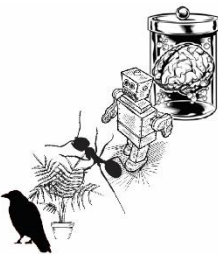


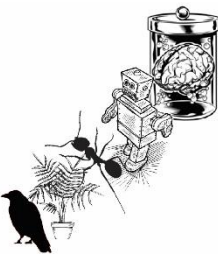
Intelligence in Animals and Machines

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THE MOTOR CONTROL PROBLEM



Motor Control is hard

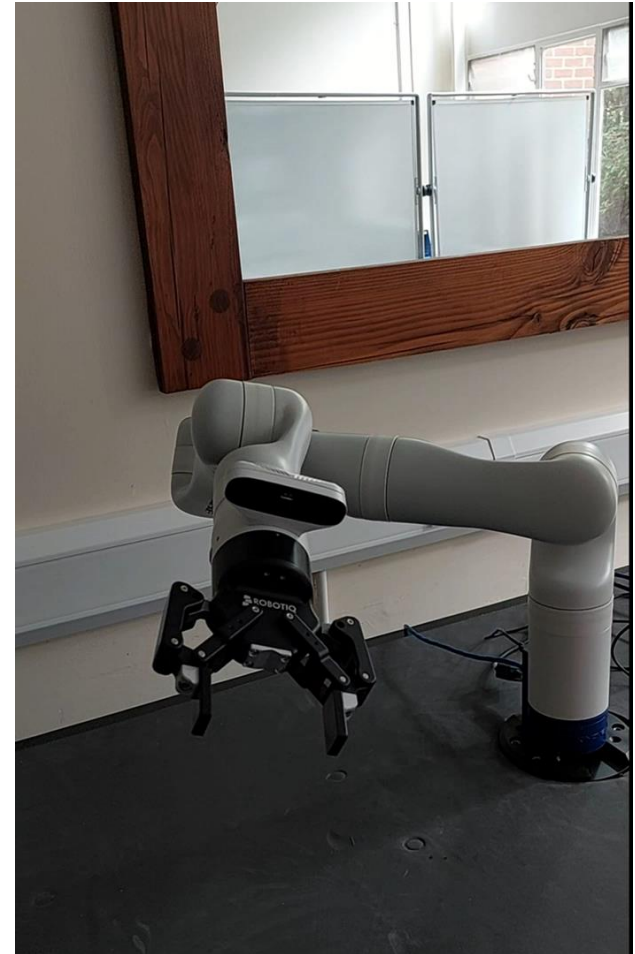


How do we control a (robot) arm?

- Reflect on problems by thinking about moving a robot arm
- One end fixed to ground (or robot body)
- Several joints with rotation around different axes and linear motion



How do I move gripper to position (x,y,z) ?
What forces needed?



- Inverse kinematics, which is hard. Why...?



Forward kinematics



To understand the inverse problem, consider **Forward kinematics**:

“If I fix the joint angles at *these* specific values, what are the resulting (x,y,z) coordinates and orientation of the hand?”

Only one
answer
Easy maths!



Inverse kinematics

However we need to solve **Inverse kinematics**:

“If my arm is hanging loose, and I want to move it to *this* (x,y,z) position and orientation to pick up the coffee – how do I get there?”



Infinite number of paths, infinite set of velocities, infinite possible solutions, not all sensible or efficient.
Horrible Maths!

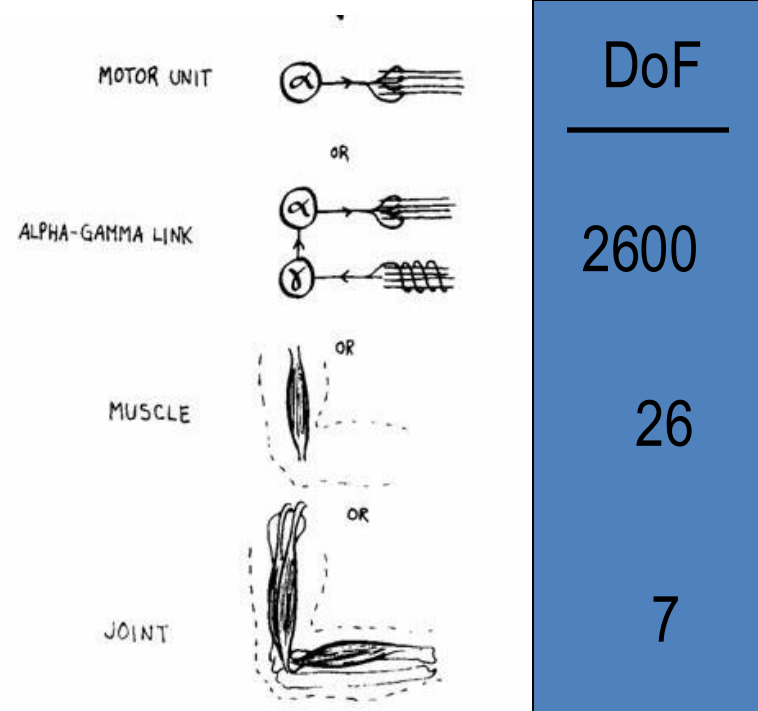


Problem 1: Redundancy

- Each position described by only 3 variables: (x,y,z) coordinates of the hand (we're ignoring rotations at this point)
- But arm and body contain many more degrees of freedom...
- Can have same hand position with different arm/body positions
- *Problem is underdetermined and system is redundant*

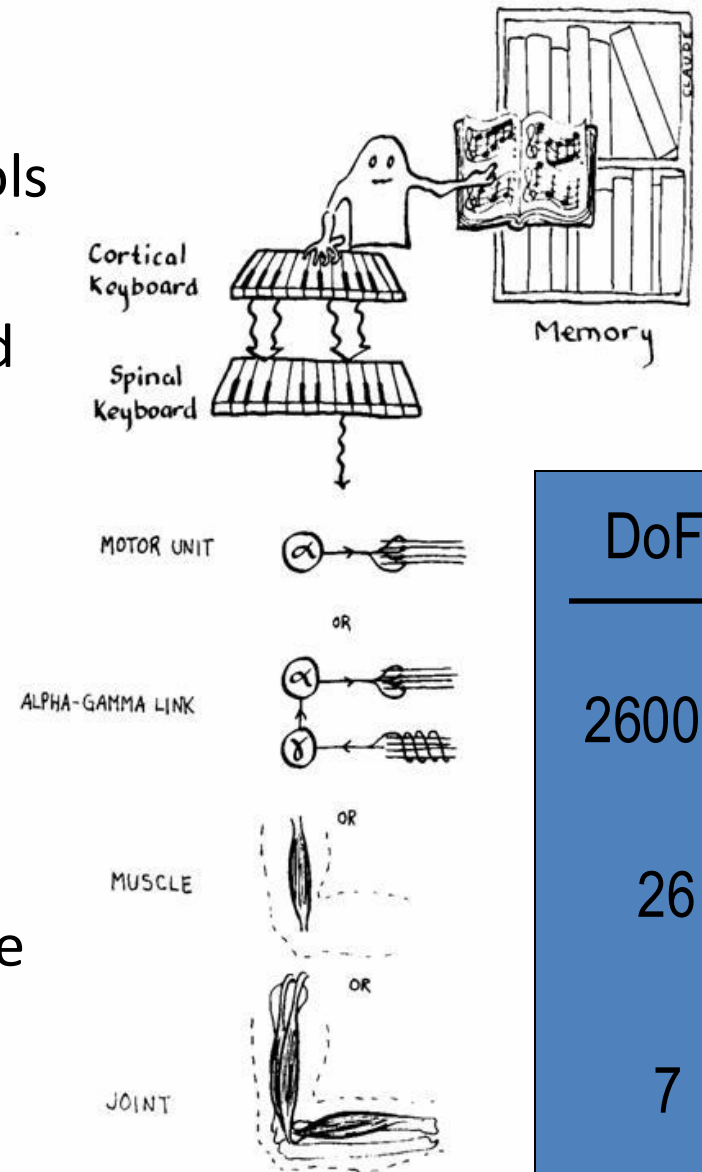
Consider arm:

- 26 muscles act across 7 joints
- multiple muscle activations achieve same position (eg stiffen arm without moving hand)
- Muscles innervated by 2600 motor neurons
- *Redundancy at multiple levels*



The Degrees of Freedom Problem

- Raises the spectre of the “Cartesian Puppeteer”: a homunculus who controls joints through countless motor units
- Imagine a puppet with limbs controlled by 1000 strings: which to pull?
- Why?
- Redundancy provides flexibility: Different strategies can be chosen depending on conditions
- But makes the problem very hard as we have many degrees of freedom to control



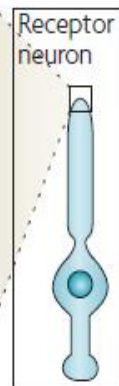
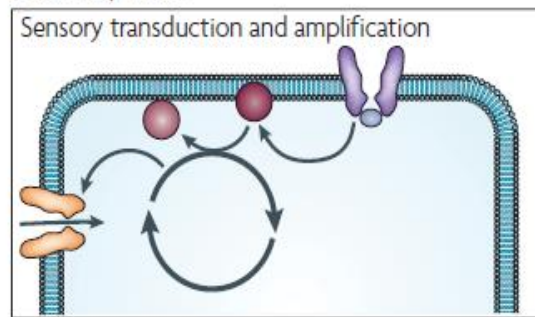
Problem 2: Delays

- In addition, control is complicated by various delays in neural circuits
 - Presynaptic signals take 1-2ms to get to postsynaptic sites
 - Axons can take 1-20ms to conduct a signal dependent on length and myelination
 - Resistance and capacitance of dendrites also cause a range of delays
- Delay in short spinal reflex $\sim 14\text{ms}$, in visual system 200-300ms
- Feedback is also delayed by different amounts dependent on the neural pathway (visual vs proprioceptive)

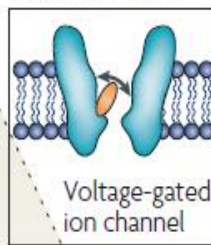


Problem 3: Noise in the nervous system

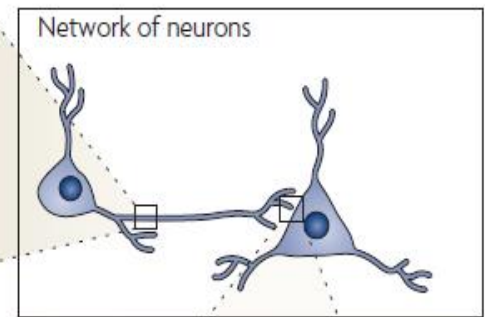
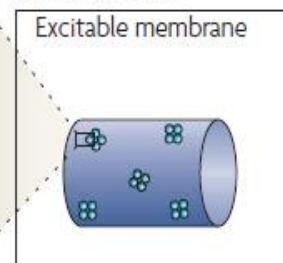
a Sensory noise



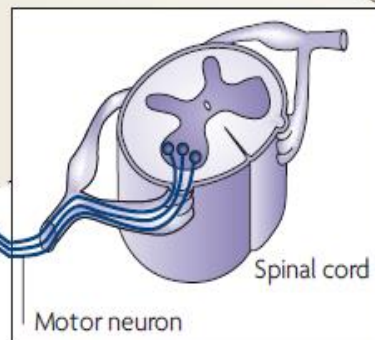
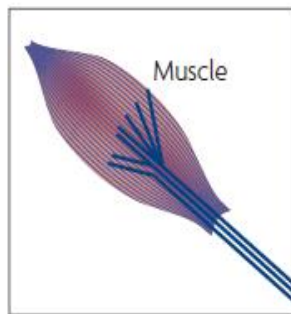
b Cellular noise



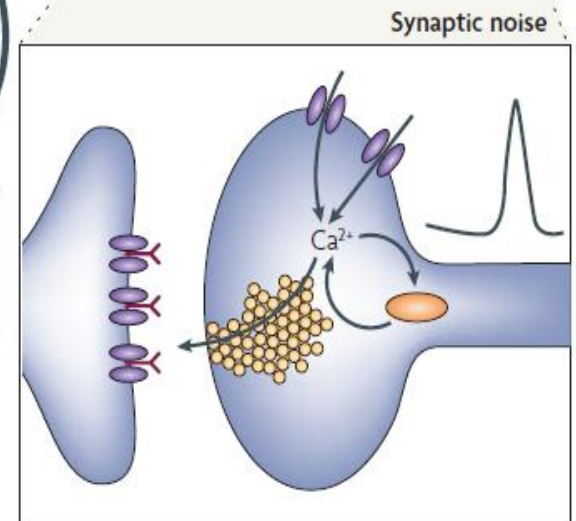
Electrical noise



c Motor noise



Spinal cord



Faisal, Selen & Wolpert
(2008) [Noise in the nervous system](#). *Nature Rev Neuro.*

Problem 4: Non-linearities

- Noise problem exacerbated because relationship between a motor command and the resulting body movement depends in a *non-linear* way on other factors
- Effect of muscle activation on a joint depends on:
 - Orientation of body segment with respect to gravity
 - Current pose of the limb
 - Current length and velocity of contraction of muscle
 - Forces due to other body parts
 - Load etc etc

Non-linear means:

- 10% increase in muscle activity when load is 10kg, is different than 10% increase in muscle activity when load is 50 kg
- Noise in signal creates different noise in joint
- **Makes the inverse problem much more complex**

Problem 5: Non-Stationarity

And the whole thing changes as

- We get older
- ... grow
- ... get stronger
- ... get tired
- ... get injured

Need a plastic controller to adapt to changing conditions at different time-scales and to learn new skills

Same structure

Tennis racket



Squash racket



Different structure

Frisbee



Need a clever puppeteer

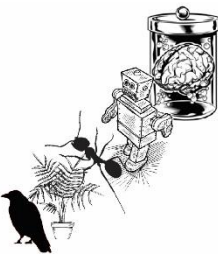
Back to our puppeteer:

1. Have multiple strings controlling each joint (redundancy)
2. There are different delays between moving different strings and the joints moving
3. The amount each control string moves the joint interacts in a non-linear way (ie moving 2 separately is different to moving 2 together)
4. Things are variable and
5. ... everything changes depending on fatigue age etc

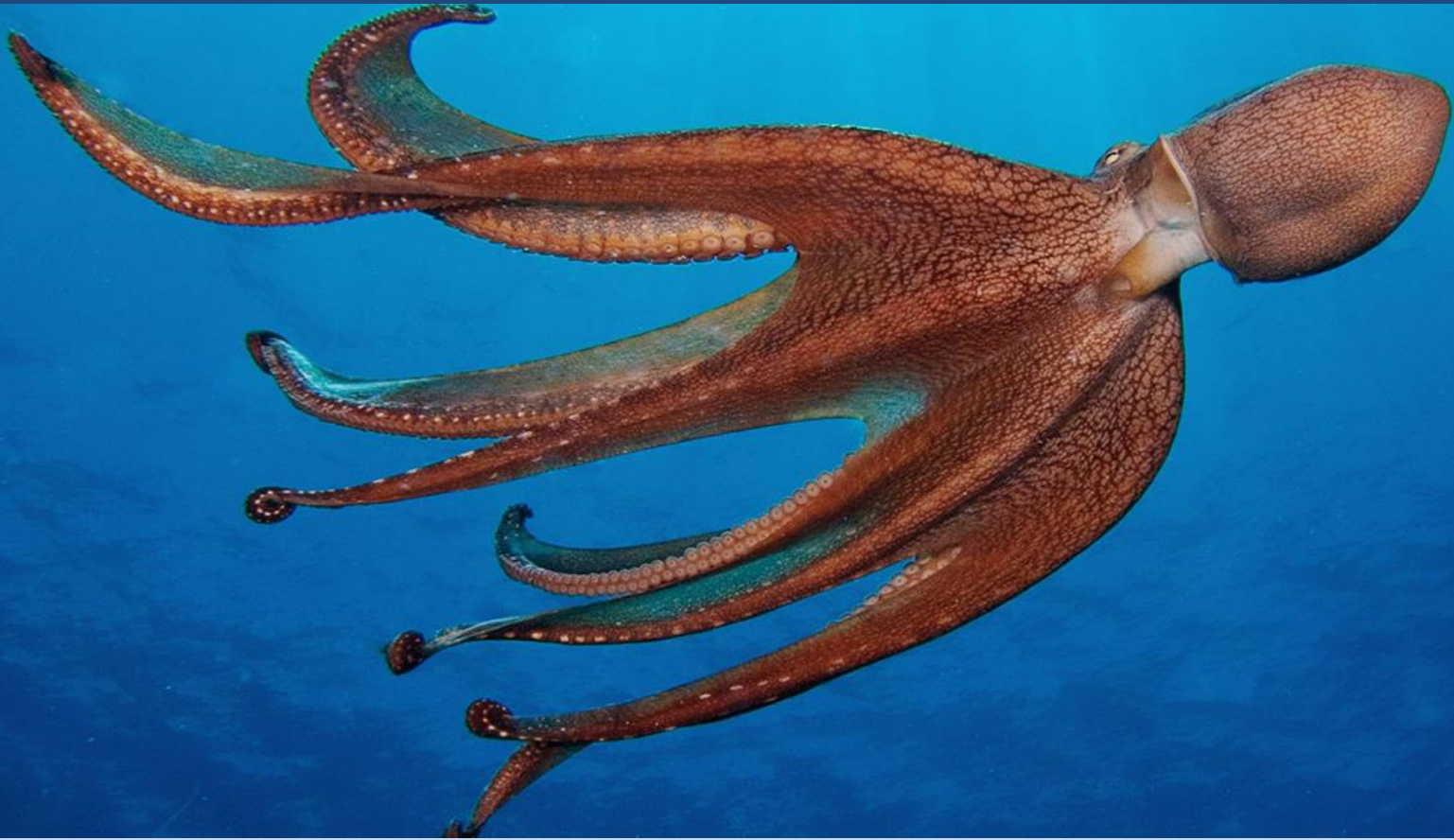
Problem must be simplified somehow: How?



Mini-break



Show of hands: What about octopuses?



Is motor control easier or harder for an octopus (than a human)?

Octopus Motor Control

Taken from Lecture Reading: Hochner (2012) An Embodied View of Octopus Neurobiology. Current Biology

Easier

- Decentralised nervous system (each leg 40 million neurons; overall 500 million)
- Situatedness – water reduces balance problems
- Soft body – more flexibility and less need for fine-motor control

Harder

- Flexible limbs mean there are an infinite # degrees of freedom.
- Much more complex sensory system, when sensors aren't constrained by a fixed body plan.

But...

- Octopus simplifies reaching by making an 'elbow' (3DF)
- This simplifies fetching by using a 'hand', 'forearm' & 'upper arm'
- These properties are dynamically computed - morphological computation



SIMPLIFYING THE MOTOR CONTROL PROBLEM



Passive Dynamic Walkers

G. T. FALLIS.

WALKING TOY.

No. 376,588.

Patented Jan. 17, 1888.

Fig. 1.

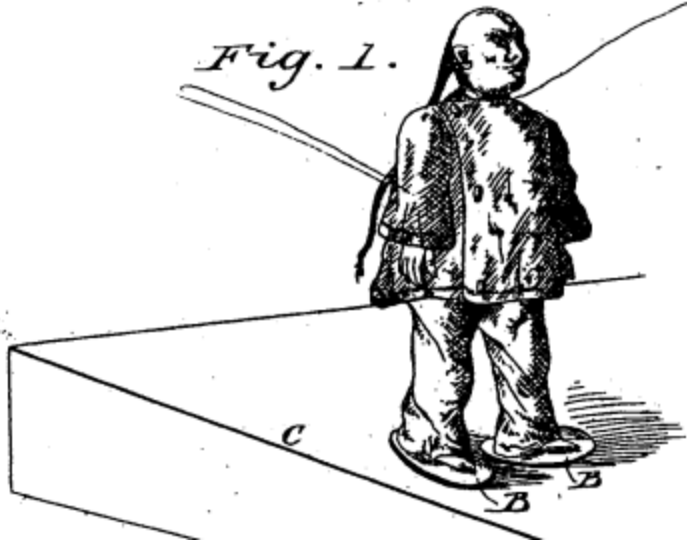


Fig. 2.

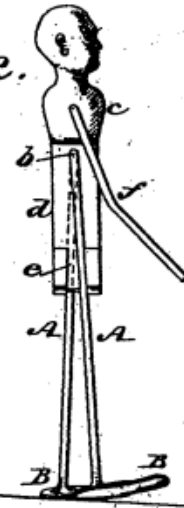
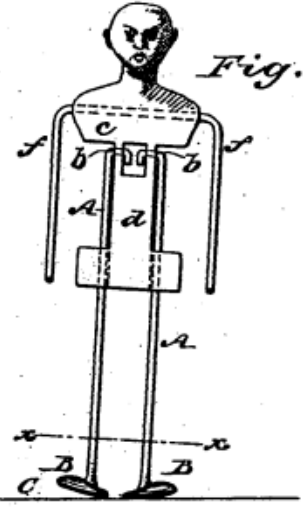
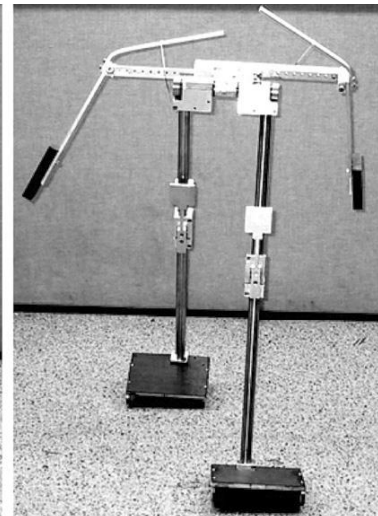


Fig. 3.

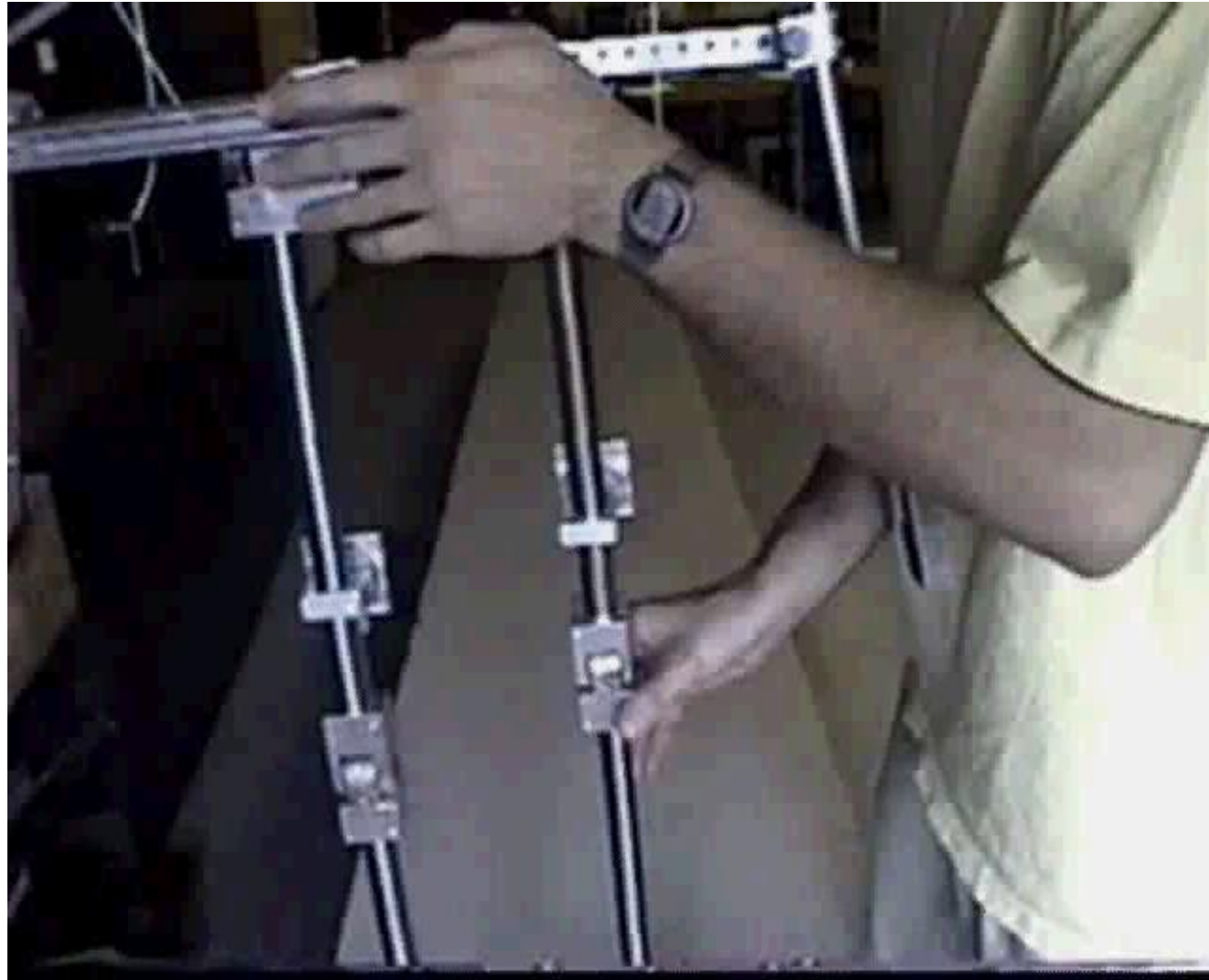


Passive dynamic walkers use morphology of body and gravity to **passively** (ie with no motors) walk down slopes



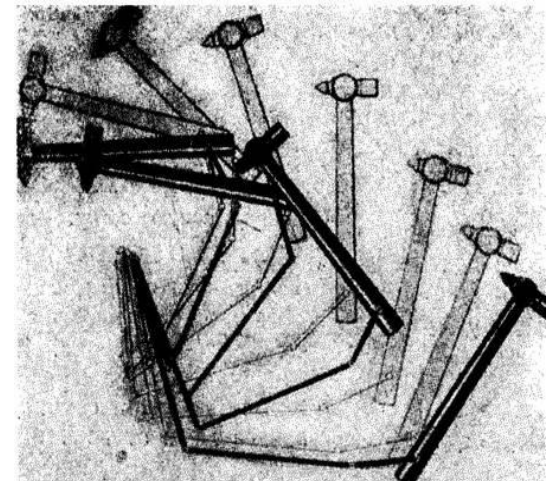
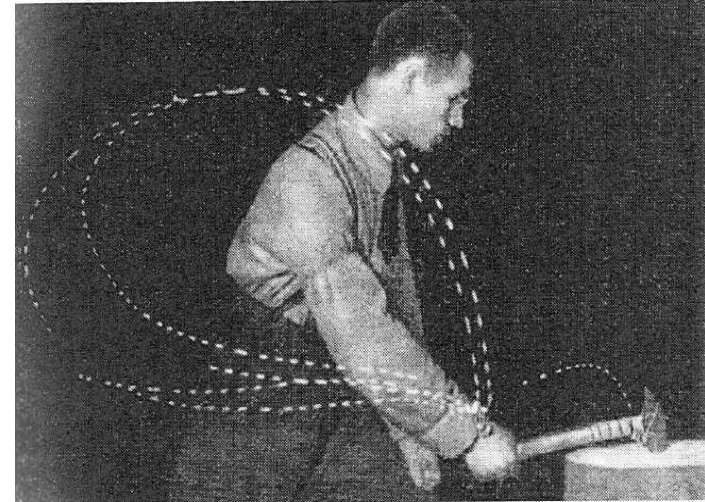
Passive Dynamic Walkers

- 'Natural' walking
- Stable to small perturbations
- Emerges from 'all body and no brain' through the physics of limbs
- Moves in a regular or invariant way: thigh swings then leg swings out
- More formally synergies



Motor Invariants and Synergies

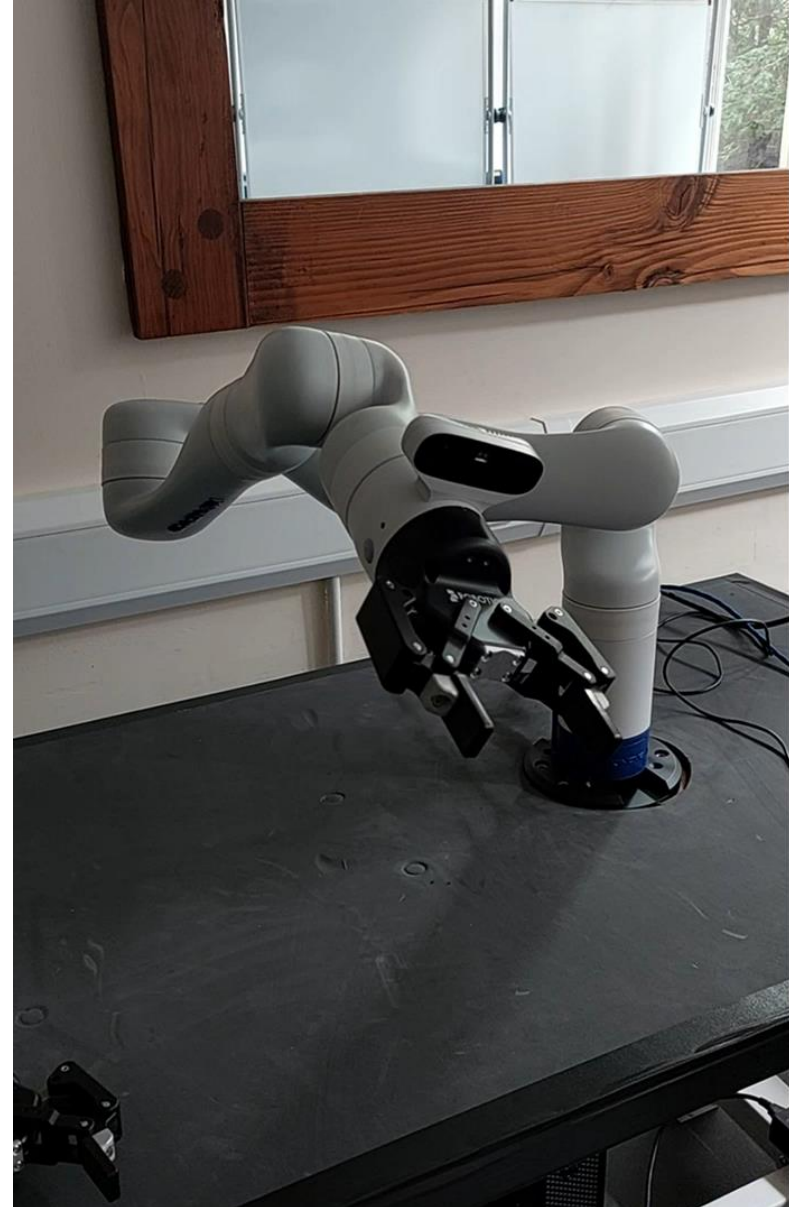
- In 1922 Bernstein saw movements as composed of sets of movements
- Bernstein suggested CNS is capable of "functionally freezing degrees of freedom": **Synergies: elbow, shoulder and wrist coordinate**
- Makes control easier by reducing the degrees of freedom: Steering 4 wheels of a car independently is difficult: Fixing rear wheels, and tying front 2 together much easier.
- Why not just fix things together? Synergies can be released to regain flexibility (eg 2->4 wheel drive)



Synergies in a robot arm



- Synergy between joints allows gripper position to be constant – demonstrates redundancy/flexibility
- Synergies also allow gripper to maintain constant angle
- In both, complex movements are controlled by up/down only



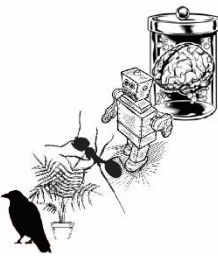
Synergies from complex embodiment



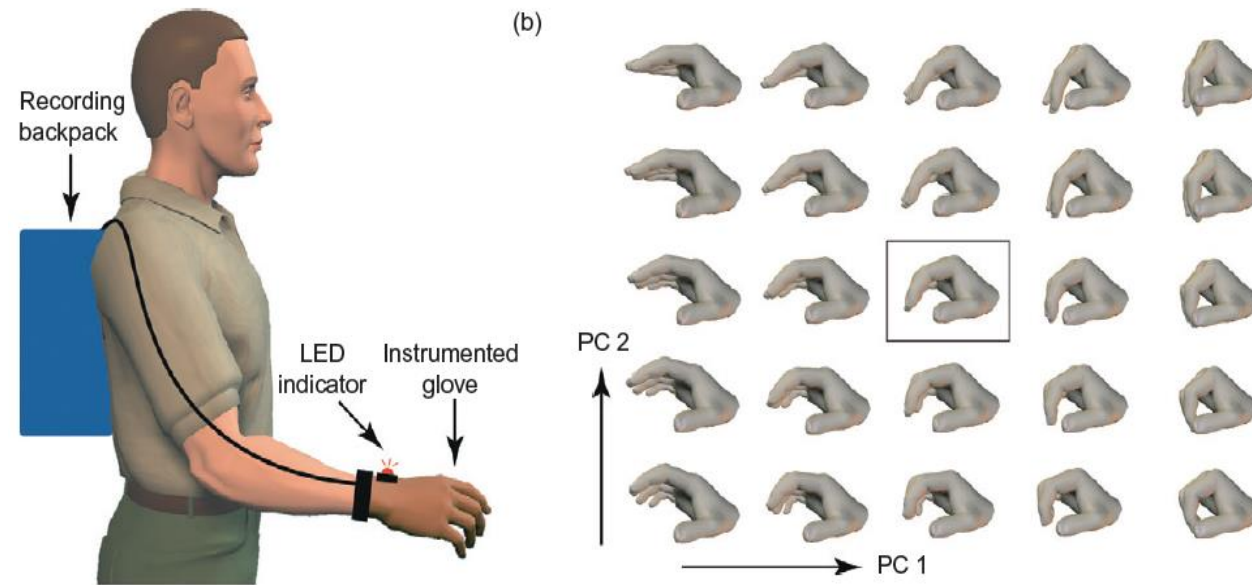
- Theo Jansen: Strandbeest
https://www.youtube.com/watch?v=LewVEF2B_pM
- Beautiful movements from constraints of a complex body



Let's try a little experiment



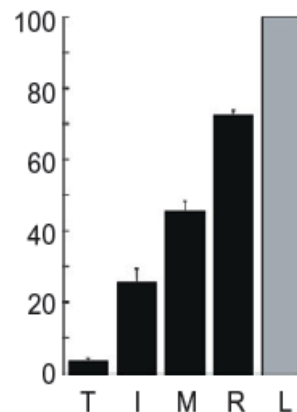
Natural hand movement synergies



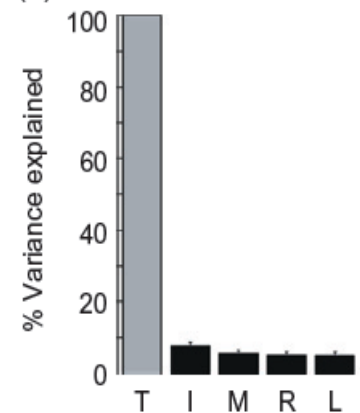
High dimensional hand movements, across many joints and muscles can be described by only two variables

See flexible synergies in finger movement

Movement of little finger predicts movements of other fingers



Movement of thumb does not



Dynamic stability

Movement is a dynamic
inexact process:

**we don't need to always get
it right**

1983 MIT hopper:

“actively balanced dynamic locomotion could be accomplished with simple control algorithms. It hopped in place, traveled at a specified rate, followed simple paths, and maintained balance when disturbed.”

<http://www.ai.mit.edu/projects/leglab/robots/robots.html>



Adding compliance and reflexes



Can do a lot with passive dynamics, but you can do more with compliance and 'reflexes' http://www.bostondynamics.com/robot_bigdog.html

Movement is dynamic and embodied

- Big Dog does calculate *roughly* where it is (and is going to be)
- But it does not have to get it exactly right because it uses feedback to continually correct: like balancing a stick.
- Continually falling over... and recovering ...
- So it only needs to get feet *roughly* in right place so control algorithms can be simple given a fast feedback loop
- Compliance (flexible body parts) helps absorb some of the variation of the world and small errors and gives extra time to respond: bounce on springy legs
- Fast pre-programmed responses (reflexes) catch bigger slips

Stable vs Unstable walking

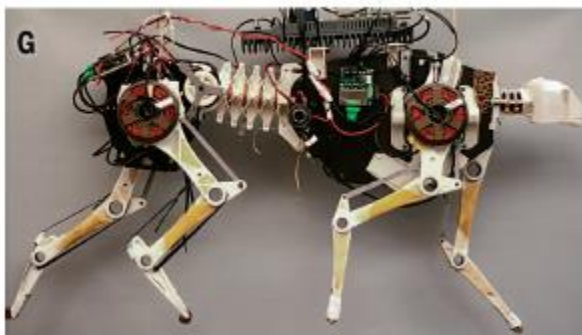


Compare Asimo

To passive dynamic
walkers



Examples of emdodiment in biorobotic movement



A. J. Ijspeert (2014) Biorobotics: Using robots to emulate and investigate agile locomotion. Science



Summary

- Controlling movement is a very hard problem due to noise, massive redundancy, delays and non-linearities
- And the problems keeps changing and you have to learn new things
- Embodiment can simplify the problem through:
 1. Clever design of body
 2. Synergies/movement invariants
 3. Being dynamic and springy allows you to be inexact as it gives time to correct errors through feedback

Don't go anywhere



Reading

- Essential
 - David W. Franklin; Daniel M. Wolpert (2011) Computational Mechanisms of Sensorimotor Control. Neuron
- Recommended
 - A. J. Ijspeert (2014) Biorobotics: Using robots to emulate and investigate agile locomotion. Science
- Optional
 - Binyamin Hochner (2012) An Embodied View of Octopus Neurobiology. Current Biology.

