Robot Locomotion

ECE594d

Prof. Katie Byl

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Prof. Katie ~~Byl~~ "Bill"

1. Locomotion overview

As roboticists, animals give great inspiration.

But, locomotion involves challenges:

- Underactuation (by nature)
- Controllability (to perform well)

Today: We'll look at some robot examples and discuss **underactuation** and **controllability**.

?

Introduction to Underactuated Robotics

Katie Byl

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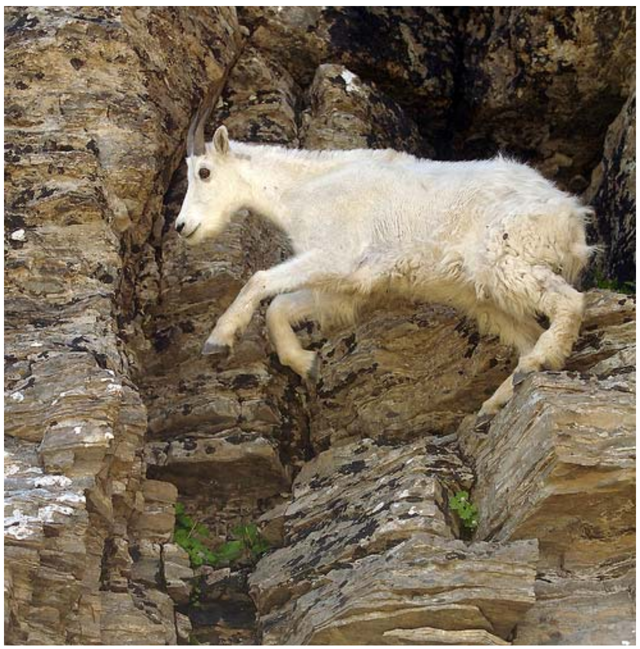

aka…

Agile robots: How?

Goals for today:

- Define underactuation
- Define controllability
- Look at different legged robots
  - Do they exploit their (passive) dynamics?
  - Are they agile? (Do they recover well?)

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Get you to agree (perhaps):

- **Control of underactuated robotics is essential for your own goals in robotics!**

Quick note on notation…

- I use **q** for **degrees of freedom** (DOF) (e.g., joint angles (not vel.) in a robot):

$$\ddot{q} = f_1(q,\dot{q},t) + f_2(q,\dot{q},t)u$$

(q matches the robot manipulator eqns…)

- …and **x** for **states** (e.g., position *and* vel.)

$$\dot{x} = Ax + Bu$$

(x matches **state-space notation**…)

Underactuated vs Fully Actuated

- Consider Newtonian, 2nd-order dynamics: $F = ma$
- More generally, acceleration is: $\ddot{q} = f(q, \dot{q}, t, u)$
- Forward dynamics of robot are affine with torque:

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Definition of fully actuated:

- **Instantaneous acceleration possible in any, arbitrary degree of freedom**
  - **Fully actuated:** $\text{rank}\left[f_2(q, \dot{q}, t)\right] = \dim\left[q\right]$
  - **Underactuated:** $\text{rank}\left[f_2(q, \dot{q}, t)\right] < \dim\left[q\right]$

Controllability

- In words, can you take the system from its initial condition to a desired, final state using some set of actuator inputs (over a finite time interval)?

- For a linear system (state-space format):

$$\dot{x} = Ax + Bu \qquad \text{(where n = dim(X) = \# of states)}$$

R is the "controllability" matrix:

$$R = [B \quad AB \quad A^2B \; \cdots \; A^{n-1}B]$$

  - **rank(R) = n   Controllable**
  - **rank(R) < n   Not controllable**

Locomotion is hard

- **Underactuation examples**
  - feet **push** but cannot **pull**
  - **Flying** and **swimming …**
  - even (often) **manipulation**
    [not always a rigid grasp…]

Why give a machine legs, anyway?

Traditional "trick" for fully-actuated robotics…

- **"Cancel out" natural (non-linear) system dynamics**

Standard **manipulator eqn**:

$$\mathbf{H}\ddot{q} + \mathbf{C}\dot{q} + \mathbf{G} = \mathbf{B}u$$

$$m\ddot{x} + b\dot{x} + kx = f$$

(Compare above to eq at left)

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Inertia matrix

$$\mathbf{H} = \mathbf{H}(q)$$

Centrifugal/coriolis

$$\mathbf{C} = \mathbf{C}(q, \dot{q})$$

Gravity

$$\mathbf{G} = \mathbf{G}(q)$$

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$$u = \mathbf{B}^{-1}\left(\mathbf{H}\ddot{q} + \mathbf{C}\dot{q} + \mathbf{G}\right)$$

← **invert matrix B**

- **Turn nonlinear dynamics into linear dynamics**
  - We have lots of tools to control linear systems!
- **Only works for VERY good model of dynamics…**
- **Only works if fully actuated**

Example: Honda’s ASIMO

Motivation: Can’t we do better?! [Part 1 of 2]

ASIMO strategy:

- Mimic a fully-actuated robot (34 servo motors)
- Use high-gain feedback
  - therefore, high torque required (short battery life)
- “Cancels out” natural dynamics

Disadvantages:

- 20x cost of transport (energy use) of human walking
- Control limited to a small part of state space
  - Must go slowly
  - Cannot deal with much uncertainty in terrain

Motivation: Can't we do better?!   [Part 1 of 2]

Motivation: Can't we do better?! [Part 2 of 2]

- Airplanes
  - A4 Skyhawk: 720 deg/sec max roll
  - Blackbird jet: 2000 mph = 32 body lengths / sec
- Birds
  - Barn swallow: >5000 deg/sec max roll
  - Pigeon: 50 mph = 75 body lengths / sec
- Birds and Insects adapt almost instantly to gusts, etc.

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General approach for underactuated control:

1. Must reason about the future (path planning…)
2. Exploit coupling of natural dynamics (not cancel!)

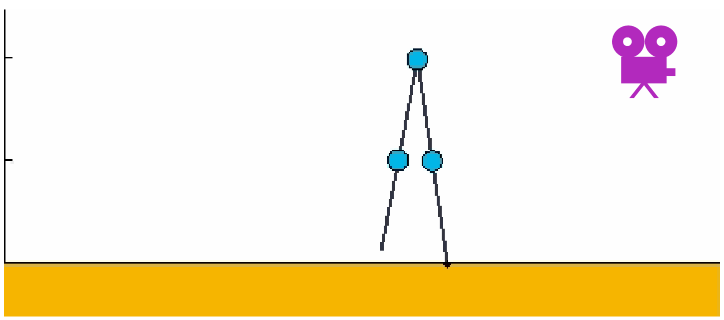
Passive dynamic walking: efficient but fragile

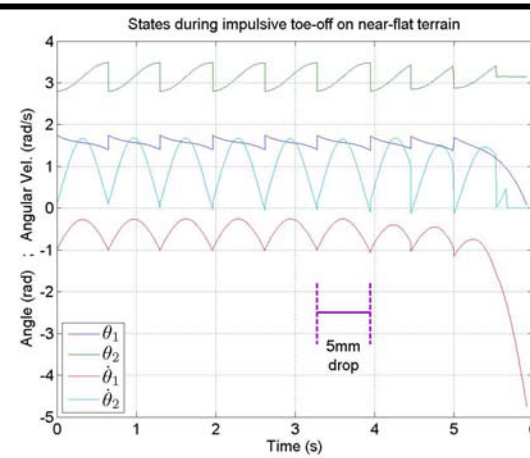
Purely passive (left)

Collins, Wisse and Ruina, 2001.

Actuated walker (right)

Hobbelen, 2008.





Actuation: impulsive toe-off at each step.

Leg = 1m, 0.005m drop in .34m step, or about 1°

Introduction — Kinodynamic Planning — Quantifying metastability — Optimizing Control

ZMP-based humanoids: complexity is good *and* bad

- fully-actuated, sequential kinodynamic planning▲
- highly choreographed

▲ Canny, Donald, Reif and Xavier, 1988.

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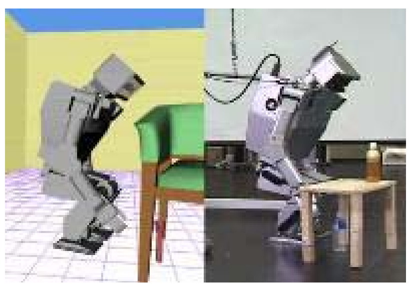
1. **find feasible kinematic poses**
2. **turn up speed (slower is safer)**



RRT ♠ : rapidly-exploring, randomized trees

♠ **LaVale and Kuffner, 2000.**

ASIMO (Honda) **HPR-3** (Kawada / AIST)

Fully-actuated regime. Zero-moment point♦ (**ZMP**) planning
e.g., Preview Control ♣ of ZMP

♣ **Kajita, 2003.**

♦ **Vukobratovic, 1975.**

Rugged-terrain robots: dynamically capable

- **RHex**
  Altendorfer, et al., 2001.
- **BigDog**
  Buehler, Playter, Raibert, 2005.

Foothold selection not solved