What is a Robot?

ESE 6510
Antonio Loquercio

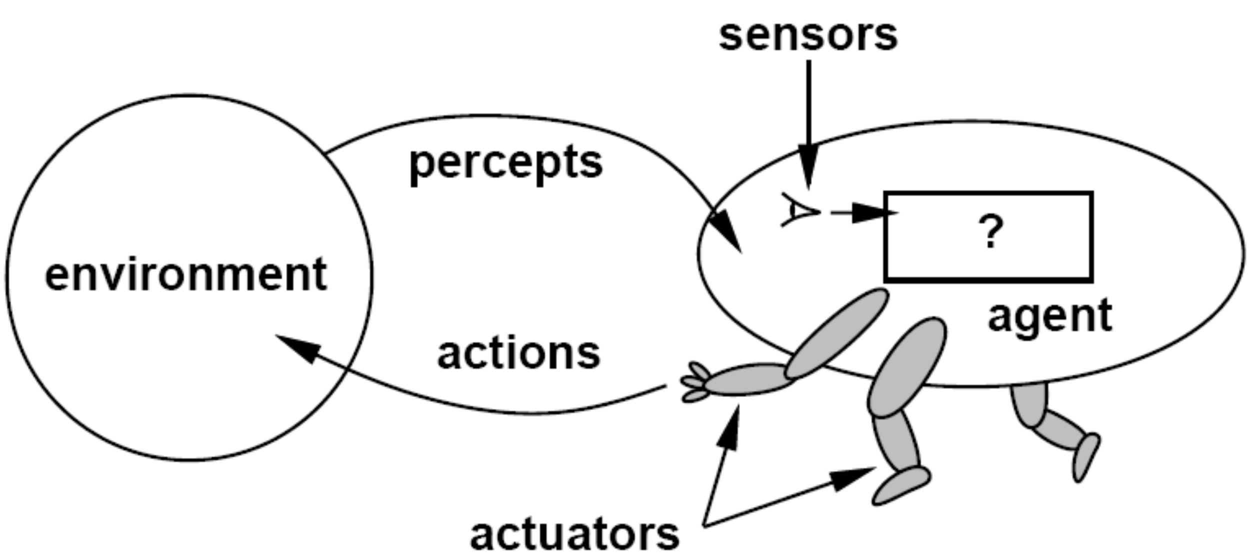
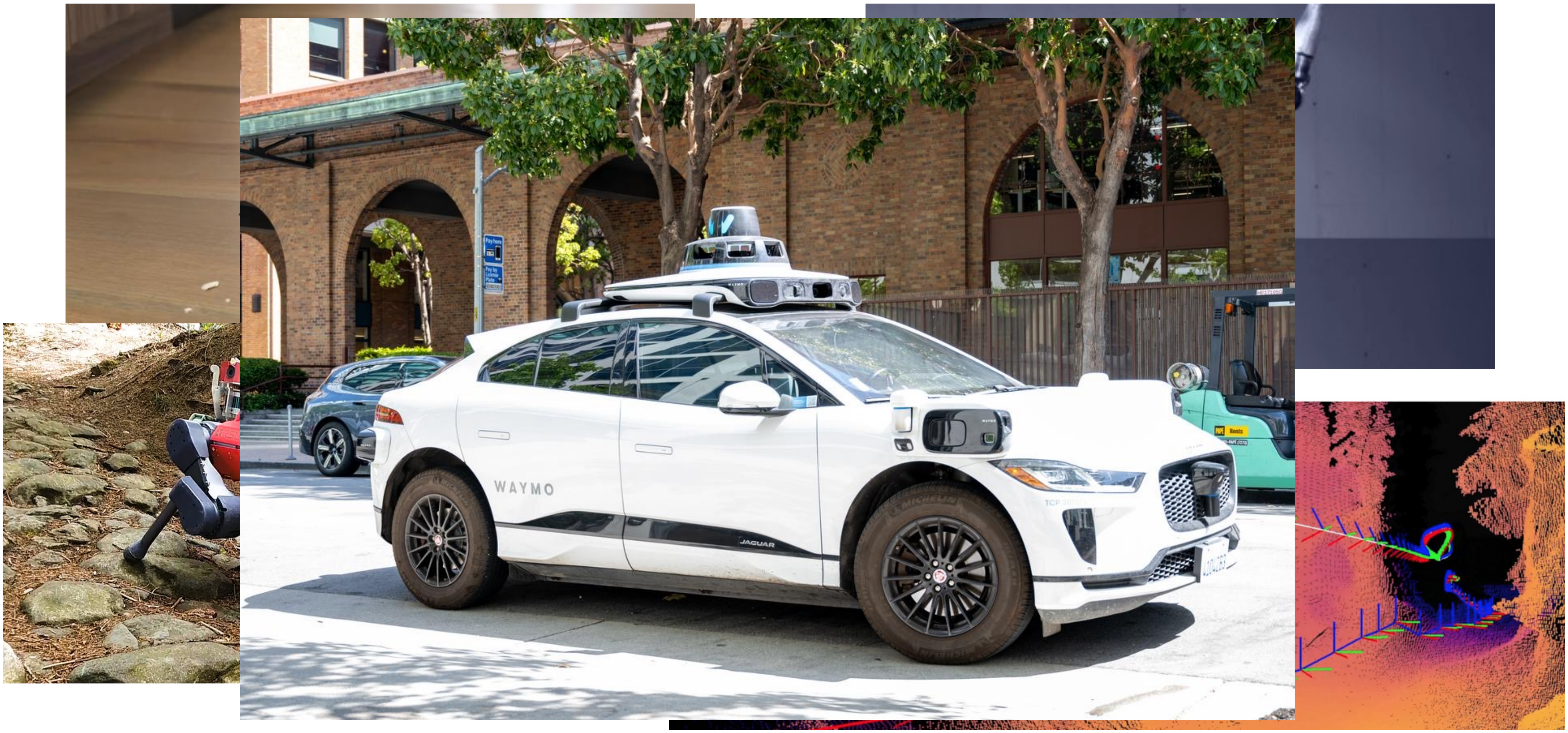


Figure from Russell & Norvig

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,*]

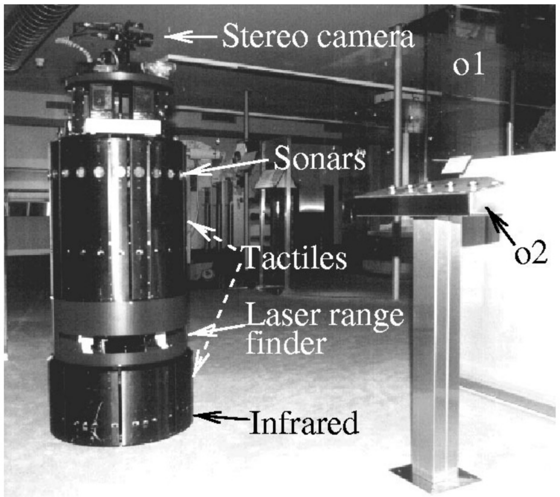


Fig. 1. The robot and its sensors.

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

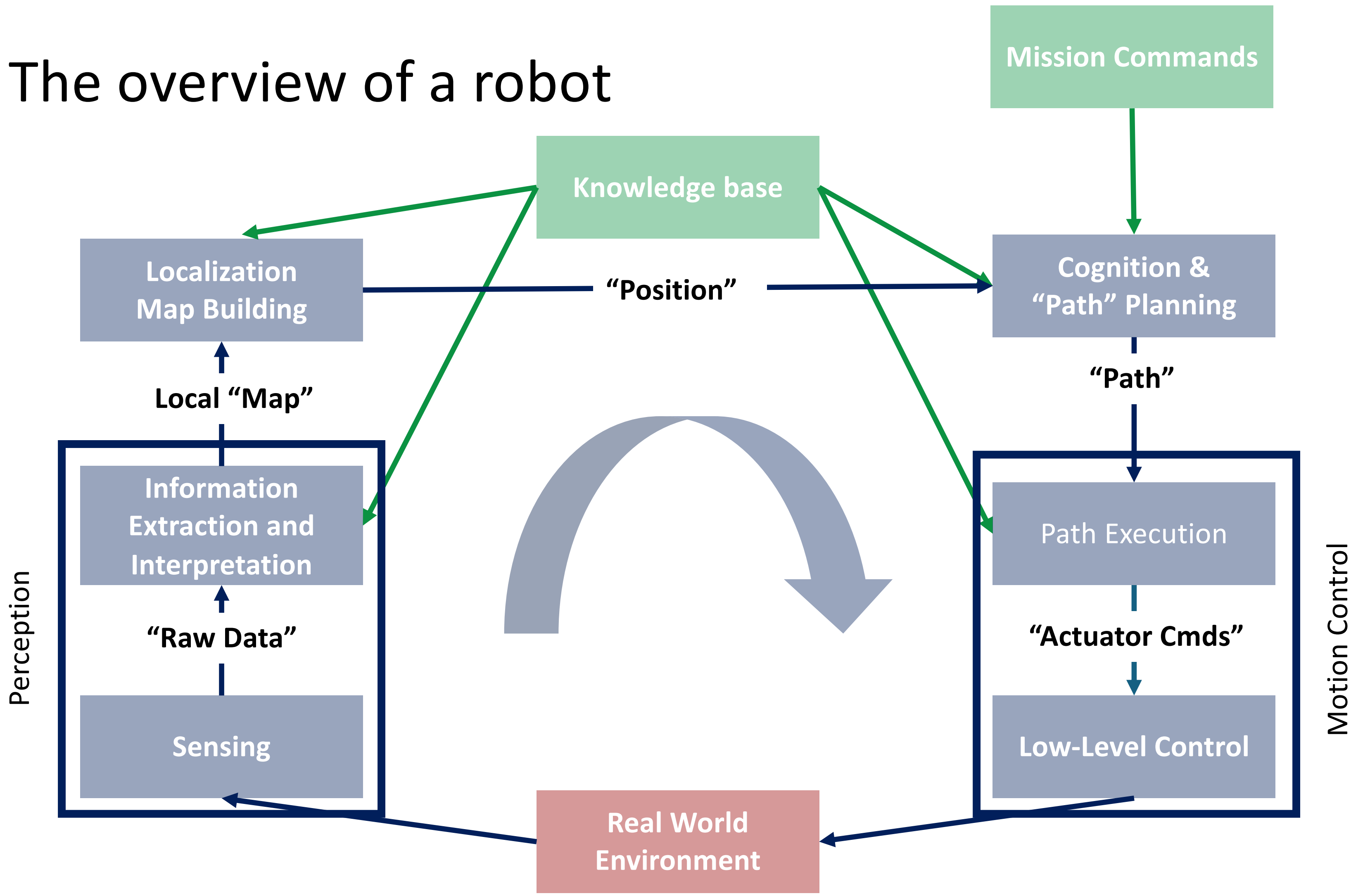
- Understand the core components of a robot

- Understand the main mechanisms that enable a robot to interact with the world:

  - Mobility

  - Manipulation

The overview of a robot

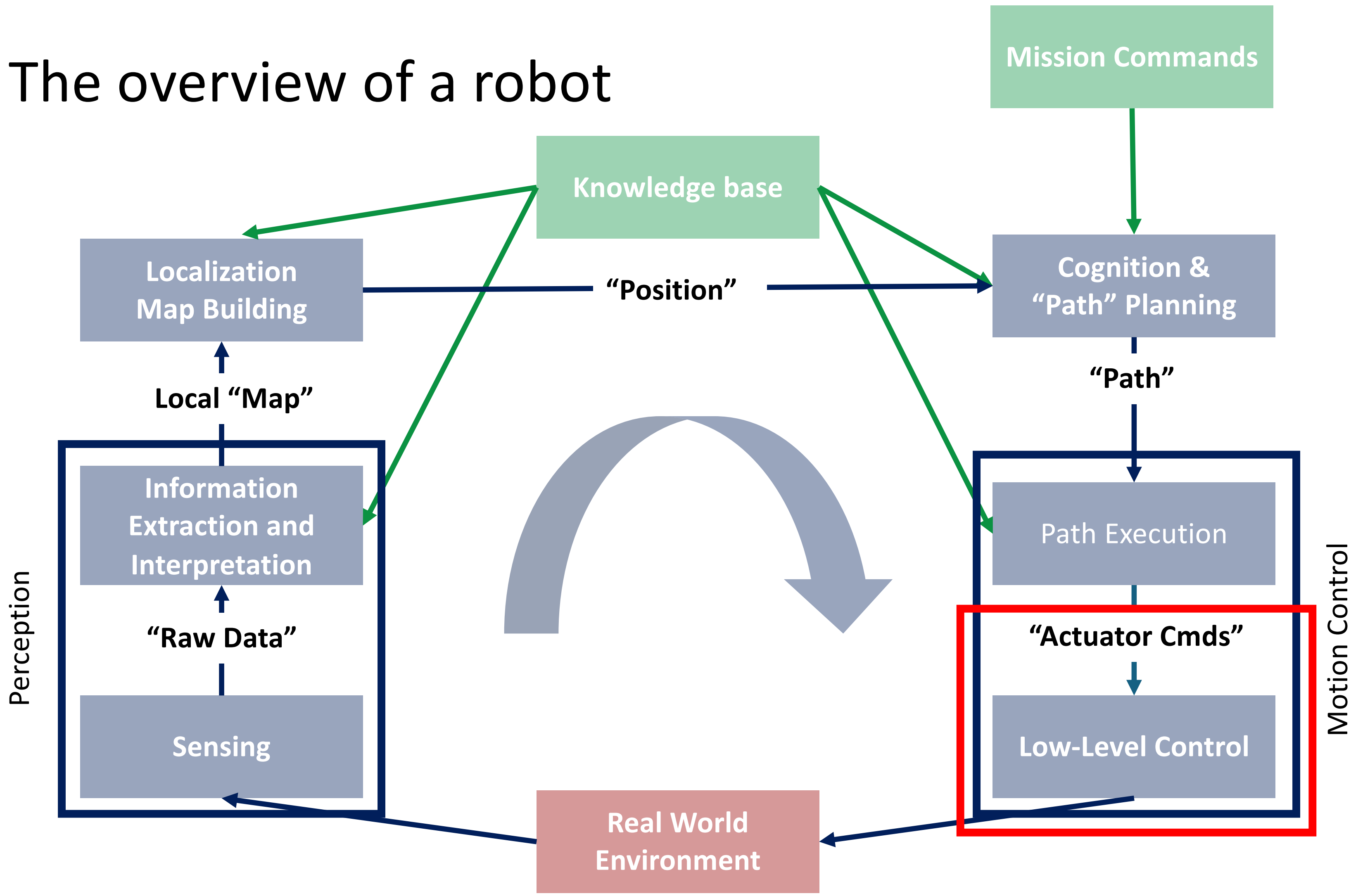


Is this a robot?

Is this a robot?

Is this a robot?

The overview of a robot



Two categories of interaction with the world

- Mobility

- Manipulation

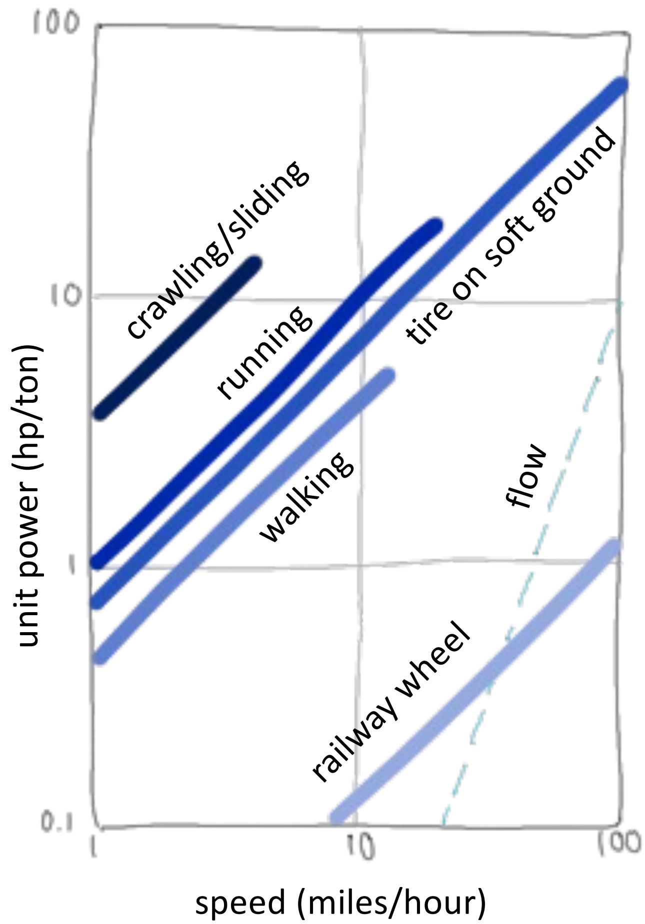
Mobility

- 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

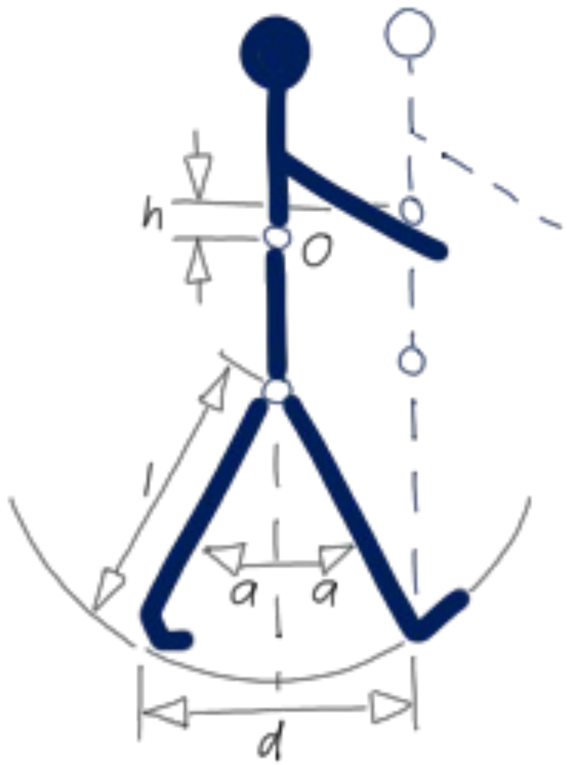
Type of Motion	Resistance to motion	Basic kinematics of motion
Flow in a Channel	Hydrodynamic forces	Eddies
Crawl	Friction forces	Longitudinal vibration
Sliding	Friction forces	Transverse vibration
Running	Loss of kinetic energy	Periodic bouncing on a spring
Walking	Loss of kinetic energy	Rolling of 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.

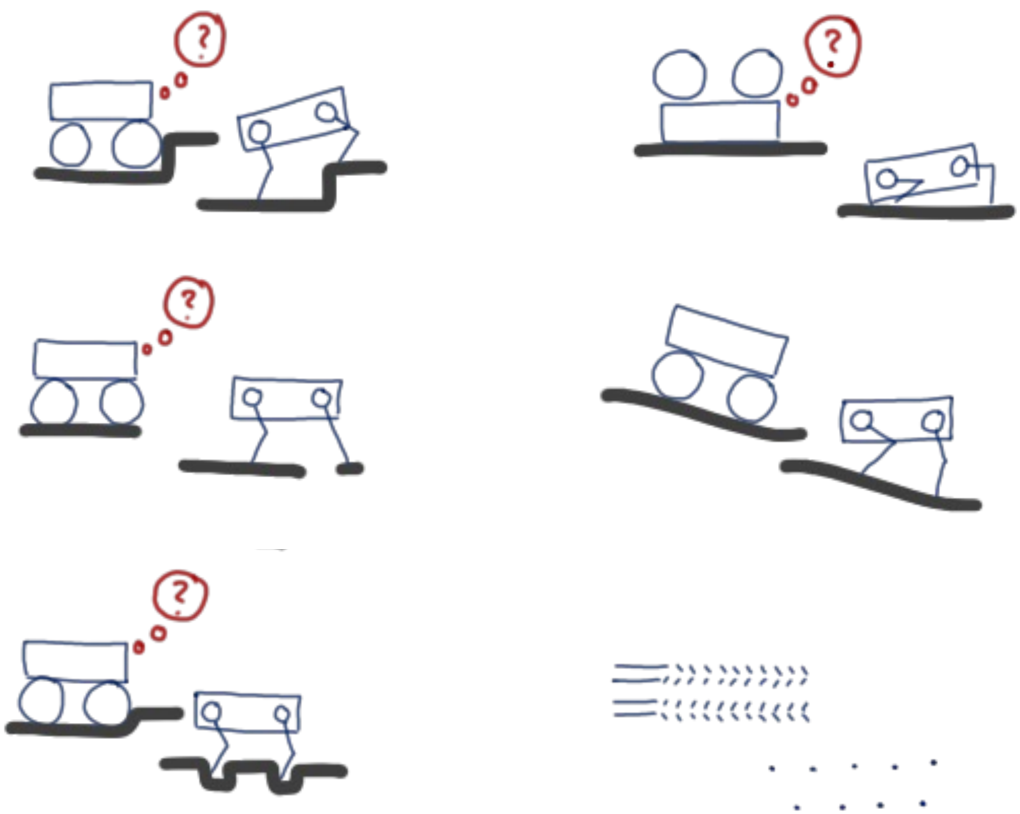
Wheels are a general case of legs



The rolling polygon

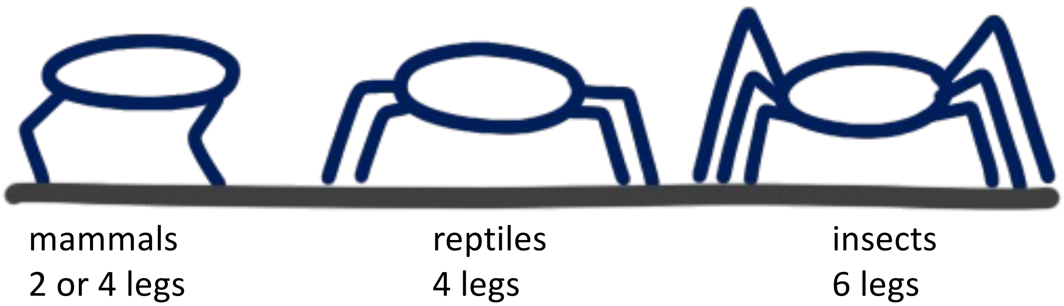
Source:
Autonomous Mobile Robots,
Siegwart et al., Ch 2.

Legs vs Wheels



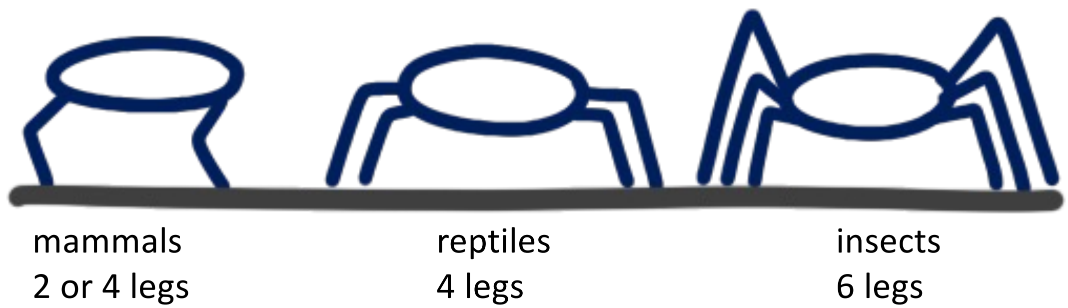
Source:
Autonomous Mobile Robots,
Siegwart et al., Ch 2.

Legs Configuration and Stability



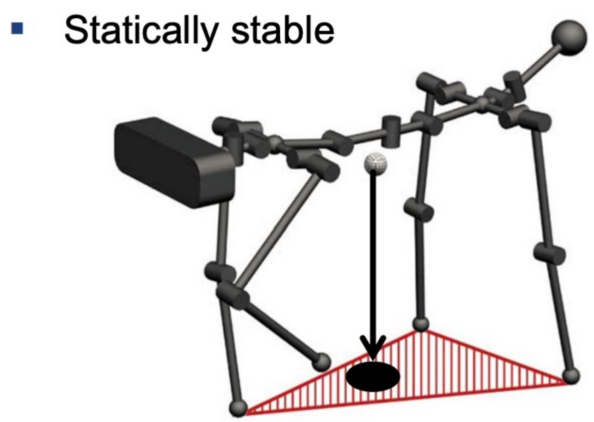
- Large animals usually have 4 legs, while insects have 6. The fewer the legs, the harder it is to maintain balance.
- The position of the center of mass induces differences in stability, speed, and rough terrain traversability (mammals vs reptiles). Joints help muscles to absorb impacts.
- Nature offers 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

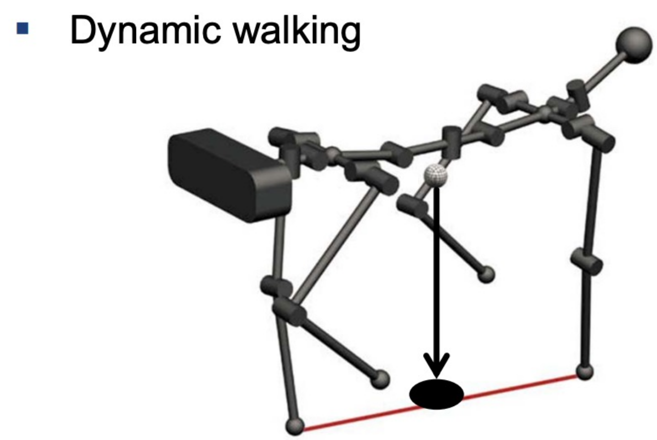


- A gait specifies **which legs are in contact with the ground at a given time** and how this pattern repeats cyclically.
- How many gaits do humans have?
- There are (2K -1)! gaits for a system with k legs!

Static vs Dynamic Stability



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



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

Source: ETH

Dynamics Consideration

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

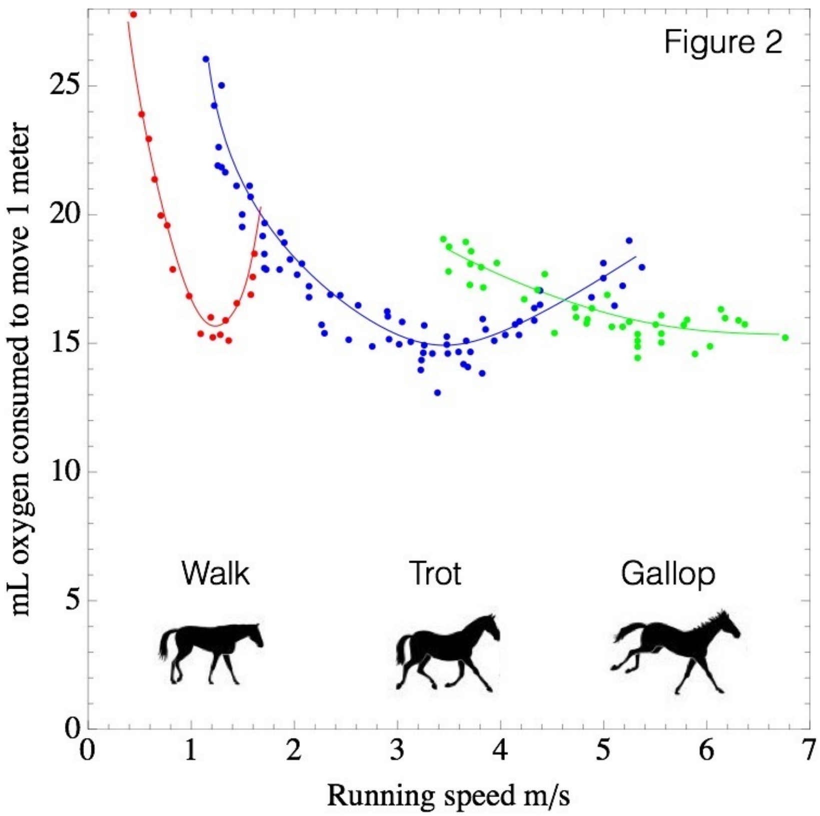
Dynamics Consideration

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

The (Powered) Ranger Robot from Cornell

40.5 miles non-stop without being touched by a human

Optimizing the Cost of Transportation

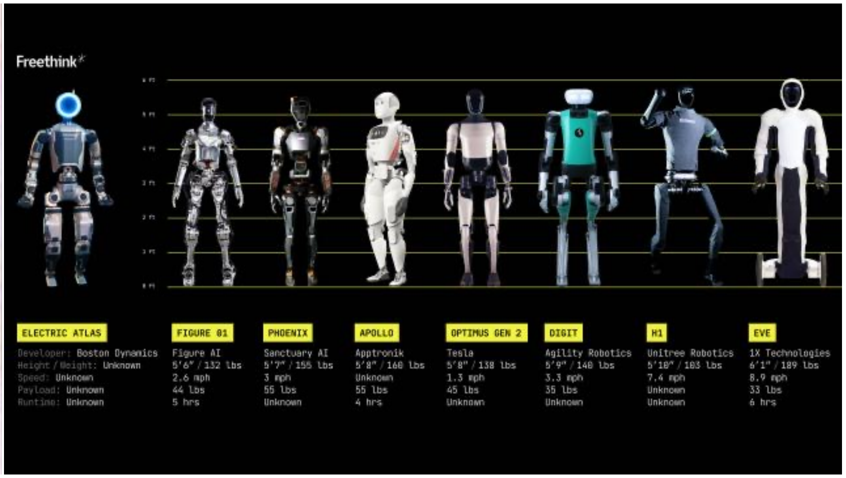


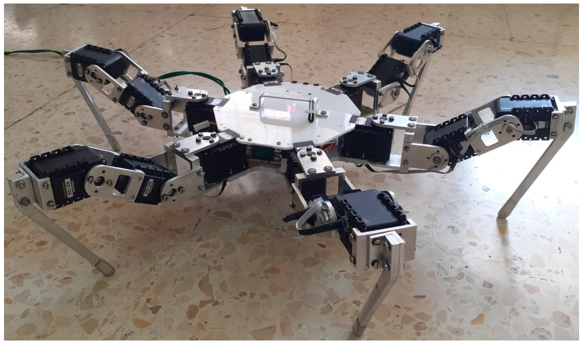
Changing gait enables using a different set of natural dynamics, minimizing the cost of transportation

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
- …

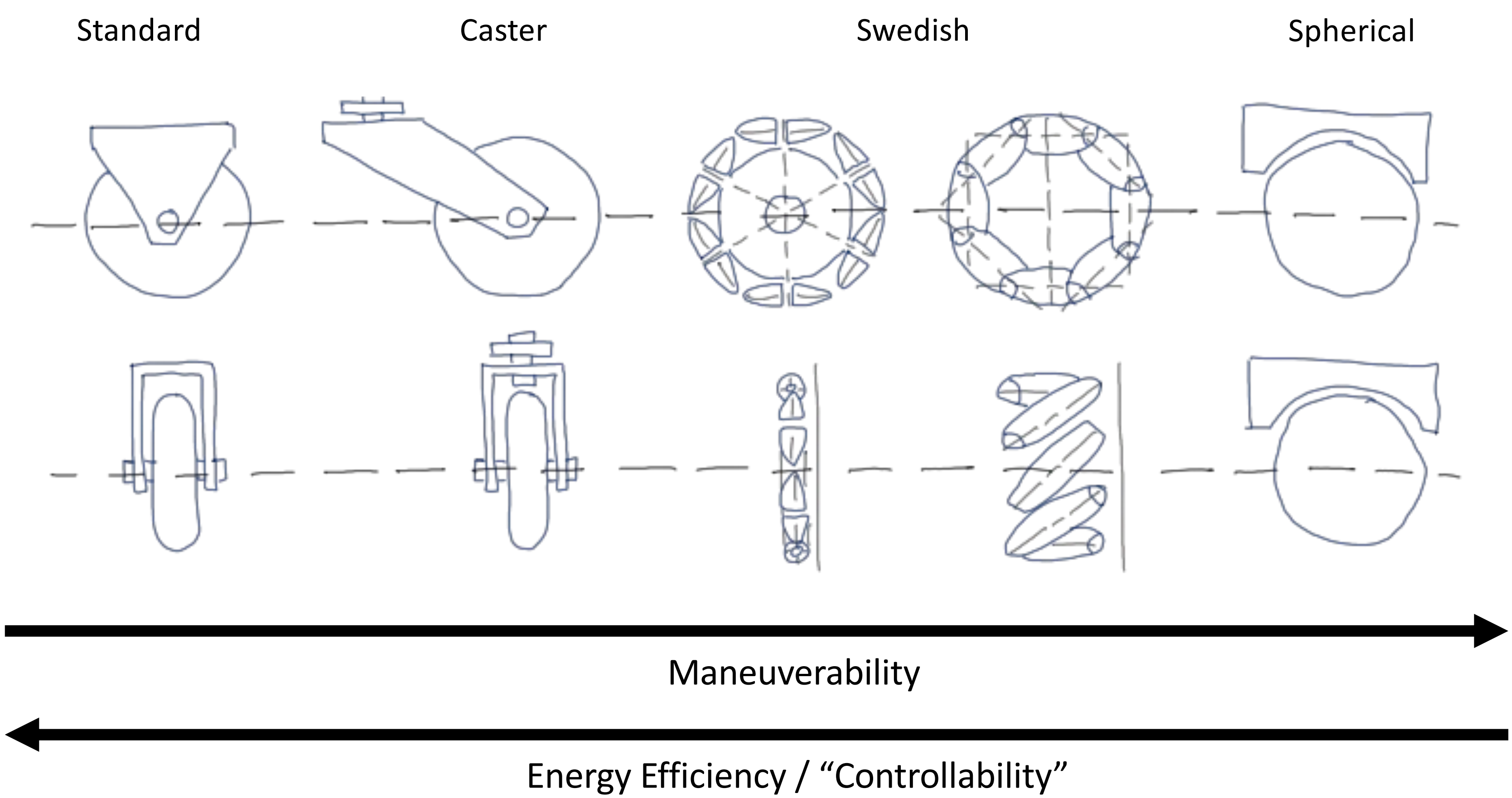




Wheeled Locomotion

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

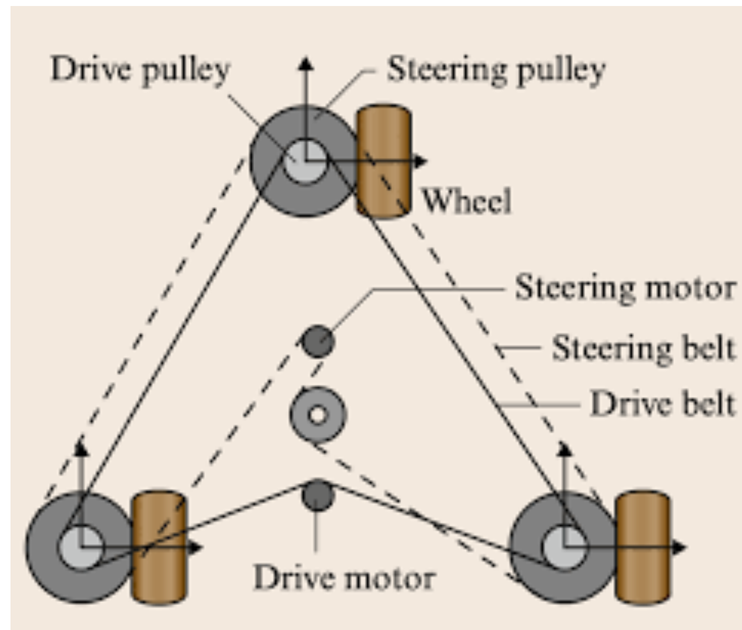
Wheeled Locomotion: Wheel Types



Wheeled Locomotion: Design Space

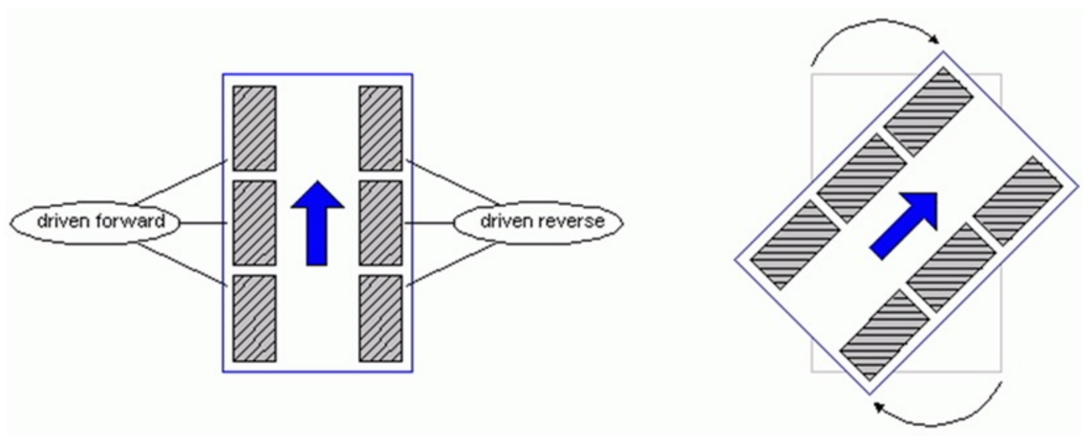
- Large design space induced:
  - Type of wheels
  - Number of wheels
  - Position of wheels
  - Suspensions
- Key optimization factors:
  - Stability
  - Maneuverability
  - Controllability
- There is **NO** ideal configuration

Synchro-Drive



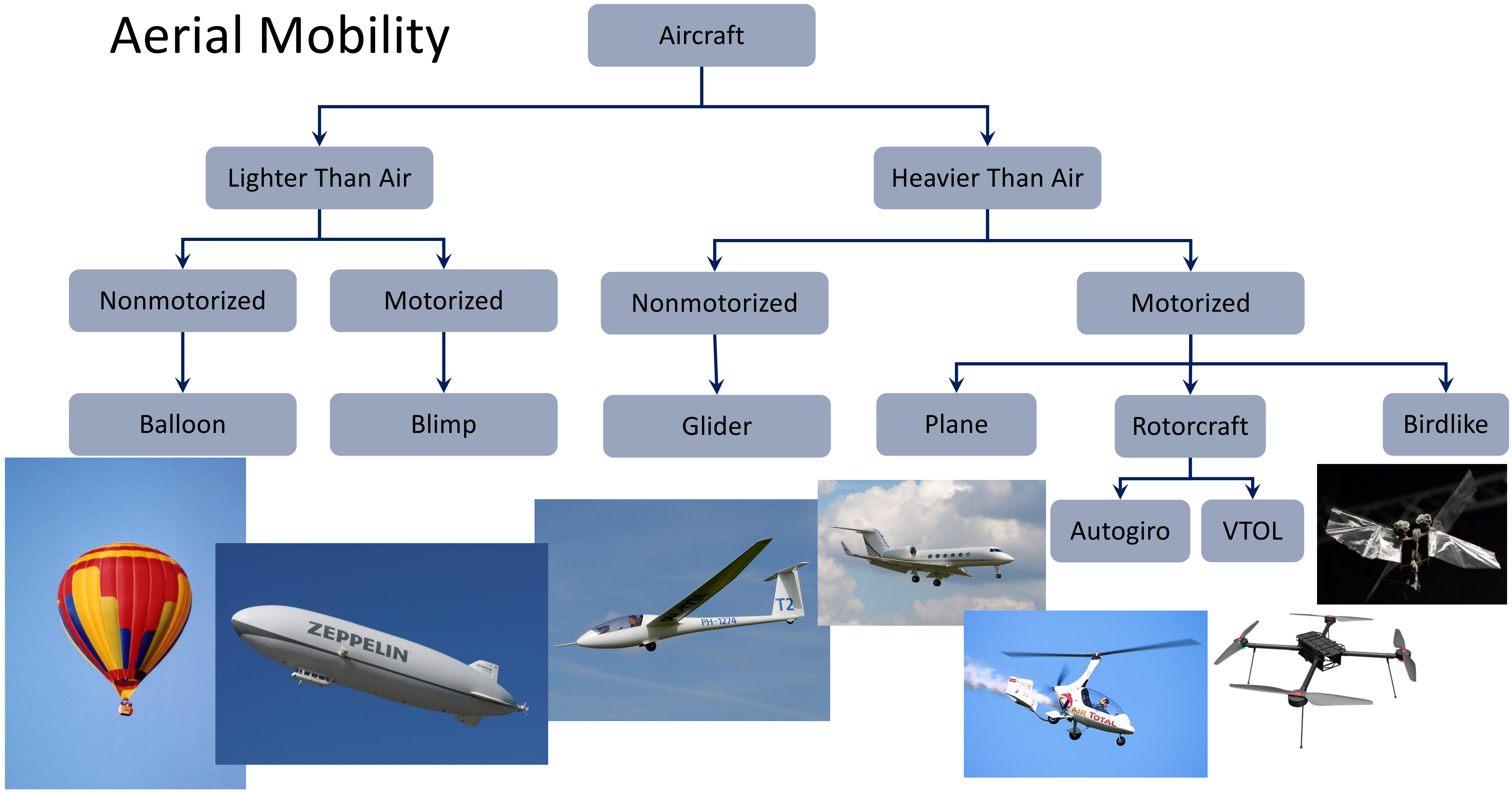
Slip/Skid Locomotion

- 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

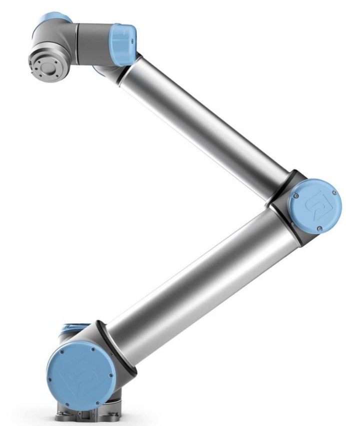
- Shares the same core issues of stability, maneuverability, and controllability.

- 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

Aside: Joint Position vs Torque Control

- Most robot arms/legs are joint position-controlled.

- Wouldn’t it be better to have torque control? In theory, we could have much better control over the dynamics...

- Short answer:
  - 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

Aside: 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

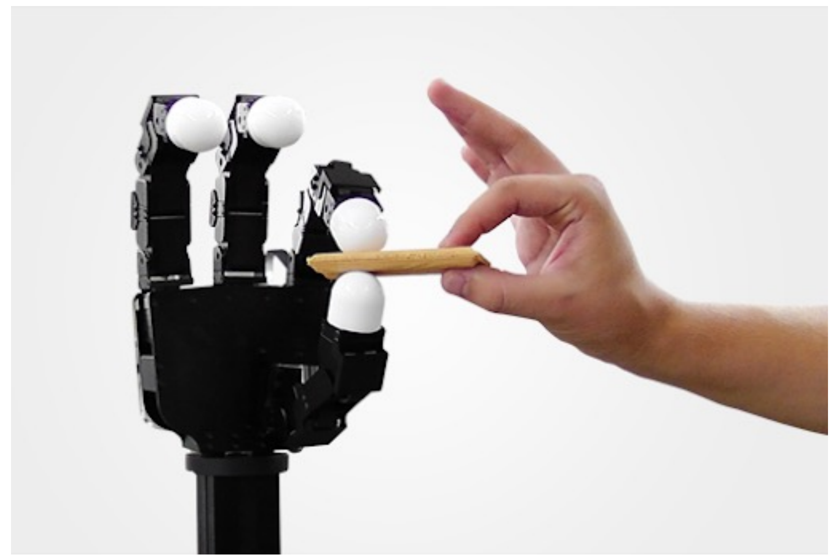
$$\tau = K_p\left(q^d - q\right) + K_d\left(\dot{q}^d - \dot{q}\right) + K_i \int \left(q^d - q\right)$$

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

Some exceptions

- 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).

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?

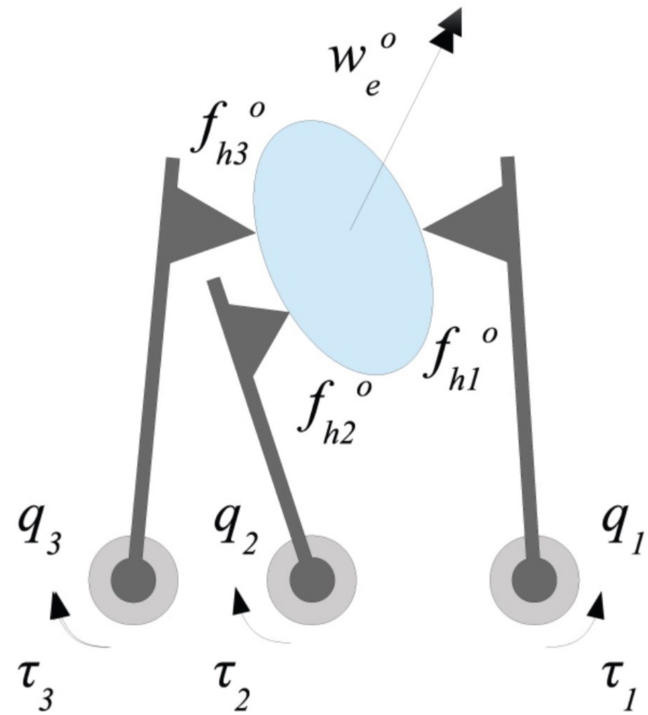
Bimanual is more important than EE type (for now)

Video from 2010!

Underactuated Hands: Core Concepts

Fully Actuated End-Effector

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

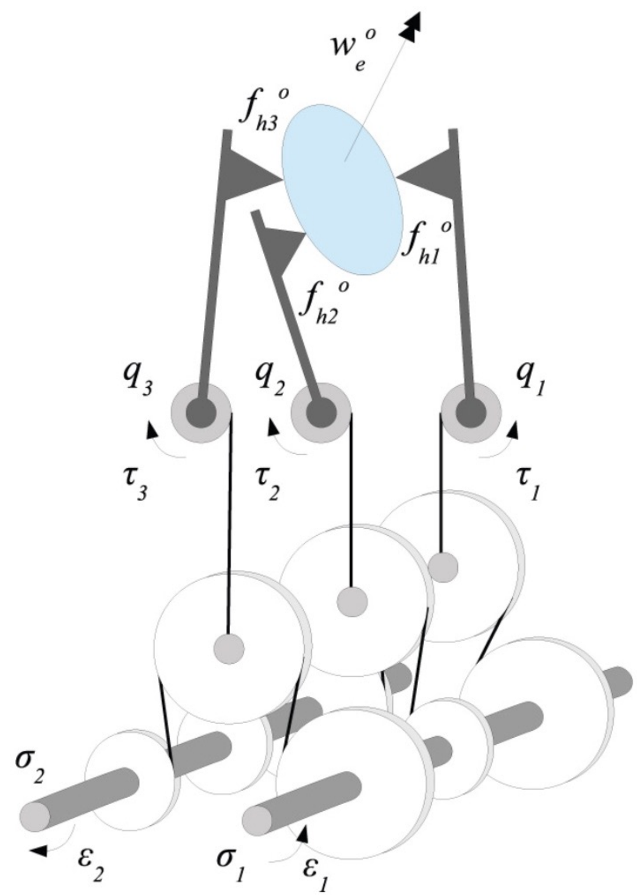


Adaptive synergies for the design and control of the Pisa/IIT SoftHand
Catalano et al., 2014.

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.



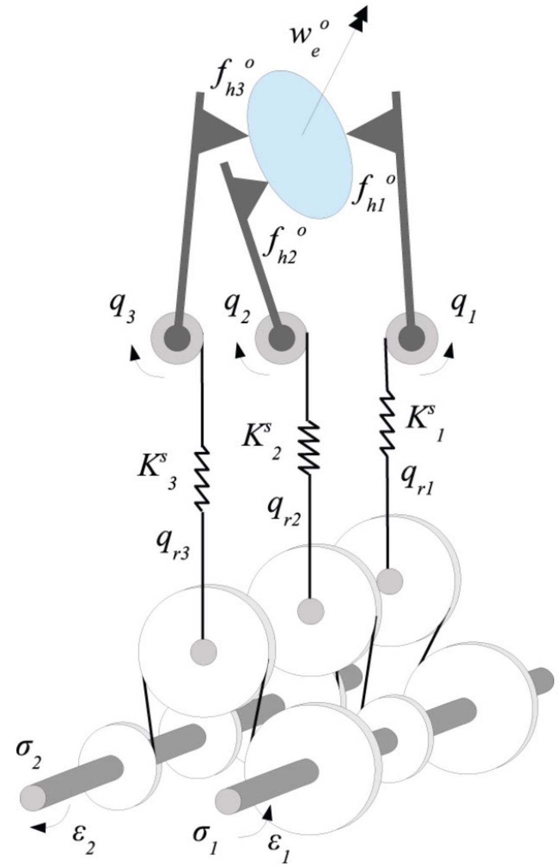
Adaptive synergies for the design and control of the Pisa/IIT SoftHand
Catalano et al., 2014.

Underactuated Hands: Core Concepts

Soft-Synergy

Adaptivity and compliance coming from the springs.

Hard to implement in practice.

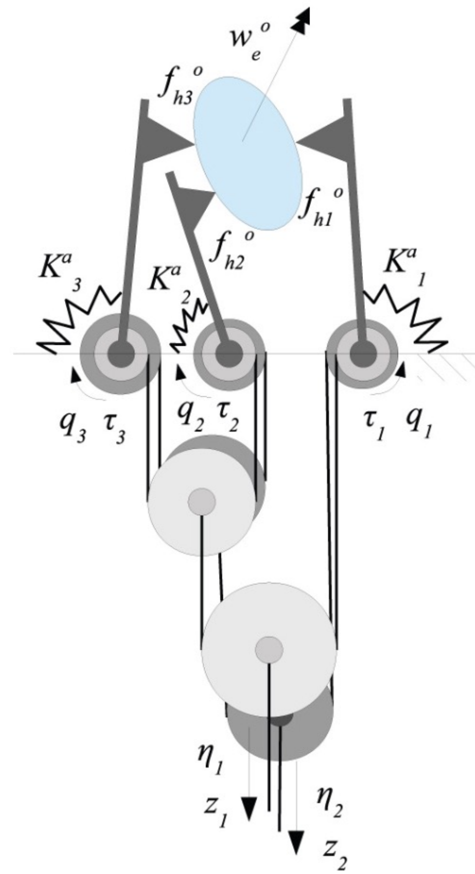


Adaptive synergies for the design and control of the Pisa/IIT SoftHand
Catalano et al., 2014.

Underactuated Hands: Core Concepts

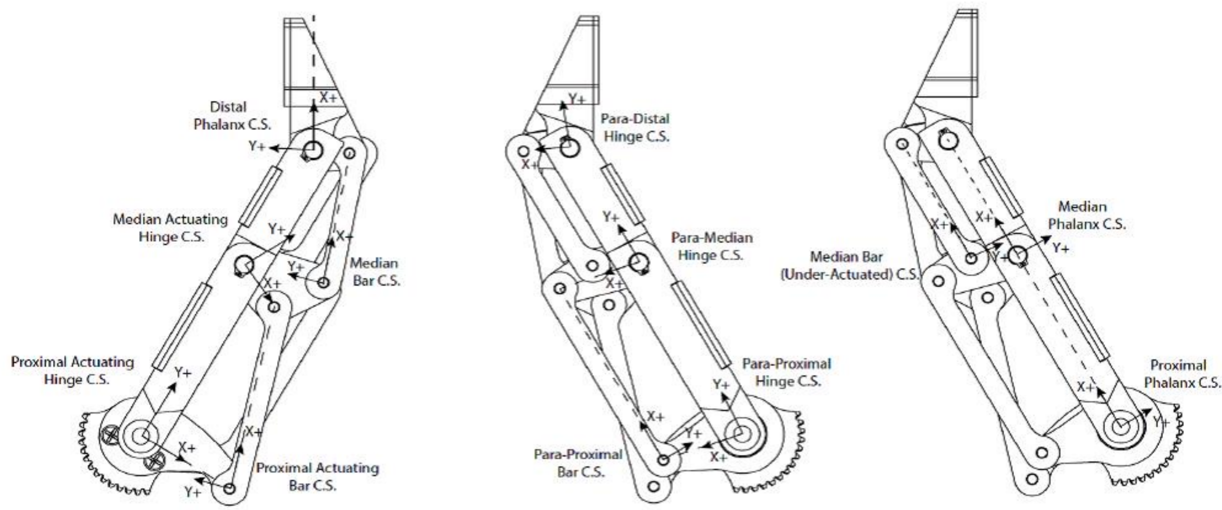
- **Shape-Adaptive Under-Actuation**
  Pulleys move automatically to adapt to the shape of the object. Simple and elegant.

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

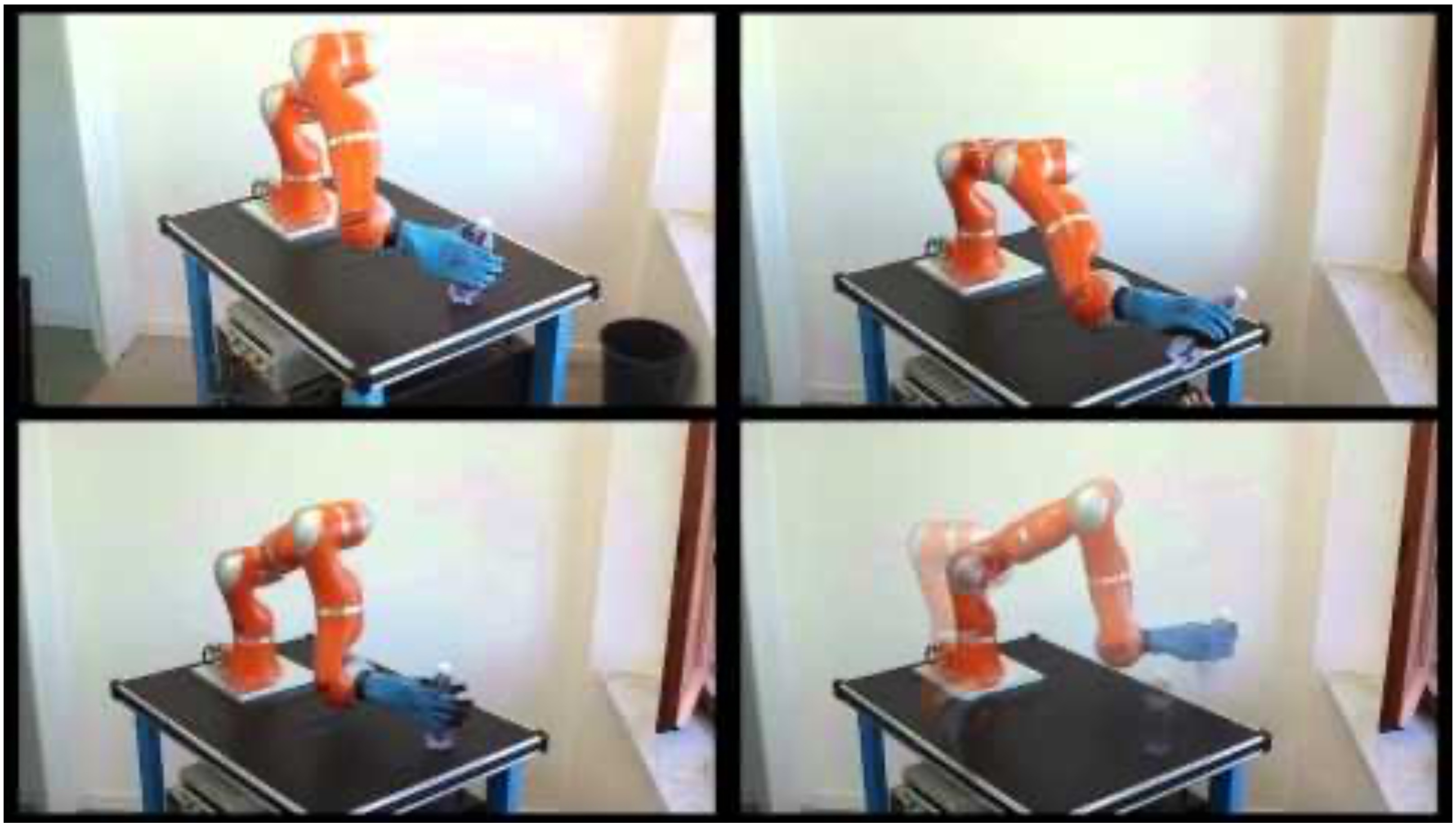


Adaptive synergies for the design and control of the Pisa/IIT SoftHand
Catalano et al., 2014.

Underactuated Hands via rigid mechanical linkages

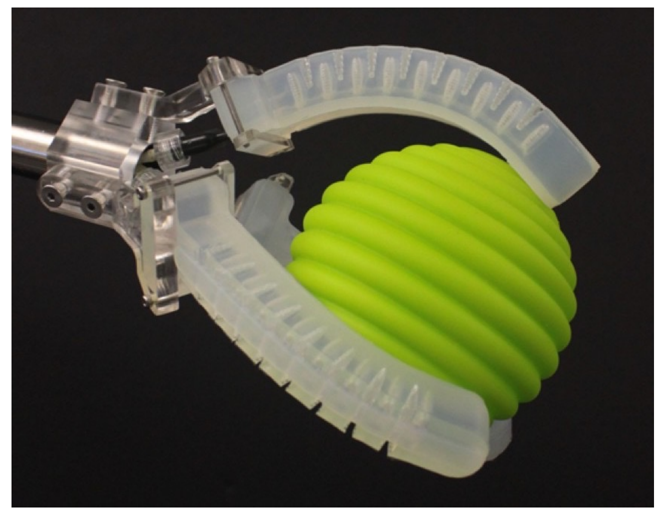


Adaptive Grasping with as few as one motor



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?



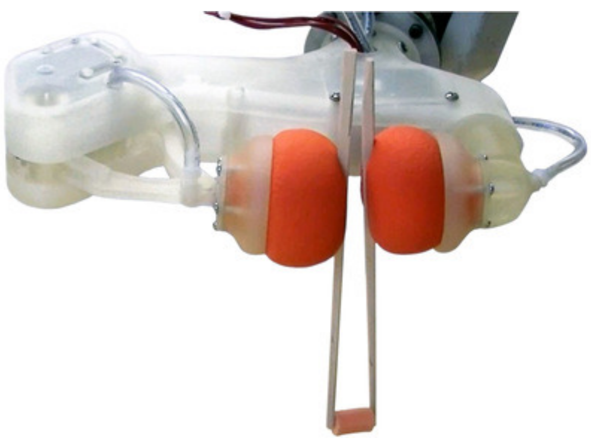
Surprisingly high dexterity

Beyond Human Hands

- Suction Cups

Beyond Human Hands

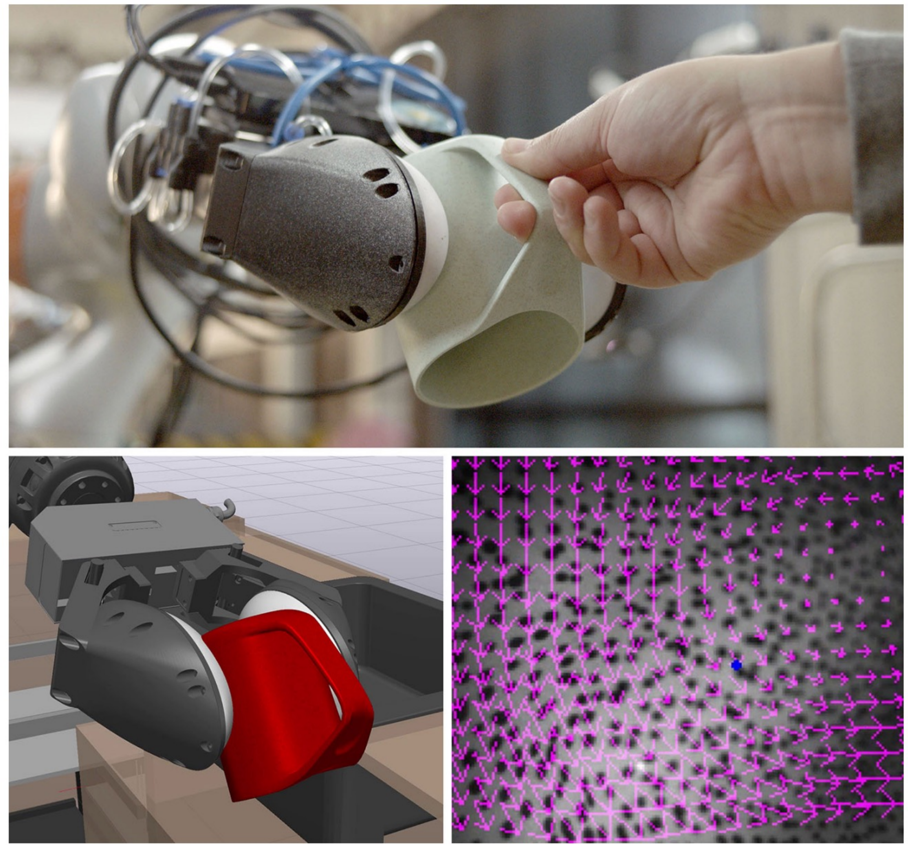
- Suction Cups
- Jamming Grippers



Creative Machines Lab, Cornell 2011

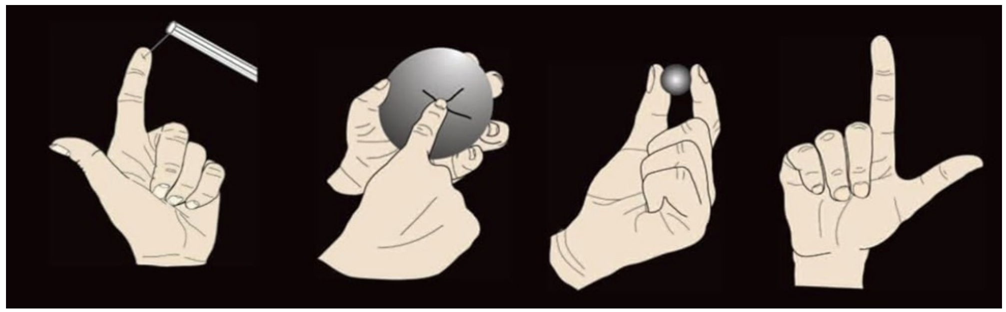
Beyond Human Hands

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



Soft-Bubble grippers for robust and perceptive manipulation, Kuppuswamy et al, 2020

The Beauty of the Human Hand

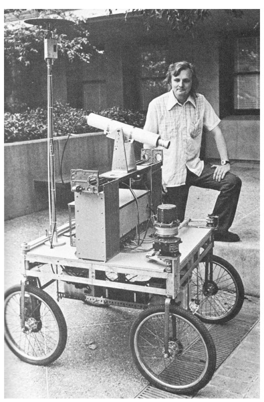


Sensory — Tactile Sensing — Active haptic sensing — Prehension — Non-prehensile skilled movements — Motor

- 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)