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Project Page



Code & Data

Introduction & Motivation

- ❖ **Low-cost robotic platforms are essential for scalable robot learning**, but their inexpensive servo actuators often lack dedicated torque and force sensors.
- ❖ **Force control and hybrid force–position control are increasingly important for contact-rich manipulation**, creating a strong need for reliable force perception on low-cost hardware.

Why Are Low-Cost Robot Platforms Challenging?

Limited Force and Torque Sensing

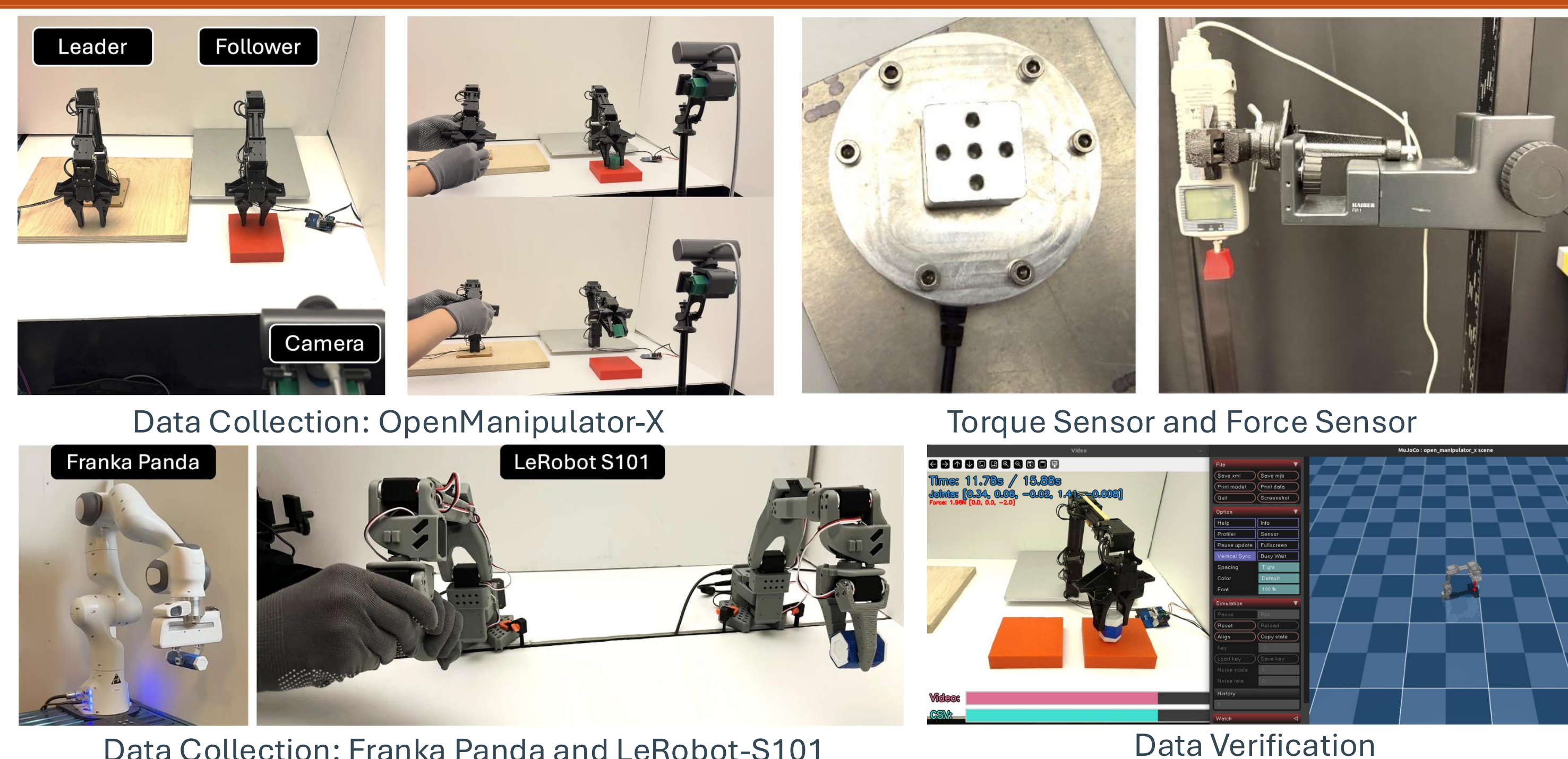
Low-cost servo-driven robots typically lack dedicated joint torque and force sensors, limiting direct feedback from physical interactions.

Nonlinear and Time-Varying Actuation

The conventional linear current-to-torque assumption breaks down because of friction, hysteresis, gearbox backlash, current saturation, and thermal drift.

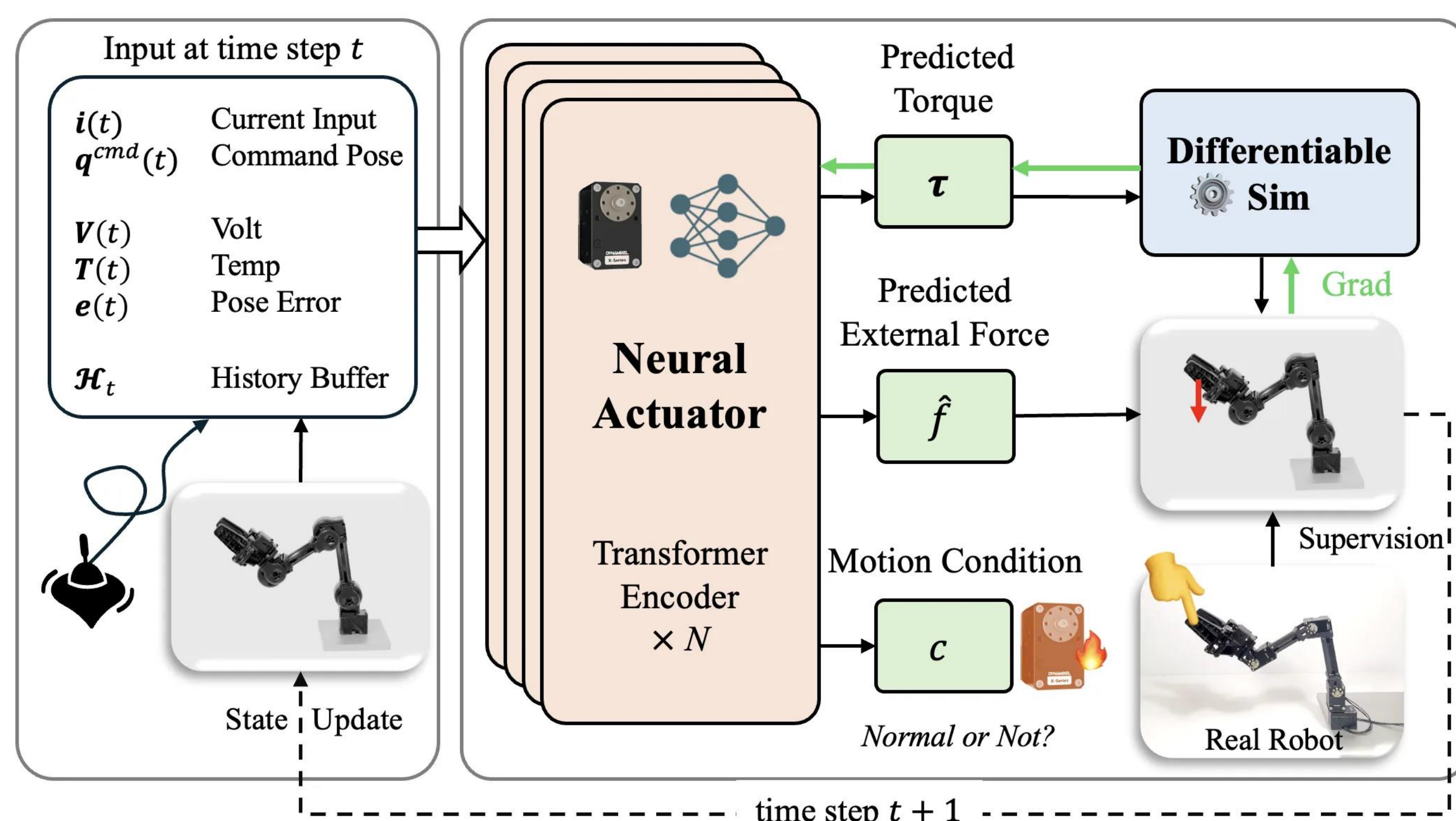
The goal of this research is to turn the low-cost actuator itself into both a dynamics model and a sensing channel, enabling torque modeling, external-force estimation, and motor-condition monitoring without dedicated torque sensors.

Neural Actuation Dataset (NAD)

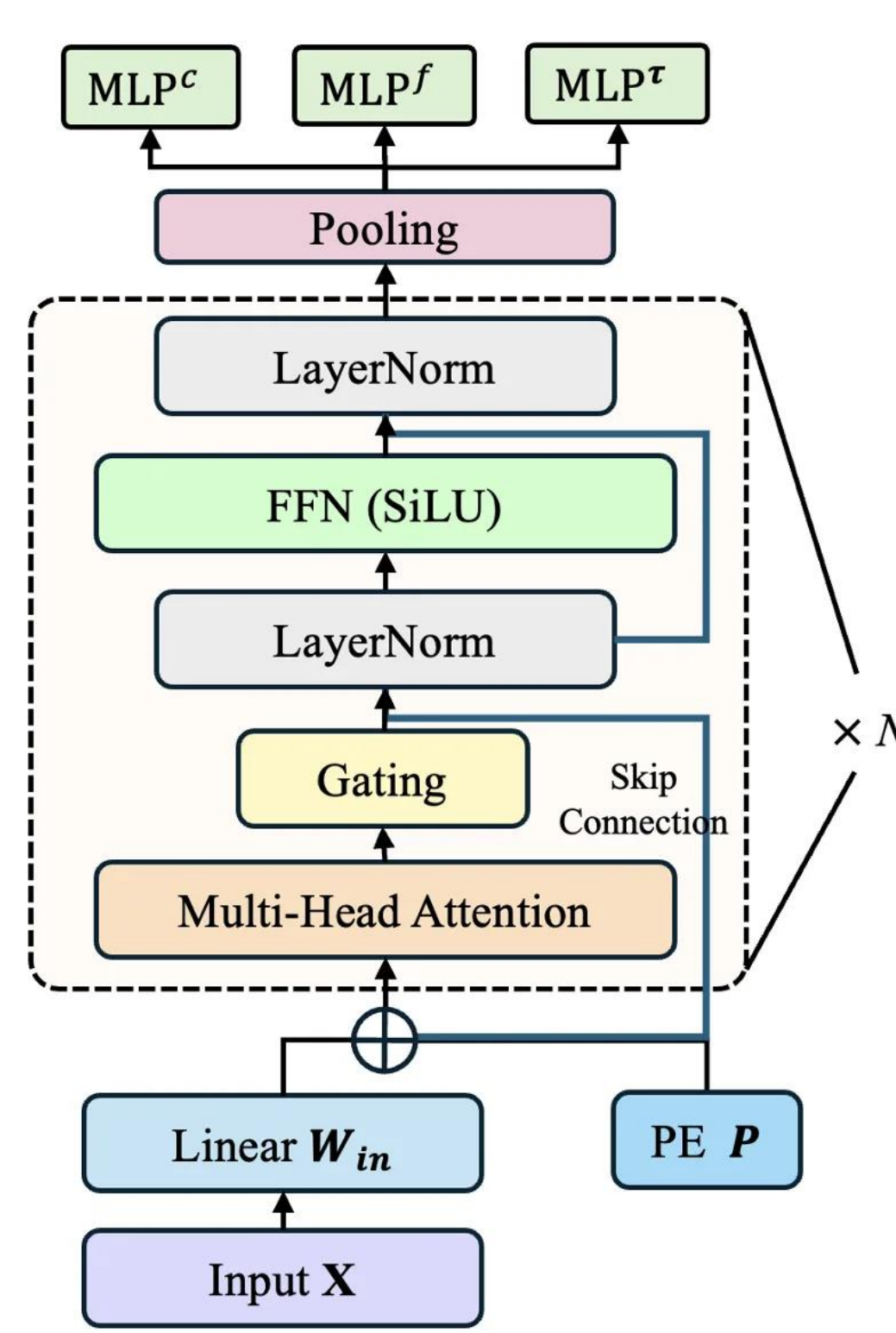


NAD is collected with a twin-arm teleoperation setup that records commanded pose, measured pose, current, voltage, temperature, and force supervision from F/T sensors, force gauges, and known payloads.

Pipeline - NeuralActuator



NeuralActuator pipeline. A Transformer-based model jointly predicts torque, external forces, and motor conditions within a differentiable simulation loop.



Torque-Supervision-Free Actuator Learning

Learns actuator torque from pose trajectories via differentiable simulation, eliminating the need for dedicated torque sensors, which are unavailable on many low-cost platforms.

$$\min_{\theta} \|\text{DiffSim}(f_{\theta}(\cdot)) - q^{\text{real}}\|$$

Neural Modeling of Nonlinear Actuator Dynamics

Captures history-dependent actuator behaviors beyond linear current–torque models, including friction, backlash, hysteresis, and thermal effects.

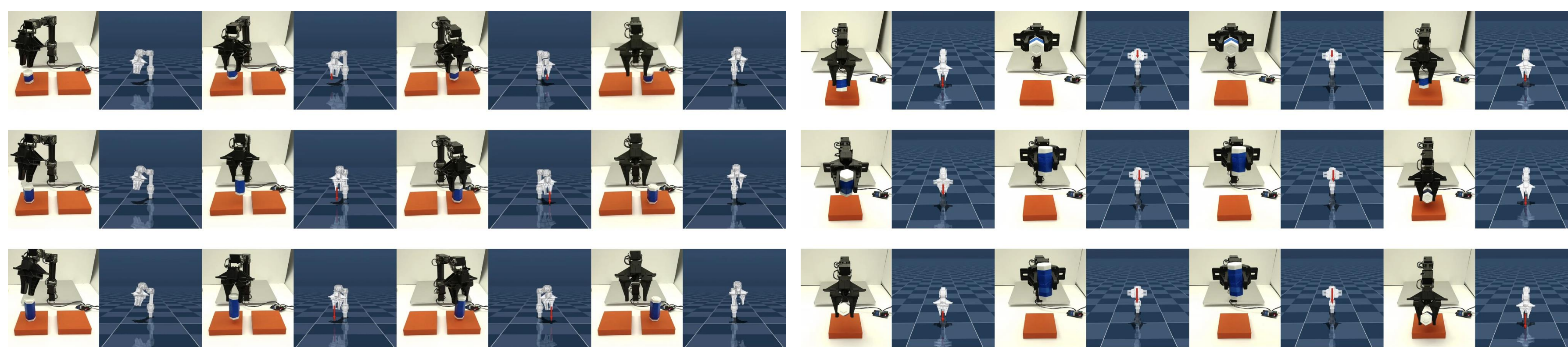
Unified Actuation Modeling and Force Perception

Jointly predicts torque, external forces, and motor conditions, enabling sensorless force-aware control on low-cost robots.

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau + \tau_{\text{ext}}$$

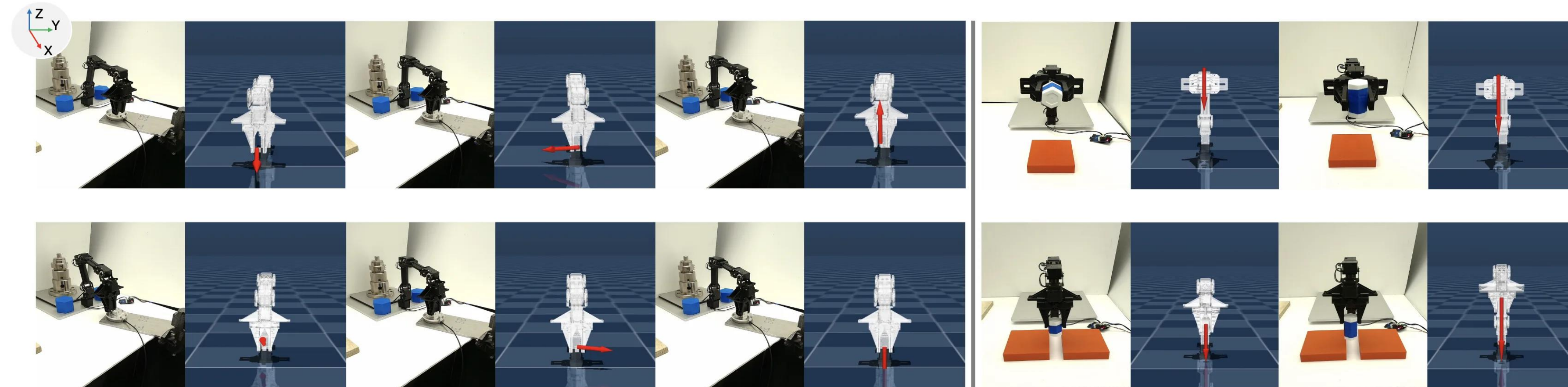
System Calibration+ Robot States

Experimental Results – External Force Estimation

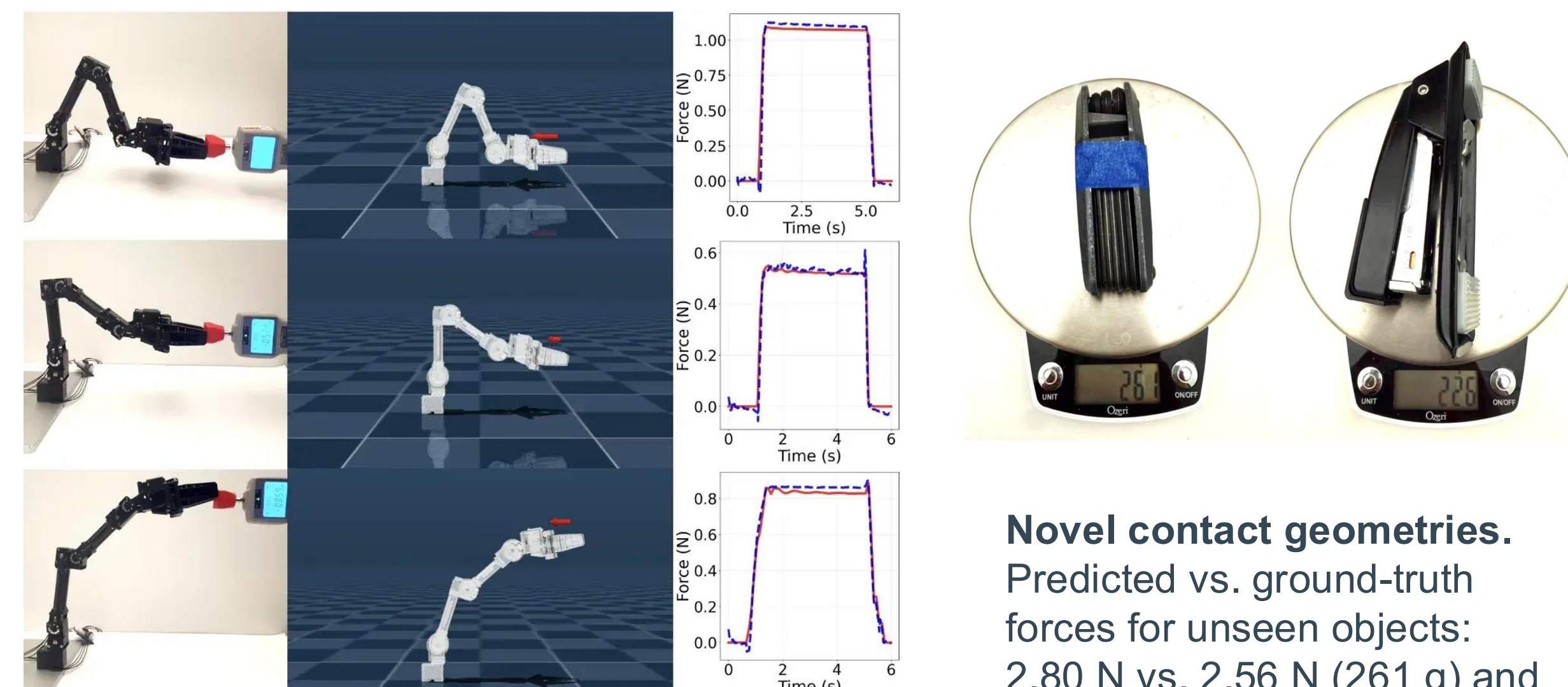


Pick-and-place with payloads.

Lift-and-hold with payloads.



External Force Estimation (GTs from F/T Sensor).



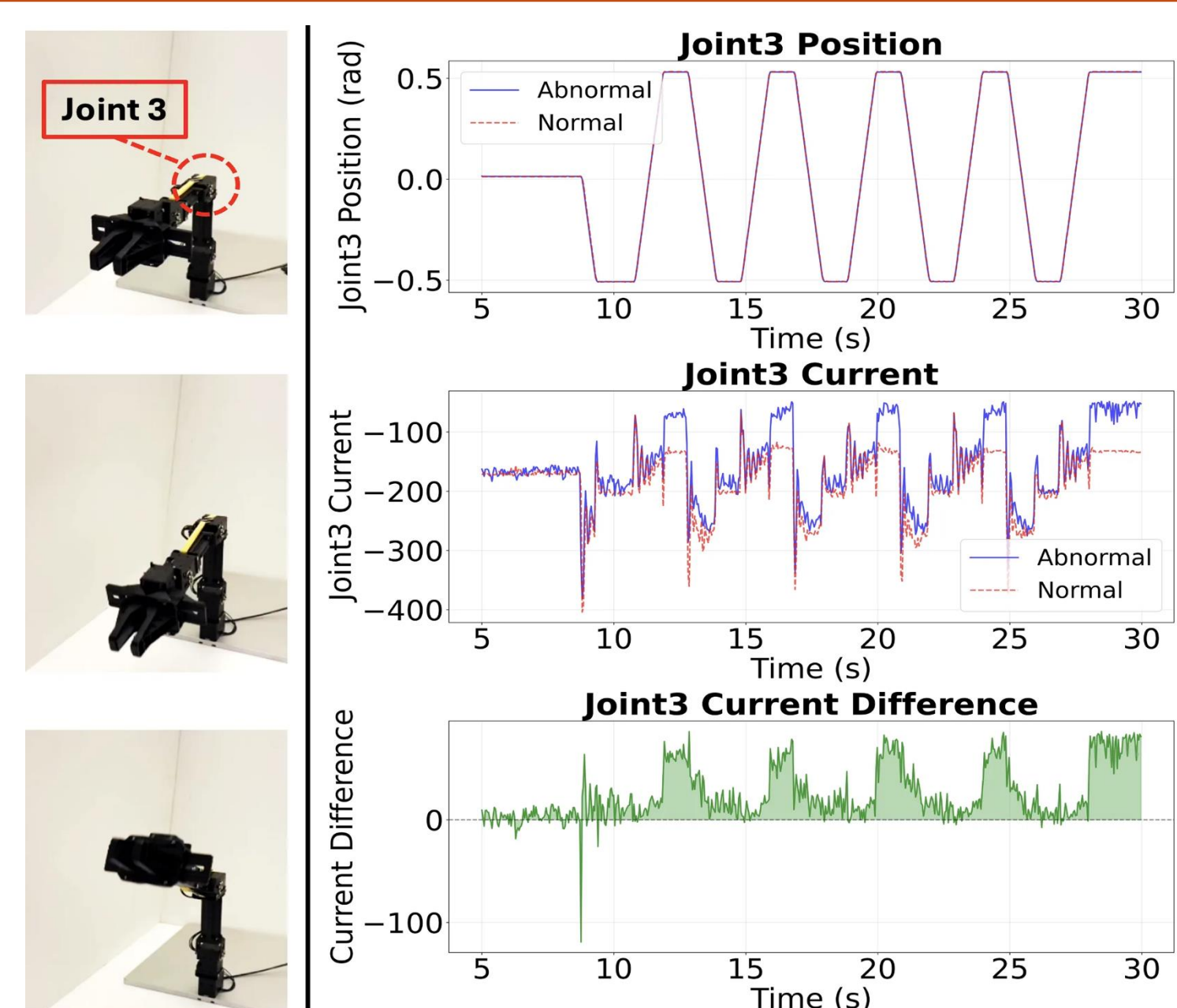
Novel contact geometries.
Predicted vs. ground-truth forces for unseen objects:
2.80 N vs. 2.56 N (261 g) and
2.40 N vs. 2.21 N (226 g).

Predicted force curves across contact onset, steady force force, and release.

Method	Go Up 200g (N)	Go Up 300g (N)	Go Up 400g (N)	Pick 200g (N)	Pick 300g (N)	Pick 400g
ID-Linear	1.37	1.81	2.30	0.72	0.95	1.22
ID-Friction	1.06	1.59	2.15	0.62	0.82	1.10
GMO	0.58	0.66	1.23	0.33	0.47	0.63
NeuralActuator	0.12	0.20	0.07	0.24	0.00	0.19

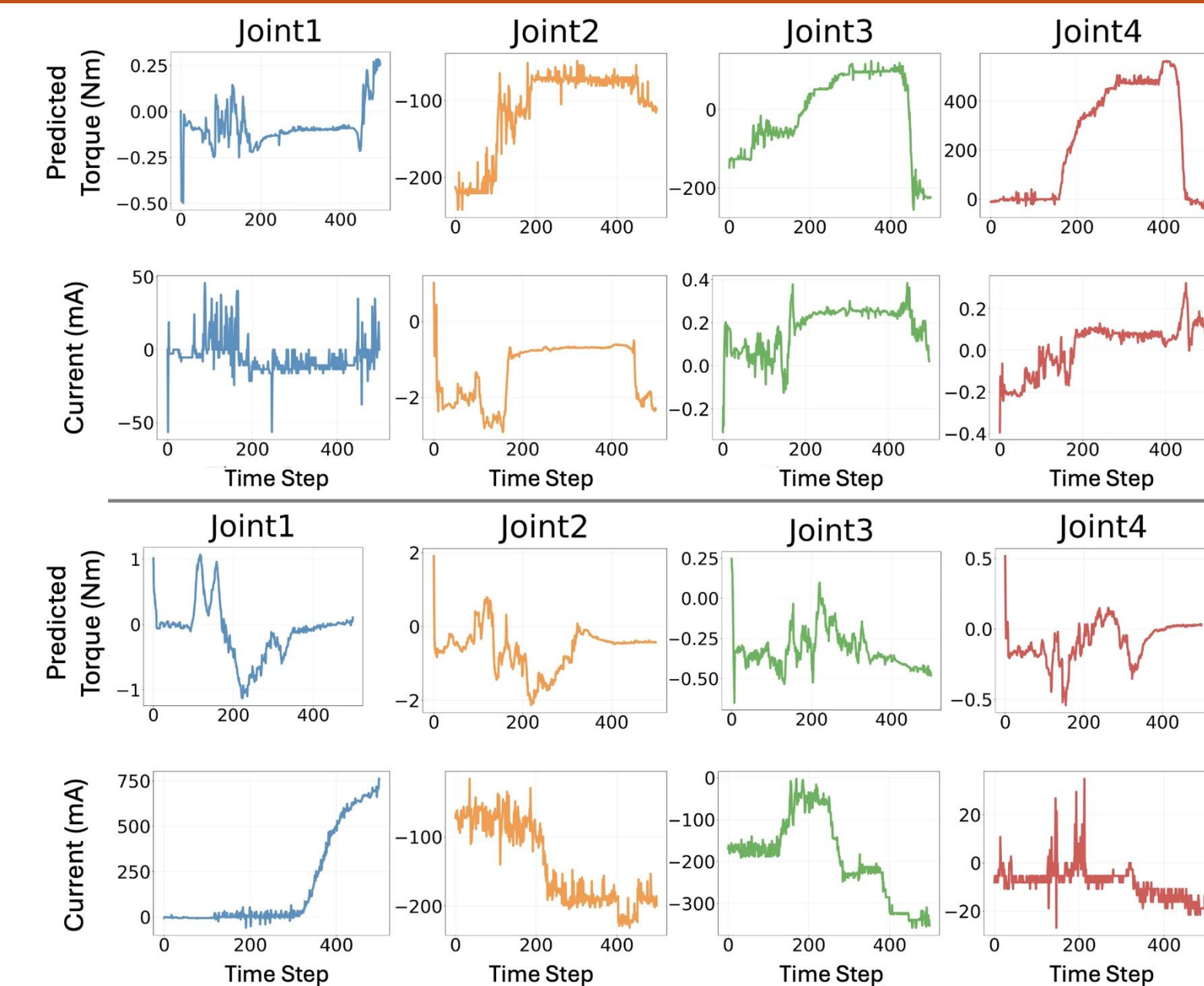
Comparison with previous methods.

Motor Condition Monitoring



Abnormal resistance produces higher current under similar position trajectories.

Learned Torque Values



The effective current-to-torque mapping varies across joints and operating phases.

Runtime Performance

METRIC	VALUE	UNIT
Parameters	1.42M	-
FLOPs (forward)	5.46M	-
Parameter memory	5.43	MB
Mean time	0.25	ms
P95 time	0.31	ms
Throughput (batch=1)	4,019	Hz
Throughput (batch=32)	10,992	Hz

The model is lightweight for real-time simulation and control.

Future Work

- ❖ **Synthetic-to-Real Actuator Pretraining**
Leverage large-scale synthetic actuator data for pretraining, followed by real-world fine-tuning to reduce costly hardware data collection.
- ❖ **Cross-Morphology Actuation Learning**
Extend NeuralActuator toward different robot morphologies and actuator families for more generalizable actuation modeling.
- ❖ **Scalable Whole-Body Force Perception**
Move beyond single-arm end-effector force estimation toward multi-joint and whole-body force-aware robot control.
- ❖ ...