Contact Sensing via Joint Torque Sensors and a Force/Torque Sensor for Legged Robots

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Agile Robot Control and Design Laboratory

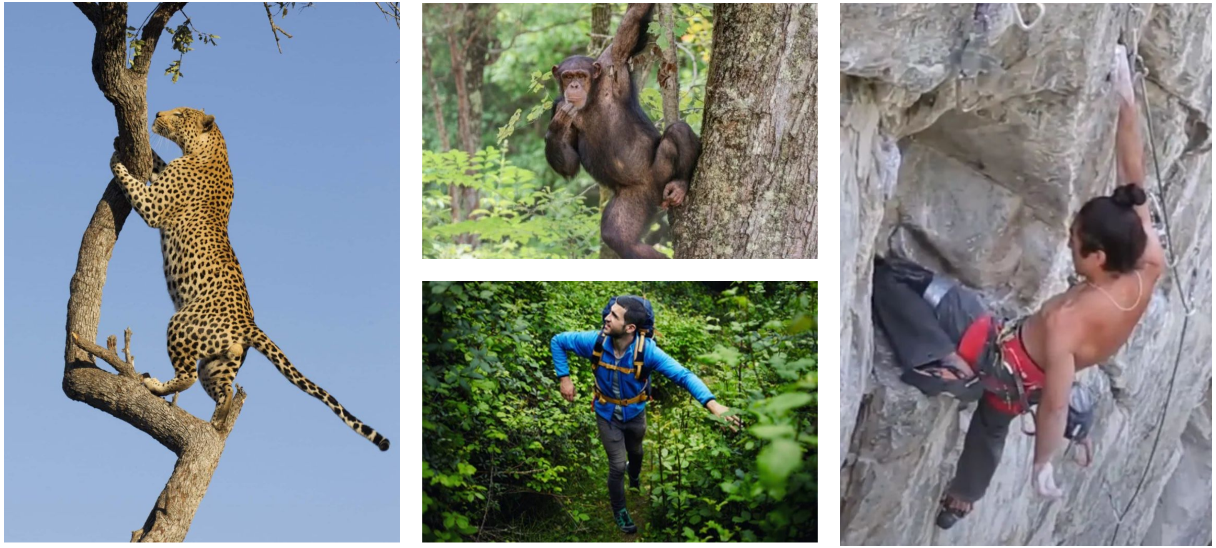
Motivation and Related Works

Animals in Complex Environments

Whole-body sensing

Multi-point contact

Adaptive stability



https://www.safariventures.com/unraveling-the-secrets-of-leopards-master-hunters-and-tree-climbers/
https://explorersweb.com/apes-downclimbing-crucial-for-human-arm-development/
https://www.shutterstock.com/image-photo/male-wanderer-walking-through-woods-overcoming-311052977
https://www.youtube.com/watch?v=H1PFWGf_1Ik&ab_channel=ClimbingTechTips

Animals in Complex Environments

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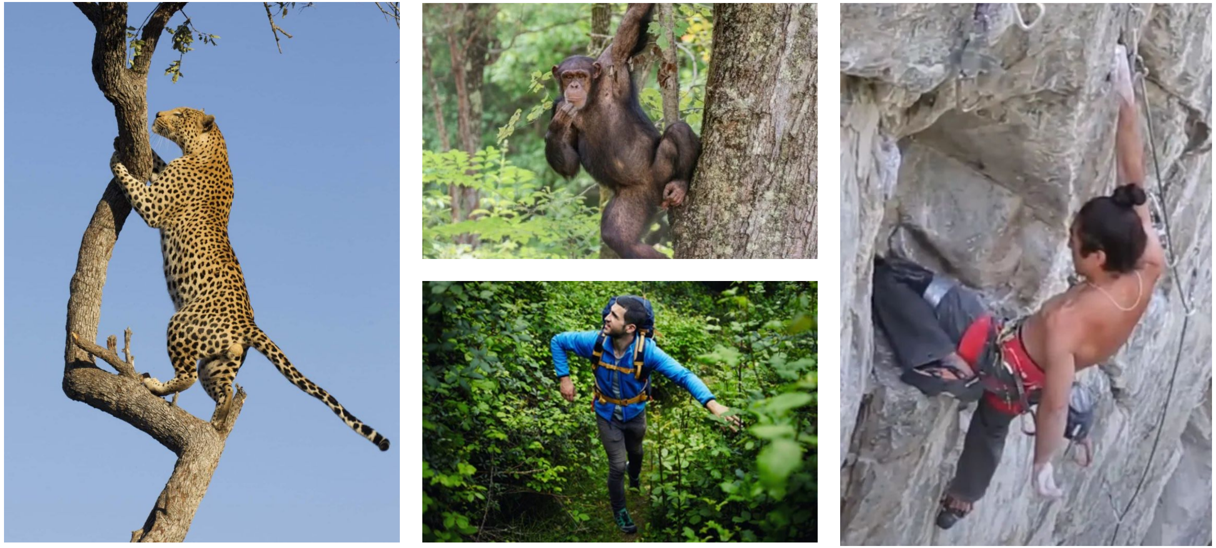
Multi-point contact

Adaptive stability



Animals excel at this - so why don't robots?

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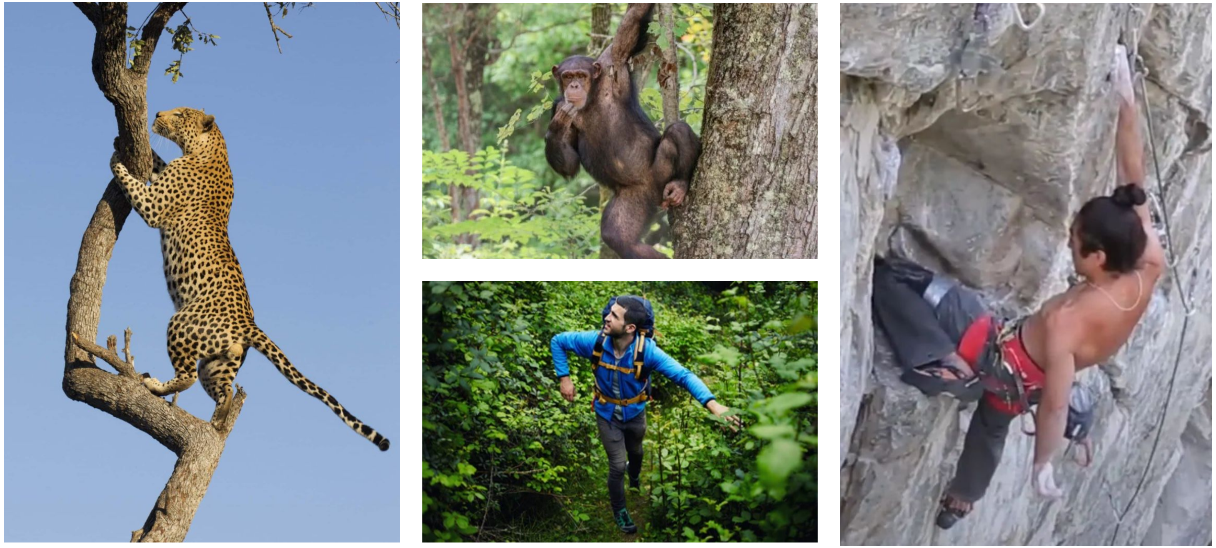

Animals excel at this - so why don't robots?

Robots need comprehensive awareness to adapt safely.

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https://www.youtube.com/watch?v=H1PFWGf_1Ik&ab_channel=ClimbingTechTips

Legged Robots in Complex Environments

Legged robots increasingly operate in **unstructured** environments

Outdoors

Warehouse

Disaster Sites

Search and Rescue

Versatile mobility

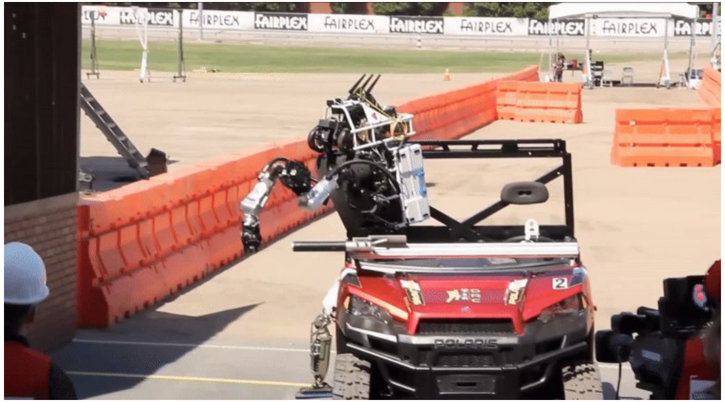
https://www.youtube.com/watch?v=cGb3bE6ZwrQ&ab_channel=MichiganRobotics%3ADynamicLeggedLocomotionLab
https://www.youtube.com/watch?v=Q8KWZB4kgTY&ab_channel=DEEPRobotics
https://bostondynamics.com/blog/starting-on-the-right-foot-with-reinforcement-learning/

The Contact Detection Gap

Detect foot contact but **miss** leg collisions.

Damage | Instability
Navigation failure

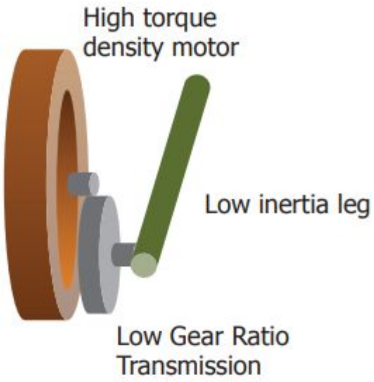
https://www.youtube.com/watch?v=aX7KypGlitg&list=PPSV&ab_channel=TheIndependent



https://www.youtube.com/watch?v=6JqvIRMQU1E&list=PPSV&ab_channel=RobotLocomotionGroup

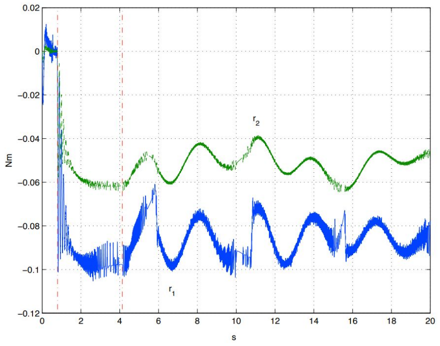
Current Approaches to Whole-Body Sensing

Torque Sensing



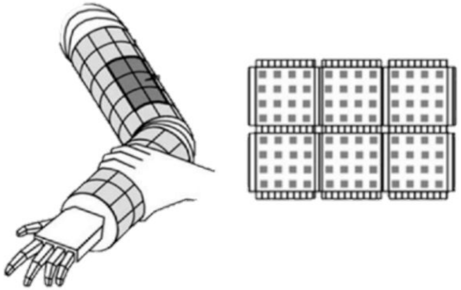
Wensing, TRO 2017

Contact Detection



De Luca, ICRA 2005

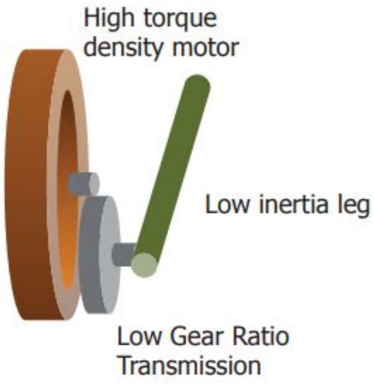
Whole-Body Coverage

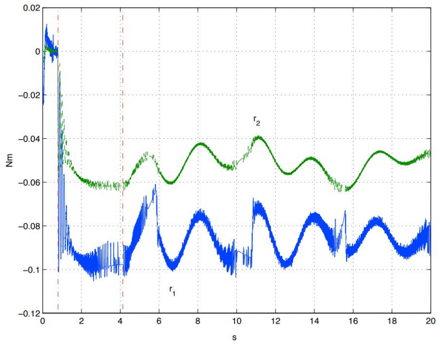


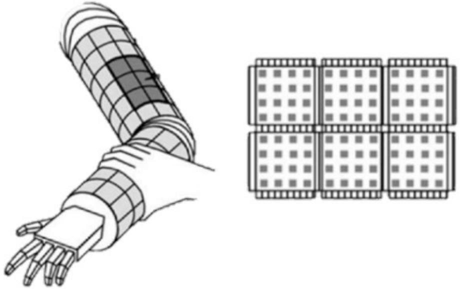
Bayer, Micromachines 2022

	Torque Sensing	Contact Detection	Whole-Body Coverage
Method	Motor Current Estimation	Momentum Observer	Alternative Sensing Modalities
Benefits	● Current $\propto$ Torque ● Uses existing hardware in QDDs	● Fast detection ● Only encoder	● Rich spatial data ● Detects across entire body

Critical Gaps in Existing Methods



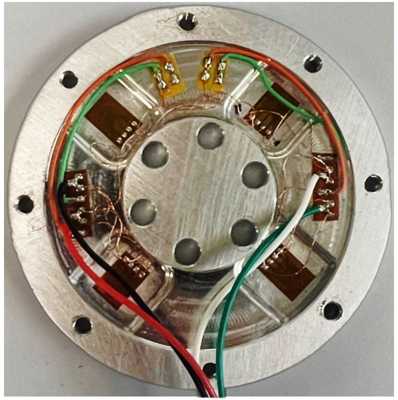




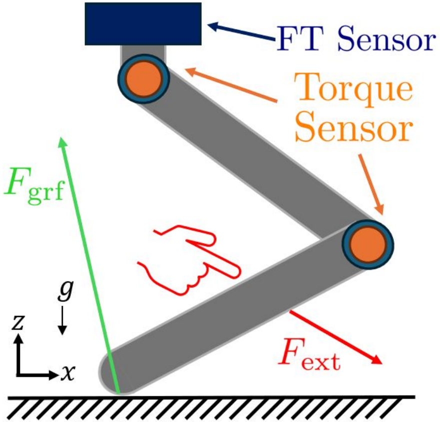
	Torque Sensing	**Contact Detection**	**Whole-Body Coverage**
	Wensing, TRO 2017	De Luca, ICRA 2005	Bayer, Micromachines 2022
Method	Motor Current Estimation	Momentum Observer	Alternative Sensing Modalities
Limitations	• Not direct measurement	• Requires friction modeling	• Extensive arrays, fragile

Our Approach: Combined Sensing for Complete Awareness

Torque Sensing



Whole-Body Coverage



Method	Direct Joint Torque Sensing	Single Hip-Mounted FT Sensor
Solution	● Bypass gearbox friction ● Scales to higher torque	● Proximal link detection ● Protected location

Methodology

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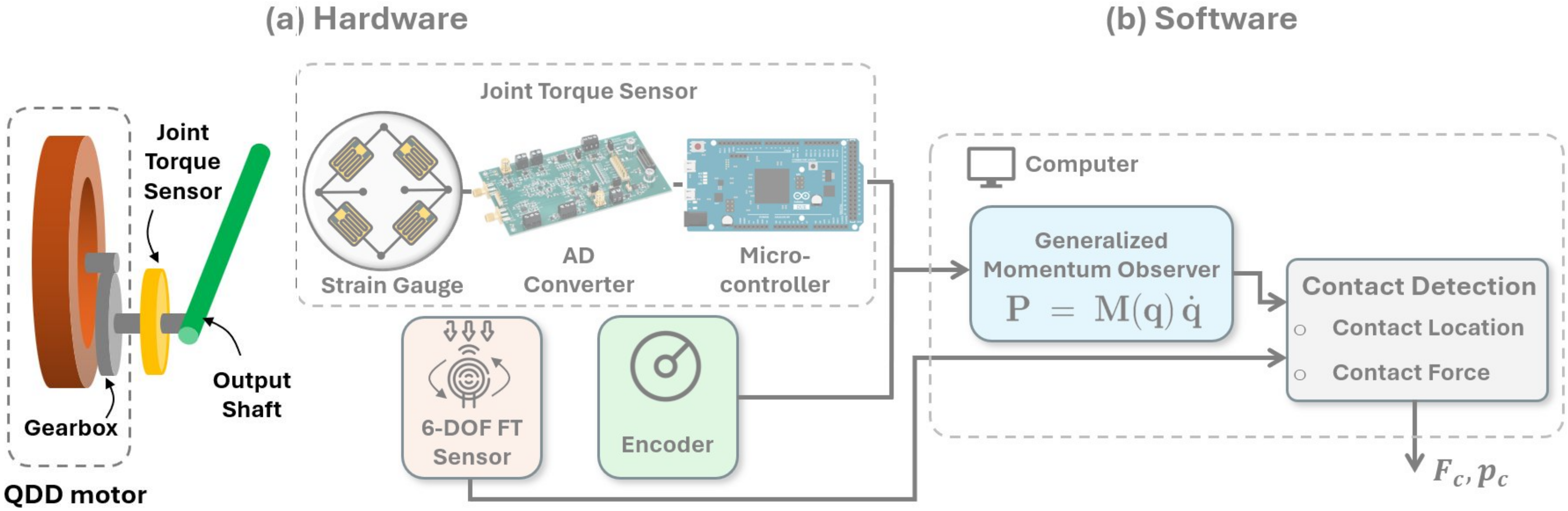
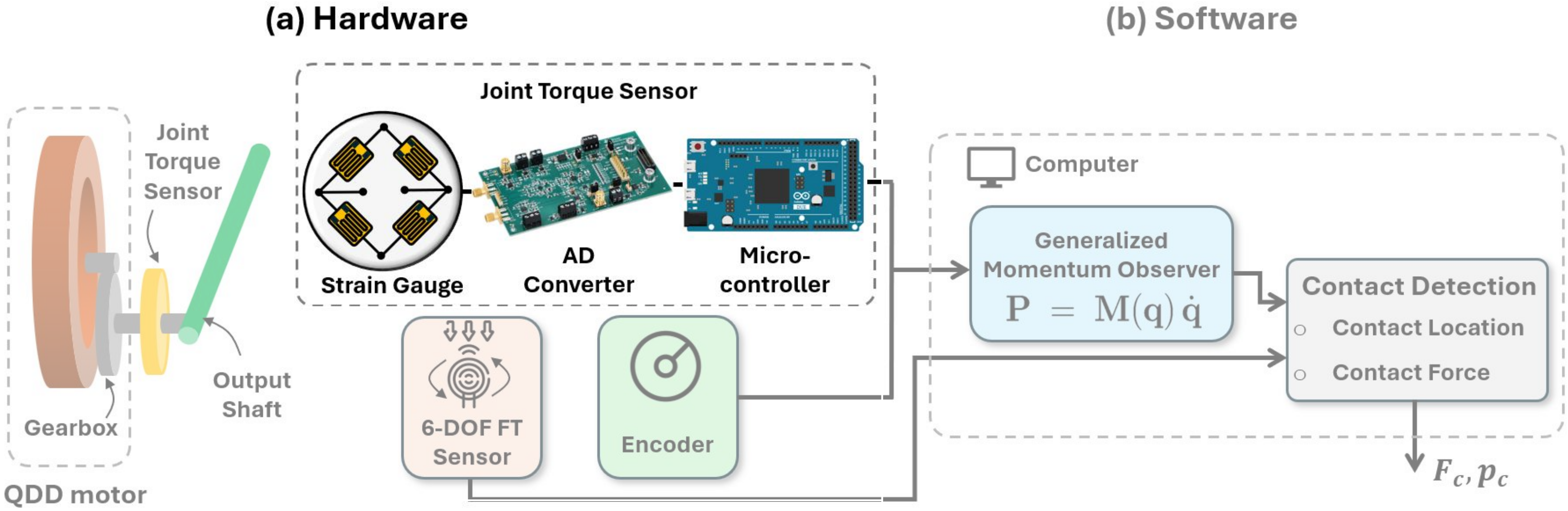
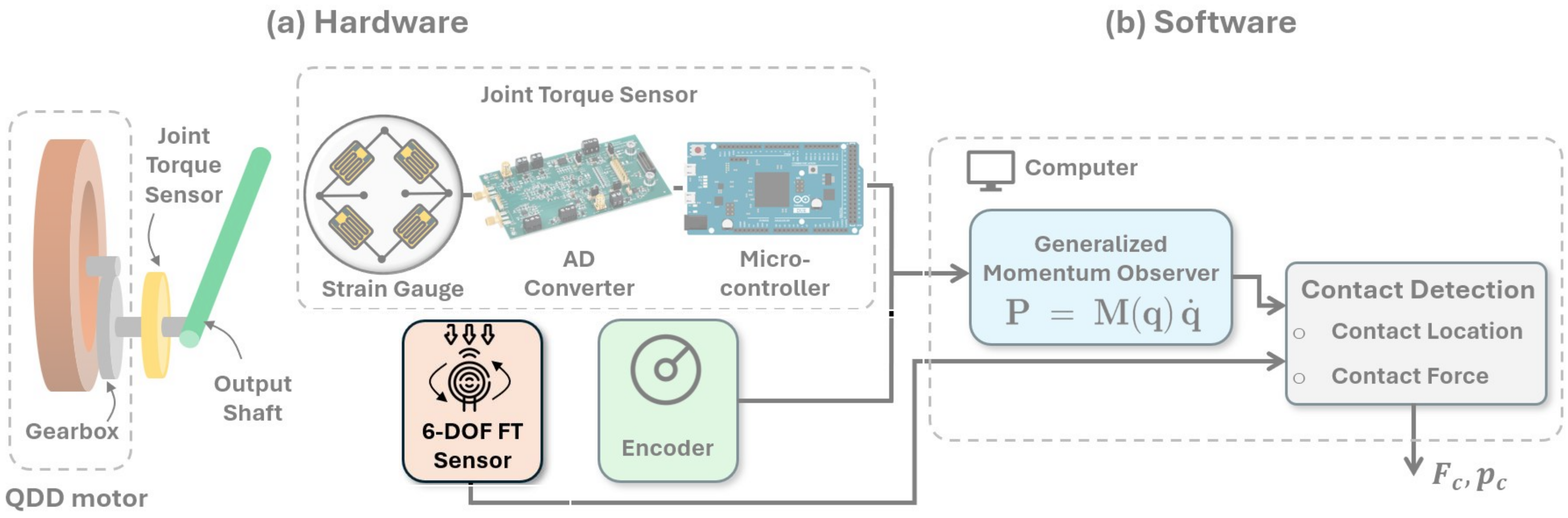
Direct Torque Sensing System Design



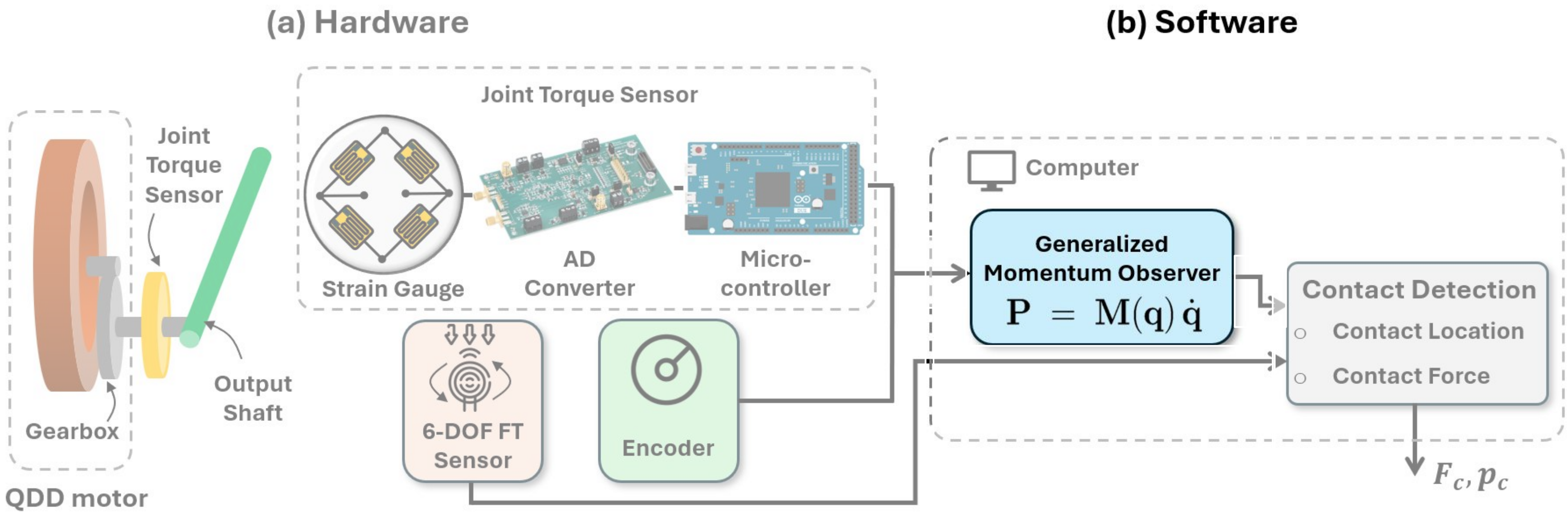
Direct Torque Sensing System Design



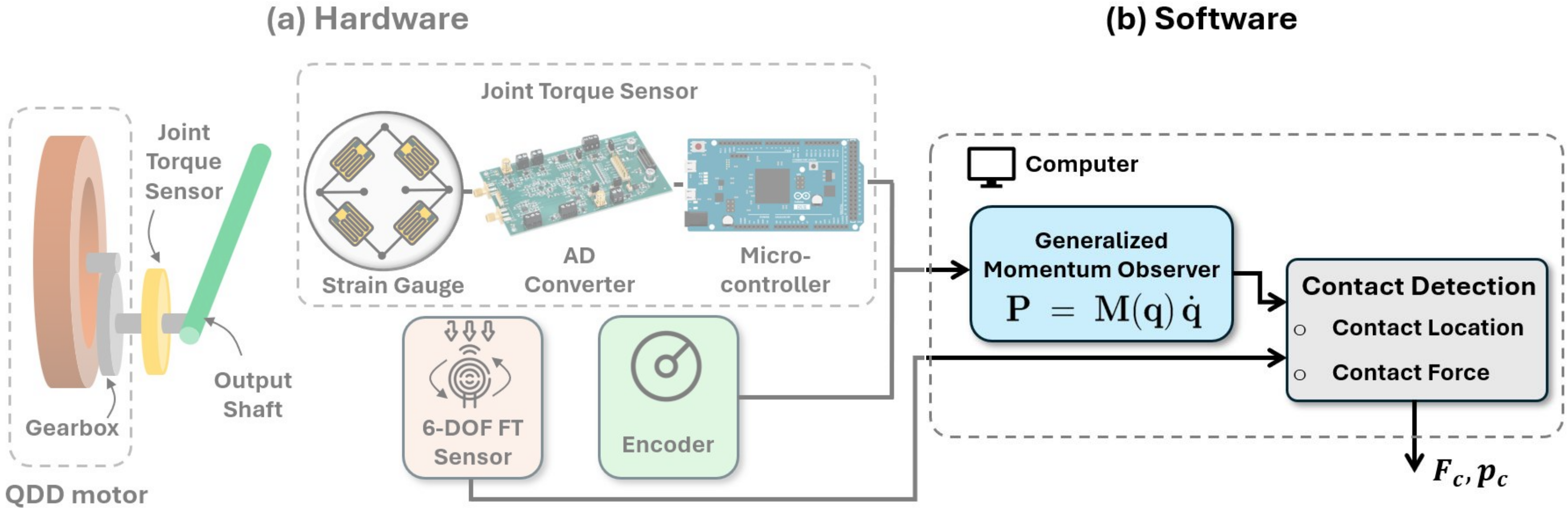
Direct Torque Sensing System Design



Direct Torque Sensing System Design



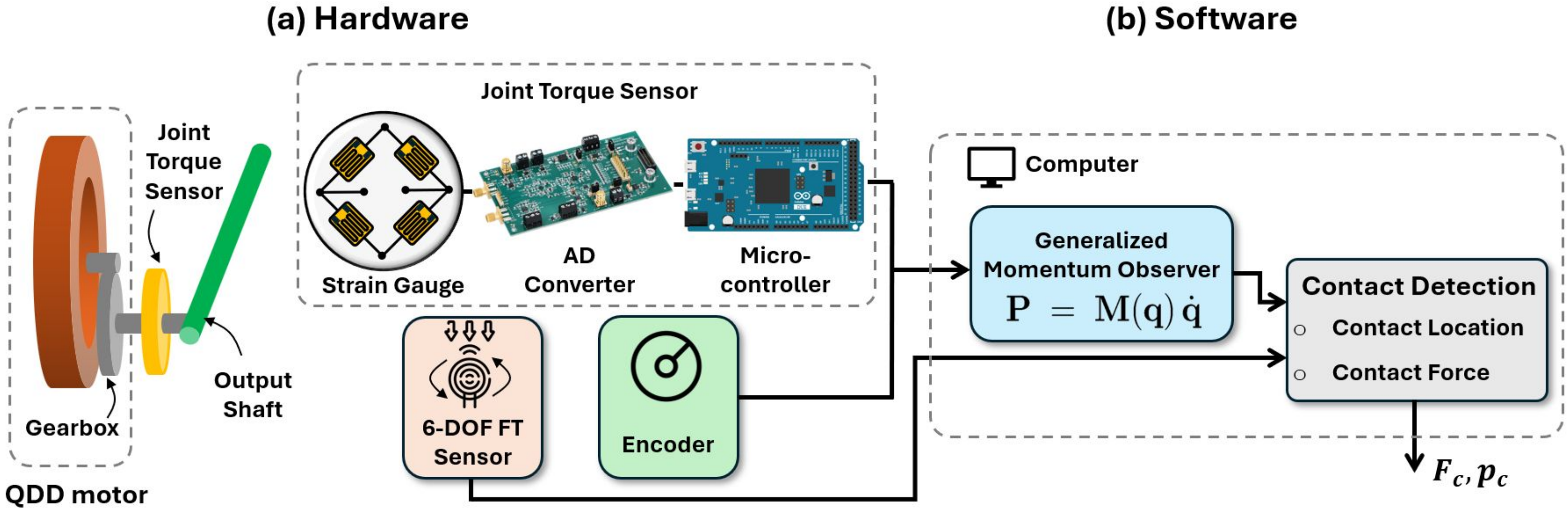
Direct Torque Sensing System Design



(a) Hardware

(b) Software

Direct Torque Sensing System Design



Robot Dynamics Foundation

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\text{fric}} + \boldsymbol{\tau}_{\text{ext}} = \boldsymbol{\tau}_{\text{motor}}$$

Robot Dynamics Foundation

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\mathrm{fric}} + \boldsymbol{\tau}_{\mathrm{ext}} = \boldsymbol{\tau}_{\mathrm{motor}}$$

$$-\ \boldsymbol{\tau}_{\mathrm{fric}} \qquad\qquad -\ \boldsymbol{\tau}_{\mathrm{fric}}$$

Robot Dynamics Foundation

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} \;+\; \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} \;+\; \mathbf{g}(\mathbf{q}) \;+\; \boldsymbol{\tau}_{\mathrm{ext}} \;=\; \boldsymbol{\tau}_{\mathrm{motor}} \;-\; \boldsymbol{\tau}_{\mathrm{fric}}$$

Robot Dynamics Foundation

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\mathrm{ext}} = \boldsymbol{\tau}_{\mathrm{motor}} - \boldsymbol{\tau}_{\mathrm{fric}}$$

$$\boldsymbol{\tau}_{\mathrm{sen}} = \boldsymbol{\tau}_{\mathrm{motor}} - \boldsymbol{\tau}_{\mathrm{fric}}$$

Robot Dynamics Foundation

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} \;+\; \mathbf{C}\big(\mathbf{q},\dot{\mathbf{q}}\big)\,\dot{\mathbf{q}} \;+\; \mathbf{g}\big(\mathbf{q}\big) \;+\; \boldsymbol{\tau}_{\text{ext}} \;=\; \boldsymbol{\tau}_{\text{sen}}$$

Robot Dynamics Foundation

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\text{ext}} = \boldsymbol{\tau}_{\text{sen}}$$

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$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\text{ext}} = \boldsymbol{\tau}_{\text{sen}}$$

Generalized Momentum

$$\mathbf{P} = \mathbf{M}(\mathbf{q})\,\dot{\mathbf{q}}$$

Robot Dynamics Foundation

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\text{ext}} = \boldsymbol{\tau}_{\text{sen}}$$

Generalized Momentum

$$\mathbf{P} = \mathbf{M}(\mathbf{q})\,\dot{\mathbf{q}}$$

$$\dot{\mathbf{P}} = \frac{d}{dt}\left[\mathbf{M}(\mathbf{q})\,\dot{\mathbf{q}}\right]$$

Robot Dynamics Foundation

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\text{ext}} = \boldsymbol{\tau}_{\text{sen}}$$

Generalized Momentum

$$\dot{\mathbf{P}} = \mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \dot{\mathbf{M}}(\mathbf{q})\,\dot{\mathbf{q}}$$

Robot Dynamics Foundation

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\text{ext}} = \boldsymbol{\tau}_{\text{sen}}$$

Generalized Momentum

$$\dot{\mathbf{P}} = \mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \dot{\mathbf{M}}(\mathbf{q})\,\dot{\mathbf{q}}$$

$$\dot{\mathbf{M}} = \mathbf{C} + \mathbf{C}^{\top}$$

Robot Dynamics Foundation

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\text{ext}} = \boldsymbol{\tau}_{\text{sen}}$$

Generalized Momentum

$$\boxed{\dot{\mathbf{P}} = \mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}\,\dot{\mathbf{q}} + \mathbf{C}^{\mathbf{T}}\,\dot{\mathbf{q}}}$$

Momentum Observer

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\,\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \boldsymbol{\tau}_{\text{ext}} = \boldsymbol{\tau}_{\text{sen}} \qquad \dot{\mathbf{P}} = \mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{C}\,\dot{\mathbf{q}} + \mathbf{C}^{\mathbf{T}}\,\dot{\mathbf{q}}$$

Momentum Observer

$$\boxed{\dot{\mathbf{P}} = \mathbf{C}^\top \dot{\mathbf{q}} - \mathbf{g} + \boldsymbol{\tau}_{\text{sen}} - \boldsymbol{\tau}_{\text{ext}}}$$

Generalized Momentum

$$\dot{\mathbf{P}} = \mathbf{C}^\top \dot{\mathbf{q}} - \mathbf{g} + \boldsymbol{\tau}_{\text{sen}} - \boldsymbol{\tau}_{\text{ext}}$$

$$\dot{\mathbf{P}} = \mathbf{u} - \boldsymbol{\tau}_{\text{ext}}$$

Residual for Contact Detection

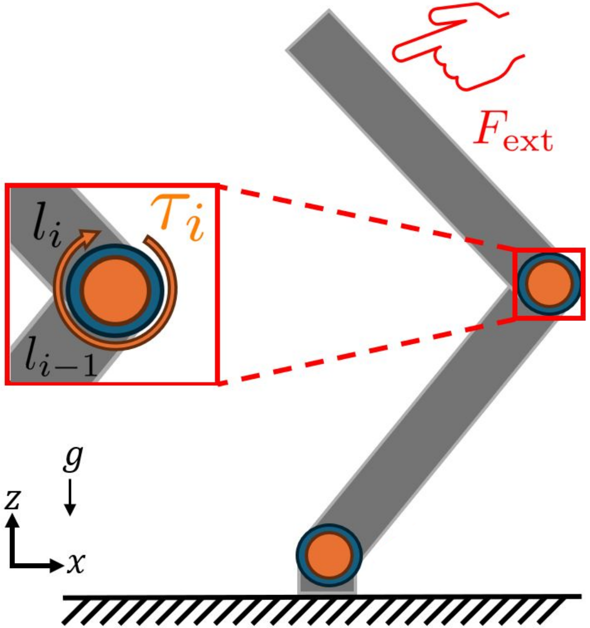
$$\mathbf{r}(t) = \mathbf{K}\left[\mathbf{P}(t) - \mathbf{p}_{\text{int}}(t) - \mathbf{P}_0\right]$$

$$\dot{\mathbf{P}} = \mathbf{u} - \boldsymbol{\tau}_{\text{ext}} \quad \rightarrow \quad \mathbf{p}_{\text{int}}(t+\Delta t) = \mathbf{p}_{\text{int}}(t) + \left[\mathbf{u} + \mathbf{r}(t)\right]\Delta t$$

Residual for Collision Link Identification

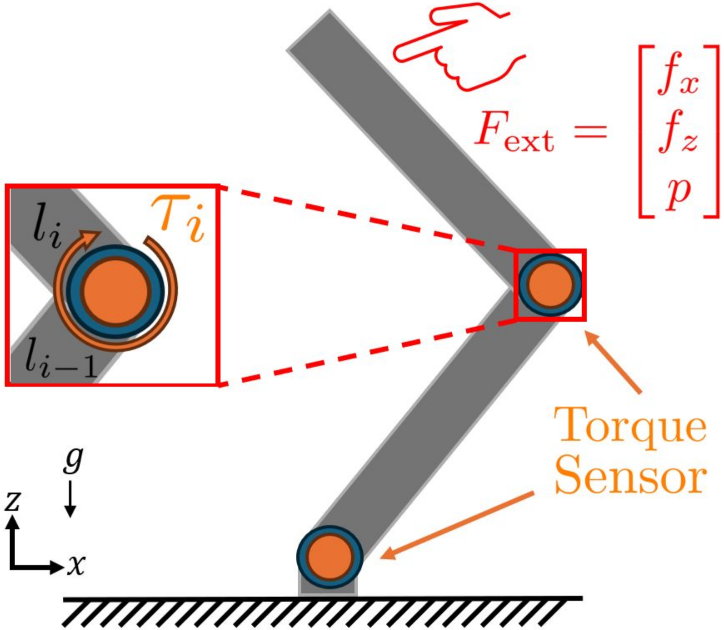
$$r_i(t) \neq 0 \quad \text{for } i = 1, \ldots, c$$
$$r_j(t) = 0 \quad \text{for } j = c+1, \ldots, n$$

$$c = \max\{\, i \in \{1, \ldots, n\} : |r_i(t)| > \epsilon_{\text{res}} \}$$



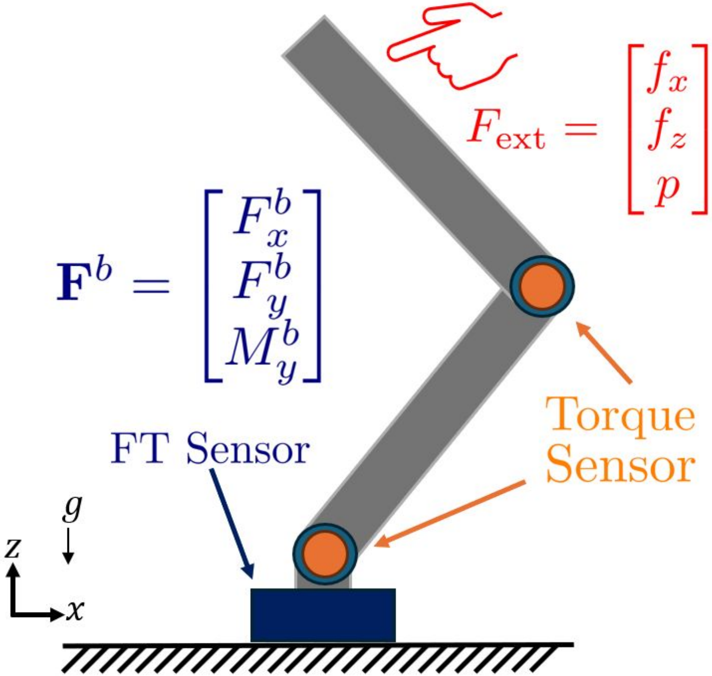
The Underdetermined Contact Problem

- 3 unknowns
- 2 known measurements
- Underdetermined system



Contact Detection → Contact Localization

- Base FT Sensor - 3 additional measurements
- Proximal to any contactable link

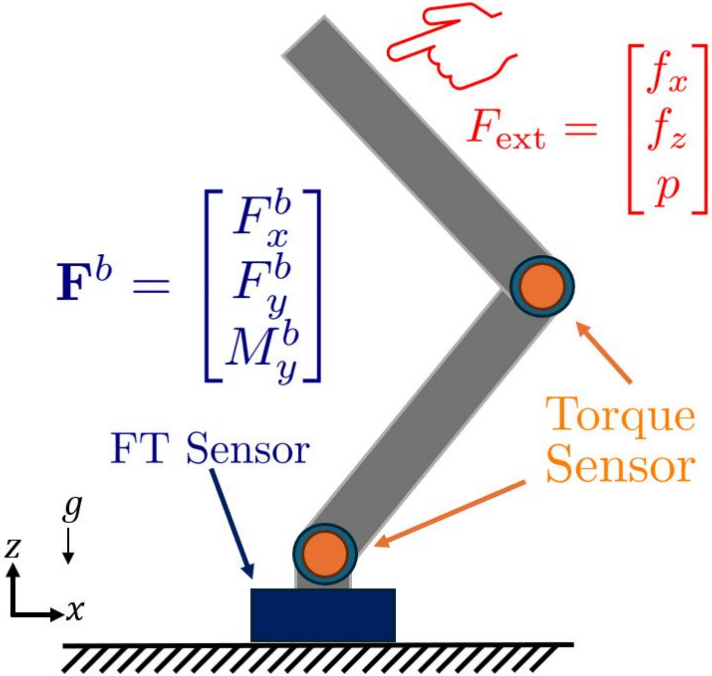


Force Calculation

$$\mathbf{w} = \mathbf{S}(\mathbf{C}\dot{\mathbf{q}} + \mathbf{g} - \mathbf{B}\,\boldsymbol{\tau}_{\text{sen}})$$

$$\mathbf{F}^u = \mathbf{w} - \mathbf{F}^b$$

$$\mathbf{F}_c = -[F^u_x, F^u_z]^\top$$

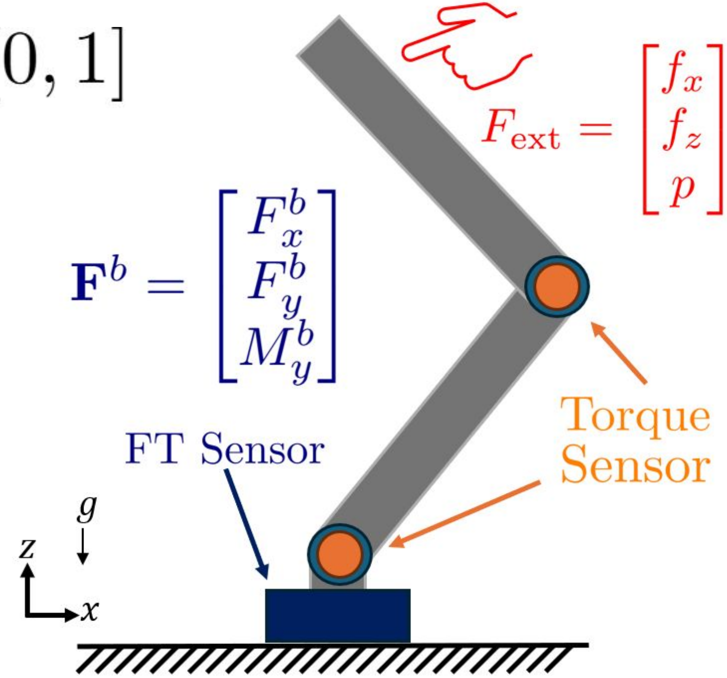


Position Calculation

$$\mathbf{p}_c = \mathbf{p}_1 + \alpha(\mathbf{p}_2 - \mathbf{p}_1),\ \alpha \in [0, 1]$$

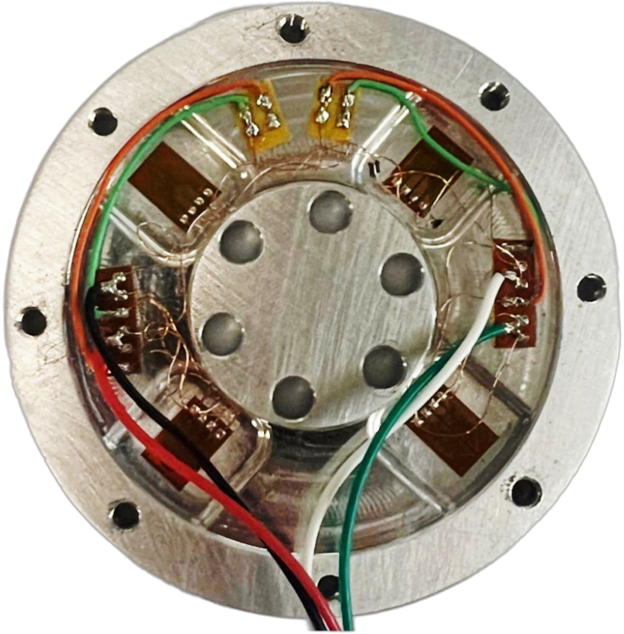
$$M_y^u + \mathbf{p}_c \wedge \mathbf{F}_{xz}^u = 0$$

$$\alpha = -\frac{M_y^u + \mathbf{p}_1 \wedge \mathbf{F}_{xz}^u}{(\mathbf{p}_2 - \mathbf{p}_1) \wedge \mathbf{F}_{xz}^u}$$



Custom Joint Torque Sensor Design

- 1 kΩ strain gauges
- Full Wheatstone bridge
- 5 V excitation
- Differential output
- 6061 Aluminum Alloy
- Under $32



Sensor Calculations

- GF = 2 (gauge factor)
- V_{ex} = 5V (excitation voltage)
- ϵ = strain

$$\frac{\Delta R}{R} = \mathrm{GF}\,\epsilon$$

$$V_o = V_{\text{ex}} \times \frac{\Delta R/R}{4}$$

Sensor Calculations

- GF = 2 (gauge factor)
- V_{ex} = 5V (excitation voltage)
- ϵ = strain

$$\boxed{V_o = V_{\mathrm{ex}} \times \frac{\mathrm{GF}\,\epsilon}{4}}$$

Sensor Calculations

$$\mathrm{LSB} = V_{\mathrm{ref}} / 2^{24} \qquad V_o = V_{\mathrm{ex}} \times \frac{\mathrm{GF}\,\epsilon}{4}$$

Sensor Calculations

$$\boxed{\epsilon_{\mathrm{min}} = \frac{4\,V_{\mathrm{ref}}}{\mathrm{GF}\,V_{\mathrm{ex}}\,2^{N}}}$$

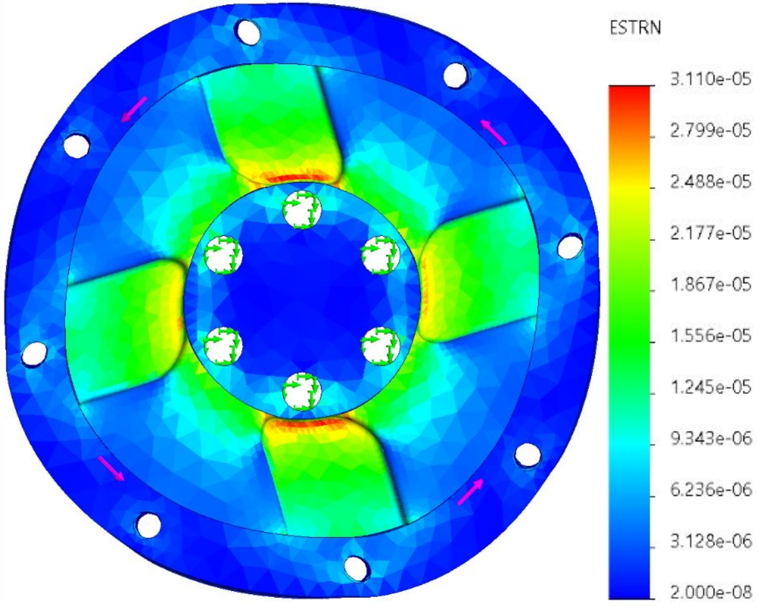
Sensor Calculations

$$\epsilon_{\mathrm{min}} = \frac{4\,V_{\mathrm{ref}}}{\mathrm{GF}\,V_{\mathrm{ex}}\,2^N} \approx 5.96 \times 10^{-8} \quad \text{(ideal)}$$

$$\approx 1.53 \times 10^{-5} \quad \text{(ENOB)}$$

Finite Element Analysis Validation

- Detects strains under typical torques
    - Ideal = 0.001 Nm
    - ENOB = 0.4 Nm
- 8.5 Nm capacity



FEA with external torque of 0.4 Nm

Experiments and Results

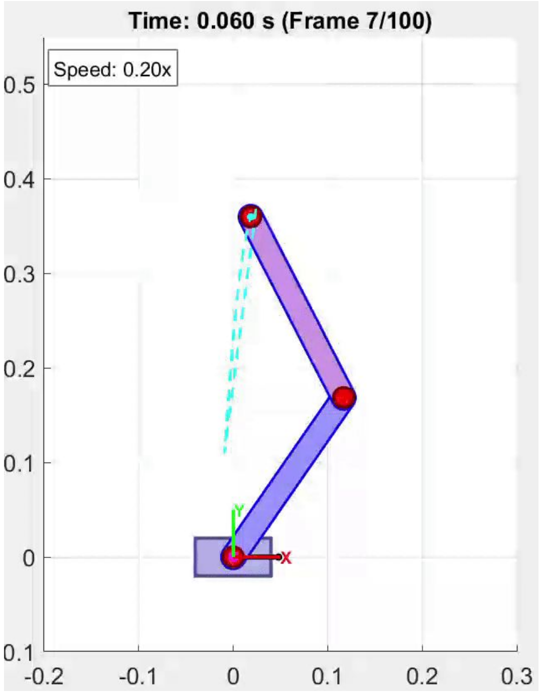
Simulation Study Overview

- **Platform:** MATLAB ODE45
- Physical parameters from actual robot
- Virtual joints at base for FT sensor emulation
- PD controller at **1kHz**
- Contact applied at **$t = 0.5$s**
- **Test Scenarios:**
    - Scenario 1: 5N force on Link 1 ($\alpha = 0.5, -\pi/3$ rad)
    - Scenario 2: 7N force on Link 2 ($\alpha = 0.8, -\pi/3$ rad)

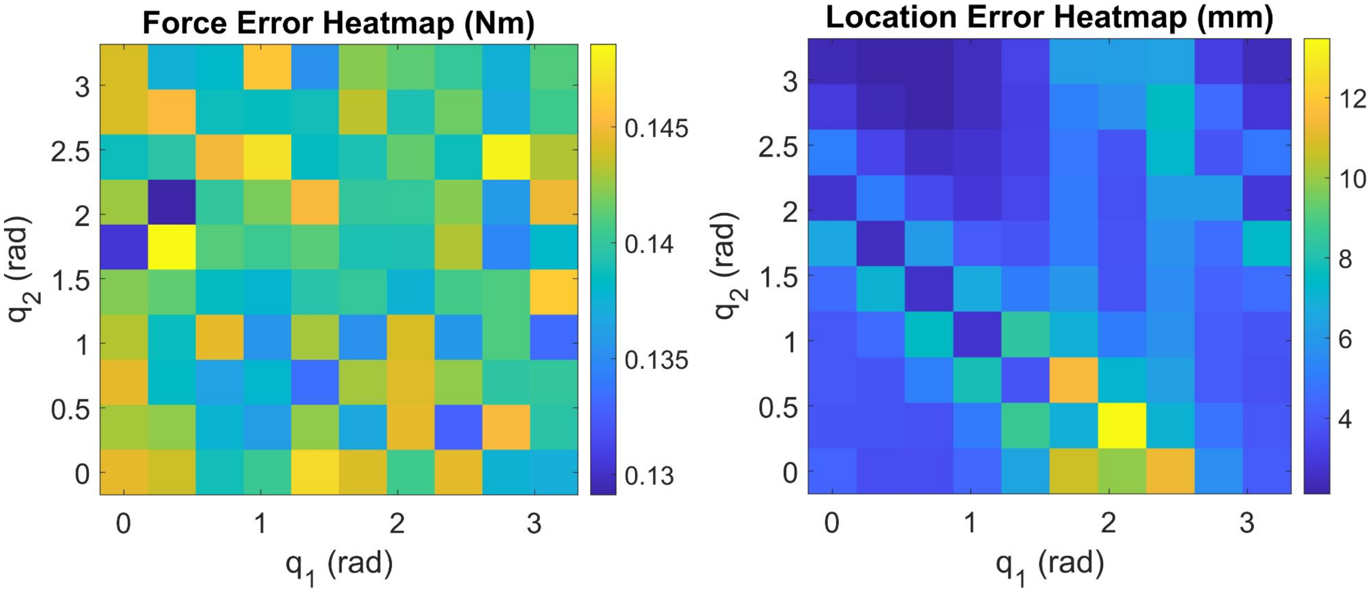
Fixed-Base Simulation

TABLE III: Results of Fixed-Base Simulation

Scenario	**Force Errors (N)**			**Position Errors (mm)**		
	Fx	Fz	$\lvert\mathbf{F}\rvert$	p_x	p_z	$\lvert\mathbf{p}\rvert$
Test 1 Mean	-0.008	-0.008	0.112	1	0	3
STD	0.089	0.090	0.058	4	1	2
Test 2 Mean	0.002	-0.006	0.142	0	2	2
STD	0.108	0.111	0.059	2	1	1

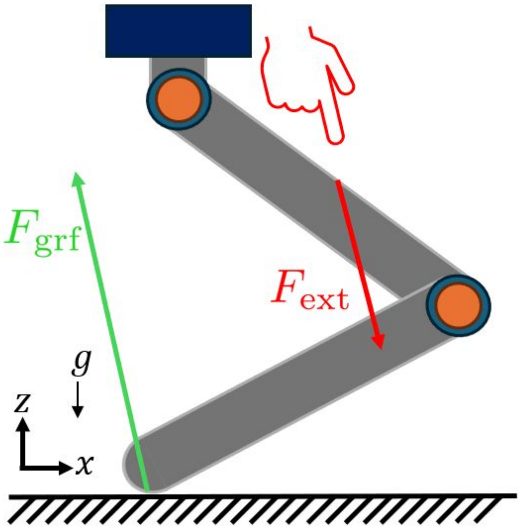


Fixed-Base Simulation Parametric Sweep of Configurations



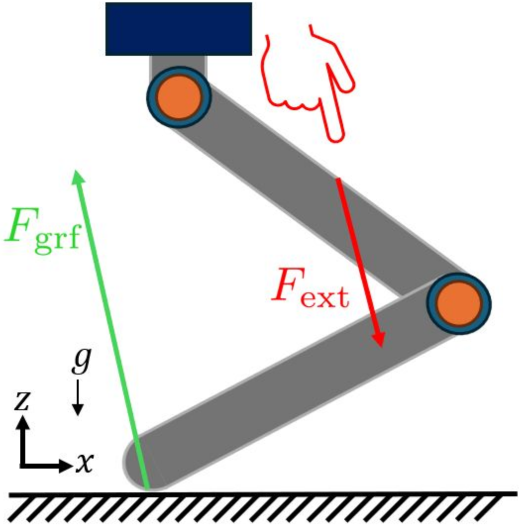
Results: <13.5m localization and <0.15N force error

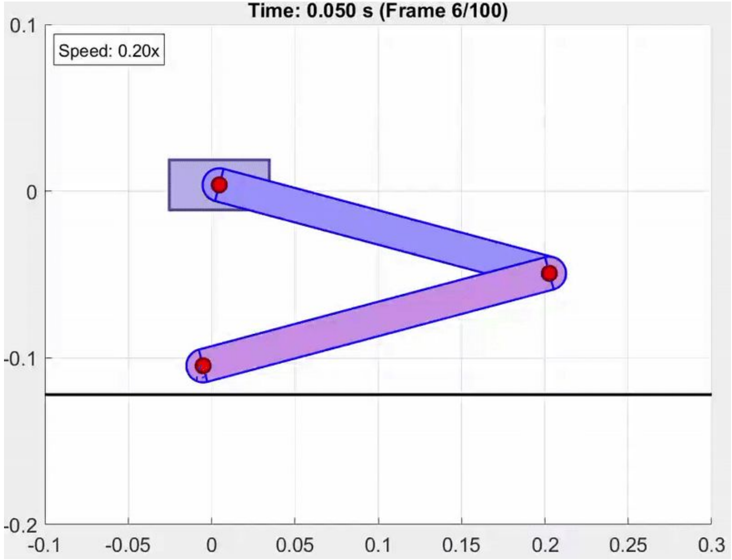
Floating-Base Simulation



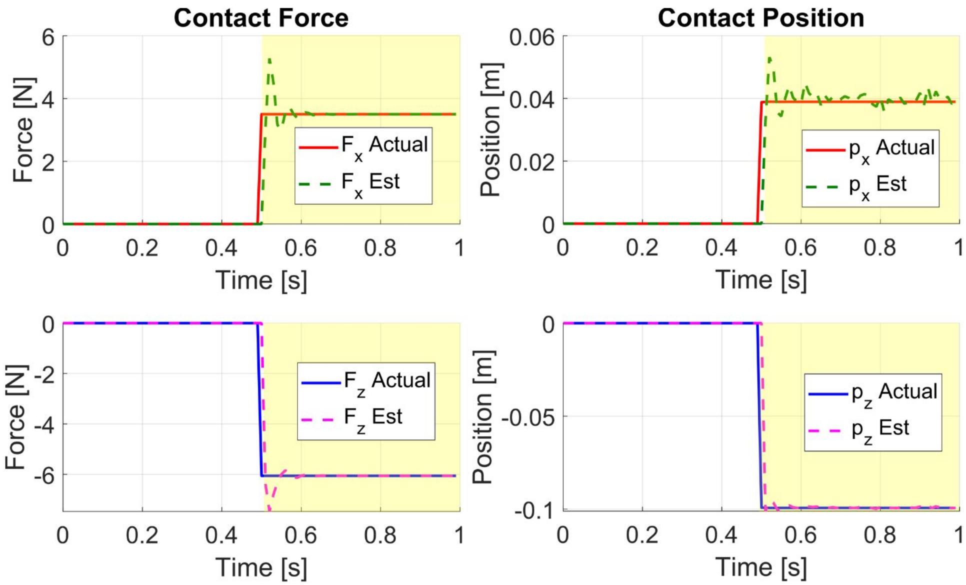
- Base can move in x and z directions
- Two additional virtual joints for base translation

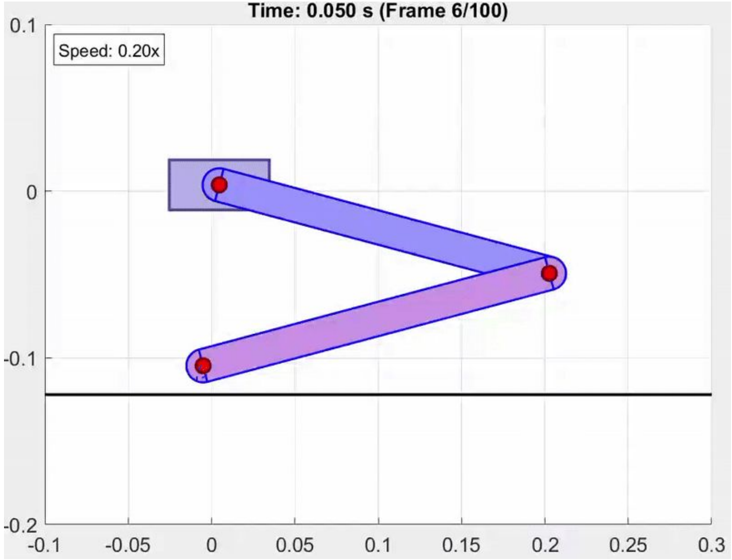
Floating-Base Simulation





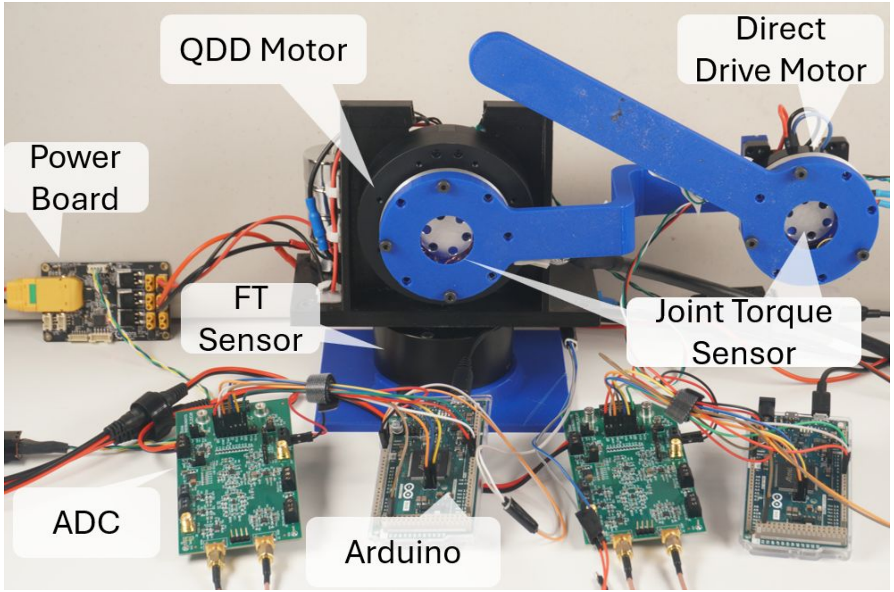
Simulation Performance: Floating Base





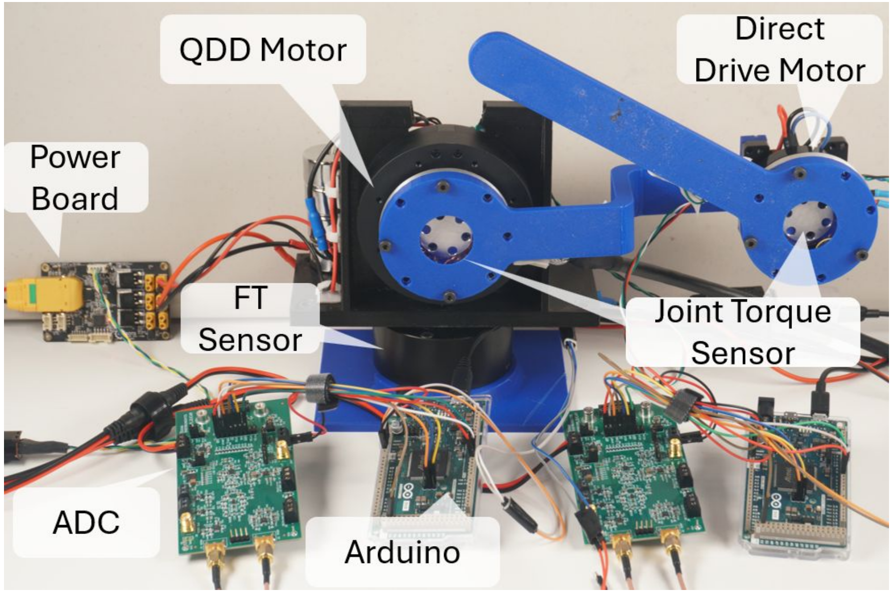
Results: Sub-cm localization and <0.2N force error

Hardware Experimental Setup: Fixed-Base



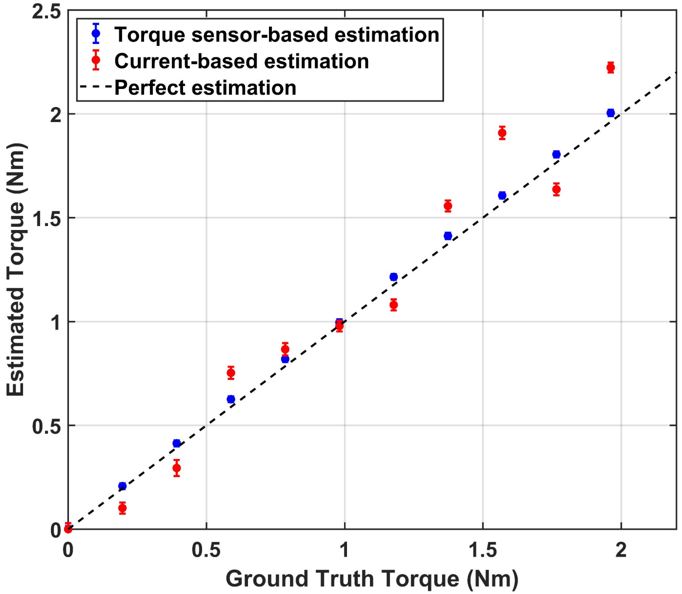
- 2-DOF planar leg testbed
- 3-4 kSps, 24-bit ADC
- Static tests: 0.05-0.5kg loads
- Positions: 25%, 50%, 75%, 100%

Contact Localization Results: Fixed-Base



Configuration	**Load (kg)**	**Location Error RMS (mm)**	**Force Error RMS (N)**
Link 1	0.1	8.89	0.129
	0.5	7.91	0.174
Link 2	0.05	4.09	0.045
	0.1	4.87	0.106

Joint Torque Sensor Characterization



Sensor 1:

$$y = 0.0115\,x + 5.0069,\text{ with } R^2 = 0.9999$$

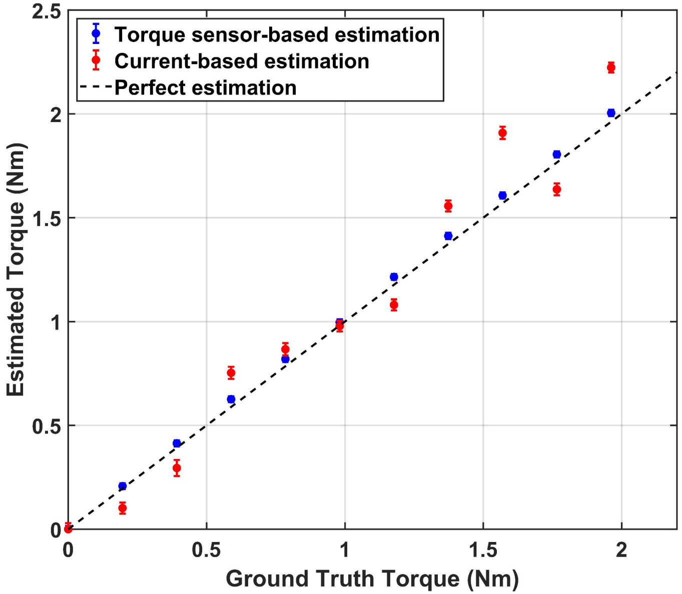
Sensor 2:

$$y = -0.0108\,x - 2.3260,\text{ with } R^2 = 0.9991$$

Sensor: **0.0317 RMSE**

Motor Current: **0.1638 RMSE**

Sensor Performance



Sensor: **0.0317 RMSE**

Motor Current: **0.1638 RMSE**

- 96.4% accuracy relative to ground truth
- MAE: 0.0286 Nm (practical resolution)

Conclusions and Discussion

Summary

- **Why This Matters:** Direct torque sensing, real time, single FT sensor
- **Advantage:** Friction-agnostic approach, scalable to any joint count, simpler than tactile arrays
- **Performance:** 96.4% sensor accuracy, sub-cm localization, <0.2N force errors
- **Limitation:** Multiple simultaneous contacts, only tested in quasi-static

Future Work

- **Additional sensing modalities:** Handle concurrent collision points
- **Dynamic Testing:** Validation during active locomotion

Q&A

Thanks for Listening!

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