Methods and Challenges in Simulation
Focus Talk Unit 3

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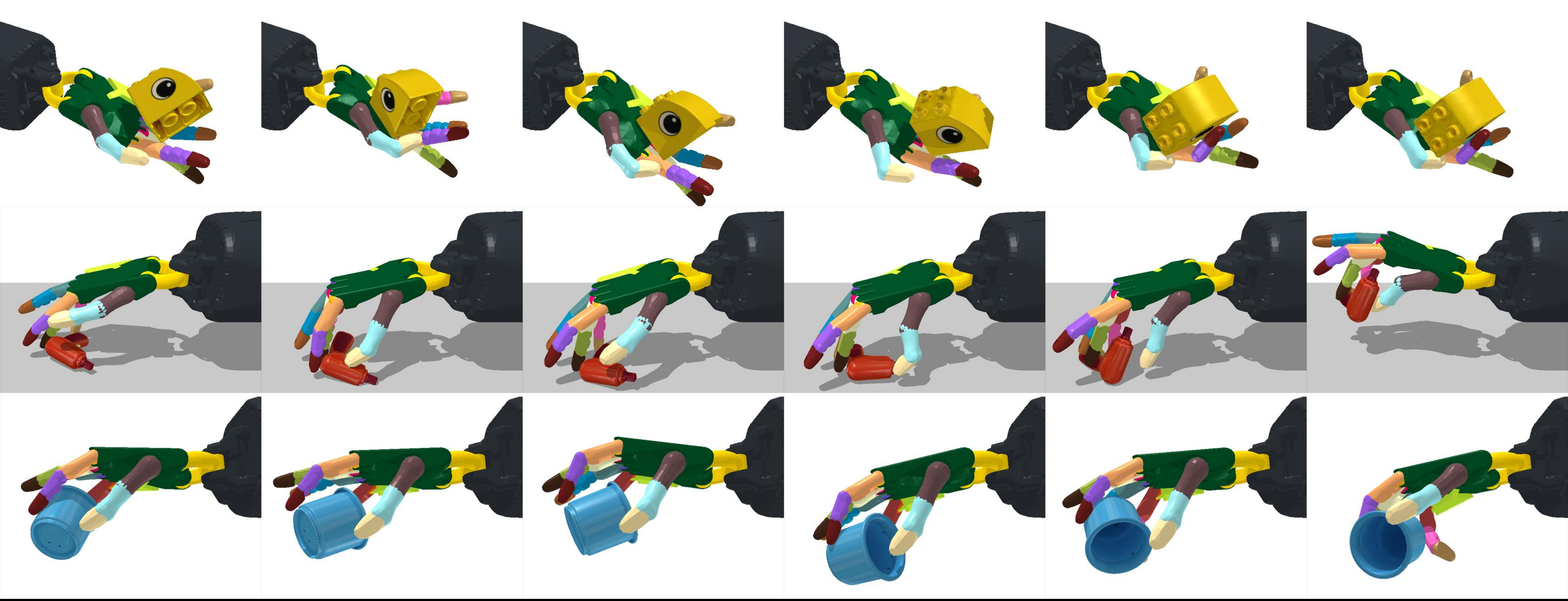
How to simulate dexterous object manipulation?



1. Chen, Tao, Jie Xu, and Pulkit Agrawal. "A system for general in-hand object re-orientation." Conference on Robot Learning. PMLR, 2022. https://taochenshh.github.io/projects/in-hand-reorientation

Why are simulators important?

Why simulators?

***Safe* and *fast* environment for testing robot controllers**

Parallelized simulation for reinforcement learning (RL)

Model-based control based on simulators

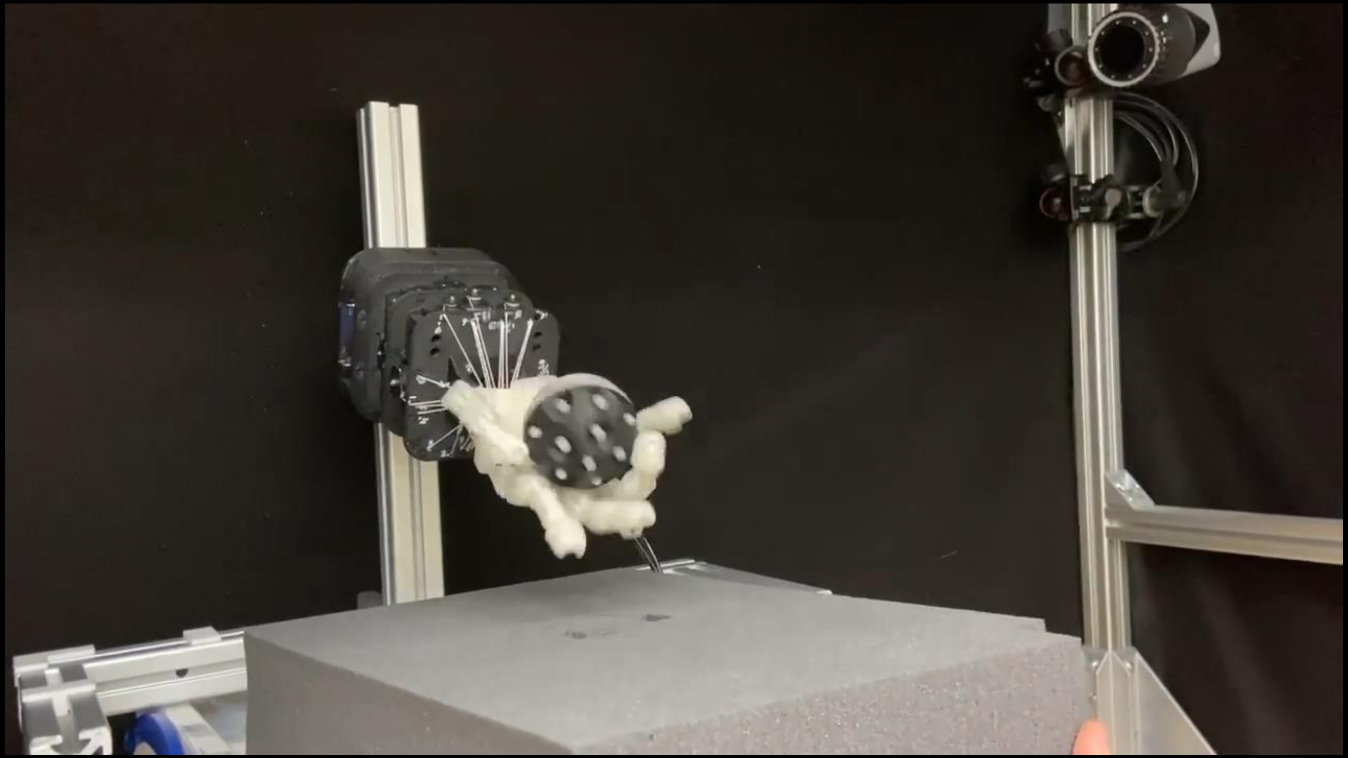
Failure in real environments are expensive

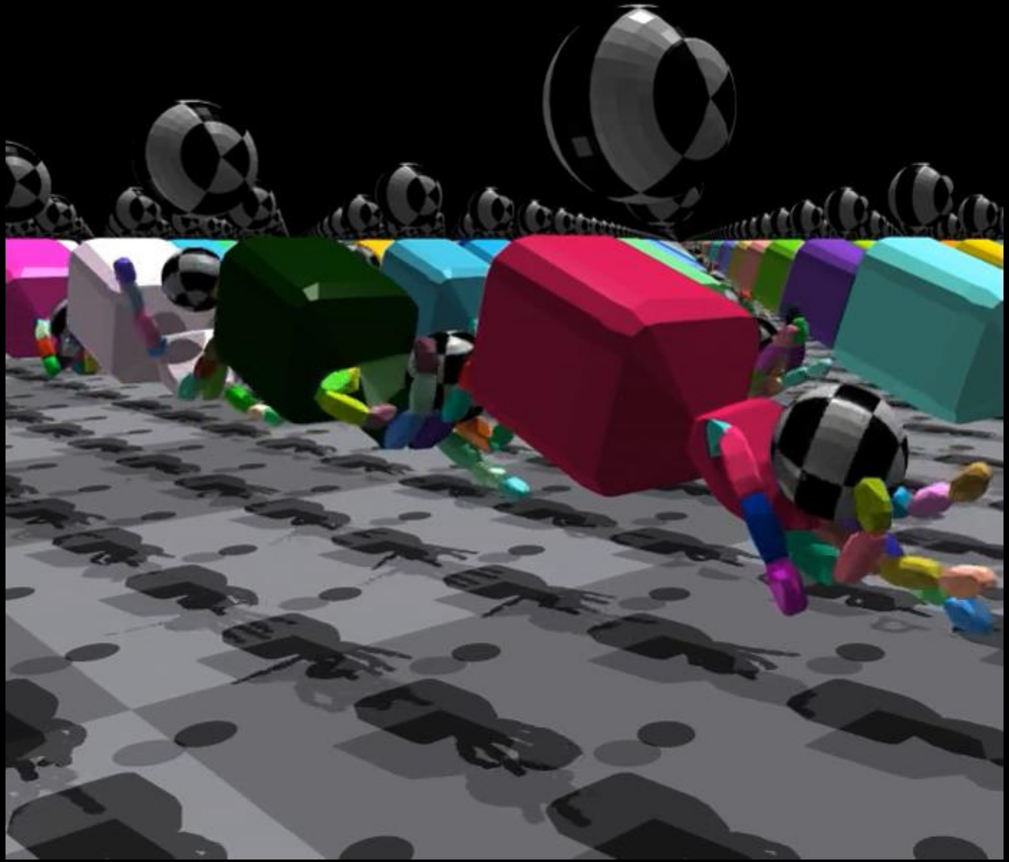
Darpa Robotics Challenge (DRC): https://www.darpa.mil/program/darpa-robotics-challenge

Simulations are safe environments

Darpa Robotics Challenge (DRC): https://www.darpa.mil/program/darpa-robotics-challenge

Simulations – Fast environments





Dynamic Dribbling with Faive: Training early stage on the real robot and in Isaac Gym

Benedek Forrai et al. 2023

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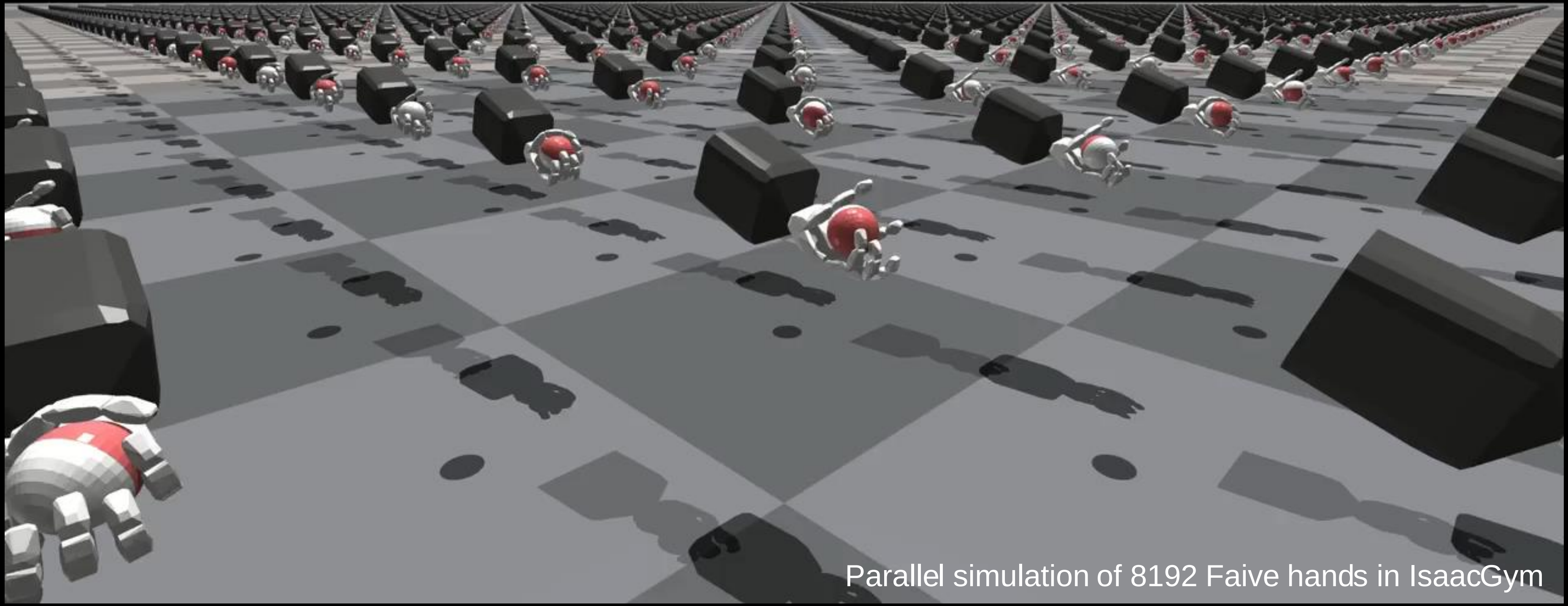
Learning-based approach for dexterous manipulation



Parallel simulation of 8192 Faive hands in IsaacGym

Proximal Policy Optimization (PPO)

- Reinforcement Learning (RL) algorithm
- Scales well to parallel environments[3]

Domain Randomization[1]

- Randomize physics
- Add noise to observations
- Make it robust for physical deployment

Parallelized Simulation

- 1000's of robots in parallel on GPU[2,3]
- Wide exploration of initial conditions, parameters and control policies

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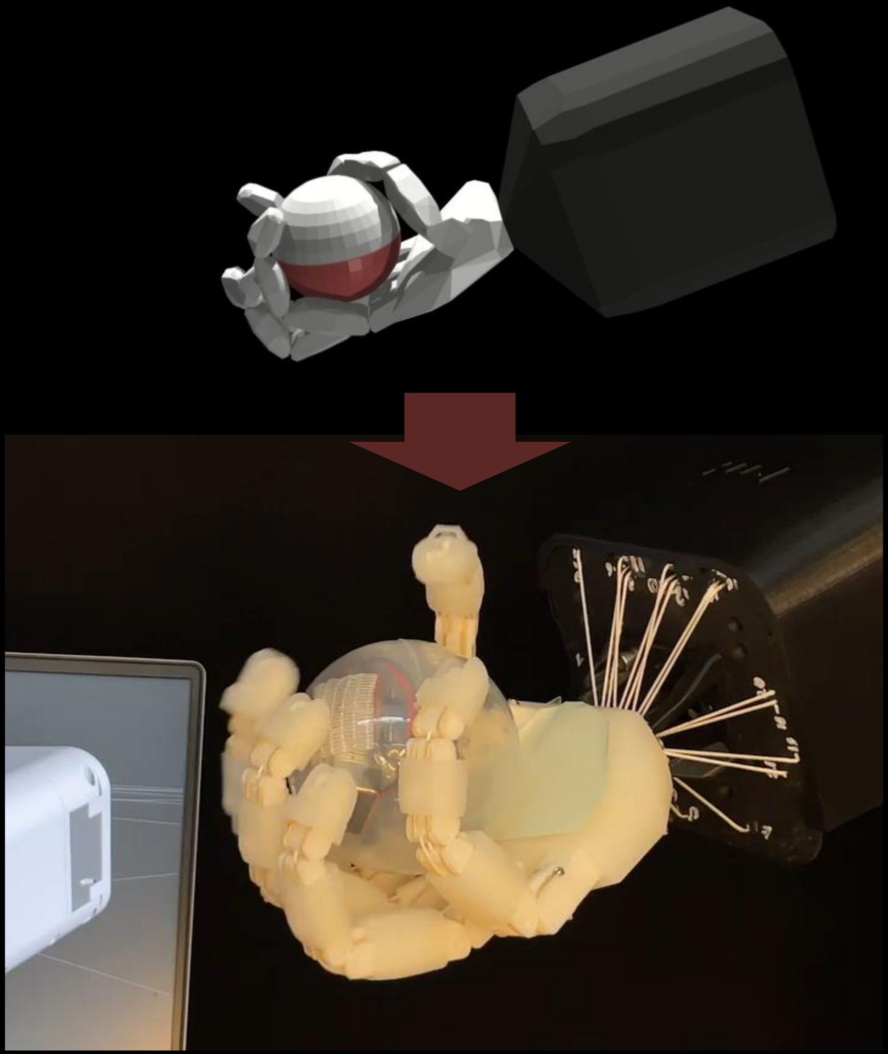
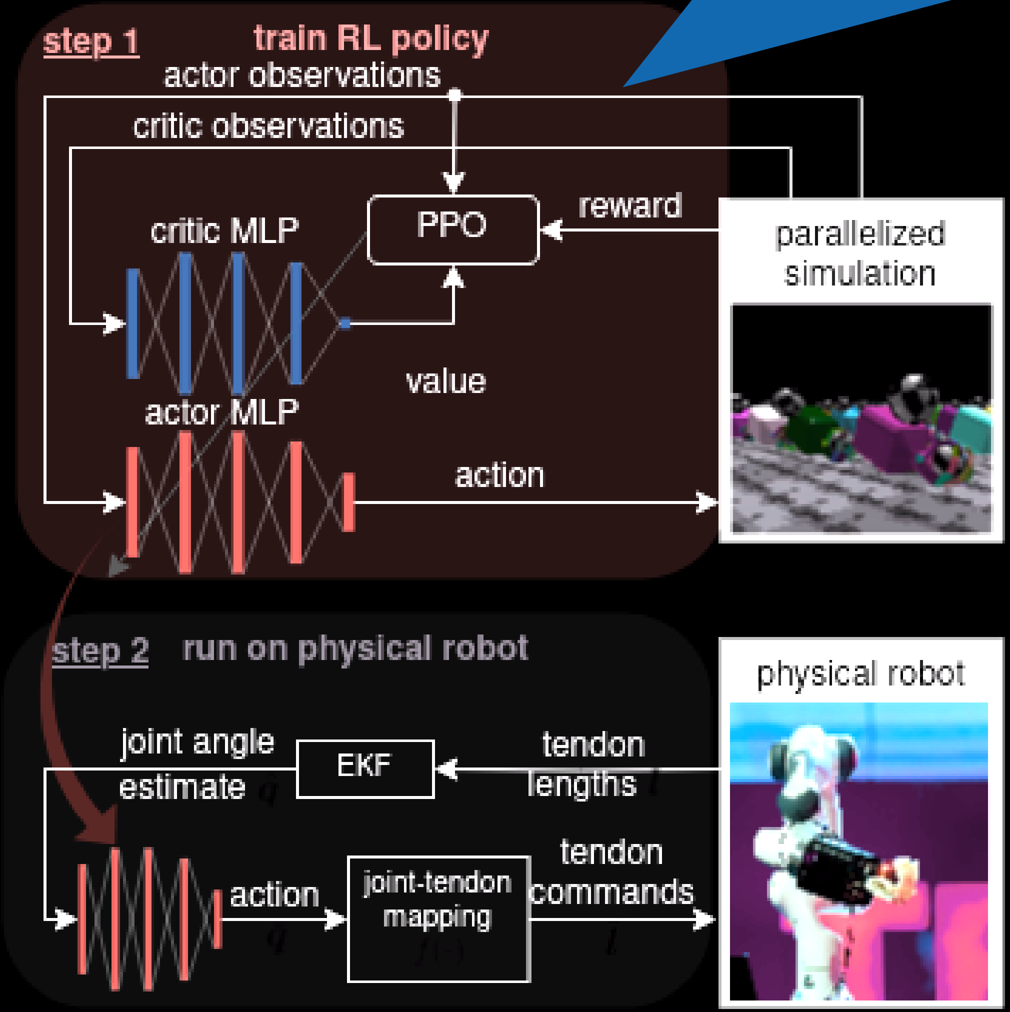
1. OpenAI, Marcin Andrychowicz, Bowen Baker, Maciek Chociej, Rafal Jozefowicz, Bob McGrew, Jakub Pachocki, et al. 2018. "Learning Dexterous In-Hand Manipulation." *arXiv [cs.LG]*. arXiv. http://arxiv.org/abs/1808.00177
2. Makoviychuk, Viktor, Lukasz Wawrzyniak, Yunrong Guo, Michelle Lu, Kier Storey, Miles Macklin, David Hoeller, et al. 2021. "Isaac Gym: High Performance GPU Based Physics Simulation For Robot Learning." *Https://openreview.net › Forumhttps://openreview.net › Forum*. https://openreview.net/pdf?id=fgFBtYgJQX_.
3. Rudin, Nikita, David Hoeller, Philipp Reist, and Marco Hutter. 2021. "Learning to Walk in Minutes Using Massively Parallel Deep Reinforcement Learning." *Https://openreview.net › Forumhttps://openreview.net › Forum*. https://openreview.net/pdf?id=wK2fDDJ5VcF.

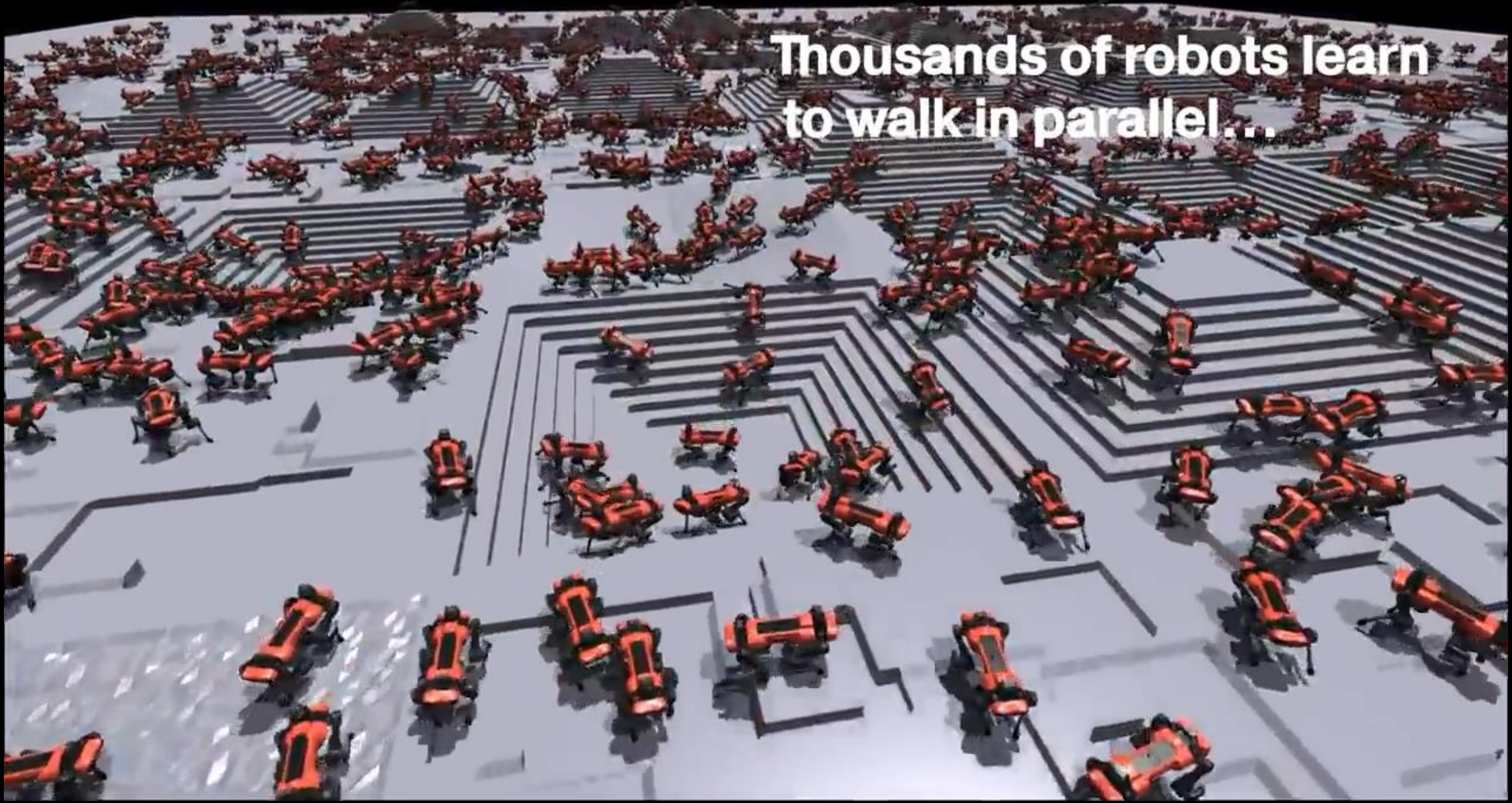
Sim2real framework for dexterous manipulation

1 hour of training time ≒ 2 months of real-time simulation



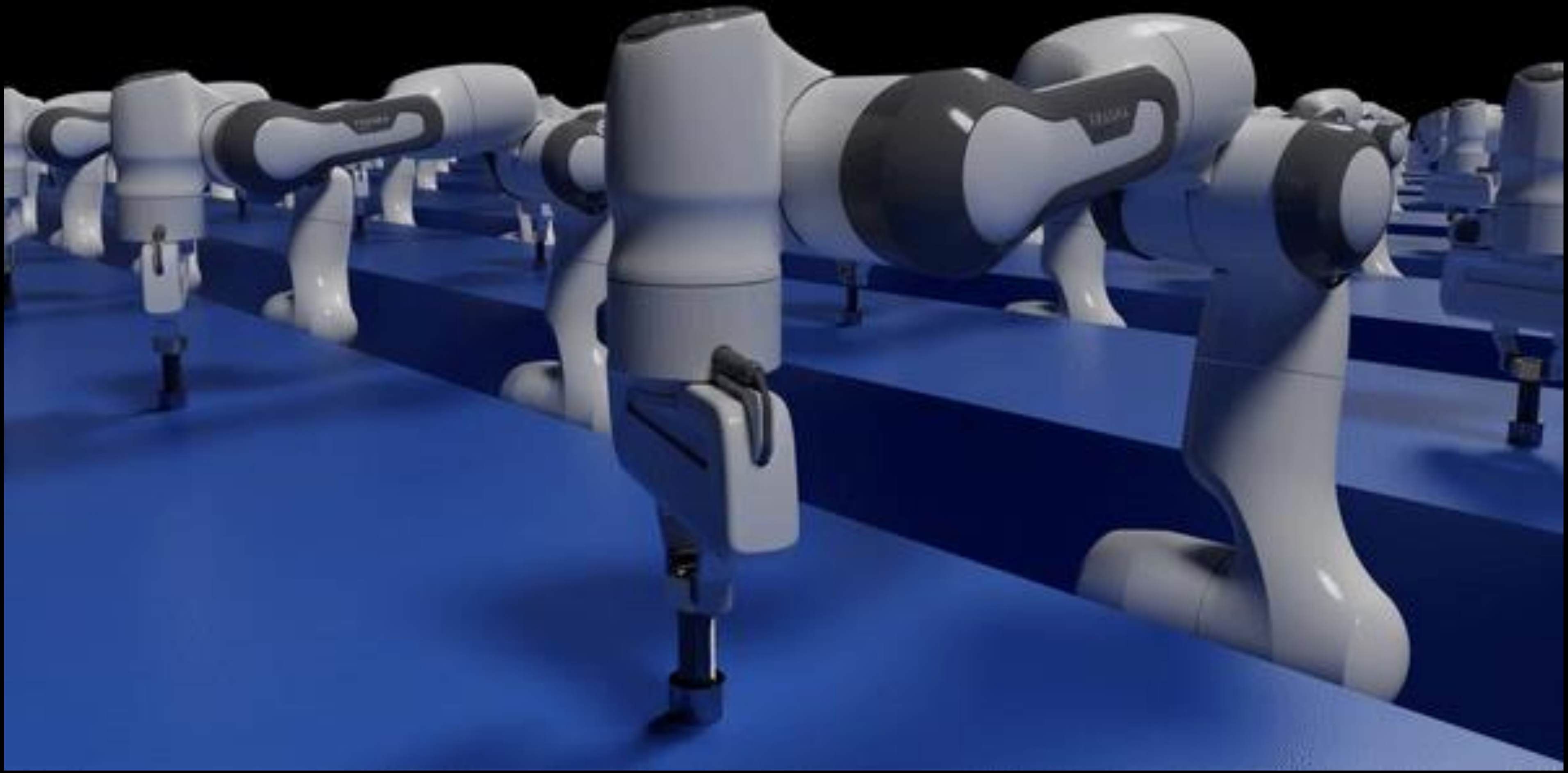


Massively parallel RL in different domains of robotics



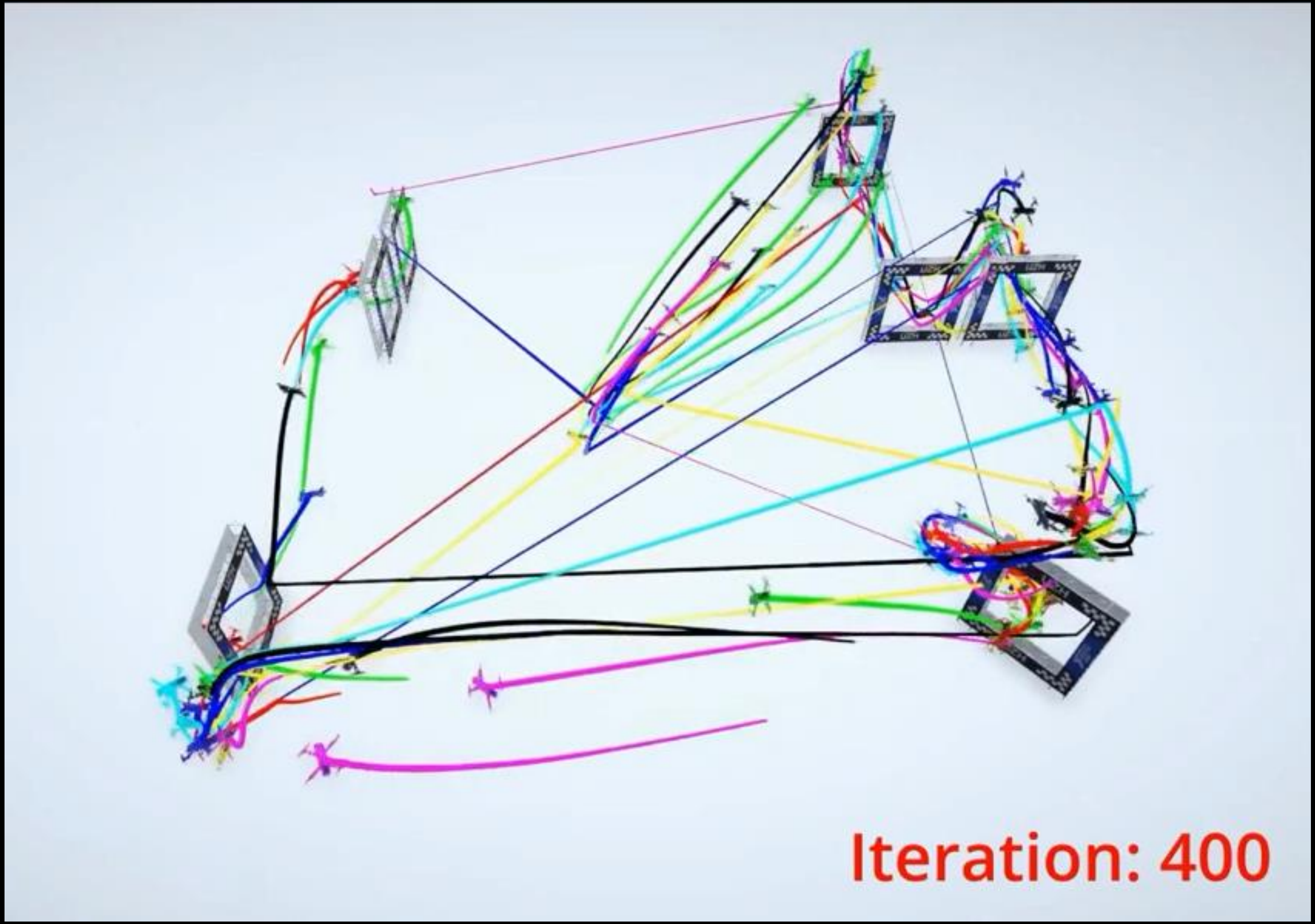
Nikita Rudin, David Hoeller, Philipp Reist, Marco Hutter: Learning to Walk in Minutes Using Massively Parallel Deep Reinforcement Learning

Massively parallel RL in different domains of robotics



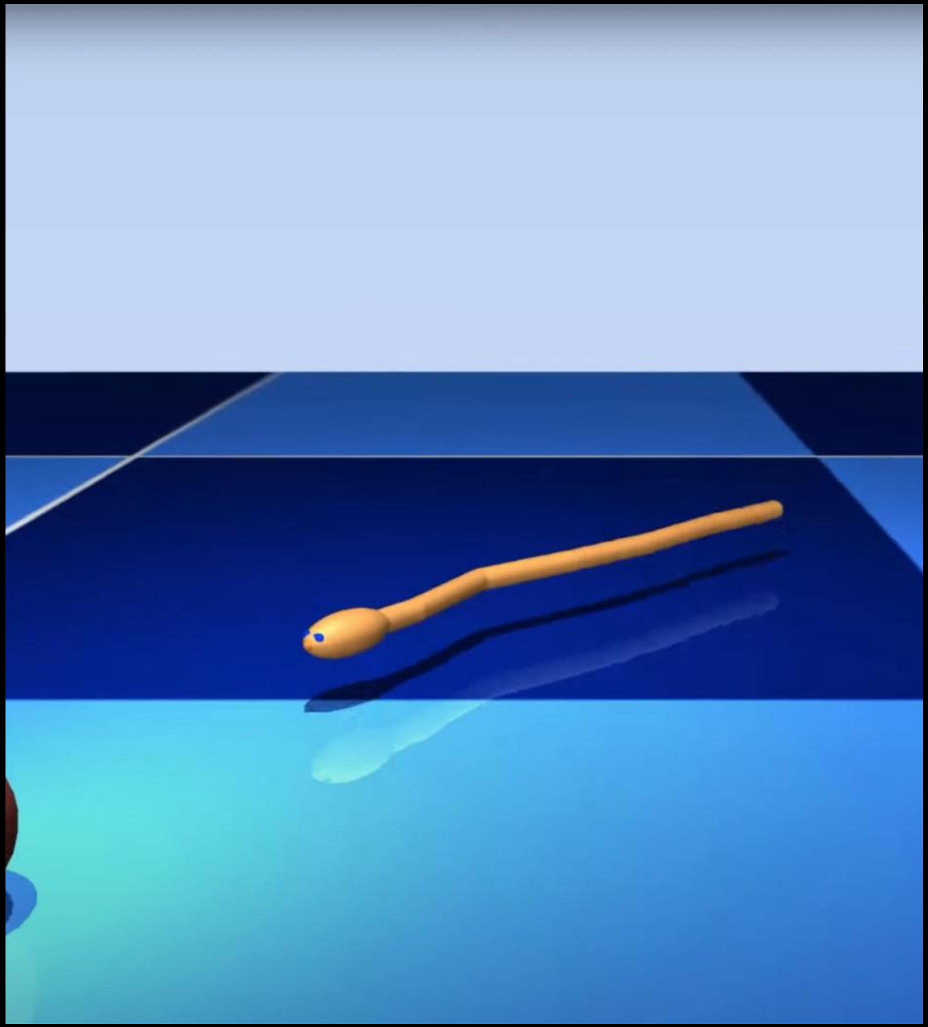
Advancing Robotic Assembly with a Novel Simulation Approach Using NVIDIA Isaac: Technical Blog

Massively parallel RL in different domains of robotics



Nico Messikommer, Yunlong Song, Davide Scaramuzza: Contrastive Initial State Buffer for Reinforcement Learning

Run model predictive control ***on*** the simulated MuJoCo model



MPC: model predictive control

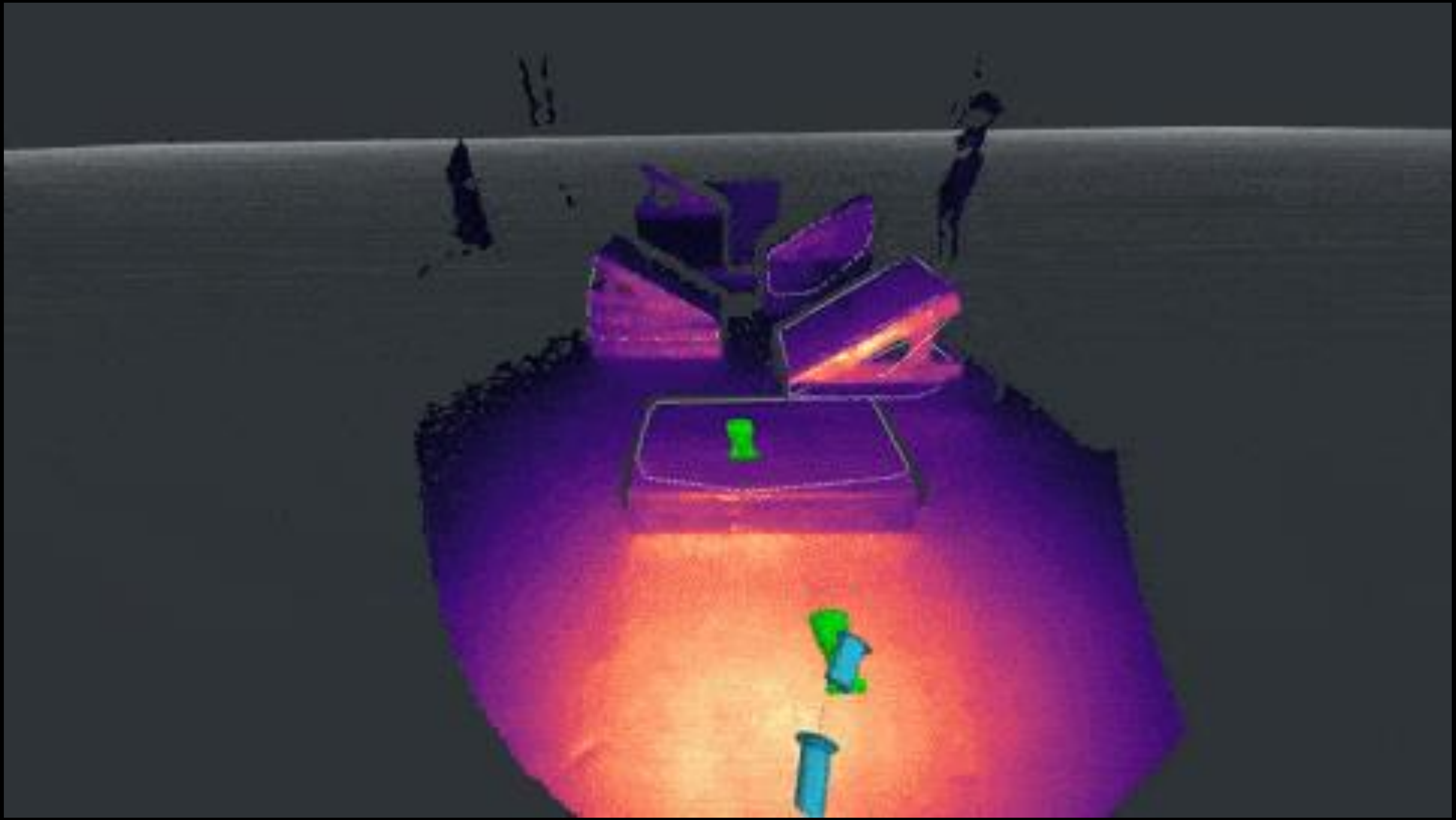
- define a cost function to minimize, encoding the desired task
- iteratively apply optimization at every step to find the “best” control inputs

MuJoCo-MPC uses the MuJoCo simulation as the ***model*** in the MPC
→ efficient and accurate model-based control

https://github.com/google-deepmind/mujoco_mpc

Howell, Taylor, Nimrod Gileadi, Saran Tunyasuvunakool, Kevin Zakka, Tom Erez, and Yuval Tassa. 2022. “Predictive Sampling: Real-Time Behaviour Synthesis with MuJoCo.” *arXiv [Cs.RO]*. arXiv. http://arxiv.org/abs/2212.00541.

Online Rigid Body Sim for BD Atlas' MPC



Flipping the Script with Atlas: Technical Blog key idea when simulating robots:

simplification

Why simplify?

Efficiency

trade off some accuracy for speed

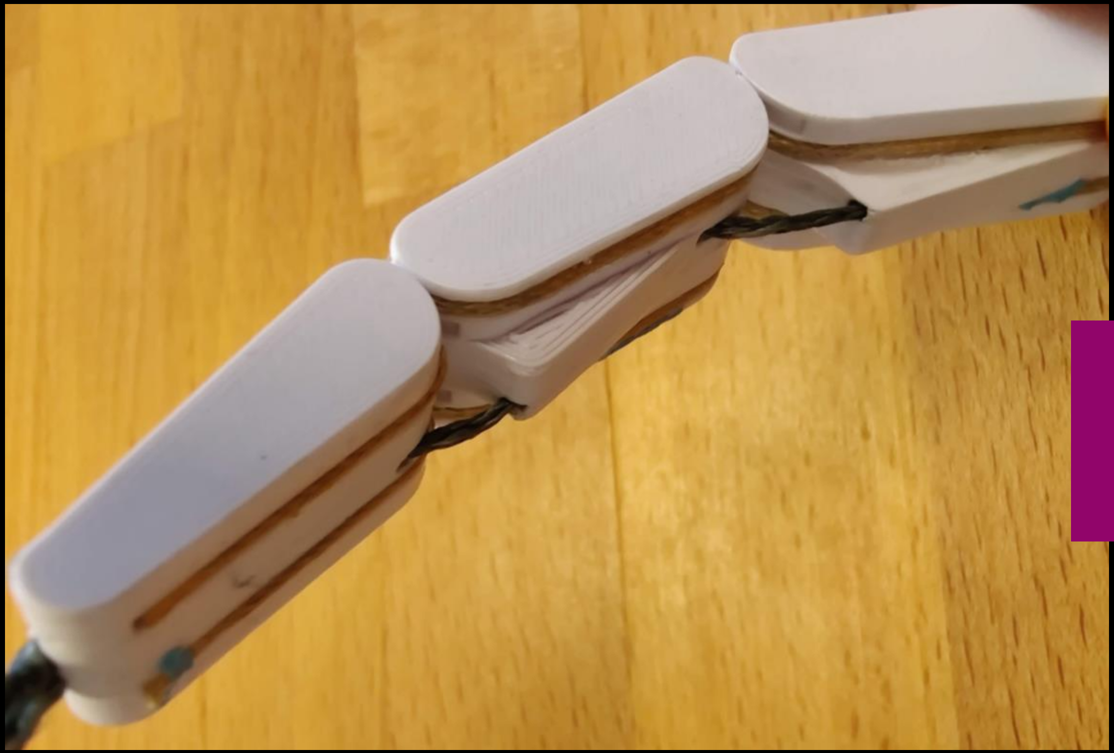
For example…
RL→ efficient simulation enables faster training
MPC→ faster exploration enables higher control frequency, longer control horizon

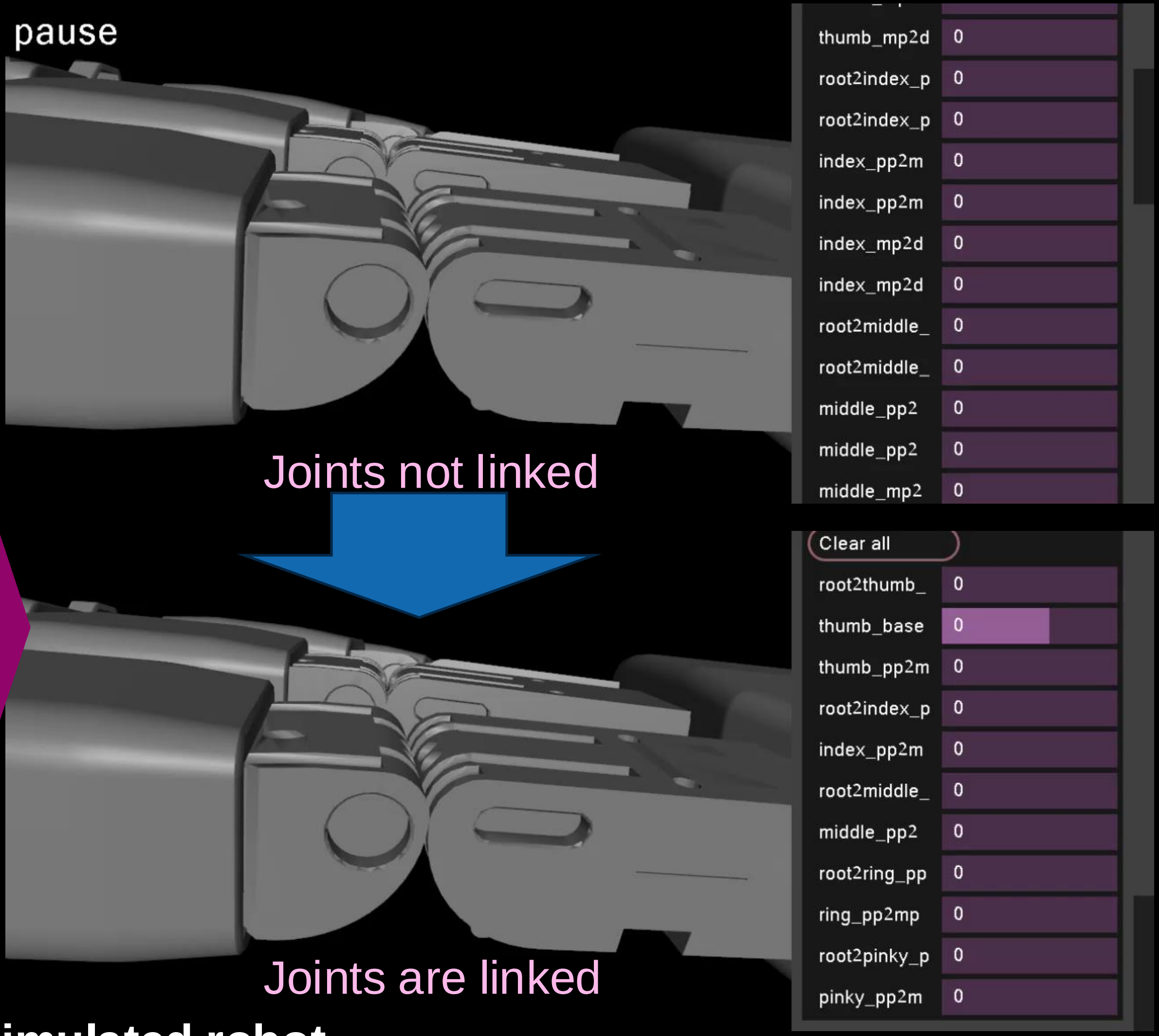
Modularity

If the real robot has a good low-level controller, the simulator can use high-level control inputs

For example…
The tendons of the Faive Hand are not (currently) replicated in the simulated model, and it accepts joint-level commands which are easier to learn

Simplification example #1:
rolling contact joints





Real robot

Contact between cylindrical surfaces

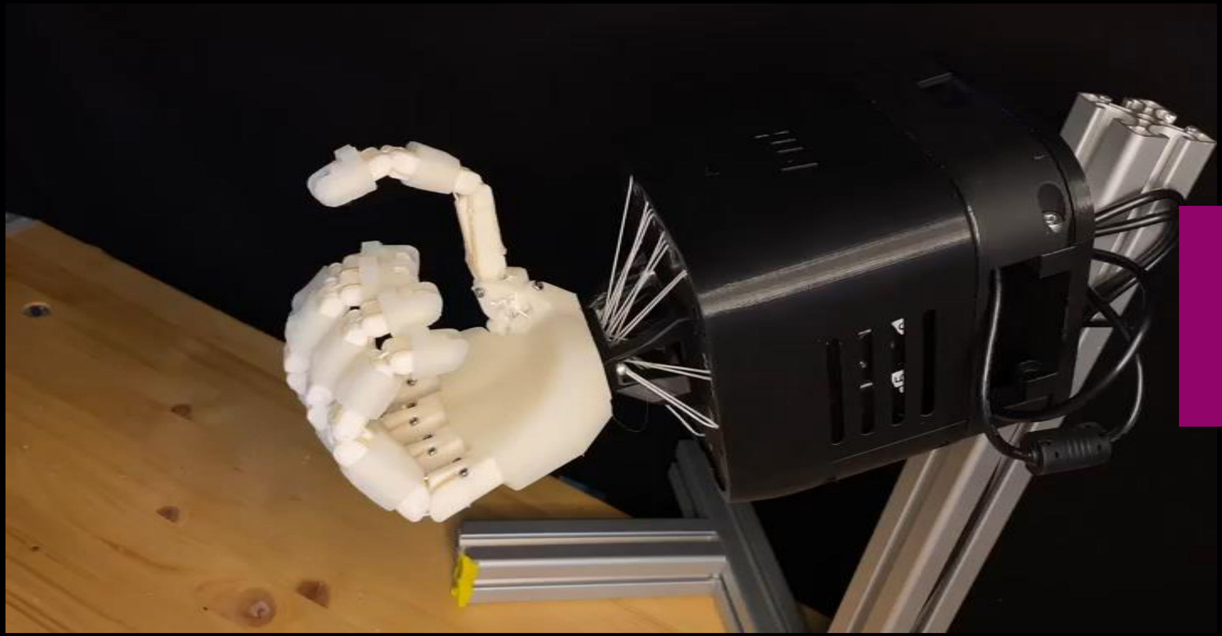
Ligaments ensure that they don't slide or move apart

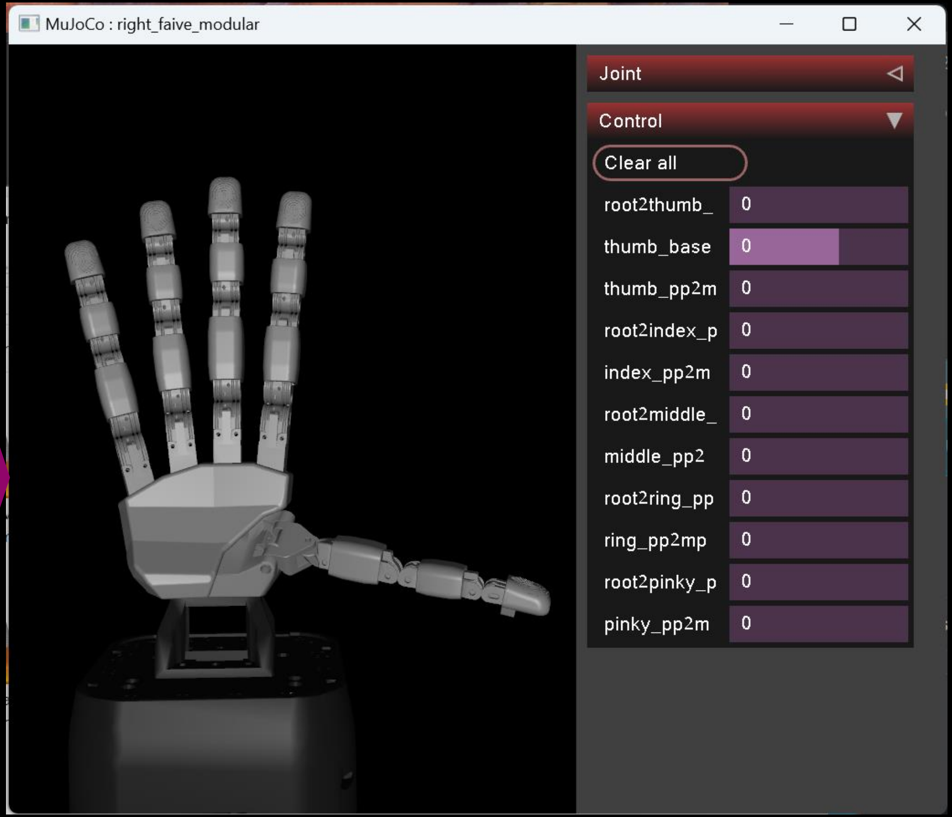
Simulated robot

Two hinge joints make up a single rolling contact joint

Constrained to roll together when the joint is actuated

Simplification example #2: tendon-driven actuation





Real robot

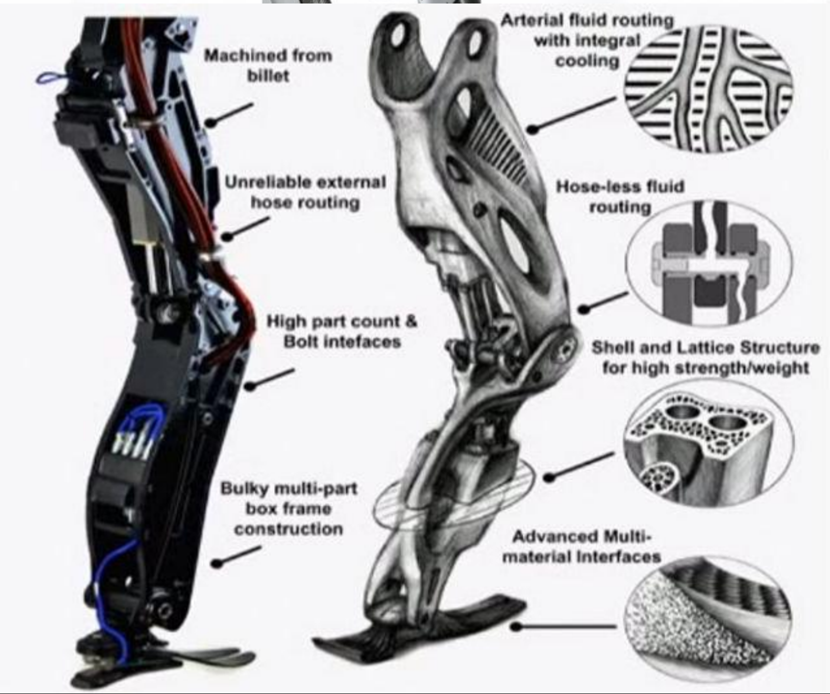
16 servo motors drive the tendons to actuate the hand

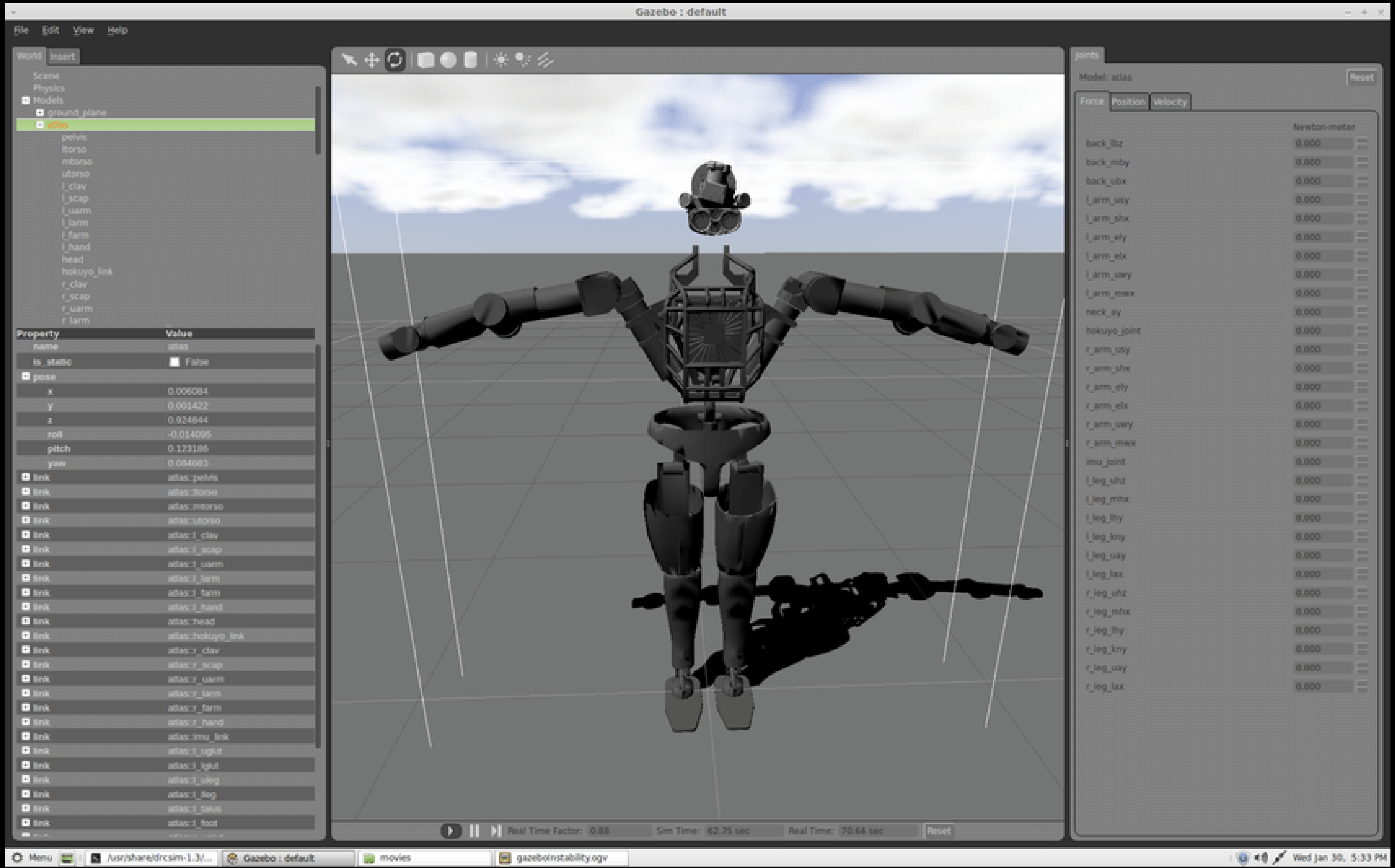
Low-level controller can convert joint angles to tendon lengths / servo motor angles

Simulated robot

Musculoskeletal tendons are ignored, and the robot is modelled purely as a 11-DoF joint axis-driven robot

Another example: Hydraulic actuators of the Atlas robot





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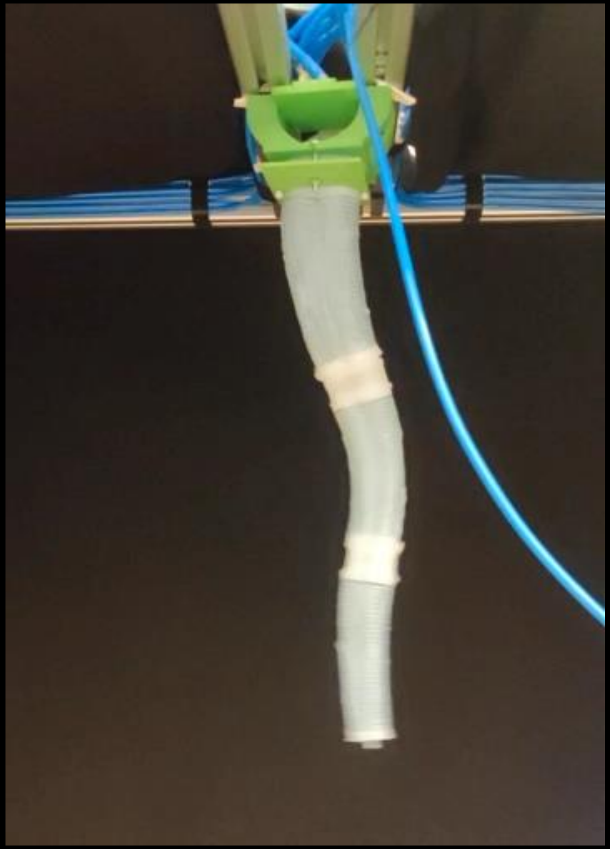
How to model completely soft robots?



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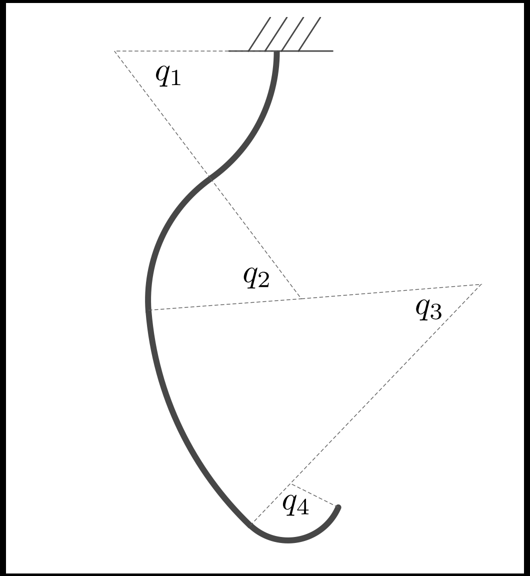
How to model completely soft robots?

FEM (finite element method)

Discretize into a mesh and compute the forces between nodes, based on an elasticity model

Minimal Parameter Modeling

Approximate into a model based on simplifying assumptions, such as piecewise constant curvature



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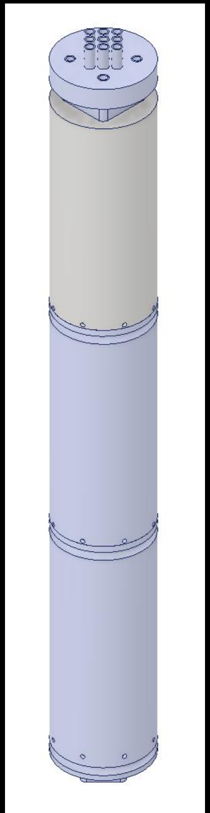
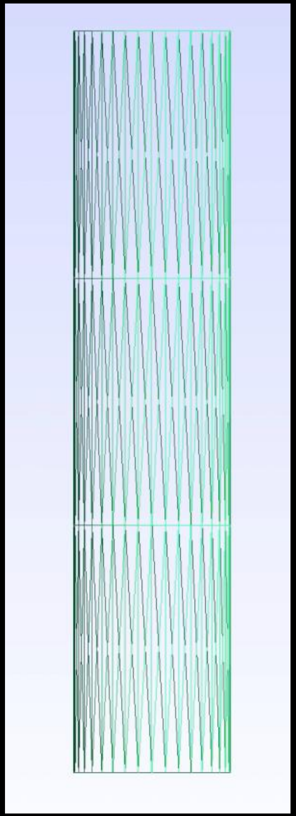
Finite Element Method:
Preparing the surface and volumetric meshes



CAD file

Any CAD software →

STL



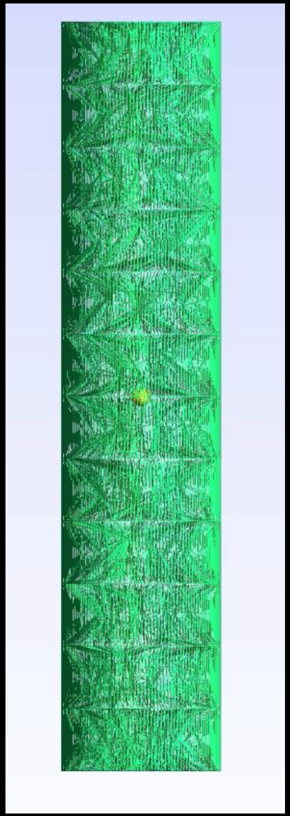
Surface Mesh

Gmsh or CGAL →

Gmsh: finite-element mesh generator

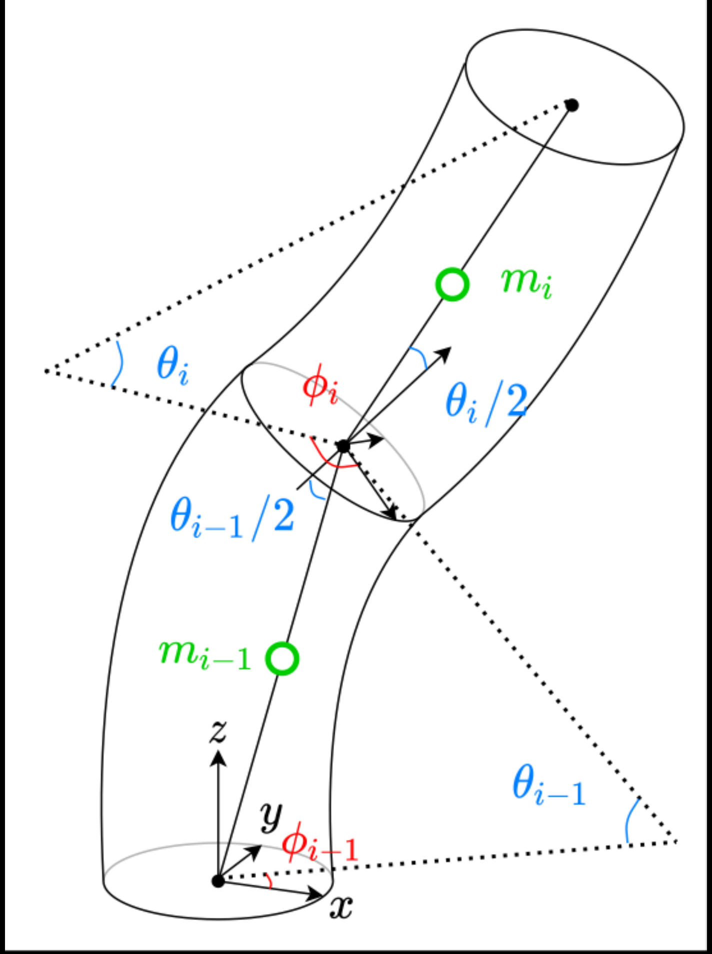
CGAL: Computational Geometry Algorithms C++ Library

VTK



Volumetric Mesh

Piecewise Constant Curvature (PCC) model

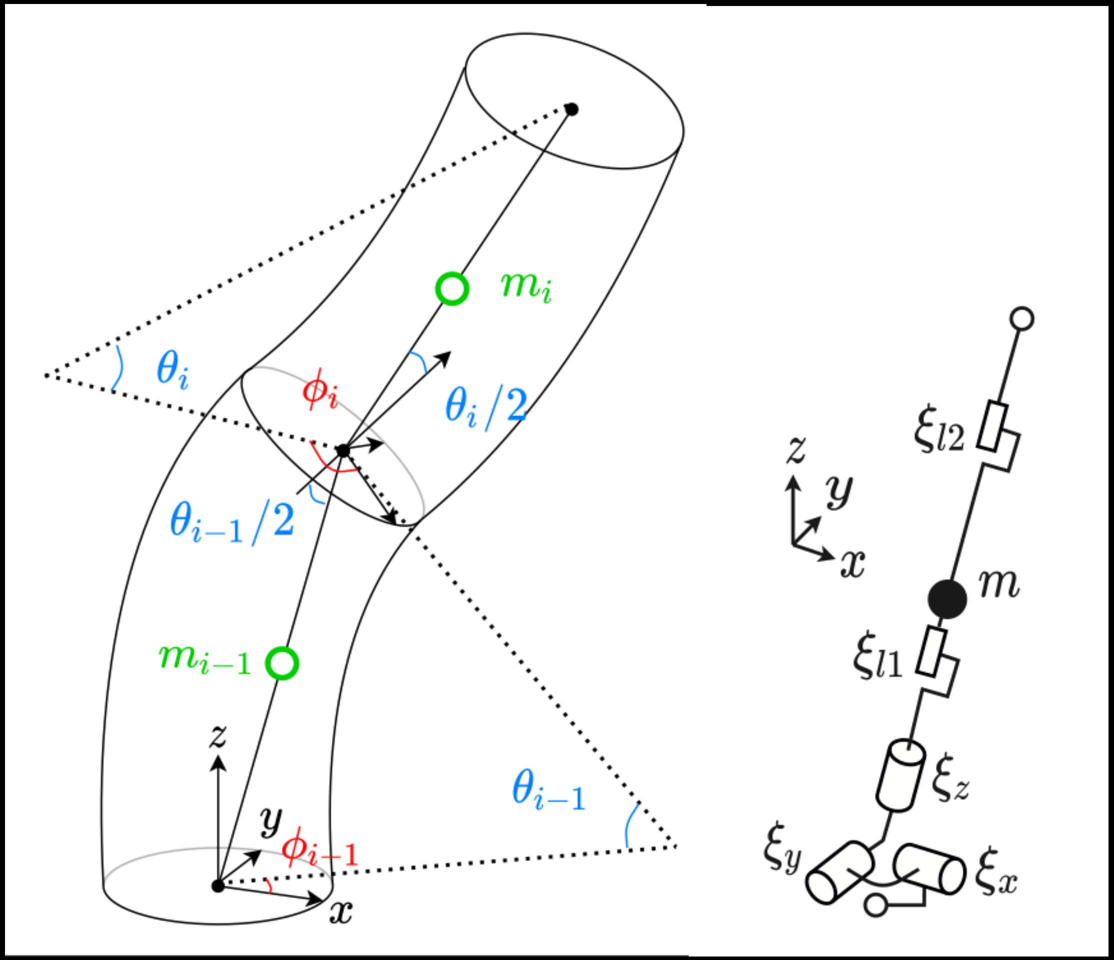


- assumes constant curvature within a PCC element
- PCC state can be described with 2 parameters
  - often used is ϕ (plane of bending) and θ (bending angle)
- by serially connecting PCC elements, continuous curvature can be described

Webster, Robert J., and Bryan A. Jones. 2010. "Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review." *The International Journal of Robotics Research* 29 (13): 1661–83.

Toshimitsu, Y., Wong, K.W., Buchner, T. and Katzschmann, R., 2021, January. SoPrA: Fabrication & dynamical modeling of a scalable soft continuum robotic arm with integrated proprioceptive sensing. In 2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 653-660). IEEE.

Augmented Rigid Link counterpart of a PCC model



Dynamics can be computed from a PCC model by introducing a rigid arm model

- kinematically match PCC element
  - pose transform between base & tip
- dynamically approximate PCC element
  - mass is located at center of link

Webster, Robert J., and Bryan A. Jones. 2010. “Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review.” *The International Journal of Robotics Research* 29 (13): 1661–83.

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Summary

Simulate and fail often to simplify later real-world experiments

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Summary of why simulators are needed

***Safe* and *fast* environment for testing robot controllers**

Parallelized simulation for reinforcement learning (RL)

Model-based control based on simulators