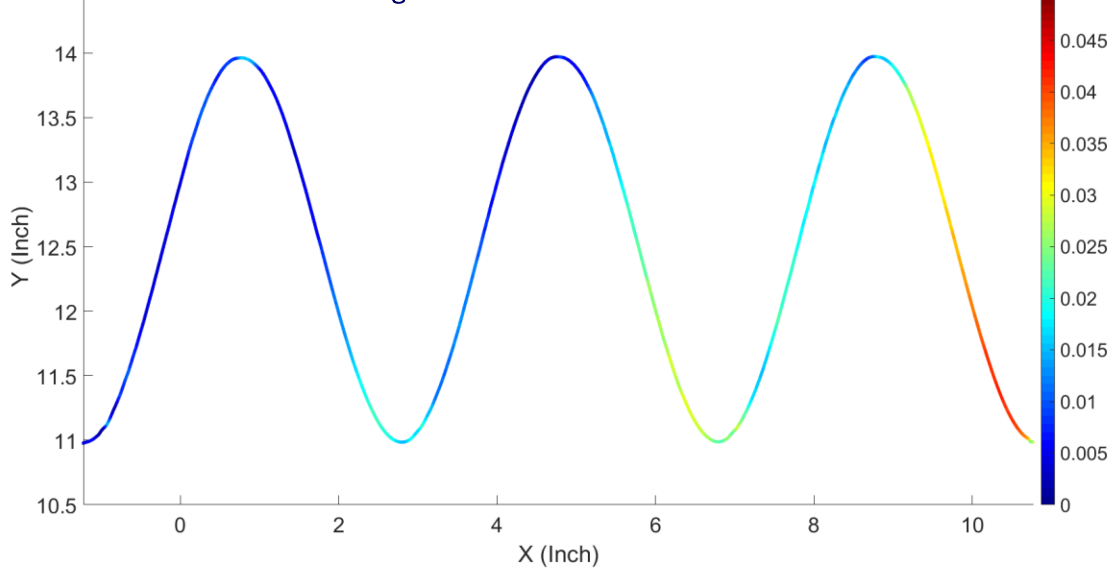


Nguyen et al., *SAE Int. J. Aero.*, 2021

Tool Tip Position Measured using Leica AT960 with T-Mac

Open Loop

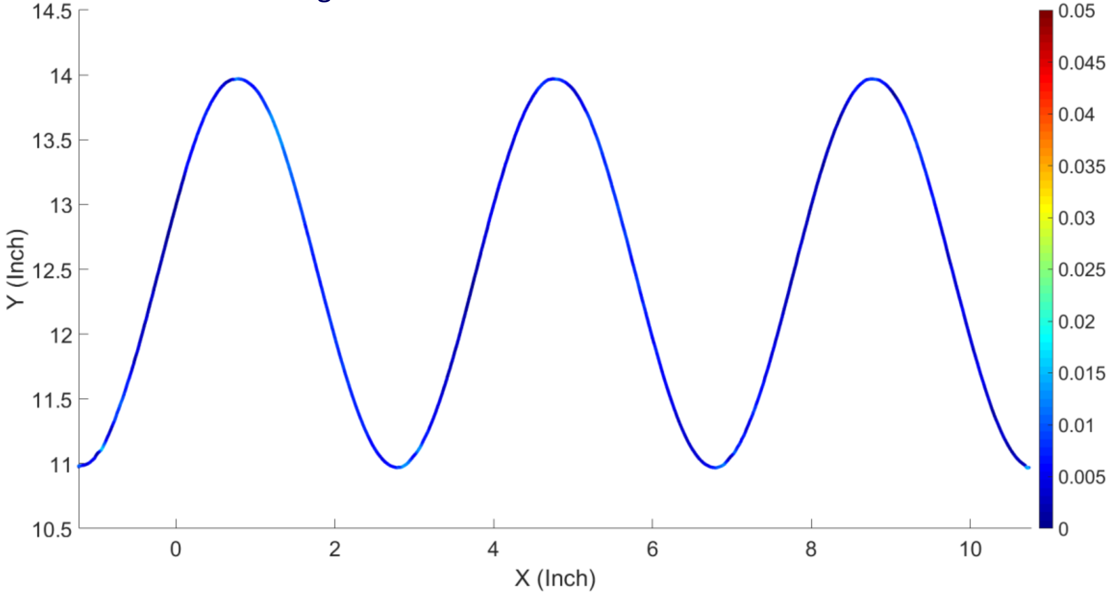
Average Position Error: 0.4 ± 0.28 mm



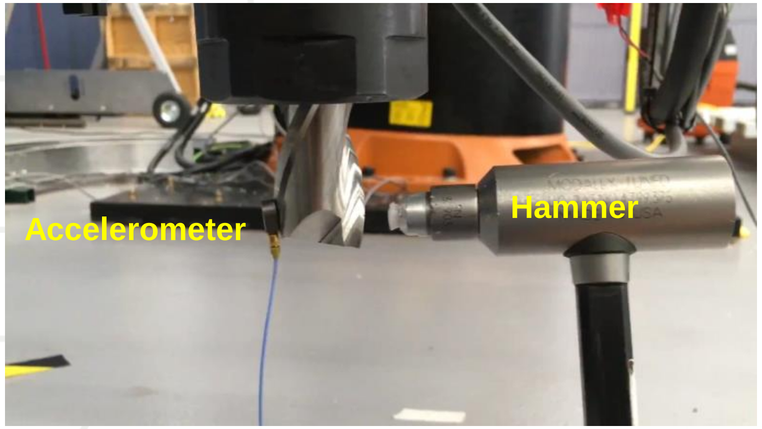
Tool Tip Position Measured using Leica AT960 with T-Mac

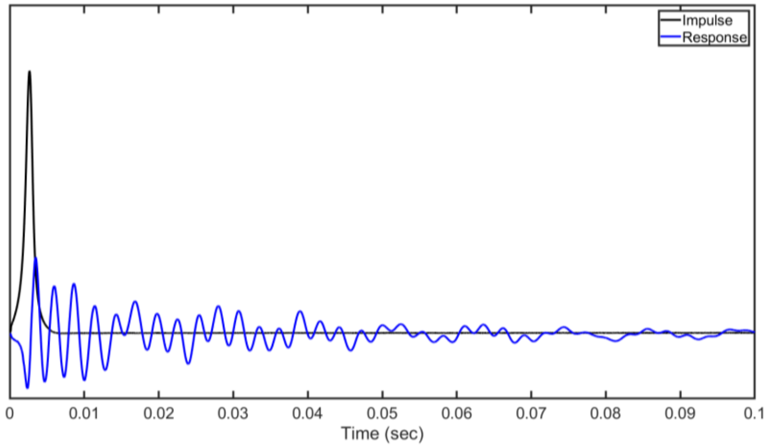
KRL Guided

Average Position Error: 0.127 ± 0.07 mm

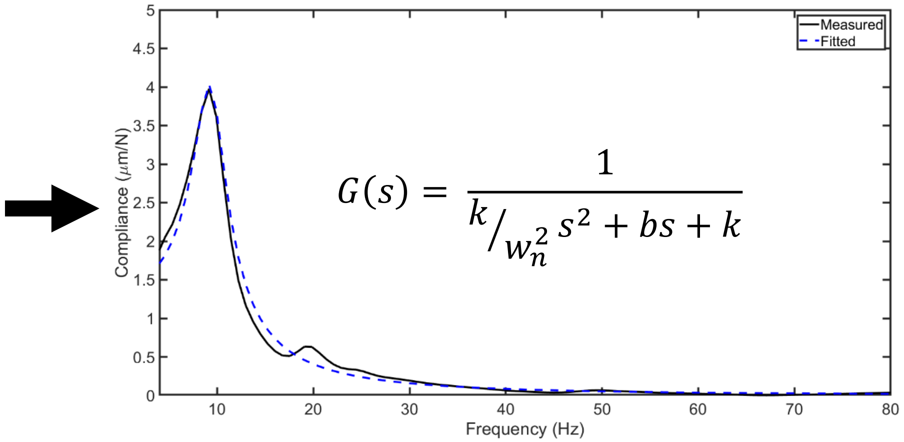


Data-driven Modeling of Robot Dynamics

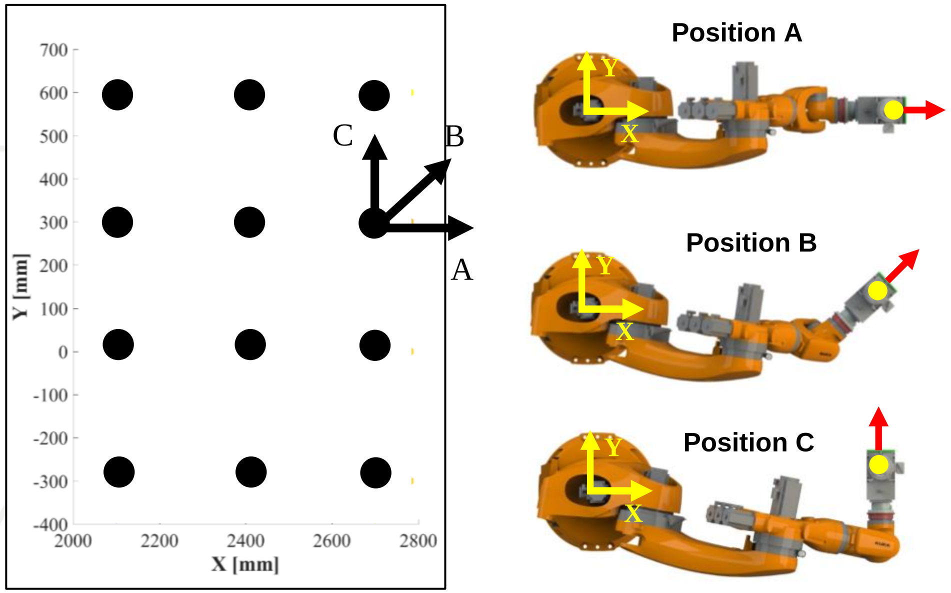




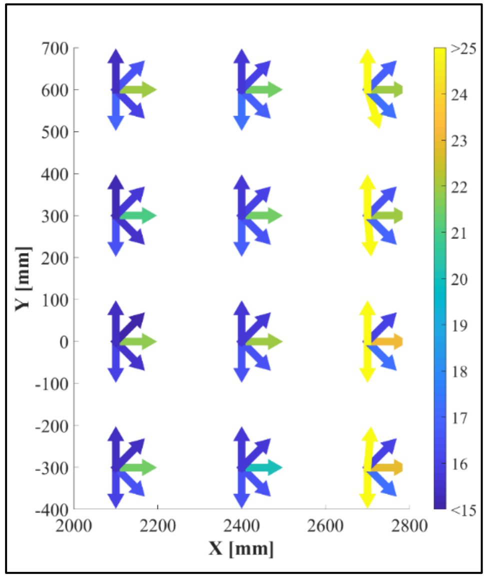
Frequency Response Function



Sampled Points in the Workspace



Natural Frequency, $f(p_i)$ [Hz]



We can model $f(p_i)$ as a Gaussian Process:

$$f(p_i) \sim GP\big(\mu(p_i), \boldsymbol{K}(p_i, p_i')\big)$$

Nguyen et al., *J. Mfg. Sci. Eng.*, 2019

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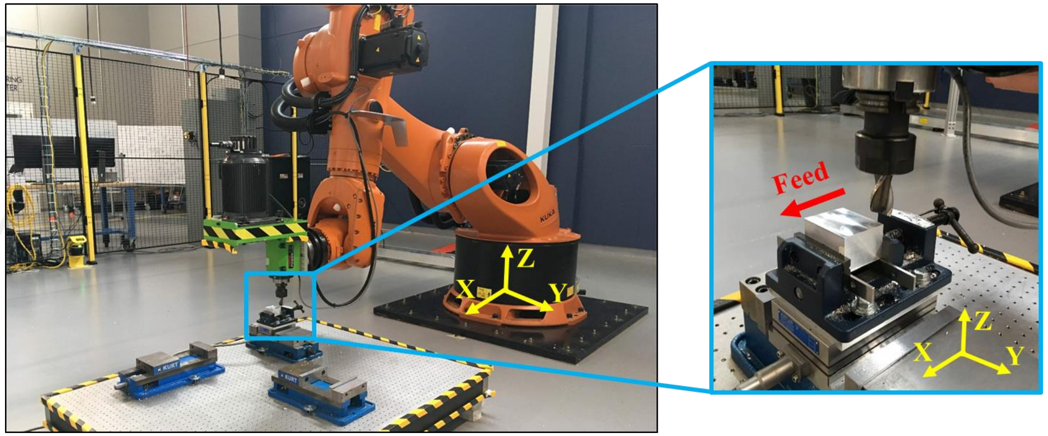
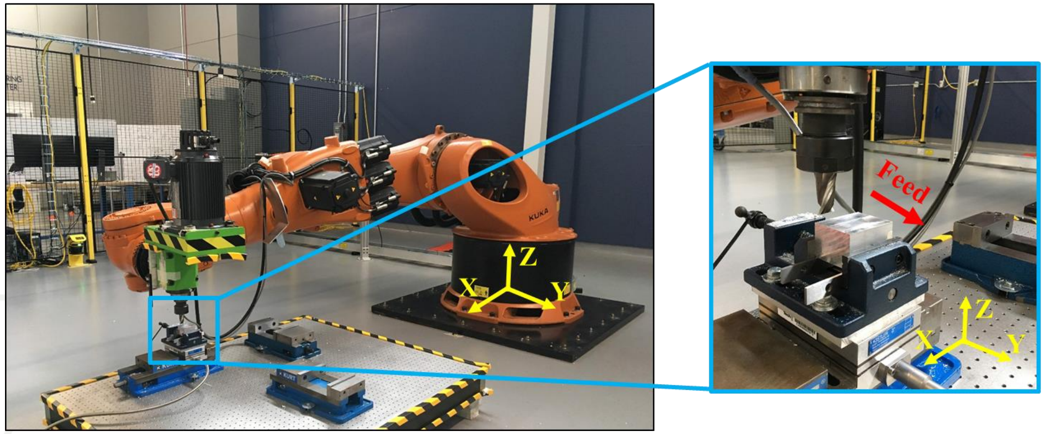
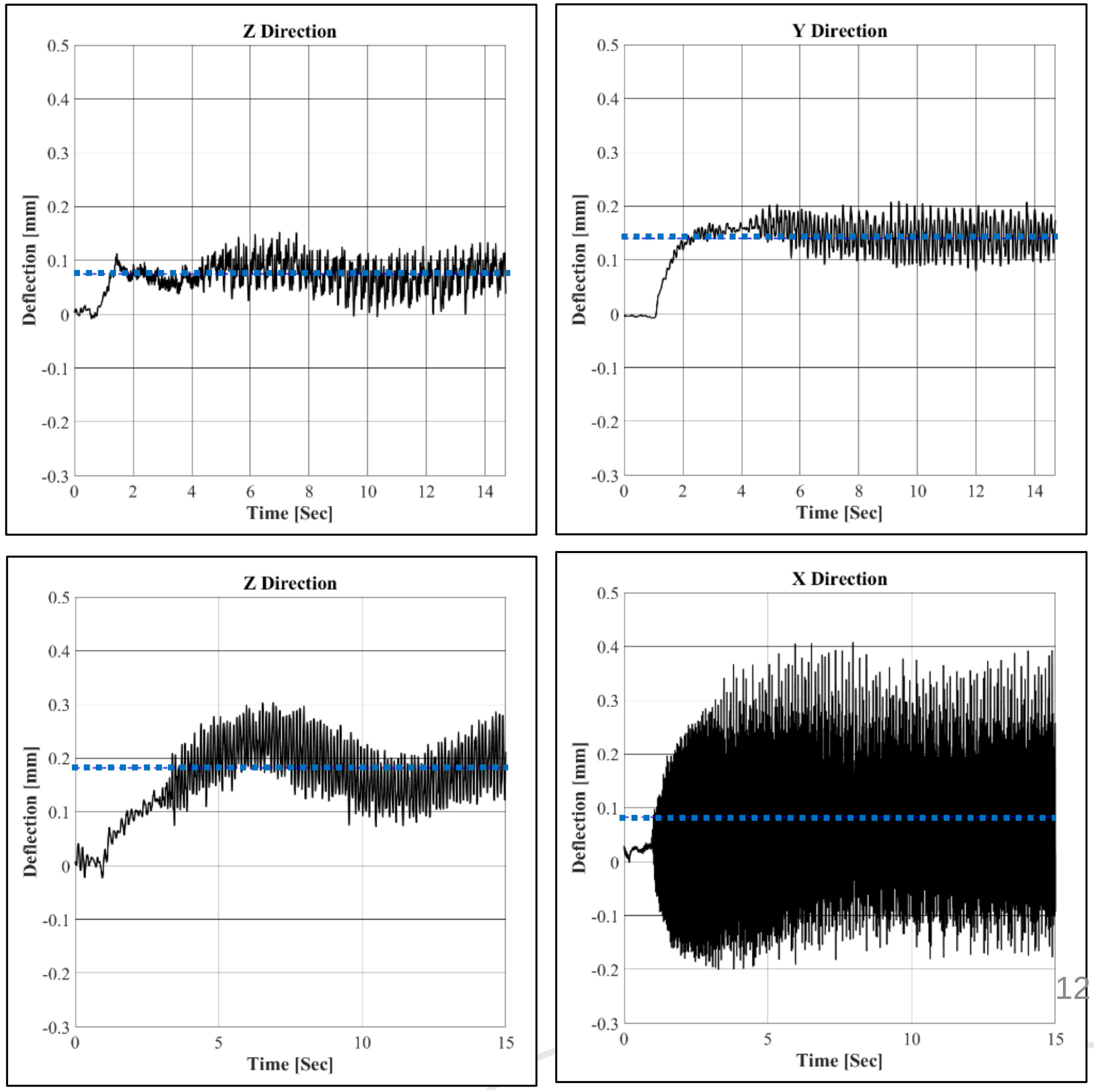
Application to Milling Vibration Prediction

Position 1



Position 2





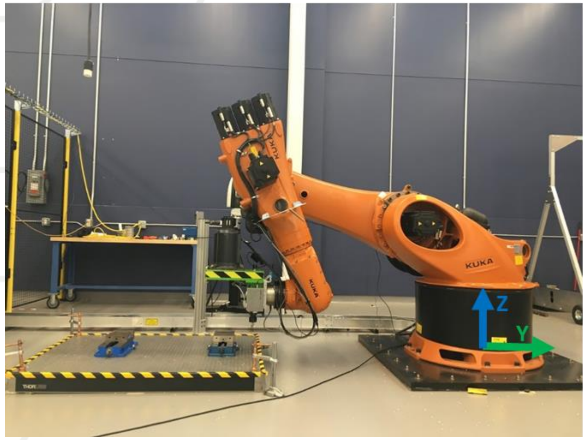
Peak-to-Valley Vibrations (mm)

	Position 1		Position 2	
	Y	Z	X	Z
Measured	0.085 ± 0.004	0.064 ± 0.005	0.506 ± 0.022	0.125 ± 0.008
Predicted	0.070 ± 0.002	0.058 ± 0.001	0.473 ± 0.014	0.100 ± 0.006

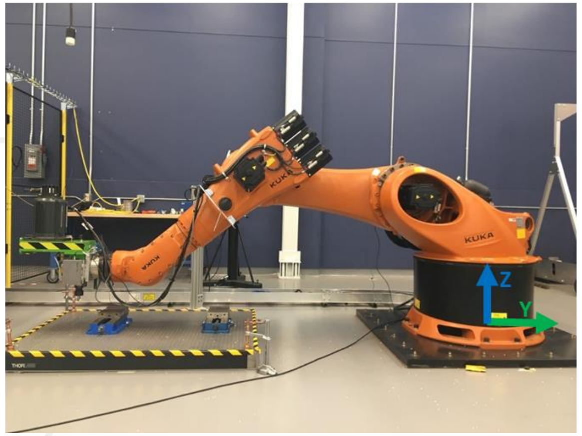
The GPR model peak-to-valley vibration predictions are correlated to the measured behavior

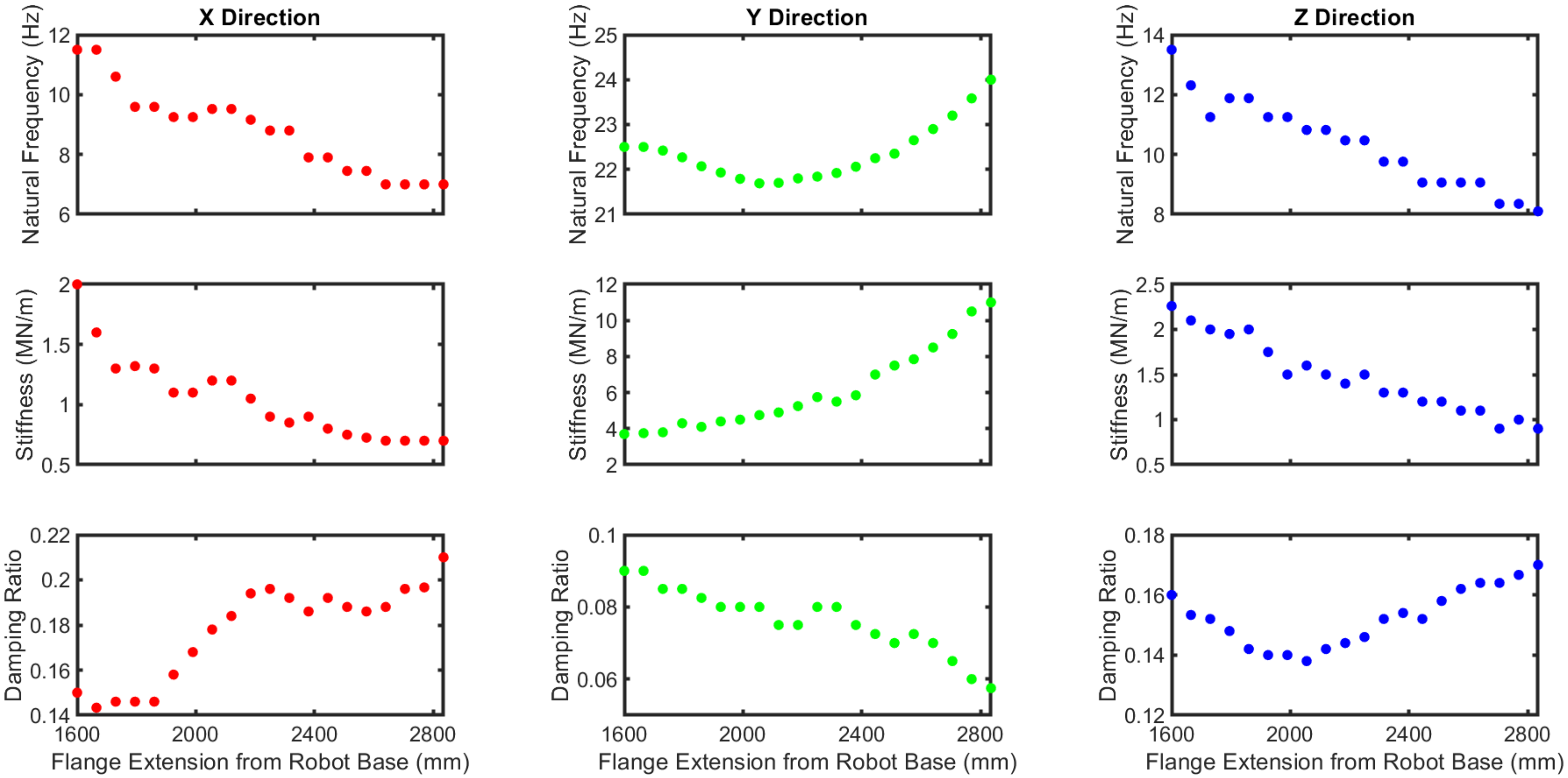
Pose Dependent Modal Properties

Start



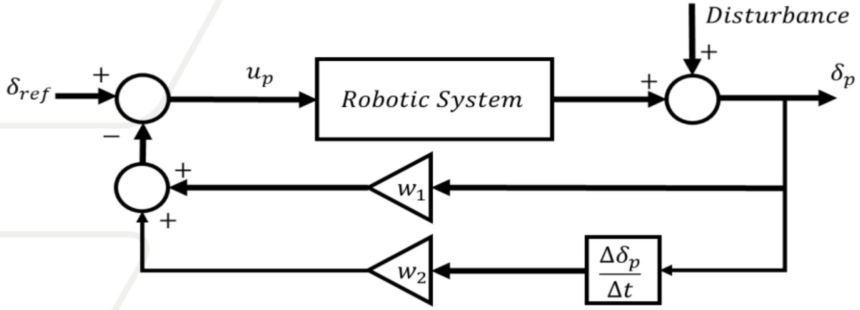
End

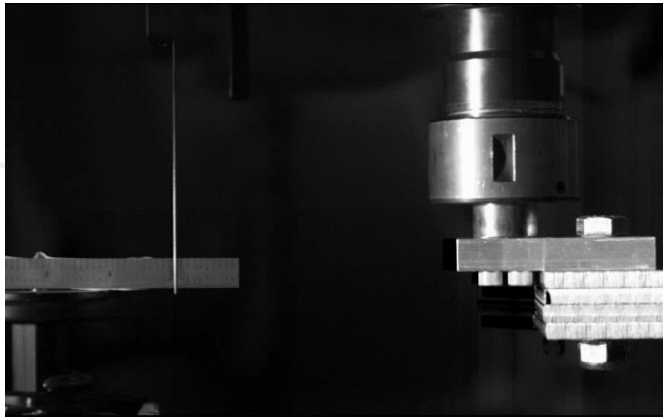




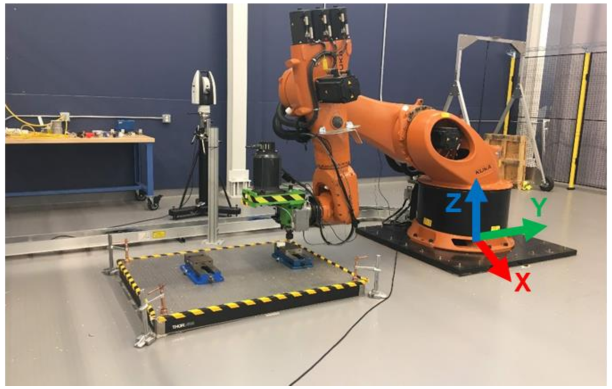
The data shows that the modal parameters change with arm configuration, and therefore arm configuration must be considered in controller tuning

Active Vibration Suppression

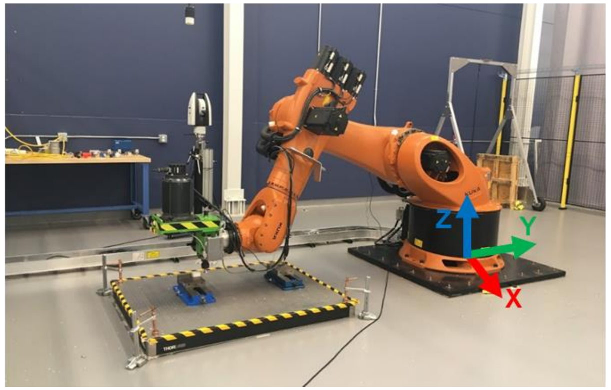


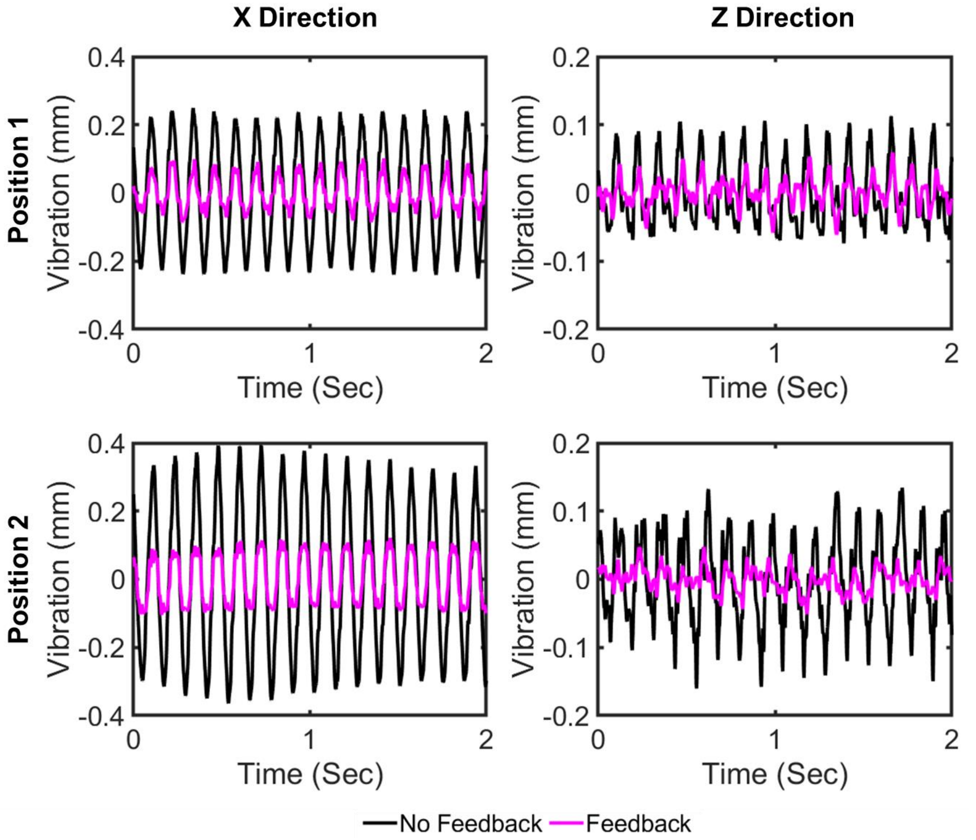


Position 1



Position 2





Nguyen et al., *Int. J. Mach. Tools & Manuf.*, 2020

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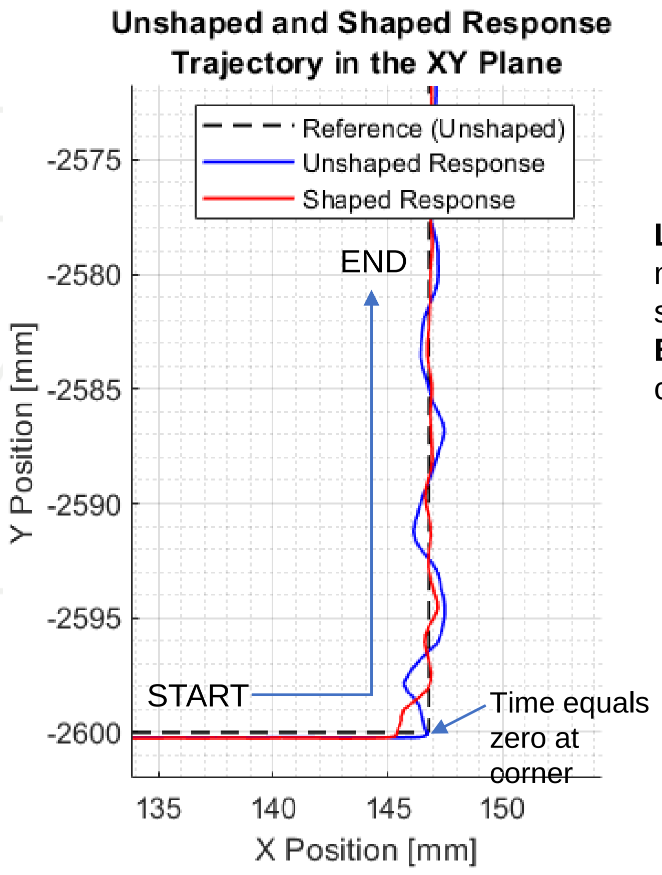
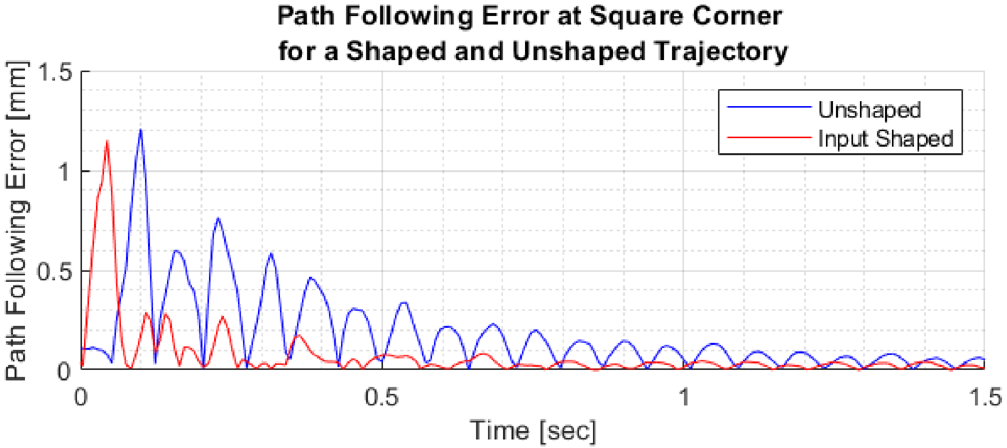
Input Shaping to Improve Dynamic Path Accuracy



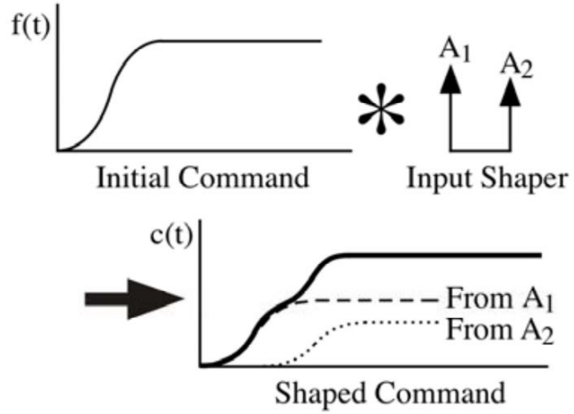
- A technique that may improve dynamic path accuracy is to apply input shaping to the desired trajectory
- Preliminary results indicate that this approach may significantly reduce vibrations from self excitation of the robot structure

Left: Square wave trajectory in the XY plane shows the reference trajectory, measured response to the unshaped trajectory, and measured response to the shaped trajectory, at 120 ipm velocity

Below: The path following error to the reference trajectory after rounding the corner in the trajectory shown at left for the shaped and unshaped trajectory



Below: Diagram showing the input shaping process [1]



[1] Singhose, W. (2009). Command shaping for flexible systems: A review of the first 50 years. International Journal of Precision Engineering and Manufacturing, 10(4), 153-168. http://dx.doi.org/10.1007/s12541-009-0084-2.

Ongoing Work

- Integrating on-robot vision-based metrology for detection of part features and their location to guide machining trajectories (e.g., trimming to a molded scribe line)

CFRP part with Scribe Line

- Input shaping of complex curvilinear trajectories to suppress structural vibration (e.g., cornering)

Needs

- Standard method to characterize the accuracy of external sensor-guided (e.g., laser tracker) robots
- Ability for users to modify robot control action at faster rates (<< 4 ms) based on external sensor feedback
- Standard method to determine the pose-dependent modal properties of industrial robots over a defined working region

Acknowledgements

- Boeing Manufacturing Development Center @ Georgia Tech
- Boeing University Innovation Program
- MxD