Robotics final project : Robot Learning From Demonstration

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Abstract

Trying to teach a simple task, like swinging and balacing a pendulum, to a robot the same way you would teach it to a child, via demonstration, is an interesting research angle in robotics. In this project, we reproduce experiences from Atkeson and Schaal's paper *Robot Learning From Demonstration* (1997).

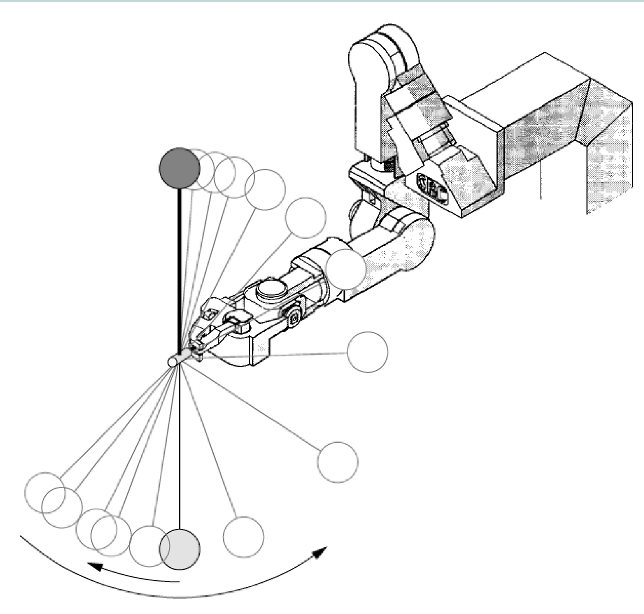

Figure: Figure from *Atkeson et Schaal*

Cart pole

The Gymnasium cart-pole environment presents a challenge where the goal is to keep a pole balanced upright on a moving cart. Interestingly, the dynamics of the pole are nearly linear when it is close to the upright position, making it a useful case for linear regression. By modeling the system's state—such as the cart's position, velocity, and the pole's angle and angular velocity—linear regression can be applied to estimate the forces needed to maintain balance. With that being said, we obtain the following linear state evolution model for $\dot{\theta}$:

Table: Linear Model Summary for Cart-Pole Evolution

Model	x	$\dot{x}$	θ	$\dot{\theta}$	u
x	1.00	0.02	0.00	0.00	0.00
$\dot{x}$	0.00	1.00	−0.01	0.00	0.20
θ	0.00	0.00	1.00	0.02	0.00
$\dot{\theta}$	0.00	0.00	0.31	1.00	−0.29

Armed with a linear model for the system's dynamic and with a reward function as defined by Atkeson and Schaal with omitted force term:

$$r(\mathbf{x}, \mathbf{u}) = 1200\theta^2 + 25\dot{\theta}^2 + 125x^2 + 50\dot{x}^2$$

we compute a Linear-quadratic regulator controller which is successful in the pole balancing problem.

Choosing the adequate arm

The arm we choose needs to be able to perform an horizontal linear movement that mimics the human movement for balancing the pendulum. After trying with the edo arm, we finally chose the UR5 arm for its simpler use. It will mimic a human movement akin to that of cleaning a table back and forth.

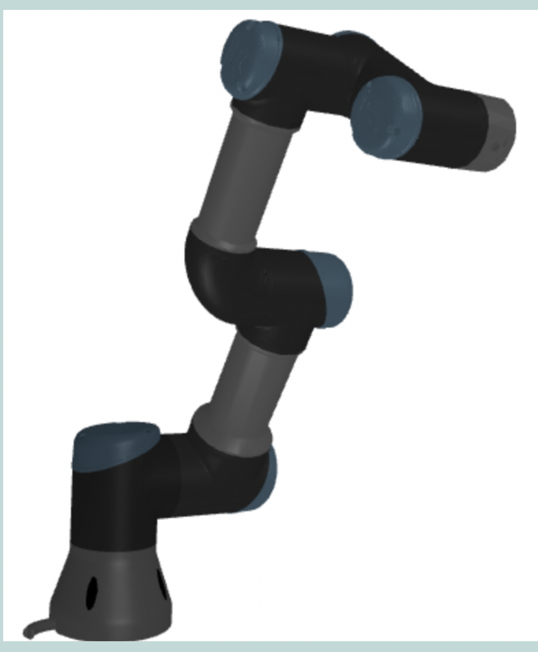

Figure: The UR5 arm

Controlling the arm via a PD controller

We hit a few bumps along the way with the PD controller, mainly due to PyBullet's physics being time-step dependent, which made things a bit unpredictable. We also had some confusion with **pybullet.TORQUE_CONTROL**, as its behavior wasn't exactly clear at first. To top it off, we forgot to compensate for gravity initially, leading to some strange results. But after a bit of trial and error, and some head-scratching, we got everything working perfectly in the end!

Balancing the pendulum in the inverted position

We extended our solution from the simple 1D cart-pole case to the more complex robotic arm operating in 3D space by focusing on the end-effector's trajectories. In the cart-pole system, the primary challenge was maintaining balance while responding to forces along a horizontal line. By drawing parallels, we treated the end-effector of the robotic arm as analogous to the cart, with its movements along a horizontal line mirroring the trajectory constraints of the cart-pole system. This approach allowed us to apply similar principles of stability and control, adapting them to account for additional degrees of freedom. The key was designing a trajectory for the end-effector that maintained the arm's balance while achieving precise positioning, enabling a seamless transition from 1D to 3D control problems

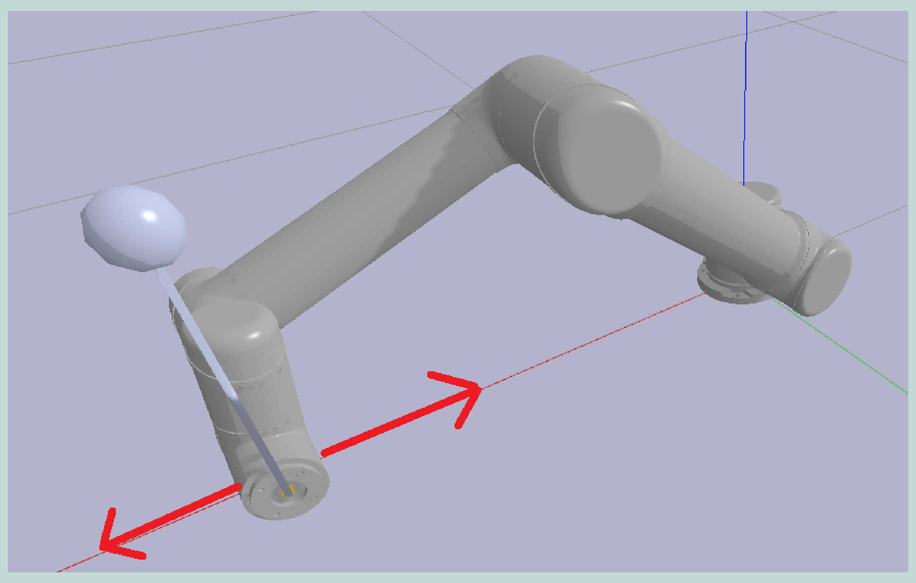

Figure: The horizontal line (red axis) for balancing the pendulum

Swinging the pendulum up

Here is the heart of the human demonstration : how to swing up the pendulum. As we don't have the material to reproduce the original experience and record a video of a human swinging the same pendulum as the robot would have to lift, we instead let the control of the robot be operated by detection of the mouse position. We then find by hierarchical/sequential optimization the policy that approximates best the human movement. Our approach is for now unrealistic since we use the same time steps as that of the human demonstration for the control optimization.

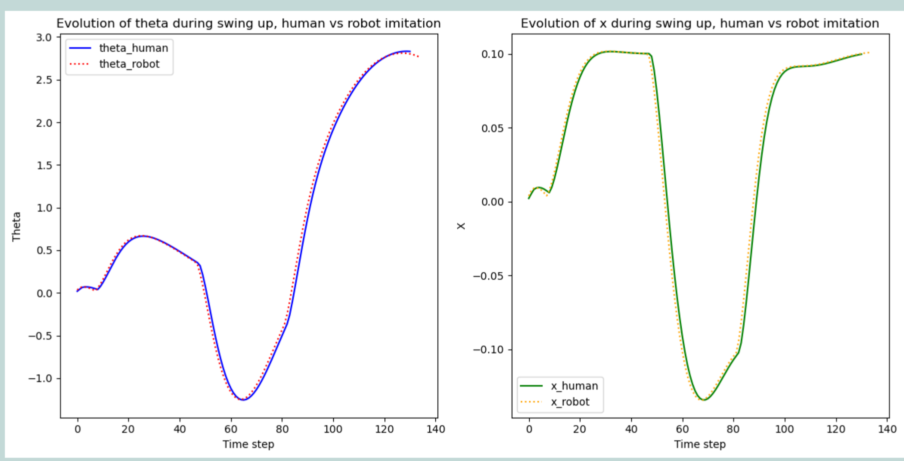

Figure: Human and robot performances at swinging up

Conclusion

We achieved success in the combined task of swing-up and balance by making the switch between the swing-up and balancing controllers at just the right moment. By ensuring that the swing-up controller leaves the system at the upright position with minimal velocity, the balancing controller is then able to take over and stabilize the pole.