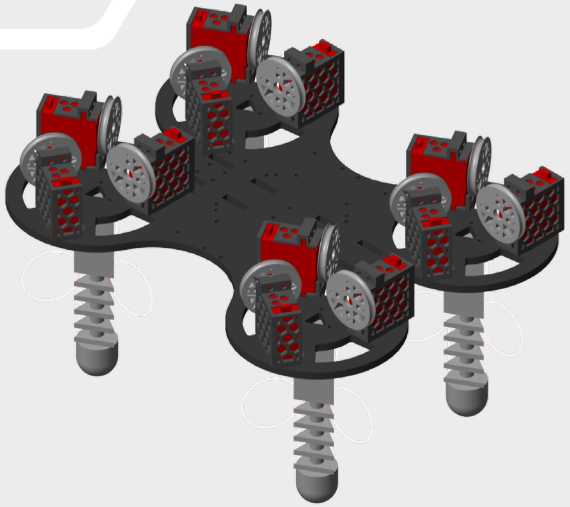
Modeling, Simulation, and Control of a Soft Quadruped Robot



Qinglei Ji *(PhD)*

Solution Engineer – Controls & AI

Volvo Cars Cooperation, Gothenburg

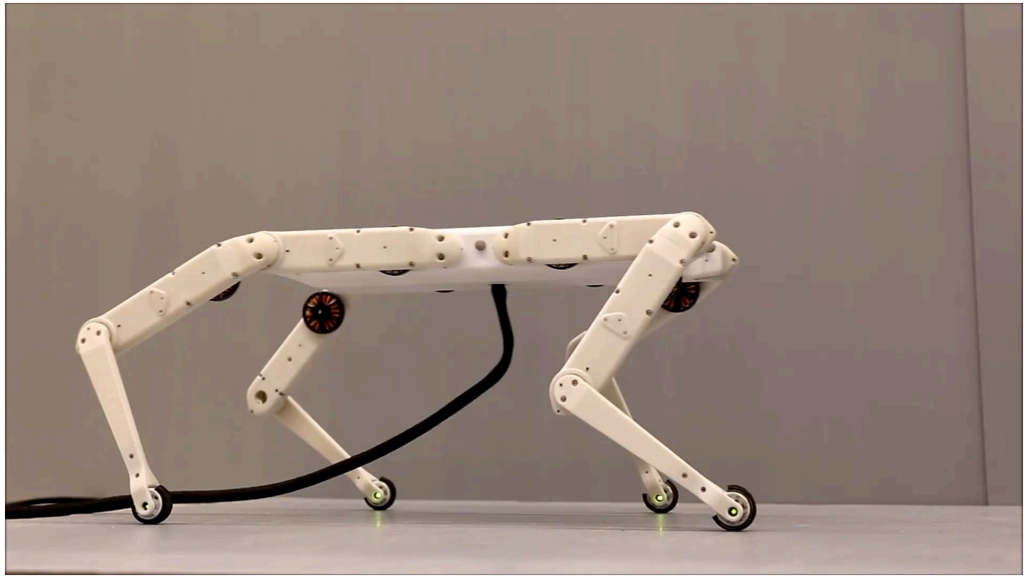
2024/10/20

The research in this presentation is performed at KTH Royal Institute of Technology, Sweden.

Quadruped Robots

Enhanced mobility and adaptability to complex environment

Spot, Boston Dynamics



3D printed Robot

https://www.youtube.com/watch?v=wlkCQXHEgjA
https://3dprint.com/270090/open-source-quadruped-robot-with-3d-printed-components/

Soft Quadruped Robots

Systems built from highly compliant materials to provide flexibility and adaptability to the workspace.

- Continuous movements
- Smooth motions
- Safe interactions
- Need for fast, precise and light-weight actuators

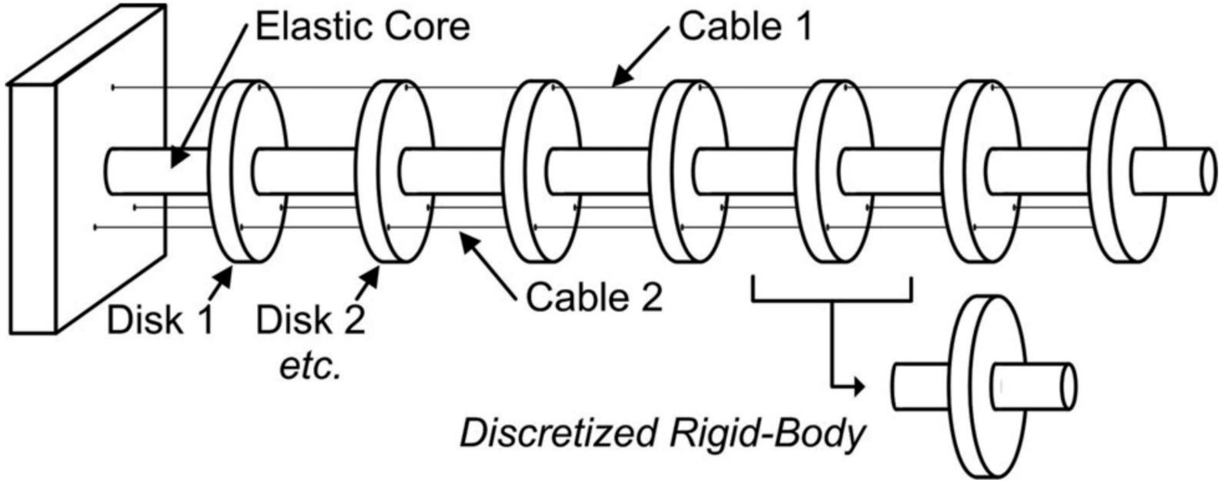
Multi-gait robot

3D printed Soft Robot

Shepherd et al.,."Multigait soft robot." Proceedings of the national academy of sciences 108, no. 51 (2011): 20400-20403.
Ishida at al., "Morphing structure for changing hydrodynamic characteristics of a soft underwater walking robot." IEEE Robotics and Automation Letters 4, no. 4 (2019): 4163-4169.

Tendon-driven Continuum Actuator

Combines fast response and compliance



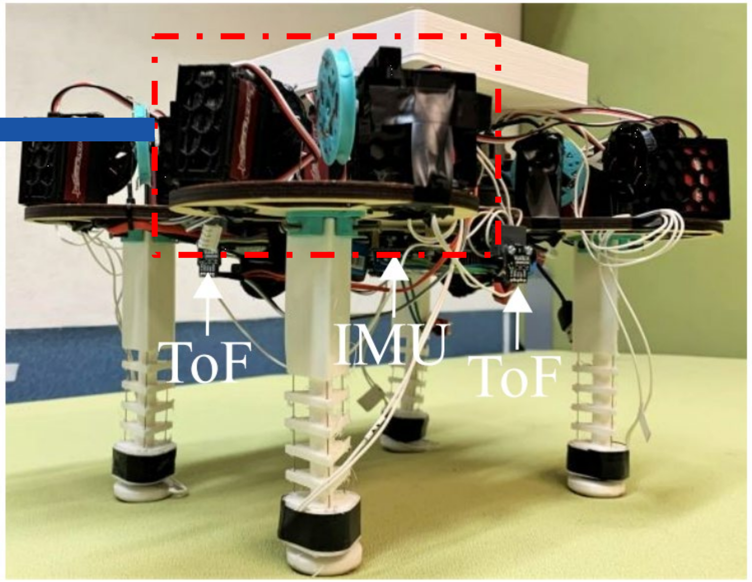
Rone, William S., and Pinhas Ben-Tzvi. "Mechanics modeling of multisegment rod-driven continuum robots." Journal of Mechanisms and Robotics 6, no. 4 (2014): 041006.

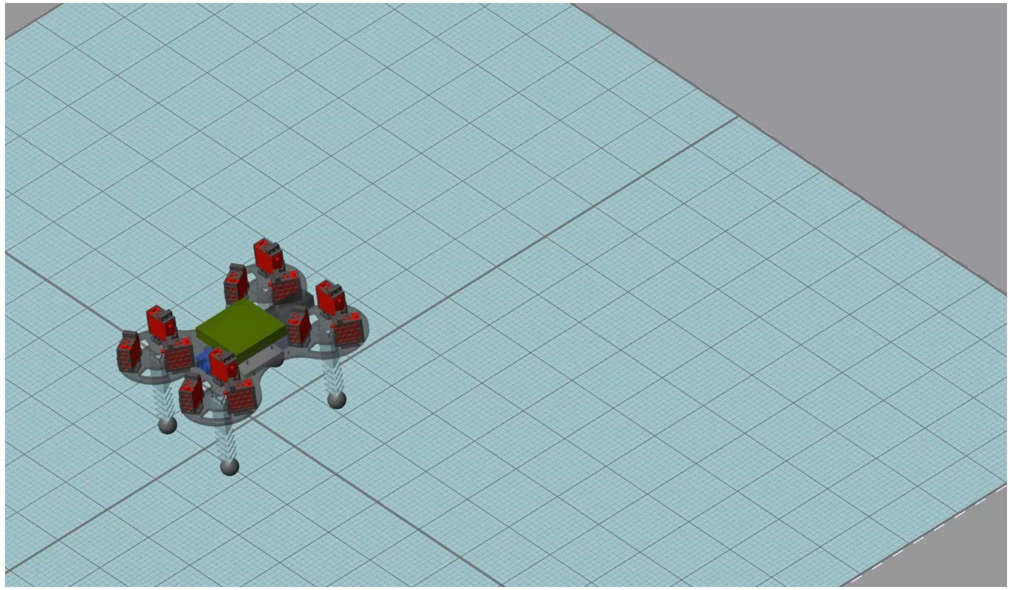
Soft Quadruped Robot at KTH

Quadruped robot enabled by tendon-driven soft actuators

- Complex to model and control
- Slow simulation

Each leg actuated by three pully-driven actuators with cables

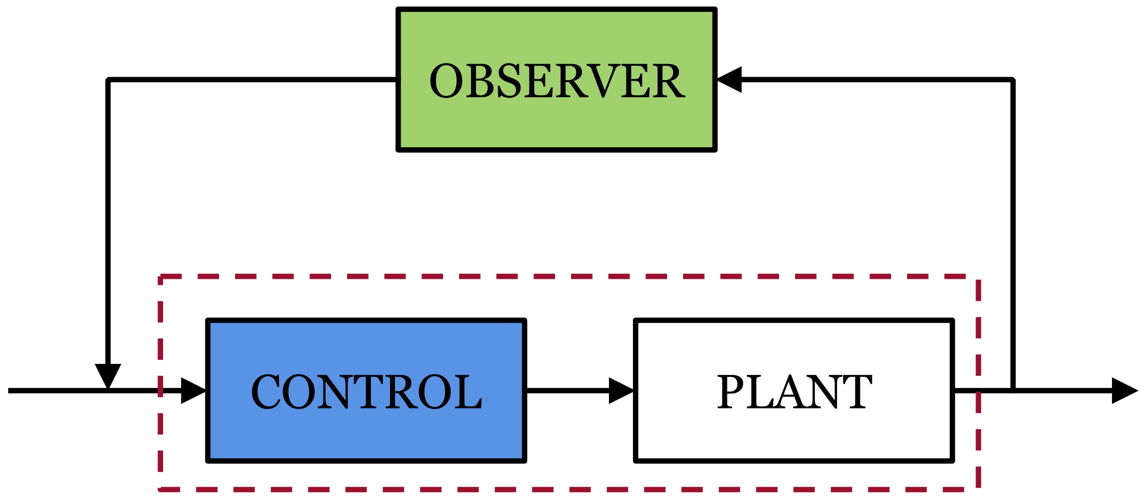




Muralidharan ST, Zhu R, Ji Q, Feng L, Wang XV, Wang L. A soft quadruped robot enabled by continuum actuators. In2021 IEEE 17th International Conference on Automation Science and Engineering (CASE) 2021 Aug 23 (pp. 834-840). IEEE.

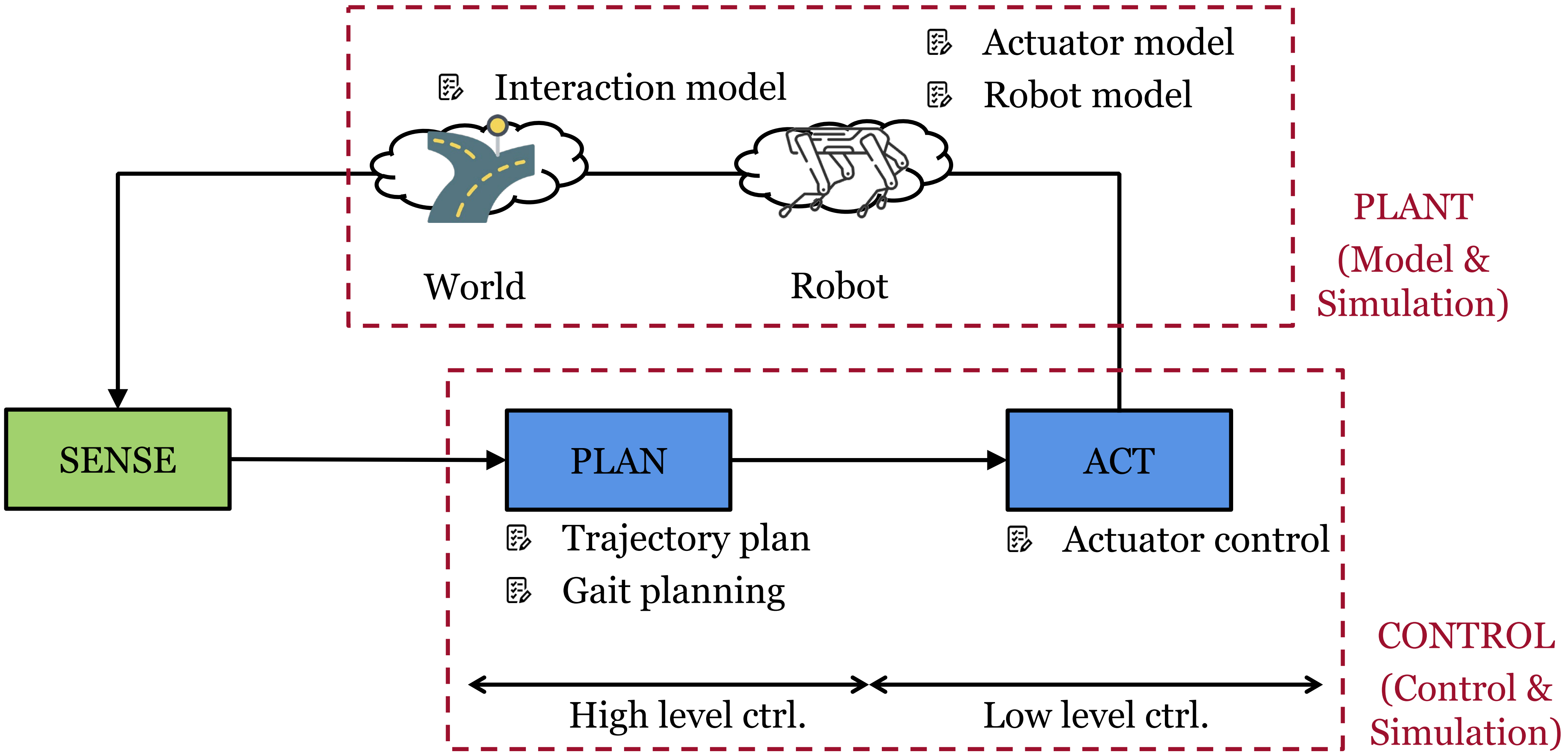
Control Architecture

- Control: Mechanism or algorithm for ensuring the system behaves in a desired manner.
- Plant: System or process being controlled (mechanical, electrical, biological or economic systems, etc.).
- Observer: Measure or estimate the internal state of the plant.



Typical feedback architecture in controls engineering.

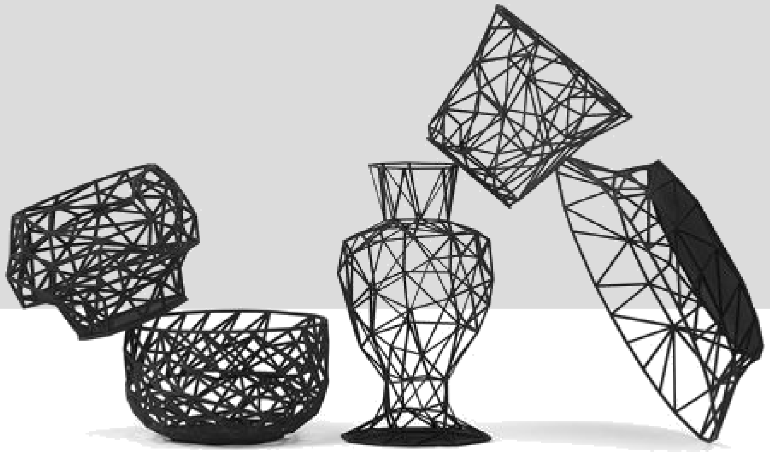
Control Architecture



Sense-Plan-Act architecture in robotic and autonomous driving systems.

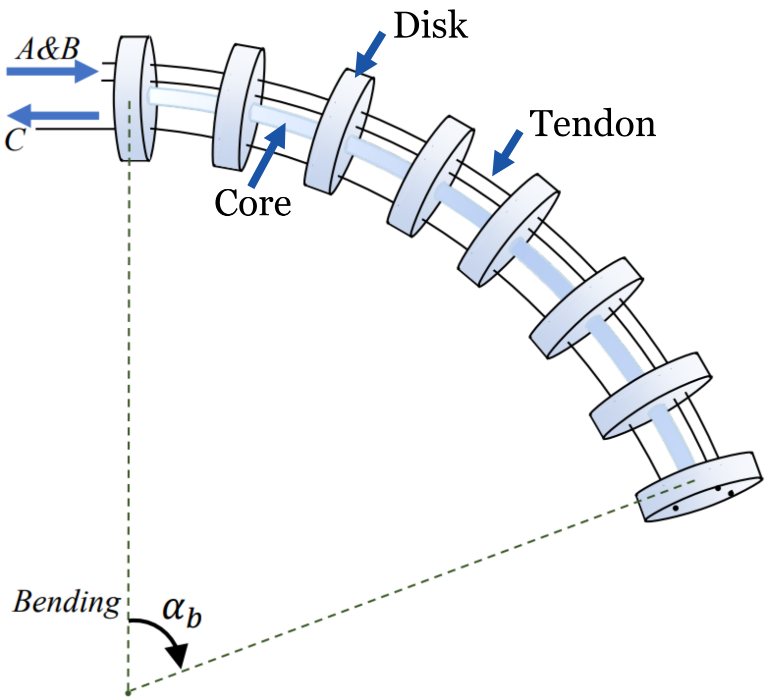
Outline

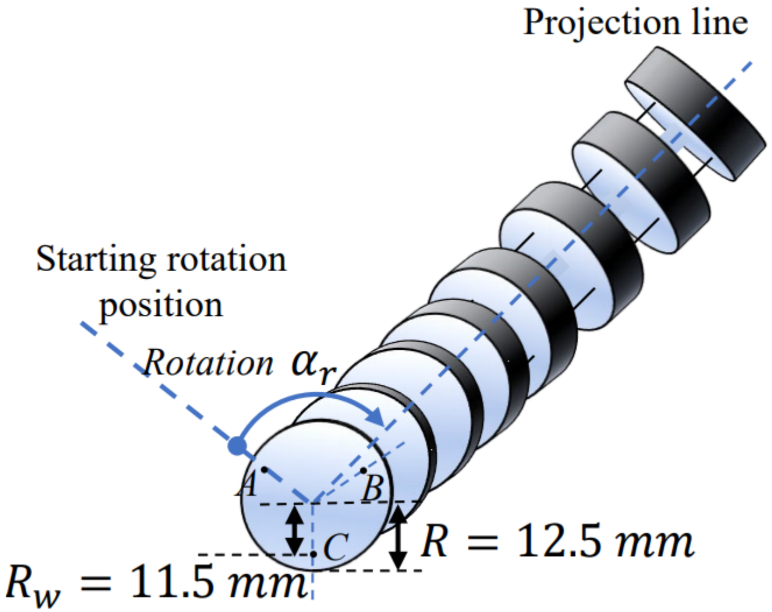
- ✔ Background
- ✔ Modeling
- ✔ Simulation
- ✔ Control
- ✔ Conclusion



Inverse Kinematics Model

Inverse kinematics model for an **incompressible** tendon-driven soft actuator





$$x_A = R_w \alpha_b \cdot \cos(\alpha_r)$$

$$x_B = R_w \alpha_b \cdot cos(\alpha_r + \frac{2}{3}\pi)$$

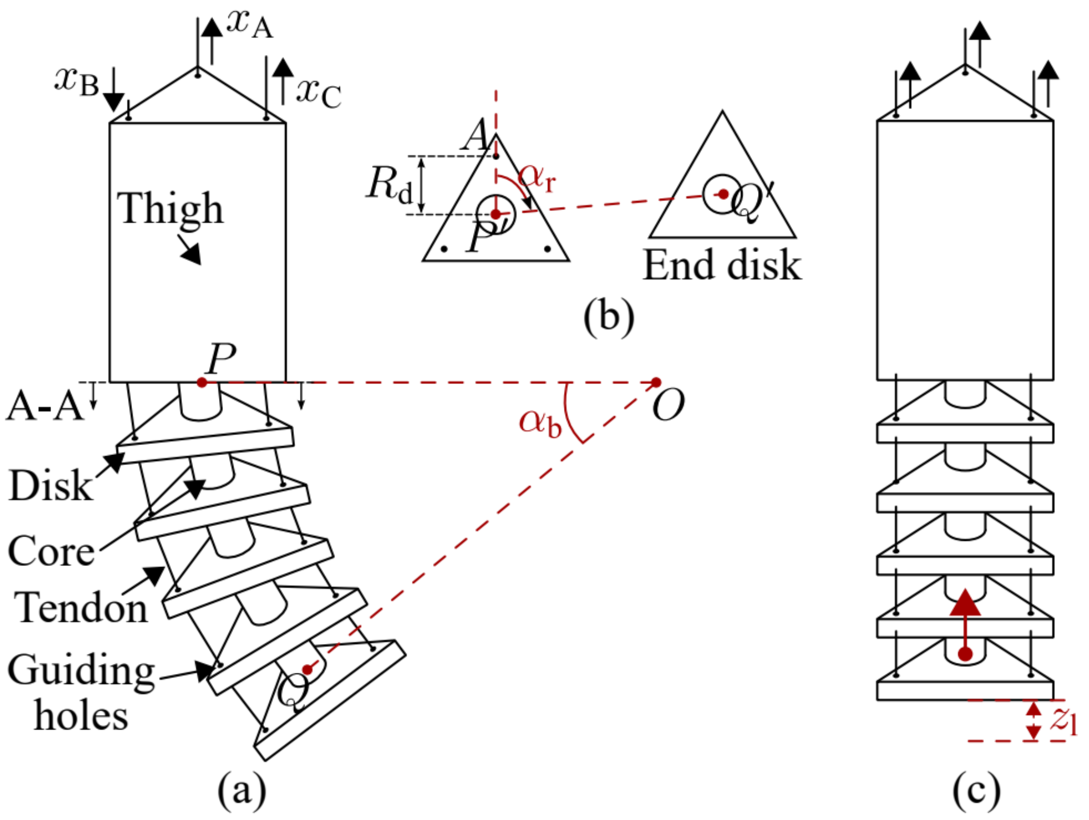
$$x_C = R_w \alpha_b \cdot cos(\alpha_r + \frac{4}{3}\pi)$$

Hsiao K, Mochiyama H. A wire-driven continuum manipulator model without assuming shape curvature constancy. In2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2017 Sep 24 (pp. 436-443). IEEE.

Muralidharan ST, Zhu R, Ji Q, Feng L, Wang XV, Wang L. A soft quadruped robot enabled by continuum actuators. In2021 IEEE 17th International Conference on Automation Science and Engineering (CASE) 2021 Aug 23 (pp. 834-840). IEEE.

Inverse Kinematics Model

Proposed model for a **compressible** tendon-driven soft actuator

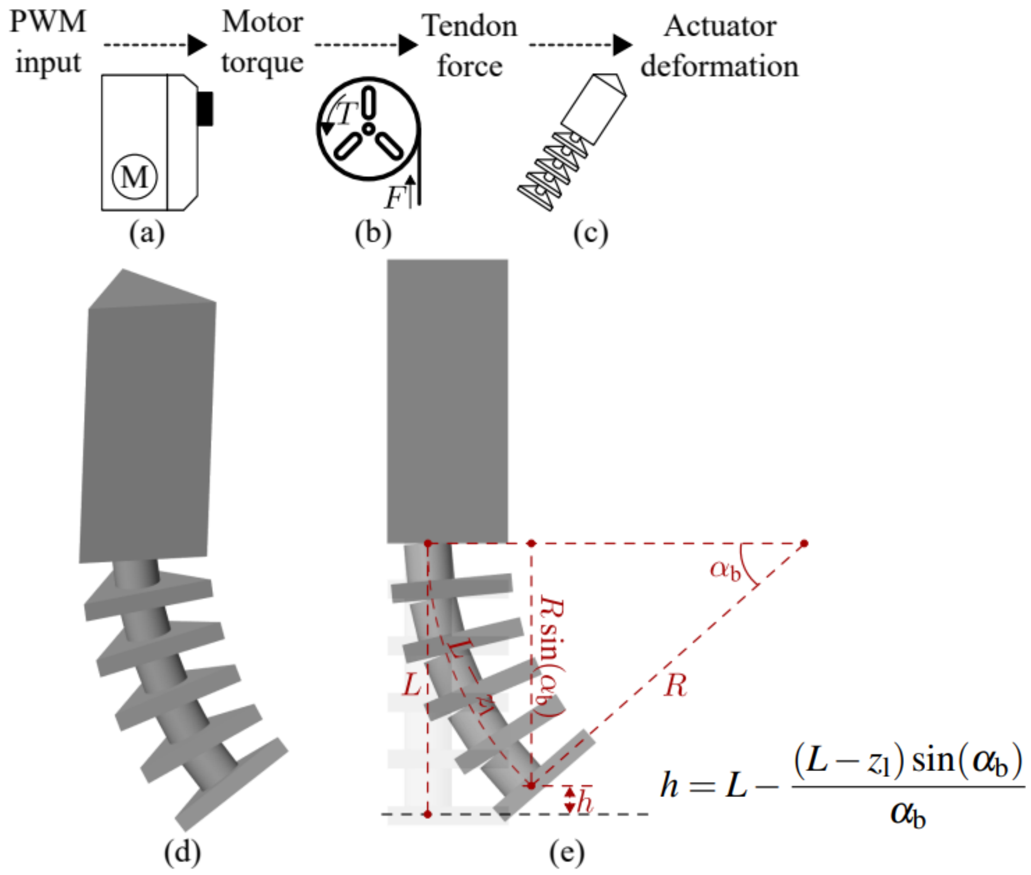


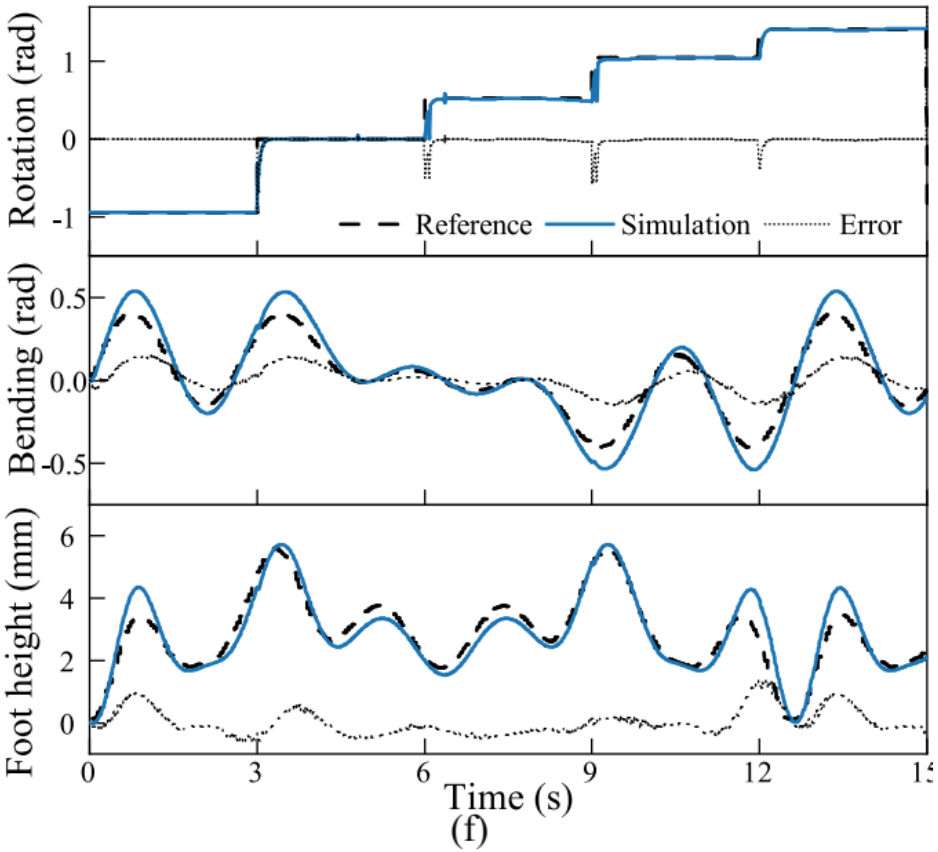
$$[x_A, x_B, x_C]^T = g\left(\begin{bmatrix}\alpha_b \\ \alpha_r \\ z_l\end{bmatrix}\right) = f\left(\begin{bmatrix}\alpha_b \\ \alpha_r\end{bmatrix}\right) + z_l \begin{bmatrix}1 \\ 1 \\ 1\end{bmatrix}$$

Ji, Qinglei, et al. "Omnidirectional walking of a quadruped robot enabled by compressible tendon-driven soft actuators." 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2022.

Inverse Kinematics Model

Model validation





Outline

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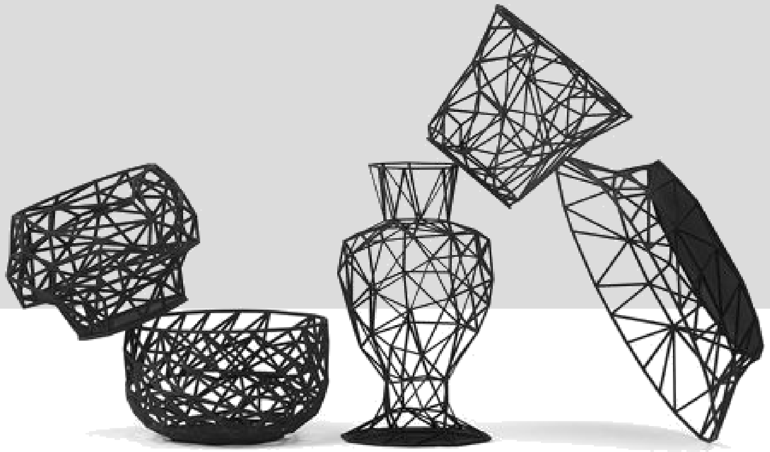
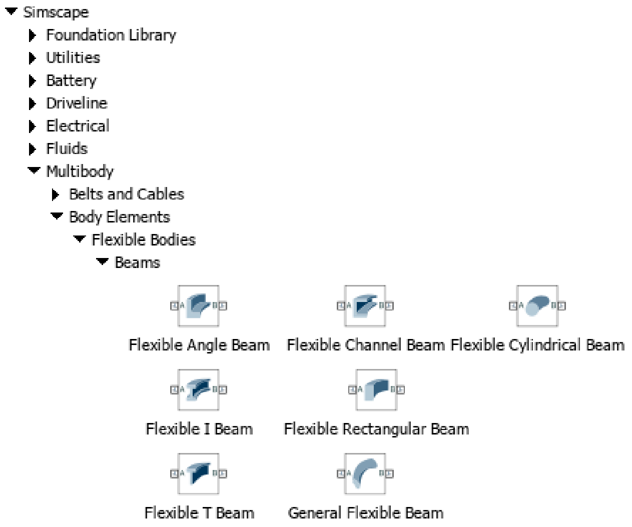
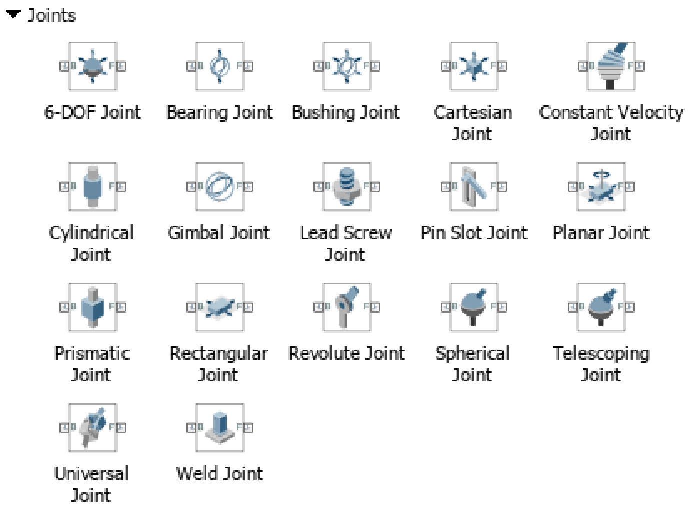
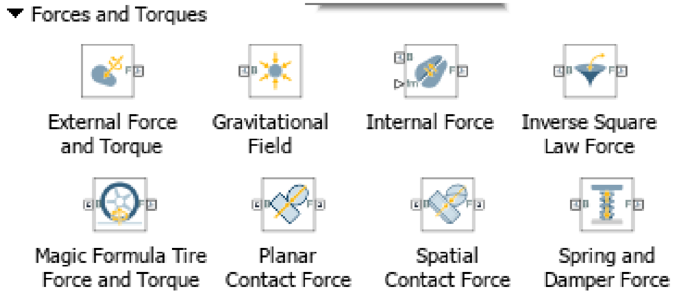


Simulation Environment

- Simscape Multibody toolbox in MATLAB Simulink (support for flexible/soft materials)
- Integrated modeling and simulation for machine learning, controller, and physical plant



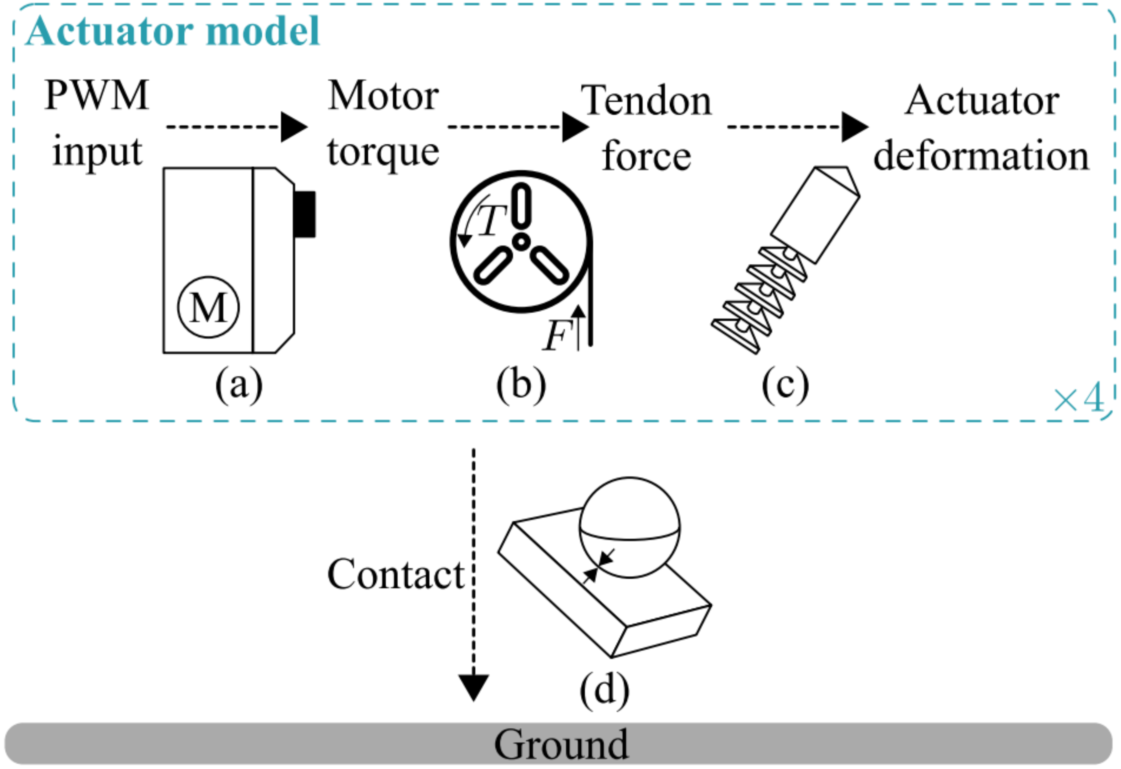




Complete body, joint, and force types for modeling soft robots.

https://se.mathworks.com/products/simscape-multibody.html

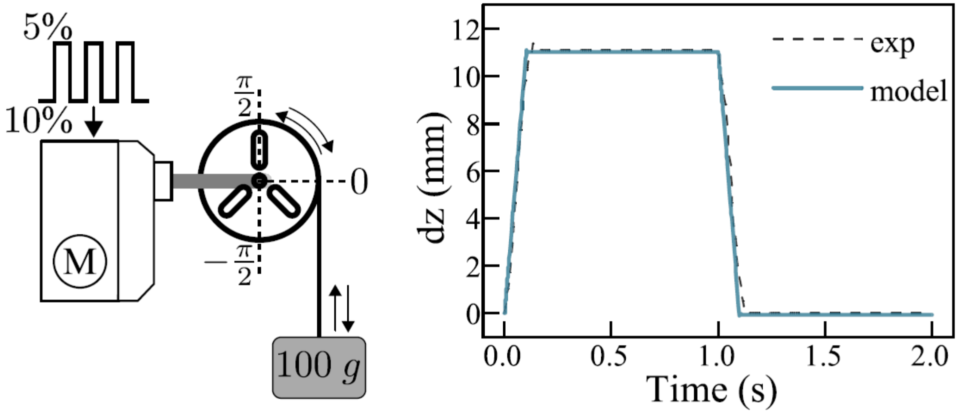
System Architecture



Overview of the quadruped robot's main subsystems.

Ji, Qinglei, et al. "Synthesizing the optimal gait of a quadruped robot with soft actuators using deep reinforcement learning." Robotics and Computer-Integrated Manufacturing 78 (2022): 102382.

Motor Parameter Characterization

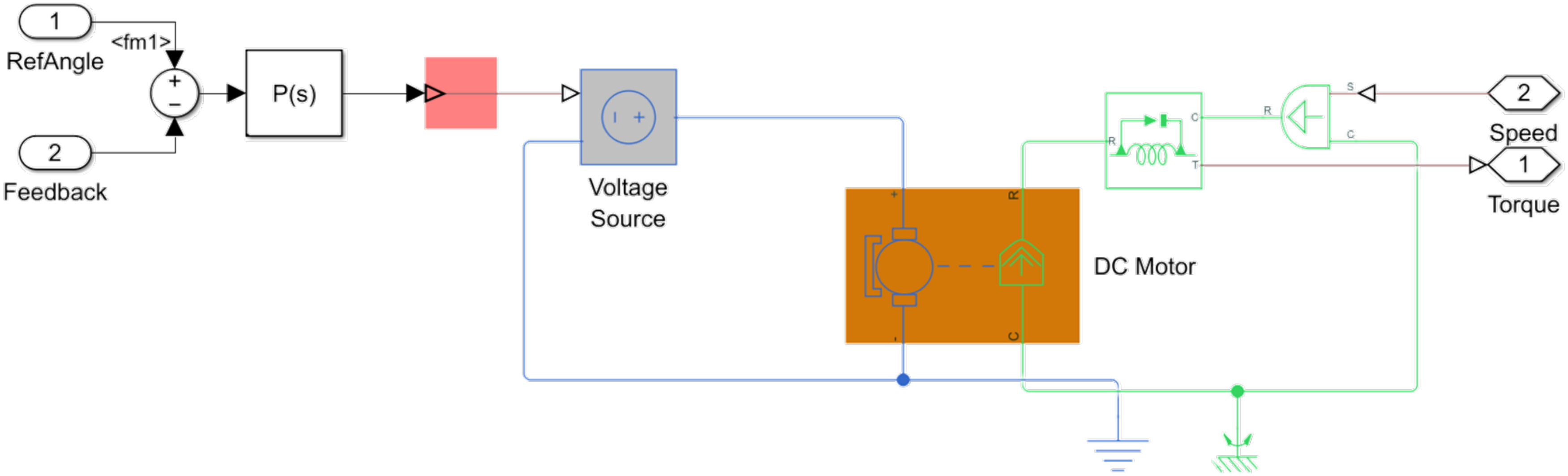


Identifying motor parameters with known load.

Table 1
Identified servo motor parameters.

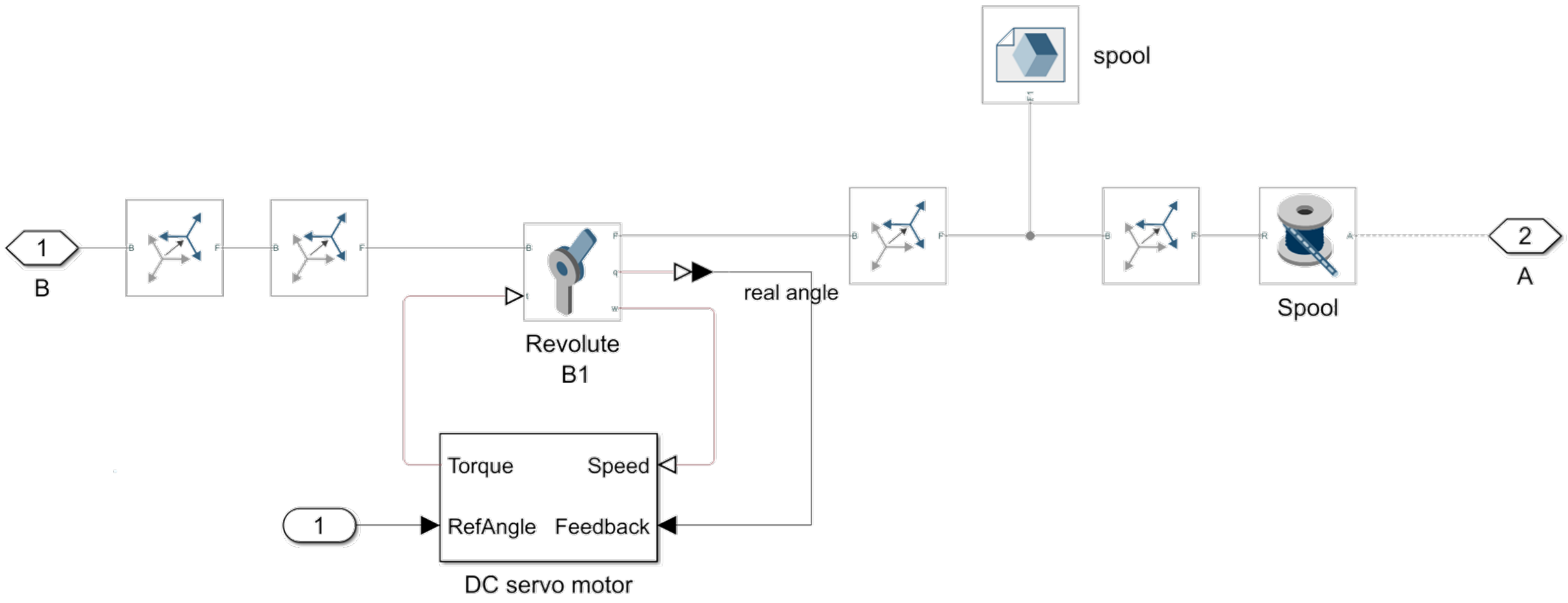
Parameters	Value
Stall torque (cm ∗ kg)	11.2
Time traveling 60° (s)	0.2
Nominal voltage (V)	6
Rotational range (rad)	$[-\pi/2, \pi/2]$

Motor Model



Servo motor with angle control.

Motor Model

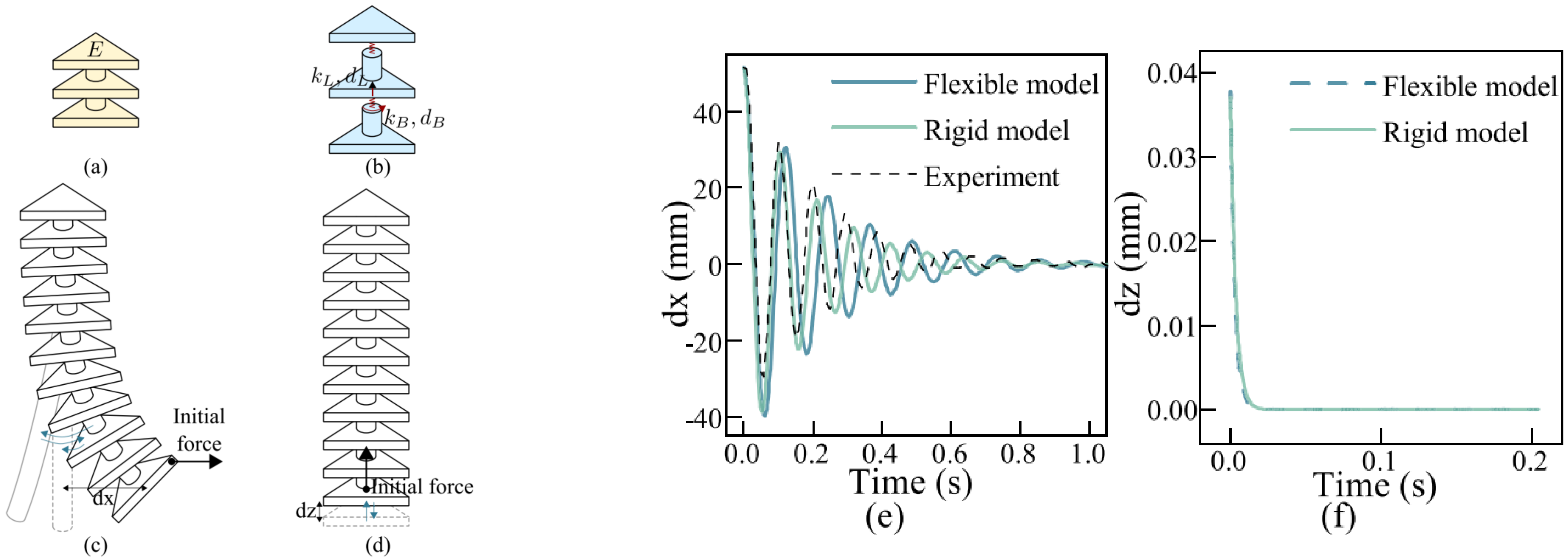


Connect to spool with force feedback.

Soft Material Model

Choices for modeling soft material

- Elastic material modelling
- Lumped parameter method with hard material

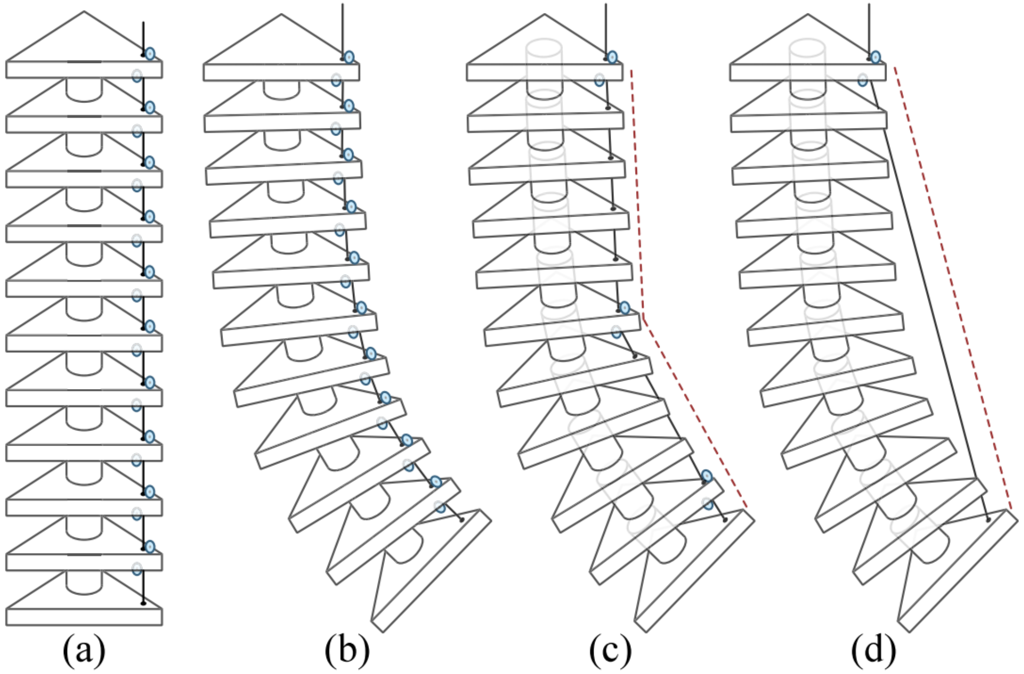


https://se.mathworks.com/content/dam/mathworks/tag-team/Objects/s/Modeling-Flexible-Bodies-Simscape-Multibody-171122.pdf

Tendon Modeling

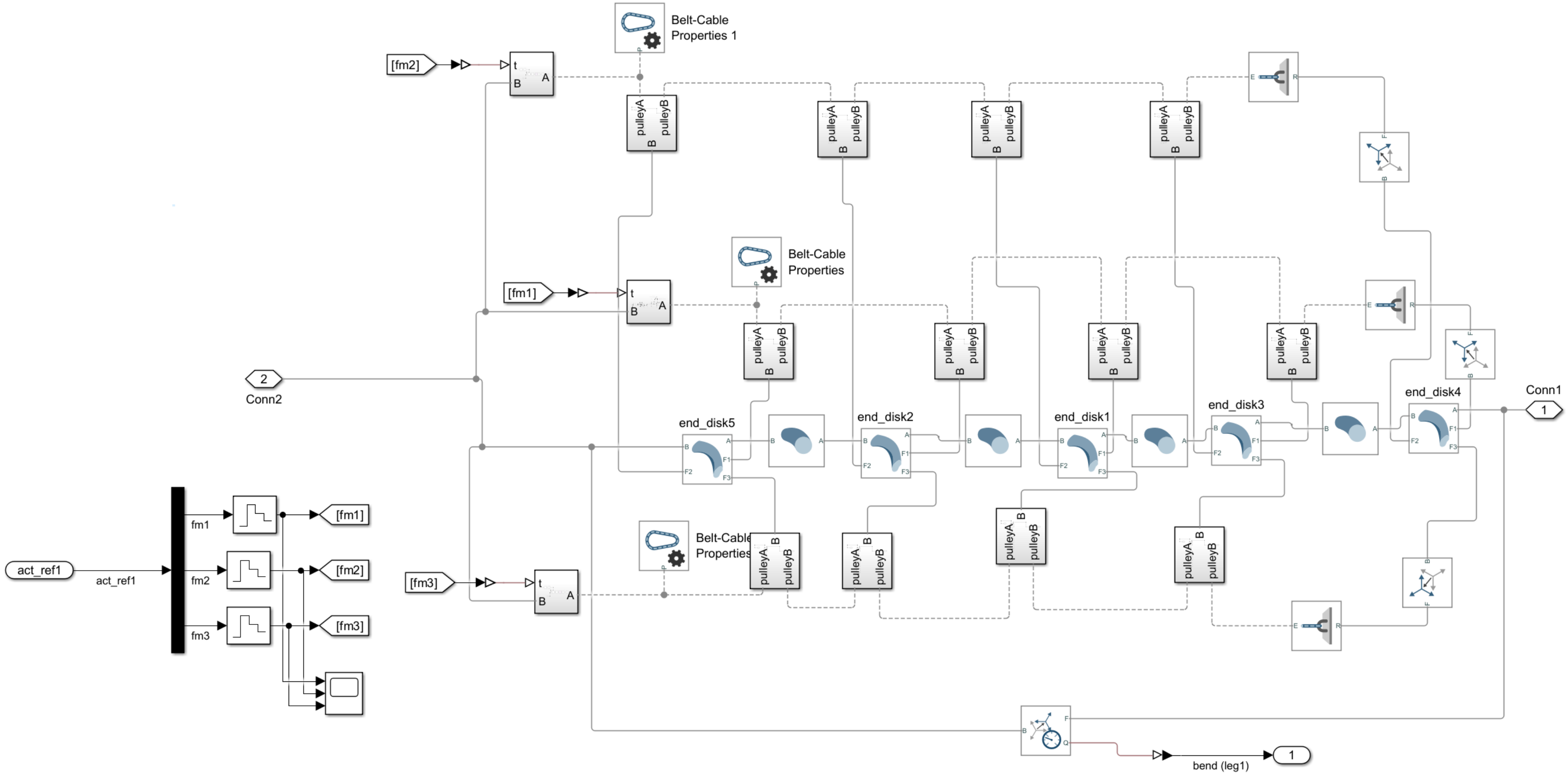
Choices for modelling tendon mechanism

- Equally distributed force pairs
- Confined cable by pully pairs
- Varying numbers of pulleys



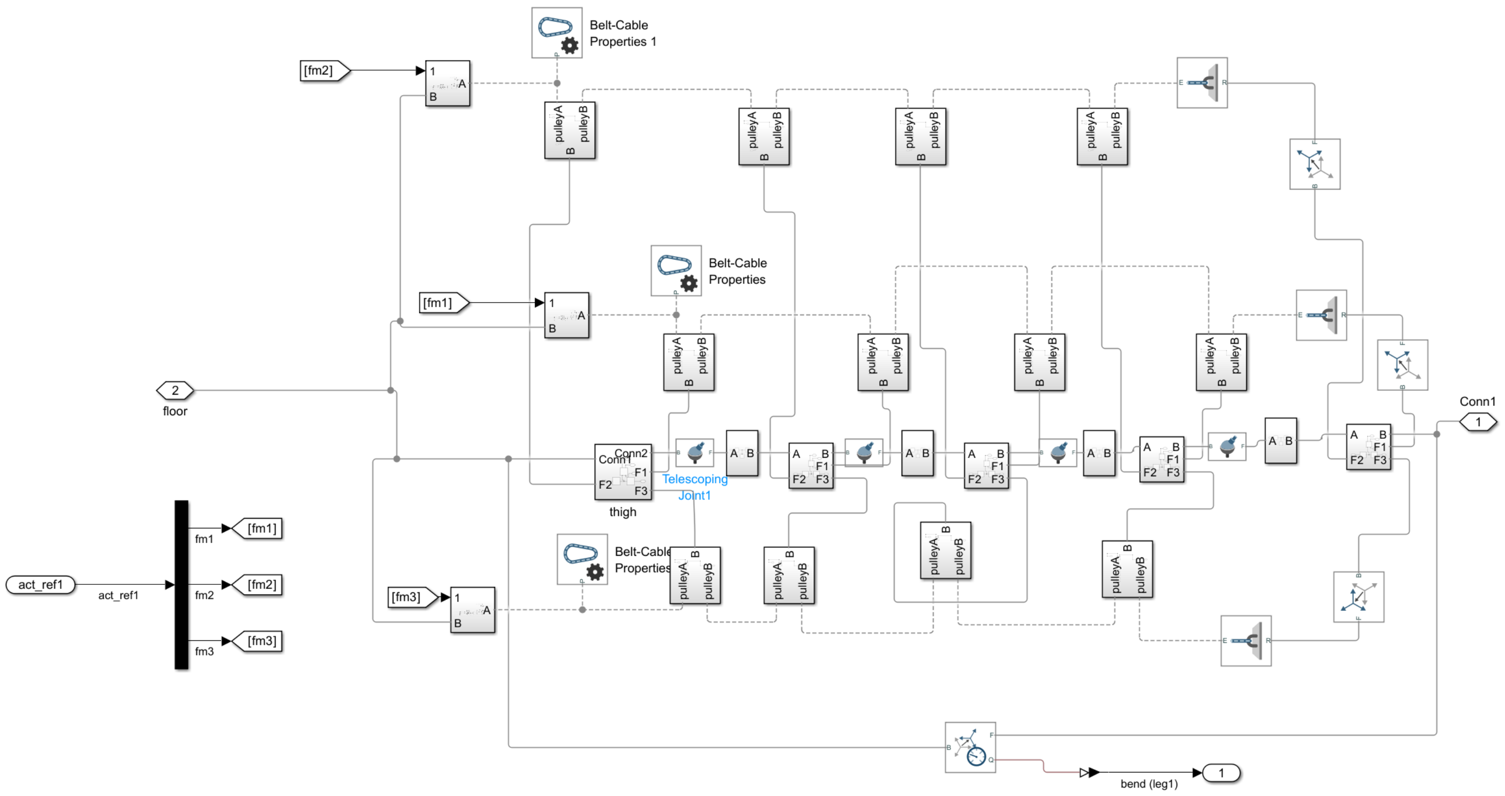
Varying numbers of pulleys for trade-off between accuracy and simulation efficiency.

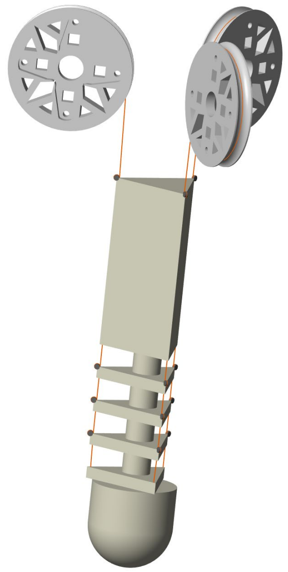
Soft Actuator Model in Simulink



Soft material sections.

Soft Actuator Model in Simulink

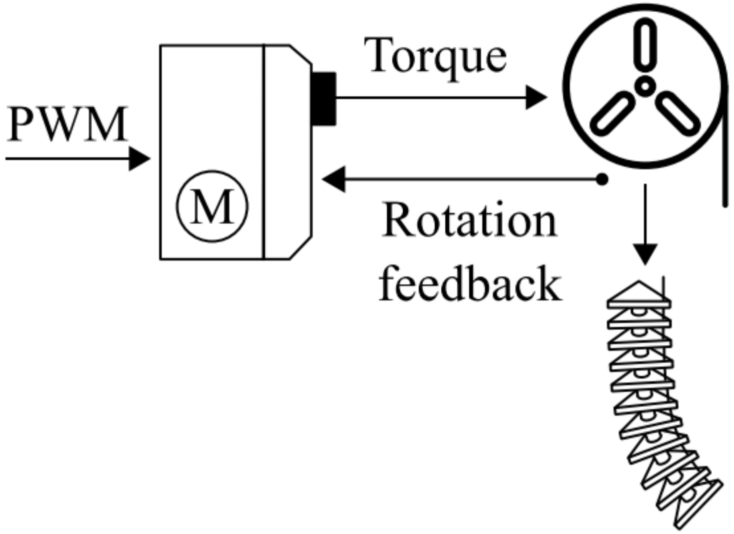




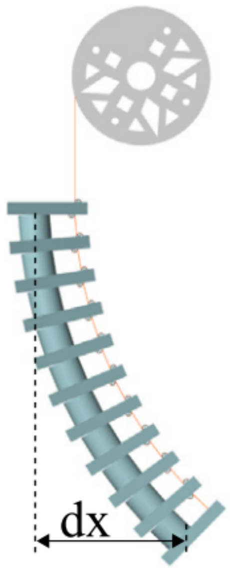
Rigid material connected by lumped joints.

Result

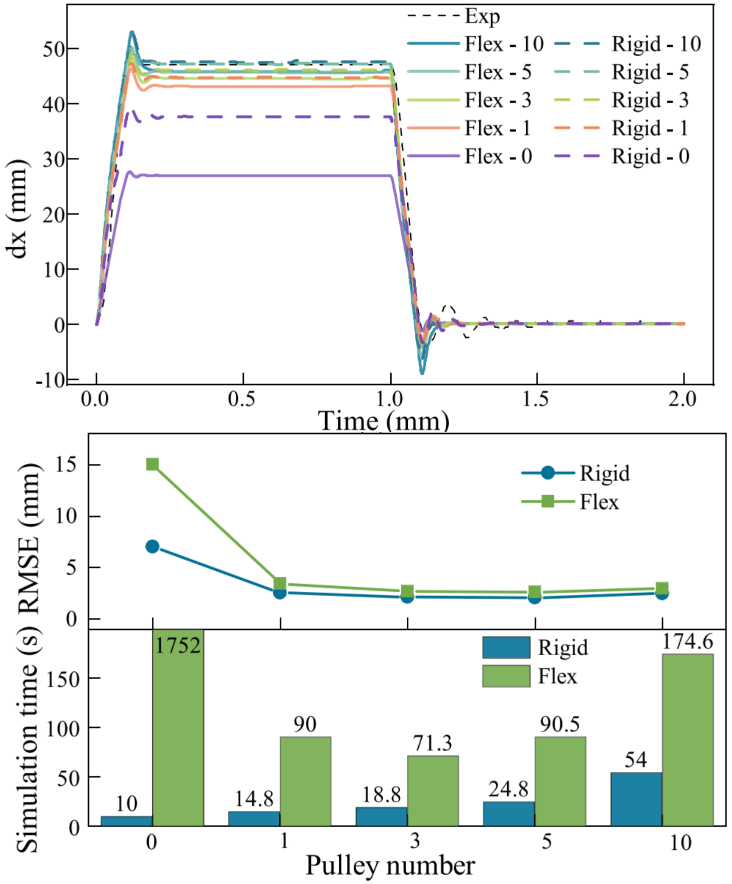
Precision *vs* simulation time



(a)

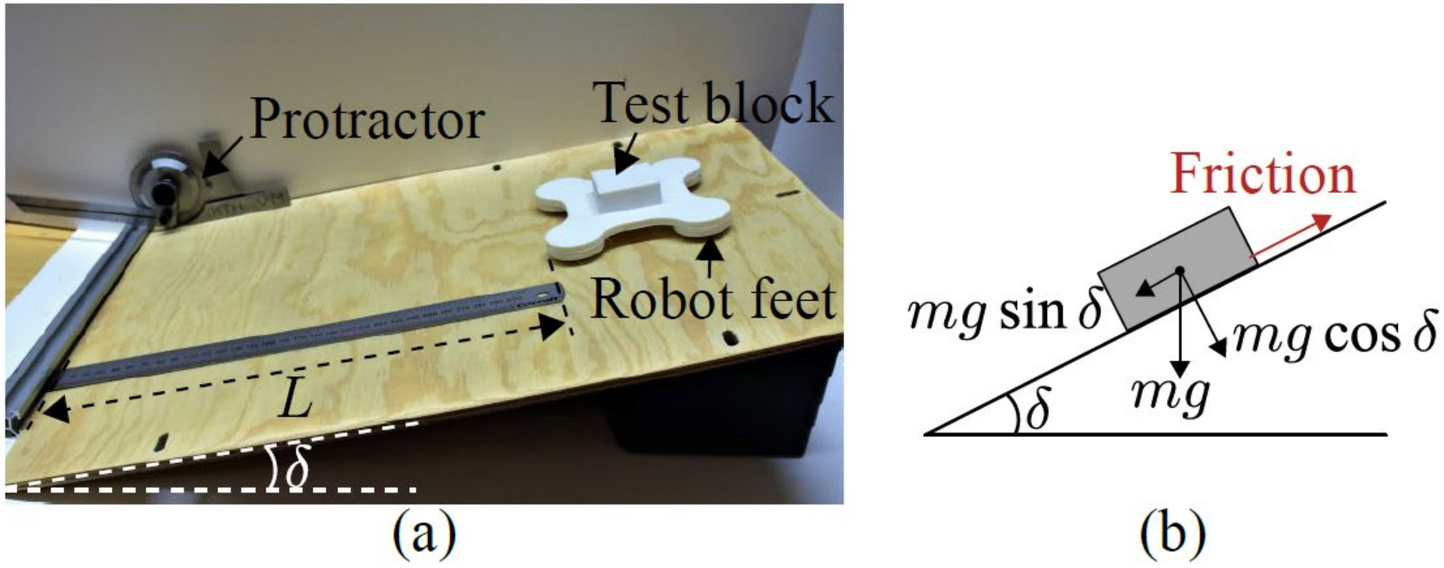


(b)

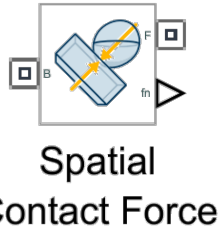


Foot-ground Contact Model

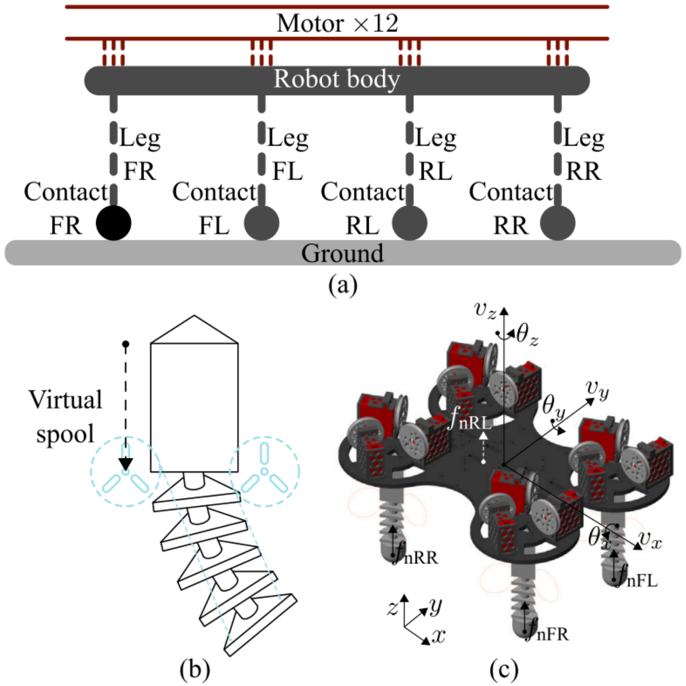
Spatial contact force block in Simscape to model the friction between foot and ground.



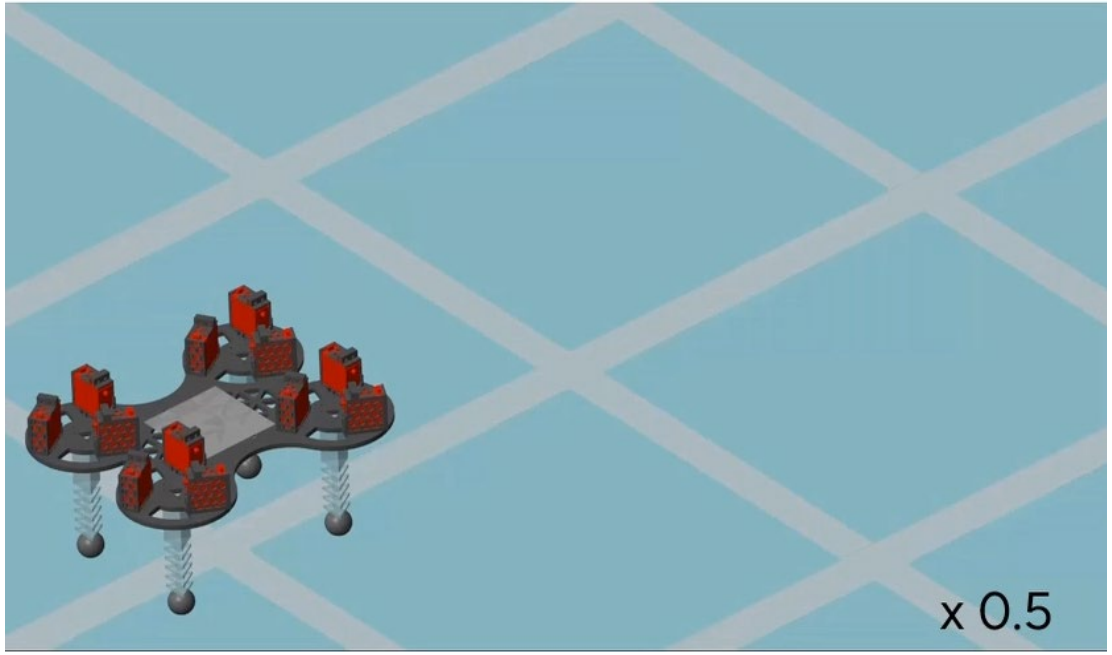
Inclined plan experiment to acquire the friction coefficient.



Simulation Demonstration



Complete robot model architecture.



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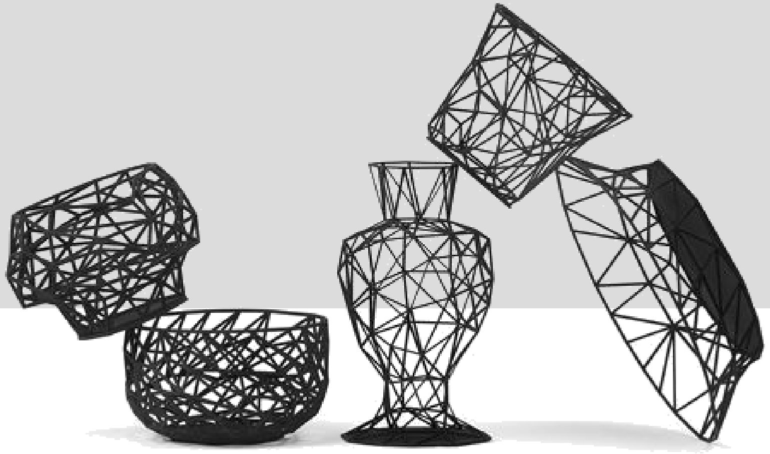
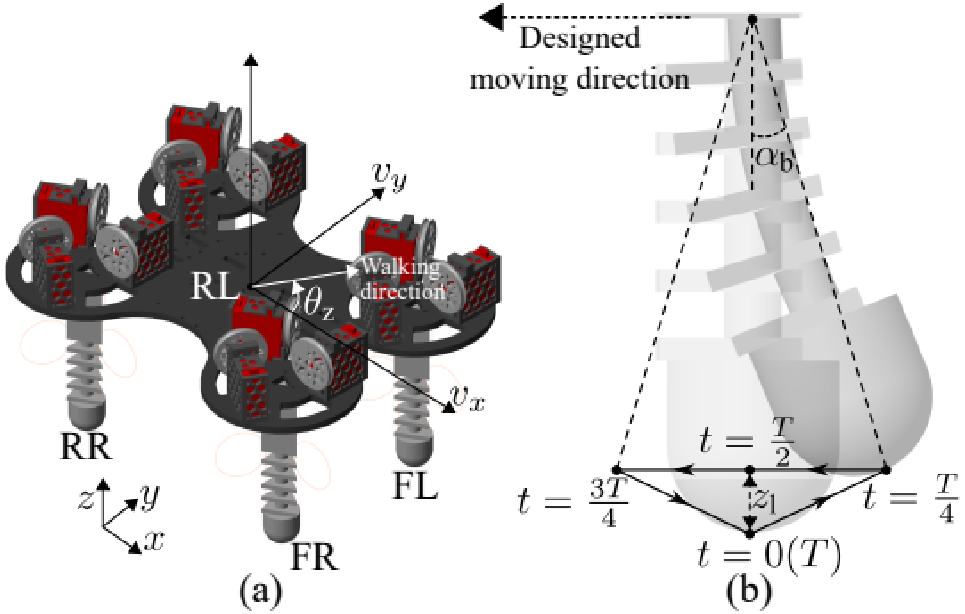
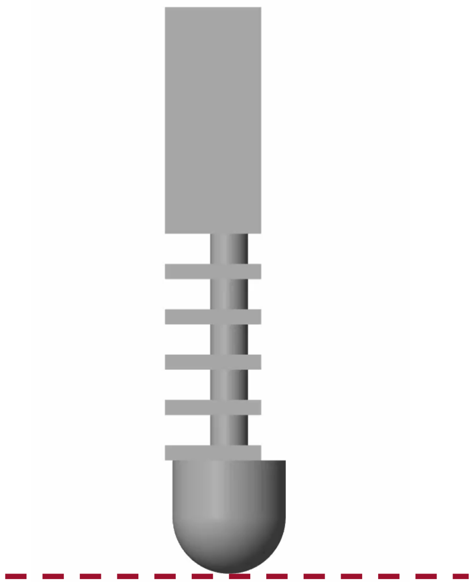


Robot Gait Development - Trot Gait

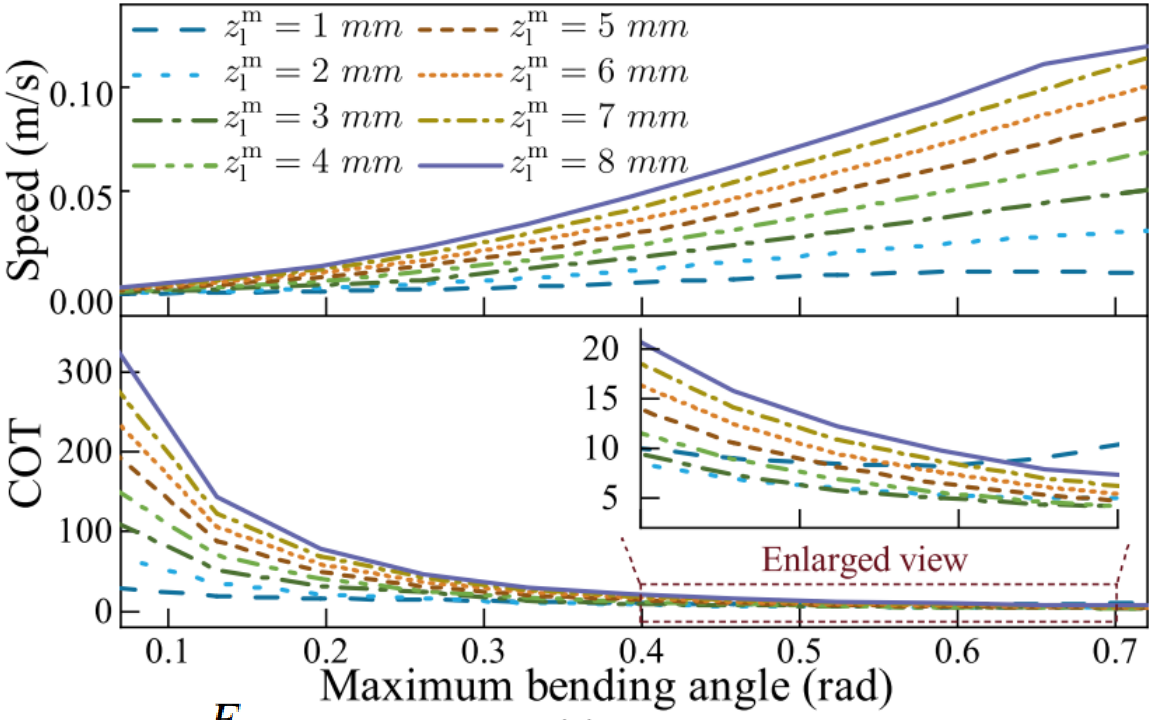
Assumption: Actuator rotational directional refers to the walking direction





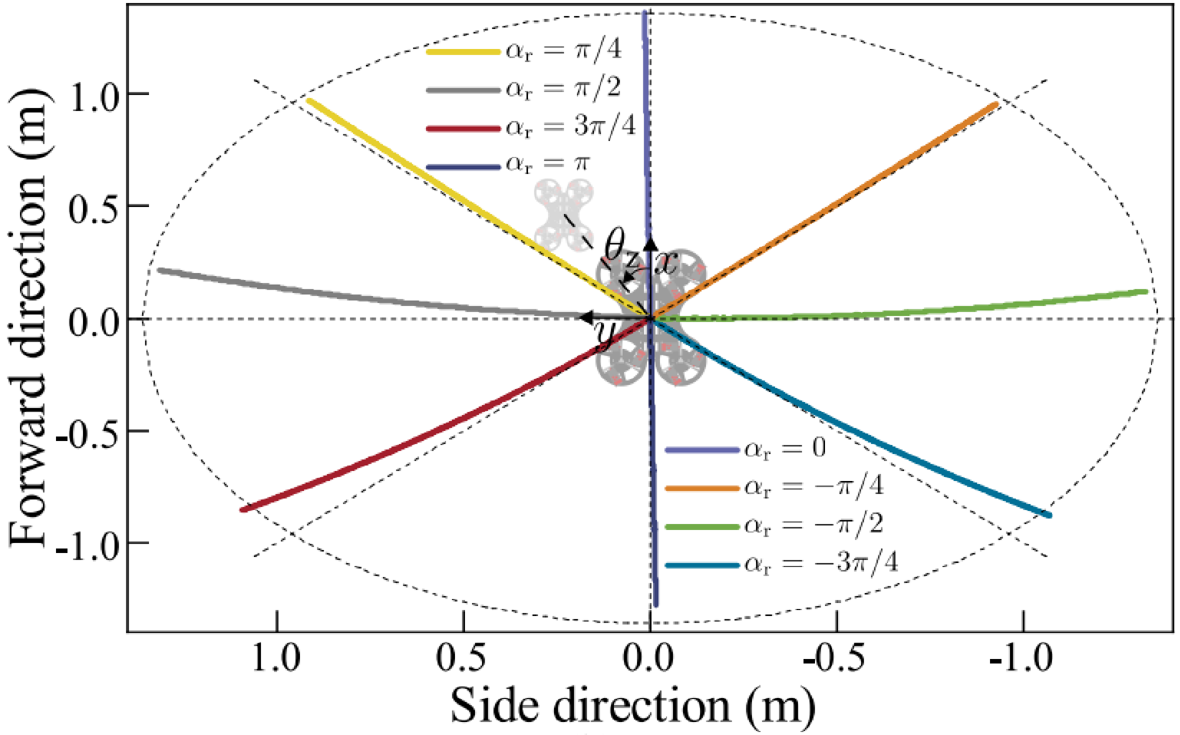
Ji, Qinglei, et al. "Omnidirectional walking of a quadruped robot enabled by compressible tendon-driven soft actuators." 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2022.

Influences of Input Parameters



(a)

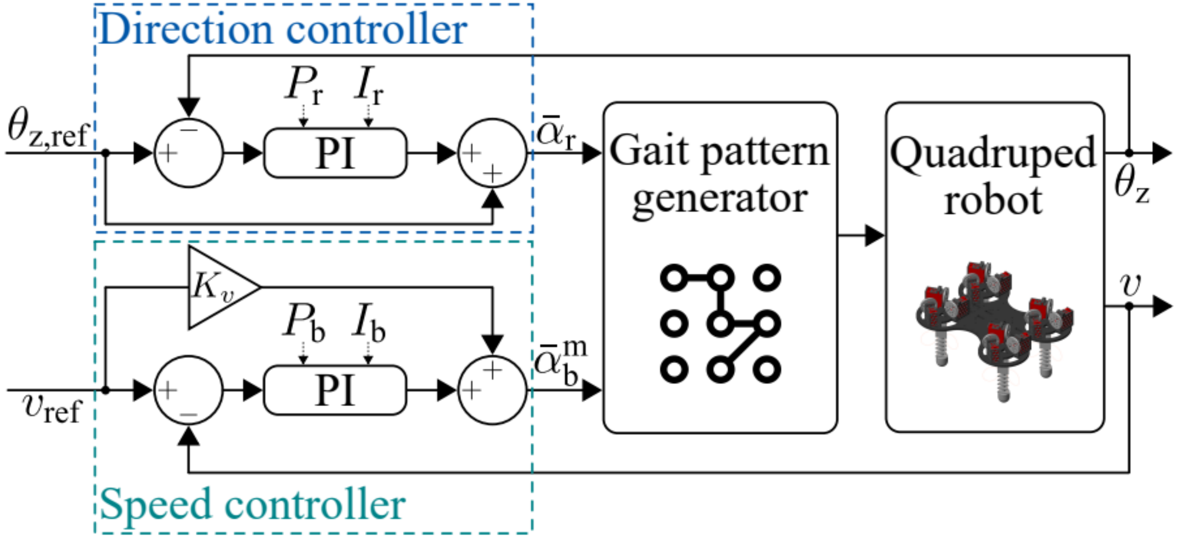
$$COT = \frac{E}{mgd}$$



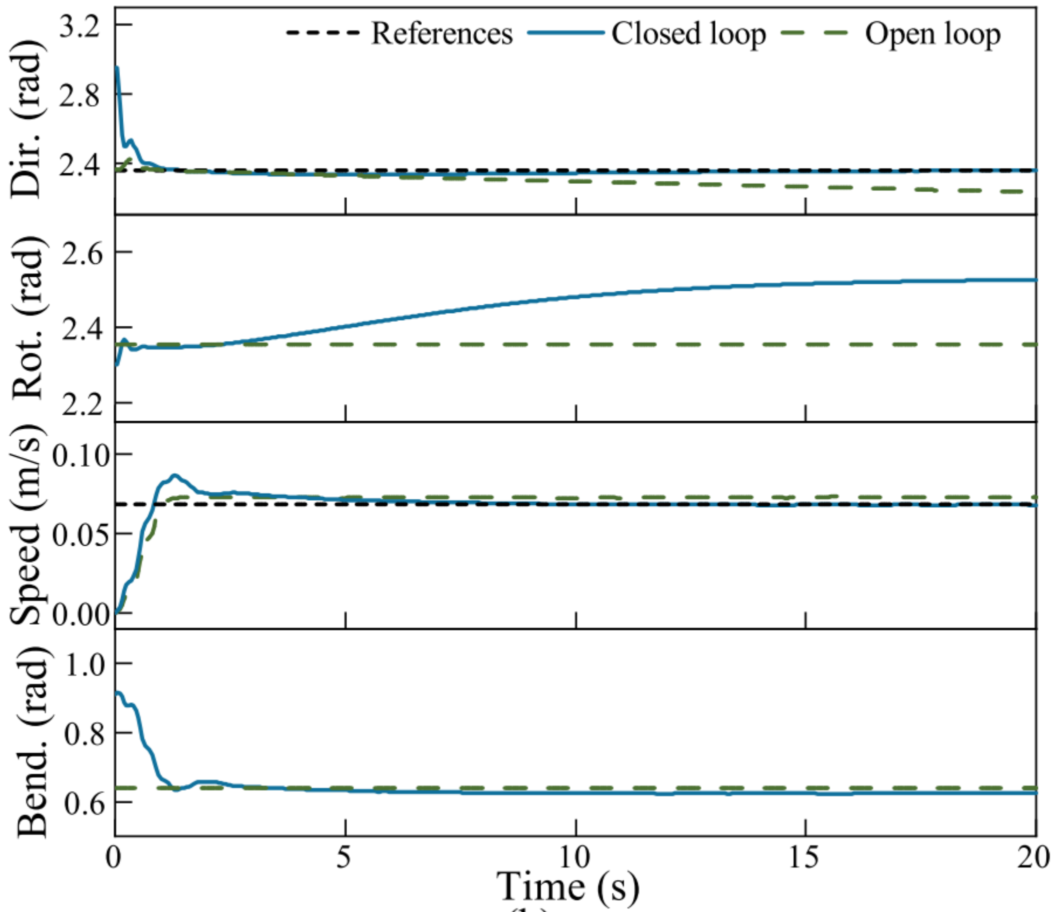
(b)

Closed-loop Direction and Speed Control

Fixed compressed length

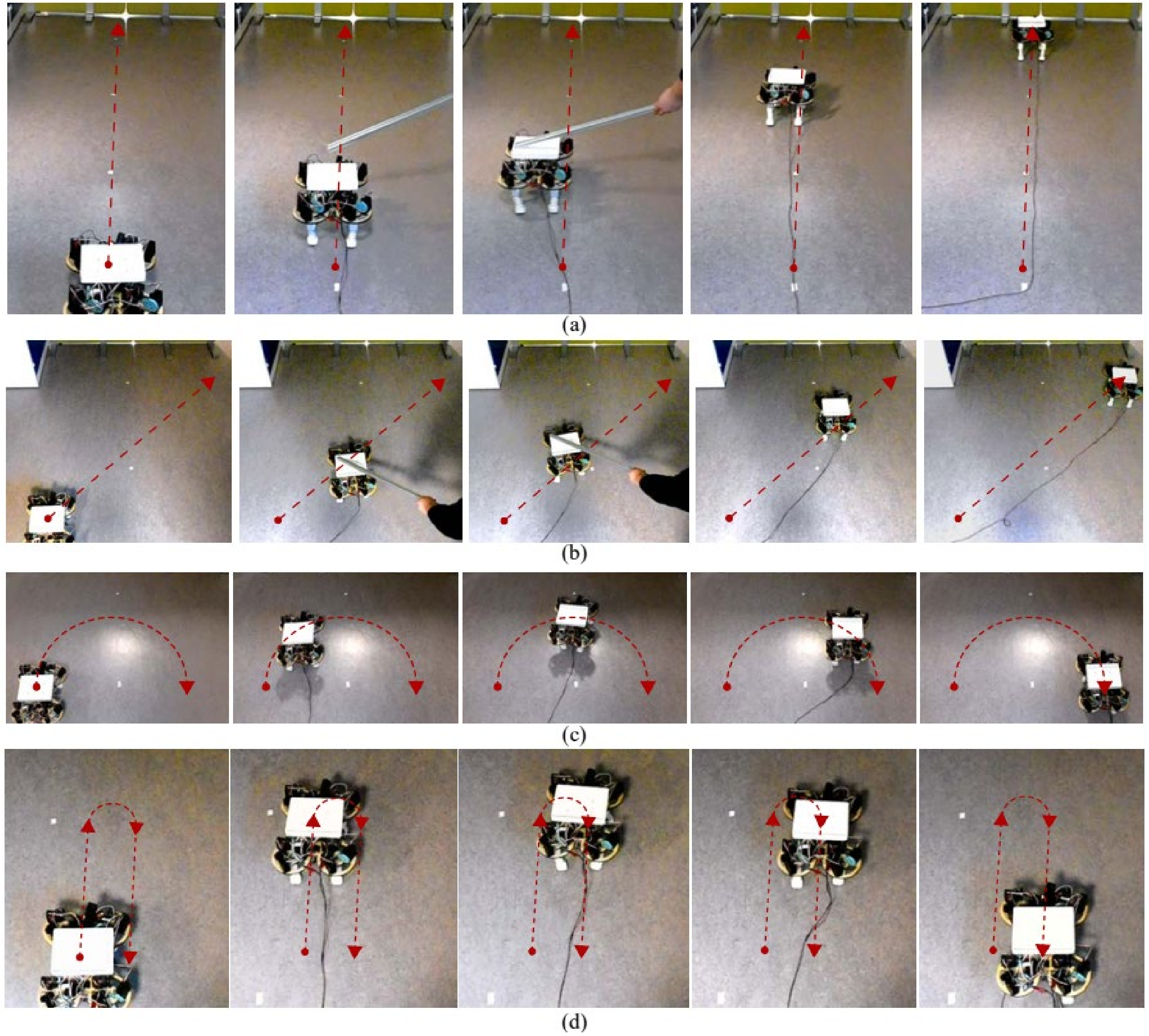


(a)



(b)

Implementation

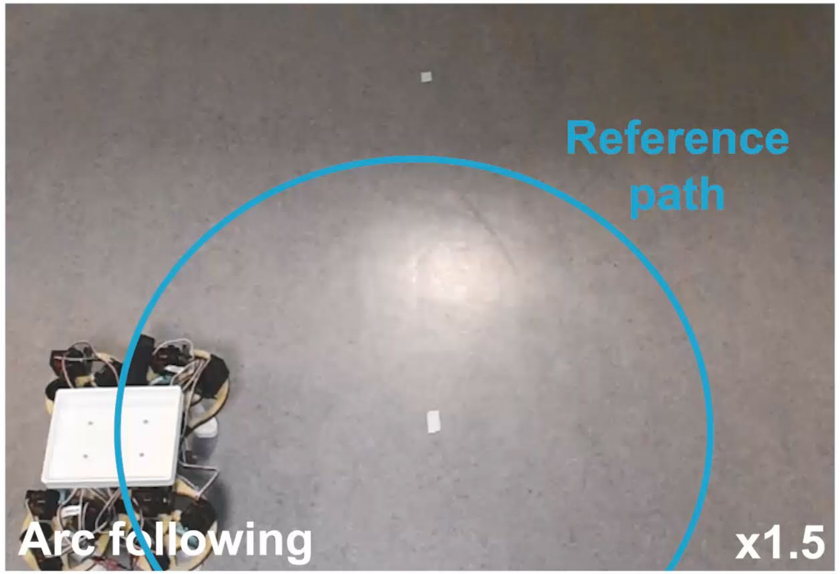


$$R = \frac{v}{\dot{\alpha}_r}$$

Omnidirectional walking of a quadruped robot enabled by compressible tendon-driven soft actuators

Qinglei Ji[1,2], Shuo Fu[2], Lei Feng[2], Georgios Andrikopoulos[2], Xi Vincent Wang[1] and Lihui Wang[1]

1 Department of Production Engineering, KTH Royal Institute of Technology, Stockholm 10044, Sweden
2 Department of Machine Design, KTH Royal Institute of Technology, Stockholm 10044, Sweden



Swedish Research Council

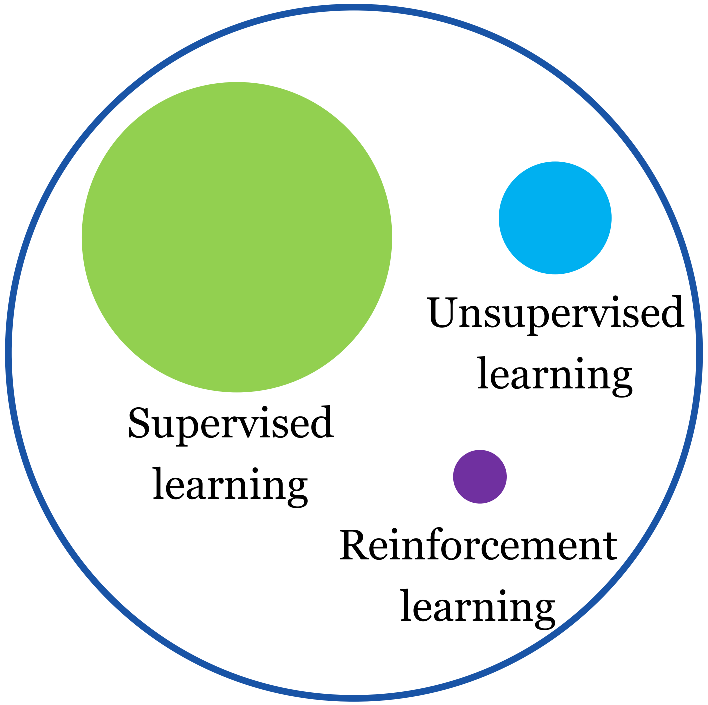
Xpres Excellence in Production Research

Reinforcement Learning

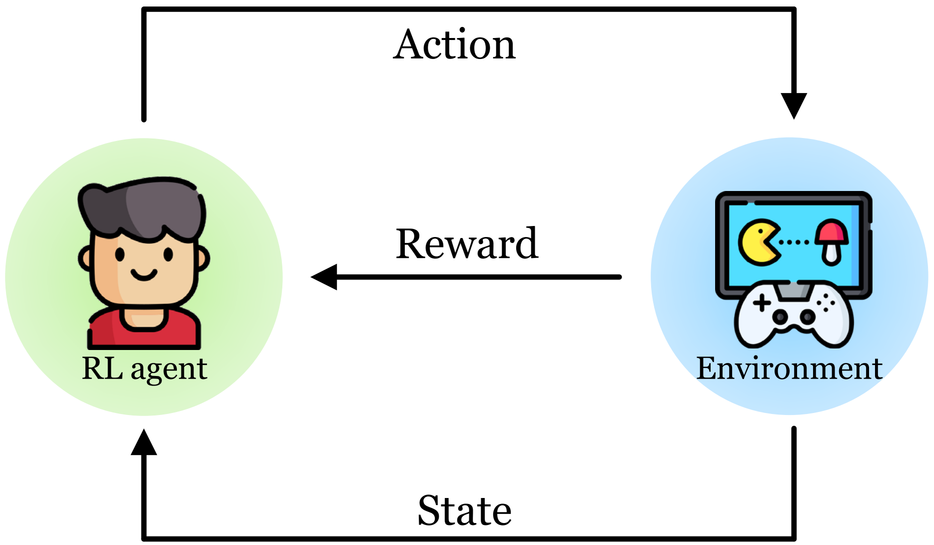
Learn with reward or penalty feedback.

Difference in design philosophy of reward in RL vs cost in optimal control:

- RL: Reward shaping is an art, often requiring intuition
- Optimal Control: Cost functions often derived from physical principles



Classifications of AI techniques

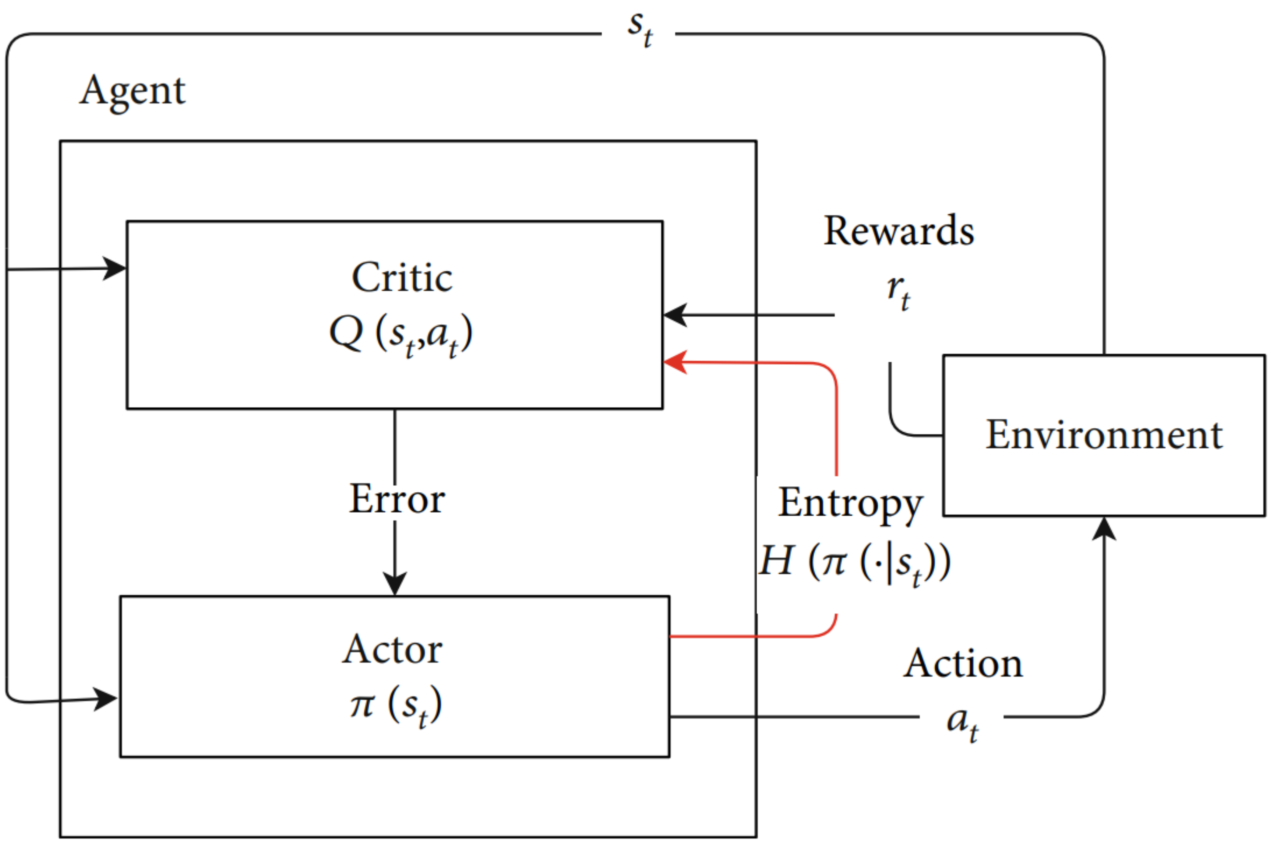


Reinforcement learning

https://www.youtube.com/watch?v=5p248yoa3oE&ab_channel=StanfordOnline
https://www.kdnuggets.com/2022/05/reinforcement-learning-newbies.html

Gait Learning for Soft Quadruped Robot

Soft Actor Critic (SAC) method

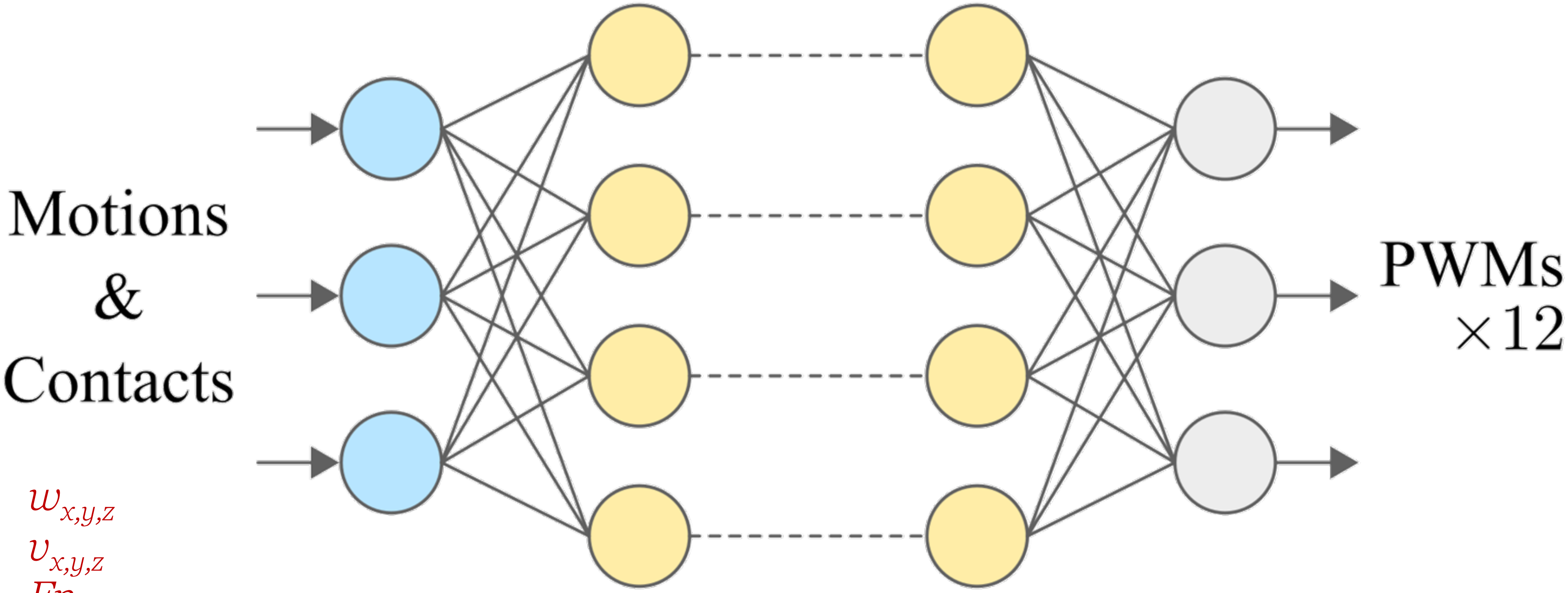


$$\pi^* = \arg\max_{\pi} \sum_t \mathbb{E}_{(\mathbf{s}_t,\mathbf{a}_t)\sim\rho_\pi}\left[r(\mathbf{s}_t,\mathbf{a}_t) + \alpha\mathcal{H}(\pi(\cdot|\mathbf{s}_t))\right]$$

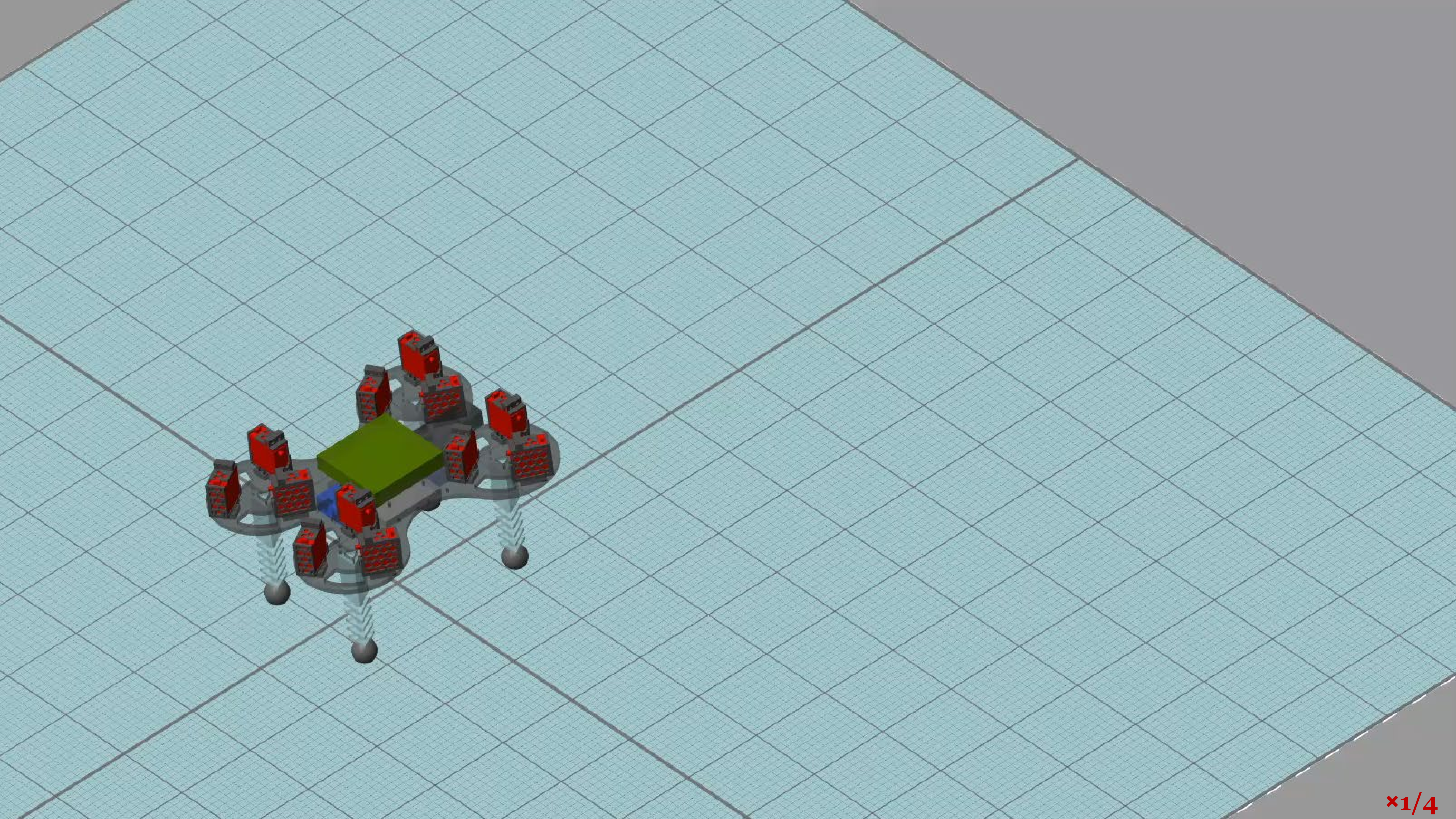
Haarnoja T, Zhou A, Hartikainen K, Tucker G, Ha S, Tan J, Kumar V, Zhu H, Gupta A, Abbeel P, Levine S. Soft actor-critic algorithms and applications. arXiv preprint arXiv:1812.05905. 2018 Dec 13.

Gait Learning for Soft Quadruped Robot

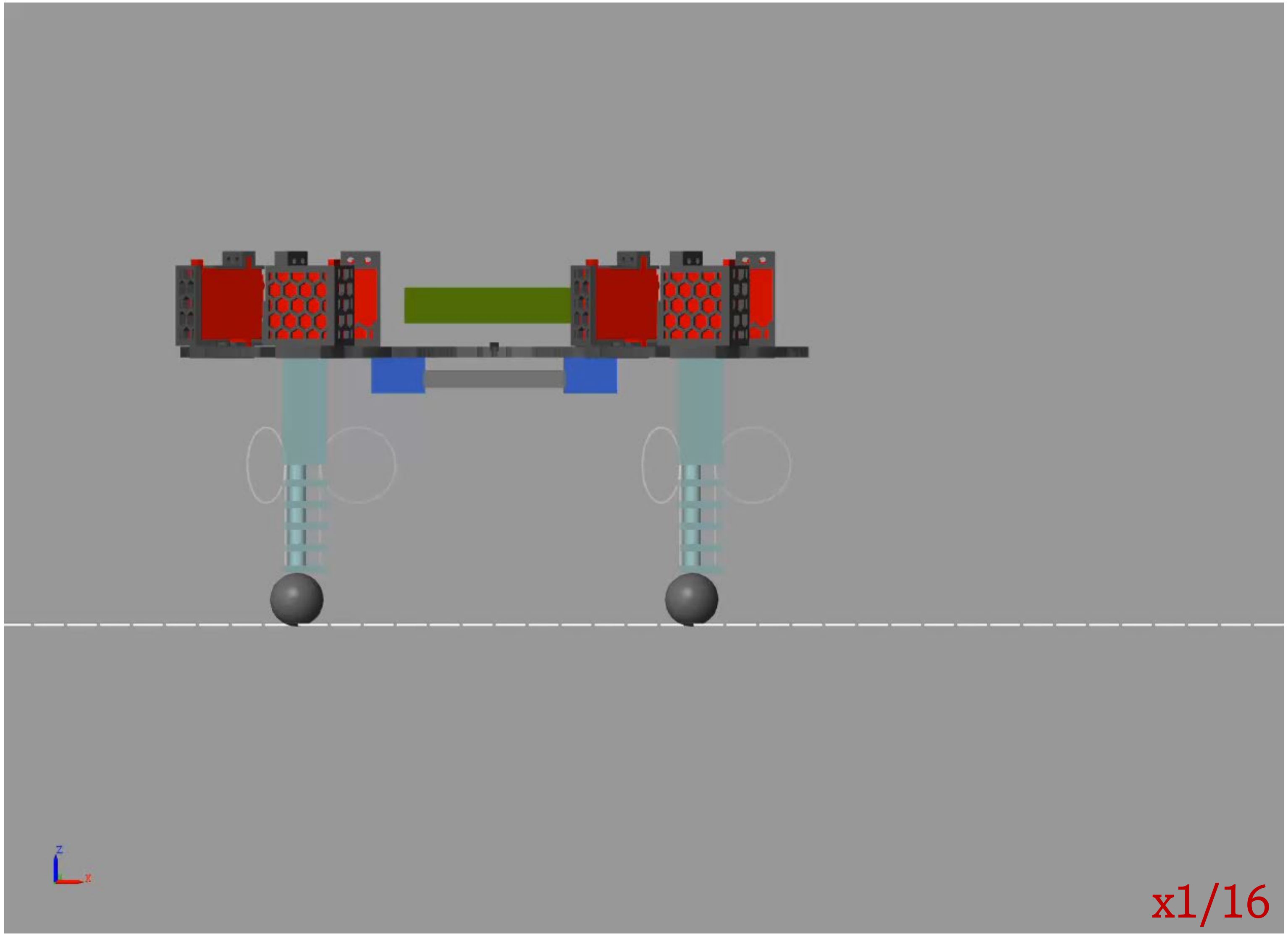
Actor network



$w_{x,y,z}$
$v_{x,y,z}$
$Fn_{FR,FL,RL,RR}$
u (PWMs x 12)

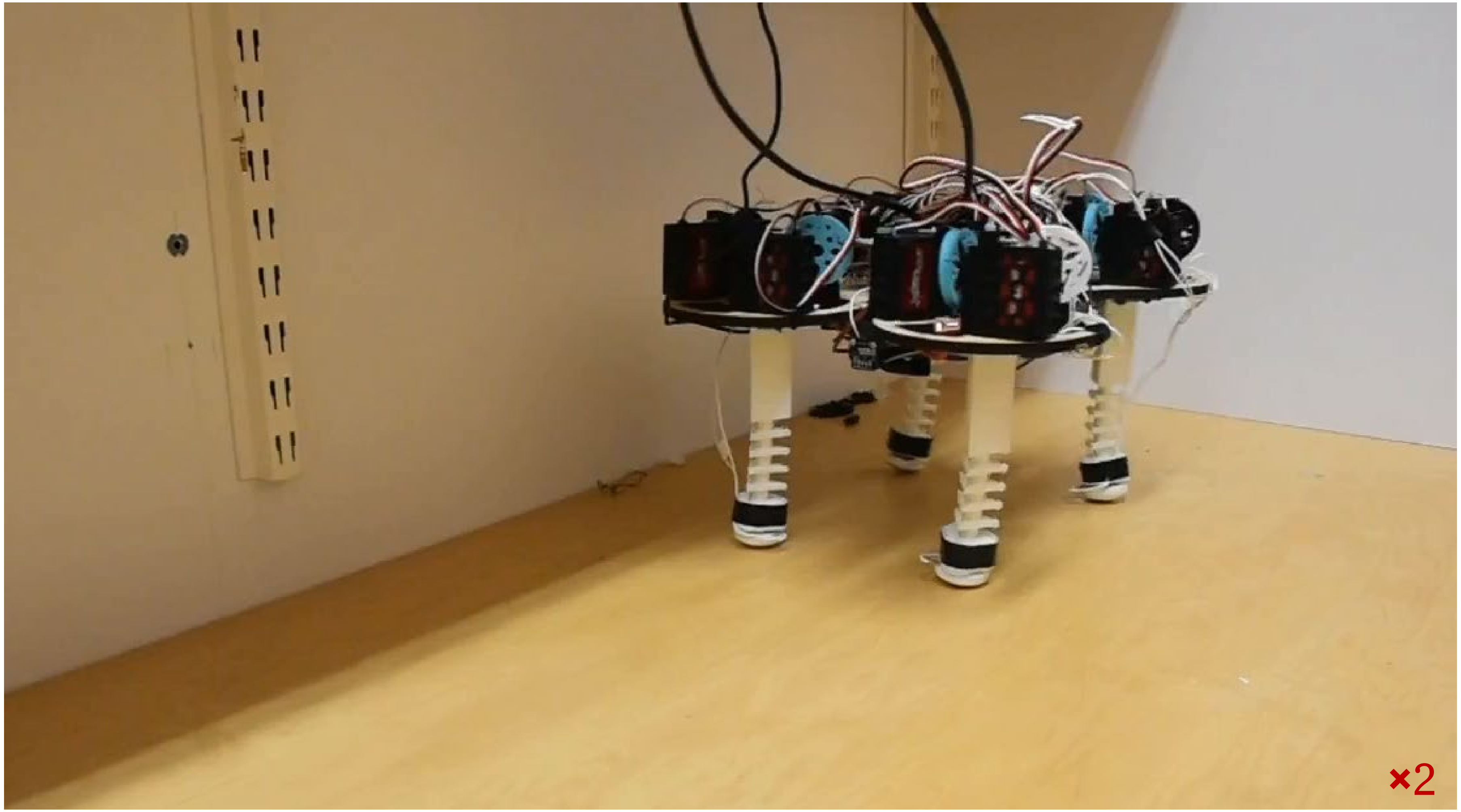

×1/4

Gait Learning for Soft Quadruped Robot



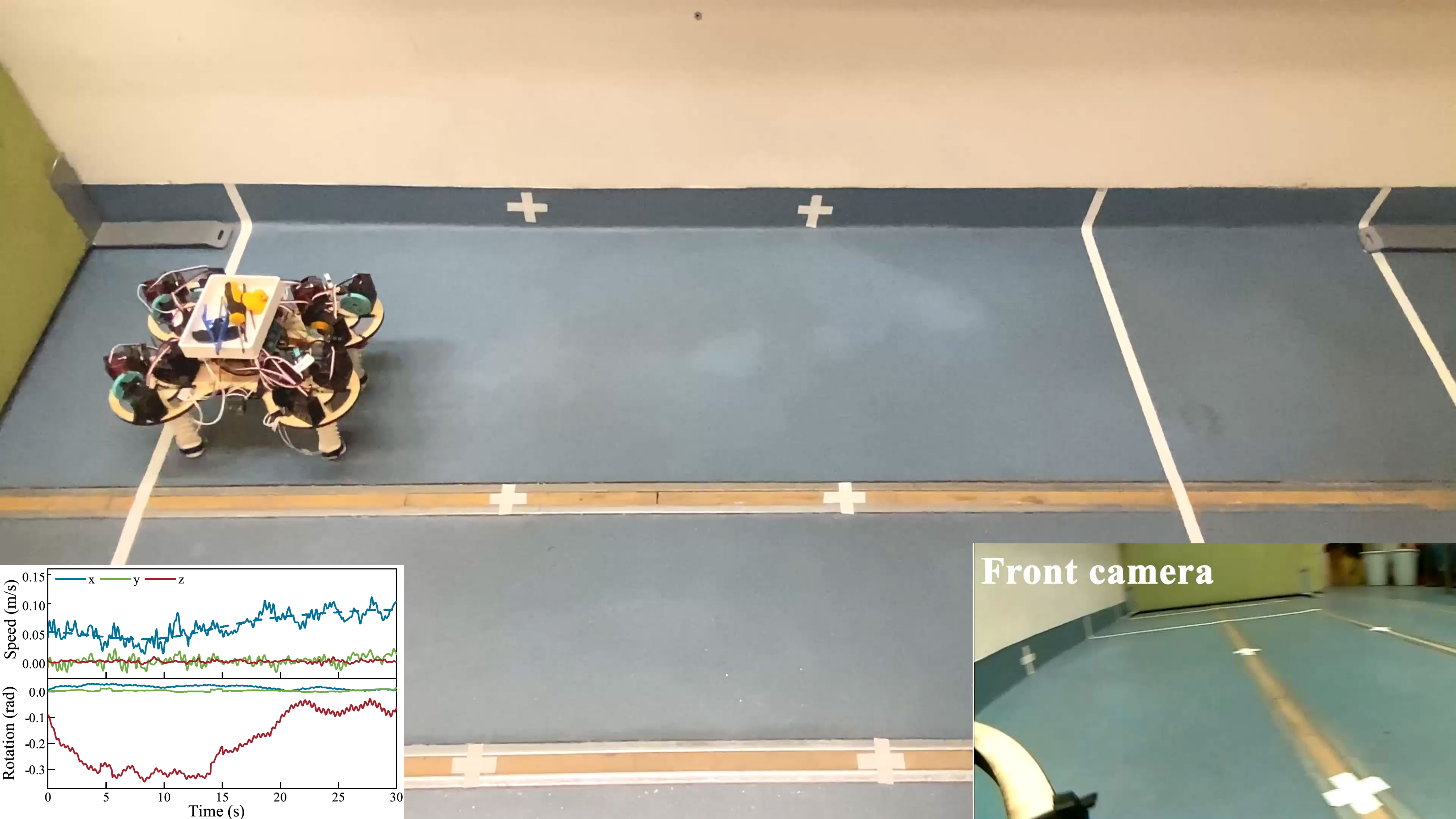
Implementation

Sim2Real gap



Solutions

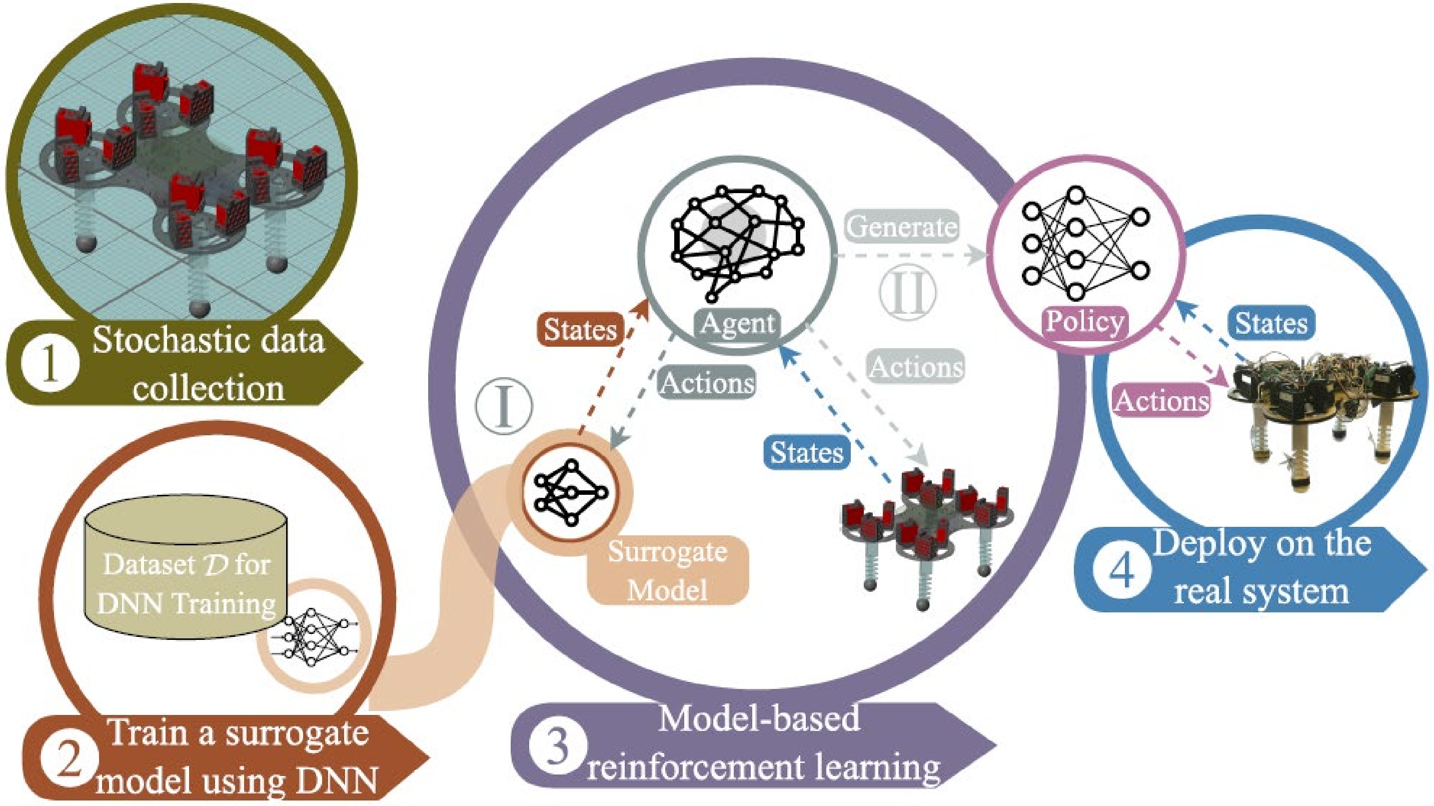
- Add random noises
- Change env. params.



x
y
z
Speed (m/s)
0.15
0.10
0.05
0.00
Rotation (rad)
0.0
-0.1
-0.2
-0.3
0
5
10
15
20
25
30
Time (s)
Front camera

Model-Based Reinforcement Learning

Training via simulation or real world is expensive

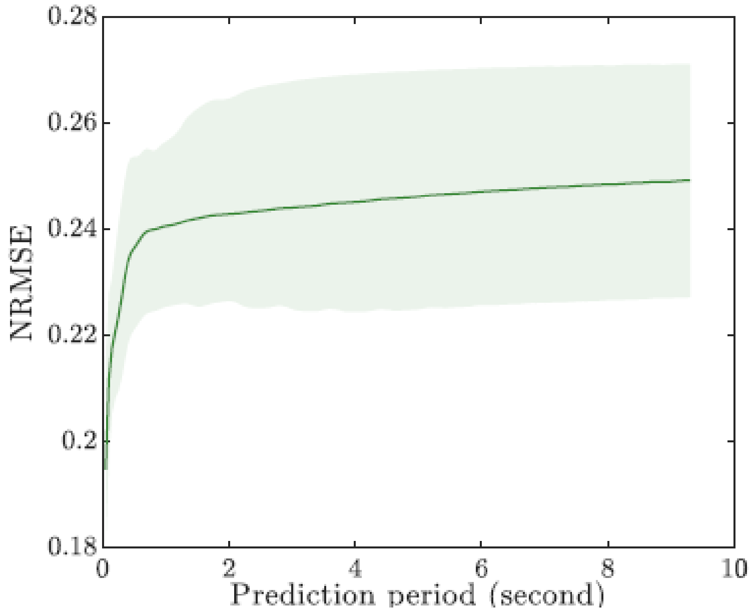


Gait control policy generation framework

Niu, Xuezhi, Kaige Tan, and Lei Feng. "Optimal Gait Control for a Tendon-driven Soft Quadruped Robot by Model-based Reinforcement Learning." arXiv preprint arXiv:2406.07069 (2024).

Surrogate Model

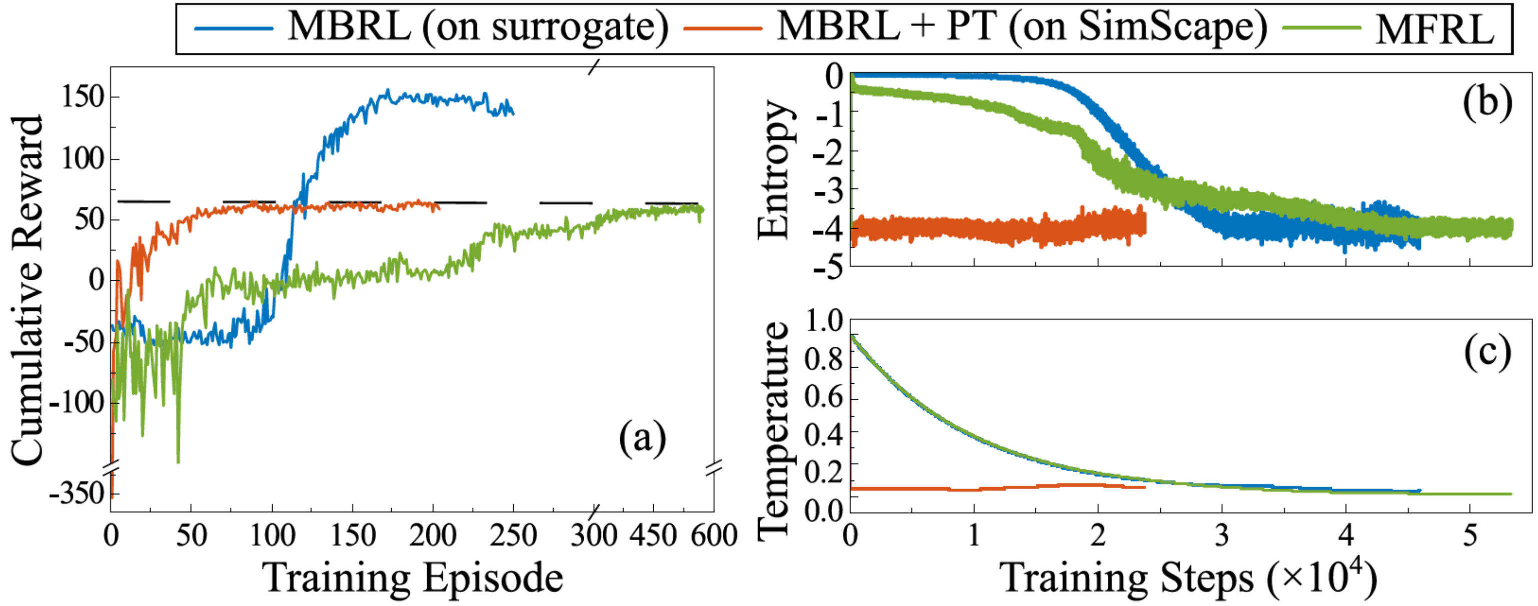
- Predict next state with current state and actions
- Precision is decreased when prediction is iterated for long term prediction
- DNN with three hidden layers (64, 128, 64)
- Supervised learning
- Long-term prediction



Prediction accuracy decreases for long term.

MBRL + Post-training

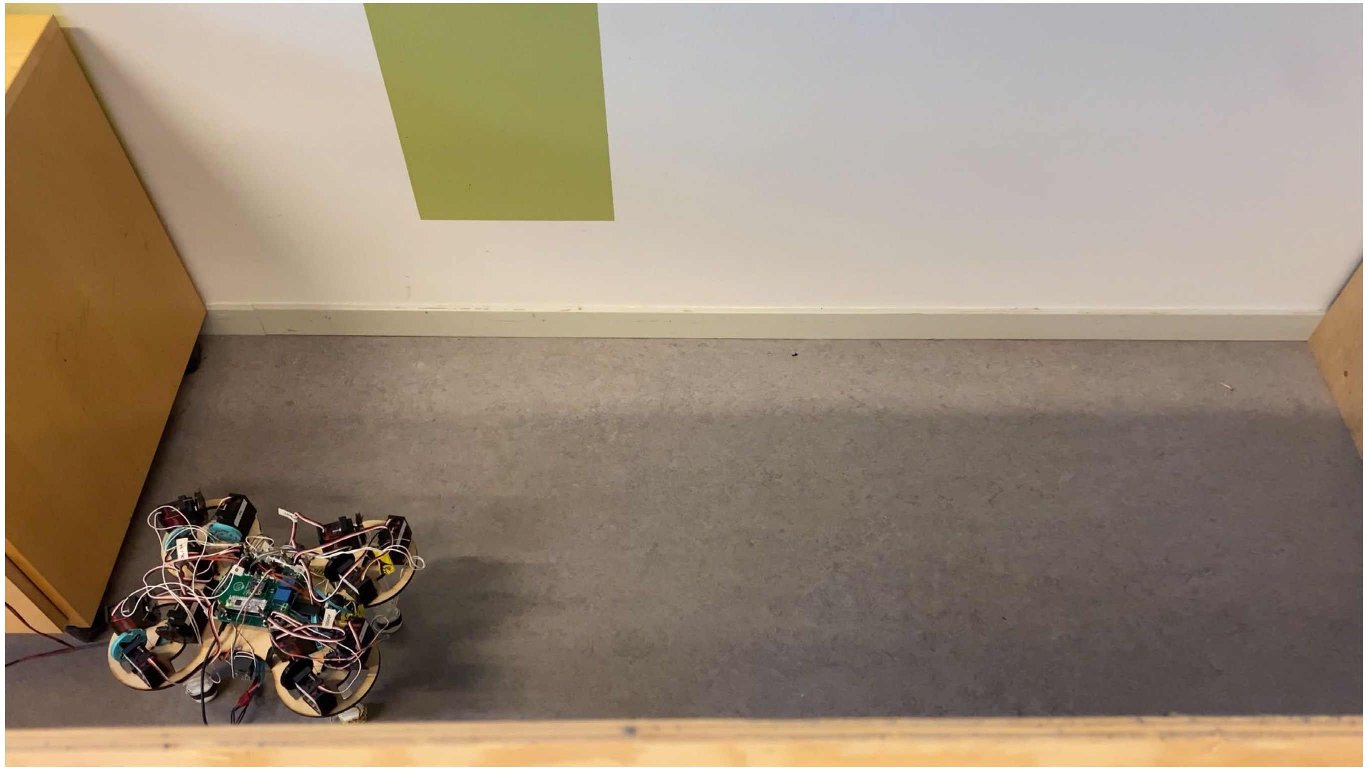
Post-Training for Improving Control Quality



The training results in 0.2 m/s reference speed. (a) Cumulative reward with training episodes. Variations in (b) entropy and (c) temperature during the training process.

Implementation

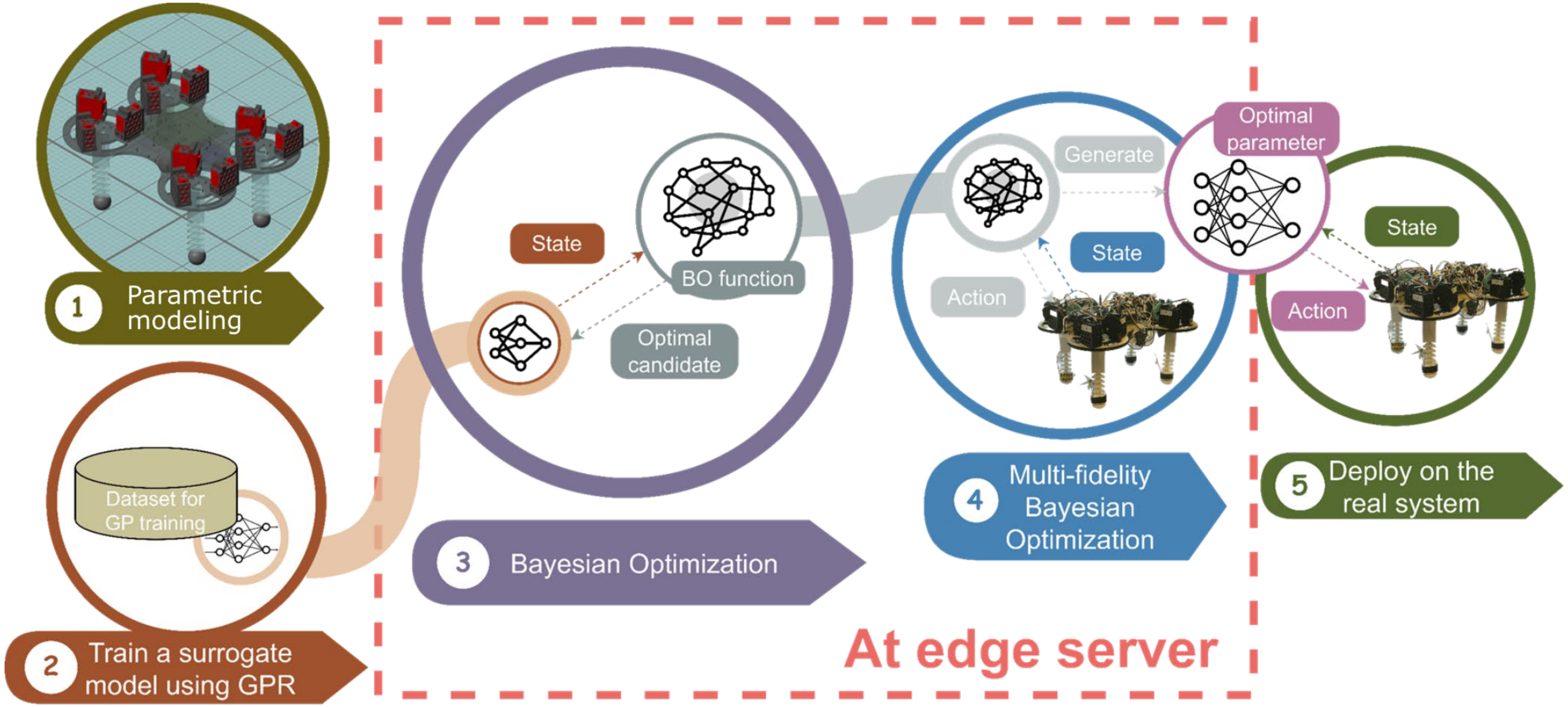
Great improvement on the training speed: 11 *vs* 48 hours



Similar stable walking speed with the identical environment

Bayesian optimization with parametric model

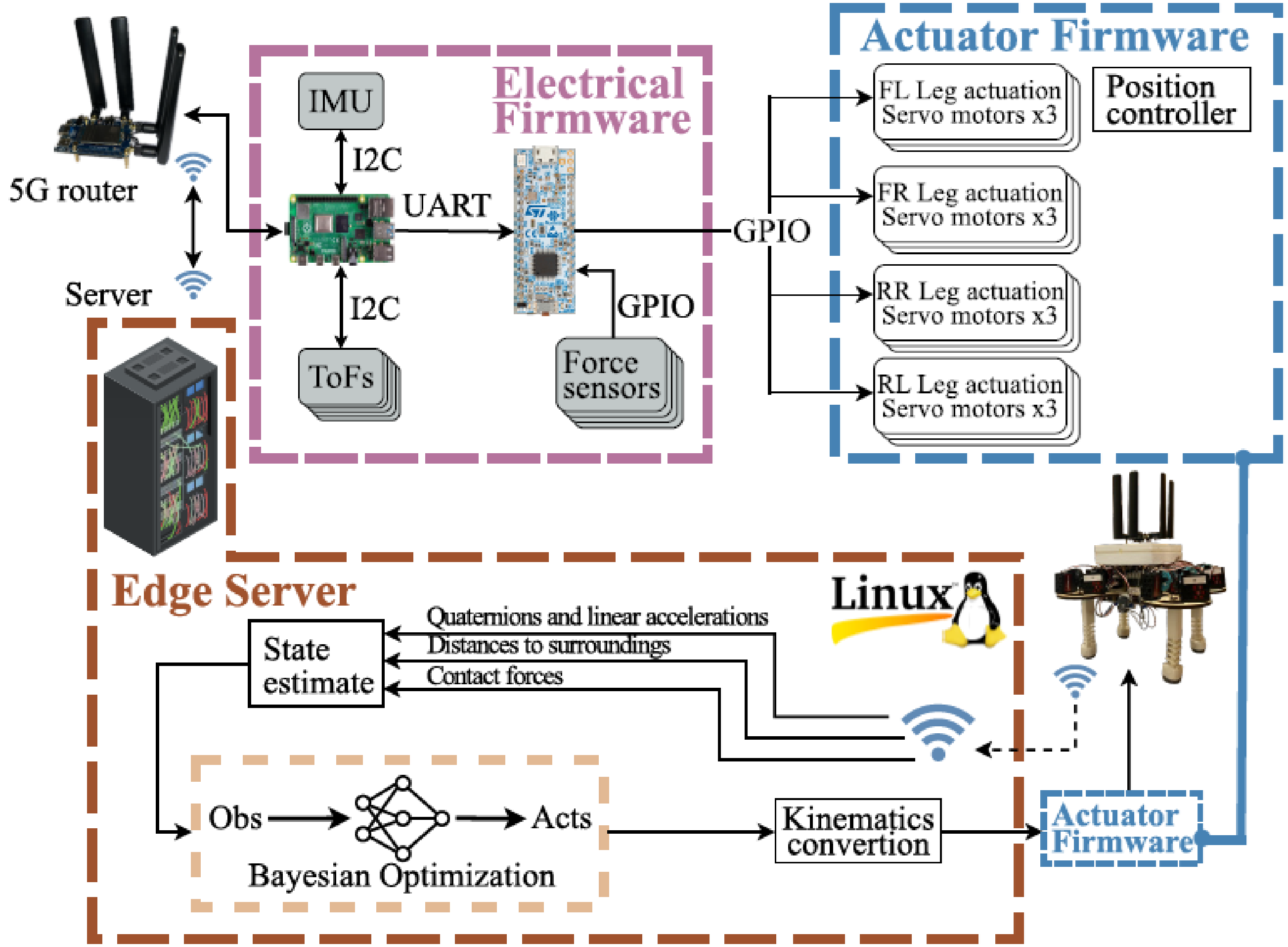
Parametric model (CPG) from expert knowledge



Tan, Kaige, et al. "Optimal Gait Design for a Soft Quadruped Robot via Multi-fidelity Bayesian Optimization." arXiv preprint arXiv:2406.07065 (2024).

Edge Computing for Online Learning and Control

Offload computing to cloud



Training iteration demos

Initial gait
(0.046m/s)

Intermidiate gait during training
(0.143m/s)

Optimal converged gait
(0.215m/s)

Final Remarks

- Unified simulation, control, and learning environment.
- Trade-off between model accuracy *vs* simplified simulation for time-efficient learning.
- Learn from simulation and real world to overcome Sim2Real gap.
- Offload computing to cloud for intensive online learning tasks.


Q
A