Lec 1

q = joint angles
u = input

Given $\ddot{q} = f_1(q,\dot{q}) + f_2(q,\dot{q})u$
Given $\ddot{q}^d$ (desired accel)
then $u = f_2(q,\dot{q})[\ddot{q}^d - f_1(q,\dot{q})]$

$\Rightarrow \ddot{q} = \ddot{q}^d$

Feedback cancellation

can think of system dynamics as
Feedback equivalent to $\ddot{q} = u$ (double integrator, has optimal solns)
still must take actions over time to origin
but know everything about controller

Robotics did this for 50 yrs, but f_2^{-1} may be power hungry/require high torques

"Erase" dynamics, impose w/ potentially lots of torque diff dynamics. partially limited by motors & control philosophy

Now, using stronger optimization tools to break out of current mold

Walking robots not fully actuated unless in the case of having big flat foot that's attached to ground and pretend no DOF btwn foot and ground that constrains motion robot can take. Now you act like fully actuated. In this regime you can make yourself a clockwork man. Such that we can think of robot as one big robot arm bolted to ground even when one leg comes off ground (as one leg is always bolted to ground)

<u>Things that break feedback equivalence:</u> (make robotics interesting, have to think of long-term consequence of actions)
W/ input saturation (controller demands torques that can't be produced)
State constraints (i.e. inequality constraint robot hand can't be inside table)
Model Uncertainty

Input saturation by generalized definition of under-actuated would make system under-actuated $u \in [-10,10]$
State constraints (holonomic, non-holonomic)

Subtlety in definitions: Put very large torques and have no limit on bandwidth in case of no coupling (hack the parameters), can effectively make underactuated system look almost fully actuated

Some gym environments lost essence of dynamics they were intended to model to make learning curve look better

Study of walking robot =study of actuated robots (unless any portion of robot bolted to ground, then fully actuated)
Config to describe location of body in space
Humanoid is under-actuated even though more tendons and muscle tissue (dim of u) than joints (dim of q). Because can't immediately control equations of motion of center of mass. As soon as i jump into air, going to take ballistic trajectory excluding aero effects. Dim m motors can't control degrees of freedom.

Drake has symbolic engine that exposes symbolic structure/derivations of equations for certain algos that need it

Manipulator Equations for rigid body mechanics

$$\underbrace{M(q)}_{\text{mass matrix (inertial matrix)}}\ddot{q} + \underbrace{C(q,\dot{q})}_{\text{Coriolis terms}}\dot{q} = \underbrace{\tau_g(q)}_{\text{gravity terms}} + \underbrace{B}_{\text{actuation selector}}\underbrace{u}_{\text{torque input}}$$

Exception: if using quaternions use diff notation

$M(q) > 0$ mass always pos (positive definite)
$T = \frac{1}{2}\dot{q}^T M(q)\dot{q}$ ($\frac{1}{2}mv^2$ in matrix form)
$\ddot{q} = M^{-1}(q)[-C(q)\dot{q} + \tau_g(q) + Bu] + \tau_{friction}$

$f_2 = M^{-1}(q)B$

if M known full rank & reversible then we only need to ask if B is full row rank (underactuated or not)

fully actuated - B is identity matrix
actuator for every motor
if low rank can't do feedback linearization

troody Pete leg lab

HONDA P2, P3, Asimo
passive dynamic walkers $\rightarrow$ heavily actuated vs natural dynamics

Moral of story: push limits of natural dynamics with minimal control
Algebraicly slightly different from full actuation but very different in rollouts

Hierarchy of controllers
Some are making that assumption of zero moment point true, rest leverage that assumption
Also requires biggest moment are at ankle

Start of leg lab was dynamic robots (Marc Raibert founder of Boston dynamics) before HONDA. Running dyanamics easier than walking as you could throw yourself in air and do intermittent control

ATLAS- exploiting dynamics, writing optimizations to leverage dynamics and not cancelling them out
A scientific challenge. Humans have motor control systems that solve this problem but we don't know how to solve it as engineers
RL to get to limits of performance

Lec 1

NOT JUST LEGS
Moral equivalent to feedback linearization in aircraft/drones is staying in low angle of attack and airflow stays attached to wing, then have considerable control authority. Safe zone. Flaps/aelerons have significant authority of over pitch and the like

Birds don't restrict themselves to this small envelope. For example when they go on a perch. They go into severe post-stall maneuvers.
Clear airflow separation. Air not attached to wings. Go into stall case, but still land
Separated flow, lose control

Rock placed in front of trout in water tunnel. Rock sheds vortices. Trout adapts gait accordingly, called von karman gait
Trout is dead. It can swim upstream since mechanics of body designed to resonate with vortices that it experiences in the world turn the energy in the vortex straits into forward propulsion with no intelligence just dynamics
Dynamics is beautiful and you should master it not cancel it out

Machine learning motivation: Using perception to operate close to limits of vehicle