Feedforward and Feedback Methods for Improving Robotic Accuracy

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Workshop on Standards for Robot Absolute Accuracy and Performance Assessment
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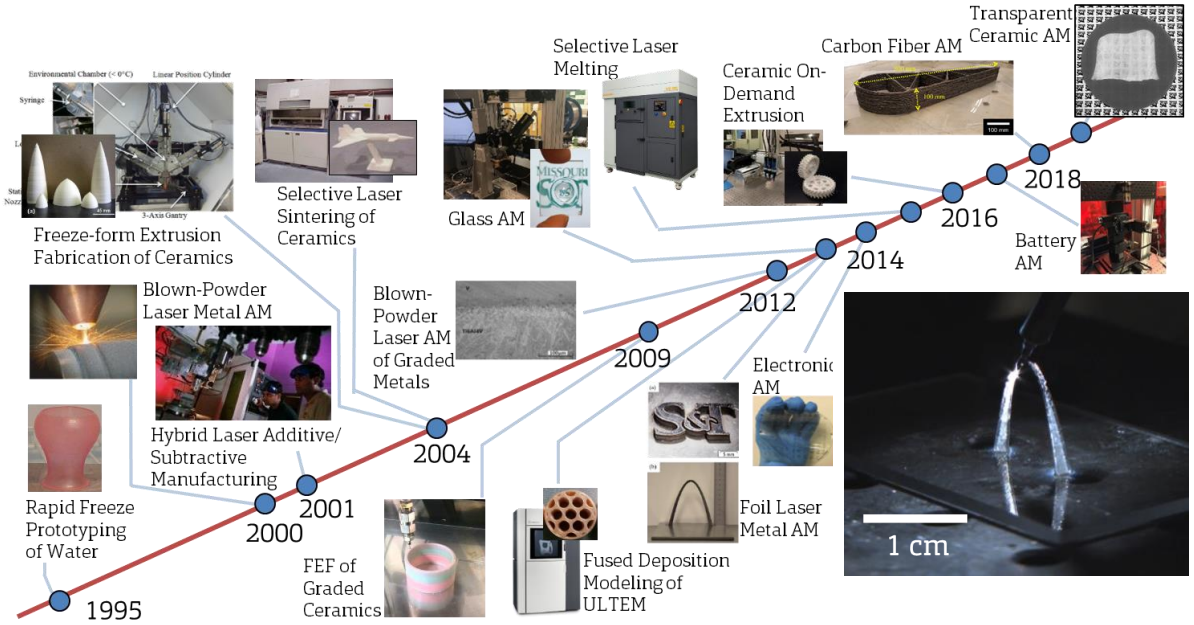
Center for Aerospace Manufacturing Technologies

camt.mst.edu

Who are we?

An academic-industry partnership with a mission to address critical needs of the aerospace manufacturing industry through technology development and workforce training since 2003.

A legacy of Additive Manufacturing Innovation…



Key Technologies…

- Additive Manufacturing (metal powder/wire hybrid DED, PBF, foil; ceramic extrusion, DED; large-scale FDM)
- Robotic Manufacturing (machining, grinding, incremental sheet forming)
- Modeling (multi-scale physics, additive manufacturing, composites)
- Metrology (metrology-in-the-loop control, high-order calibration, reverse engineering)
- Repair (automated reverse engineering + hybrid DED)

2024 Membership

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The Missouri Protoplex

Launch Partners:
- Boeing
- Lockheed Martin
- Caterpillar
- Army

Facility:
- 40,000 sq. ft. High Bay
- 80,000 sq. ft. Lab and Office

Equipment:
- DMG-Mori LASERTEC 65
- DMG-Mori LASERTEC 4300
- SLM 500 Quad Laser 700W LPBF
- SPEE3D Cold-Spray
- VRC Gen IV Cold-Spray
- Bond GL7 Friction Stir
- Wire-Arc AM + Machining Cell
- Robotic Machining Cell
- Alpha Laser Micro Welding 900W
- Impossible Objects Composites AM

Dr. Richard Billo
Distinguished Professor, Mechanical and Aerospace Engineering
Director, Missouri Protoplex

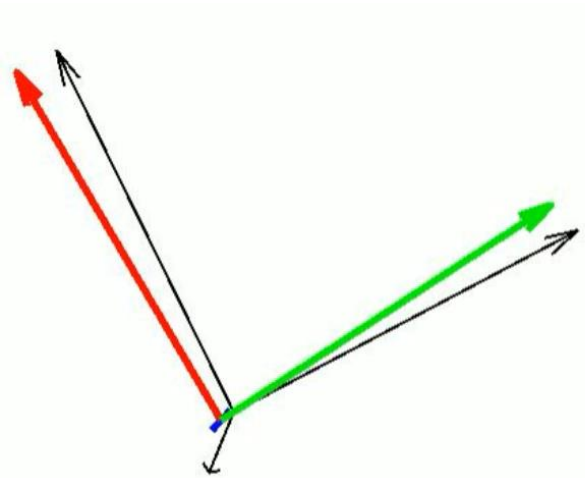
Opens Spring 2026

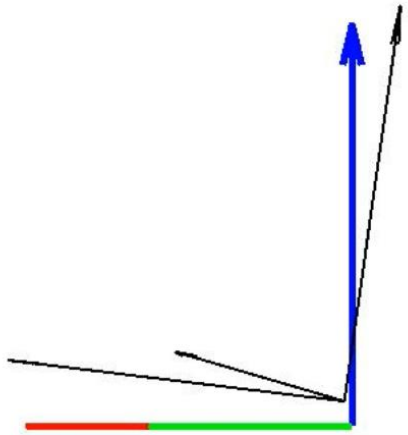
What Do Kinematic Errors Look Like?

Direct measurement of 6 DoF motion error projected onto Joint 2.

Orientation error amplified for clarity.

Error motion is complicated.





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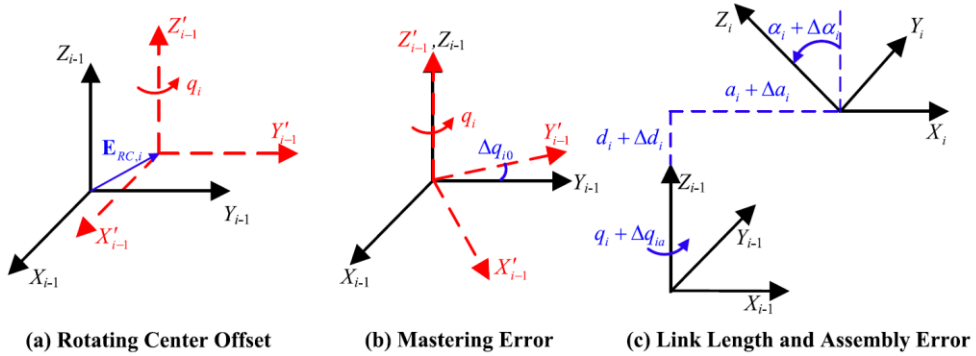
Kinematic Error Modeling

Error Taxonomy



Kinematic Model

Nominal Kinematics

$$\mathbf{F}_a(\mathbf{q}) = \mathbf{E}_1^0(q_1,s_1)\mathbf{T}_1^0(q_1)\mathbf{E}_2^1(q_2,s_2)\mathbf{T}_2^1(q_2)\ldots\mathbf{E}_n^{n-1}(q_n,s_n)\mathbf{T}_n^{n-1}(q_n)$$

"Lumped" Kinematics Errors

$$\mathbf{E}_i^{i-1}(q_i,s_i) \approx \begin{bmatrix} 1 & -\varepsilon_Z(q_i,s_i) & \varepsilon_Y(q_i) & \delta_X(q_i) \\ \varepsilon_Z(q_i,s_i) & 1 & -\varepsilon_X(q_i) & \delta_Y(q_i) \\ -\varepsilon_Y(q_i) & \varepsilon_X(q_i) & 1 & \delta_Z(q_i) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- 6 DoF joint-angle dependent error
- "Cam-like" motion error
- Independent forward and backward motion models for rotation around joint angle; i.e., hysteresis

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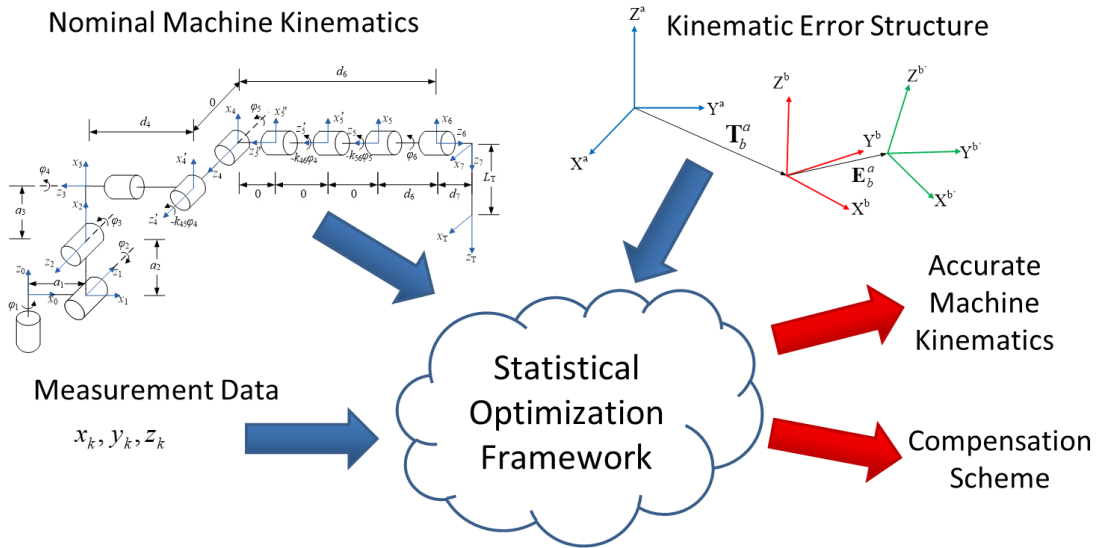
Model Identification

Identification Challenges

- Robot repeatability and measurement noise are:
  - Individually significant; on the order of 10% or more of desired accuracy.
  - Different in different directions and in different poses.
- Throughput is limited to 1 measurement every 10-15 seconds (motion + measure).
- Thermal variations over measurement period can be a factor.

The Right Solution

- Measure/model variances
- Statistical optimization
  - Manages non-homogenous variances
  - Avoids over-fitting data



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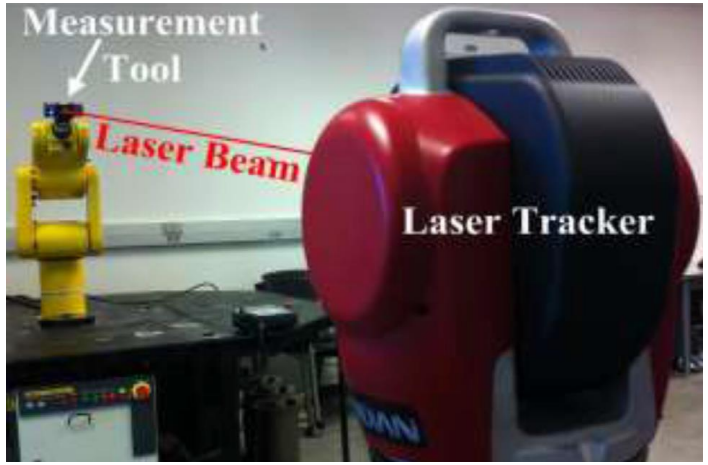
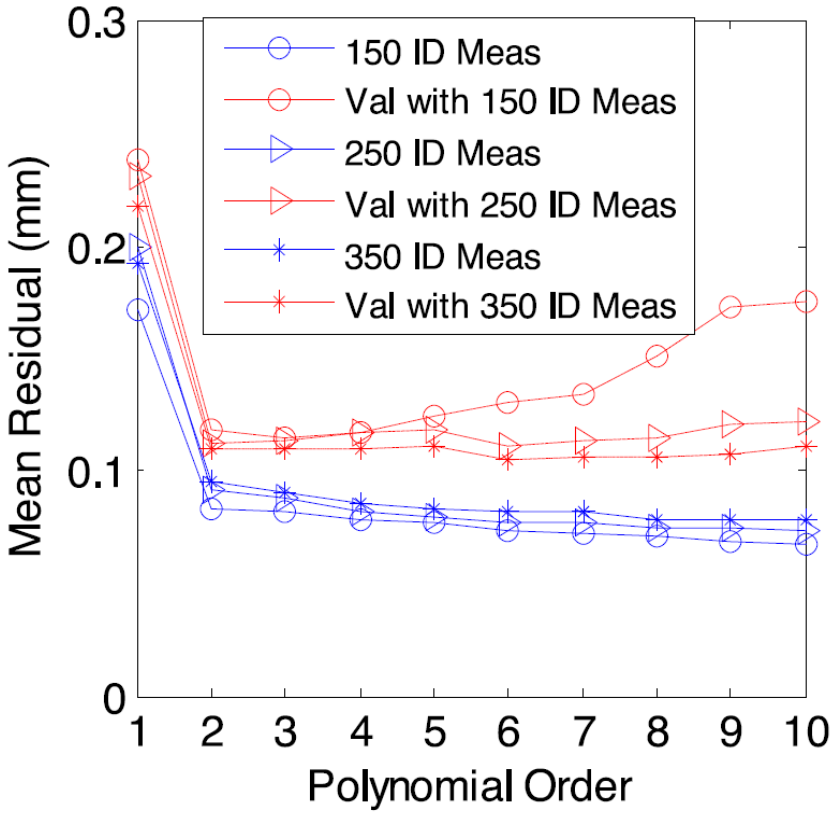
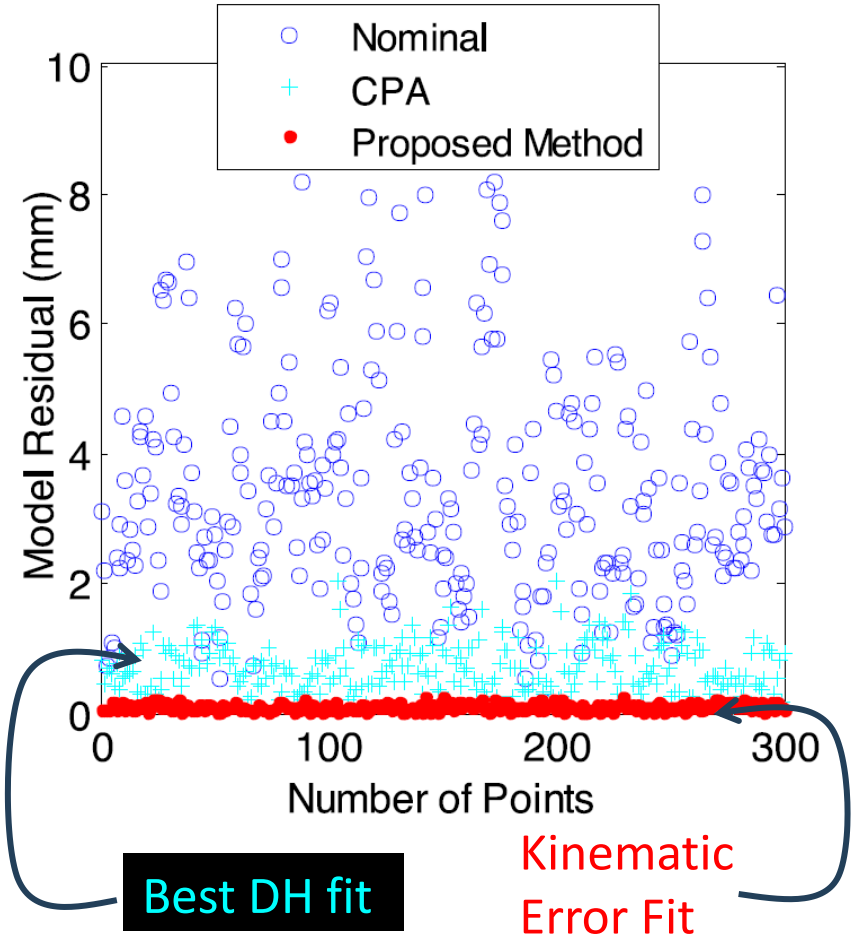
Results

Fanuc LR-Mate 200i



Does not overfit





Validation Data

	Mean residual (mm)	Maximum residual (mm)	Gamma 99% (mm)
Nominal	3.418	8.210	8.721
CPA method	0.705	2.061	1.875
Proposed method	0.104	0.261	0.277

10x Better than DH fit

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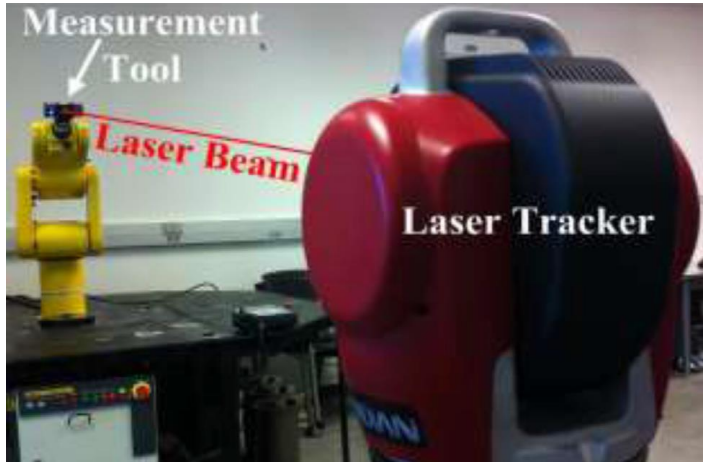
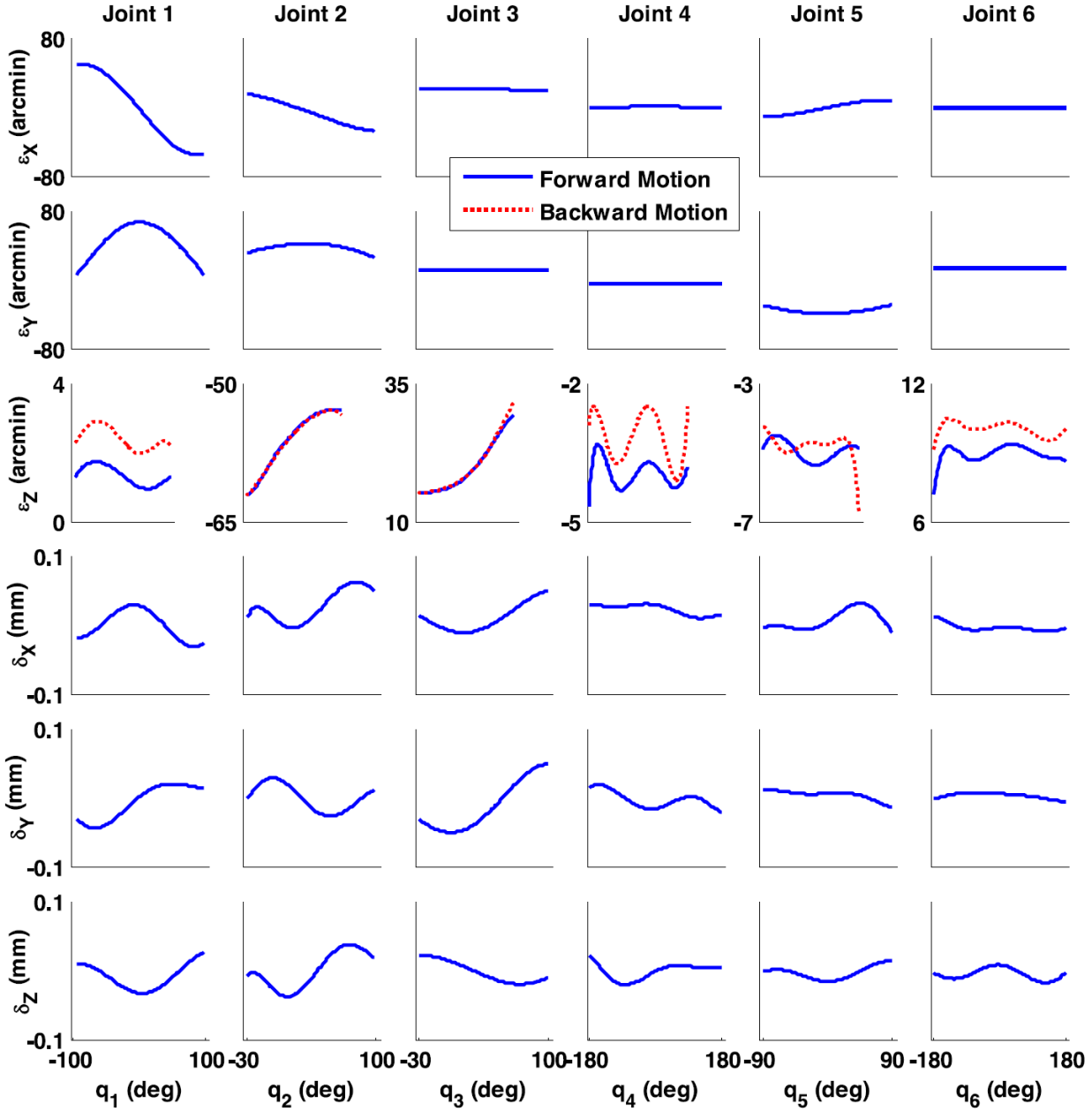


Error Kinematic Model



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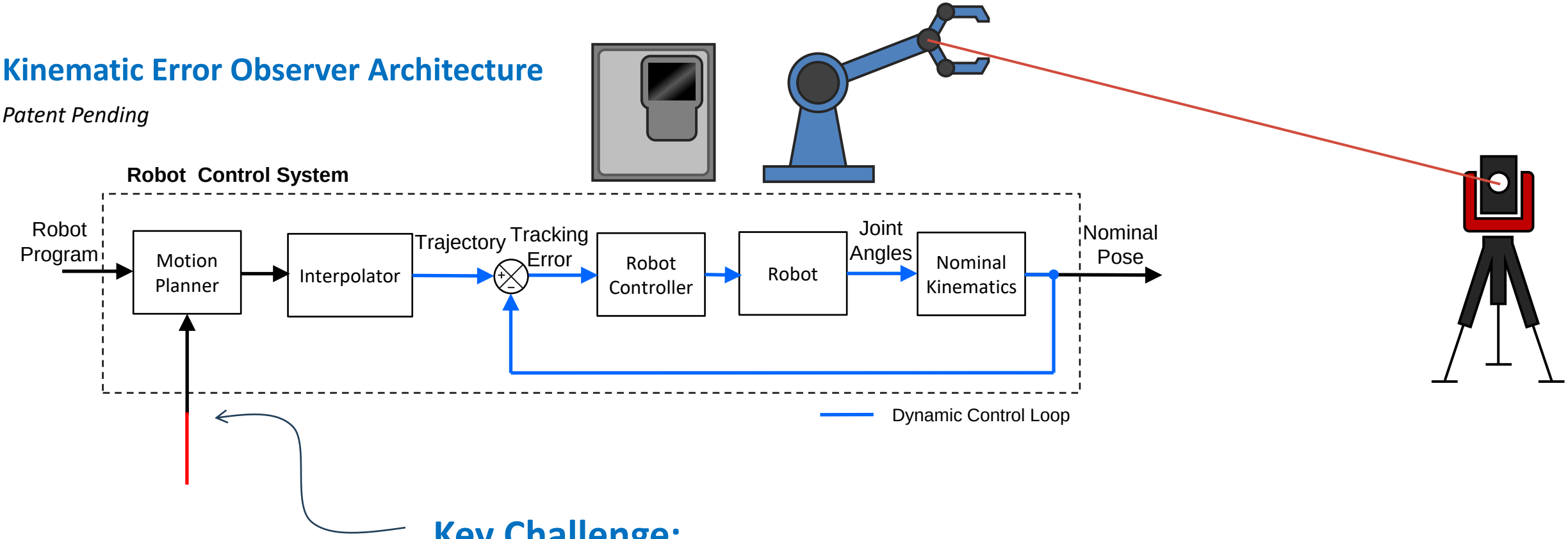
Metrology in the Loop (MitL)

Kinematic Error Observer Architecture

Patent Pending



Key Challenge:

The position-offset channel has up to 250 ms of delay on robot controllers!

Closed-loop bandwidth through this channel limited to 1-2 Hz. Too low for tracking.

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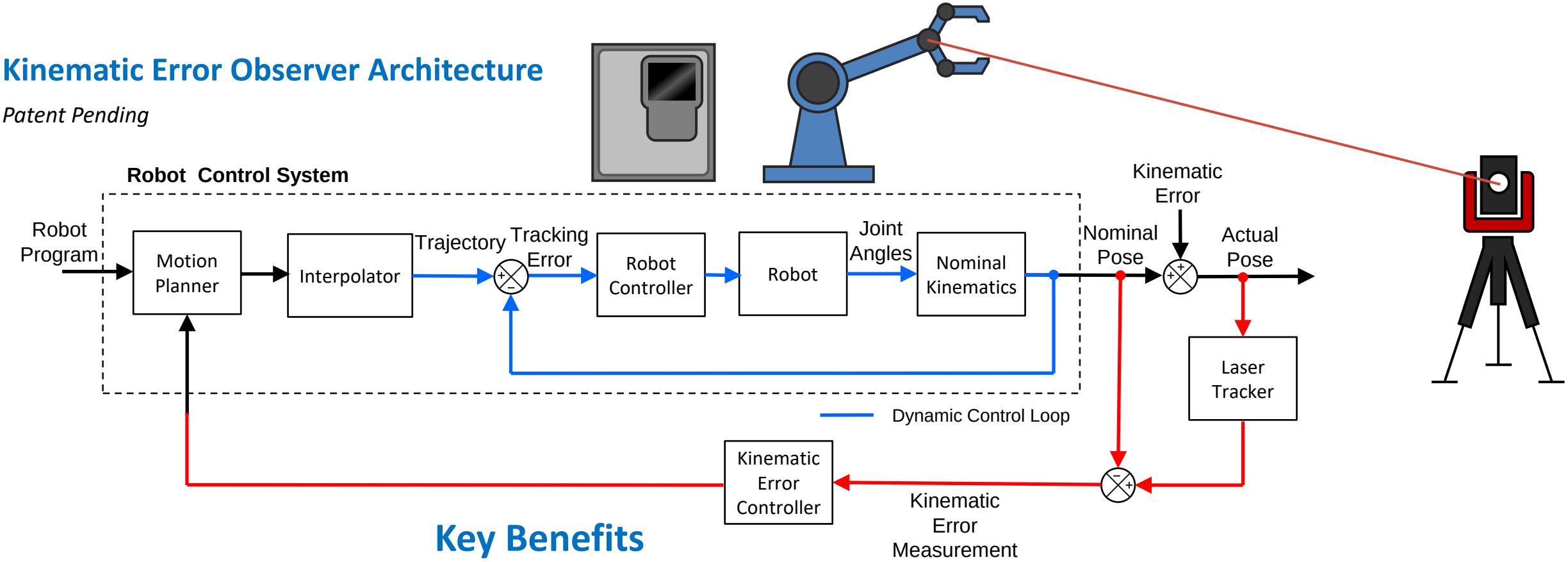

Key Benefits

- **Non-Invasive** → Works with existing robot control system, not in place of it.
- **Simple Activation** → Enabled with a single command.
- **High Performance** → Submillimeter accuracy
- **Extremely Robust** → Minimal instability risk

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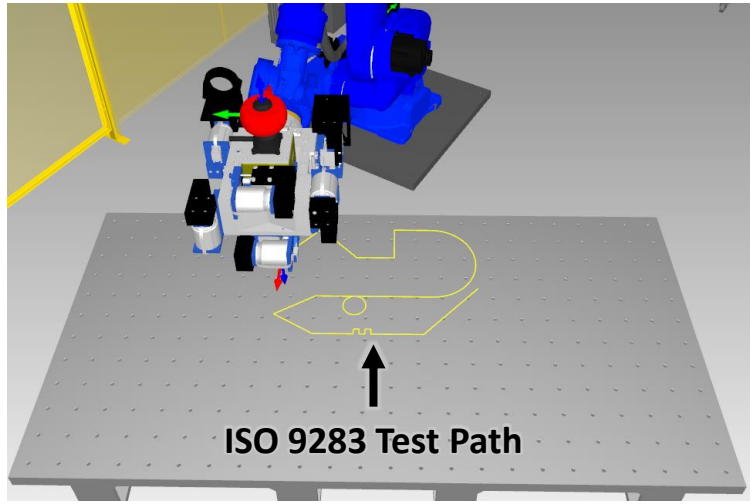
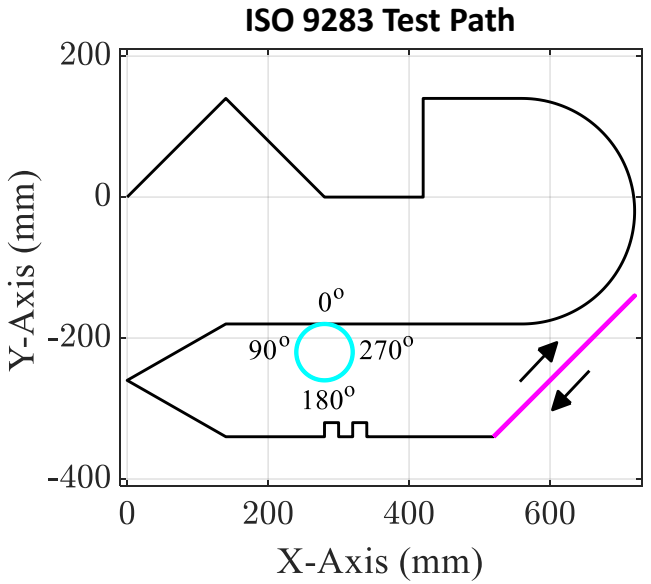
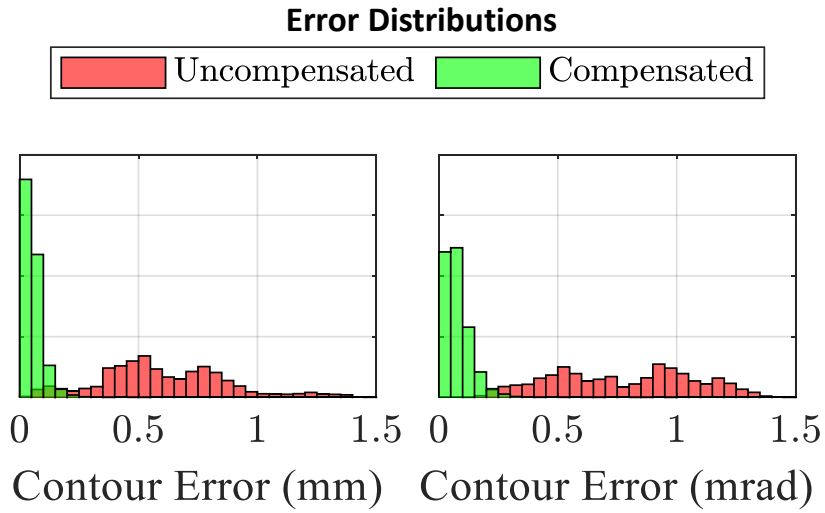
Path Accuracy







- Reduced avg. error by order of magnitude
- Max errors at direction changes (hysteresis)
  - Can reduce with careful programming
  - Potential to reduce with feedforward design – current investigation underway

Position Error Statistical Characteristics

	Mean (mm)	Std. Dev. (mm)	Max (mm)
Out-of-the-Box	0.601	0.266	1.473
MitL	0.055	0.039	0.525

Orientation Error Statistical Characteristics

	Mean (mrad)	Std. Dev. (mrad)	Max (mrad)
Out-of-the-Box	0.771	0.293	1.457
MitL	0.078	0.056	0.964

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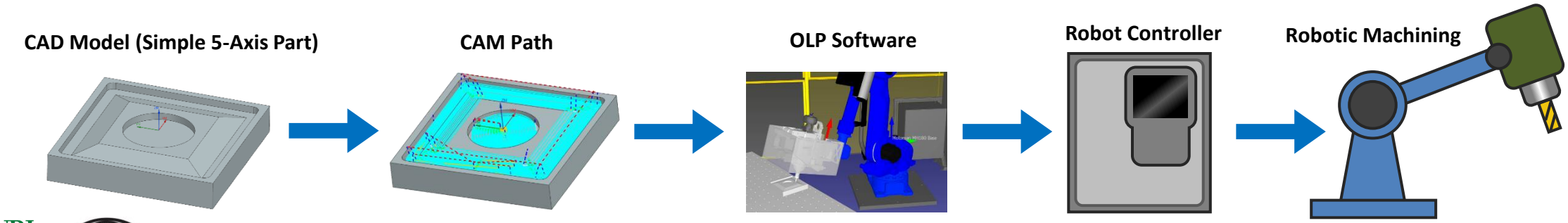
MitL Simple Machining

Face Milling

3+2-Axis Machining

Programming Pipeline



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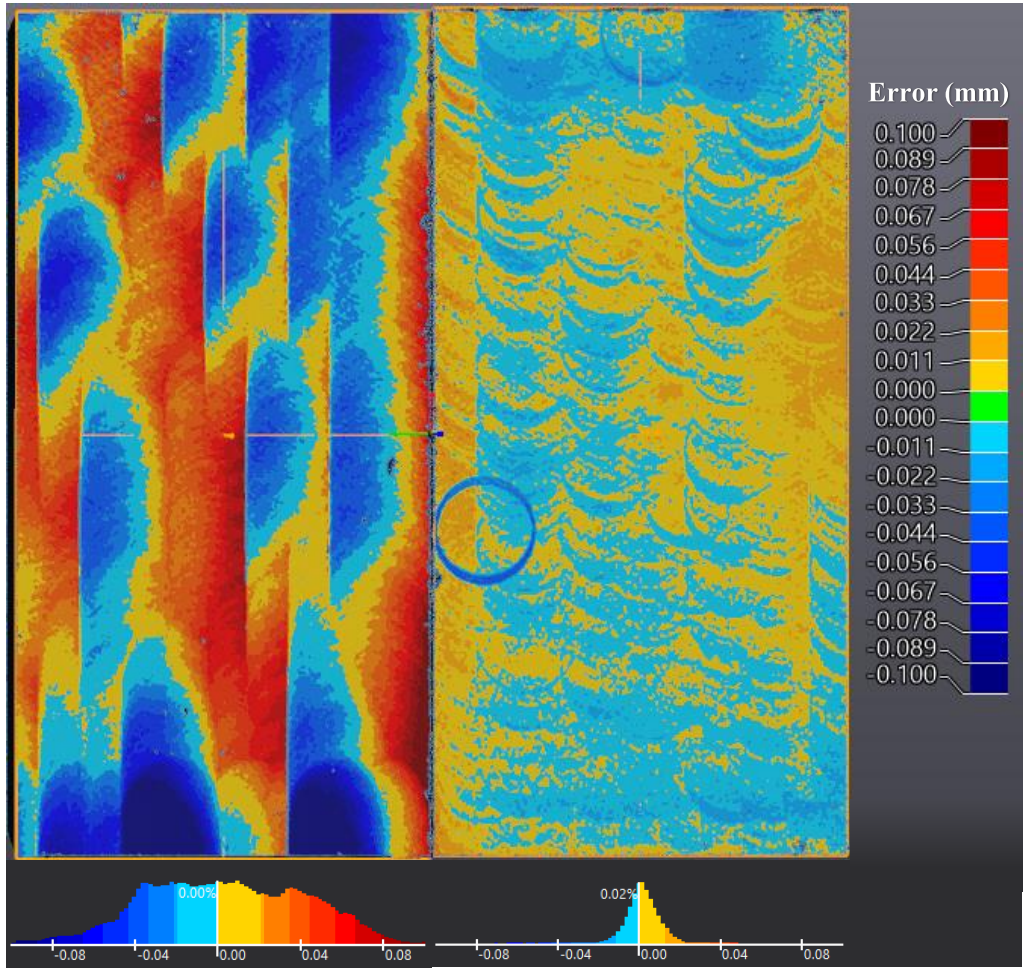
MitL Simple Machining Results

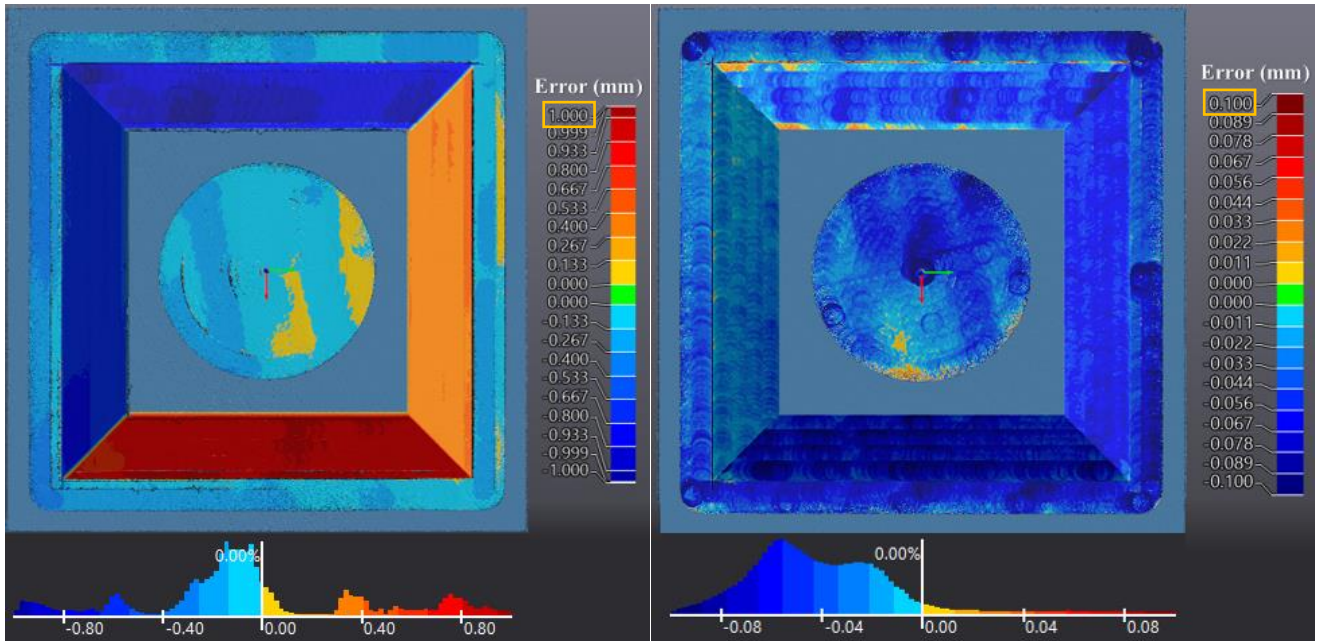
Face Milling

Out-of-the-Box MitL



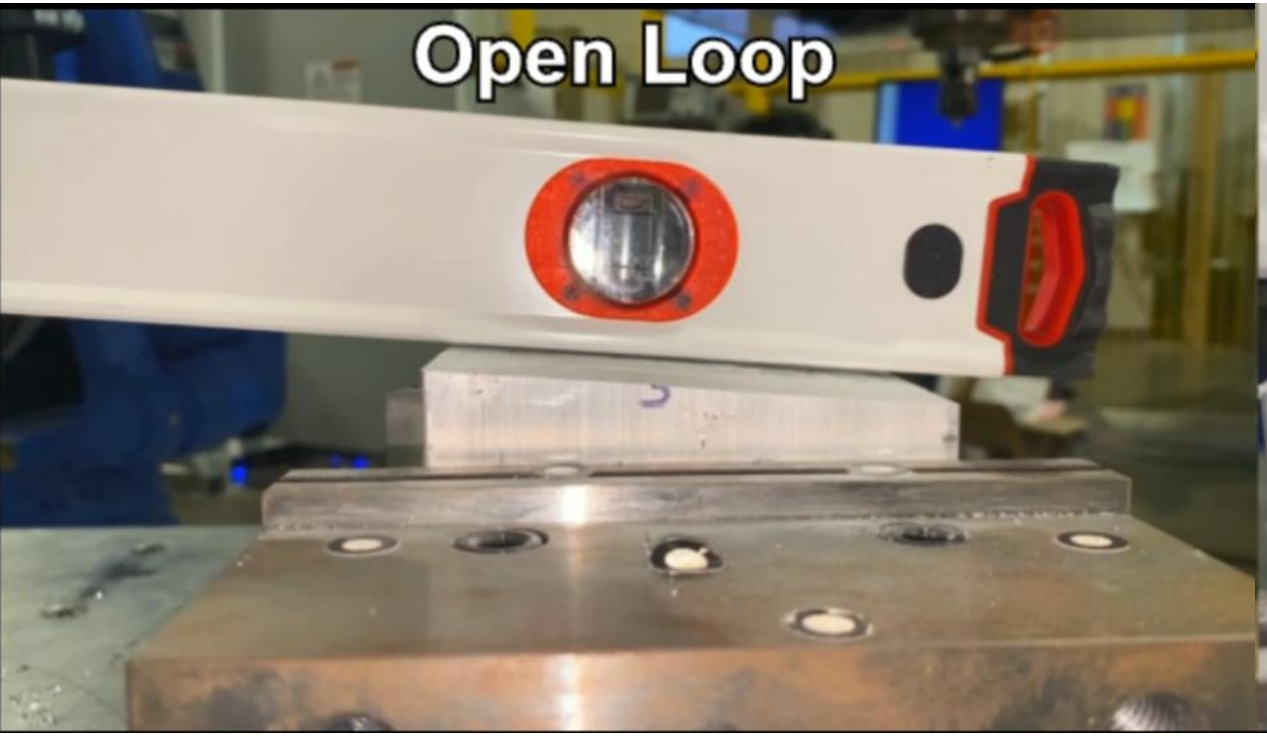
3+2-Axis Machining

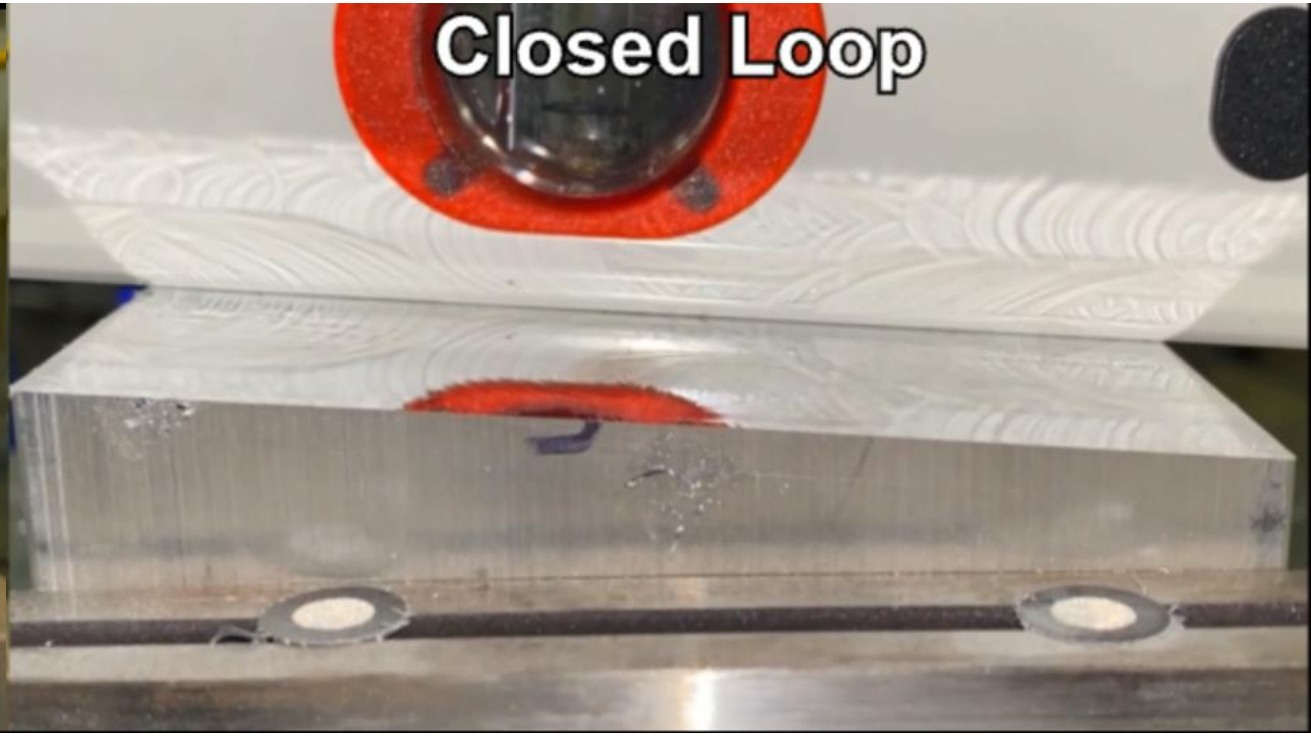
Out-of-the-Box MitL



MitL improved 5-axis machining accuracy by order of magnitude and achieved a flatness of 25 µm!

MitL Large Part Accuracy





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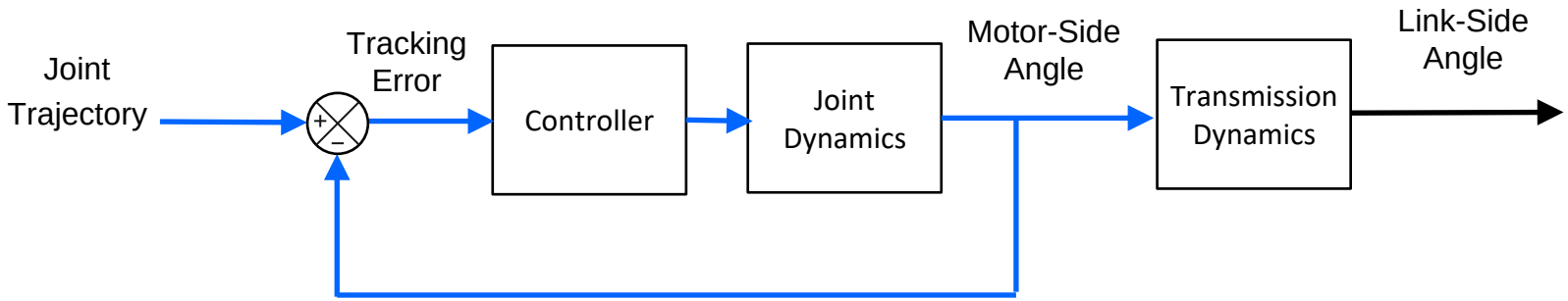
Can I Use MitL Strategy on Dual-Encoders?

What makes dual-encoders challenging?

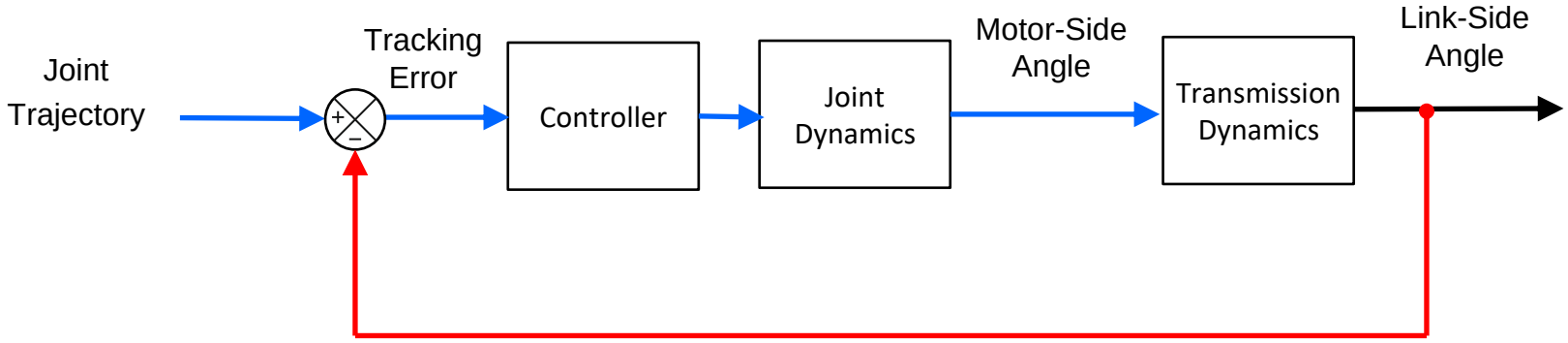
Standard Configuration

- Transmission dynamics actually *add* to loop phase increasing stability.



Link-Side Feedback

- Significant phase loss in loop, increases instability.
- Low-resolution on link-side reduces opportunity for high-gain derivative stabilization.



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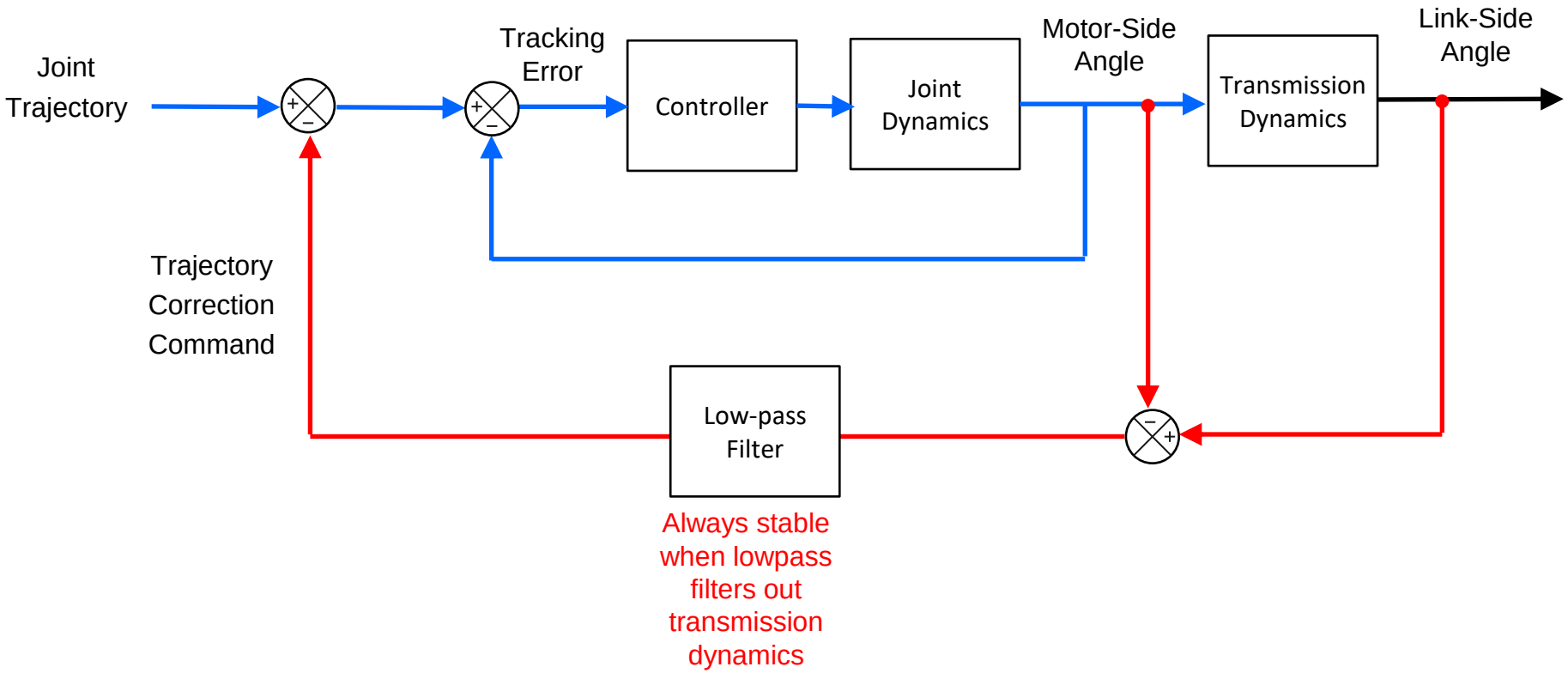
Can I Use MitL Strategy on Dual-Encoders?

Yes!



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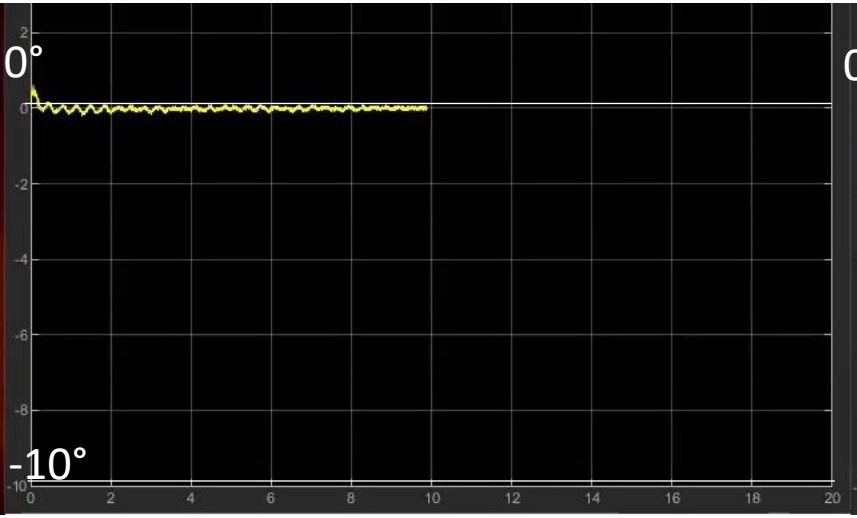
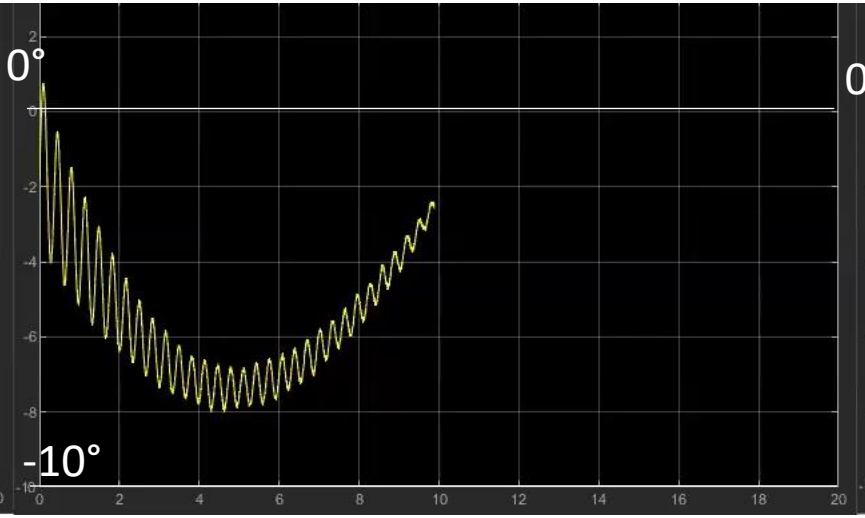
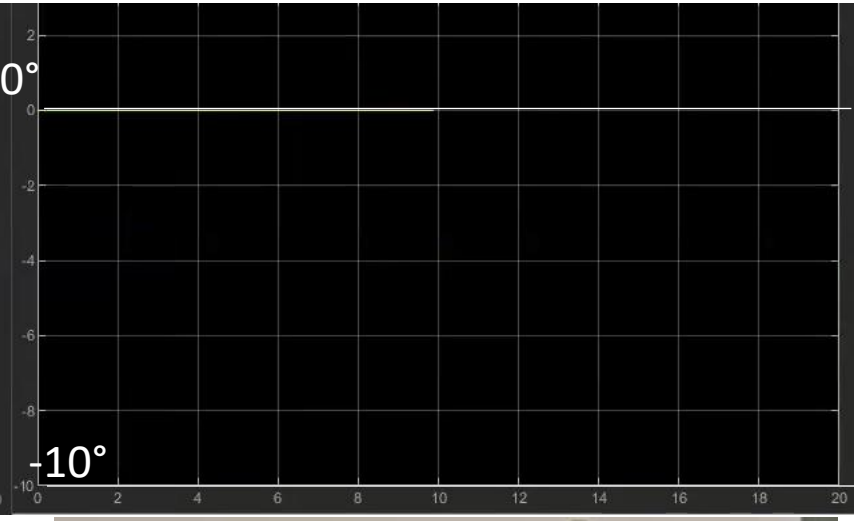
Motor Side Error



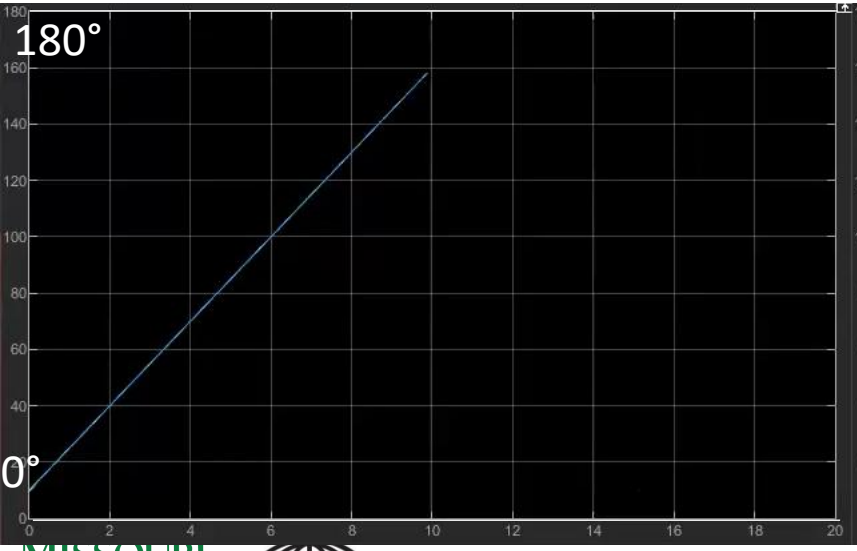
Link Side Error



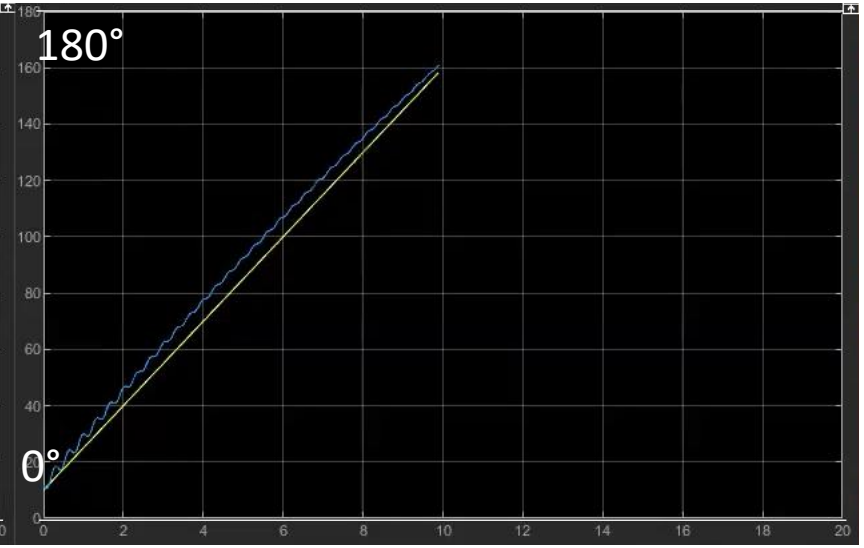
Reference Correction



Motor Side Tracking



Link Side Tracking



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Questions?