Effectiveness of Kinesthetic Sensing in In-Hand Rotation of Objects with an Eccentric Center of Mass

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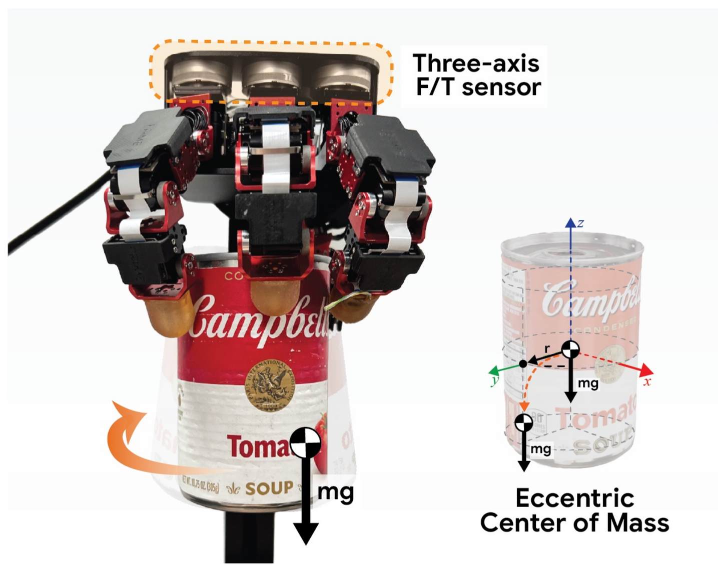
Watch the project video!

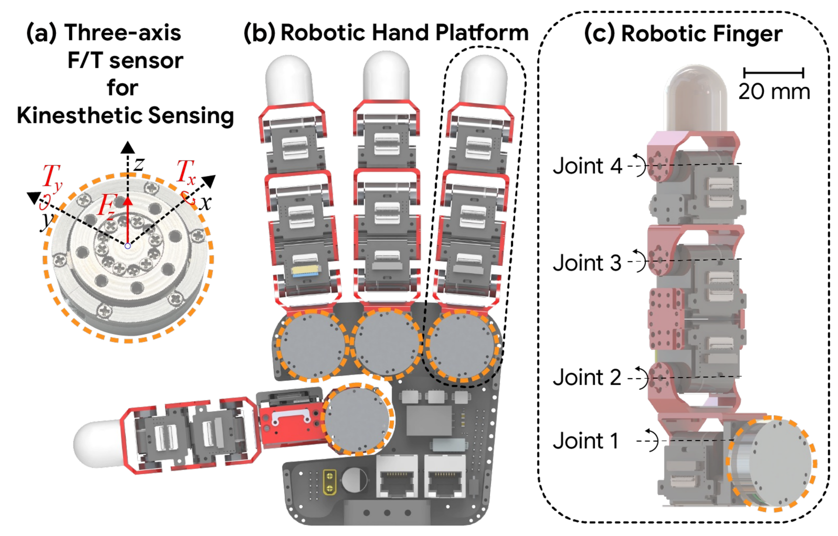
Project Website:
https://cold-young.github.io/kinesthetic_rotation/

Introduction

Research Aim

- ✓ Investigation of how kinesthetic feedback (joint forces and torques) enables adaptation to object properties such as weight and center of mass (CoM)
- ✓ Evaluation of the effectiveness of reinforcement learning in leveraging kinesthetic feedback for robust downward-facing in-hand rotation

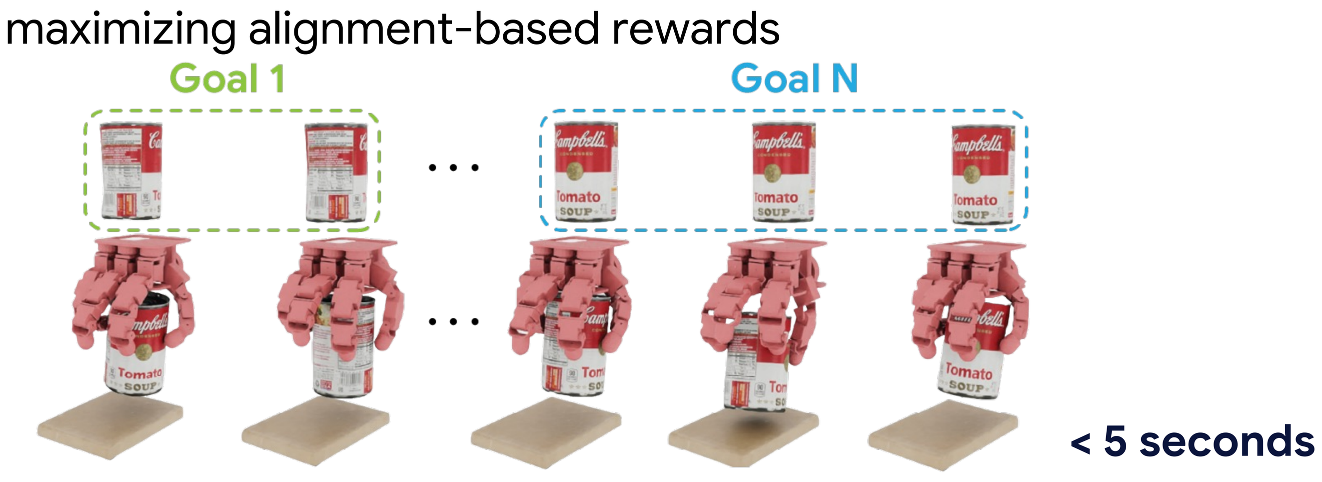




Problem Formulation

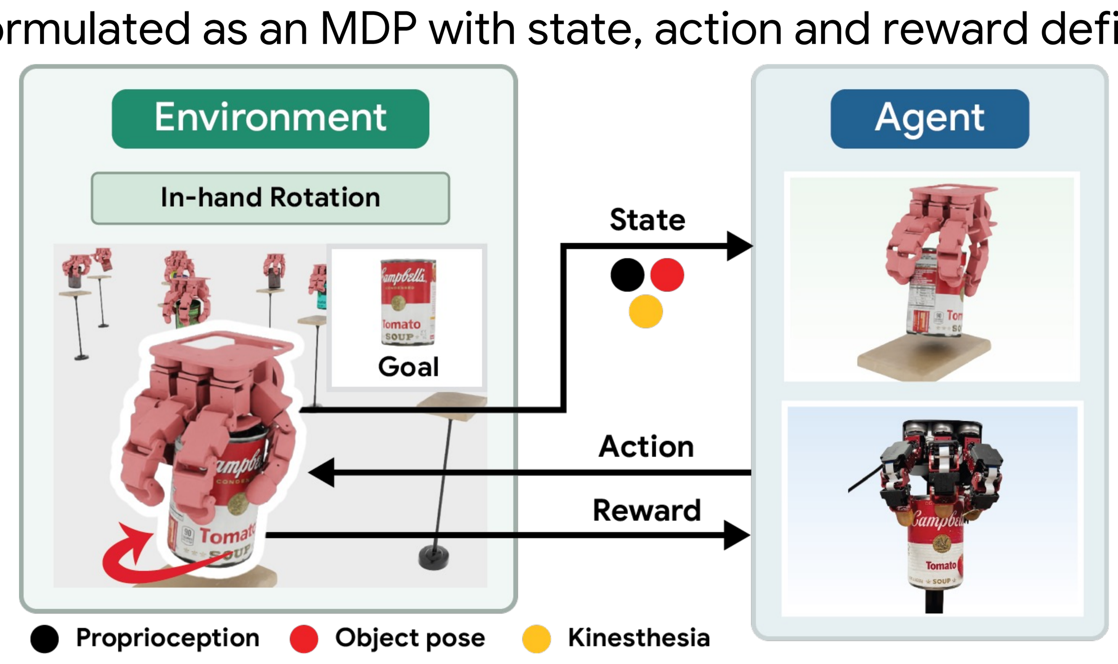
Task Objective

- ✓ Exploration of stable in-hand rotation strategies for cylindrical objects with an eccentric CoM
- ✓ **Target:** Object rotation toward a downward-facing goal within a 5-second rollout, maximizing alignment-based rewards



Formulation as MDP

- ✓ Task formulated as an MDP with state, action and reward definitions



- **Action:** 16-DoF joint position commands

$$\tilde{a}_t = \eta a_t + (1-\eta)\tilde{a}_{t-1} \quad t \geq 1,\ \tilde{a}_t = 0,\ \eta = 0.035$$

- **Reward:** alignment with goal, penalty for fall/contact, velocity constraint, success bonus (see Table 1)

Table 1. Reward Components

r_{rot}	Alignment with target orientation
r_{fall}	Penalty when the object falls off the table
r_{cont}	Penalty for contact between object and table
r_{vel}	Penalty for excessive rotational speed
r_{dist}	Reward based on proximity to the target pose
r_{goal}	Sparse reward for achieving the final goal orientation

- **State:** joint angles, object pose, goal orientation, delta rotation, fingertip pose, previous target, and kinesthetic feedback (F/T)

Evaluation Setup

Simulation Setup

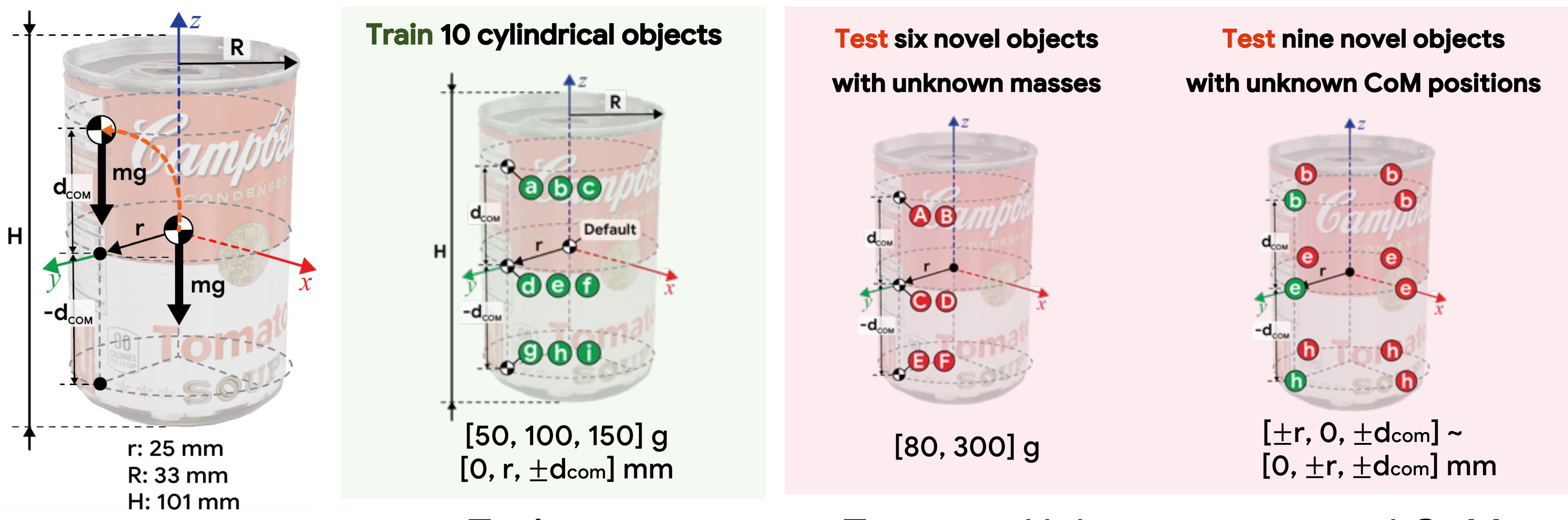
- ✓ Used 25 cylindrical objects with varying mass and CoM
- ✓ Three policy variants differ only in observation modalities (see Table 2):

Simulation: Isaac Sim with 4096 parallel environments
Training: PPO, 40K steps, Five random seeds
Evaluation: 500 rollouts per instance
Hardware: Single RTX 4090 GPU

Performance Evaluation

Impact on Sensory Modalities on Performance

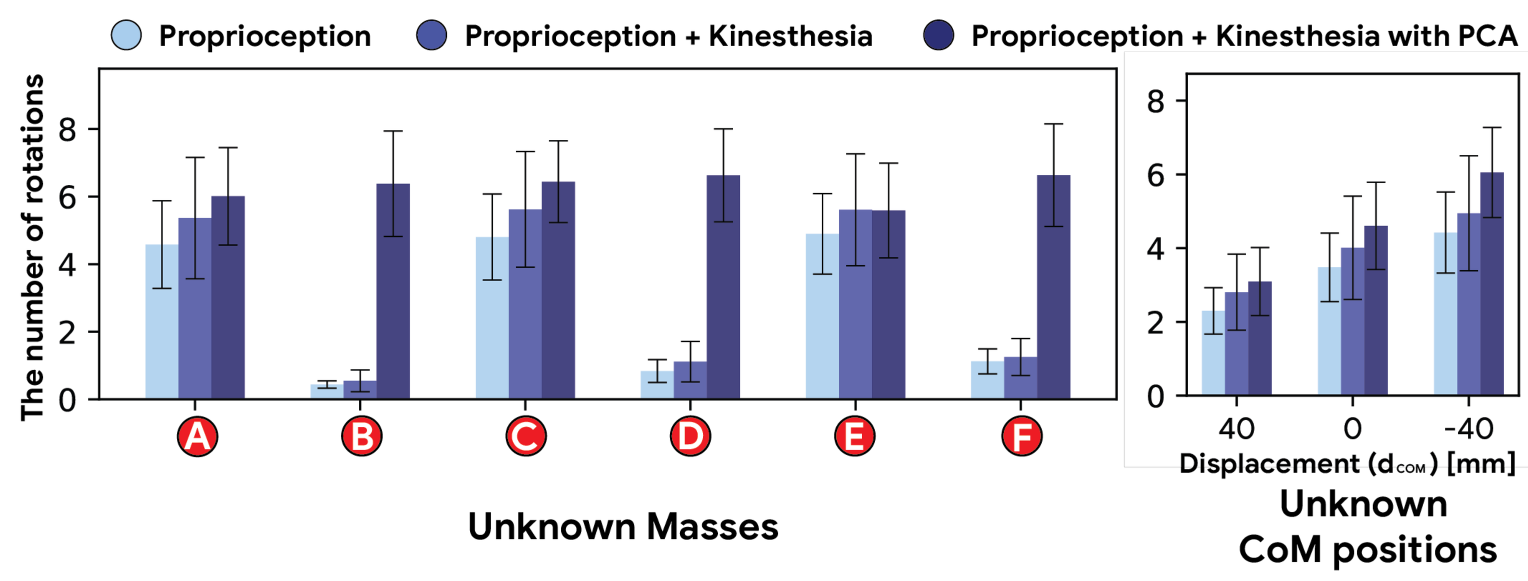
- ✓ Three state configurations: without kinesthetic feedback, with kinesthetic feedback, and with PCA-compressed kinesthetic feedback



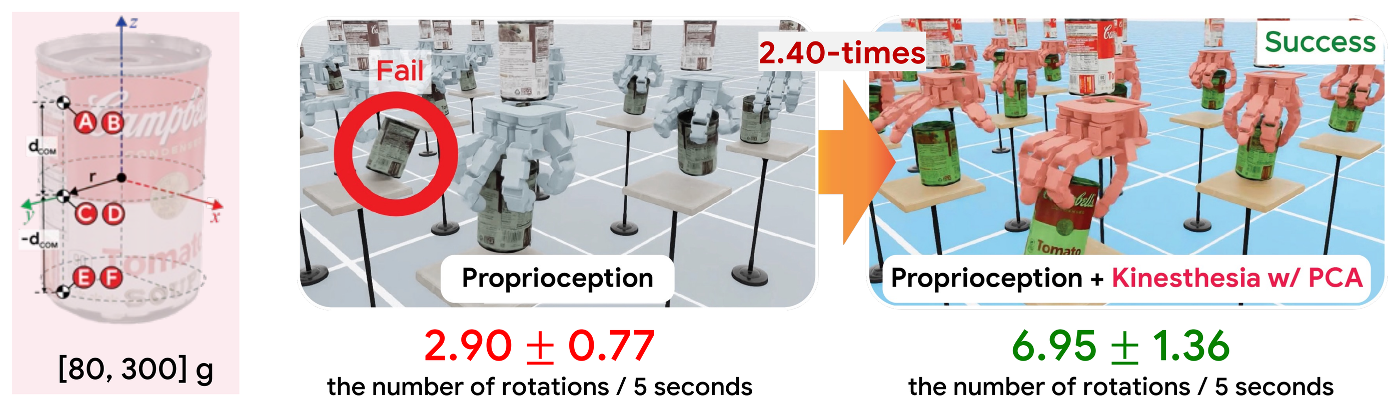
Train set — Test set: Unknown mass and CoM

Results

- ✓ Demonstrate that kinesthetic feedback significantly improved performance in in-hand rotation task



1. Performance on Unknown CoM position



2. Performance on Unknown Mass

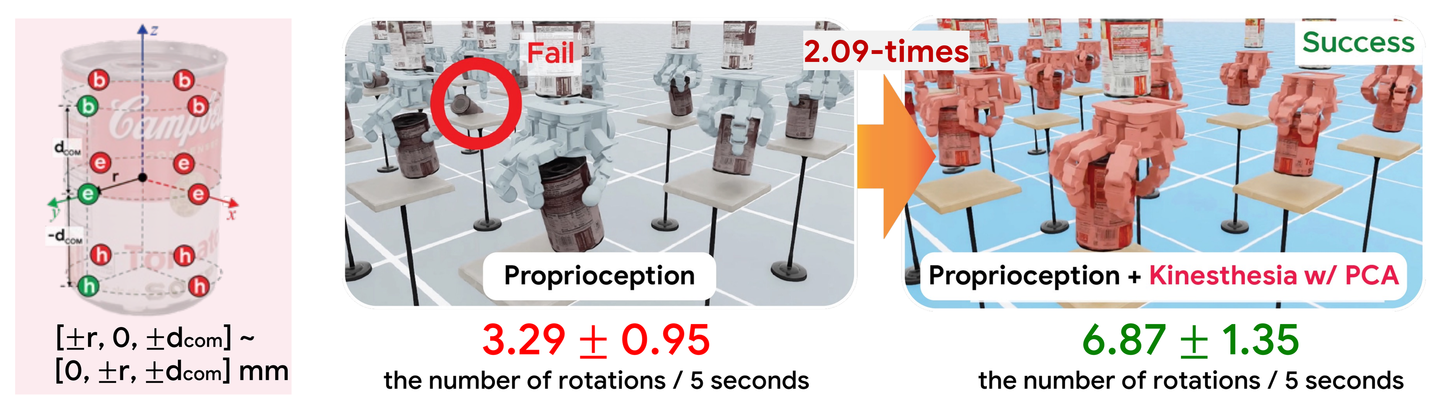


Table 3. Results of the In-Hand Rotation

	Max Reward (mean)	Pre-trained Samples	Unknown Mass	Unknown CoM Positions
Proprioception	419.05 ± 92.41	4.47 ± 1.14	3.29 ± 0.95	2.90 ± 0.77
Proprioception + Kinesthesia	477.30 ± 143.31	5.01 ± 1.75	3.73 ± 1.26	3.35 ± 1.19
Proprioception + Kinesthesia with PCA	569.71 ± 104.59	6.78 ± 1.24	6.87 ± 1.35	6.95 ± 1.36
		1.52x	2.09x	2.40x

Conclusion & Future Work

Conclusion

- ✓ Improved adaptability through kinesthetic feedback in in-hand manipulation
- ✓ 1.52-, 2.09-, and 2.40-times performance from incorporating kinesthetic sensing across CoM variations

Future Work

- ✓ Extend the current approach to real-world robotic experiments to assess robustness under sensor noise and mechanical compliance

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