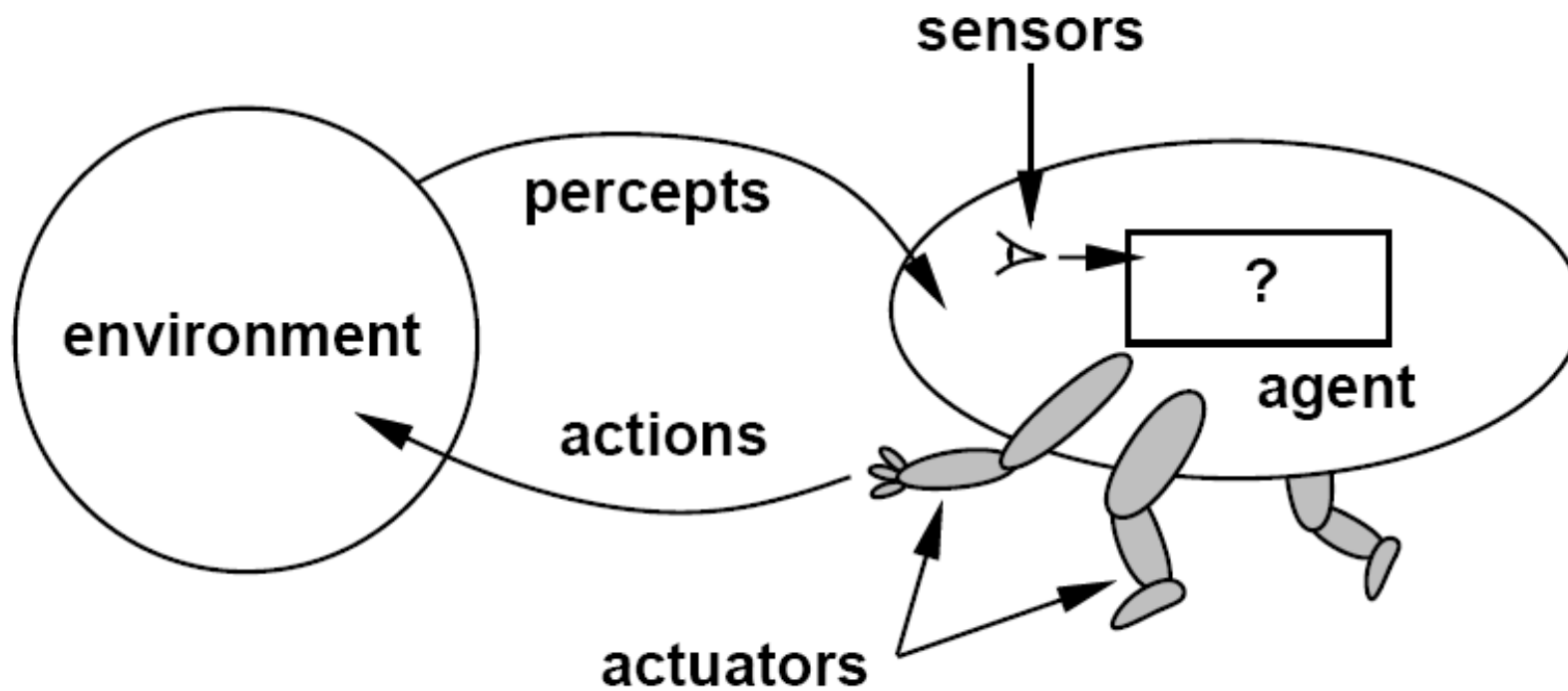


What is a Robot?

ESE 6510
Antonio Loquercio

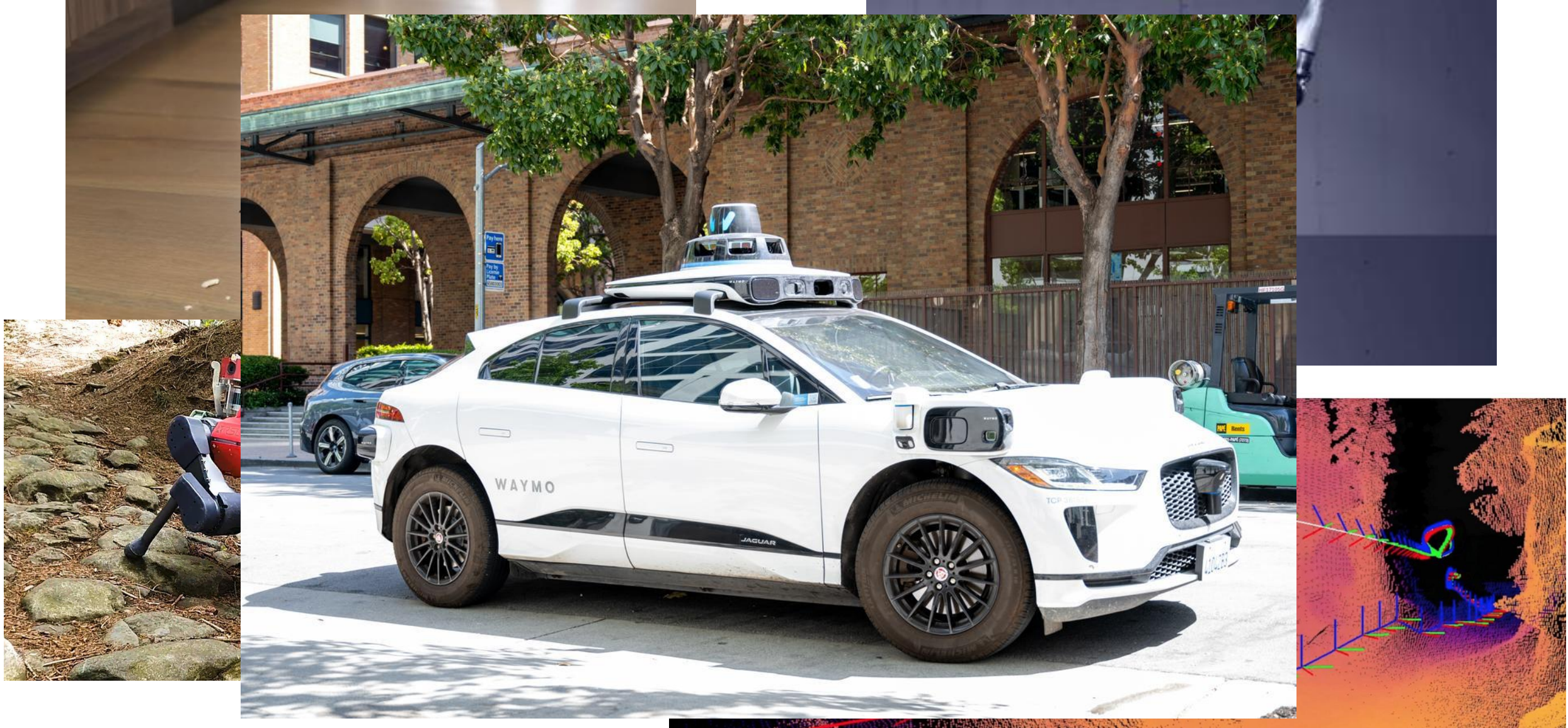


Robotics is already a large industry



Source: NYT

Is mobility the problem?



Challenging to operate around humans?

Experiences with an interactive museum tour-guide robot

Wolfram Burgard^a, Armin B. Cremers^a, Dieter Fox^b, Dirk Hähnel^a,
Gerhard Lakemeyer^c, Dirk Schulz^a, Walter Steiner^a, Sebastian Thrun^{b,*}

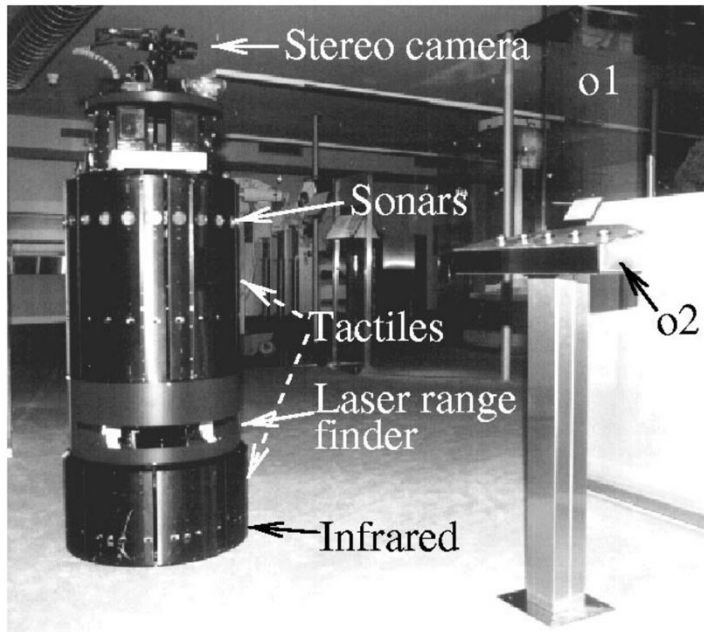


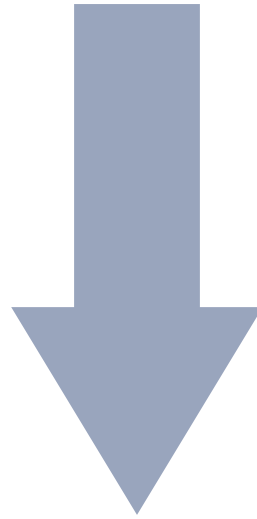
Fig. 1. The robot and its sensors.



Fig. 2. RHINO, pleasing the crowd.

So, what is the fundamental blocking factor?

- Lack of adaptability
- Designed either for one task or one environment

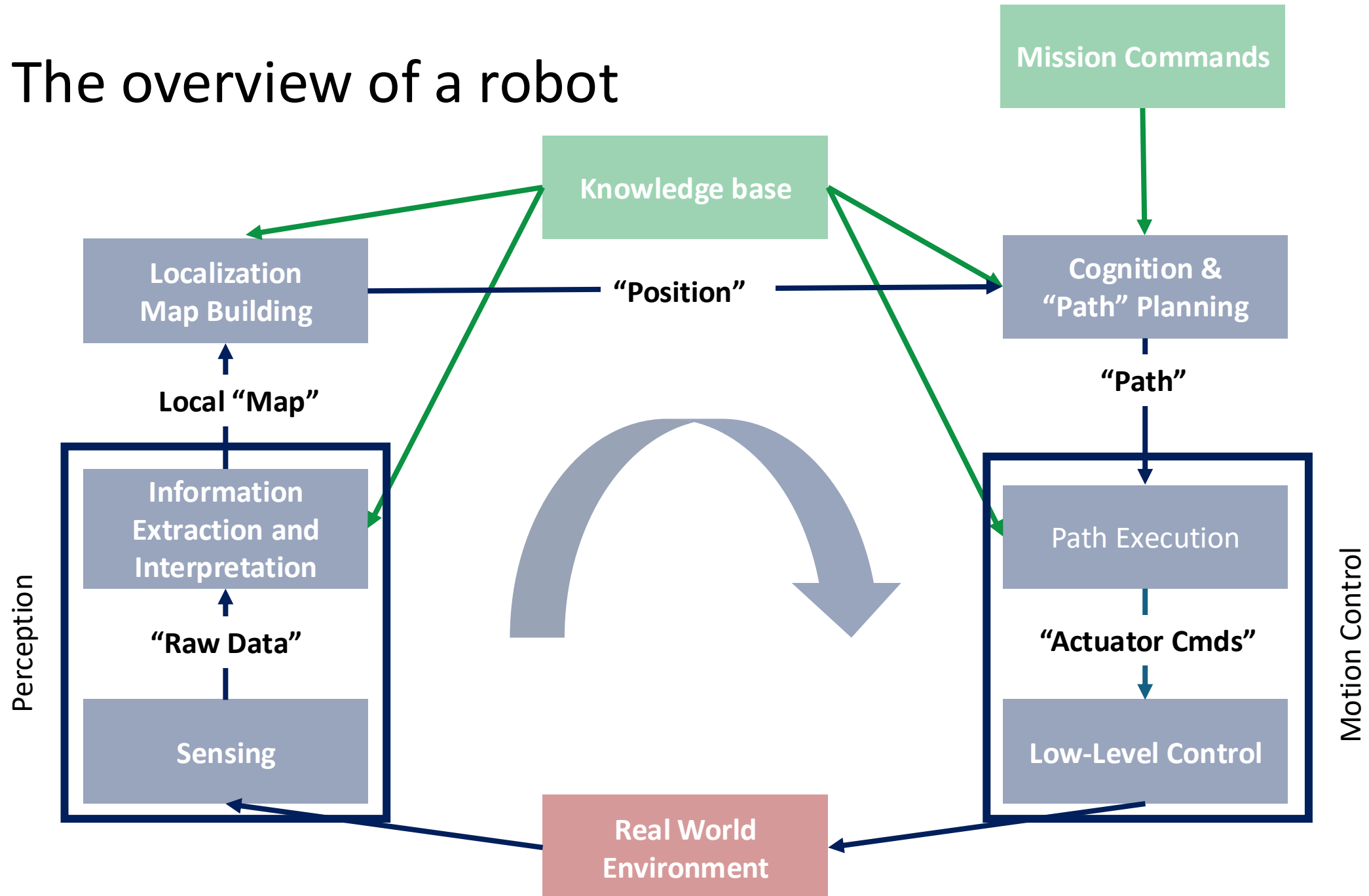


- Adaptability is at the foundation of biological **physical** intelligence
- (Probably) at the foundations of artificial **physical** intelligence as well

Goal of today's lecture

- Understand the core components of a robot
- Understand the main mechanisms that enable a robot to interact with the world:
 - Actuation: From energy to motion
 - Mobility
 - Manipulation

The overview of a robot



Is this a robot?



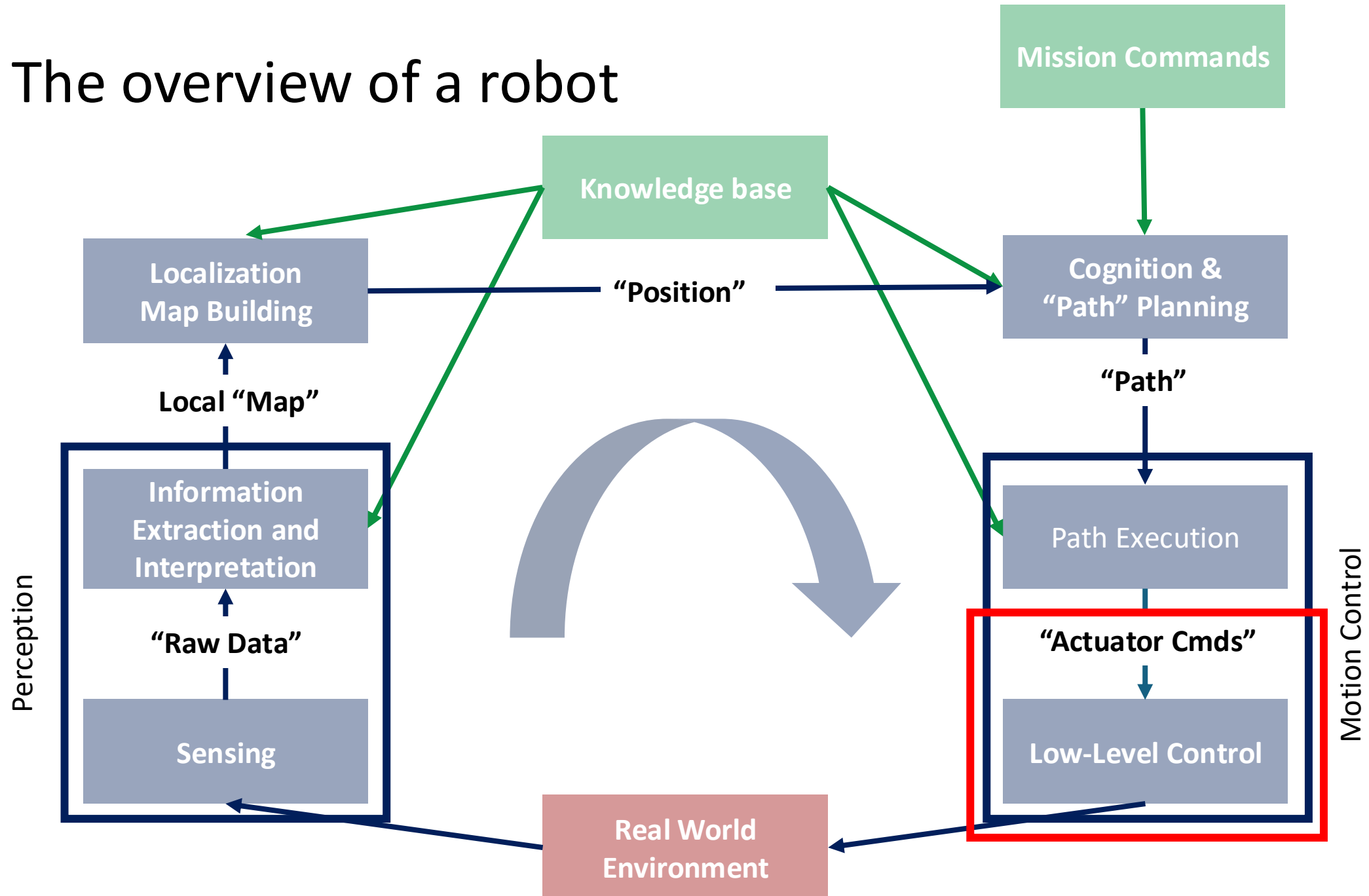
Is this a robot?



Is this a robot?

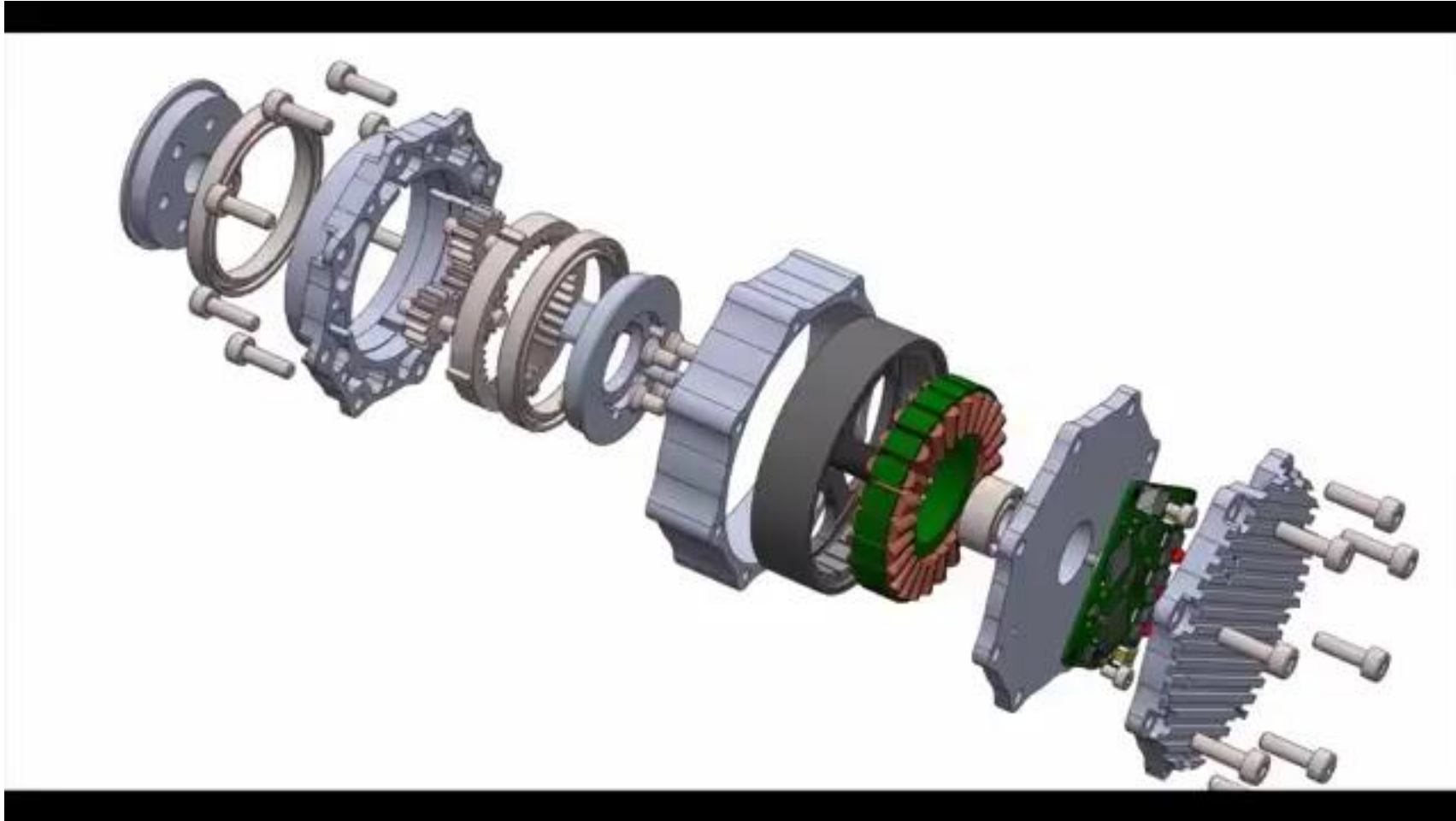


The overview of a robot



Actuators

- A complex system to transform energy into motion



Types of Actuators

- Rotary
- Linear
- Oscillatory (e.g., voice coils).

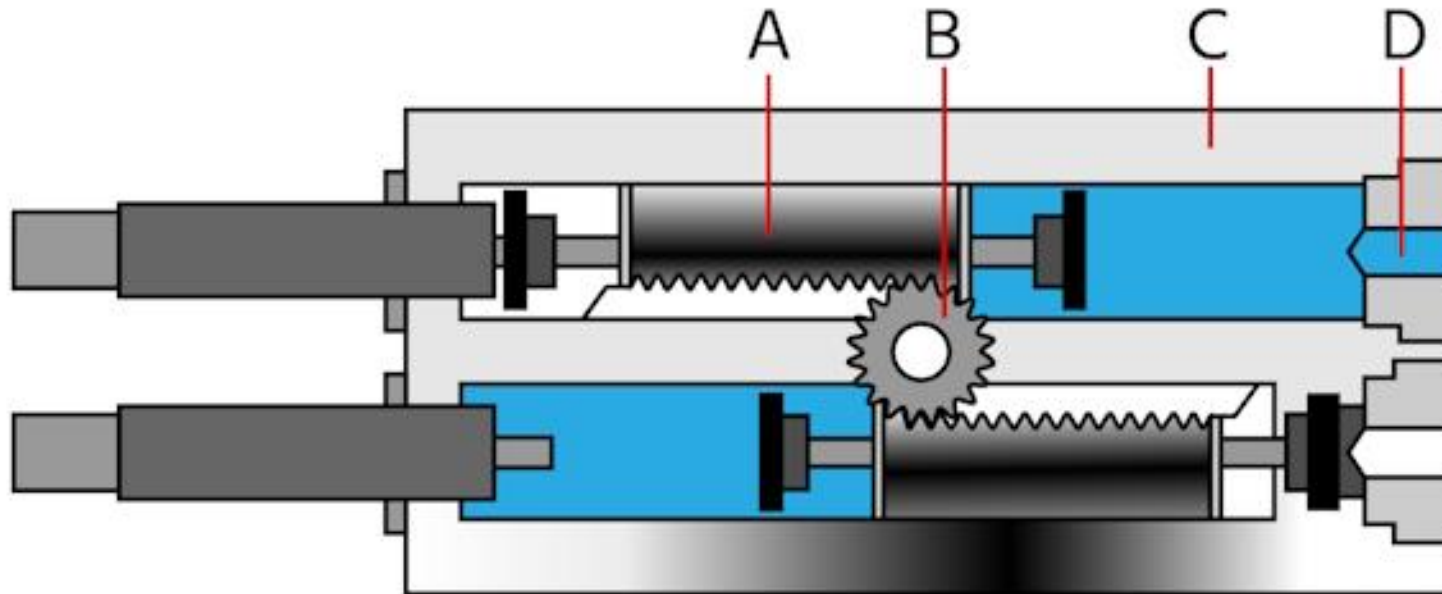
Types of Actuators

- Electric rotary actuators



Types of Actuators

- Electric linear actuators



Reducers

- Transmit the torque of a (generally small and fast) motor to bigger gears.
- Many other types exist:
 - Planetary
 - Harmonic
 - Cycloidal
 - Rotary Vector
 - ...

Types of Reduction Gears



Reducers

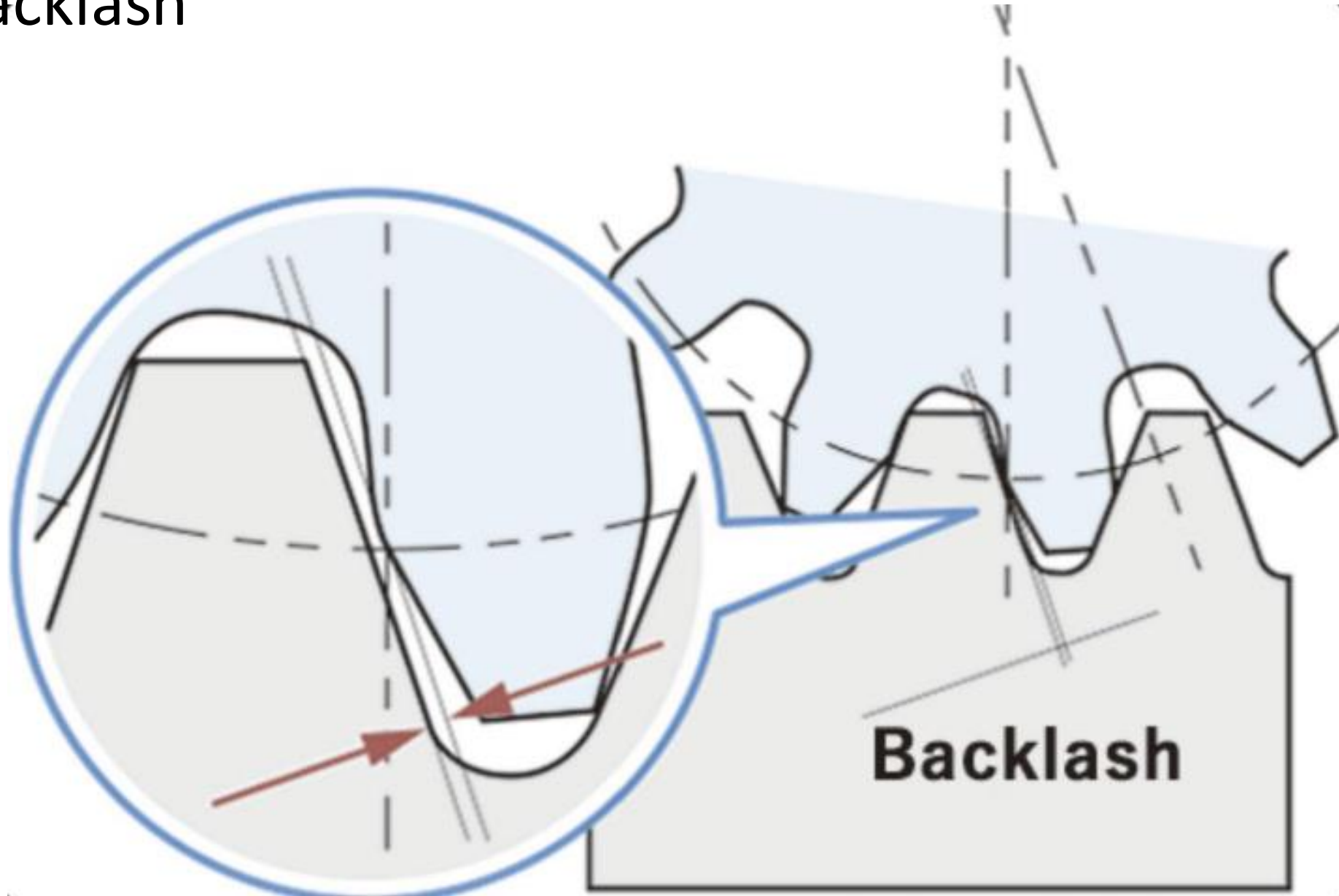
Planetary Gears

The oldest reducer design.



Source: X (JacklouisP)

Backlash



Backlash

- Small electric motors have large gear reductions (which makes them attractive from a cost/weight standpoint).
- Gear reductions come with dynamic effects that are hard to model
- No simple relationship between torque and current
- Torque Transparency
 - How accurately input torque reflect at output.
 - If input torque $\approx$ output torque, you can do force control without extra sensors. The robot can feel what it's pushing against.

Joint Position vs Torque Control

- Position sensors (inexpensive, accurate, and robust) make position control much more attractive

- They can be used for joint position control using a PID controller

$$\tau = K_p(q^d - q) + K_d(\dot{q}^d - \dot{q}) + K_i \int (q^d - q)$$

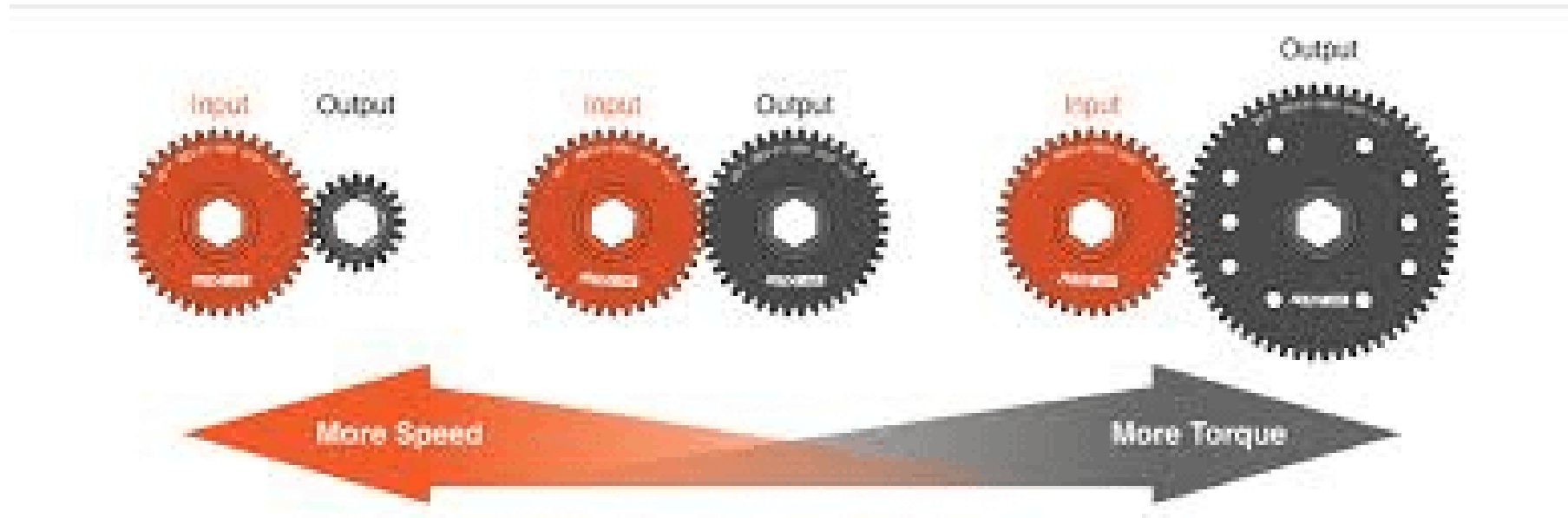
- PID controllers operate at high speed (kHz), so they quickly recover from errors (we will come back to this).

Some exceptions: Actuation in Torque Control

- Quasi-Direct Drive (i.e., with small gear reductions).
 - Typically, with outrunner and frameless motors.
 - Very common for legs due to compliance
- Hydraulic actuations
- Adding torque sensors (e.g., Kuka) or Series Elastic Actuators (adding springs to the transmission).

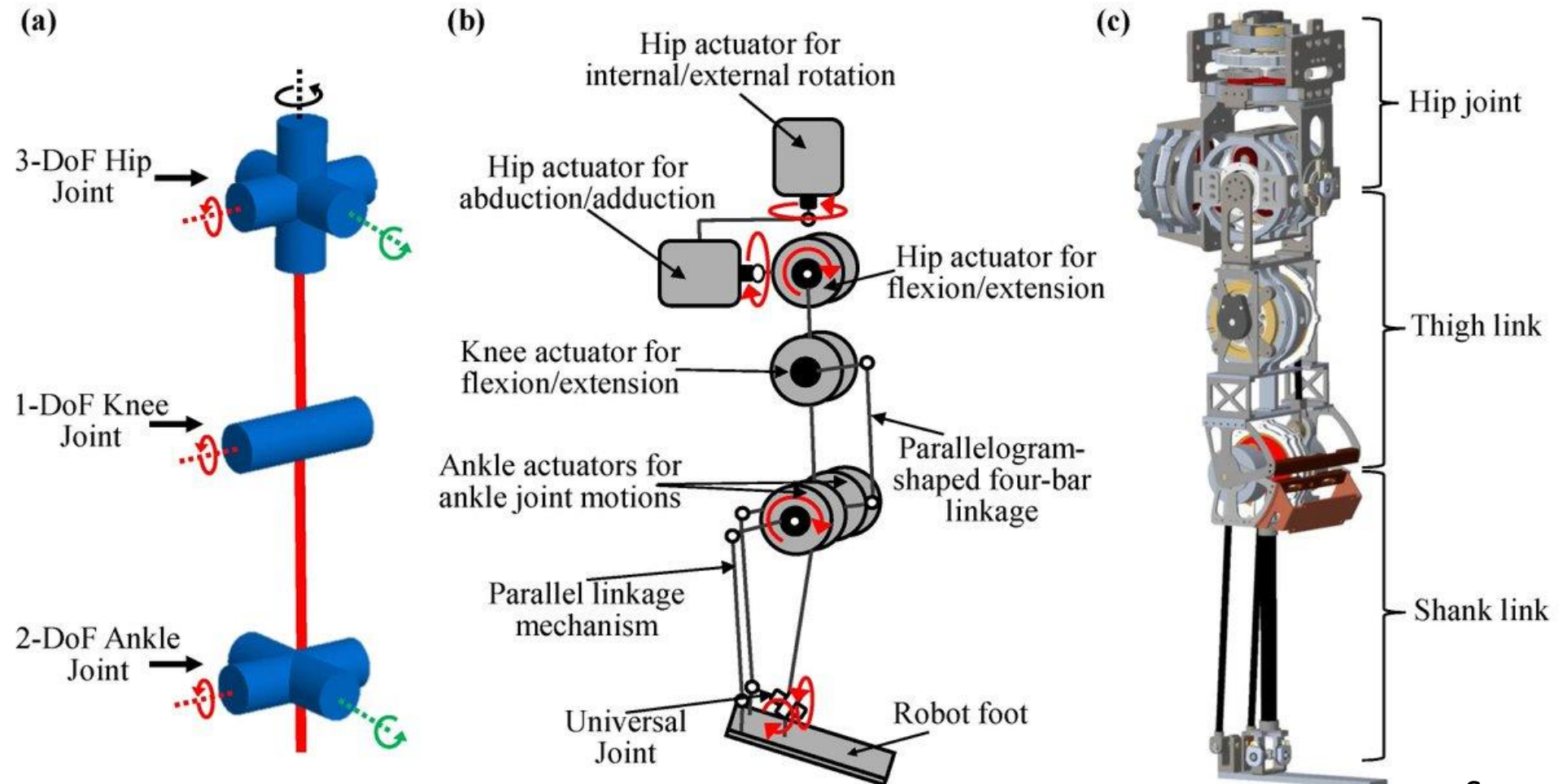
The Trade Off

- Low ratio = transparency, feel, safety
- High ratio = more torque, but numb and rigid
- Need to trade off these two objectives.



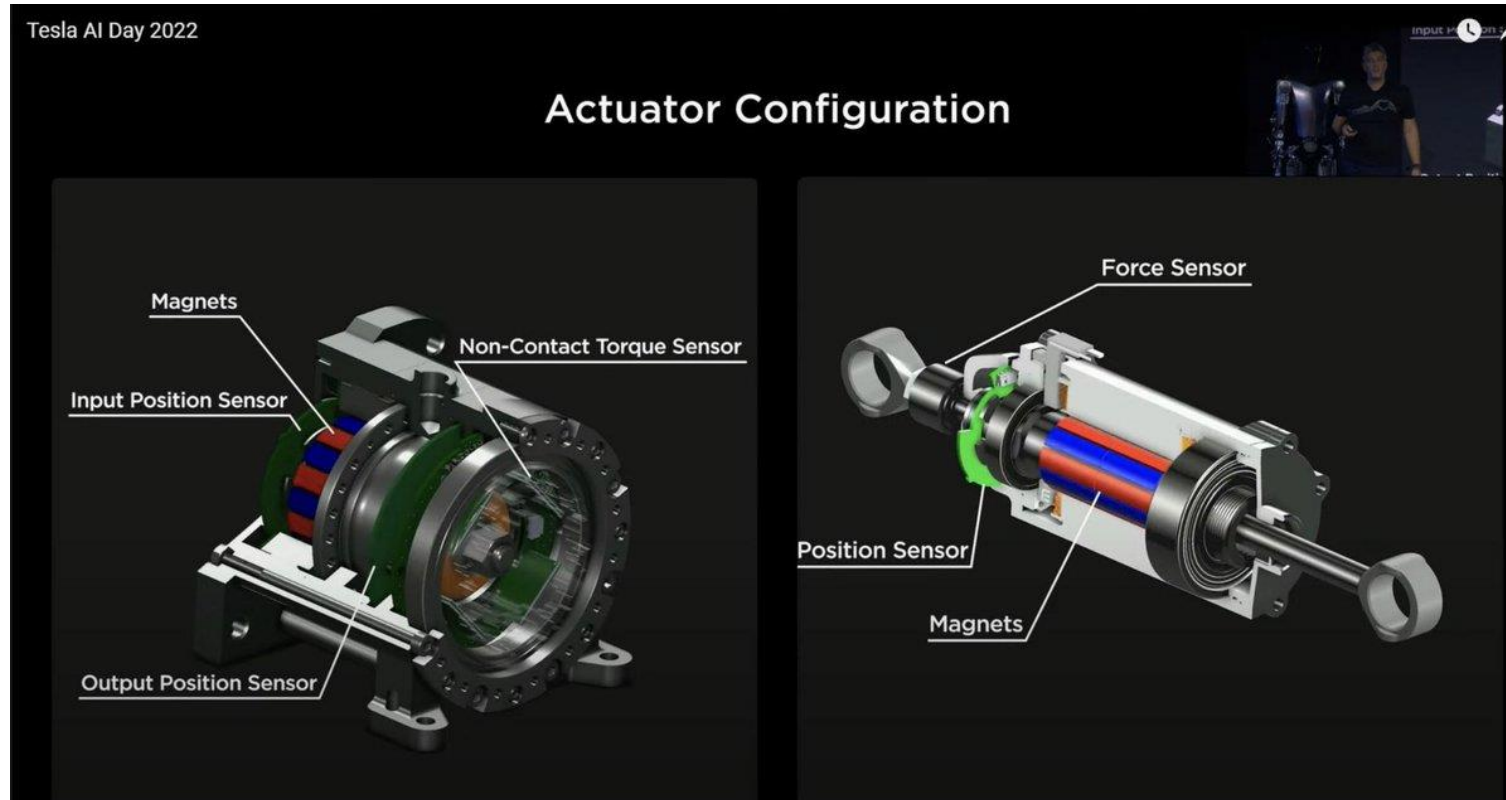
“Remote” Actuation

- The actuators are connected via linkage to the movable joints.



Tesla Optimus (2022 Version)

- Tesla uses **inverted** planetary roller screws.
- The nut is inside, the thread is on the shaft interior.
- Why inverted? Packaging. It creates a more compact actuators.



Questions?

Two categories of interaction with the world

- Mobility
- Manipulation

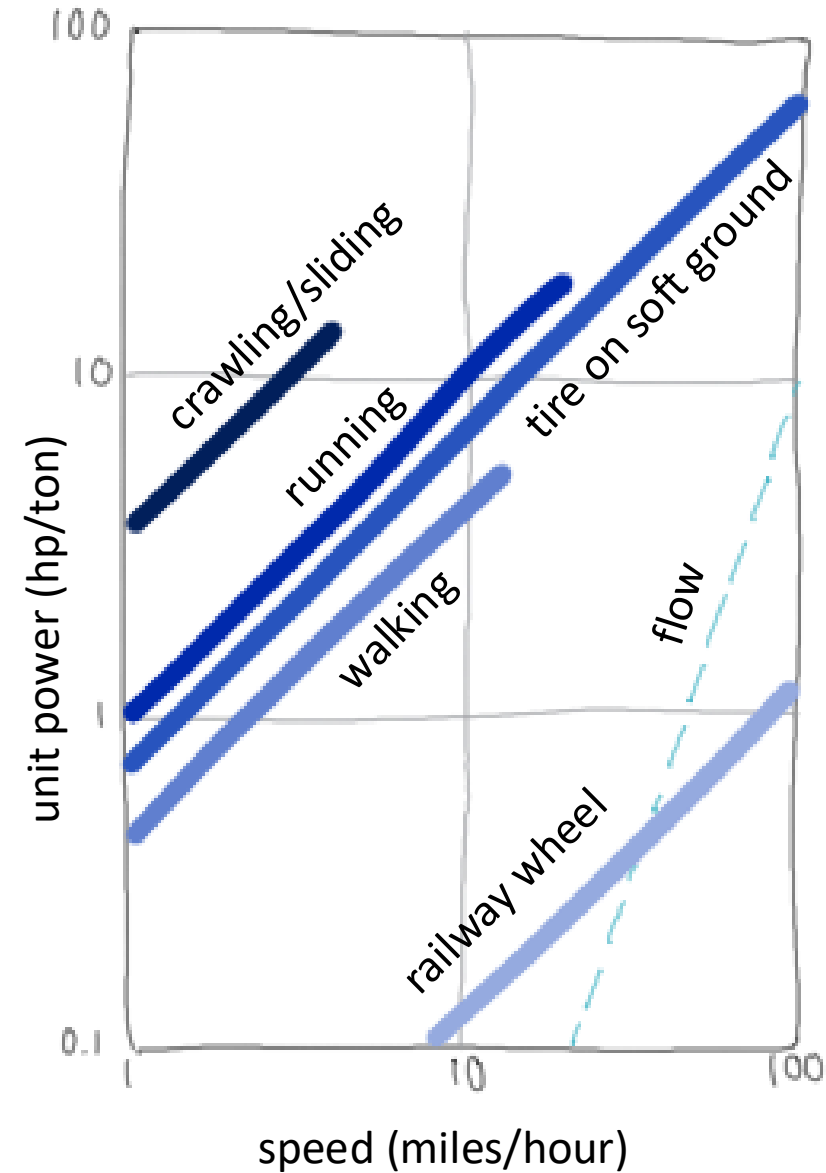
Mobility

- There is a wide variety of mechanisms for robots to move throughout the environment
 - Walk, jump, run, slide, swim, fly, roll
- Most mechanisms have been inspired by nature. What is the exception?
- Biological systems still far exceed the response time and conversion efficiency of scaled man-made systems.
 - Mechanical complexity is easily achieved by structure replication
 - Cells are “microscopic” building blocks that enable miniaturization

Mobility Mechanisms

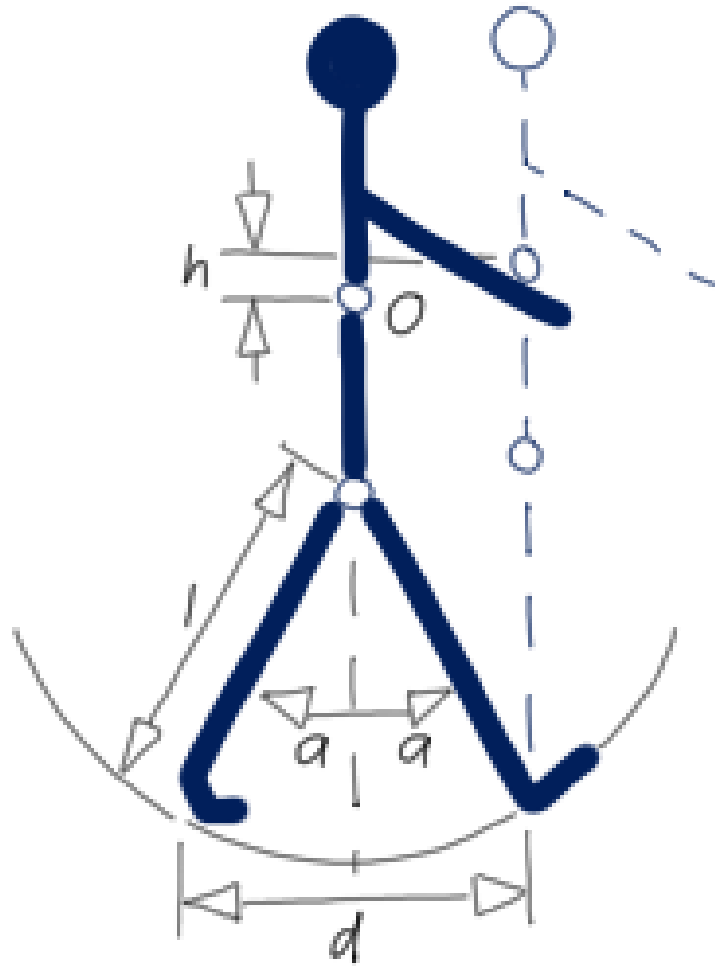
Type of Motion		Resistance to motion	Basic kinematics of motion
Flow in a Channel		Hydrodynamic forces	Eddies
Crawl		Friction forces	Longitudinal vibration
Sliding		Friction forces	Transverse vibration
Running		Loss of kinetic energy	Periodic bouncing on a spring
Walking		Loss of kinetic energy	Rolling of a polygon
Flying		Aerodynamic forces	Flapping, Gliding
Swimming		Hydrodynamic forces	Undulatory & oscillatory motion

Efficiency of motion



Source:
Walking Machines: An
introduction to legged robots;
Todd D.J.

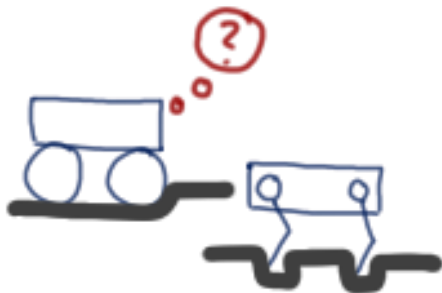
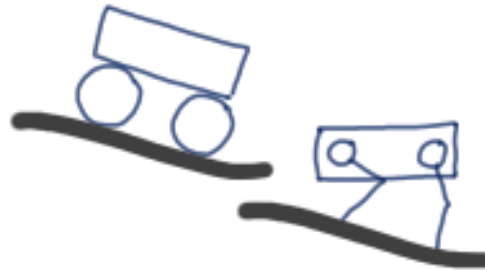
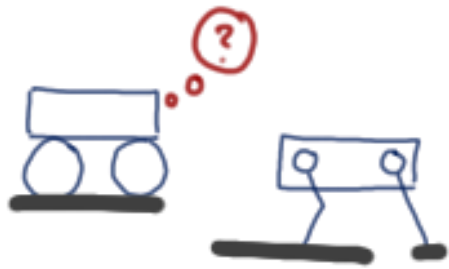
Wheels are a general case of legs



The rolling polygon

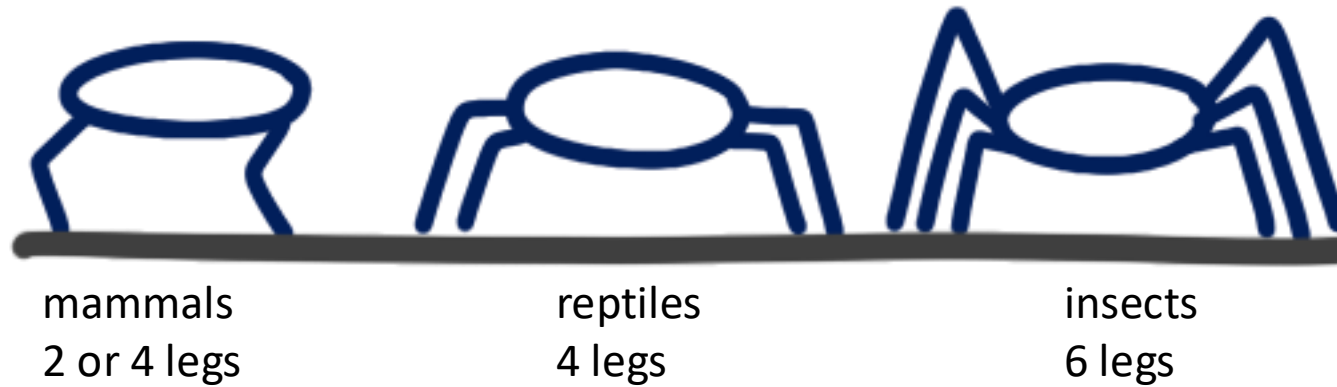
Source:
Autonomous Mobile Robots,
Siegwart et al., Ch 2.

Legs vs Wheels



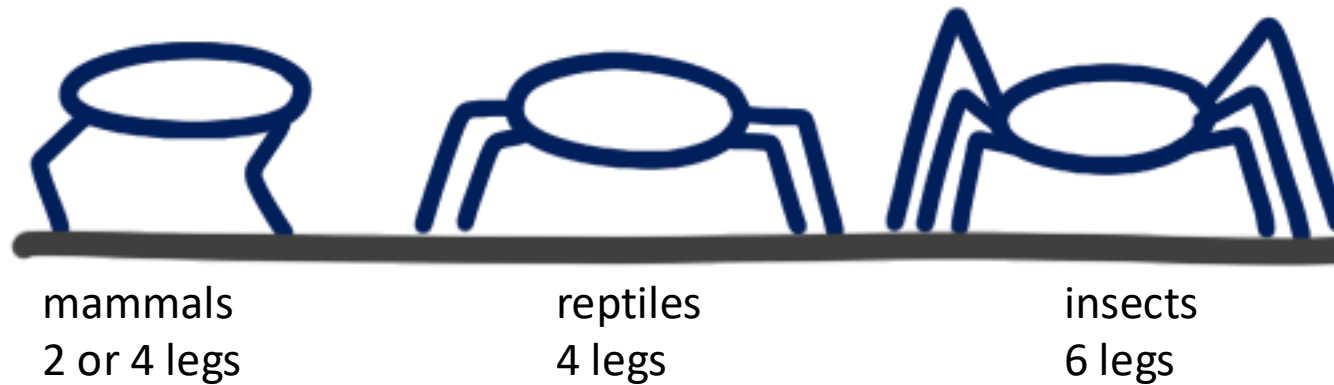
Source:
Autonomous Mobile Robots,
Siegwart et al., Ch 2.

Legs Configuration and Stability



- Large animals usually have 4 legs, while insects have 6. The fewer the legs, the harder it is to maintain balance.
- The position of the center of mass induces differences in stability, speed, and rough terrain traversability (mammals vs reptiles). Joints help muscles to absorb impacts.
- Nature offers a great variety of extrema: The caterpillar case 🐛
- The human leg has 7 major DOF, with further actuation in the toes.

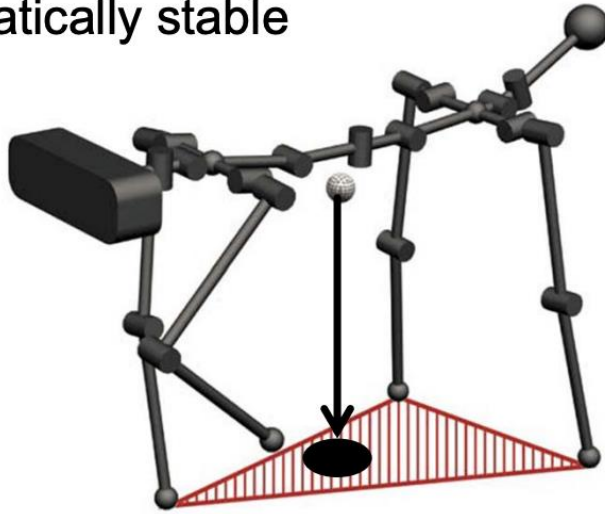
Legs coordination or Gait Control



- A gait specifies **which legs are in contact with the ground at a given time** and how this pattern repeats cyclically.
- How many gaits do humans have?
- There are $(2K - 1)!$ gaits for a system with k legs!

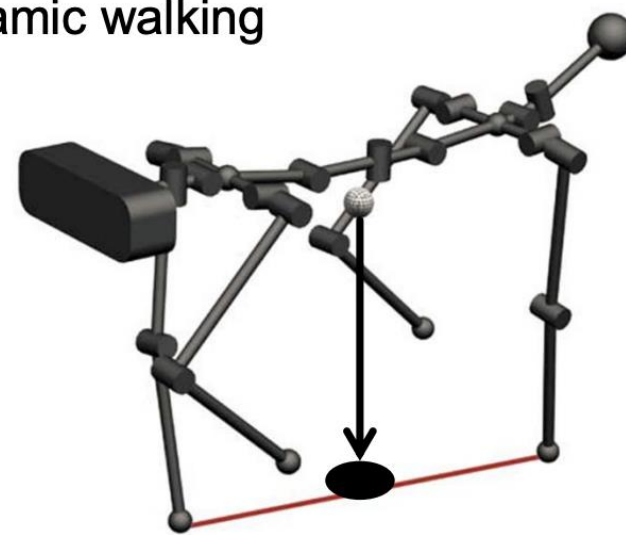
Static vs Dynamic Stability

■ Statically stable



- Bodyweight supported by at least three legs
- Even if all joints “freeze” instantaneously, the robot will not fall
- Safe and slow

■ Dynamic walking



- The robot will fall if not continuously moving
- Less than three legs can be in ground contact
- Demanding for actuation and control

Dynamics Consideration

- Static legged locomotion is energy inefficient
 - Joints accelerate and decelerate. Actuators can work against each other.
- Exploiting dynamics for more efficient motion

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- Static legged locomotion is energy inefficient
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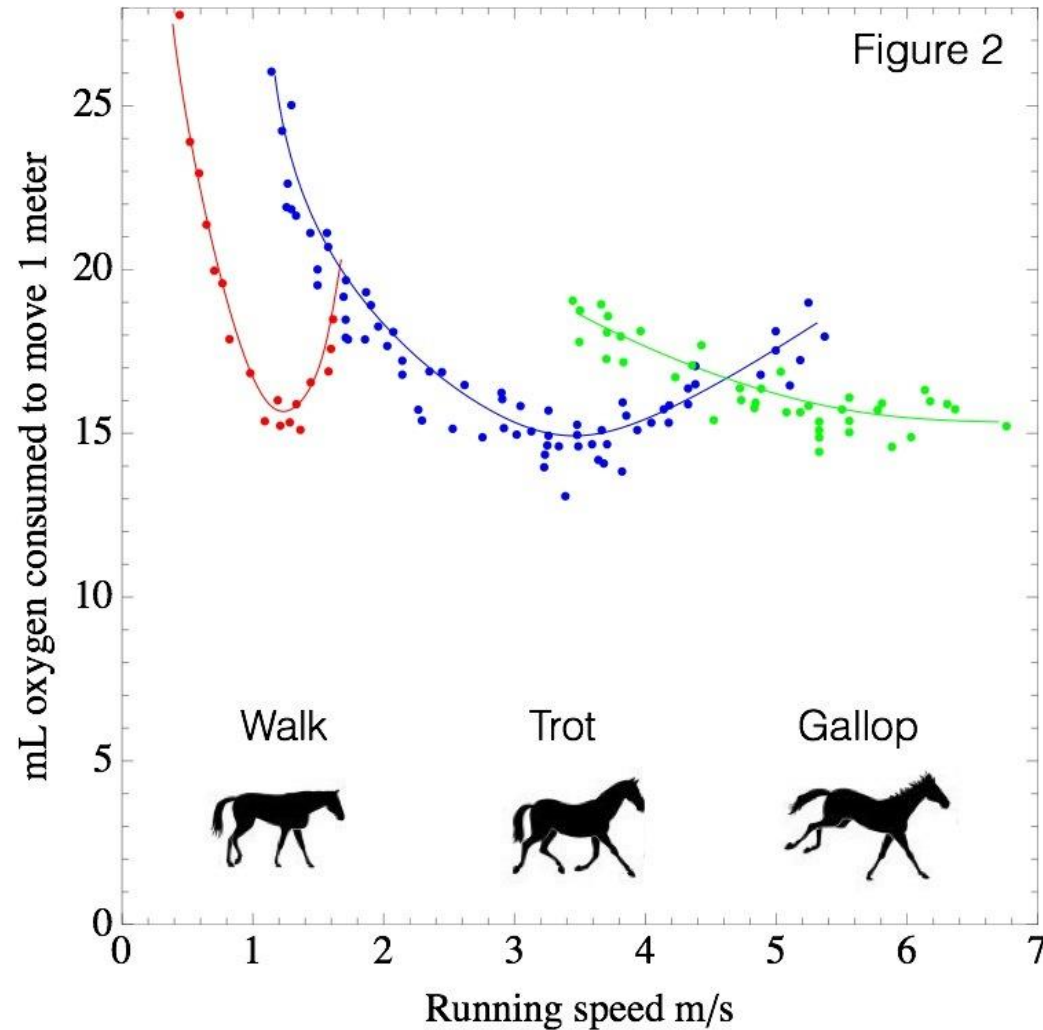


The (Powered) Ranger Robot from Cornell

40.5 miles non-stop without being touched by a human



Optimizing the Cost of Transportation

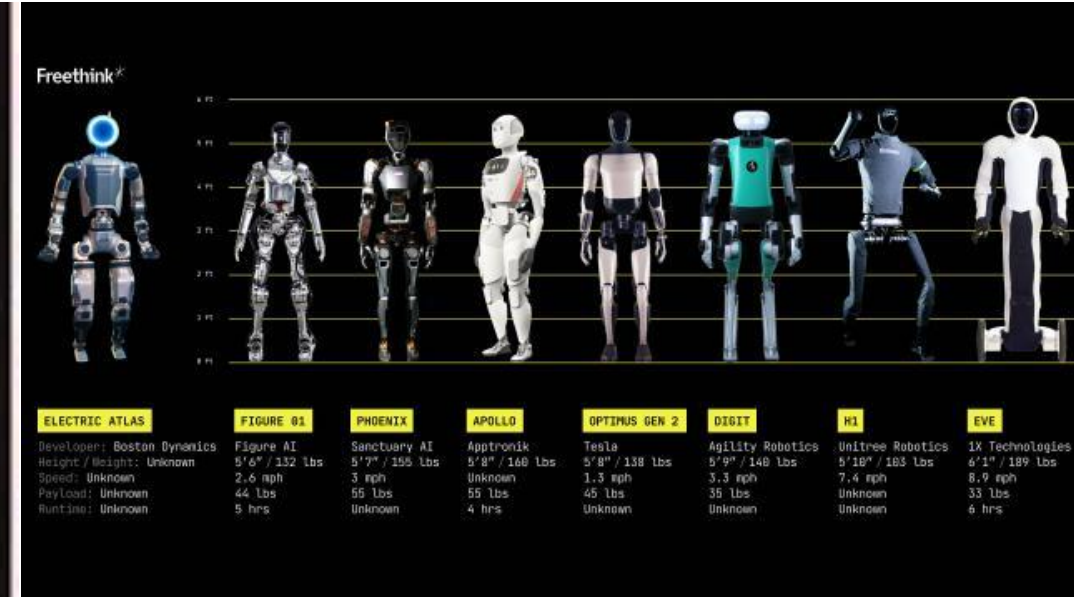
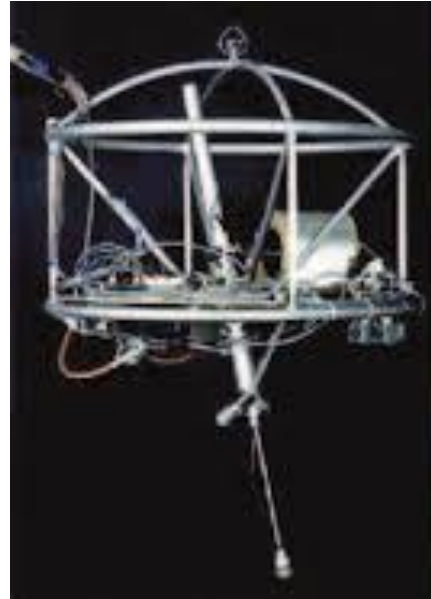


Changing gait enables using a different set of natural dynamics, minimizing the cost of transportation

Gait and the energetics of locomotion in horses,
Hoyt and Taylor,
Nature 1981

The design space of legged robotics

- One-leg hoppers
- Humanoids
- Quadrupeds
- Hexapods
- ...



Wheeled Locomotion

- Highly efficient energetically
- Relatively simple mechanical implementation
- Balance is not an issue
- Core problems: traction, stability, and maneuverability
- Also has a large design space

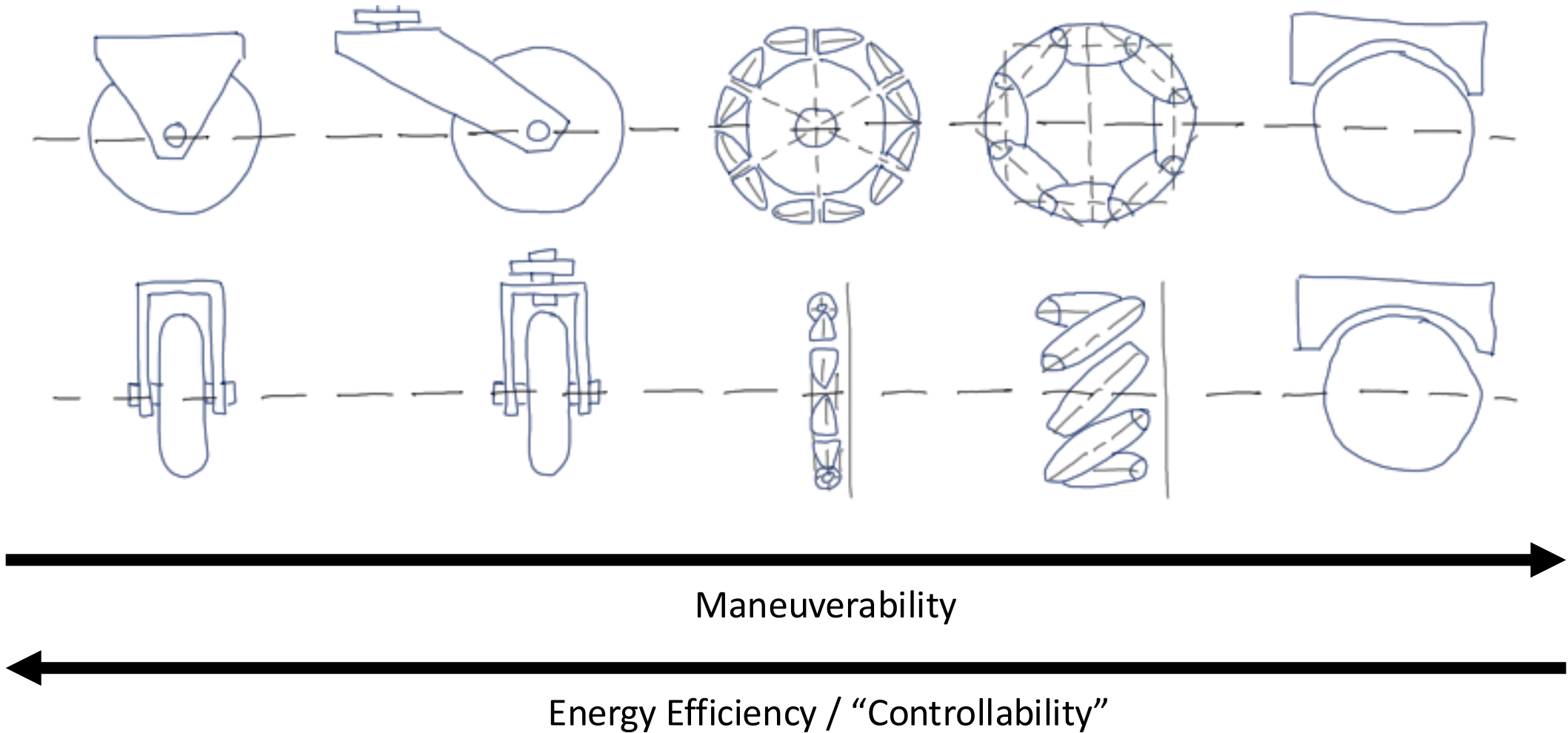
Wheeled Locomotion: Wheel Types

Standard

Caster

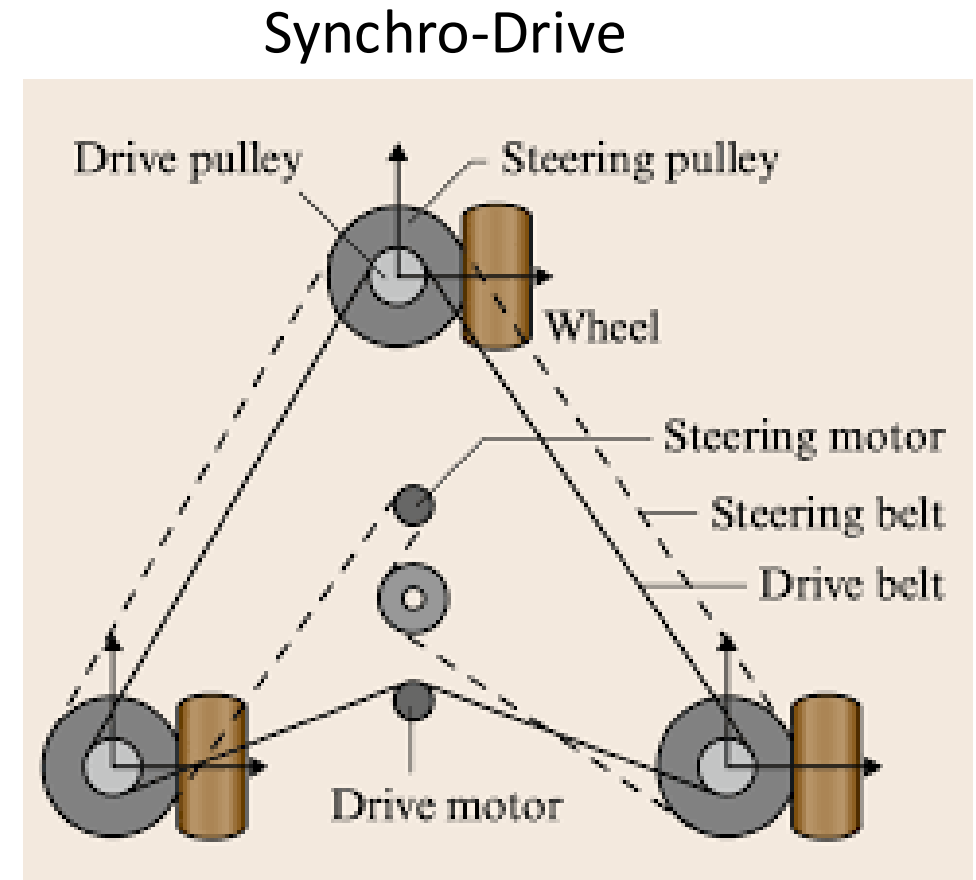
Swedish

Spherical



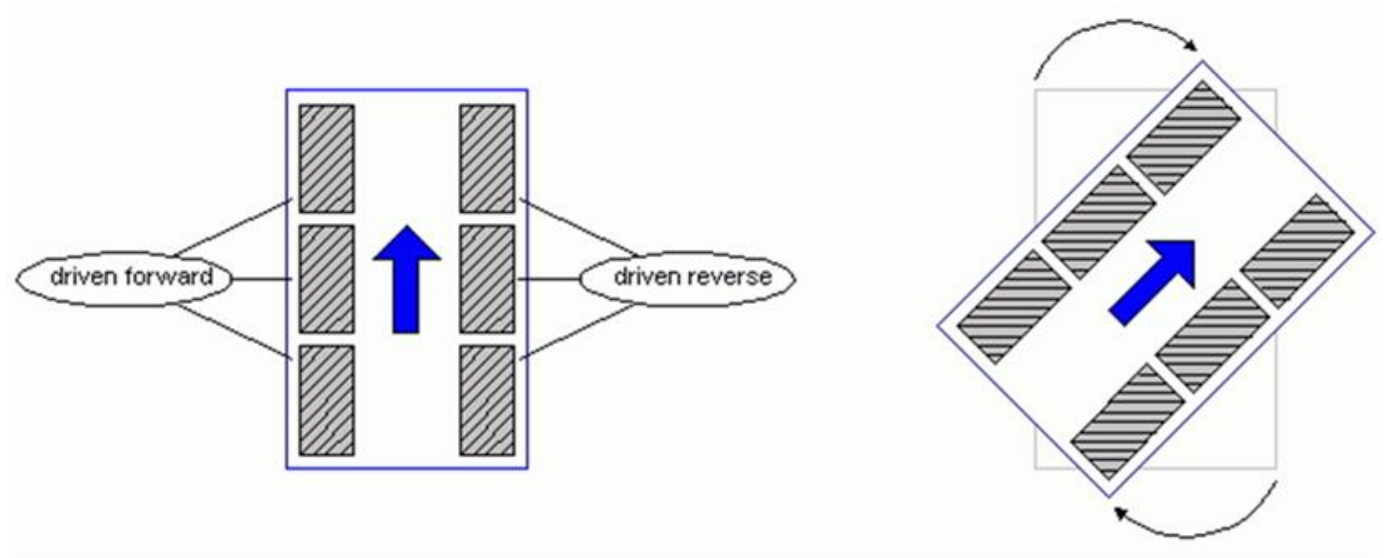
Wheeled Locomotion: Design Space

- Large design space induced:
 - Type of wheels
 - Number of wheels
 - Position of wheels
 - Suspensions
- Key optimization factors:
 - Stability
 - Maneuverability
 - Controllability
- There is **NO** ideal configuration



Slip/Skid Locomotion

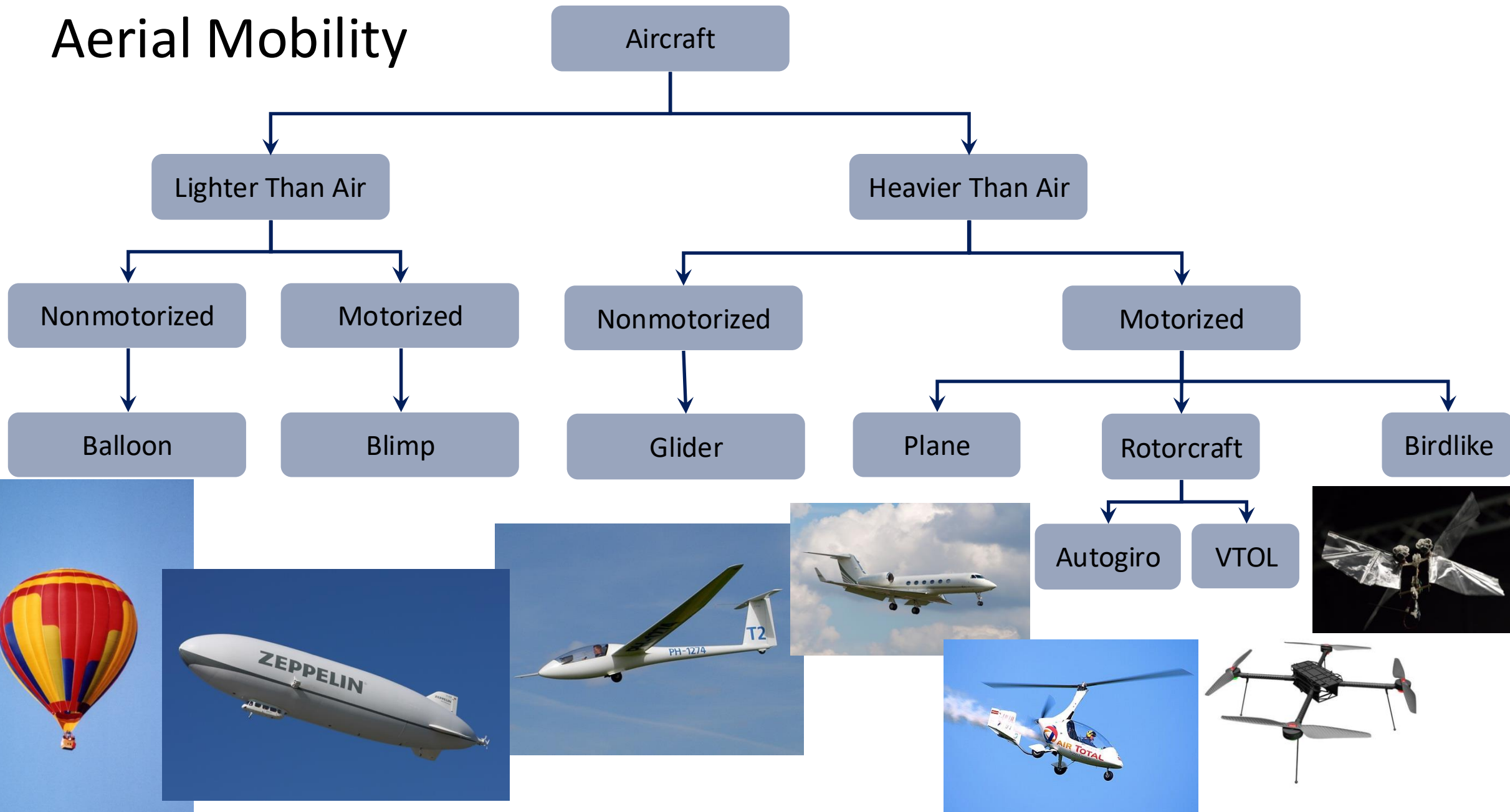
- Tank-style motion: slip/skid to change orientation
- Larger ground contact patches: high maneuverability and traction in rough and loose terrain
- Energy inefficient



Combination of Wheels and Legs



Aerial Mobility



Questions?

Manipulation

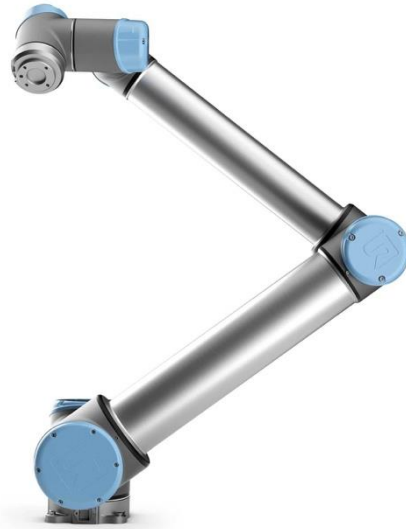
- The dual of locomotion
- Seeking instead of avoiding collision
- Shares the same core issues of stability, maneuverability, and controllability.
- Design space includes:
 - Number and geometry of contact points
 - Characteristic of contact (friction, angle, shape, and path)

Arms

- Essentially an inverted leg. What is a key difference?
- Differences in cost, reliability, usability, payload, range of motion, sensing, etc.



Kuka



UR

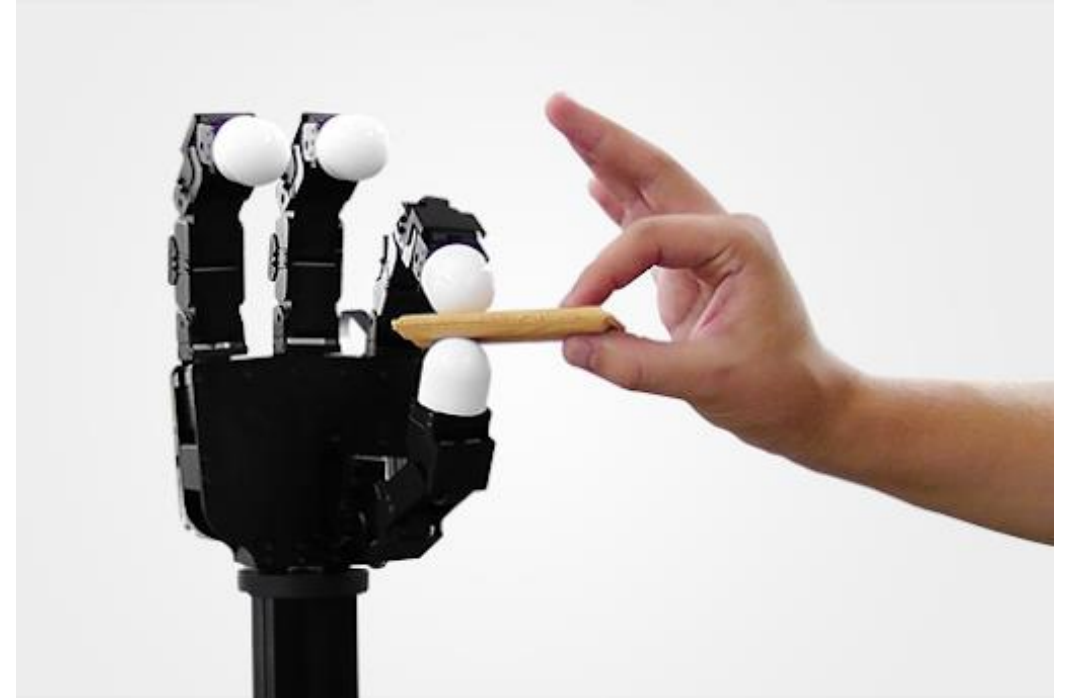


xArm



Franka

End Effectors



You can do solid research with both!

Arguments for Simple Gripper

- Easy to model and control
- Robust
- Cheap
- Mature technology: plenty of available options from industry
- Easy to teleoperate
- Anything else?

Arguments for Dexterous Hand

- More fine-grained motions are possible
- Smaller human-to-robot gap
- Can leverage the technology of prosthetics
- Anything else?

Bimanual is more important than EE type (for now)

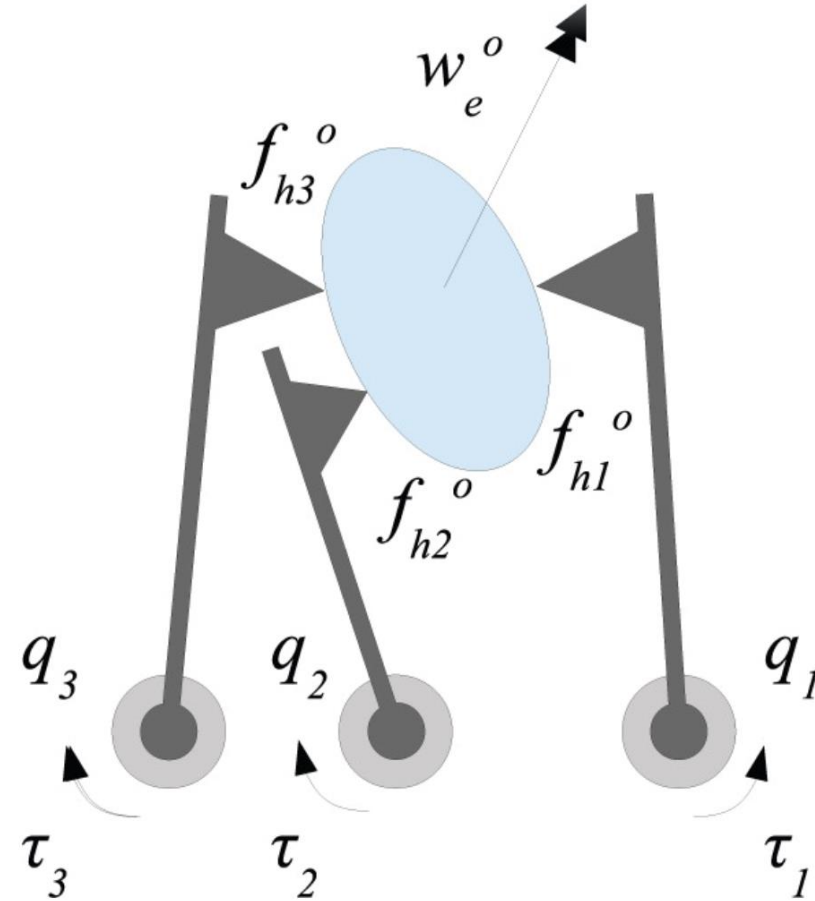


Video from 2010!

Underactuated Hands: Core Concepts

Fully Actuated End-Effector

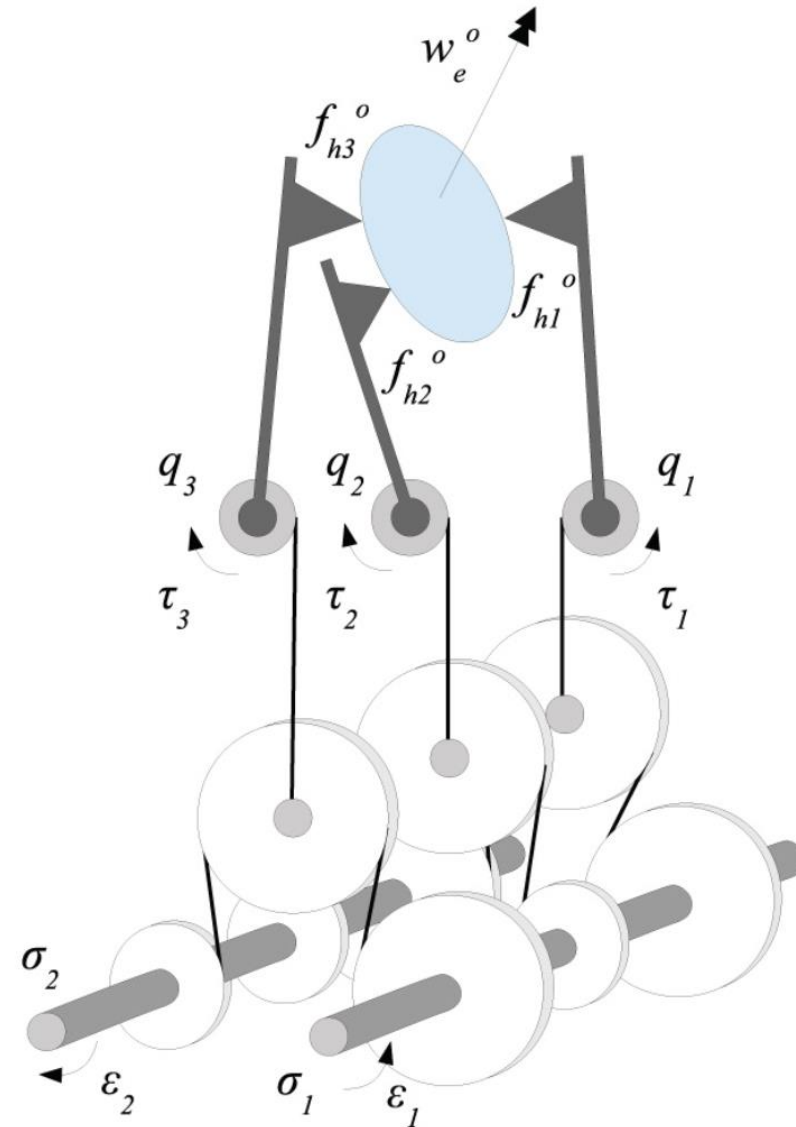
Each joint is independently actuated. Can apply any desired force on the object.



Underactuated Hands: Core Concepts

Hard-Synergy

Turning the shaft of a pulley train generates a joint motion pattern, which can be designed to correspond to a desired synergy vector.

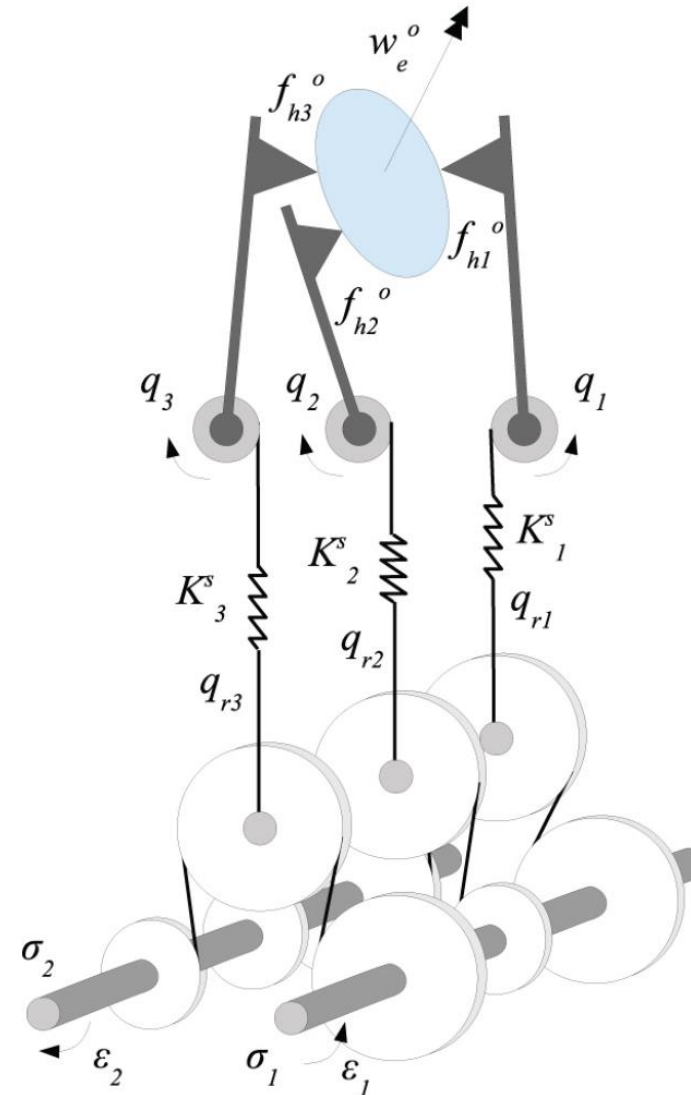


Underactuated Hands: Core Concepts

Soft-Synergy

Adaptivity and compliance
coming from the springs.

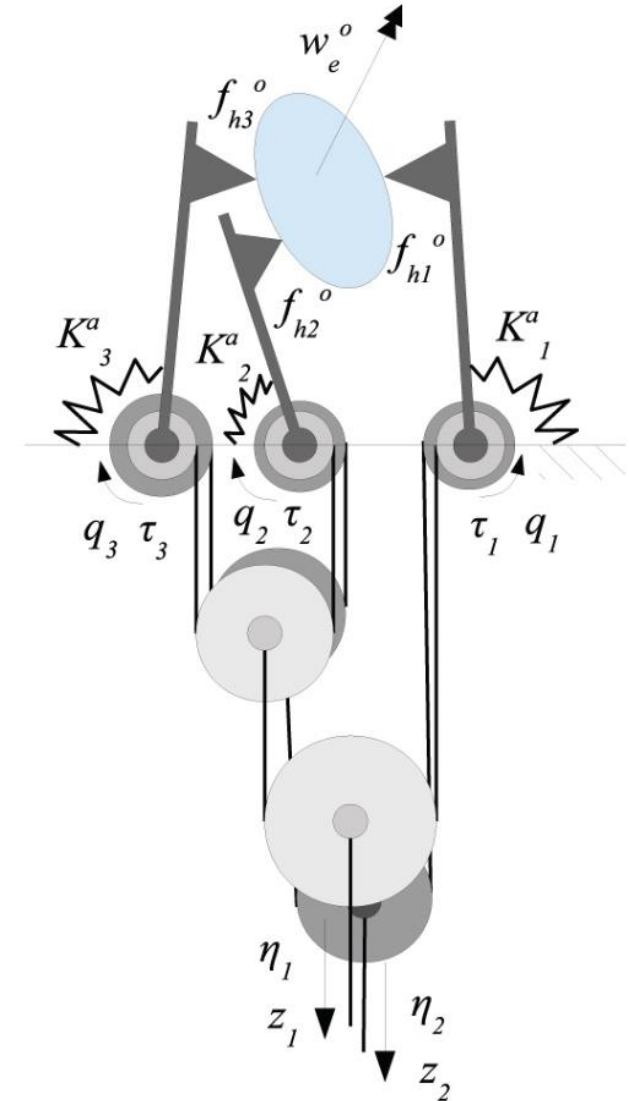
Hard to implement in practice.



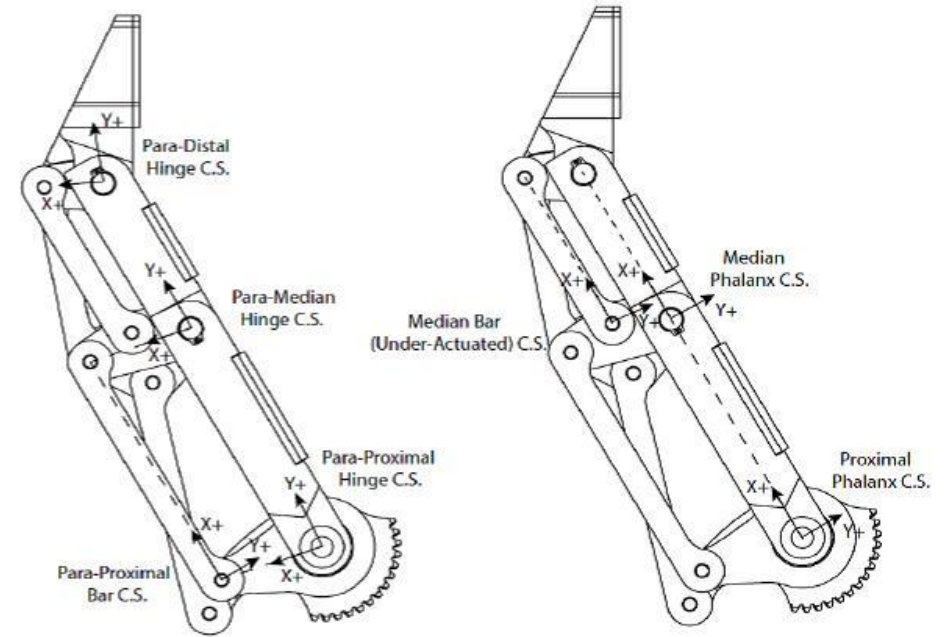
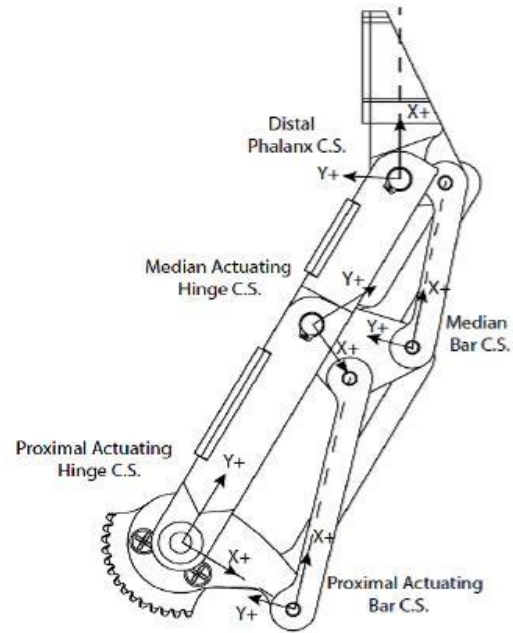
Underactuated Hands: Core Concepts

- **Shape-Adaptive Under-Actuation**
Pulleys move automatically to adapt to the shape of the object. Simple and elegant.

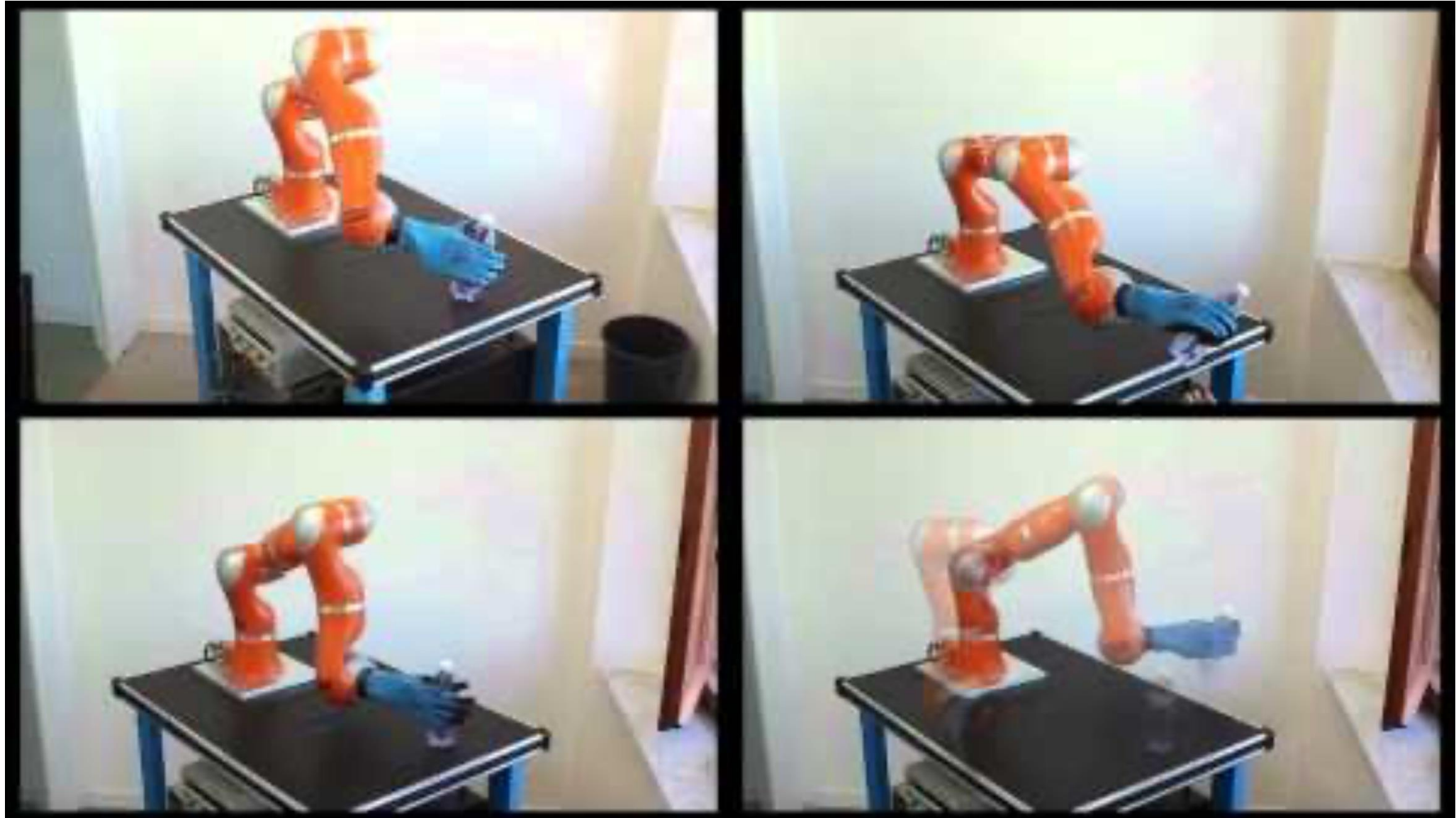
Springs are in parallel with the actuation system, and not in series.



Underactuated Hands via rigid mechanical linkages

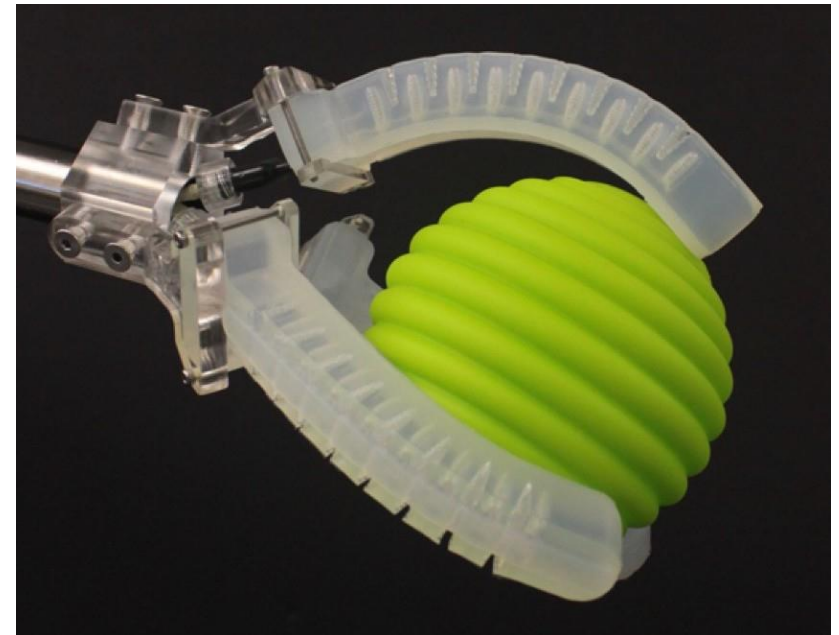


Adaptive Grasping with as few as one motor



Soft End Effectors

- Take the adaptability and compliance argument to the limit.
- State of the art quickly evolving: actuators, power sources, sensors, appendages...
- Potentially safer around humans
- But... What are possible limitations?



Surprisingly high dexterity



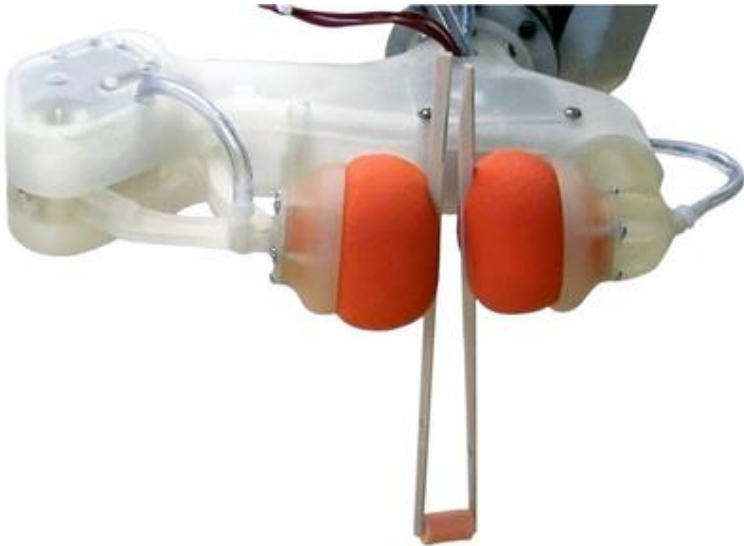
Beyond Human Hands

- Suction Cups



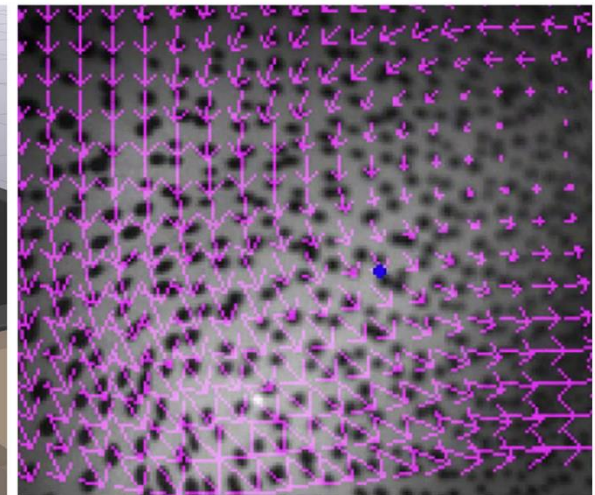
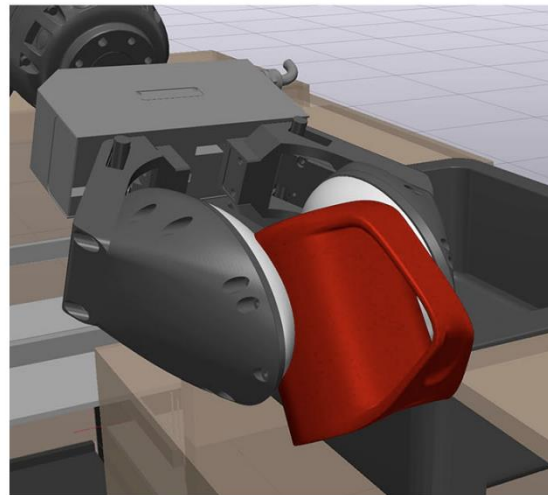
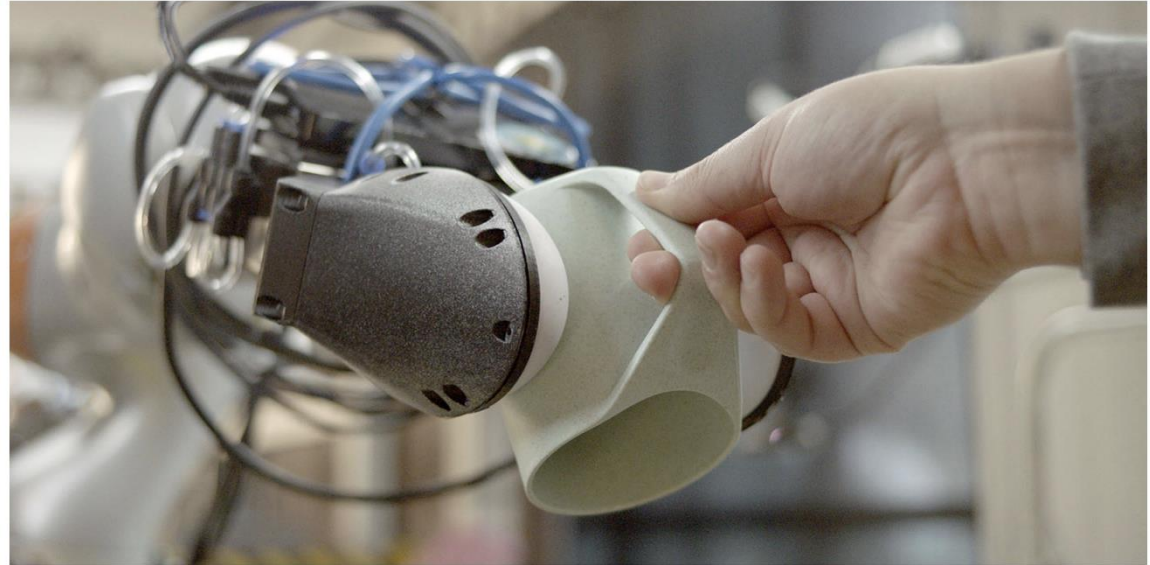
Beyond Human Hands

- Suction Cups
- Jamming Grippers

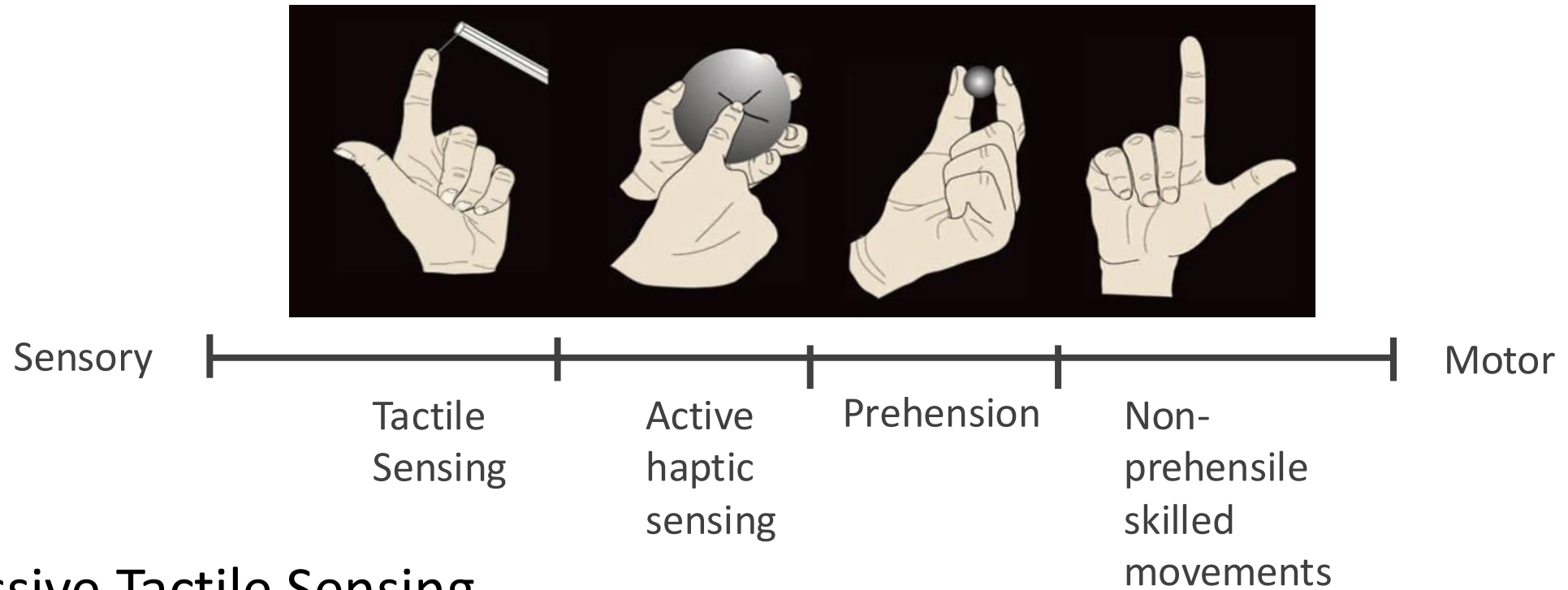


Beyond Human Hands

- Suction Cups
- Jamming Grippers
- Soft Bubbles
- Many more...
(active research topic)



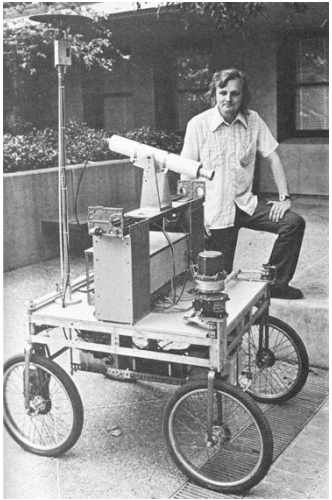
The Beauty of the Human Hand



- Passive Tactile Sensing
- Active Haptic Sensing
- Prehensive motion, e.g., pick and place
- Non-prehensile motion, e.g., playing a piano, gesture, typing

Human Hand Function
Lynette A. Jones, Susan J. Lederman

Science-Fiction Aside: Fractal Hands



From Hans Moravec's
Mind Children



The overview of a robot (Next Class)

