

Robot Locomotion

ECE594d

Prof. Katie Byl

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^ “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

Introduction to Underactuated Robotics

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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: $\text{rank}[f_2(q, \dot{q}, t)] = \dim[q]$
 - Underactuated: $\text{rank}[f_2(q, \dot{q}, t)] < \dim[q]$

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):

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

R is the “controllability” matrix:

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

- **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**:

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

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

(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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$$u = \mathbf{B}^{-1}(\mathbf{H}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{G}) \quad \leftarrow \text{invert matrix } \mathbf{B}$$

- 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.

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

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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)

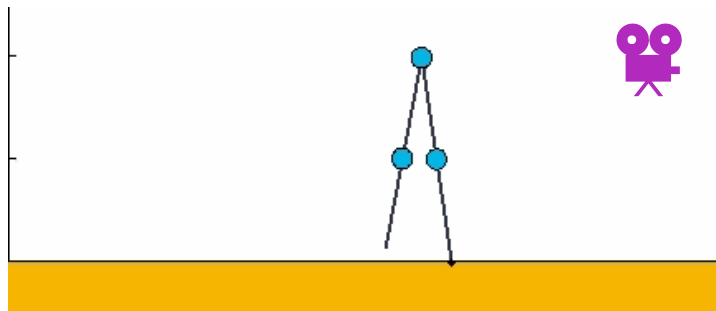


Collins, Wisse and Ruina, 2001.

Actuated walker (right)

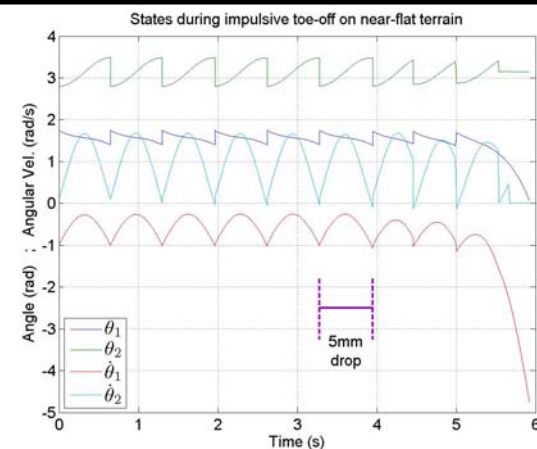


Hobbelen, 2008.



Actuation: **impulsive toe-off at each step.**

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



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

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

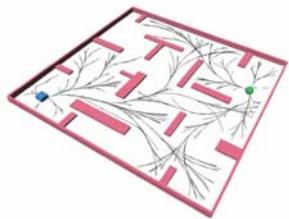
▲ Canny, Donald, Reif and Xavier, 1988.

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



RRT ♠ : rapidly-exploring, randomized trees

♠ LaValle 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

