# May the Force Be with You

## Emergent Force-aware Capabilities in Legged Robots

Baoxiong Jia

BIGAI

# About me

buzz-beater.github.io

Peking University
B.S. in CS
2014-2018

UCLA
Ph.D. in CS
2018-2022

BIGAI
Research Scientist
2022-Present

UniTree Kungfu Kid 6.0, UniTree 2025

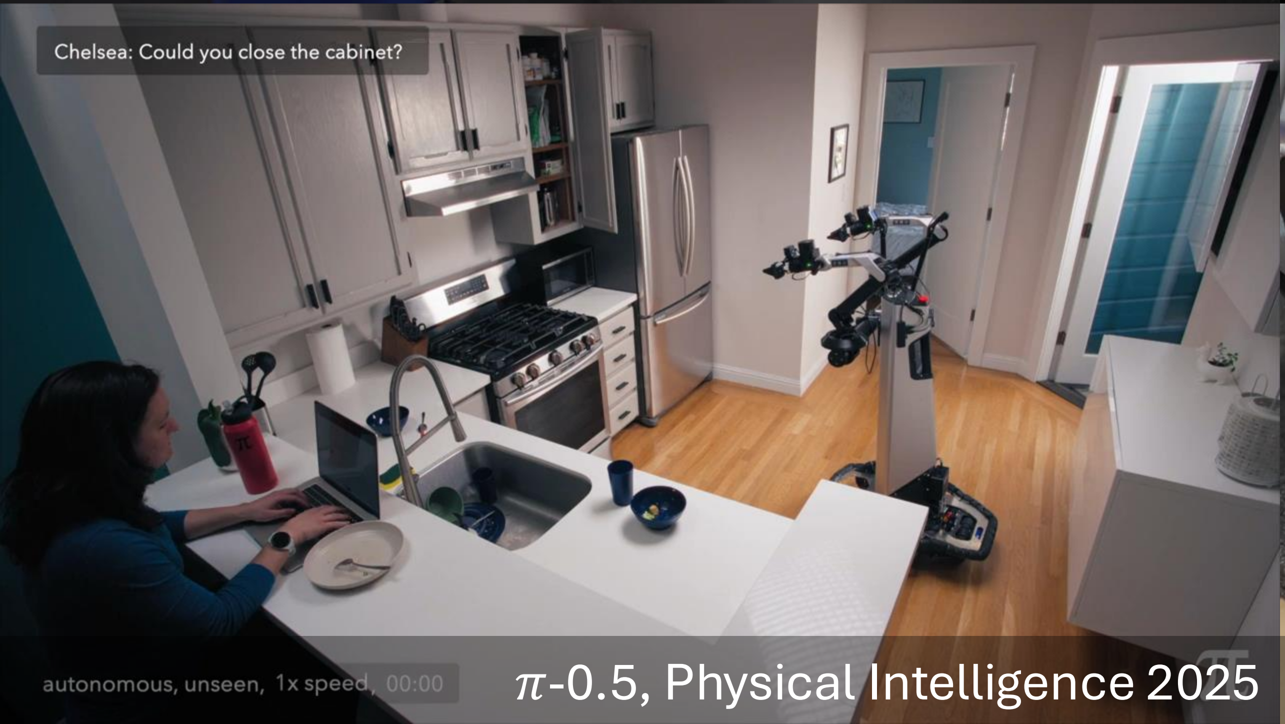

Walk, Run, Crawl, RL Fun, Boston Dynamics 2024


Playing Badminton against Humans, ETH 2025

UniTree B2-W Talent Awakening, UniTree 2024


Loco-Manipulation, Boston Dynamics 2025

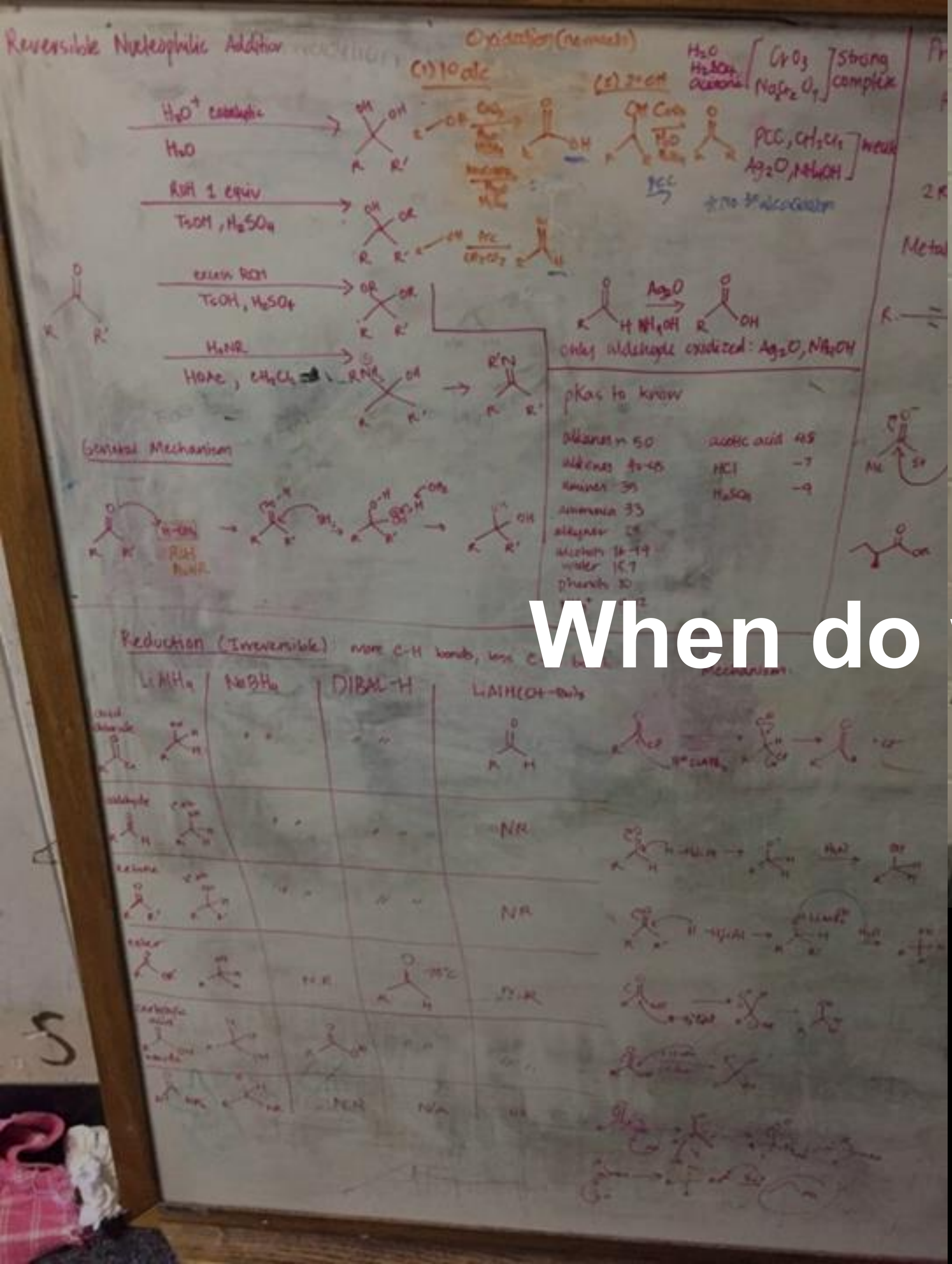

Introducing Helix, Figure 2025

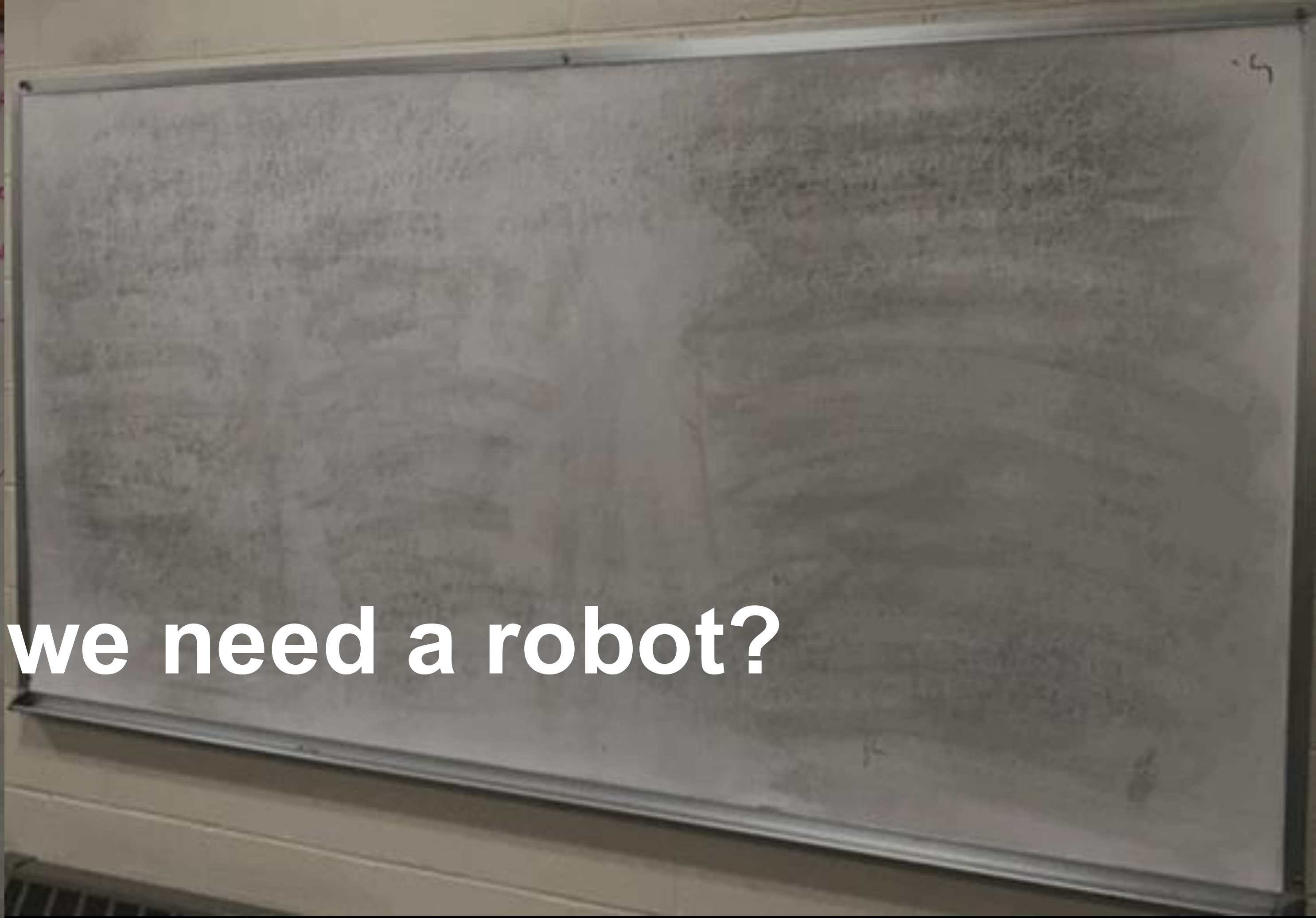



$\pi$-0.5, Physical Intelligence 2025

Early Preview of Model Capabilities, Generalist 2025

COME-Robot (Zhi et al., ICRA 2025)



# When do we need a robot?

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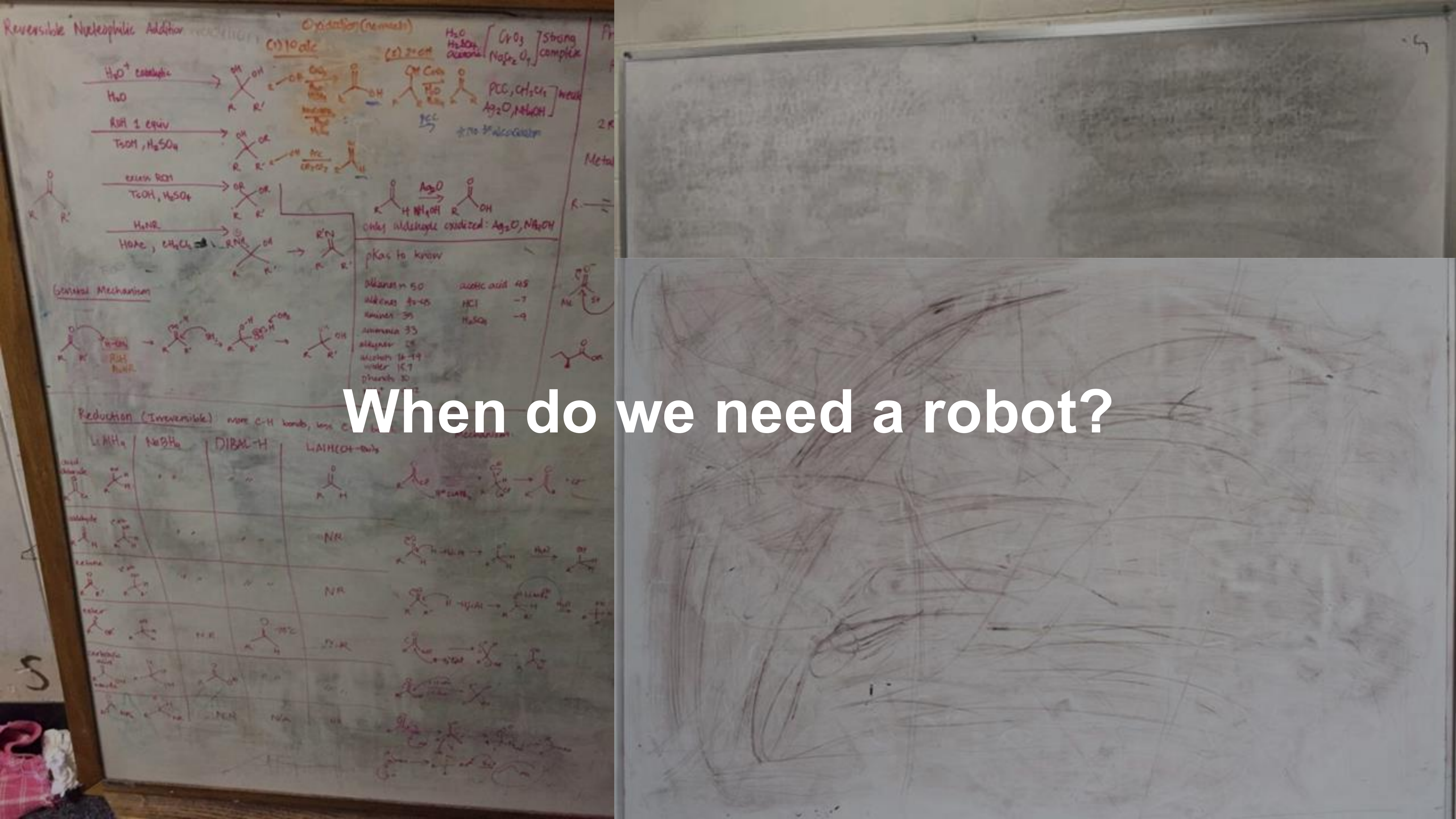
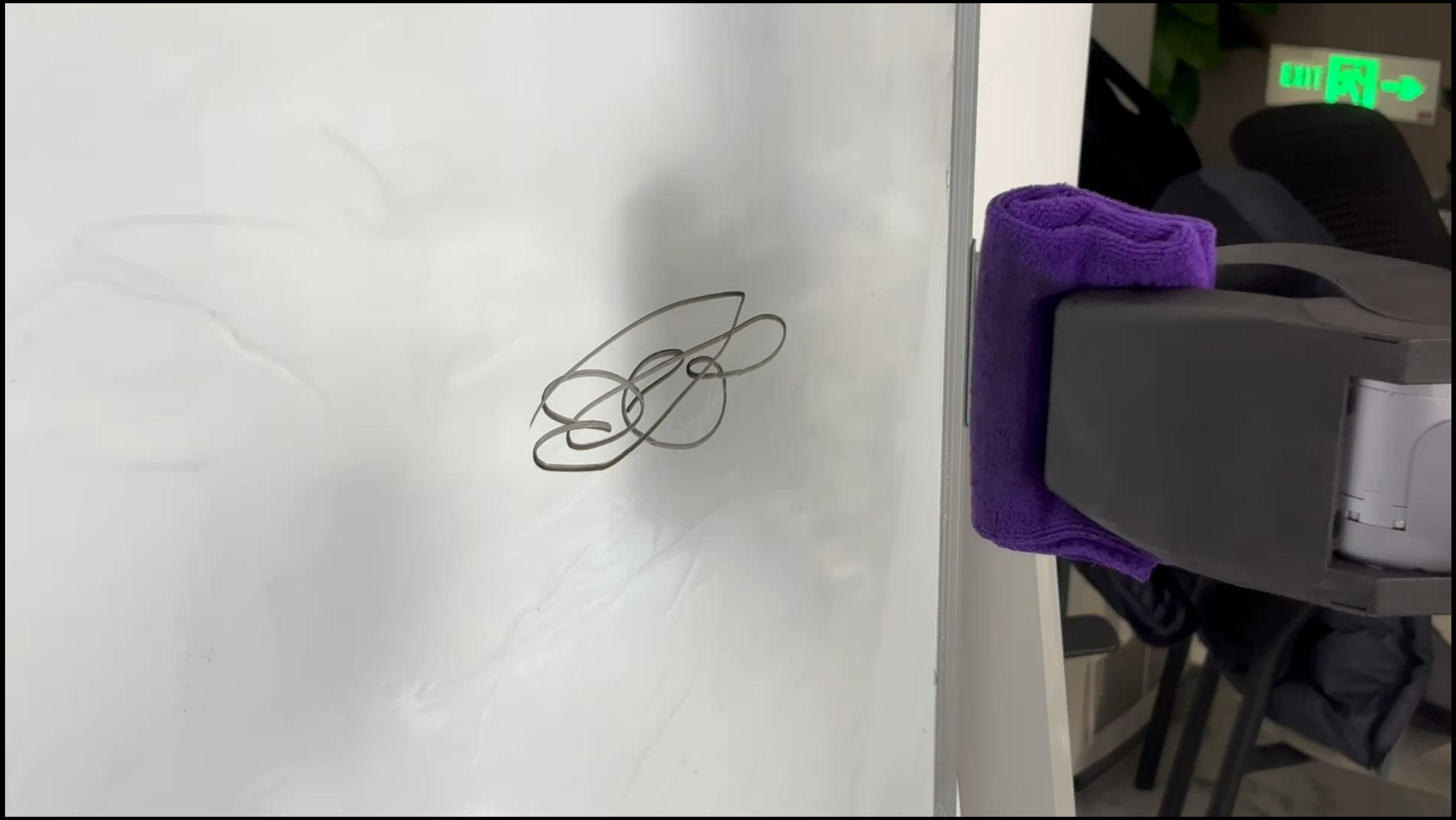


OK, can we let the robot help us wipe the whiteboard first after meeting?

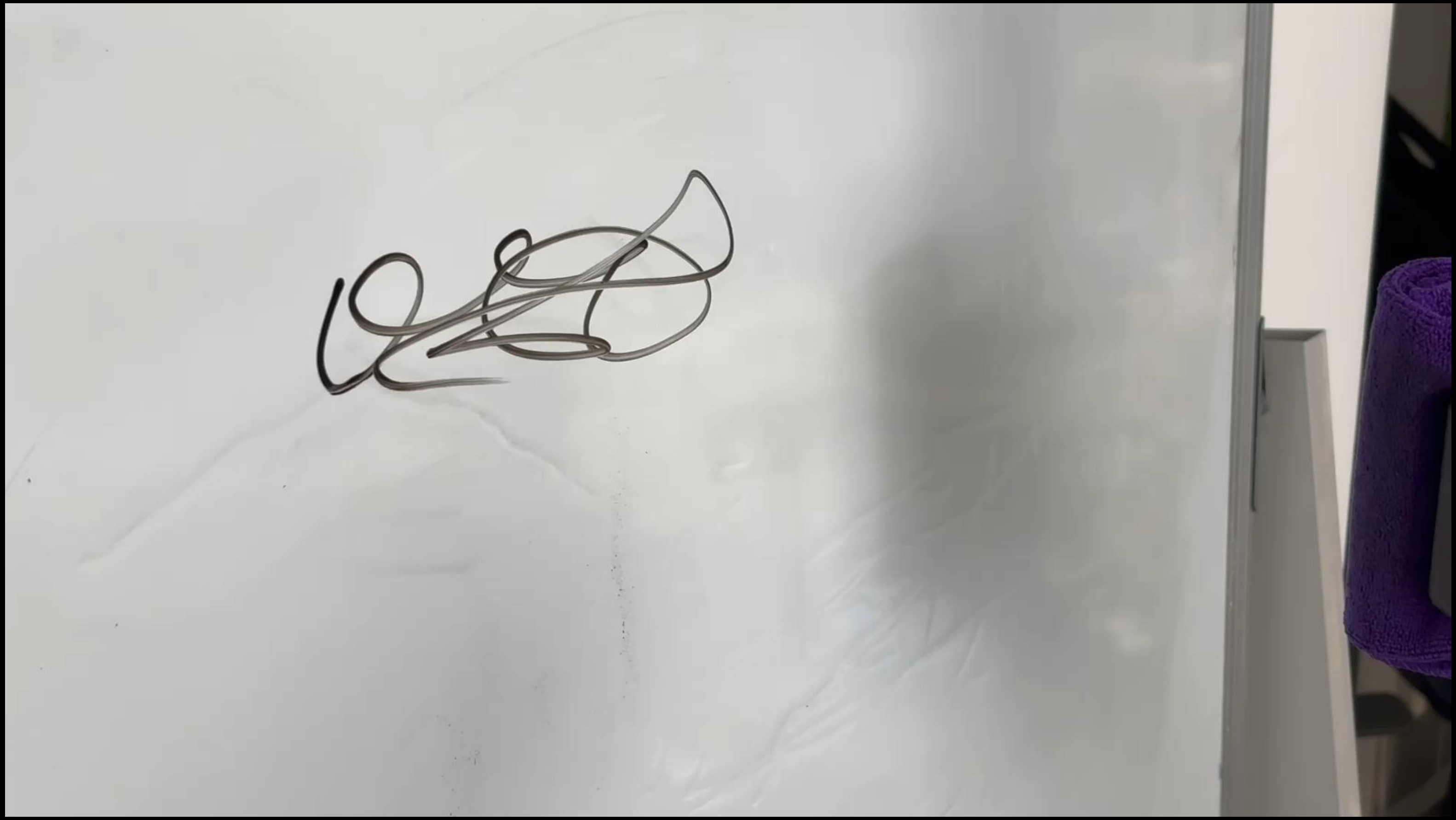
Let me collect the data and imitation learning will solve the rest ☺




Data collection is a disaster

OK, can we let the robot help us wipe the whiteboard first after meeting?

Let me collect the data and imitation learning will solve the rest ☺



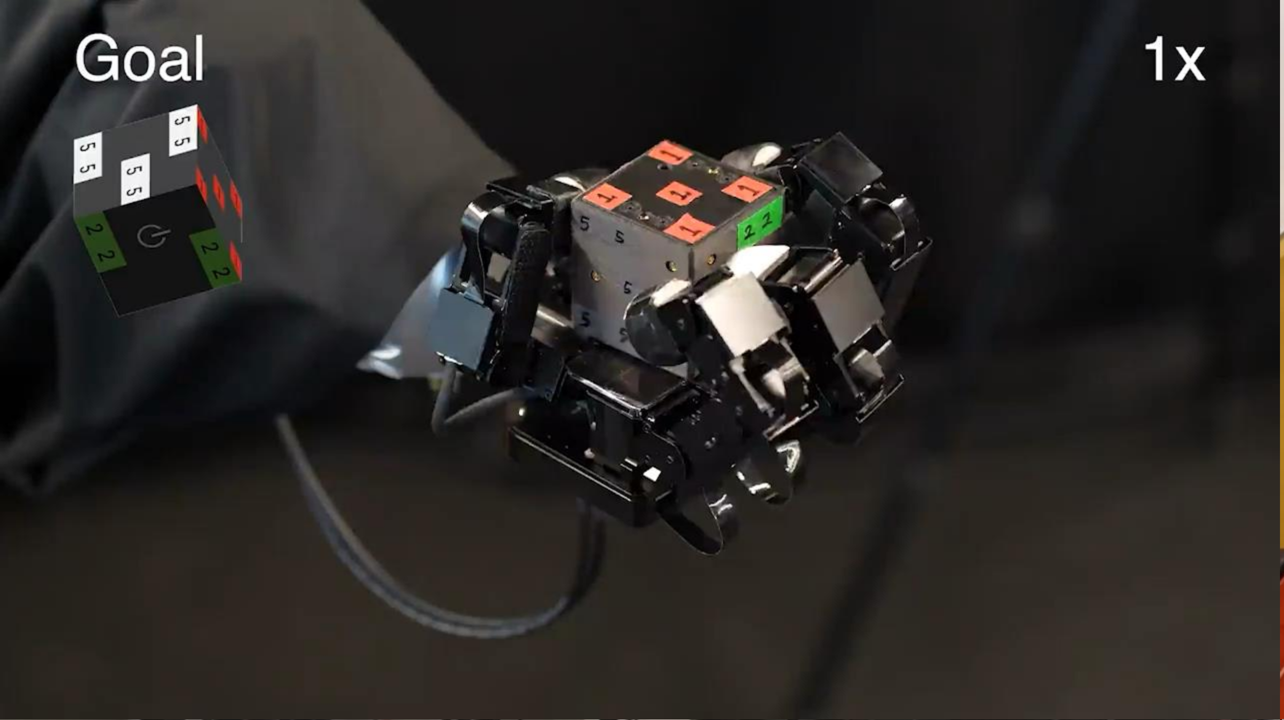
Of course, the learned policy failed no matter how much data used ☹

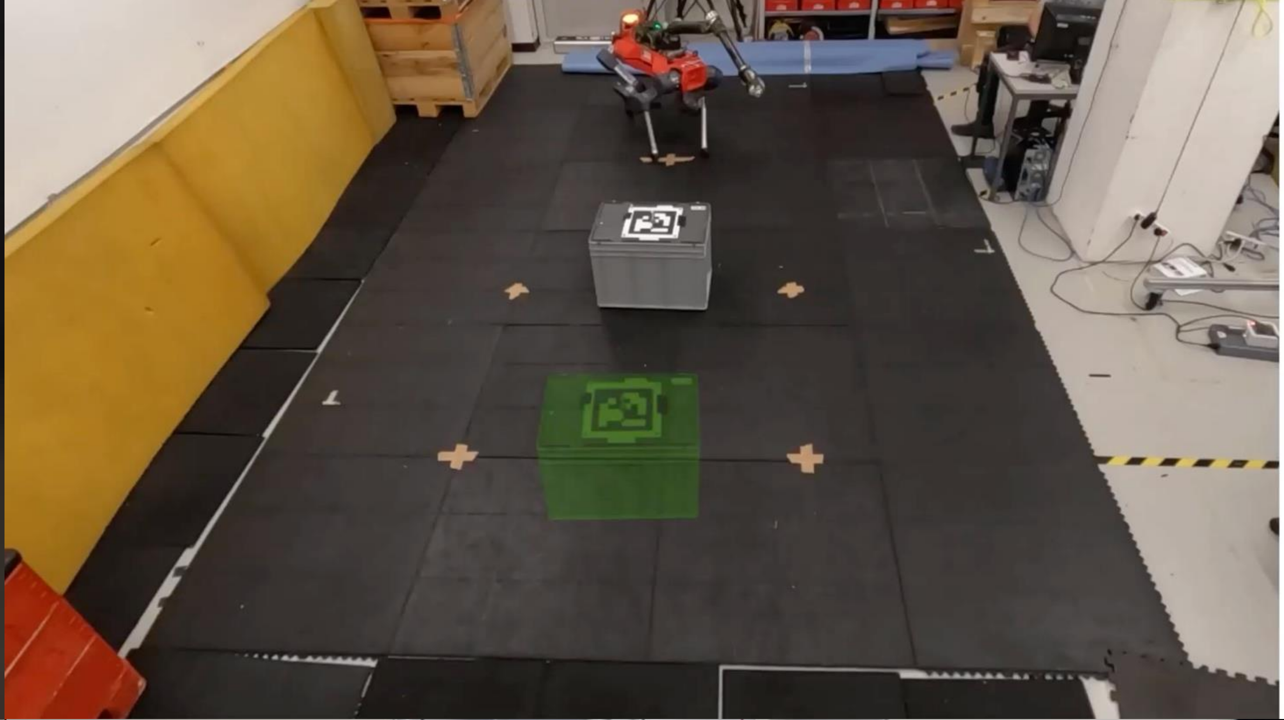
OK, can we let the robot help us wipe the whiteboard first after meeting?

Let me collect the data and imitation learning will solve the rest ☺

Wiping blackboards is a contact-rich problem, simply scaling data does not work. It requires simultaneous position and force modeling.

How difficult can that be, learning it’s not rocket science 🚀


Goal
1x




Task 1
Mustard Bottle
2x Speed
Contact-rich@ICRA, 2025

OK, can we let the robot help us wipe the whiteboard first after meeting?

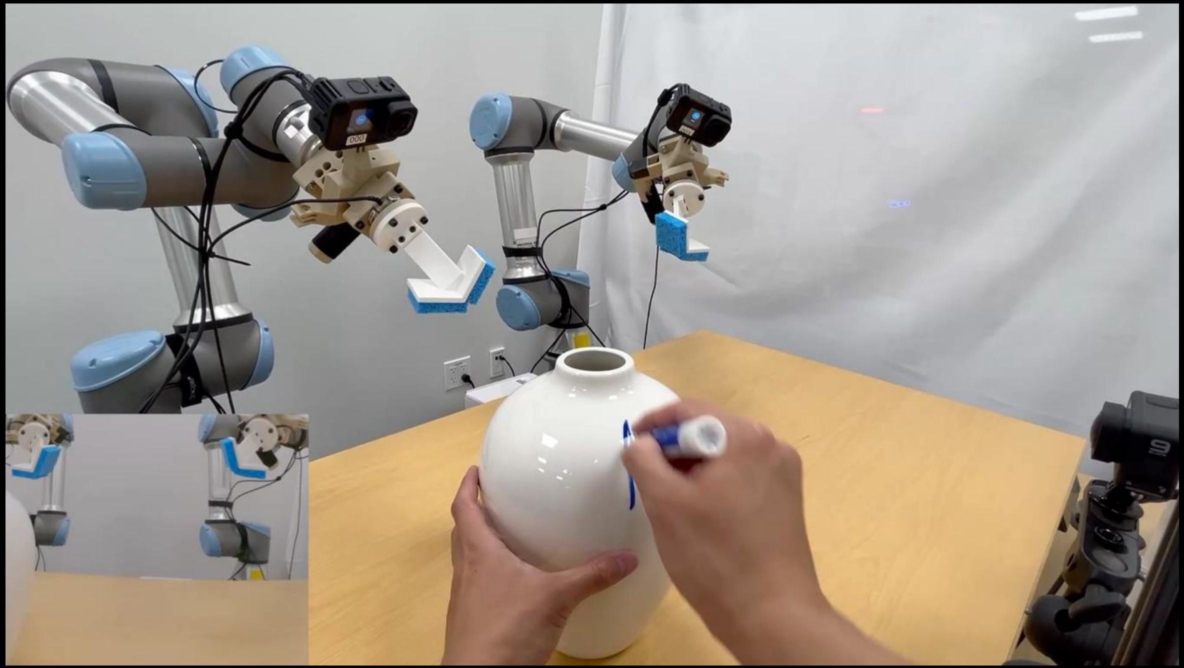
Let me collect the data and imitation learning will solve the rest ☺

Wiping blackboards is a contact-rich problem, simply scaling data does not work. It requires simultaneous position and force modeling.

How difficult can that be, learning it's not rocket science 🚀

Typically, you can't model the contact without force sensors.

# Learning force-aware policies



Adaptive Compliance Policy (Hou et al., ICRA 2025)

Reactive Diffusion Policy (Xue et al., RSS 2025)

**Force sensing is critical for reactive behaviors**

OK, can we let the robot help us wipe the whiteboard first after meeting?

Let me collect the data and imitation learning will solve the rest ☺

Wiping blackboards is a contact-rich problem, simply scaling data does not work. It requires simultaneous position and force modeling.

How difficult can that be, legged robots are already skyrocketing 🚀

Typically, you can’t model the contact without force sensors.

Mounting them on our robots is somewhat difficult and costly, and it also requires complex planning for joint force and position control.

That’s not equipped on legged robots, at least not what we have. GG

OK,  then why don’t we learn a unified policy for legged robots that jointly models force and position control without relying on force sensors.

Best Paper

# UniFP

## Learning a Unified Policy for Position and Force Control in Legged Loco-Manipulation

CoRL

# Revisiting the control formulation

**mass-spring-damper system**

$$\boldsymbol{F} = K\left(\mathrm{x} - \boxed{\mathrm{x}^{\mathrm{cmd}}}\right) + \cancel{D\left(\dot{\mathrm{x}} - \boxed{\dot{\mathrm{x}}^{\mathrm{cmd}}}\right)} + \cancel{M\left(\ddot{\mathrm{x}} - \boxed{\ddot{\mathrm{x}}^{\mathrm{cmd}}}\right)}$$

$$\mathrm{x} = \mathrm{x}^{\mathrm{cmd}} + \frac{F}{K}$$

**And if the end effector moves really slowly…**

# Revisiting the control formulation

**mass-spring-damper system**

$$\boldsymbol{F} = K\left(\mathrm{x} - \mathrm{x}^{\mathrm{cmd}}\right) + \cancel{D\left(\dot{\mathrm{x}} - \dot{\mathrm{x}}^{\mathrm{cmd}}\right)} + \cancel{M\left(\ddot{\mathrm{x}} - \ddot{\mathrm{x}}^{\mathrm{cmd}}\right)}$$

$$\mathrm{x} = \mathrm{x}^{\mathrm{cmd}} + \frac{F}{K}$$

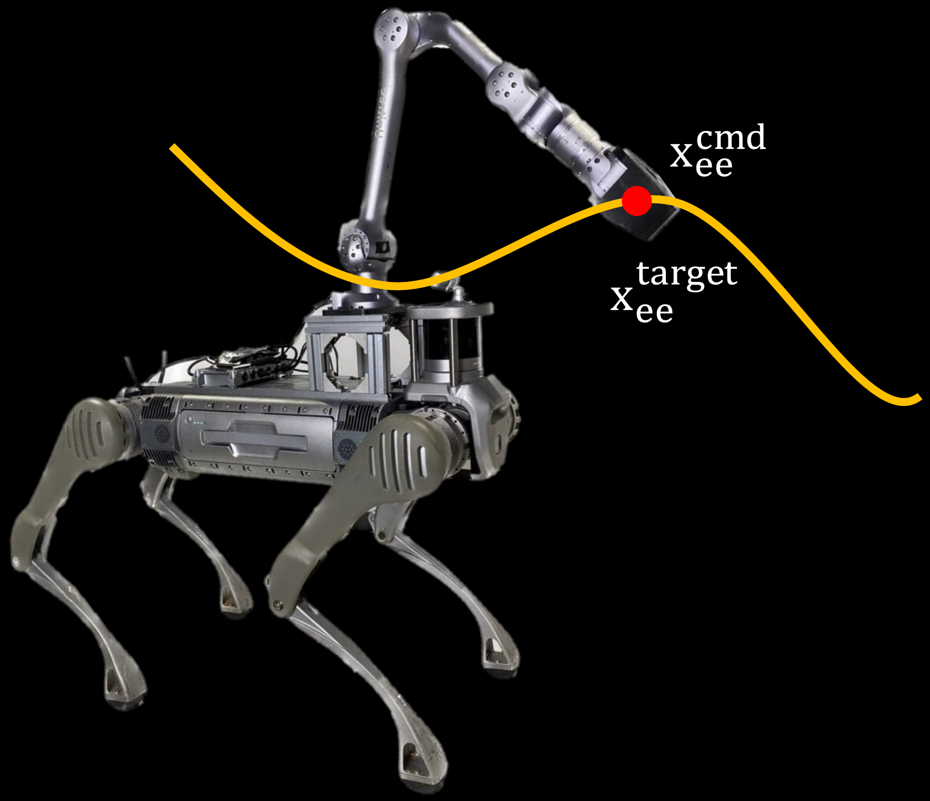
**Force can be estimated via position offsets!**
**Tracking the force-adjusted position enables joint force-position control.**

# Formulating forces with positions

$$\boldsymbol{F} = K\left(\mathrm{x} - \mathrm{x}^{\mathrm{cmd}}\right)$$

## Position control

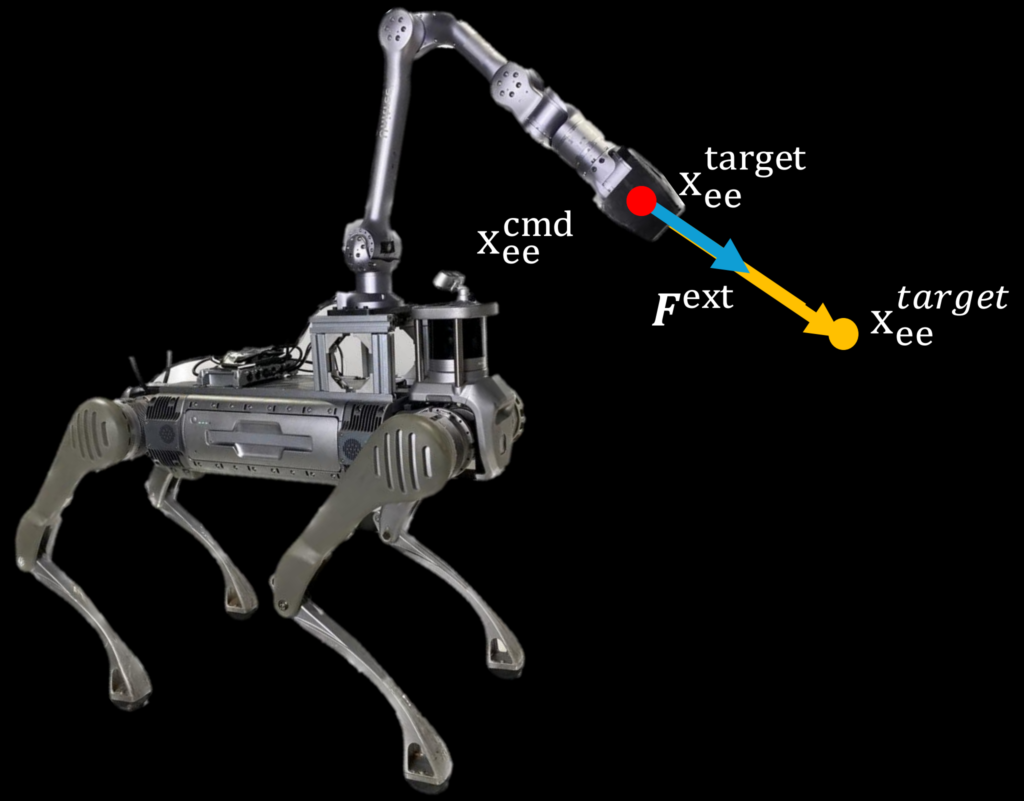
$$\mathrm{x}^{\mathrm{target}} = \mathrm{x}^{\mathrm{cmd}}$$



# Formulating forces with positions

$$\boldsymbol{F} = K\left(\mathrm{x} - \mathrm{x}^{\mathrm{cmd}}\right)$$

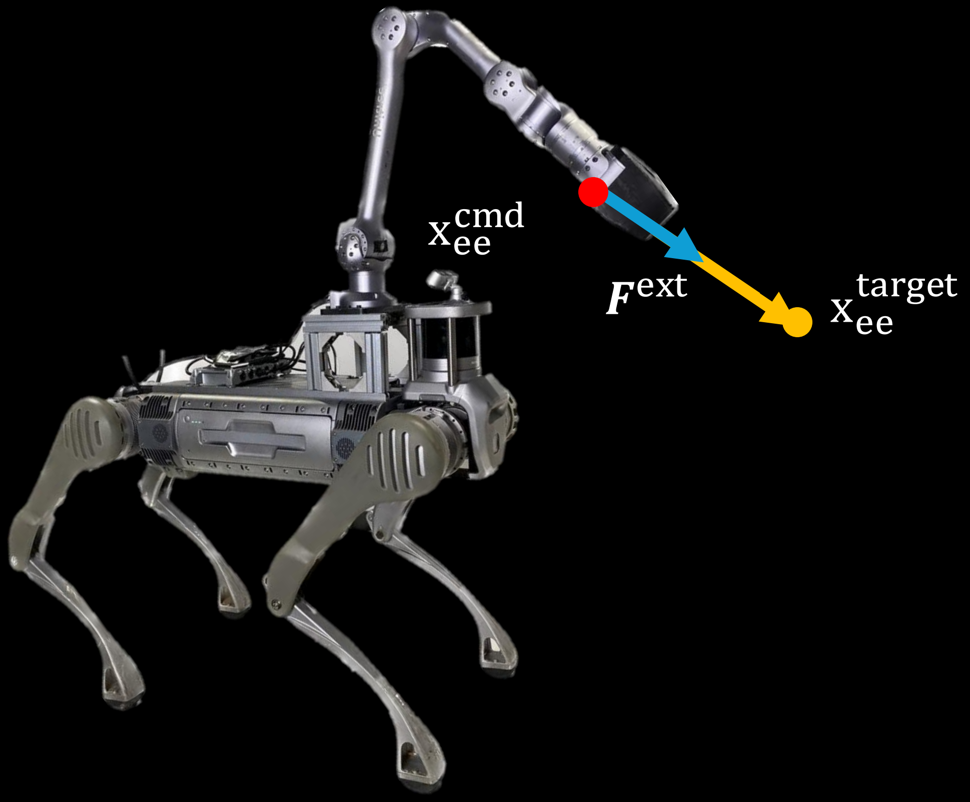
When with external force

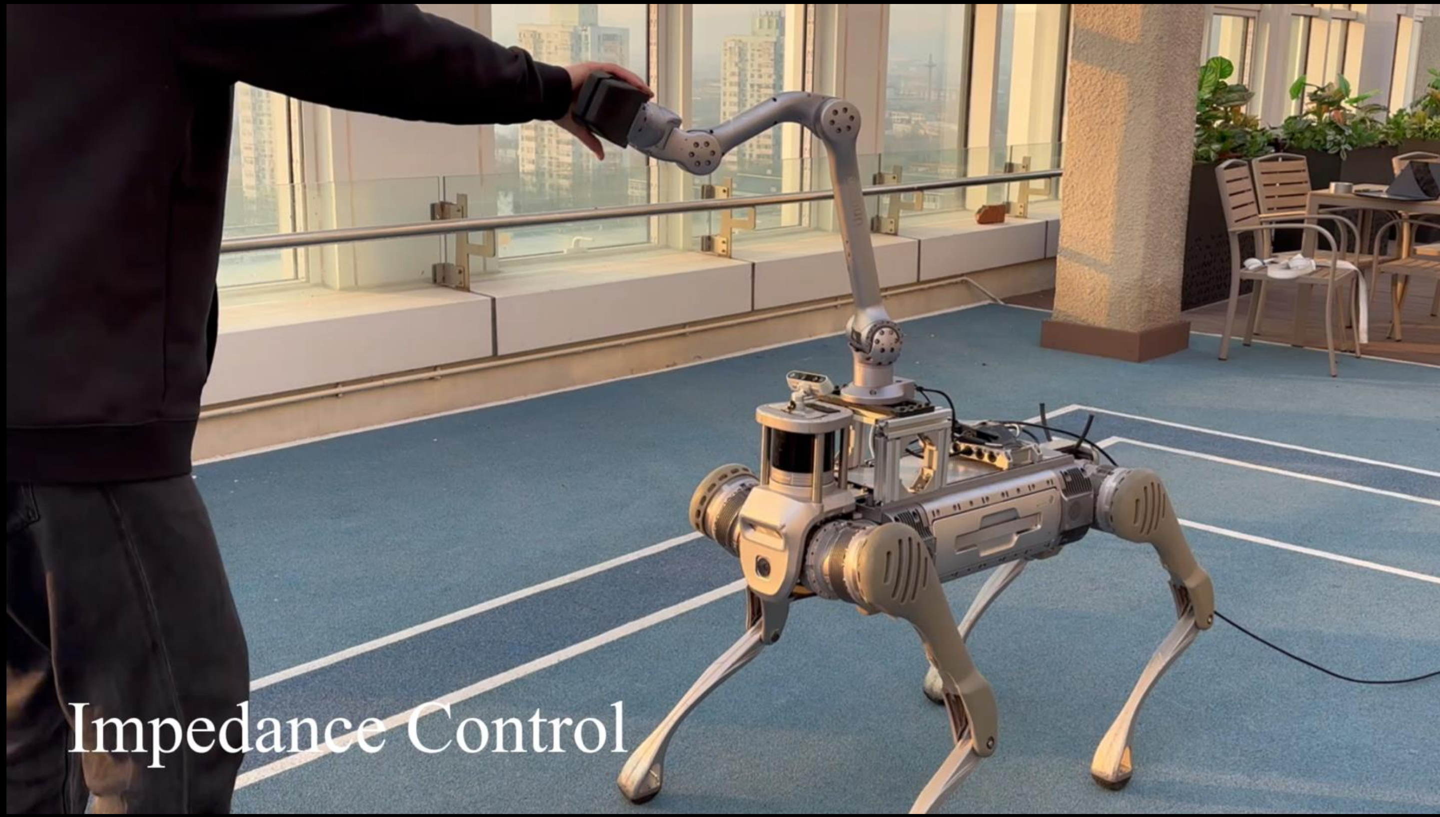


# Formulating forces with positions

$$\boldsymbol{F} = K\left(\mathrm{x} - \mathrm{x}^{\mathrm{cmd}}\right)$$

**Impedance control** $$\mathrm{x}^{\mathrm{target}} = \mathrm{x}^{\mathrm{cmd}} + \frac{\boldsymbol{F}^{\mathrm{ext}}}{K}$$



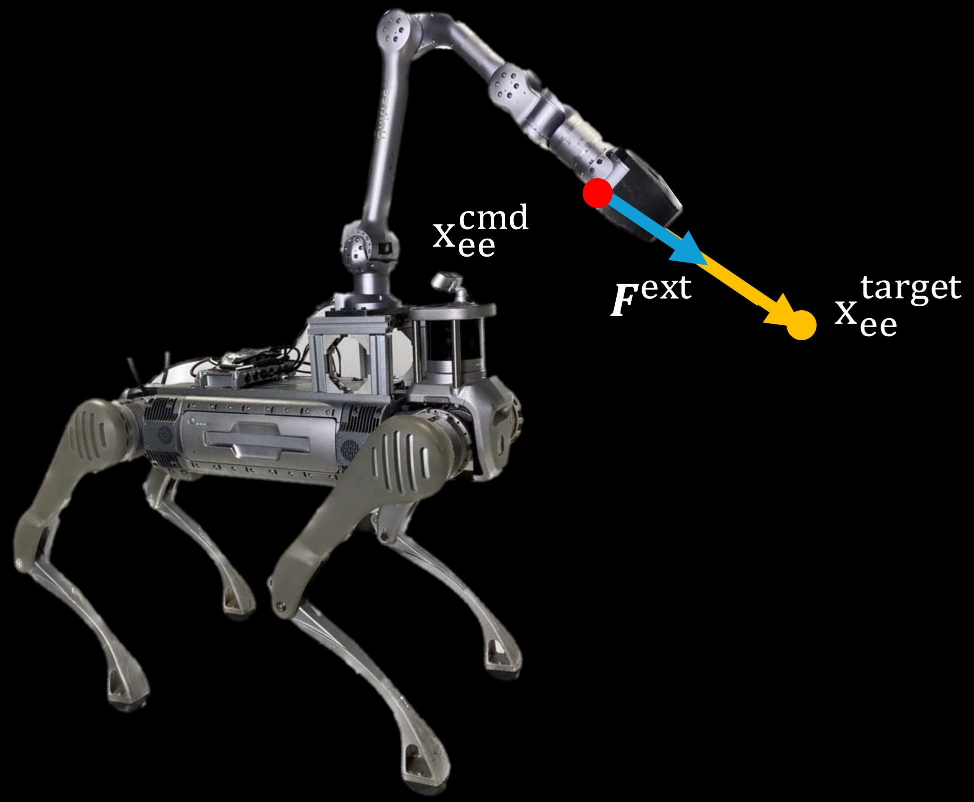



# Formulating forces with positions

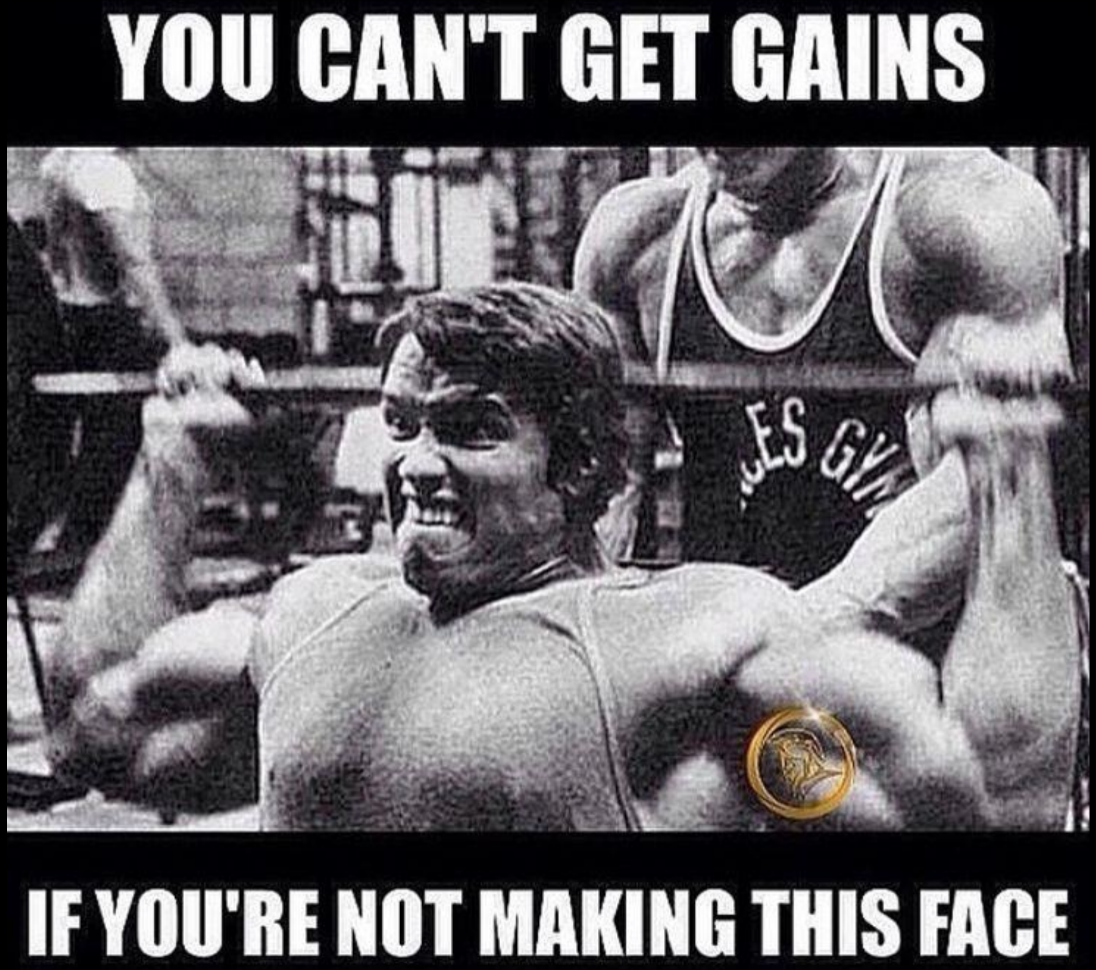
$$\boldsymbol{F} = K\left(\mathrm{x} - \mathrm{x}^{\mathrm{cmd}}\right)$$

**Force tracking**

$$\mathrm{x}^{\mathrm{target}} = \mathrm{x}^{\mathrm{cmd}} + \frac{\boldsymbol{F}^{\mathrm{ext}}}{K}, \qquad \mathrm{x}_{t+\Delta t}^{\mathrm{cmd}} = \mathrm{x}_{t}^{\mathrm{cmd}} + \frac{\boldsymbol{F}^{\mathrm{ext}}}{K}\Delta t$$




## When applying a force?





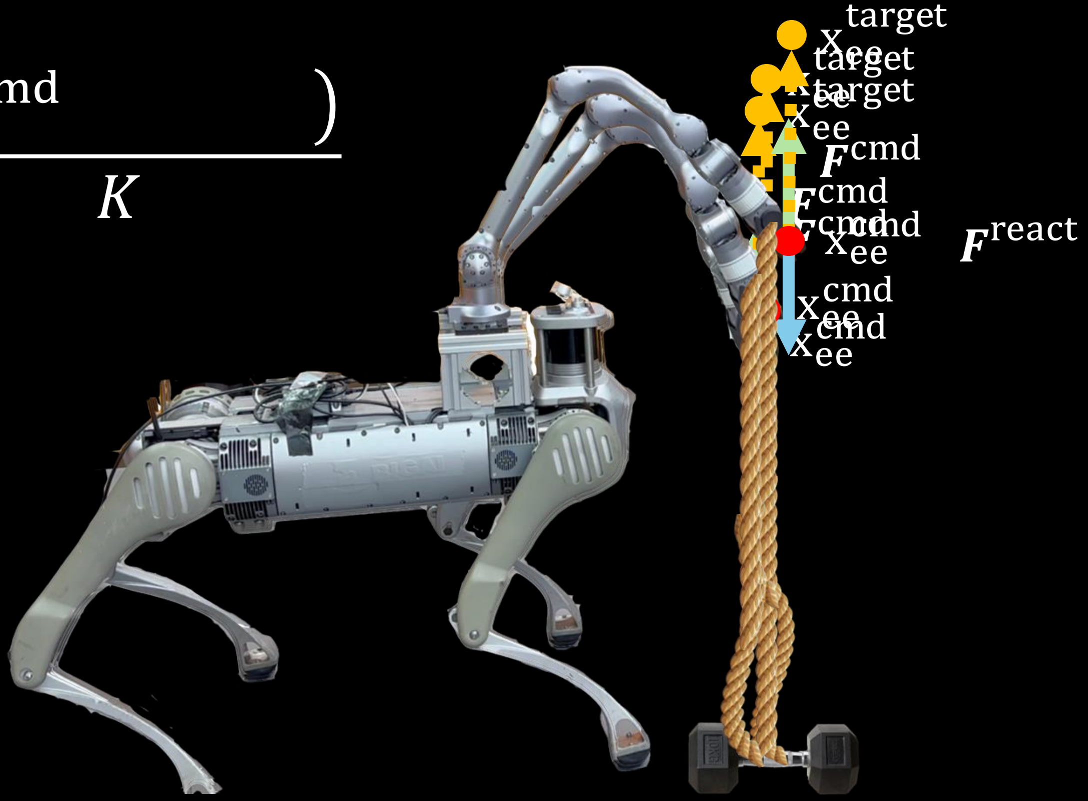
**Actively applying a force is obtaining the reaction force of the same value**

# Formulating forces with positions

$$\boldsymbol{F} = K\left(\mathrm{x} - \mathrm{x}^{\mathrm{cmd}}\right)$$

## When applying a force

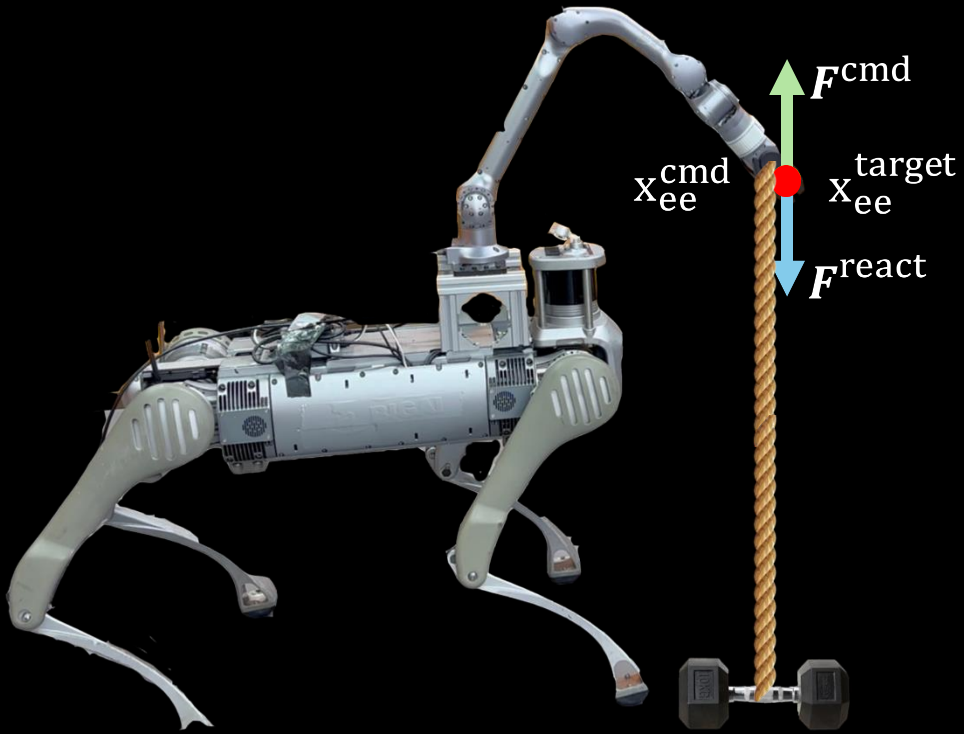
$$\mathrm{x}^{\mathrm{target}} = \mathrm{x}^{\mathrm{cmd}} + \frac{\left(\boldsymbol{F}^{\mathrm{cmd}}\right)}{K}$$



# Formulating forces with positions

$$\boldsymbol{F} = K\left(\mathrm{x} - \mathrm{x}^{\mathrm{cmd}}\right)$$

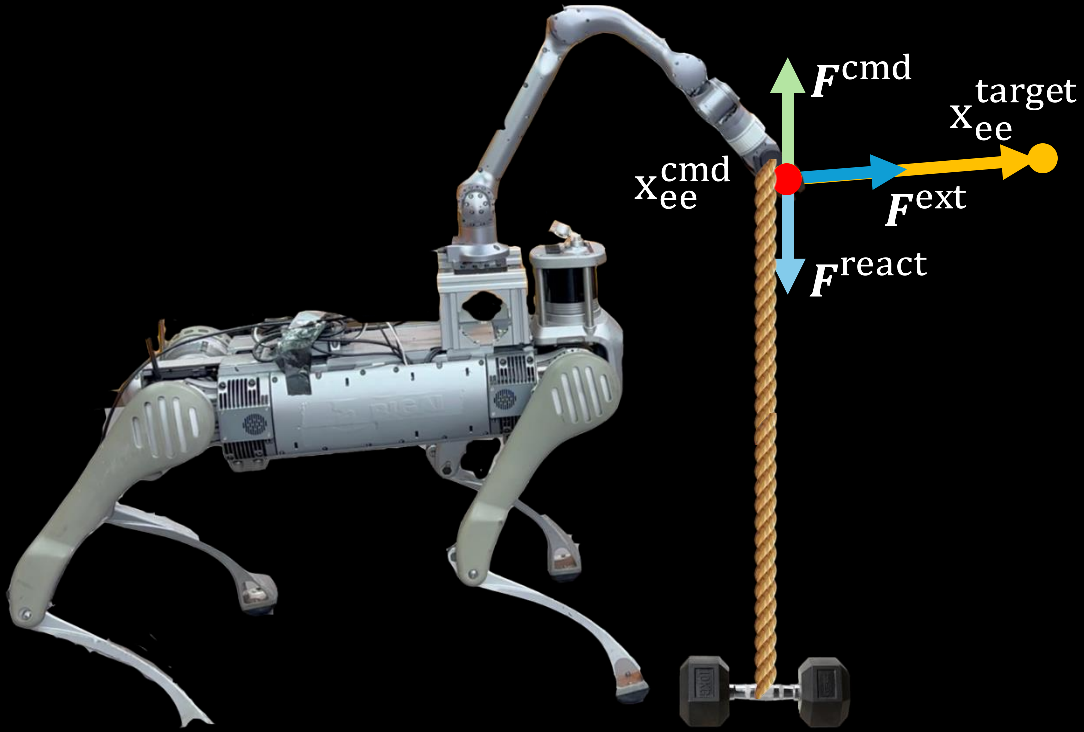
**Force control** $\mathrm{x}^{\mathrm{target}} = \mathrm{x}^{\mathrm{cmd}} + \frac{\left(\boldsymbol{F}^{\mathrm{cmd}} - \boldsymbol{F}^{\mathrm{react}}\right)}{K}, \quad \mathrm{x}_{t+\Delta t}^{\mathrm{cmd}} = \mathrm{x}_t^{\mathrm{cmd}} + \frac{\left(\boldsymbol{F}^{\mathrm{cmd}} - \boldsymbol{F}^{\mathrm{react}}\right)}{K}$




# Formulating forces with positions

$$\boldsymbol{F} = K\left(\mathrm{x} - \mathrm{x}^{\mathrm{cmd}}\right)$$

**Force control** $\mathrm{x}^{\mathrm{target}} = \mathrm{x}^{\mathrm{cmd}} + \dfrac{\boldsymbol{F}^{\mathrm{ext}} + \left(\boldsymbol{F}^{\mathrm{cmd}} - \boldsymbol{F}^{\mathrm{react}}\right)}{K}, \mathrm{x}_{t+\Delta t}^{\mathrm{cmd}} = \mathrm{x}_{t}^{\mathrm{cmd}} + \dfrac{\boldsymbol{F}^{\mathrm{ext}} + \left(\boldsymbol{F}^{\mathrm{cmd}} - \boldsymbol{F}^{\mathrm{react}}\right)}{K}$




# Revisiting the control formulation

**mass-spring-damper system**

$$\boldsymbol{F} = K\cancel{\left(\mathrm{x} - \mathrm{x}^{\mathrm{cmd}}\right)} + D\left(\dot{\mathrm{x}} - \dot{\mathrm{x}}^{\mathrm{cmd}}\right) + M\cancel{\left(\ddot{\mathrm{x}} - \ddot{\mathrm{x}}^{\mathrm{cmd}}\right)}$$

**And if we care about the locomotion**

# Revisiting the control formulation

**mass-spring-damper system**

$$\boldsymbol{F} = \cancel{K(\mathrm{x} - \mathrm{x}^{\mathrm{cmd}})} + D(\dot{\mathrm{x}} - \dot{\mathrm{x}}^{\mathrm{cmd}}) + \cancel{M(\ddot{\mathrm{x}} - \ddot{\mathrm{x}}^{\mathrm{cmd}})}$$

$$\dot{\mathrm{x}} = \dot{\mathrm{x}}^{\mathrm{cmd}} + \frac{F}{D}$$

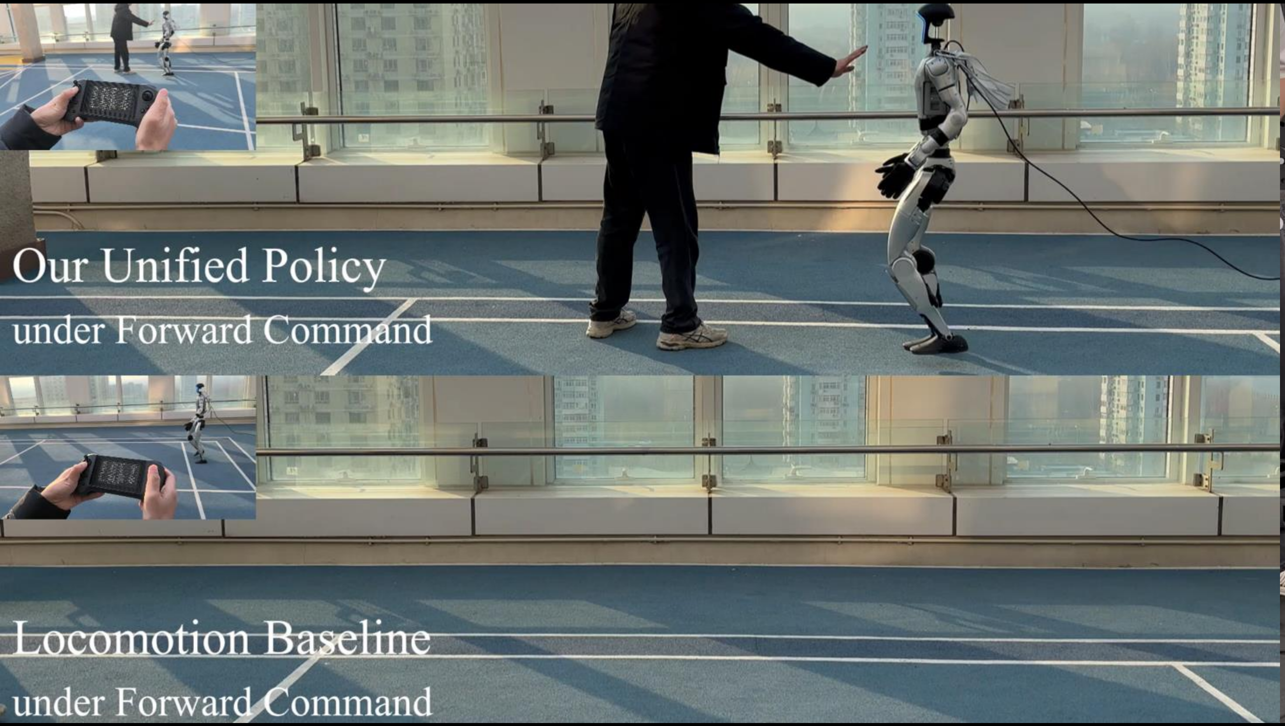
**Force-adjusted velocity enables compliant locomotion**

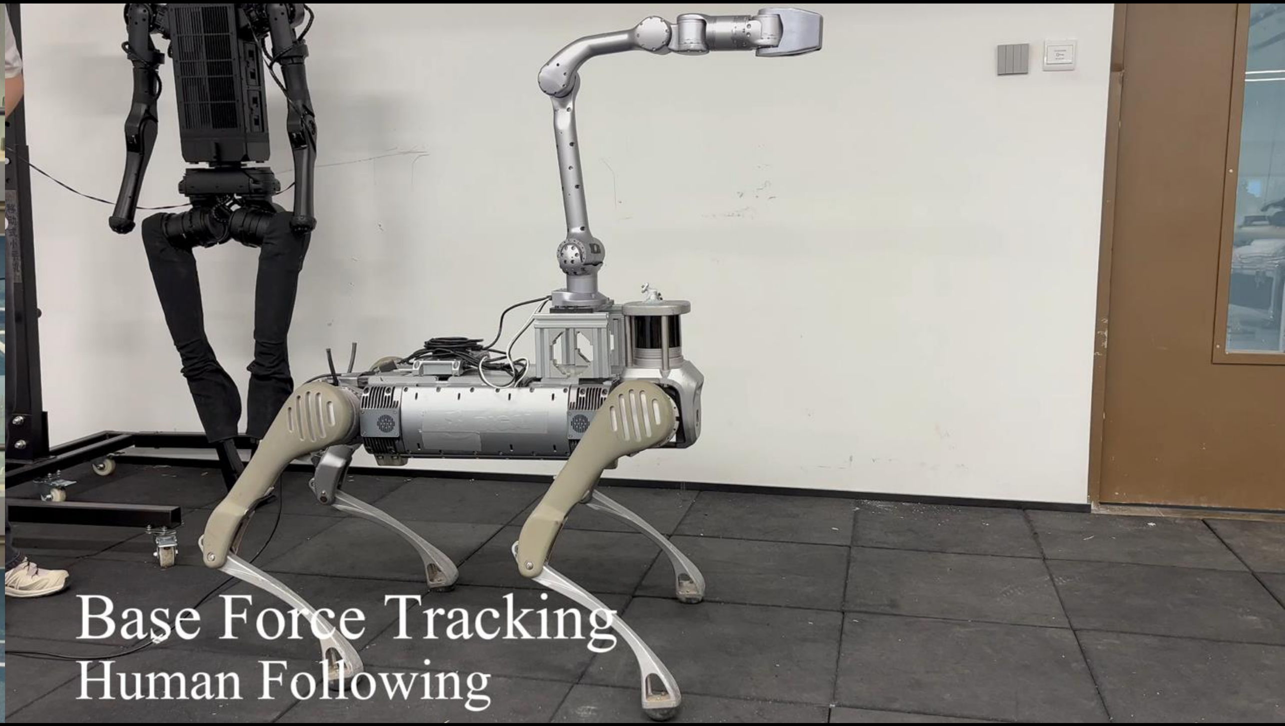
# Formulating forces with velocities

$$\boldsymbol{F} = D\left(\dot{\mathrm{x}} - \dot{\mathrm{x}}^{\mathrm{cmd}}\right)$$

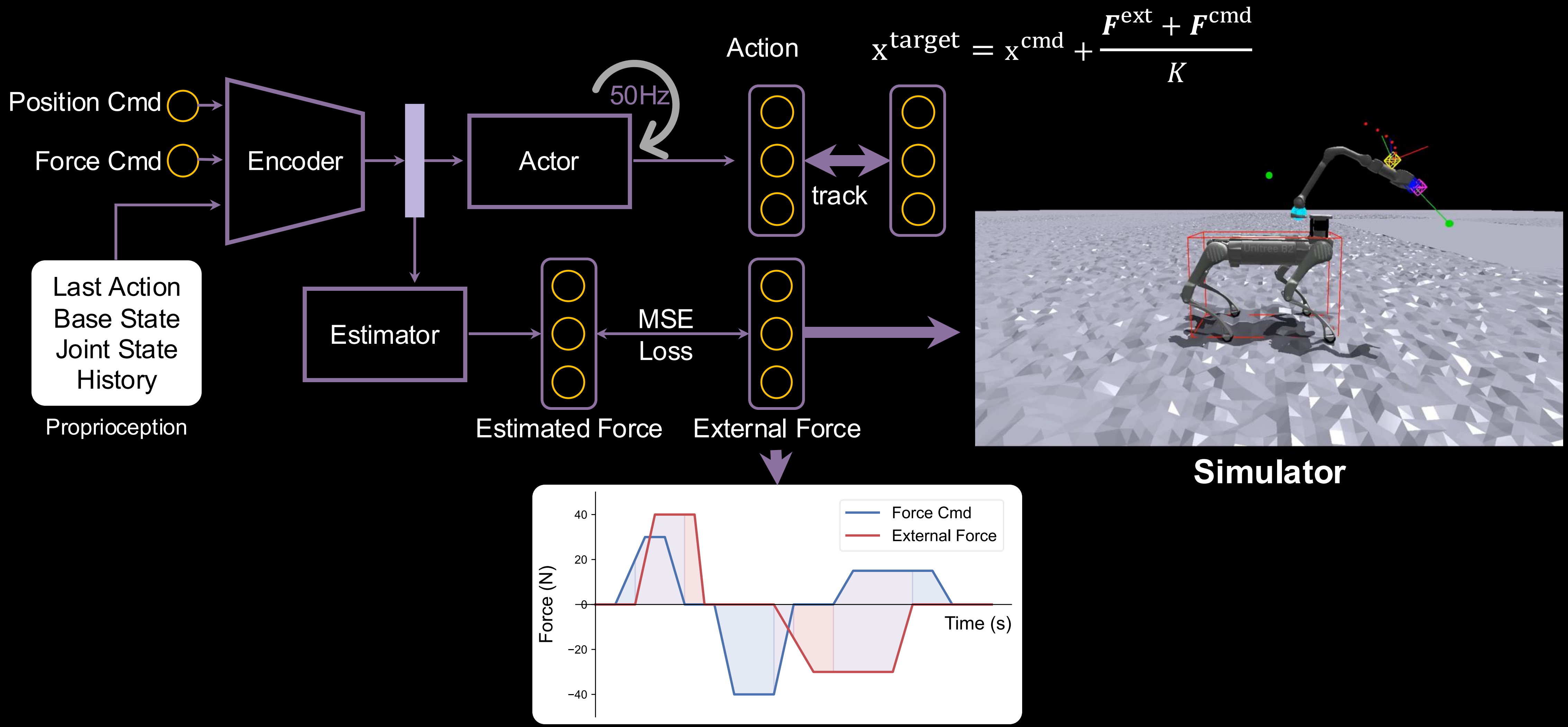
**Compliant locomotion**

$$\dot{\mathrm{x}}^{\mathrm{target}} = \dot{\mathrm{x}}^{\mathrm{cmd}} + \frac{F^{\mathrm{ext}}}{D}$$



# UniFP via RL with force-position sampling in simulator



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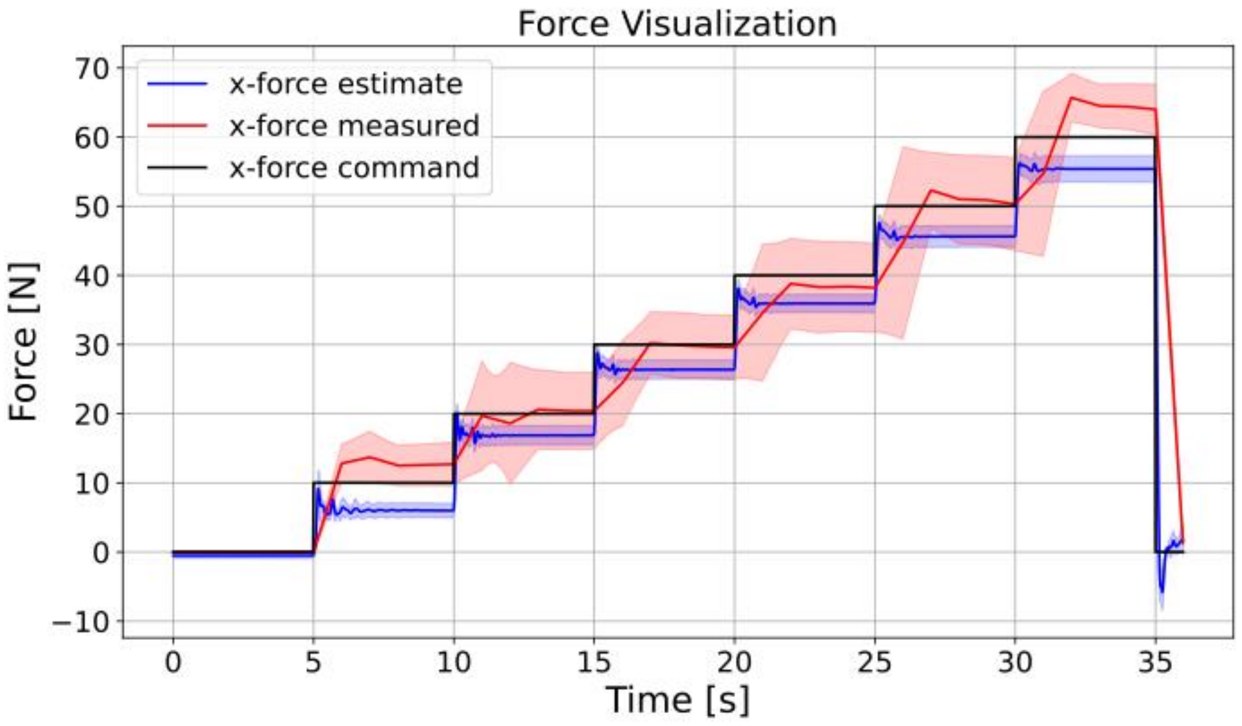
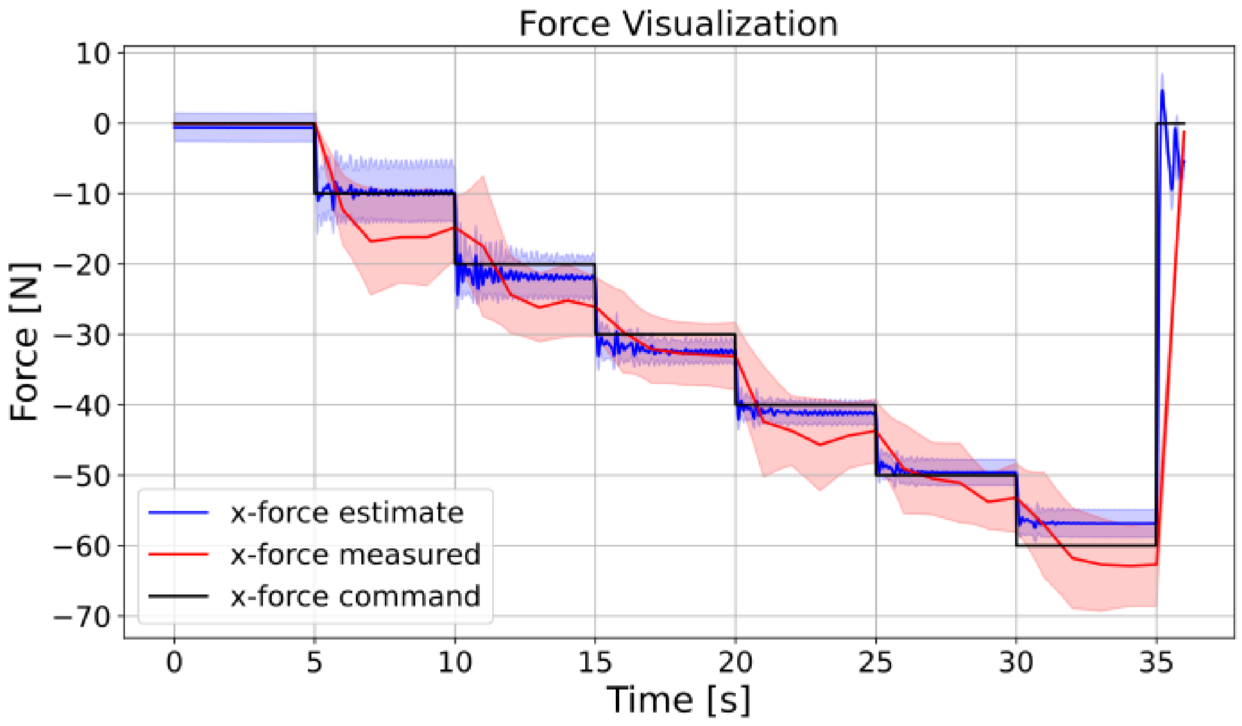
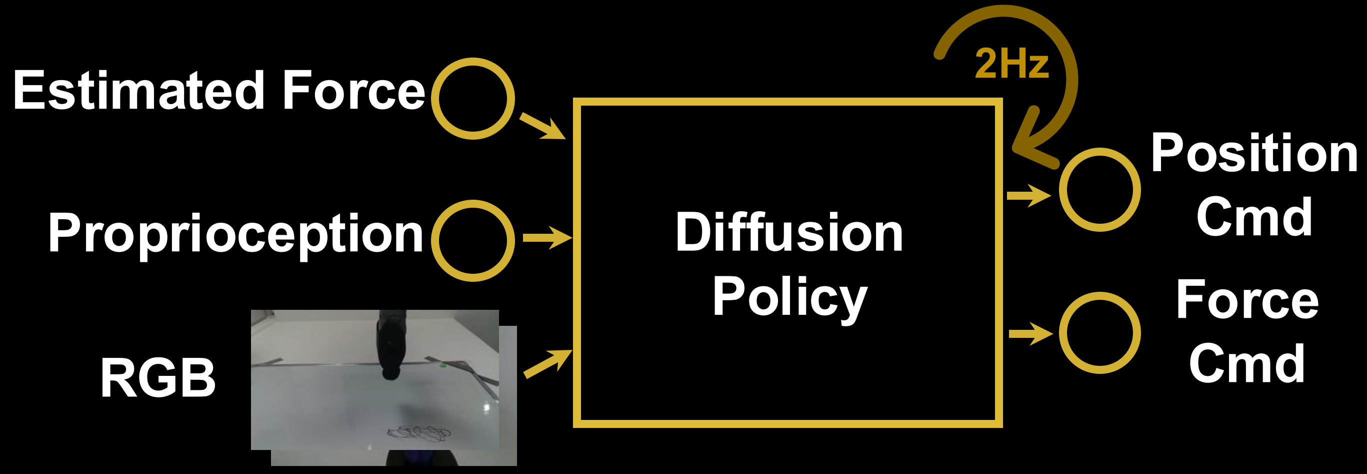
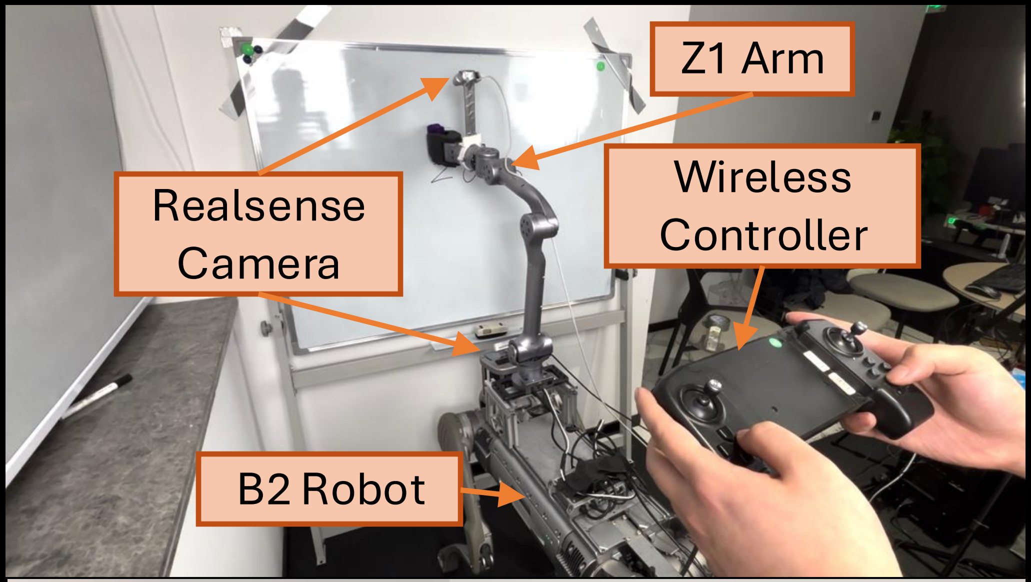



**Can successfully apply the force and estimate the reaction force ☺**

# UniFP for force-aware real-world imitation learning




- Data collection with estimated forces
- Imitation learning with position and force command targets
- Inference with UniFP

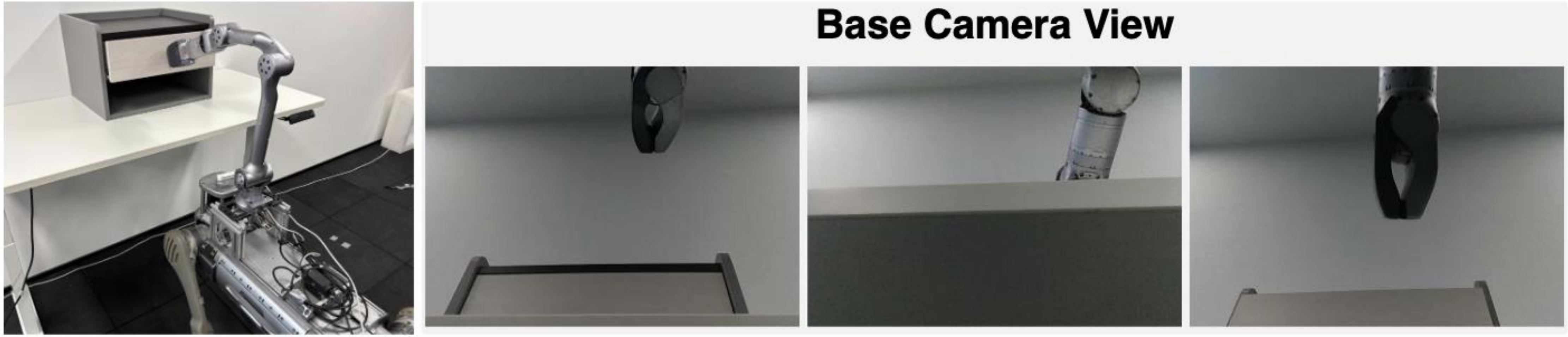
# UniFP for force-aware real-world imitation learning


**Tested on 4 tasks with each task taking 50 demonstrations**

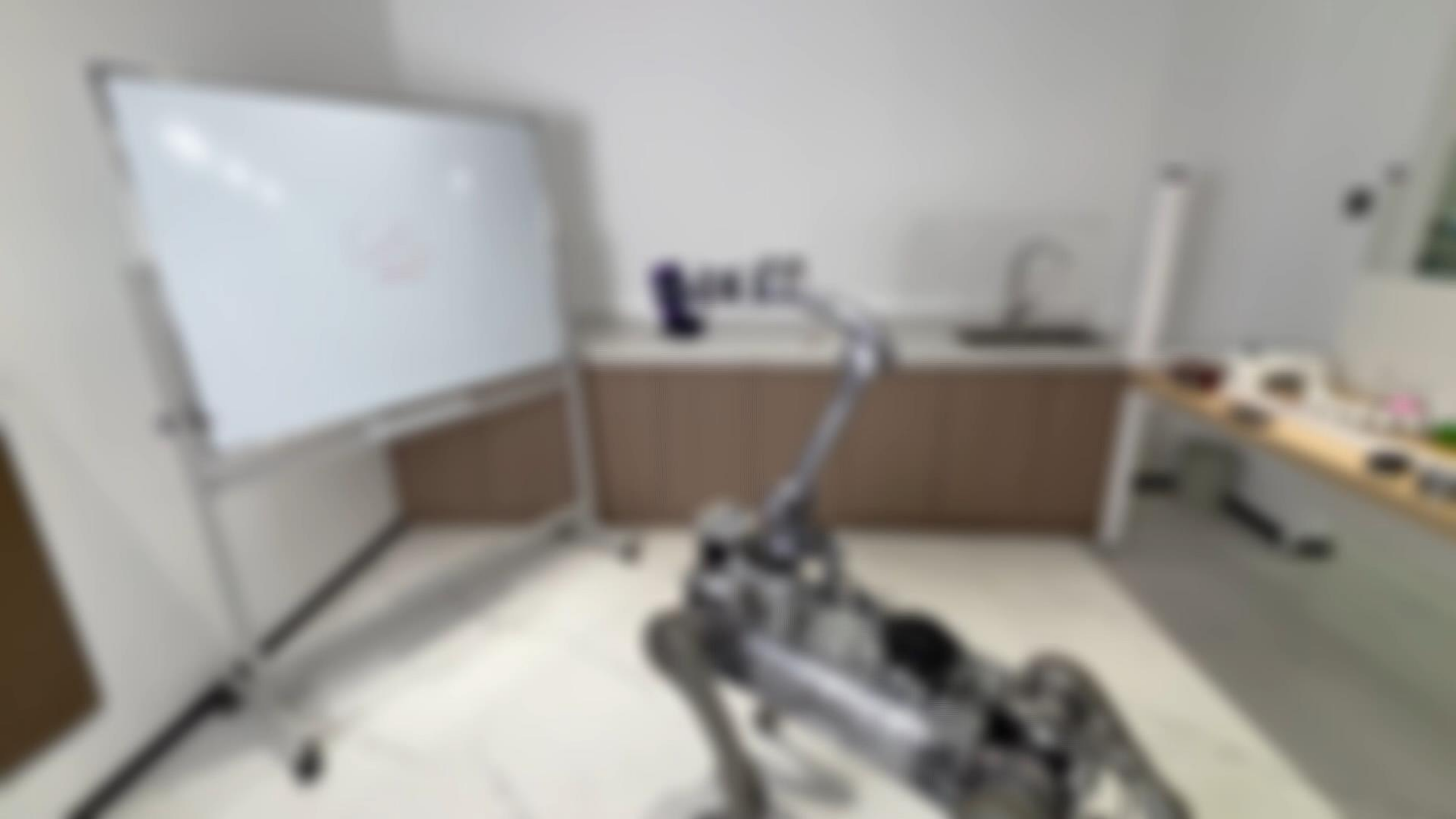
# UniFP for force-aware real-world imitation learning

Table A.3: Imitation learning results (**50 trials per task**)

| Task | wipe-blackboard | open-cabinet | close-cabinet | open-drawer-occlusion |
|---|---|---|---|---|
| **w/o Force** | 0.22 | 0.36 | 0.30 | 0.30 |
| **w/ Force** | 0.58 | 0.70 | 0.72 | 0.76 |




**Achieves ~39.5% higher success rate than the vanilla DP policy**




Robot Exercising in Gym
Kettlebell Pulling
Tug-of-war
Throw the trash

# Limitations

- Precise sensing/estimation and application of force
  - Incorporating robot kinematics for more accurate force modeling

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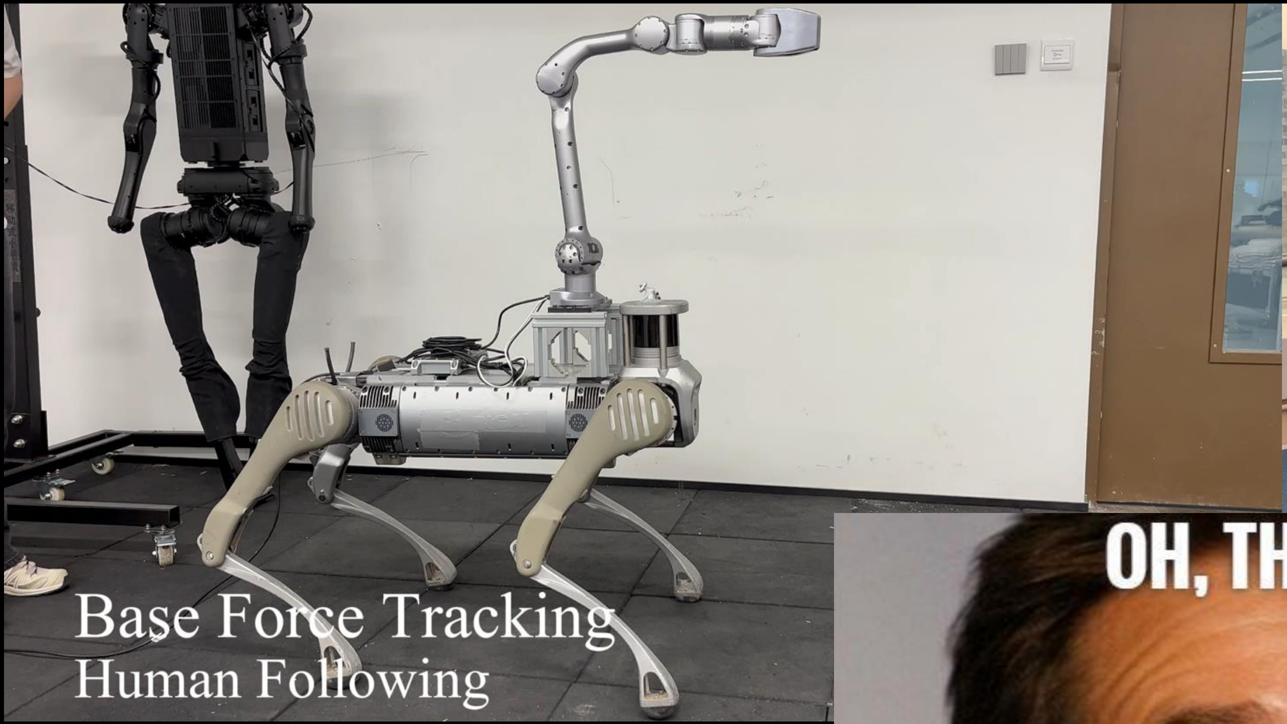
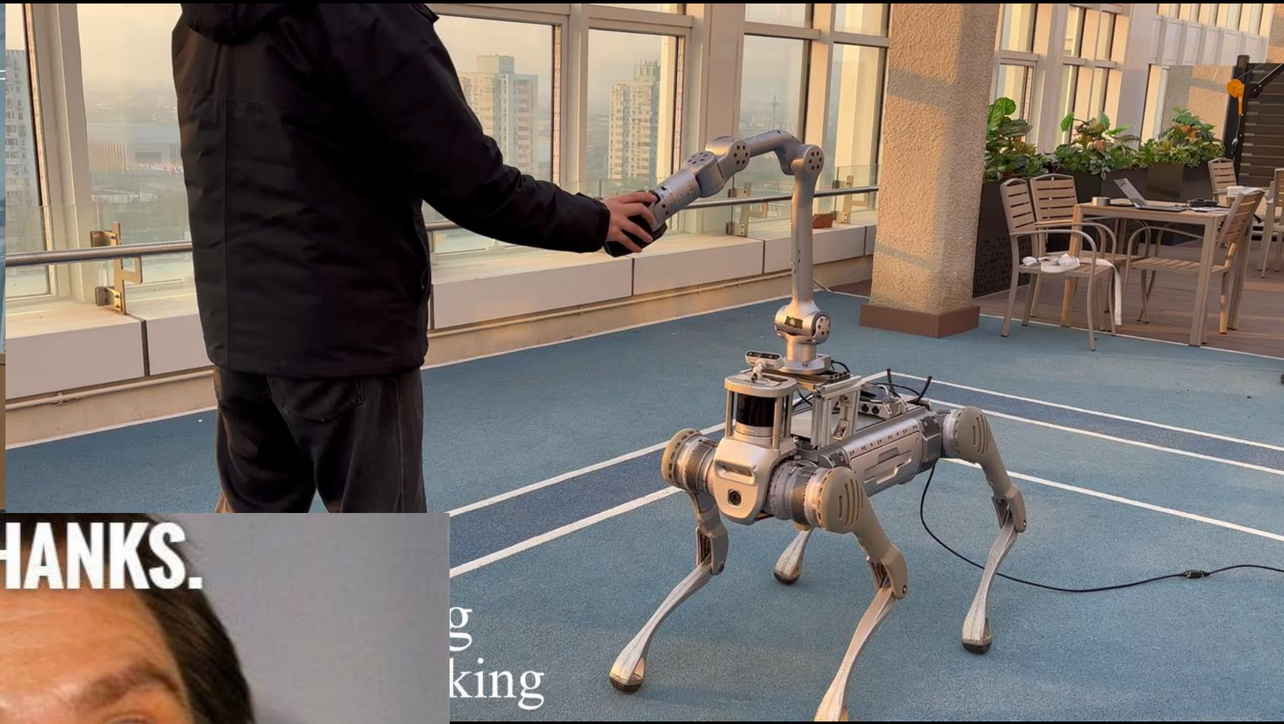
- Precise sensing/estimation and application of force
  - Incorporating robot kinematics for more accurate force modeling
- Support of different control/compliant behaviors during on more diverse and dexterous manipulation tasks
  - More powerful hierarchical VLA with force-aware low-level policy

# Limitations

- Precise sensing/estimation and application of force
  - Incorporating robot kinematics for more accurate force modeling
- Support of different control/compliant behaviors during on more diverse and dexterous manipulation tasks
  - More powerful hierarchical VLA with force-aware low-level policy
- Mainly tested on separate control behaviors without consideration of nested behaviors in real-world scenarios
  - The formulation enables such composition but requires careful design on position commands, force commands, compensation…

# So how is this important…



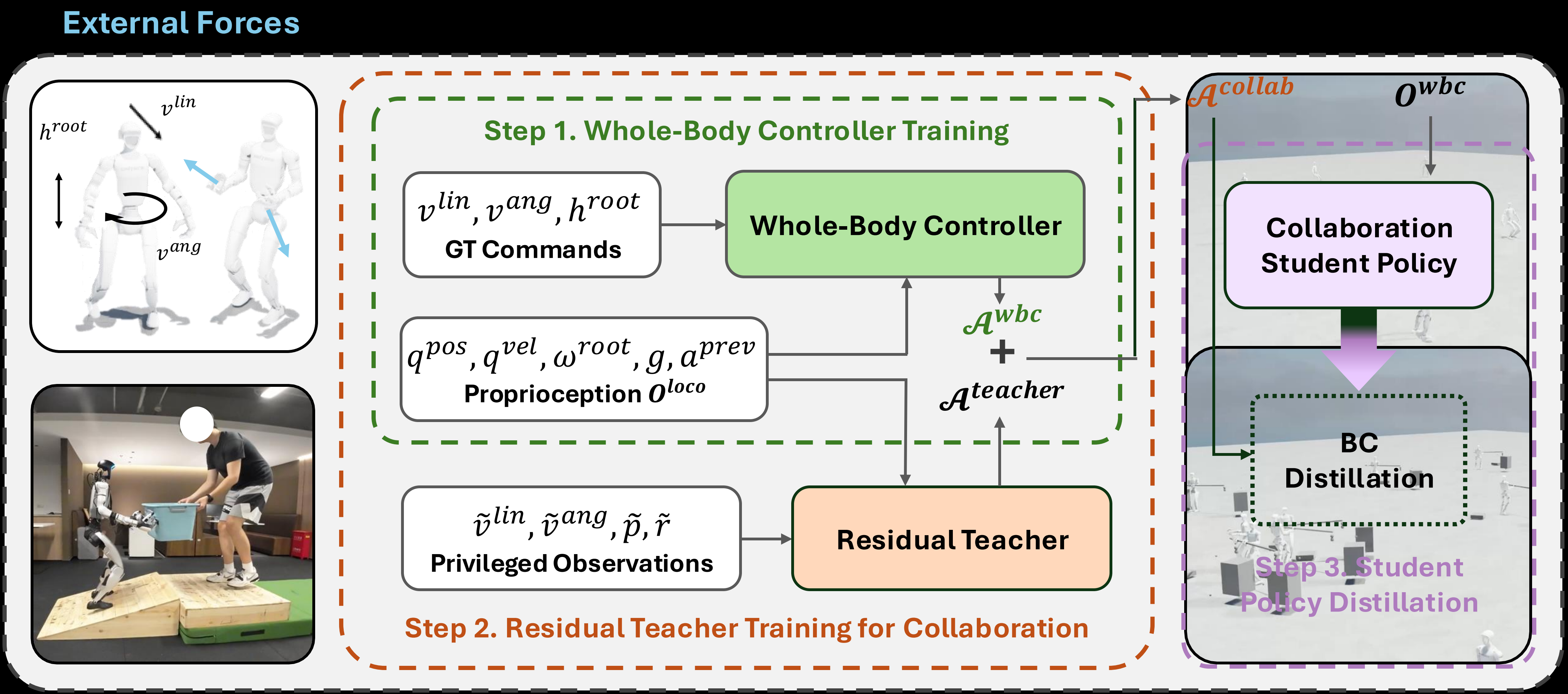



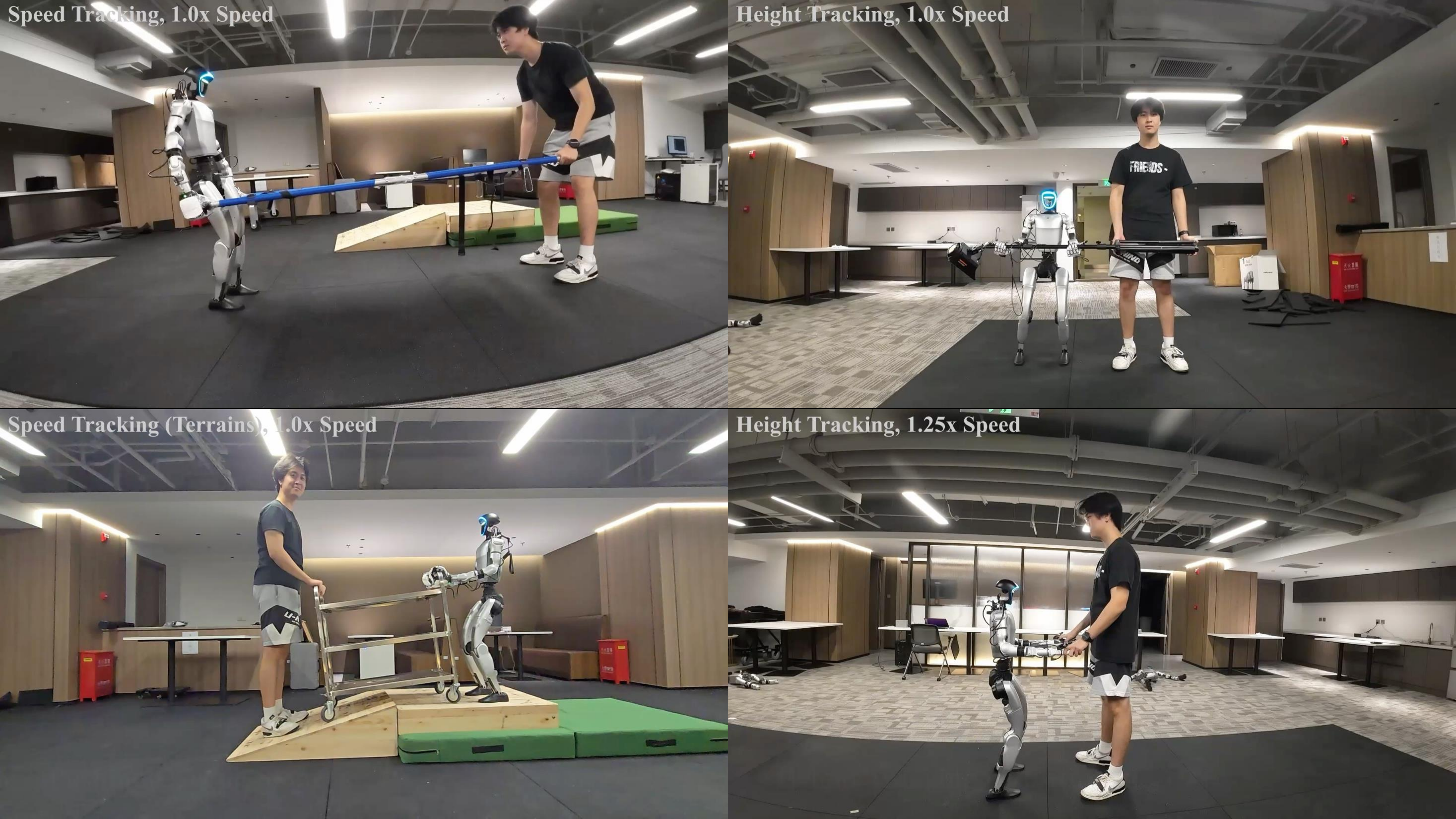

**Movement Tracki** **ompliant Holding**

**The composition of thes** **nan-robot collaboration**


EXIT

# COLA for collaborative object carrying




Speed Tracking, 1.0x Speed
Height Tracking, 1.0x Speed
Speed Tracking (Terrains), 1.0x Speed
Height Tracking, 1.25x Speed


Long Distance Testing (102.4m Total), 1.0x Speed


Speed Tracking, 1.25x Speed


Speed Tracking, 1.0x Speed
'Shopping Assistant' with Payload (15kg)

# Takeaways

- Offsets between commands and actual robot status entails force and interaction information ☺
    - Precision and accuracy still needs to be improved ☹

# Takeaways

- ➢ Offsets between commands and actual robot status entails force and interaction information ☺
  - ❖ Precision and accuracy still needs to be improved ☹
- ➢ Compliant behaviors are important in human-robot collaboration especially for safety considerations ☺
  - ❖ Coordination with vision inputs are necessary ☹

# Takeaways

- Offsets between commands and actual robot status entails force and interaction information ☺
  - Precision and accuracy still needs to be improved ☹
- Compliant behaviors are important in human-robot collaboration especially for safety considerations ☺
  - Coordination with vision inputs are necessary ☹
- Unified policies can help VLA-type learning ☺
  - Autonomy only on certain tasks, need task specific tuning ☺

CLONE (CoRL 2025)

ControlVLA (CoRL 2025)

**Learning a Unified Policy for Position and Force Control in Legged Loco-Manipulation**

**CoRL 2025 Best Paper**

**https://unified-force.github.io/**

# Thank you
# Q&A

VideoArtGS (arXiv 2025)

SceneWeaver (NeurIPS 2025)

**COLA: Learning Human-Humanoid Coordination for Collaborative Object Carrying**

**arXiv:2510.14293**

**https://yushi-du.github.io/COLA/**