Reinforcement Learning for Robotics

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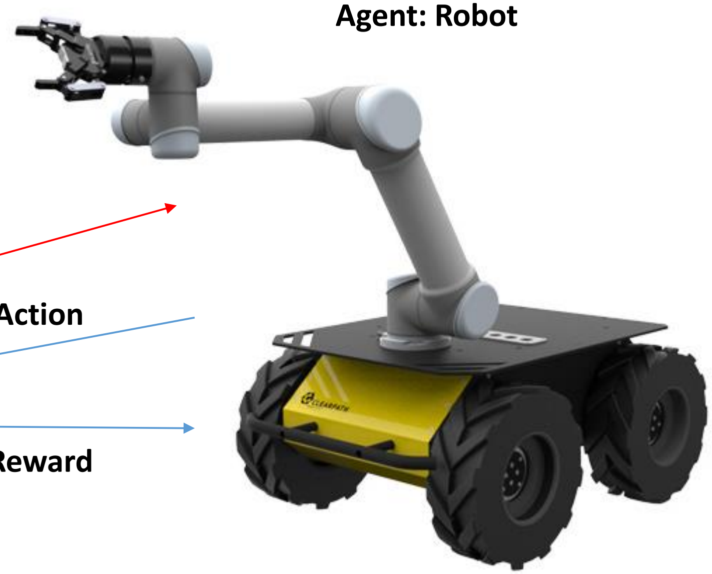
Reinforcement Learning

1. François Chollet, Deep Learning with Python, 2nd Edition. Manning, 2021.
2. R. Atienza, Advanced Deep Learning with Keras: Apply deep learning techniques, autoencoders, GANs, variational autoencoders, deep reinforcement learning, policy gradients, and more, 2018.
3. R.S. Sutton, A.G. Barto, Reinforcement Learning: An Introduction (Adaptive Computation and Machine Learning series) 2nd Edition, 2018.
4. W. Zhao, J.P. Queralta, T. Westerlund, Sim-to-Real Transfer in Deep Reinforcement Learning for Robotics: a Survey, 2020 IEEE Symposium Series on Computational Intelligence (SSCI), 2020.
5. Benedek Forrai, Takahiro Miki, Daniel Gehrig, Marco Hutter, Davide Scaramuzza, Event-based Agile Object Catching with a Quadrupedal Robot, IEEE International Conference on Robotics and Automation (ICRA), London, 2023.

Reinforcement Learning



Agent: e.g. a Robot

Environment: is in a certain state.

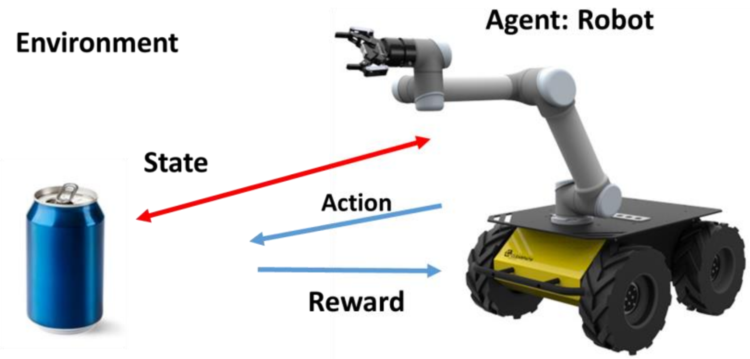
Agent Actions: Agent (Robot) performs an action

- ⇒ Environment transitions to a new state
- ⇒ Agent receives a reward

Policy: decides for each given state which action should be taken.

Goal: Learn a policy that maximizes the accumulated future rewards

Markov Decision Process



Environment

At time step t the environment is in state $s_t \in S$,
where S is the state space, s_0 is the start state, s_t is the current end state.

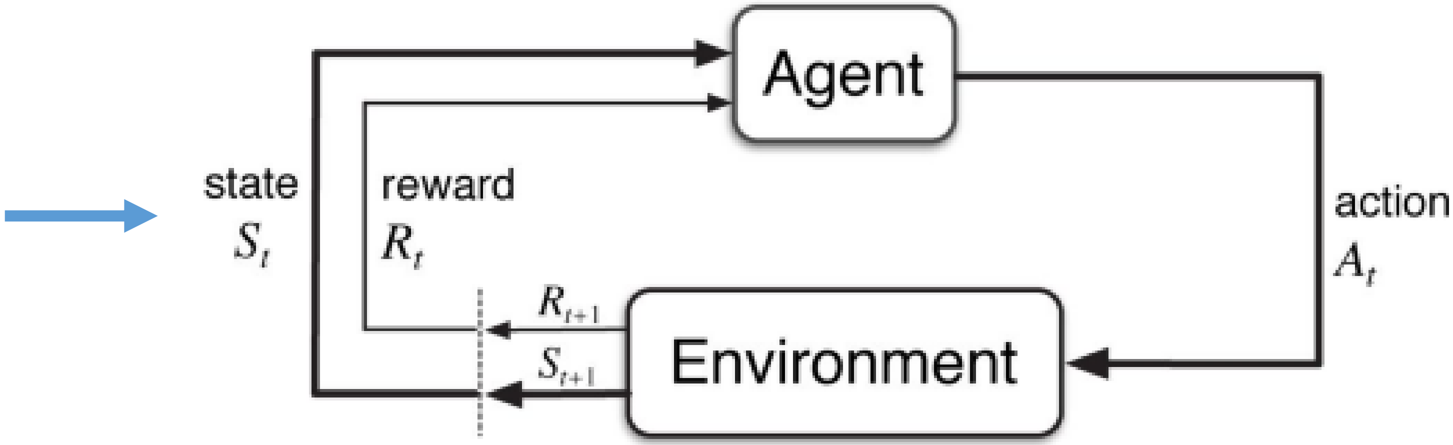
Actions

The agent takes actions from the action space A.
It follows a probabilistic policy $\pi(a_t|s_t)$
i.e., the probability that action a_t is taken given the environment is in state s_t.

Reinforcement Learning (RL) methods specify how
an agent changes its policy π_t as a result of its experience.

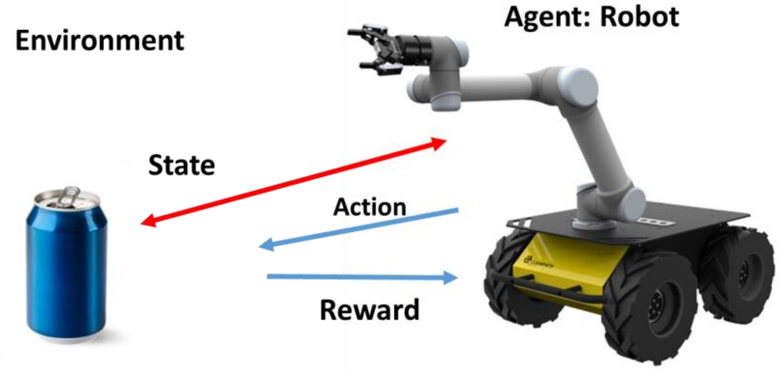
Environment: responds using the state transition $T(s_{t+1}|s_t, a_t)$.
Reward: The agent receives a reward $R_{t+1} = R(s_t, a_t, s_{t+1})$

Agent-Environment Interaction



The Markov Decision Process and Agent give rise to a **trajectory**: $\mathbf{S_0}$, A_0, R_1, $\mathbf{S_1}$, A_1, R_2, $\mathbf{S_2}$, A_2, R_3, $\mathbf{S_3}$, …

Markov Decision Process (MDP)



Environment at time t in state $s_t \in S$.

Action: - a_t following $\pi(a_t|s_t)$

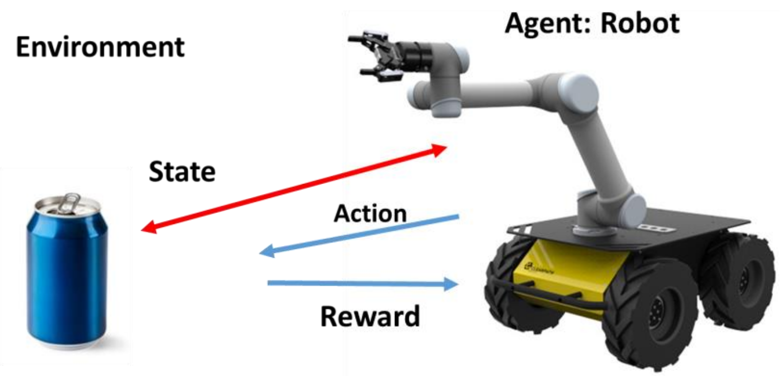
Result: - Environment state transition $T(s_{t+1}|s_t, a_t)$.

- Agent's reward $R_{t+1} = R(s_t, a_t, s_{t+1})$

Note:

- Functions T and R may or may not be known to the agent.
- Future rewards can be discounted by γ^k, where $\gamma \in [0,1]$, and k a future time step.
- Process can have episodes => a horizon H is used, with T the number of time steps to complete one episode from s_0 to s_T, …, etc.

Reinforcement Learning (RL)



Environment

- Can be fully or Partially Observable (=> PO-MDP)

Note:

- The decision process sometimes takes past observations into account.
- Obeying the **Markov-property**: all information should be maintained in the current state.

Our robot agent:

- **State** can be a camera estimate of the 3D position of the soda can with respect to the gripper.
- **Reward**
  - +1, if the robot gets closer to the soda can.
  - -1, if the robot gets farther away from the soda can.
  - +100 when it successfully picks up the soda can.

Markov Decision Process (MDP) Framework

Time

- can be abstract, stages

Actions

- low-level: voltages applied to a motor in a robot arm, …
- high level: grab lunch, grab can, recharge, …
- abstract: internal actions

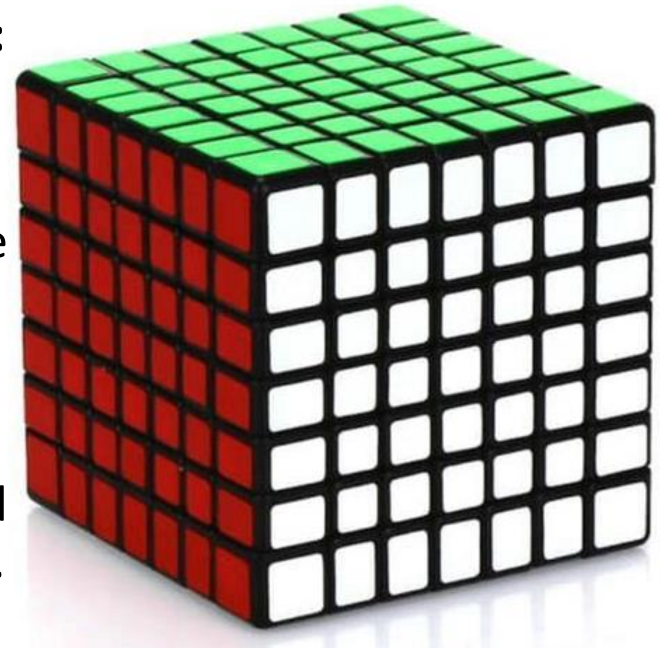
Environment and States

- low-level: sensor readings, …
- high level: symbolic descriptions of objects, …
- abstract: past sensations, subjective, etc.

Markov Decision Process (MDP) Framework

Boundary between Environment and Agent:

- motors, links, and sensors are part of environment
- Represents the limit of the agent's absolute control, not of it's knowledge



Note: An Agent may know everything about how it's environment works, but still it would be a challenging reinforcement learning task.

Example I: Pick and Place Robot

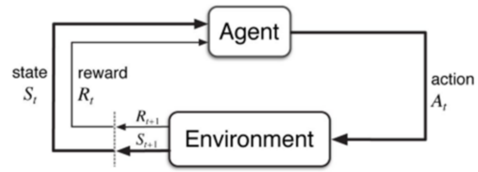
Task: control the motion of a robot arm in a repetitive pick and place task.
Goal: fast and smooth movements

Agent:
- Direct low level control of motors
- Low-latency information of position and velocities of mechanical links

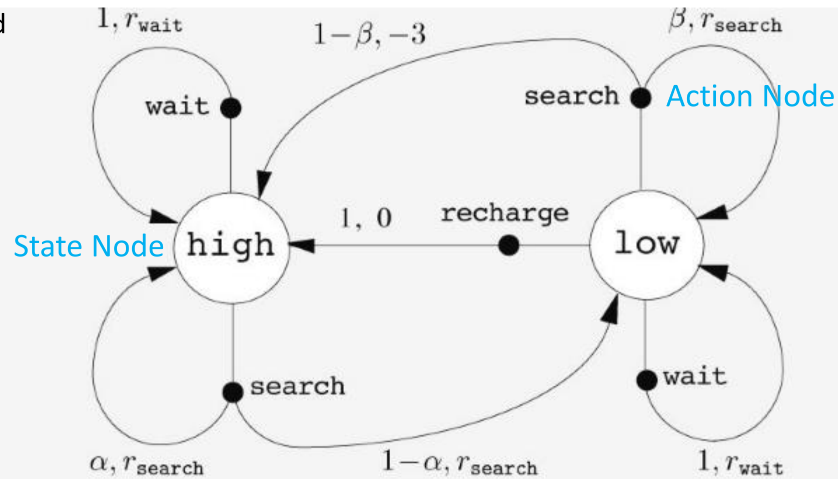
Actions
- Voltage applied to each motor at each joint
- Readings of joint angles and velocities

Reward
- +1 for each object that is picked and placed
- Small negative reward as function of the jerkiness of the motion (per moment).

Example II: Recycling Robot



Current state s	Transition Action a	Next state s'	Transition prob. $p(s' \mid s, a)$	Transition reward $r(s, a, s')$
high	search	high	α	$r_{\texttt{search}}$
high	search	low	$1 - \alpha$	$r_{\texttt{search}}$
low	search	high	$1 - \beta$	-3
low	search	low	β	$r_{\texttt{search}}$
high	wait	high	1	$r_{\texttt{wait}}$
high	wait	low	0	$r_{\texttt{wait}}$
low	wait	high	0	$r_{\texttt{wait}}$
low	wait	low	1	$r_{\texttt{wait}}$
low	recharge	high	1	0
low	recharge	low	0	0



High level agent decides to search, wait or recharge:

- Environment State space: two charge levels: high, low
- Robot Action set: state low -> {search, wait, recharge}; state high -> {search, wait}

Environment responds with state s' and reward r(s, a, s')

Goals and Rewards

- Agent receives after each time step t a reward R_{t+1}
- Goal is to maximize the total amount of received rewards.

The maximization of the expected value of the cumulative sum of a received scalar signal (called reward).

More formally (but still a simplification):

Sequence of rewards after time step t: $R_{t+1}, R_{t+2}, R_{t+3}, \ldots$

T final time step, sum of rewards $G_t = R_{t+1} + R_{t+2} + R_{t+3} + \ldots + R_T$

Reinforcement Learning (RL)

Goal:

- Maximize the expected discounted return:

$$G_t = R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{T+3} + \cdots = \sum_{k=0}^{\infty} \gamma^k R_{t+k+1}, \qquad \gamma \in [0,1]$$

Note, discount rate γ allows different scenario's:

- $\gamma \in [0,1]$ the discount rate.
- $\gamma = 0$, if only the immediate reward matters
- $\gamma = 1$, if future rewards weigh the same as the immediate reward

Reinforcement Learning (RL)

Goal:

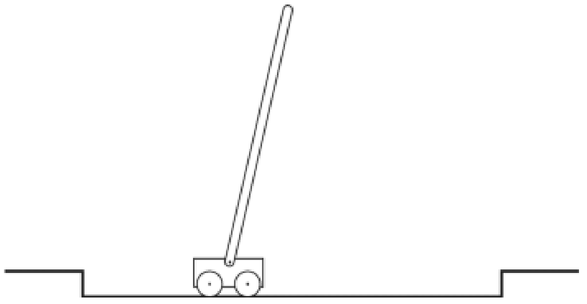
- Maximize the expected discounted return:

$$G_t = R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{T+3} + \cdots = \sum_{k=0}^{\infty} \gamma^k R_{t+k+1}, \qquad \gamma \in [0,1]$$

Note:

$$\begin{aligned} G_t &= R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{T+3} + \cdots \\ &= R_{t+1} + \gamma(R_{t+2} + \gamma R_{t+3} + \gamma^2 R_{T+4} + \cdots) \\ &= R_{t+1} + \gamma G_{t+1} \end{aligned}$$

Example III: Pole-Balancing



Objective: Apply forces to the cart such that pole does not fall over.
Failure: If pole falls, or cart runs off the track.

Task of pole-balancing seen as repeated attempts, episodes, during which it is balanced:
Reward: +1 for every time step without failure
$\Rightarrow$ expected return -> ∞ if successful balancing for ever.

Pole-balancing seen as a continuous task:
Reward: -1 on each failure, 0 otherwise.
=> discounted return related to $-\gamma^K$ ($\gamma \in [0,1]$), where K is the number of time steps before failure.

Policies and Estimations: Value Functions

Try to estimate value-functions (of states, or state-action pairs) that estimate for an agent:

1. how good it is to be in a state or
2. how good it is to perform a given action in a given state

(1) The **value function** of a state s under a policy π is defined as:

$$v_\pi(s) = \boldsymbol{E_\pi[G_t|S_t = s]} \qquad = \mathrm{E}_\pi[\textstyle\sum_{k=0}^{\infty} \gamma^k R_{t+k+1}|S_t = s], \text{ for all } s \in S$$

(2) The **expected return** starting from s, taking action a and further on following policy π is defined as:

$$q_\pi(s,a) = \boldsymbol{E_\pi[G_t|S_t = s, A_t = a]} \qquad = \mathrm{E}_\pi[\sum_{k=0}^{\infty} \gamma^k R_{t+k+1}|S_t = s, A_t = a]$$

Note: G_t is discounted return

Reinforcement Learning (RL)

Goal:

- Learn an optimal policy π^*, where

$$\pi^* = argmax_\pi G_t, \qquad \text{where } G_t = \sum_{k=0}^{T} \gamma^k R_{t+k+1}, \qquad \gamma \in [0,1],$$

$$\text{and} \quad R_{t+1} = R(s_t, a_t)$$

Methods:

- Brute Force, Tabular Methods, Monte Carlo Methods, DNN for RL, Adversarial RL, Sim-to Real Transfer DeepRL, etc.

Note: G_t is discounted return

[1] L. Pinto, J. Davidson, R. Sukthankar, A. Gupta,
Robust Adversarial Reinforcement Learning, March 2017.

Deep neural networks successes in the field of Reinforcement Learning:

- Fast computations
- Fast Simulations
- Improved networks

But, most RL-based approaches **fail to generalize**, because:

1. gap between simulation and real world
2. policy learning in real world is hampered by data scarcity

2024: [1] 909 citations.

RL Challenges for Real-world Policy Learning

The training of the agent's policy in the real-world:

- too expensive
- dangerous
- time-intensive

⇒ scarcity of data.
⇒ training often restricted to a limited set of scenarios, causing overfitting.
⇒ If the test scenario is different (e.g., different friction coefficient, different mass), the learned policy fails to generalize.

But a learned policy should be robust and generalize well for different scenarios.

RL in the Real World: use more robots

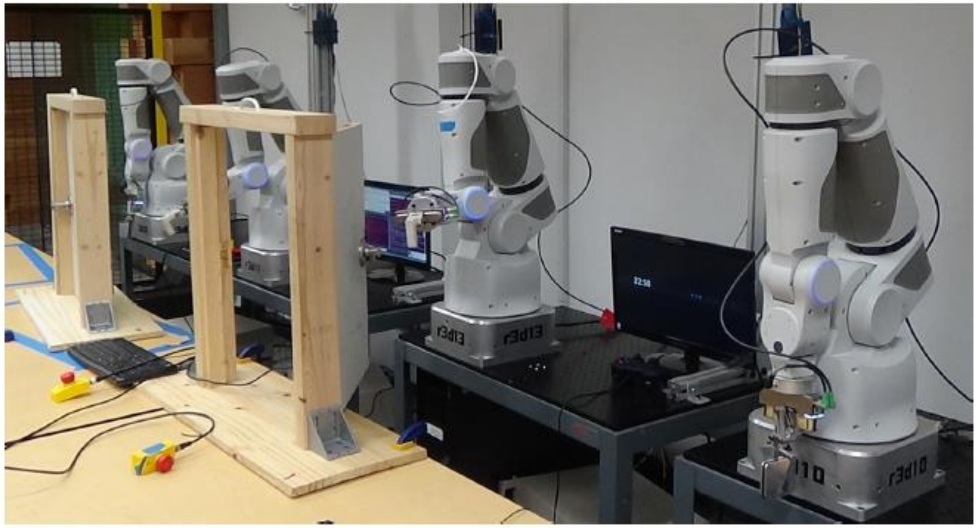


Fig. 1: Two robots learning a door opening task. We present a method that allows multiple robots to cooperatively learn a single policy with deep reinforcement learning.

From [2] Gu et al. , Nov. 2016.

Reinforcement Learning in simulation:

Facing the **data scarcity** in the real-world by
- Learning a policy in a simulator
- Transfer learned policy to the real world

But:
environment and physics of the simulator are not the same as the real world.

=> Reality Gap

This reality gap often results in an unsuccessful transfer, if the learned policy isn’t robust to modeling errors (Christiano et al., 2016; Rusu et al., 2016).

Robust Adversarial Reinforcement Learning (RARL)

Training of an agent in the presence of a **destabilizing adversary**

- Adversary can employ disturbances to the system
- Adversary is trained at the same time as the agent
- Adversary is reinforced: it learns an optimal destabilization policy.

Here policy learning can be formulated as
a zero-sum, minimax objective function.

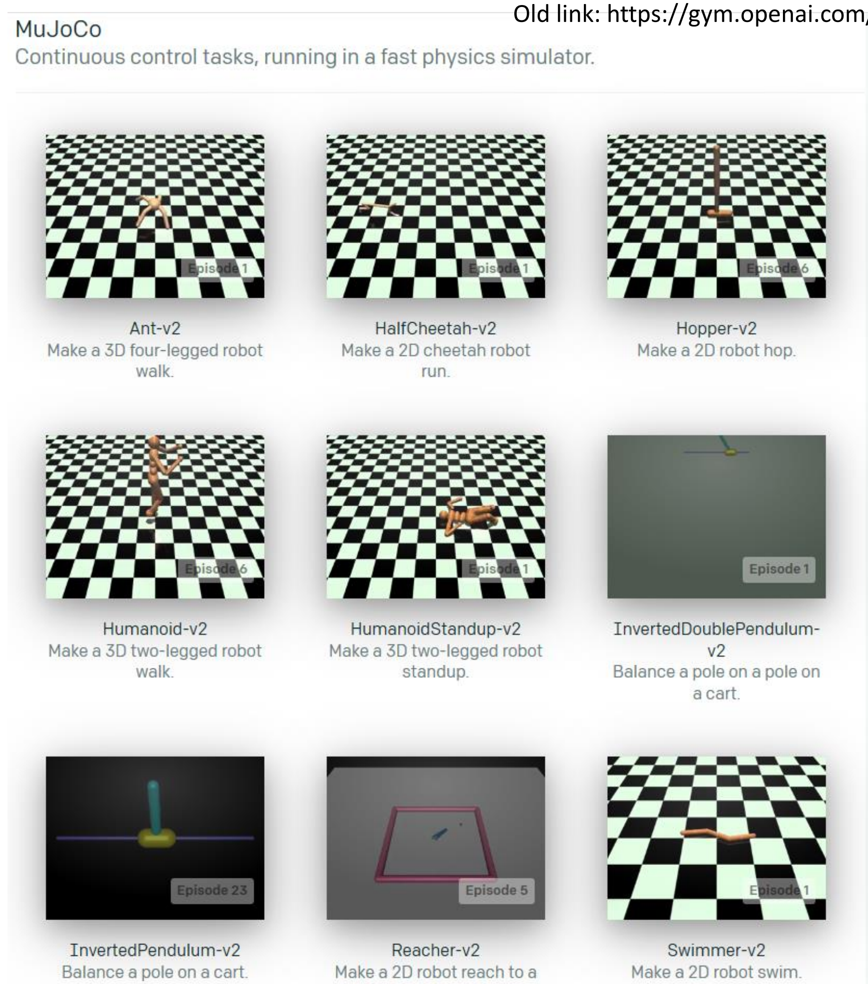
Minimax in zero-sum games: minimizing the opponent's maximum payoff.
Here a zero-sum game is identical to:
- minimizing one's own maximum loss, and to
- maximizing one's own minimum gain

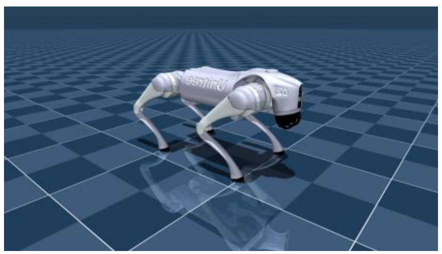
Zero-sum game: gain and loss cancel each other out.

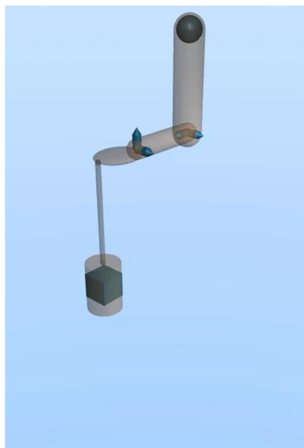
Experimental Environments

- InvertedPendulum
- HalfCheetah
- Swimmer
- Hopper
- Walker2d

Old link: https://gym.openai.com/







2024:
https://mujoco.org/
https://github.com/google-deepmind/mujoco/releases

Unconstrained Scenarios: Challenges

In unconstrained scenarios:

- the space of possible disturbances could be larger than the space of possible actions

=> sampled trajectories for learning etc. become even sparser

Challenges of unconstrained scenarios

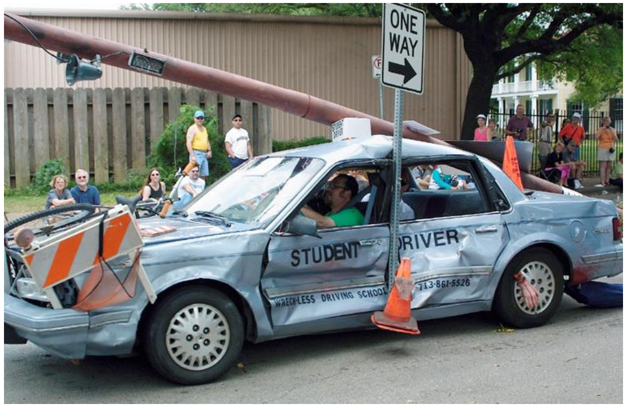
Use adversaries for modeling disturbances:

- we do not want to and can not sample all possible disturbances
- we jointly train a second agent (**the adversary**)
- goal of adversary is to impede the original agent (**the protagonist**)
  - by applying destabilizing forces.
  - rewarded only for the failure of the protagonist

=> the adversary learns to sample hard examples, disturbances that make original agent fail

=> the protagonist learns a policy that is robust to any disturbances created by the adversary.

Challenges of unconstrained scenarios



Use adversaries that incorporate domain knowledge:

- Naïve: **give adversary the same action space as the protagonist**
  - Like a driving student and driving instructor fighting for control of a dual-controlled car.

Proposal paper:

- exploit **domain knowledge**
- focus on the protagonist's weak points;
- give the adversary "super-powers"

=> it can affect the robot or environment in ways the protagonist cannot

e.g. sudden changes in frictional coefficient, mass, etc.

Adversary with Domain Knowledge

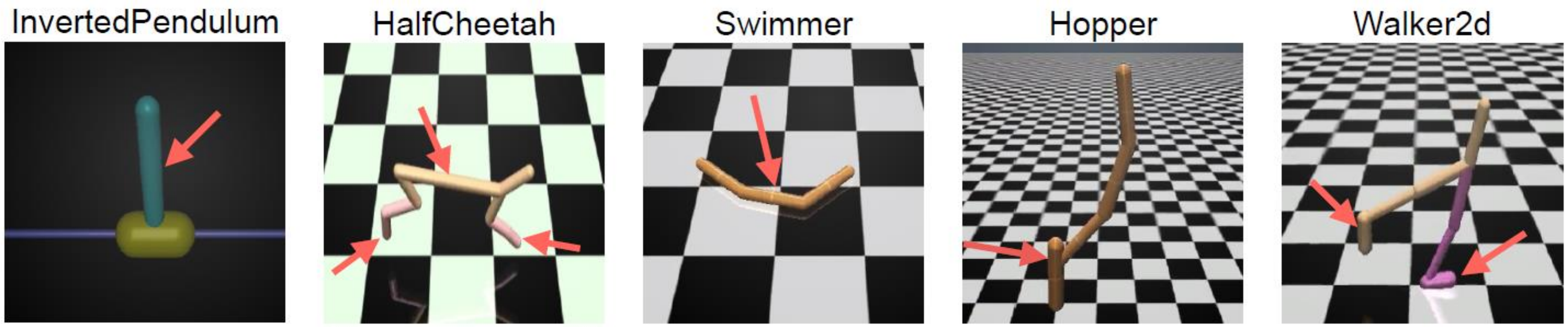


Figure 1. We evaluate RARL on a variety of OpenAI gym problems. The adversary learns to apply destabilizing forces on specific points (denoted by red arrows) on the system, encouraging the protagonist to learn a robust control policy. These policies also transfer better to new test environments, with different environmental conditions and where the adversary may or may not be present.

Figure from [1].

Standard Reinforcement Learning (RL)

RL for continuous space Markov Decision Processes

$(S, A, P, r, \gamma, s_0)$, where

S the set of continuous states
A the set of continuous actions
$P: S \times A \times S \to \mathbb{R}$ the transition probability
$r: A \to \mathbb{R}$ the reward function
γ the discount factor
s_0 the initial state distribution

Standard Reinforcement Learning (RL)

- RL for continuous space Markov Decision Processes

  $(S, A, P, r, \gamma, s_0)$, where

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  γ the discount factor

  s_0 the initial state distribution

Batch policy algorithms [Williams 1992, Kakade 2002, Shulman 2015]:

Learning a stochastic policy:

$\pi_\theta: S \times A \to \mathbb{R}$ which maximizes

$\sum_{t=0}^{T-1} \gamma^t r(s_t, a_t)$

the cumulative discounted reward

- Θ the parameters of the policy π.
- Policy π: probability taking action a_t given state s_t at time t

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2 Player γ discounted zero-sum Markov Game
(Litman 1994, Perolat 2015)

- **2 Player continuous space Markov Decision Processes**
  $(S, A_1, A_2, P, r, \gamma, s_0)$, where

  S the set of continuous states
  A_1 the set of continuous actions of Player 1
  A_2 the set of continuous actions of Player 2
  $P: S \times A_1 \times A_2 \times S \rightarrow \mathbb{R}$ the transition probability
  $r: S \times A_1 \times A_2 \rightarrow \mathbb{R}$ the reward function of both players
  γ the discount factor
  s_0 the initial state distribution

If Player 1 use strategy μ and Player 2 use strategy ϑ , then the reward function $r_{\mu,\vartheta}$ is given by:

$$r_{\mu,\vartheta}=E_{a^1\sim\mu(.|s),\, a^2\sim\vartheta(.|s)}[r(s,a^1,a^2)]$$

Player 1 tries maximizing while Player 2 minimizes the exp. cummulative γ discounted reward R^1
(=> Zero Sum 2 player game)

$$R^{1*} = \min_{\nu} \max_{\mu} R^1(\mu,\nu) = \max_{\mu} \min_{\nu} R^1(\mu,\nu)$$

Robust Adversarial RL Algorithm

The initial parameters for both players' policies are sampled from a random distribution.

Two phases

1. Learn the protagonist's policy while holding the adversary's policy fixed.
2. Learn the adversary's policy while protagonist's policy is held fixed.

Repeat until convergence.

In each phase a *roll*-function is used sampling the N_{traj} trajectories in environment $\mathcal{E}$.
$\mathcal{E}$ contains the transition function P and reward functions r^1 and r^2

Algorithm 1 RARL (proposed algorithm)

Input: Environment $\mathcal{E}$; Stochastic policies μ and ν (= ϑ in our notation)

Initialize: Learnable parameters θ_0^μ for μ and θ_0^ν for ν

for i=1,2,..N_{iter} **do**

  $\theta_i^\mu \leftarrow \theta_{i-1}^\mu$

  for j=1,2,..N_μ **do**

    $\{(s_t^i, a_t^{1i}, a_t^{2i}, r_t^{1i}, r_t^{2i})\} \leftarrow \text{roll}(\mathcal{E}, \mu_{\theta_i^\mu}, \nu_{\theta_{i-1}^\nu}, N_{\text{traj}})$

    $\theta_i^\mu \leftarrow \text{policyOptimizer}(\{(s_t^i, a_t^{1i}, r_t^{1i})\}, \mu, \theta_i^\mu)$

  end for

  $\theta_i^\nu \leftarrow \theta_{i-1}^\nu$

  for j=1,2,..N_ν **do**

    $\{(s_t^i, a_t^{1i}, a_t^{2i}, r_t^{1i}, r_t^{2i})\} \leftarrow \text{roll}(\mathcal{E}, \mu_{\theta_i^\mu}, \nu_{\theta_i^\nu}, N_{\text{traj}})$

    $\theta_i^\nu \leftarrow \text{policyOptimizer}(\{(s_t^i, a_t^{2i}, r_t^{2i})\}, \nu, \theta_i^\nu)$

  end for

end for

Return: $\theta_{N_{\text{iter}}}^\mu, \theta_{N_{\text{iter}}}^\nu$

Experimental Setup

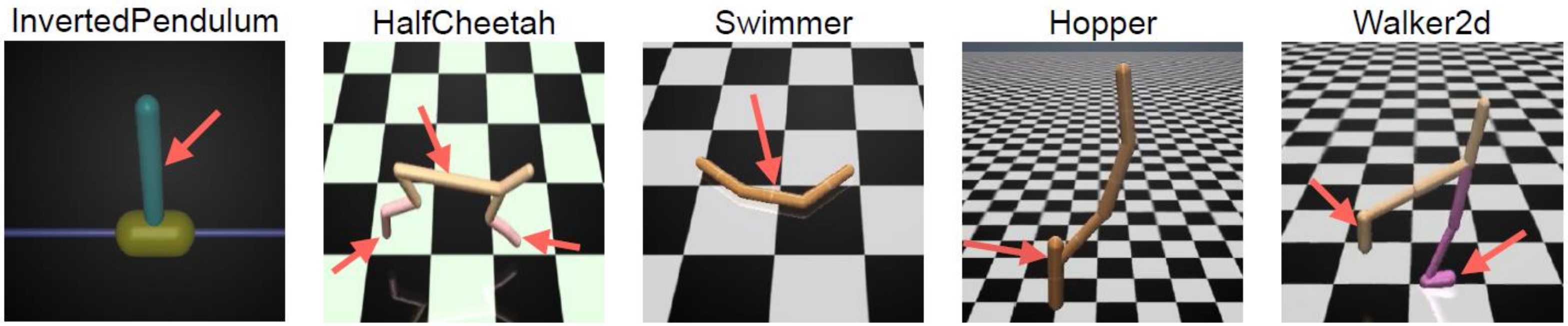
- Environments built using OpenAI gym's (Brockman et al., 2016).
- Control of environments with the MuJoCo physics simulator (Todorov et al., 2012) .

RARL is built on top of rllab (Duan et al., 2016)
Baseline: Trust Region Policy Optimization (TRPO) (Schulman et al., 2015)

For all the tasks and for both the protagonist and adversary,
a policy network with two hidden layers with 64 neurons per layer is used.

Robust Adversarial RL and the baseline are trained with
- 100 iterations on InvertedPendulum
- 500 iterations on the other environments

Hyper-parameters of Trust Region Police Optimization (TRPO) are selected by grid search.



InvertedPendulum

- State space 4D: position, velocity
- Protagonist: 1D forces; Adversary: 2D forces on center of pendulum

HalfCheetah

- State space 17D: joint angles and joint velocities, …
- Adversary: 6D actions with 2D forces

Swimmer

- State space 8D: joint angles and joint velocities, …
- Adversary: 3D forces to center of swimmer

Hopper

- State space 11D: joint angles and joint velocities, …
- Adversary: 2D force on foot

Walker2d

- State space 17D: joint angles and joint velocities, …
- Adversary: 4D actions with 2D forces on both feet

Actions of Adversary

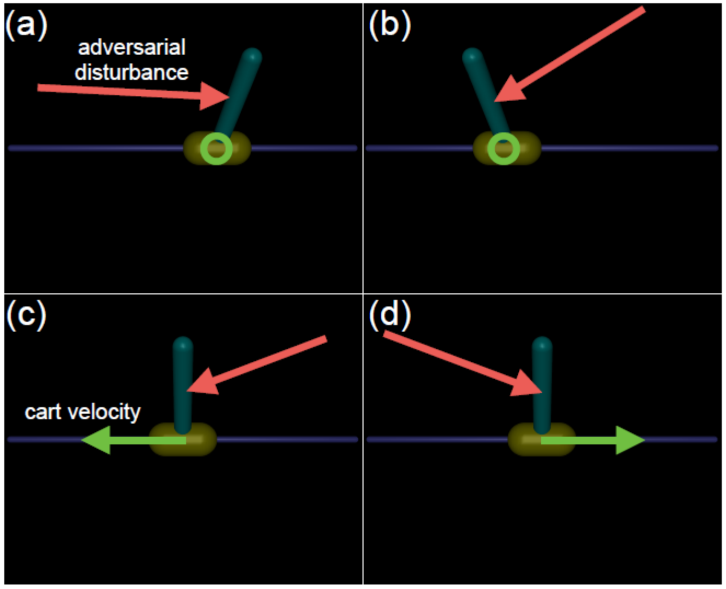


Figure 8. Visualization of forces applied by the adversary on InvertedPendulum. In (a) and (b) the cart is stationary, while in (c) and (d) the cart is moving with a vertical pendulum.

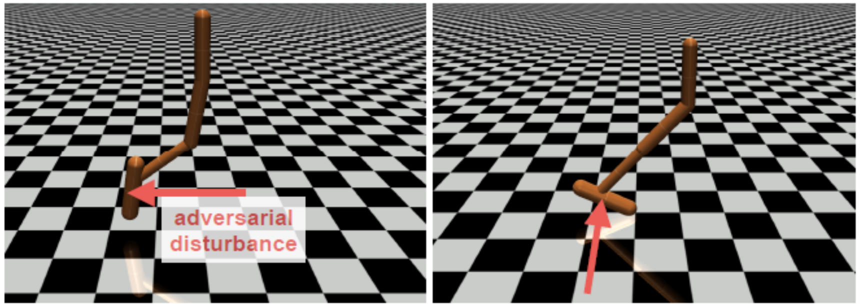


Figure 9. Visualization of forces applied by the adversary on Hopper. On the left, the Hopper's foot is in the air while on the righ the foot is interacting with the ground.

Results

RARL achieves better mean than Baseline.

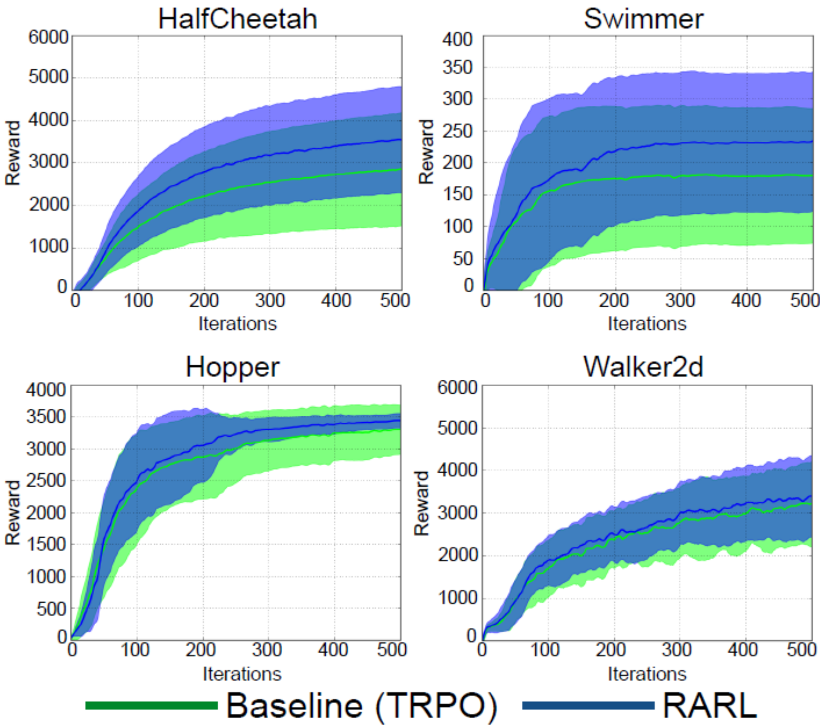


Figure 2. Cumulative reward curves for RARL trained policies versus the baseline (TRPO) when tested without any disturbance. For all the tasks, RARL achieves a better mean than the baseline. For tasks like Hopper, we also see a significant reduction of variance across runs.

Table 1. Comparison of the best policy learned by RARL and the baseline (mean±one standard deviation)

	InvertedPendulum	HalfCheetah	Swimmer	Hopper	Walker2d
Baseline	1000 ± 0.0	5093 ± 44	358 ± 2.4	3614 ± 2.16	5418 ± 87
RARL	1000 ± 0.0	5444 ± 97	354 ± 1.5	3590 ± 7.4	5854 ± 159

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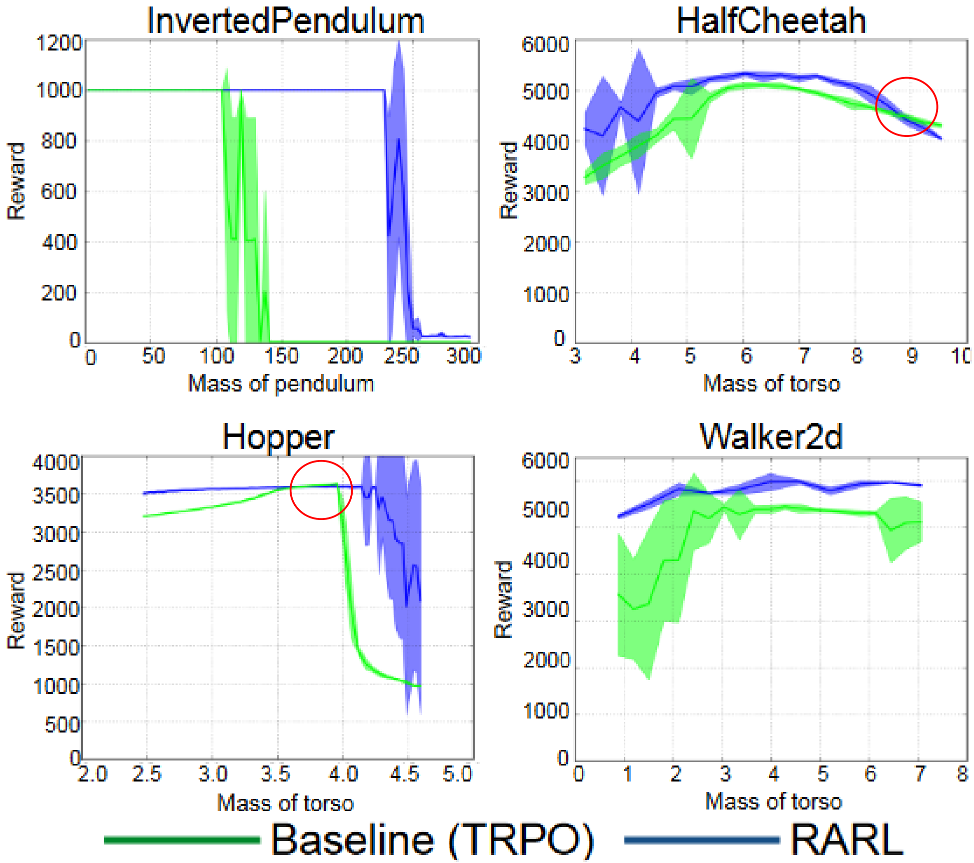
Higher is better

Results
Robustness to Changing Mass



Inverted Pendulum:
- mass of pendulum changed.

For others:
- mass of torso changed.

Results Robustness to Changing Friction

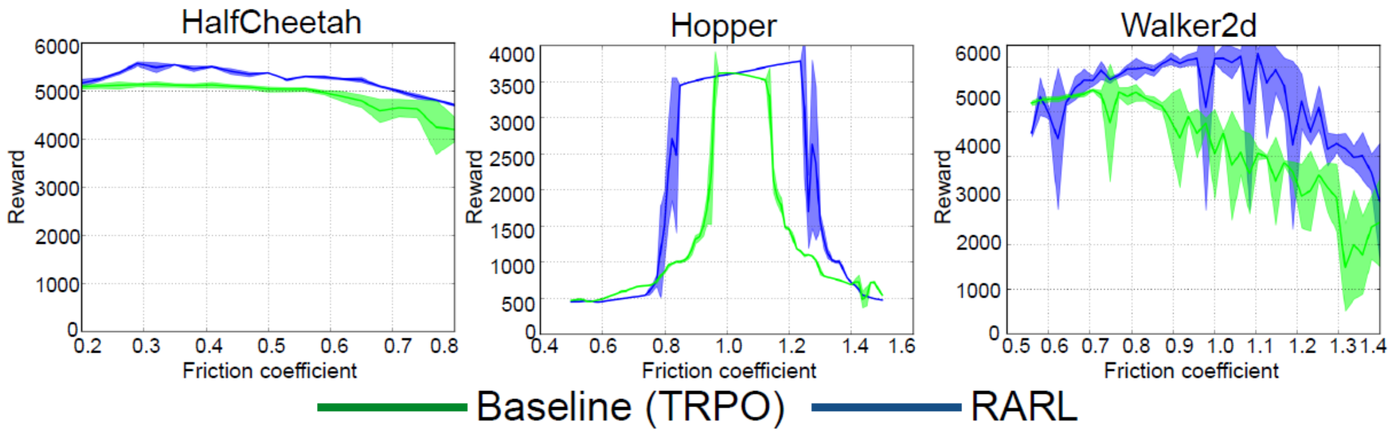


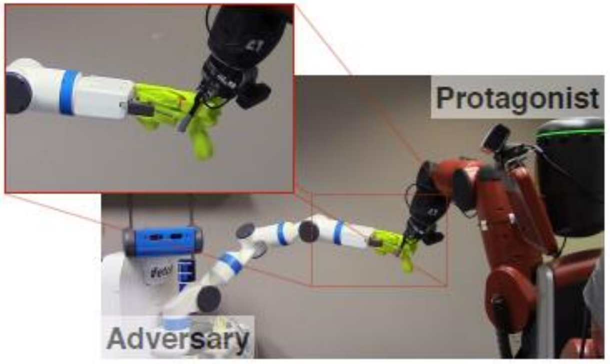
Figure 6. The graphs show robustness of RARL policies to changing friction between training and testing. Note that we exclude the results of InvertedPendulum and the Swimmer because friction is not relevant to those tasks.

Conclusions Experiment Results

1. improves training stability
2. is robust to differences in training/test conditions
3. outperform the baseline even in the absence of the adversary

Discussion

- Results for completely simulated environments: how does it translate to the real world?
- Adversary can be very easily too powerful. How do you incorporate/ formulate the adversary's powers in your RARL model?
- Can you think of a good hybrid setup: part simulator, part the real thing. Have the adversary coming from/to the real world into the simulation…
- …



From [4] Pinto et al., 2016.

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P. Zhai et al. Robust Adversarial Reinforcement Learning with Dissipation Inequation Constraint, AAAI 2023.

Problem: systems sensitive to disturbances or which are difficult to stabilize, it is easier to learn a powerful adversary than establish a stable control policy

=> strong adversary, unstable learning process, less robust policies

- Impose constraints to normal and adversarial agents
- Reduce the influence of disturbance on the reward/quality signals (see paper for details)
- applicable to RL algorithms, such as Proximal Policy Optimization (PPO, J. Schulman 2017), Trust Region Policy Optimization (TRPO, J. Schulman 2015), Soft Actor-Critic (SAC, T. Haarnoja et al. 2018)
- Used MuJoCo (https://mujoco.readthedocs.io/en/stable/overview.html) and GymFC (https://github.com/wil3/gymfc)

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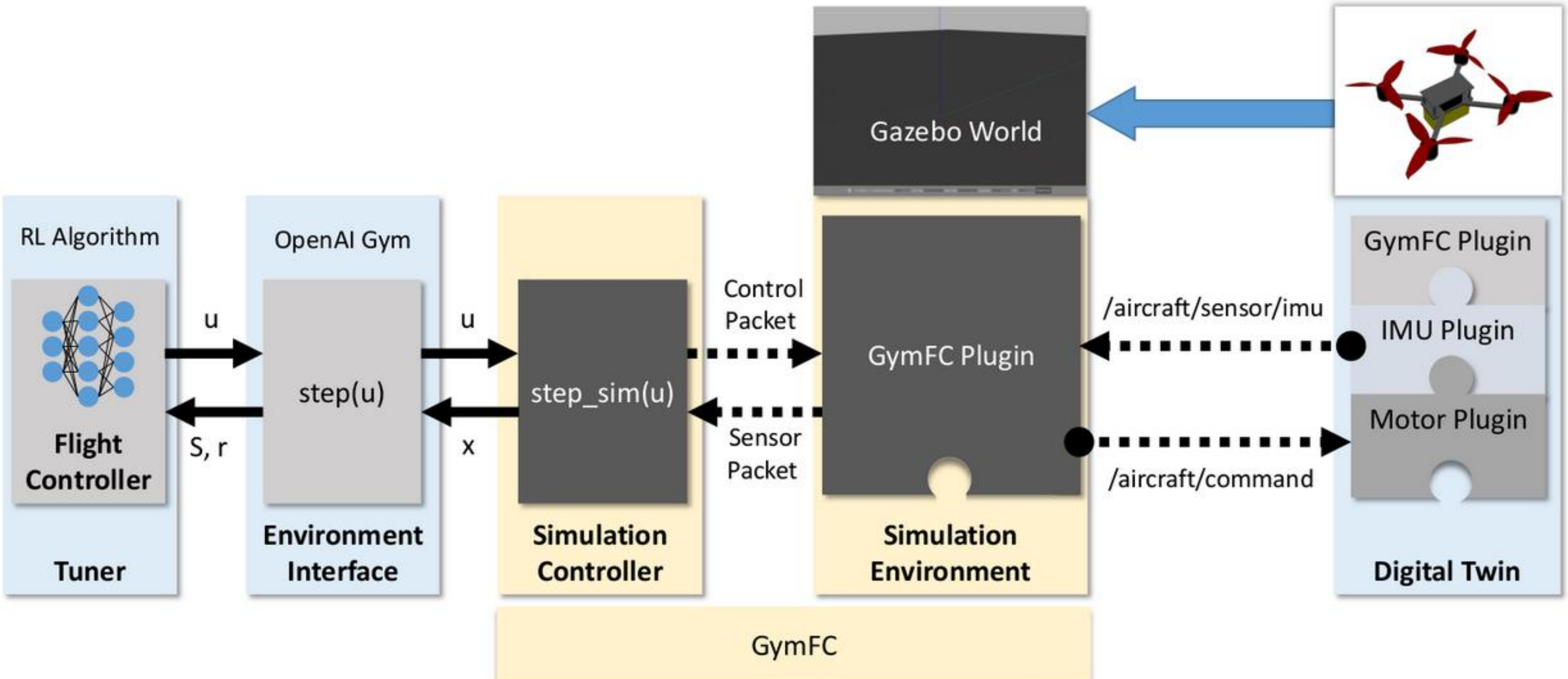
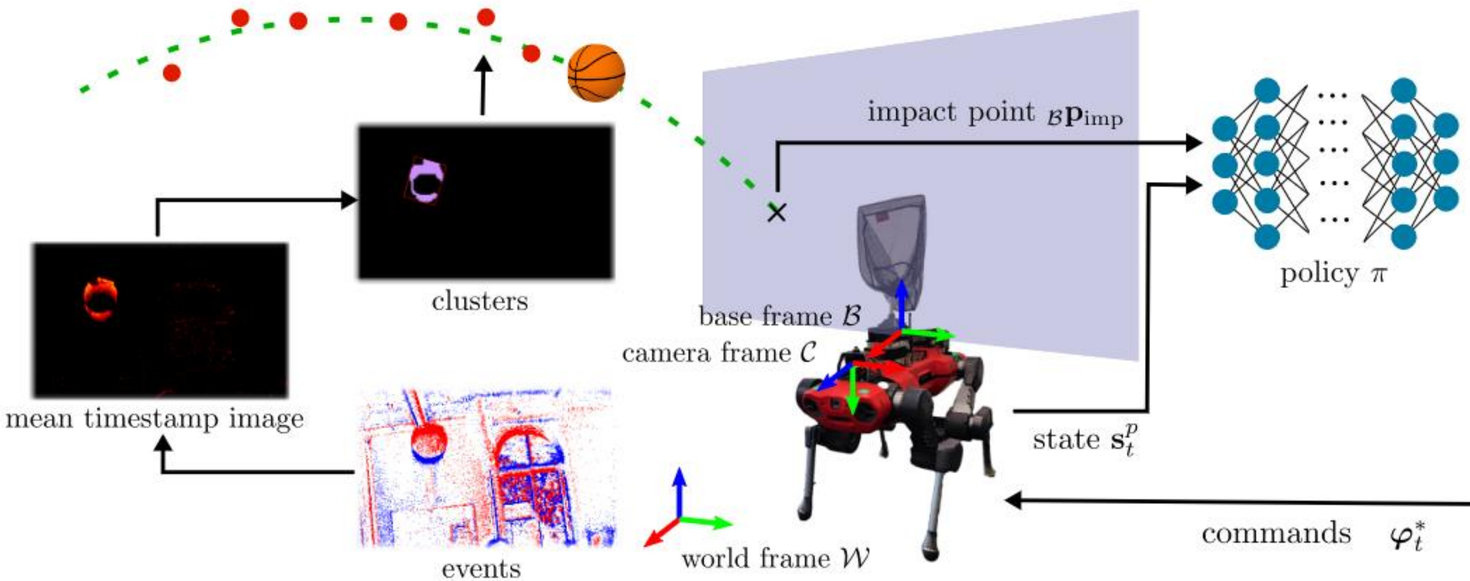
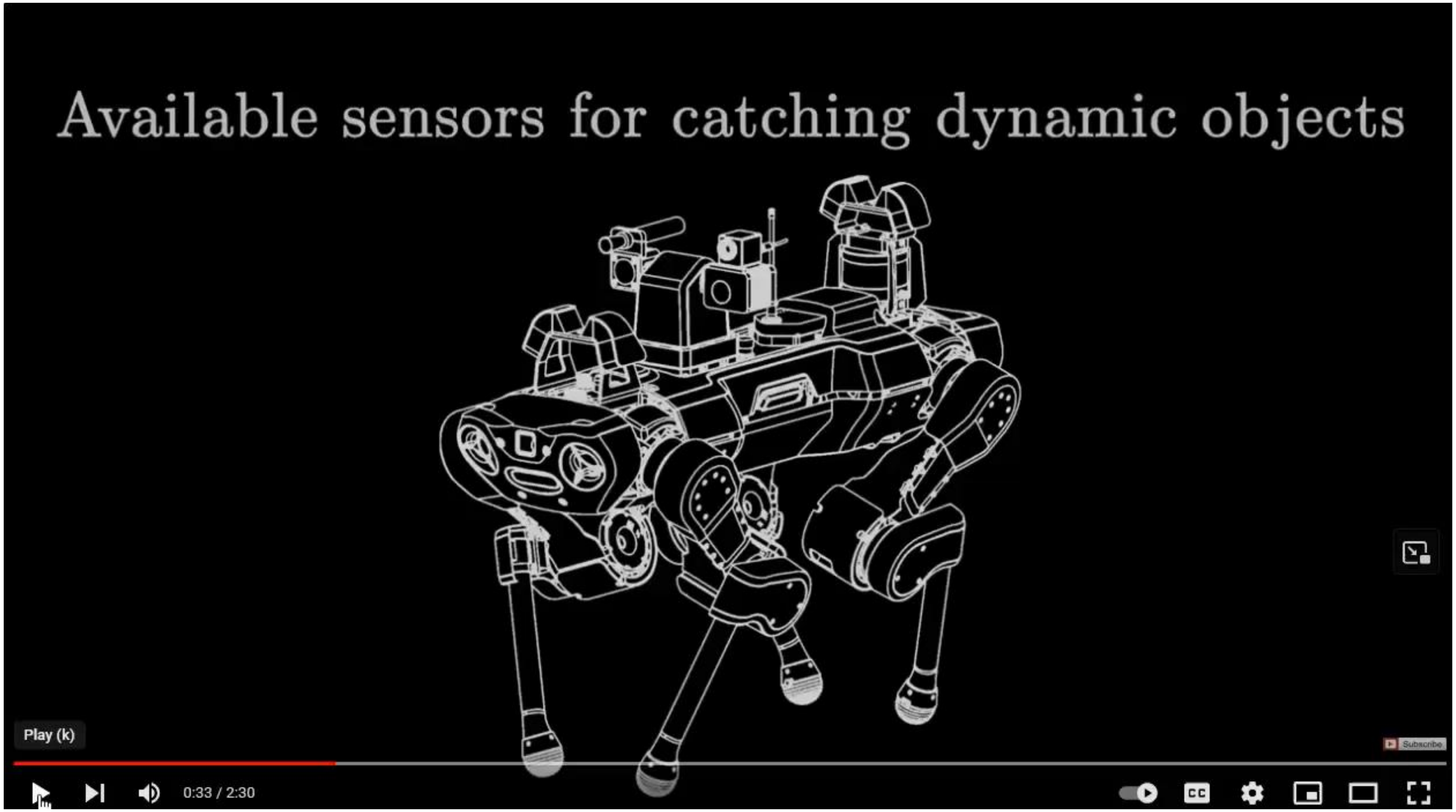


B. Forrai et al. Event-based Agile Object Catching with a Quadrupedal Robot, ICRA 2023.

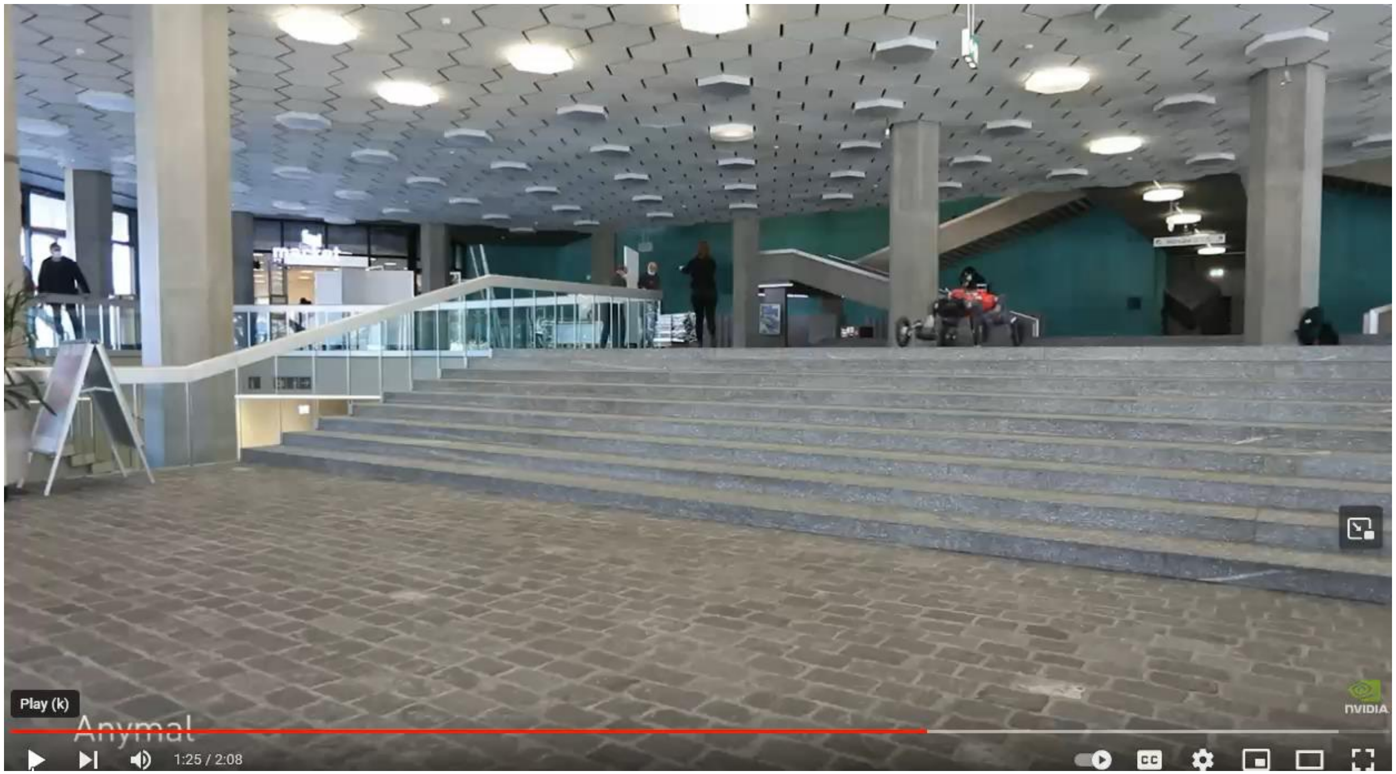




See also: UZH Robotics and Perception Group Videos:
https://www.youtube.com/@ailabRPG

NVIDIA Isaac Sim

An extensible robotics simulation platform powered by Omniverse™ for scalable, photorealistic, and physically accurate virtual environments for high-fidelity simulations.



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Very nice primer for RL to have a look at:

- https://spinningup.openai.com/en/latest/spinningup/rl_intro.html

- MuJoCo is a proprietary software that requires a license,
- There is a free trial and above that it is free for students.

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