Lecture 03:
Robot Mechanism (2)

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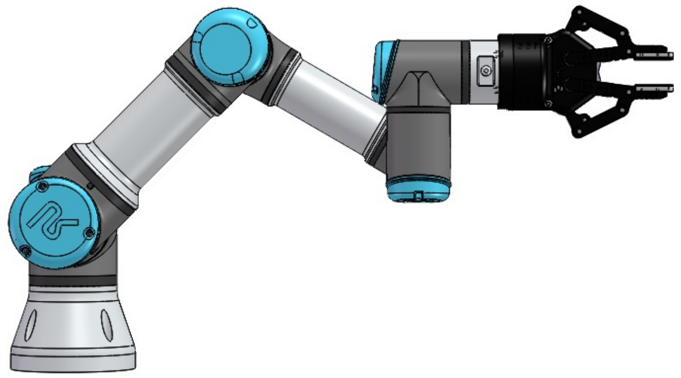
Sep. 3, 2024

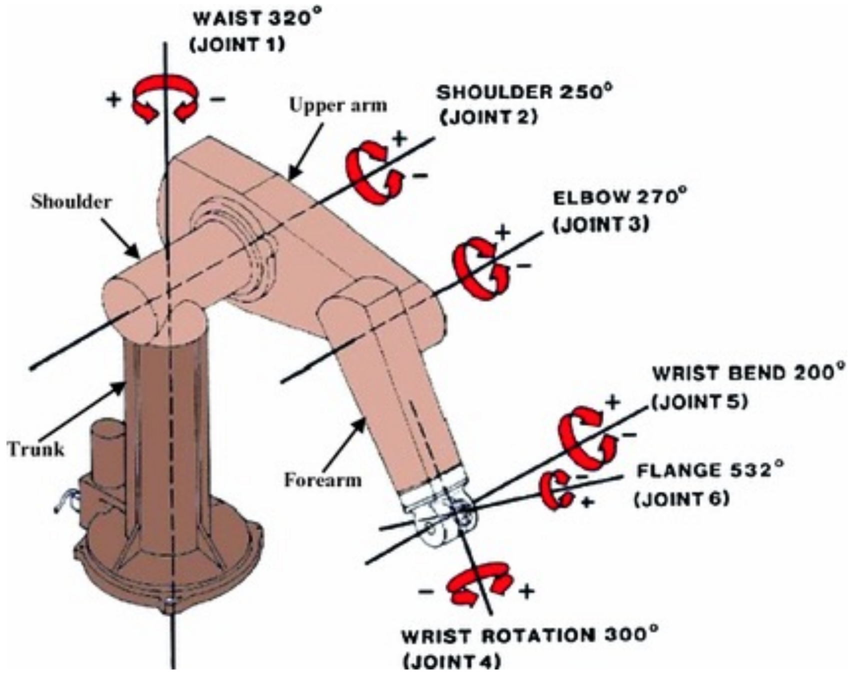
Serial robots

- a sequence of links and joints that begins at a base and ends with an end-effector



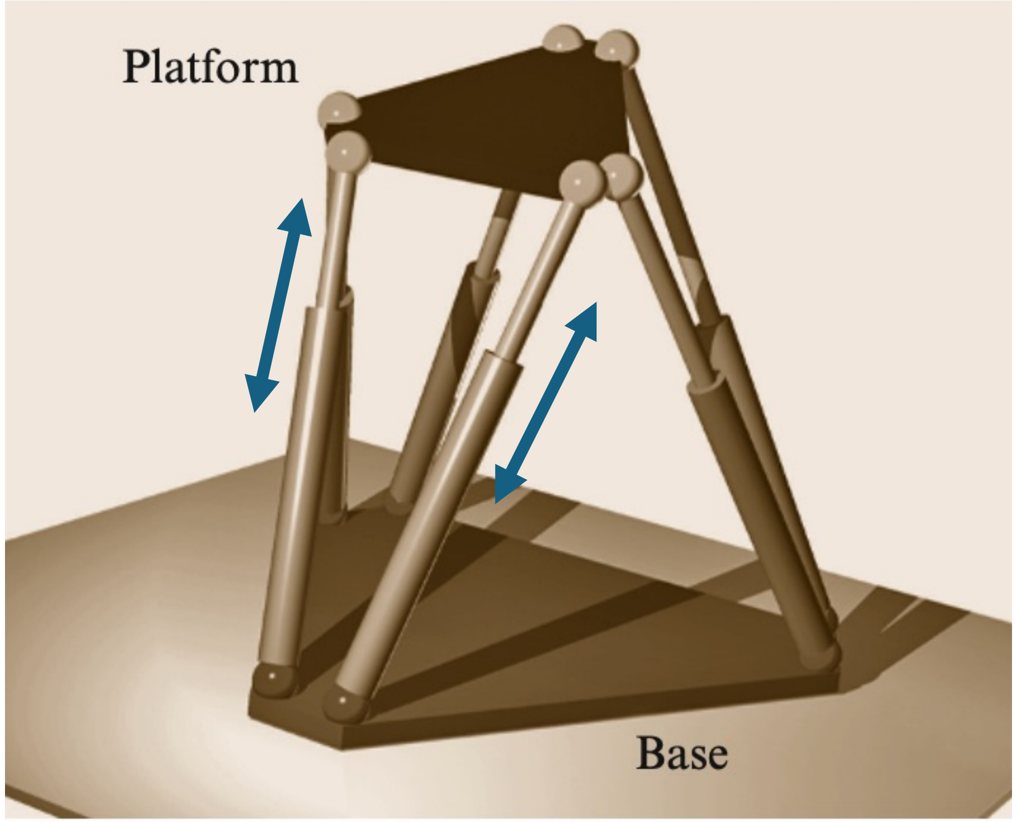
How many joints are there?
What's the DoF of the robot?

What's the Dof of the end-effector?



Parallel robots

A robot system that two or more serial chain robots support an end-effector

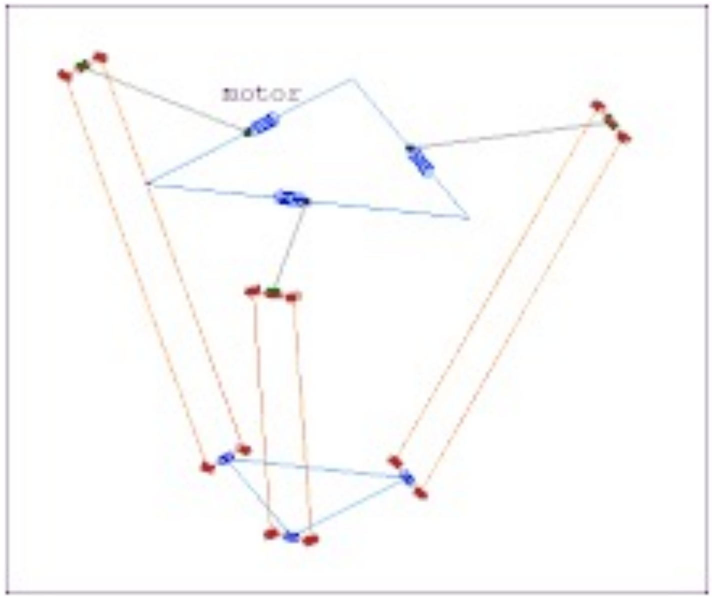


Stewart platform

http://handbookofrobotics.org/view-chapter/04/videodetails/640

Parallel robots

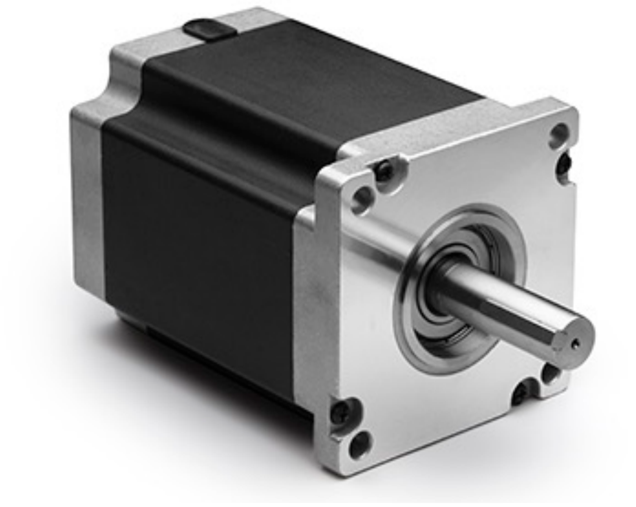
- Higher precision; higher stiffness and rigidity

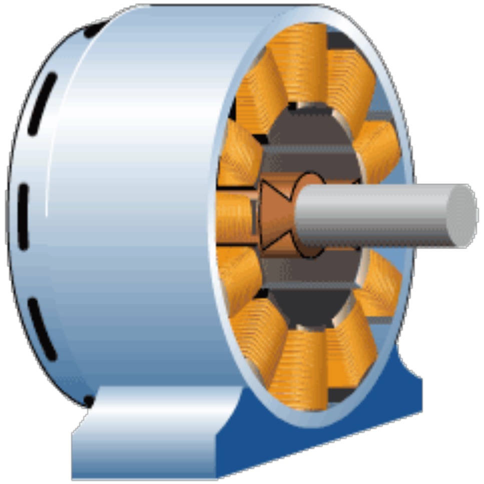


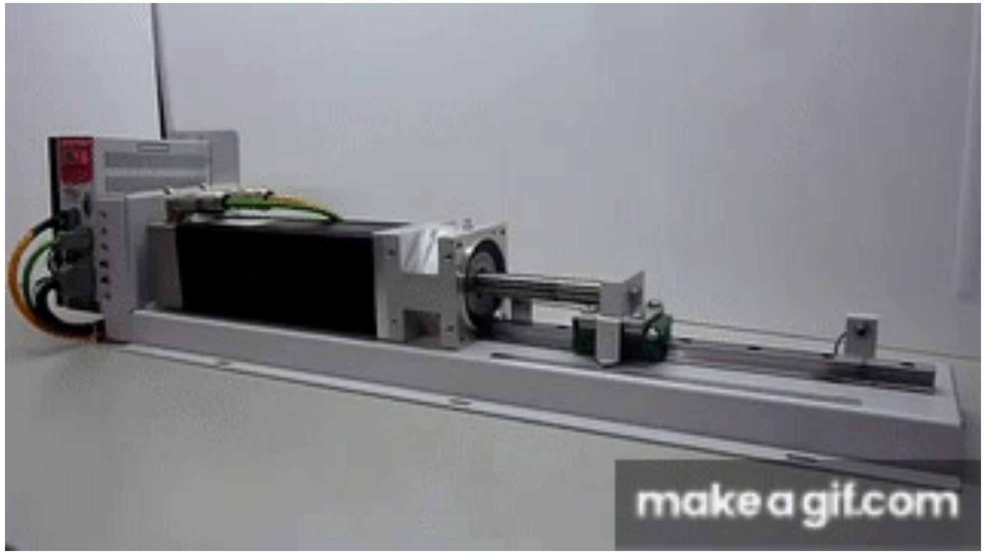
Wikipedia: Delta Robot

Actuators

- Actuators supply the motive power for robots.
- The most common types of actuators in robots today are electromagnetic actuators.







The magnetic field exerts a force on a movable component called the armature

Electromagnetic actuators

- *Servomotors* accurately follow the desired position
  - Position sensor (encoder) + closed-loop control
  - they have structures similar to ordinary electric motors, but with low inertia and large torque capably for high accelerations.

$$\tau_m = K_t i_a$$

τ_m is the motor torque
K_t is the torque constant [N m=A]
i_a is the armature current [A].

$$v_b = K_b \omega_m$$

v_b back electromotive force (emf)
Kb is the back emf constant [V=(rad=s)]
ω_m is the angular speed of the motor [rad=s]

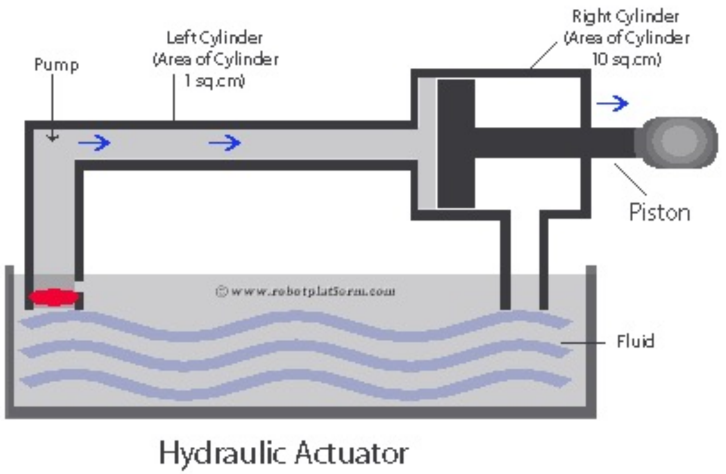
Electromagnetic actuators

- *Stepper motors* for open-loop position and velocity control
  - Can provide very high-resolution position control
  - Relatively low in cost, and interface easily to drive circuits
  - For small, simple robots

- Permanent-Magnet DC Motor
  - Low cost

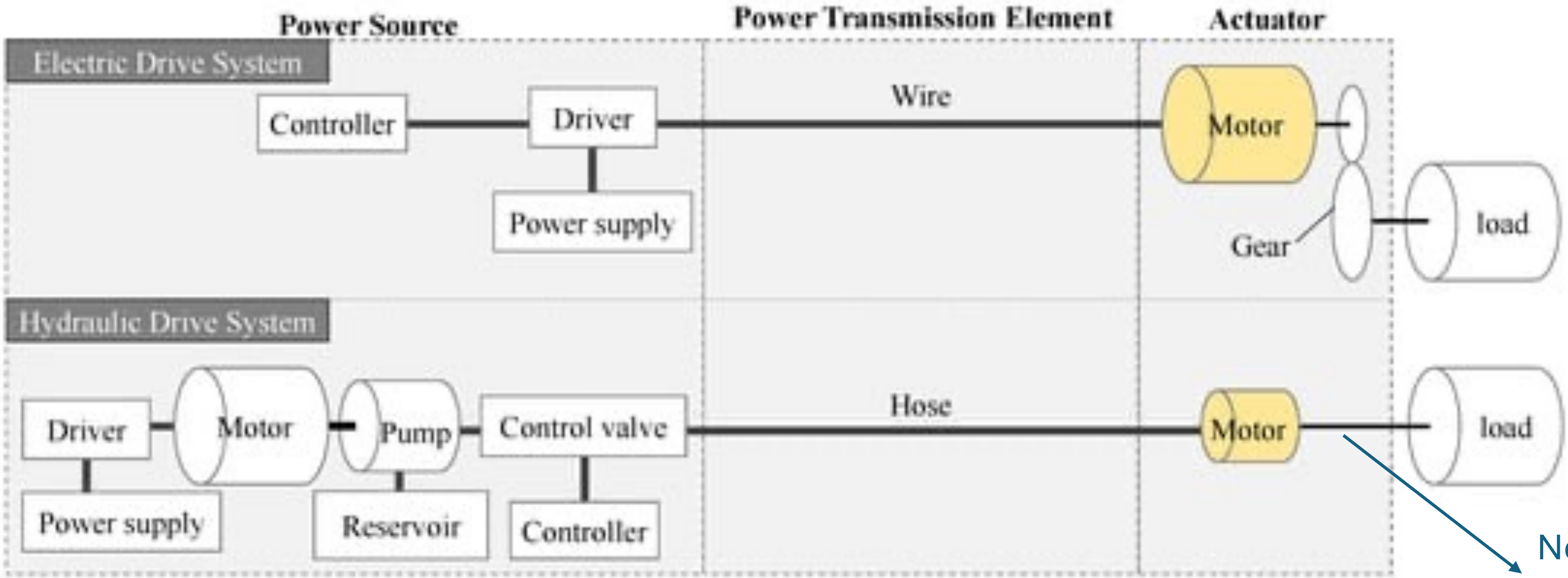
Hydraulic actuators

- Offer very large force capability and high power-to-weight ratios
- The hydraulic power supply is bulky and the cost of the proportional, fast-response servovalves are high
- Leaks and maintenance issues
- Good with force control, but not as good with position or speed control



From robotplatform.com

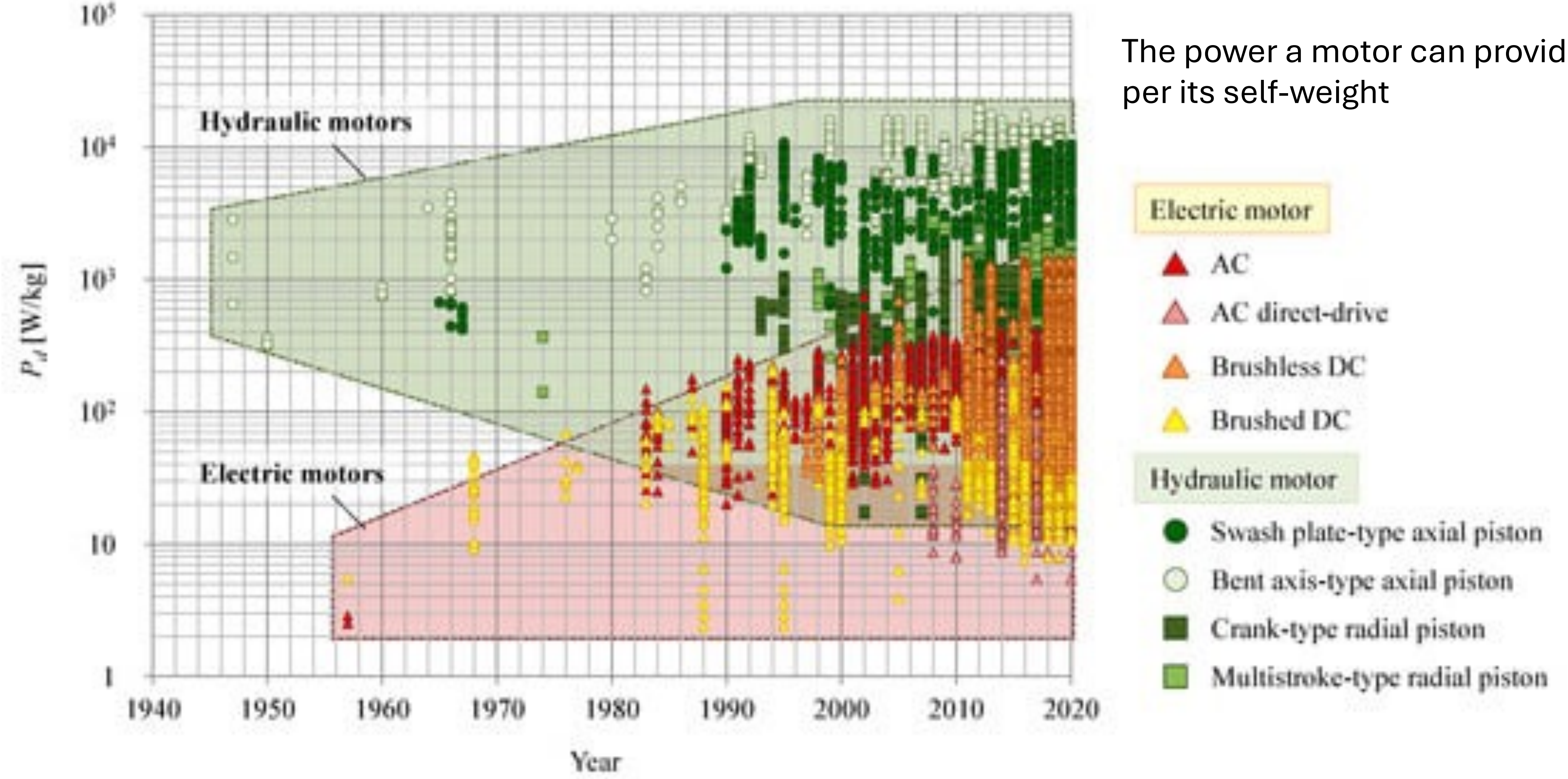
Hydraulic vs electric motor: system overview



No gear boxes needed, because the output torque is large

Sakama, Tanaka and Kaminura. “Characteristics of Hydraulic and Electric Servo Motors.” 2022

Hydraulic motors vs Electric motors – power density

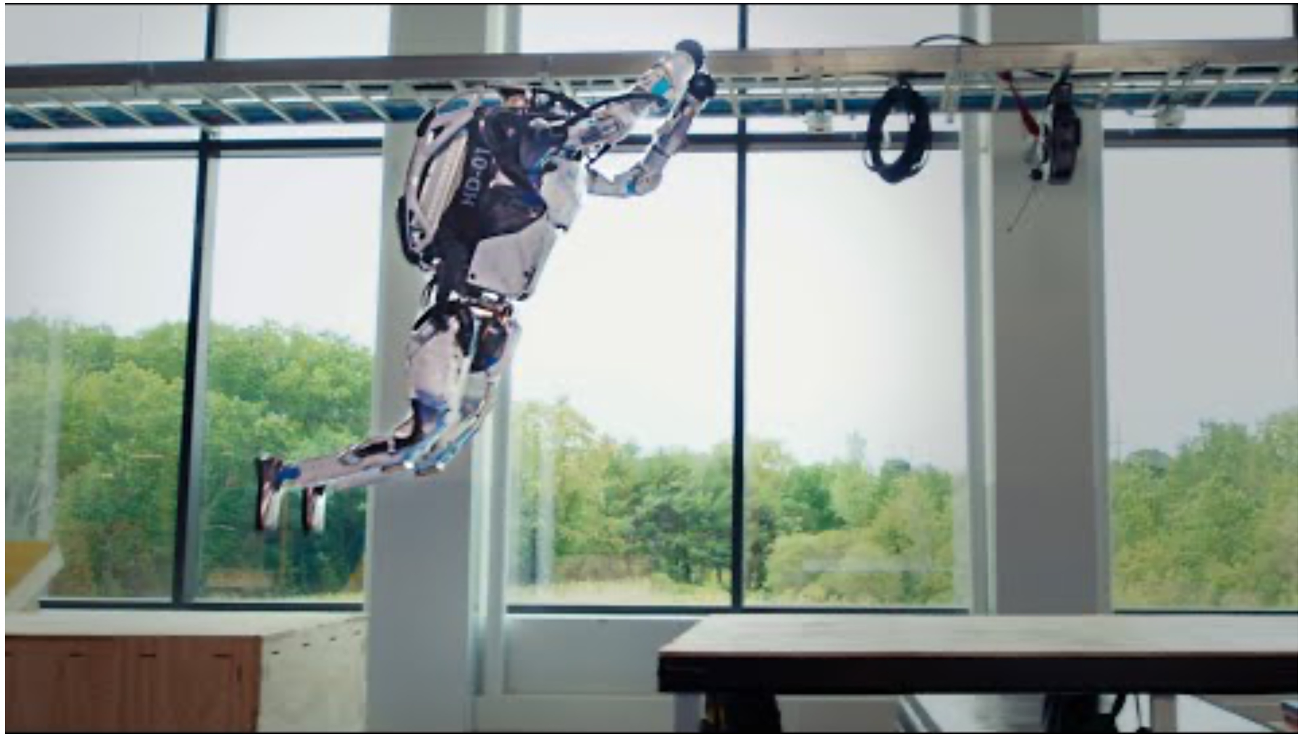


The power a motor can provide per its self-weight

Sakama, Tanaka and Kaminura. "Characteristics of Hydraulic and Electric Servo Motors." 2022

Hydraulic actuated robot

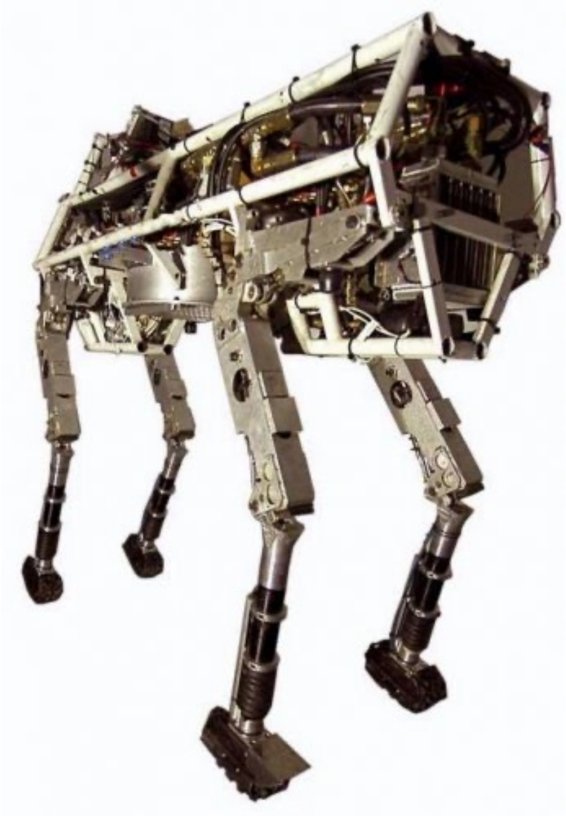
Atlas(es) robots from Boston Dynamics



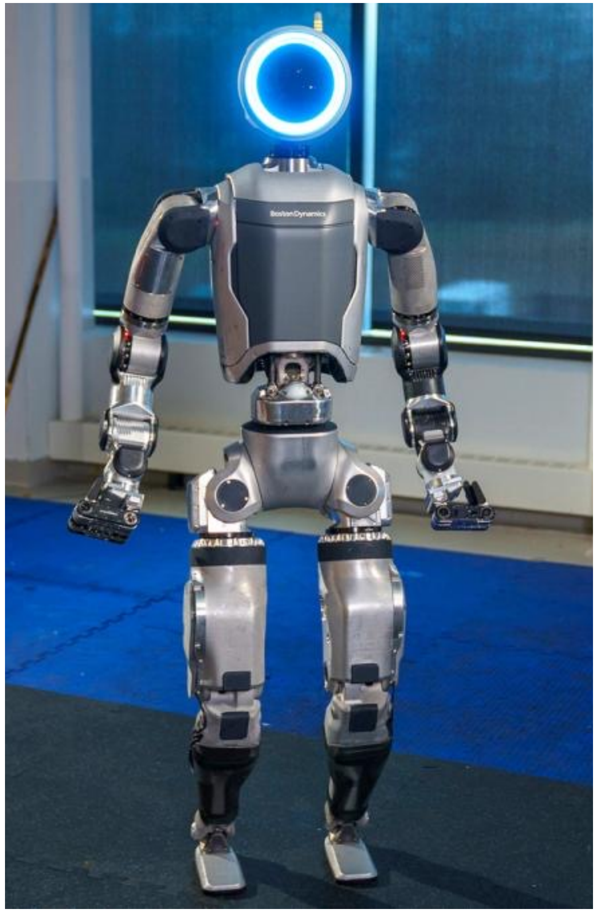
https://www.youtube.com/watch?v=tF4DML7FIWk

Hydraulic actuated robot

Big Dog from Boston Dynamics



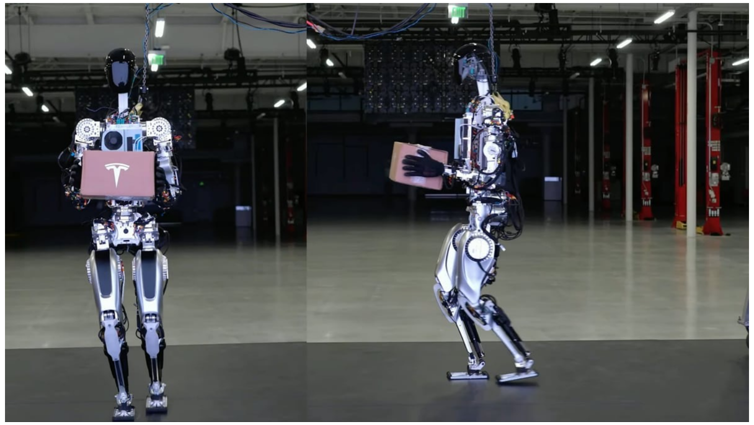
Trend to move to electric motor



New Atlas by Boston Dynamics

Spot by Boston Dynamics, their commercialized version of dog

Cassie and Digit by Agility

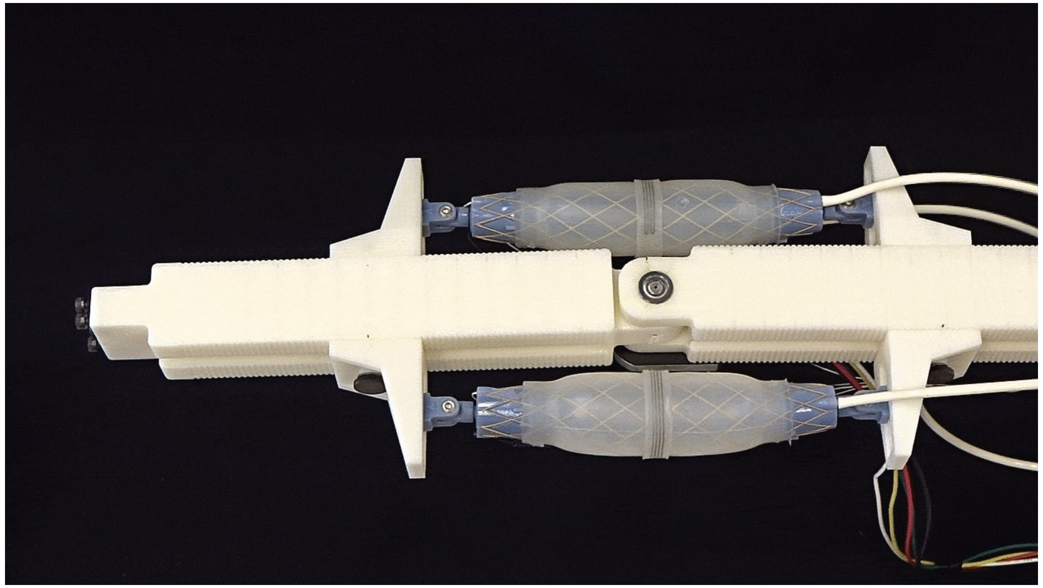


Optimus by Tesla Robot

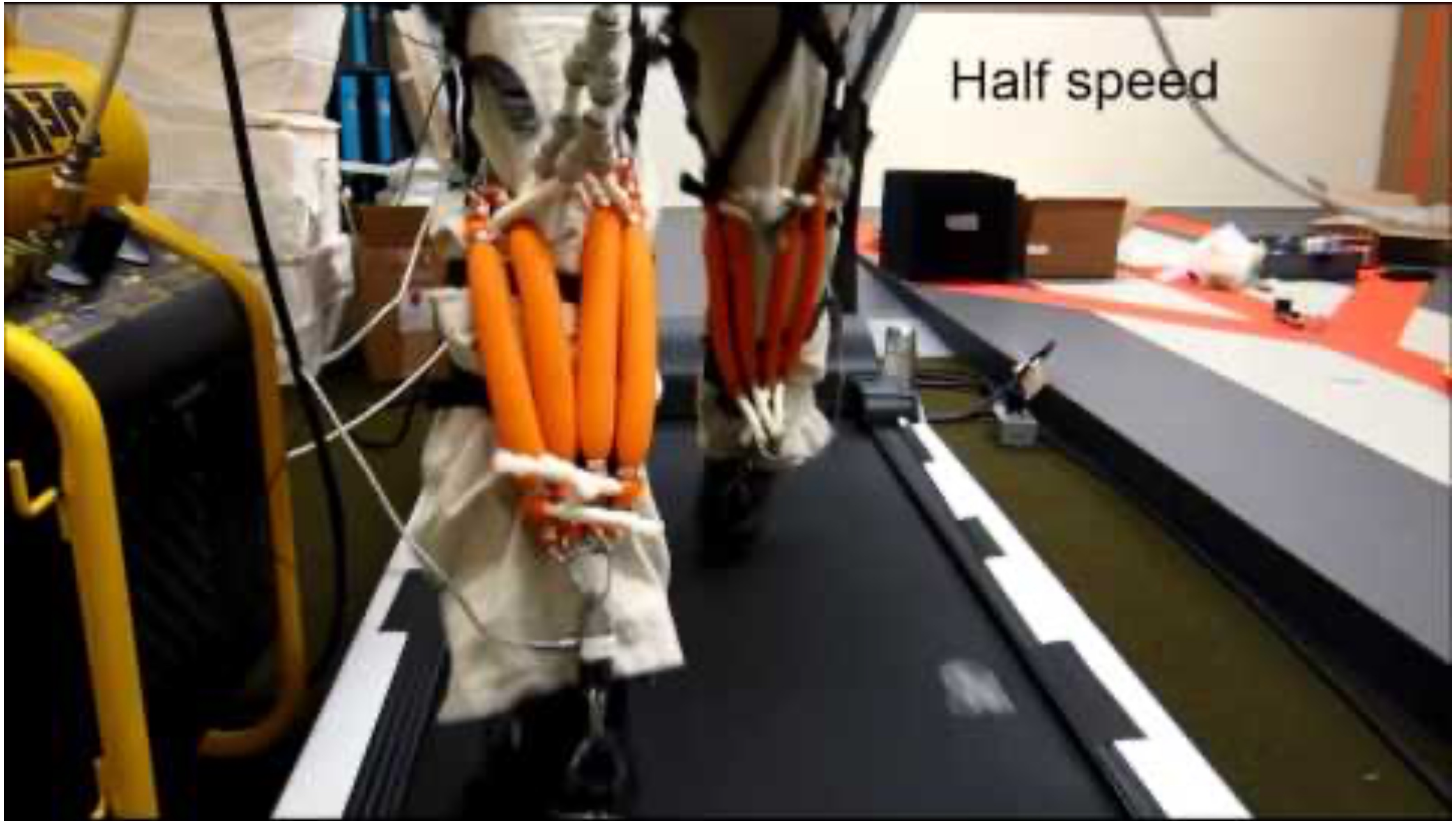
Check about Marc Raibert's points on hydraulic vs electric actuation: Link

Pneumatic actuators

- Relative safe in the explosive environment. They are also less affected by ambient temperature, humidity, or magnetic field
- Produce less power
- Robot hands and artificial muscles; where require high power-to-weight ratios



Exoskeleton driven by pneumatic actuators



https://www.youtube.com/watch?v=eU897nPqUCM

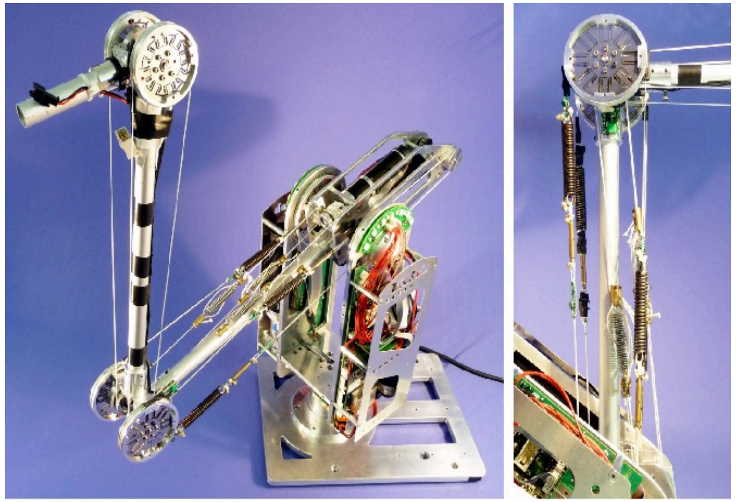
Consideration about actuation

- Power!
- Precision
  - Position/speed control
  - Force control
- Friction
- Size and weight
- Back drive

Transmission

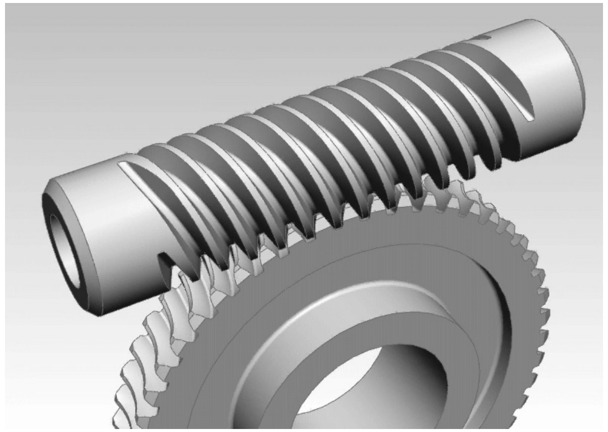
- Where shall we place the motor?
- Direct drives – just at the joint
- Remotely – away from the joint
    - Limited by space
    - Adding extra components for actuation, like compliance

Transmission



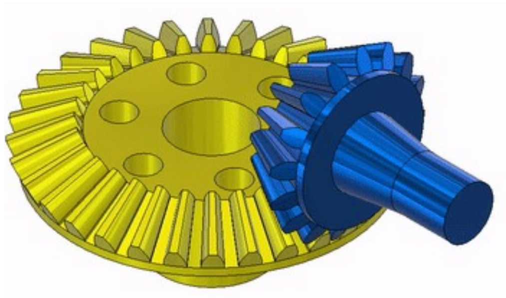
Lens and Stryk. 2013

Tendon driven

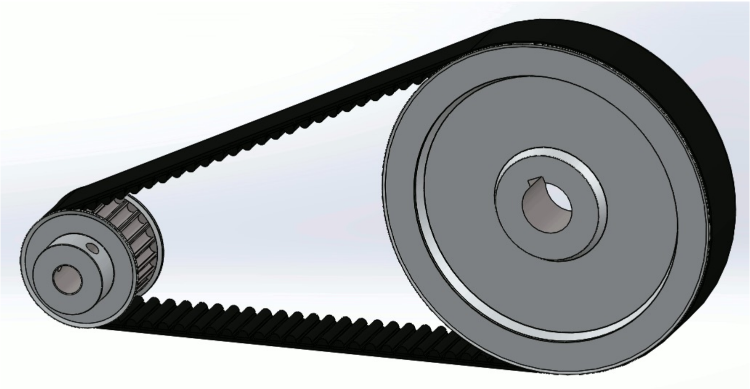


Worm gear

Long shaft

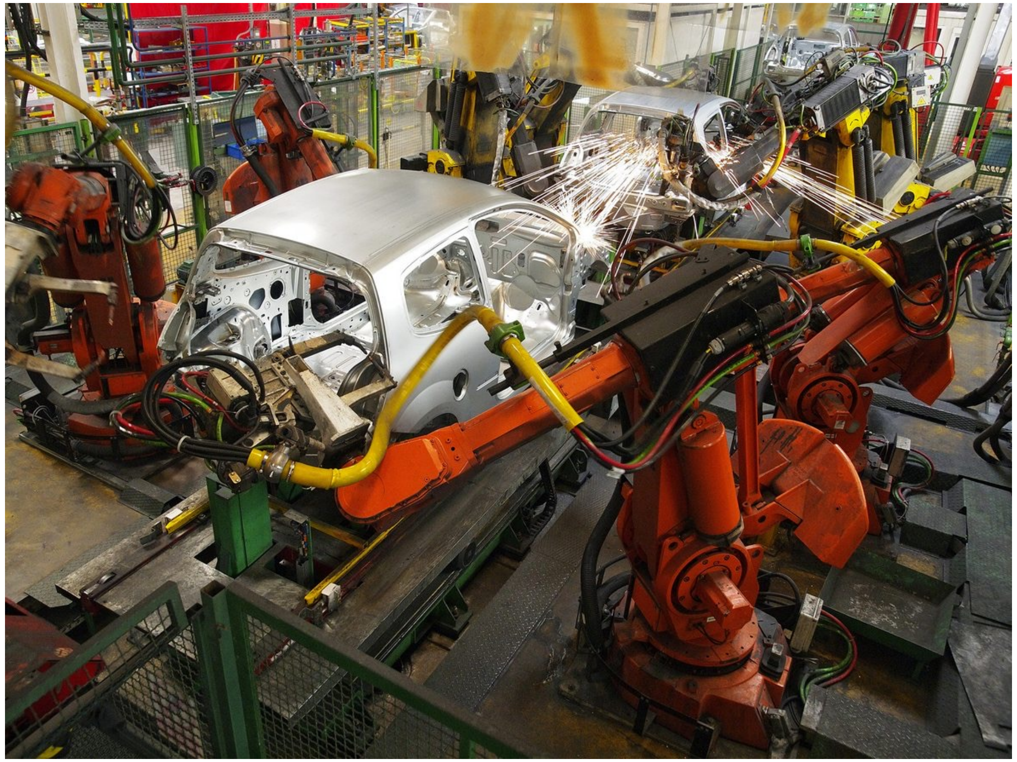


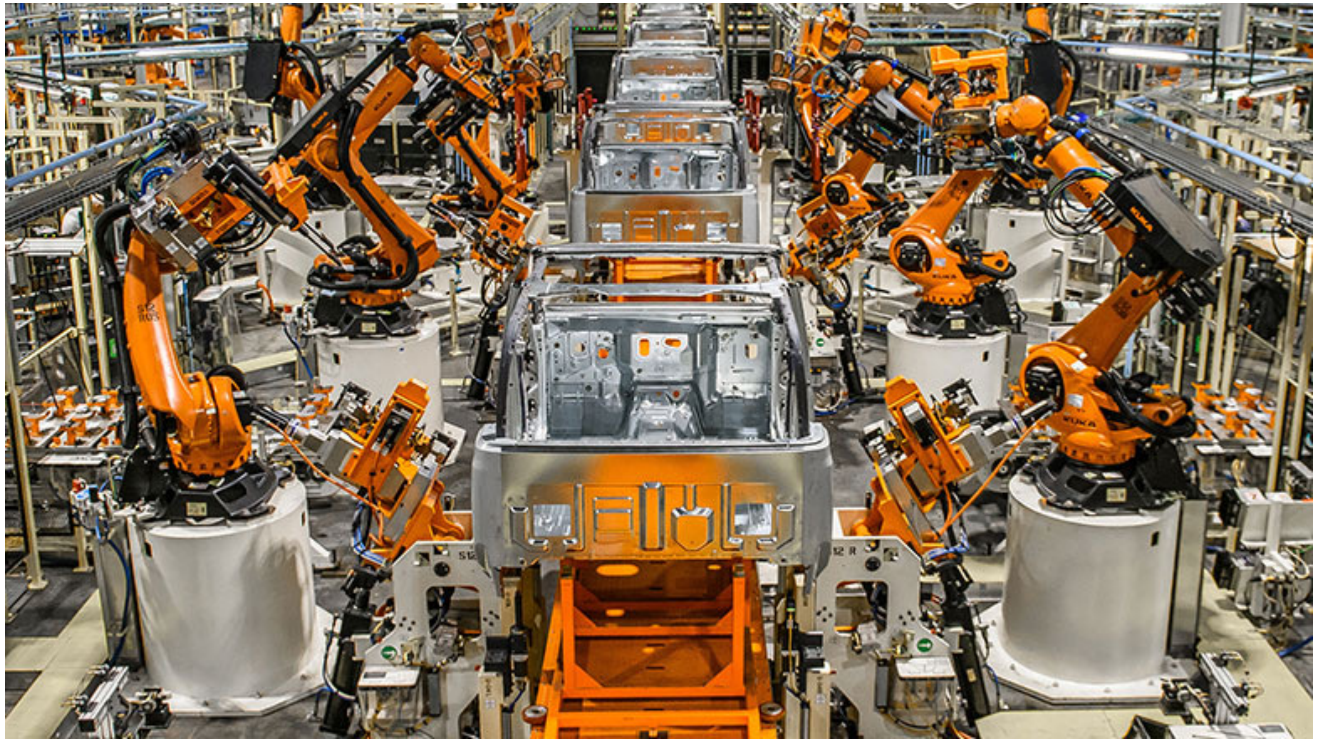
Bevel gear



Belt

Industrial robot arms





In car manufacturing:

Started in 1960s, widely grew in 1970s, and become a standard in 1980s

- Precision
- Speed
- High-payload
- Fixed trajectory and complex programming

Industrial robot arms vs. collaborative robot arms (Cobot)

Fact: industrial robots are kept in cages to prevent human approaching, for safety reason

Collaborative robot: no cage needed. You can work with one as a green hand in the lab

Safety!! Won't hit a human (to ICU)

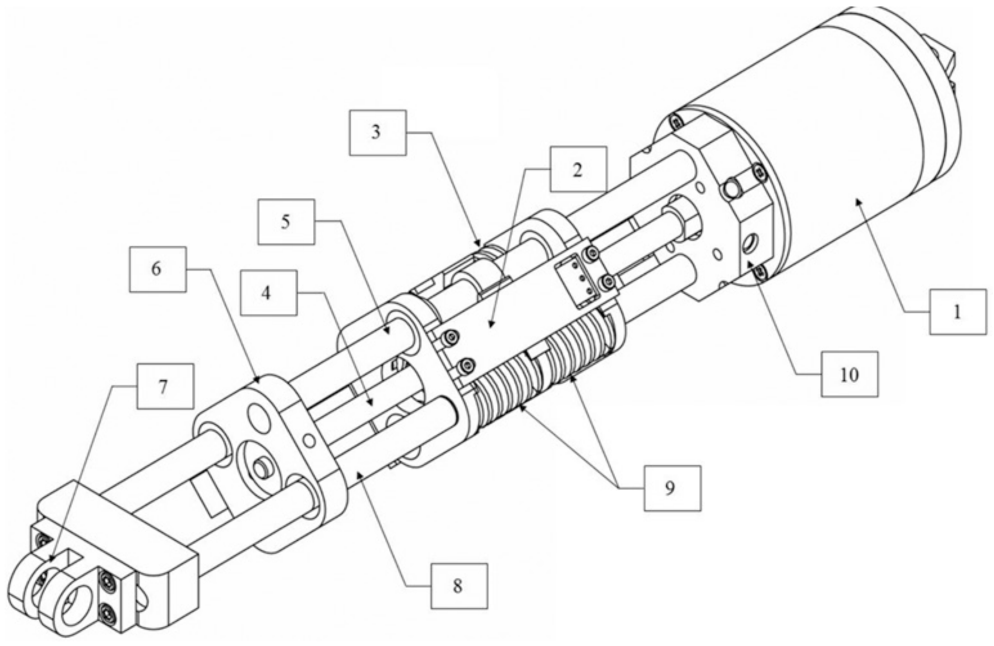
How to achieve this?

Flexibility in robot joints

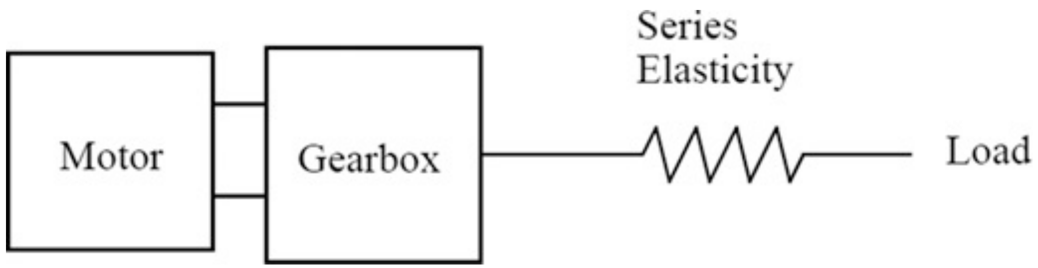
- Adding flexibility: robots comply to external force
  - Versus precision: reaching the target position/speed regardlessly
  - Safety to humans; compliant to the environment
- Mechanically compliant design
  - Series elastic actuators (SEA) – providing controlled compliance
  - Flexibility in transmission
  - Flexibility in software – depending on precise sensing

Series elastic actuator

- An elastic output element (spring) with a displacement sensor (measures spring stretch) in series with a stiff actuator and transmission component

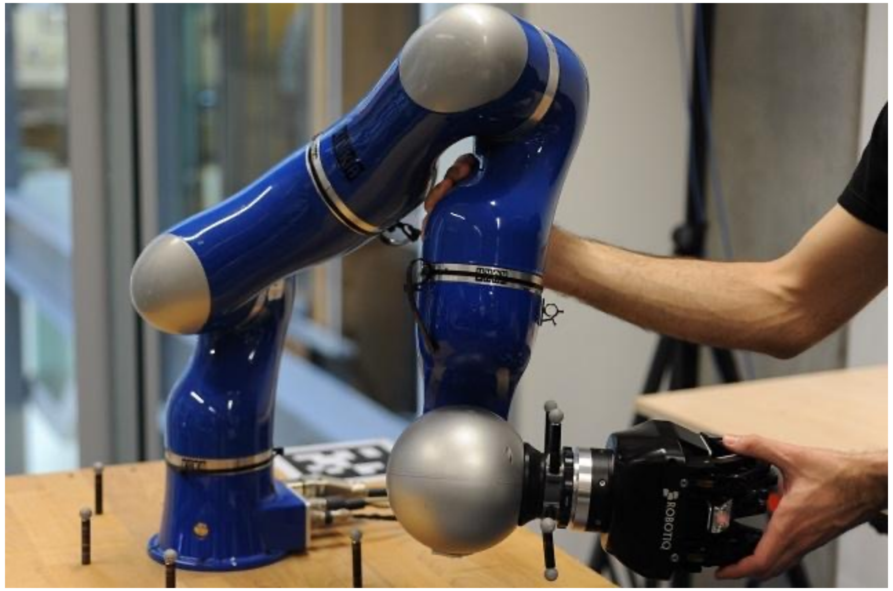


A linear electric driven SEA by Pratt et al., 2002
The motor with gearbox (1) drives the ball screw (4) which moves the ball nut plate (3). Ball nut plate (3) then moves the springs (9) against the moving sub-assembly (2) which is fixed to the moving rods (8), thus causing the displacement of the load connection terminal (7). All the force exerted by the motor assembly on the load is directly supported by the springs

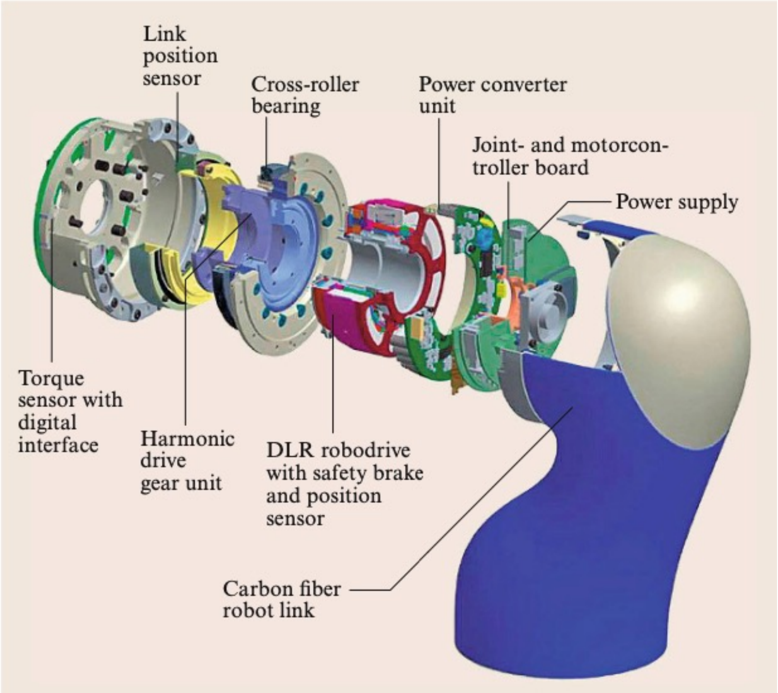


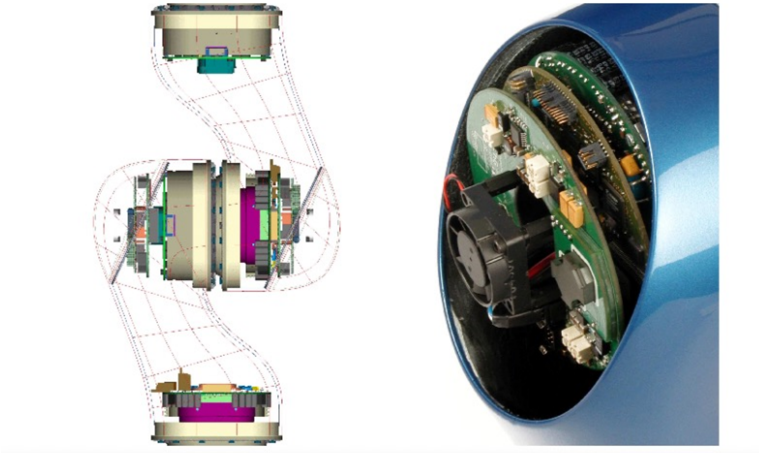
Series elastic actuator schematic (Williamson, 1995).

Compliance for Cobots



DLR LWR-III arm (2003)





KUKA arm 2006

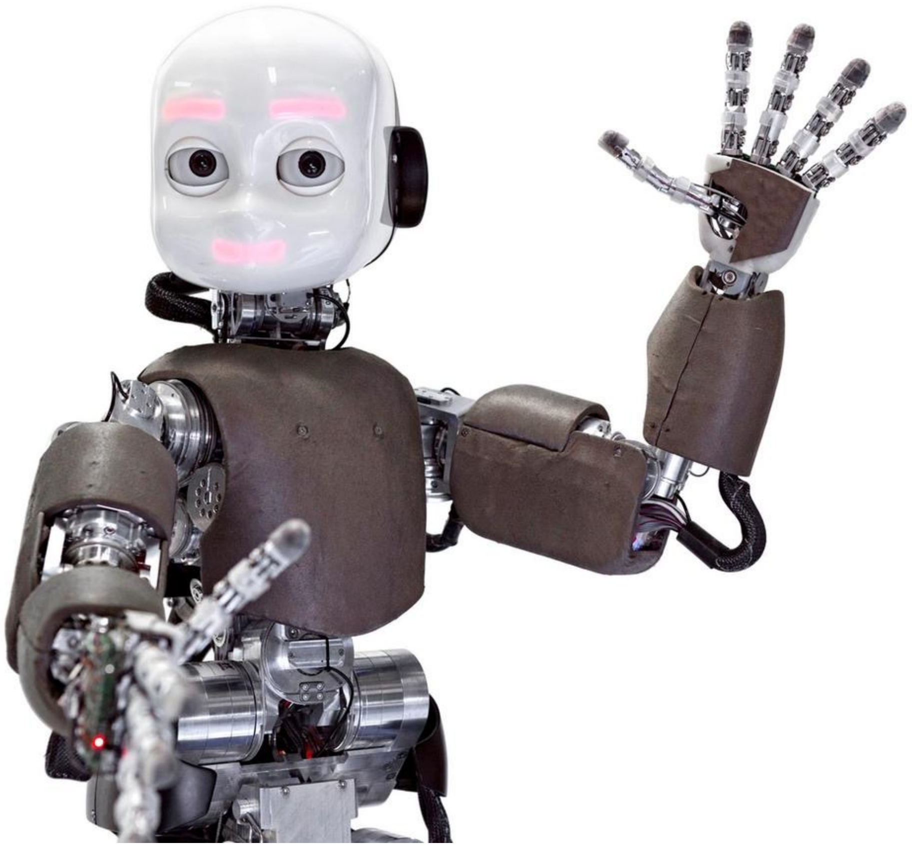
KUKA LBR IIWA

Adjustable compliance based on closed-loop motor control based on sensor feedback

Robot hand

- The most challenging mechanism in a robot
- High DoFs in a small space

How many DoF should there be?

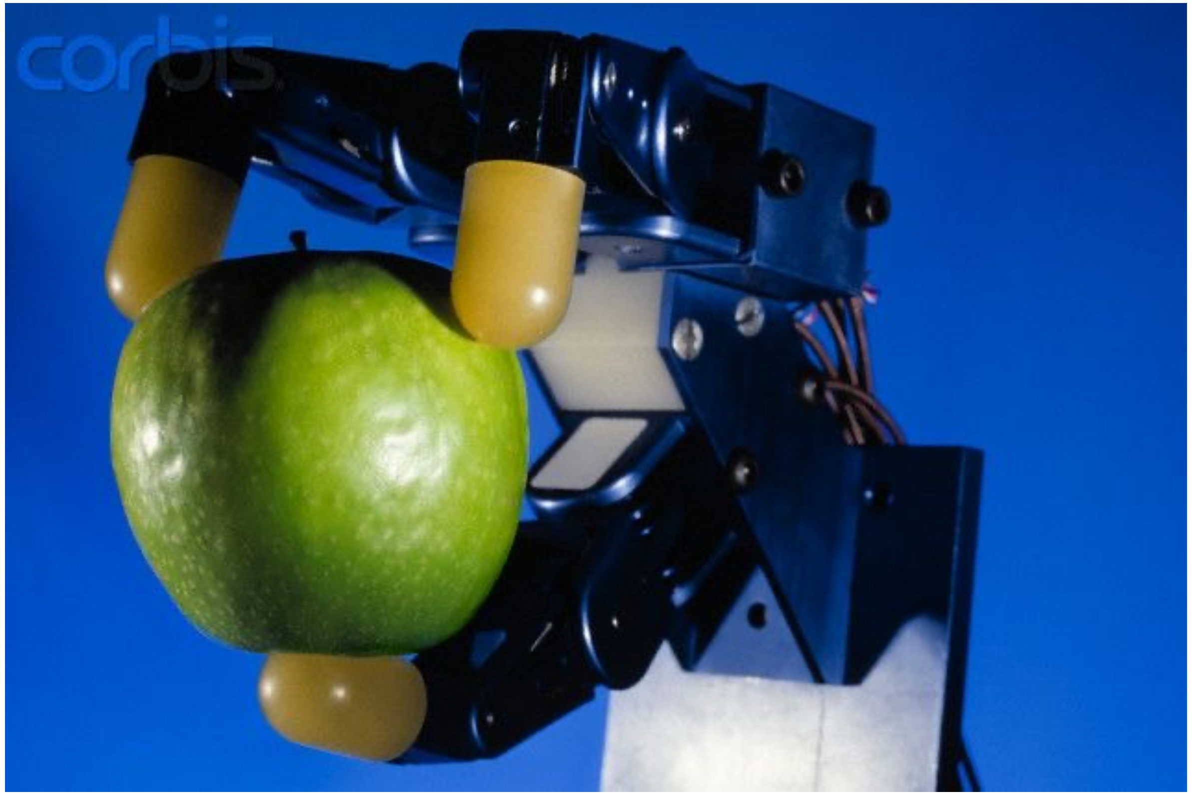


iCub robot developed by
Istituto Italiano di Tecnologia (IIT)

Hands in 1980s: Utah-MIT hand

https://www.youtube.com/watch?v=PTMCE6bkLQs

Hands in 1980s: the Salibury Hand



https://www.youtube.com/watch?v=Q2z8pJMN1dM

Robot Hand Designs

- One main issue: proper actuation and transmission system
  - Placing the motors as close as possible to each joint, even as the joint itself
  - Placing the motors into the palm or in the forearm, with a transmission system

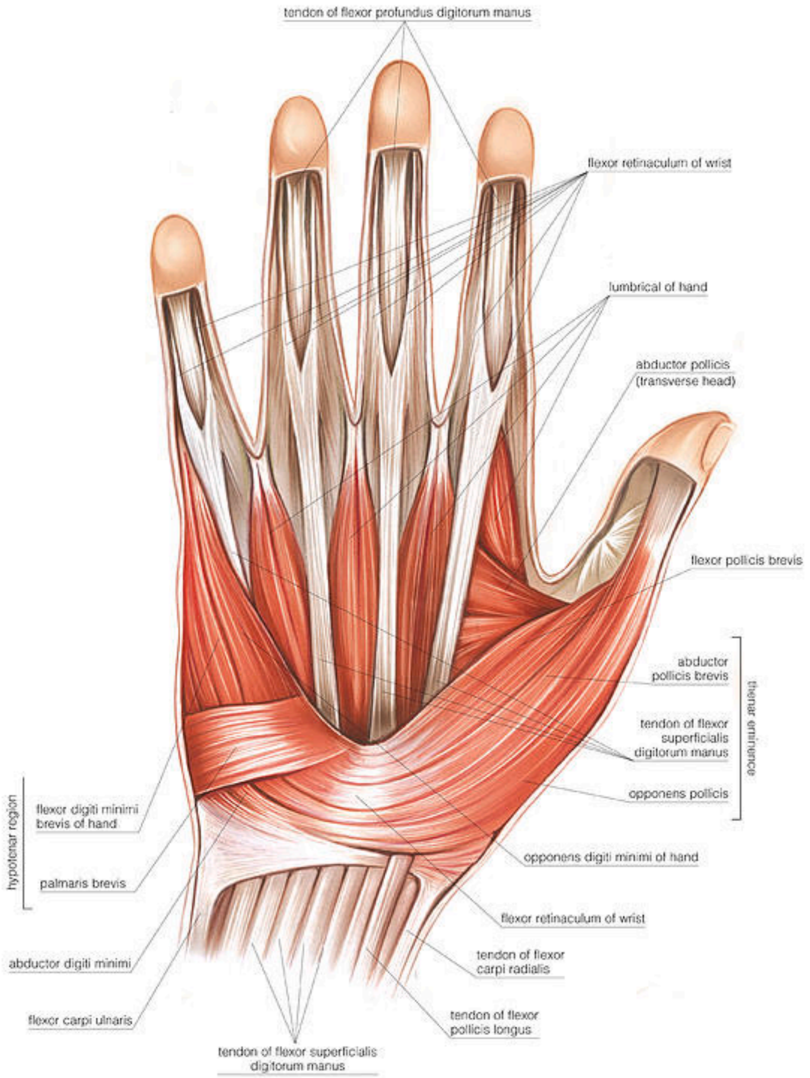
In-site actuation

- Simplifies the mechanical design
- The size of the finger is imposed by the dimension of the actuators (usually notably larger than a human hand)
- No space for other elements in the fingers, e.g. sensors, compliant skin layer

Allegro Hand. A fully actuated 4-fingered hand

Remote actuation

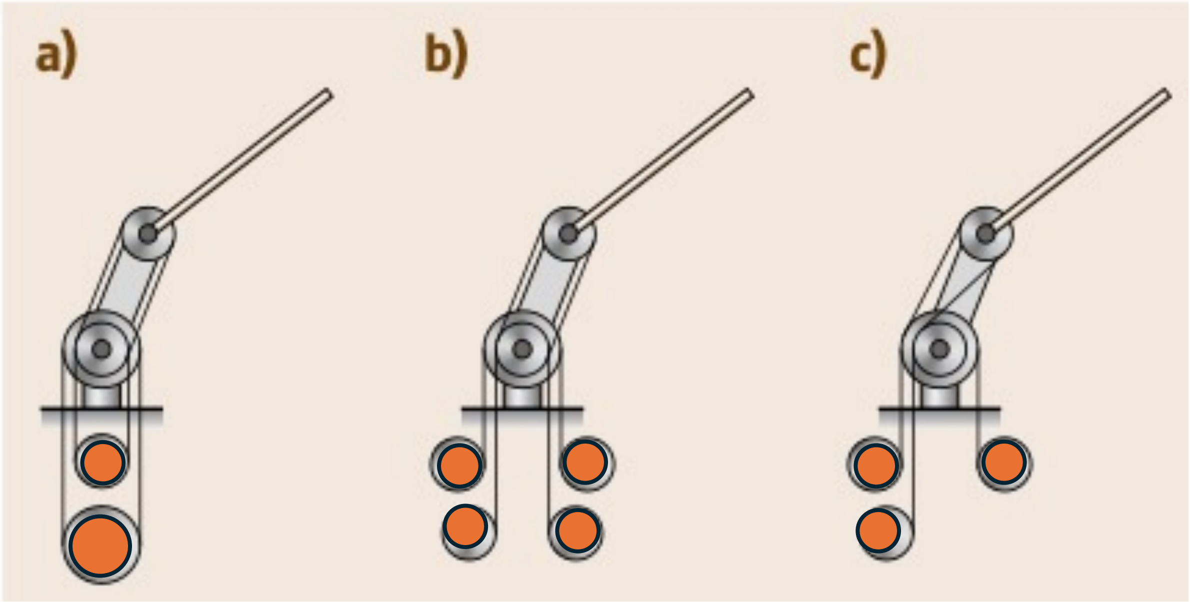
- the joints are driven by actuators placed outside the links
- requires a motion transmission system
- In some way, remote actuation must consider the problem of kinematic coupling between the actuated joint and the previous ones



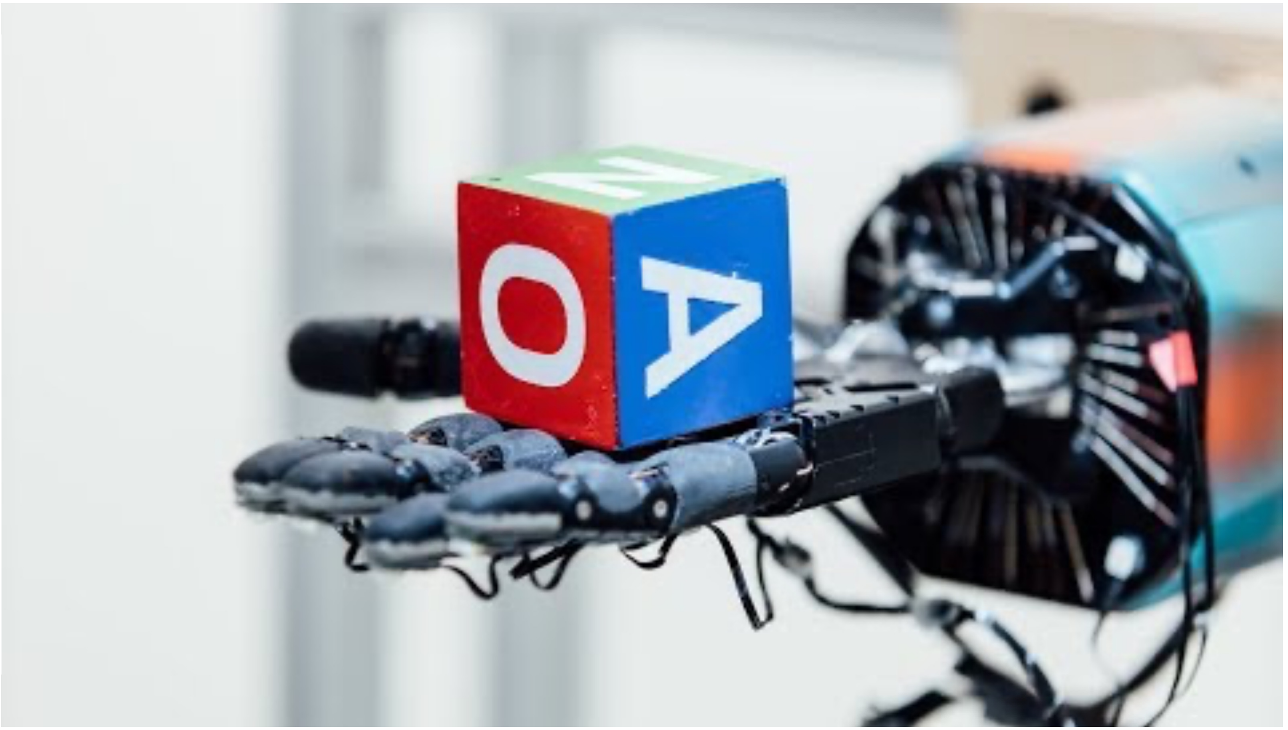
For humans: finger joints are moved by muscles placed on the palm or in the forearm

Remote actuation

- tendons, chains, belts, gears



Example: Shadow Dexterous hand



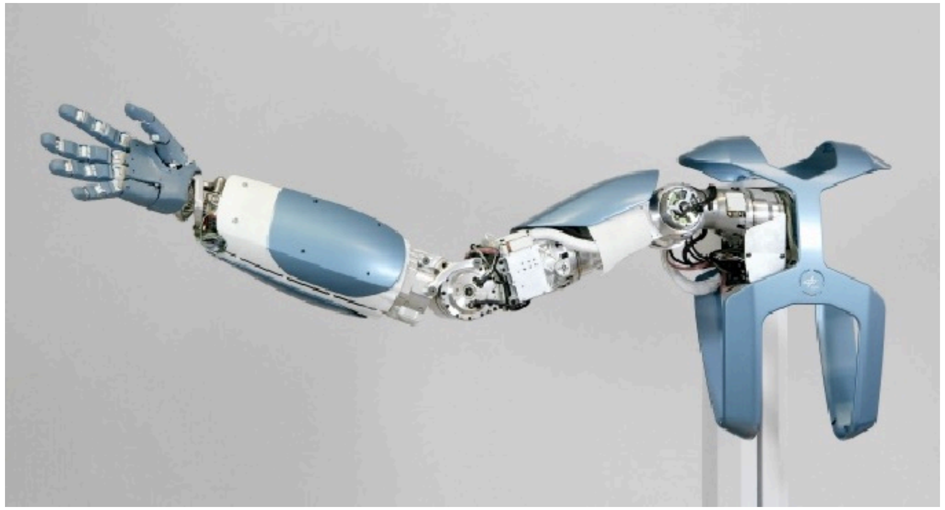
OpenAI - Learning Dexterity. 2018
https://www.youtube.com/watch?v=jwSbzNHGflM

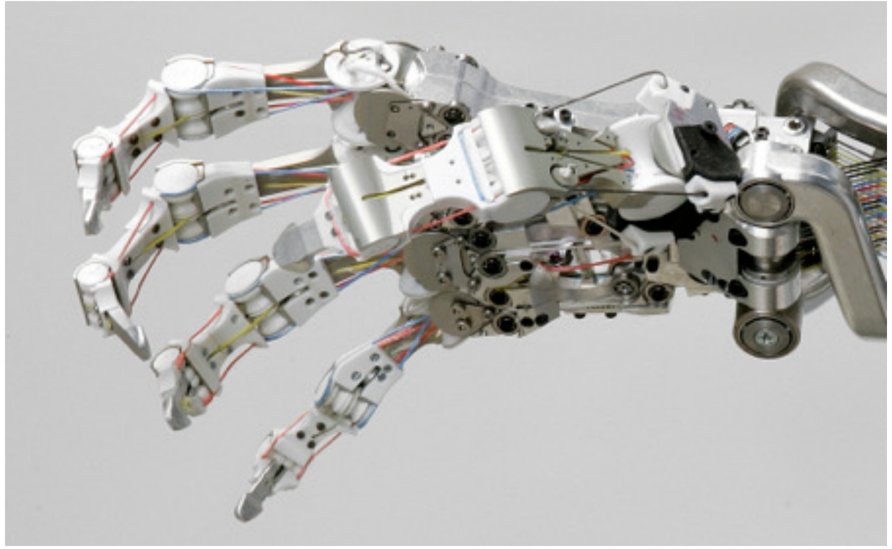
Example: Shadow Dexterous hand

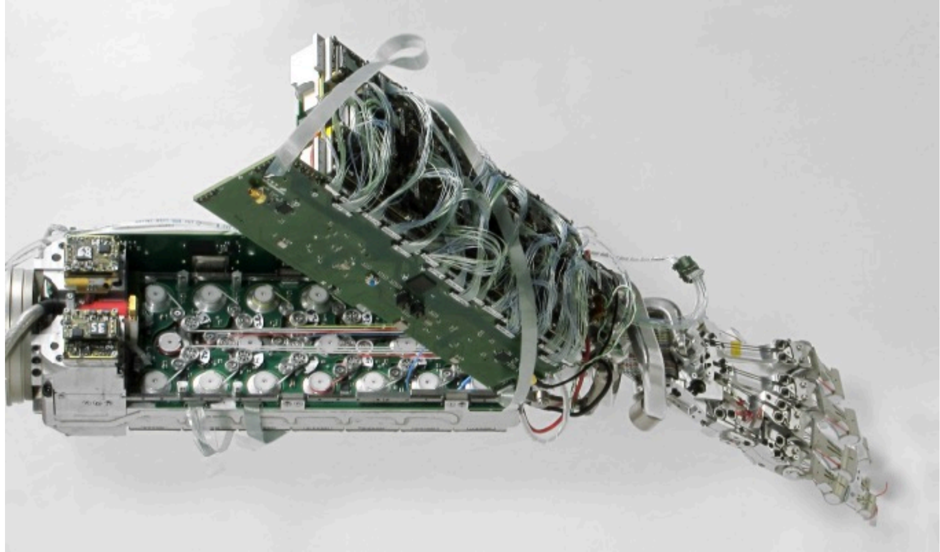
https://www.youtube.com/watch?v=3ju4upwhdvM

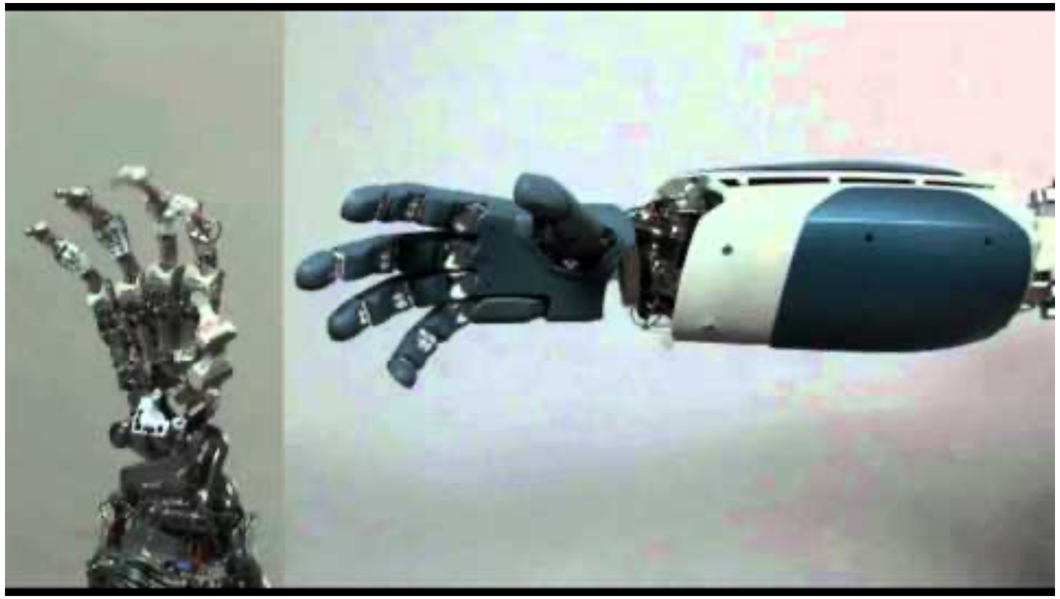
The earliest version is based on pneumatic actuators

Example: DLR Hand 2011









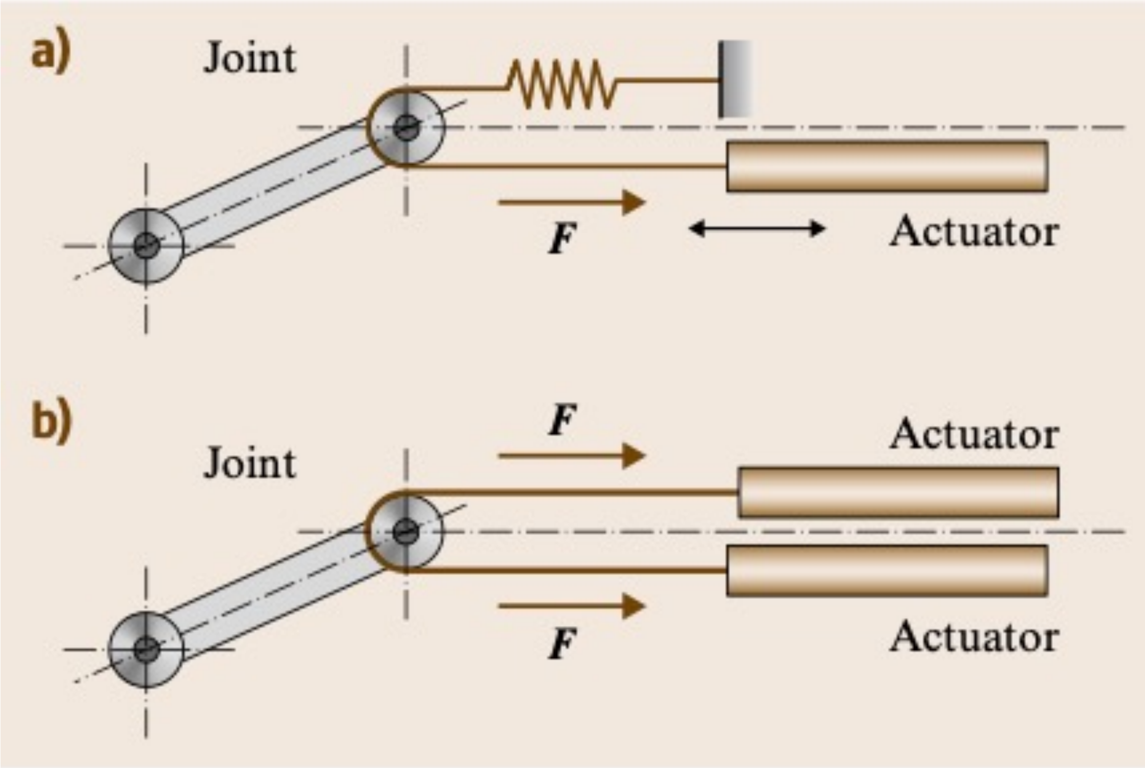
https://www.youtube.com/watch?v=YqmRKqFqiok

Actuation architectures

- Each joint has its own actuator
- Number of joints is smaller than number actuators
  - More than one actuator is operating on a single joint
- Number of joints is larger than number actuators
  - Some joints are passive, coupled, or underactuated

Why do we need more actuators for one joint?

- A joint can have multiple DoF
- While some actuators are *double-acting actuators*, some are *single-acting actuators*
  - They can generate controlled motion in one direction only
  - Return motion must be obtained by an external action. E.g. a spring, another motor

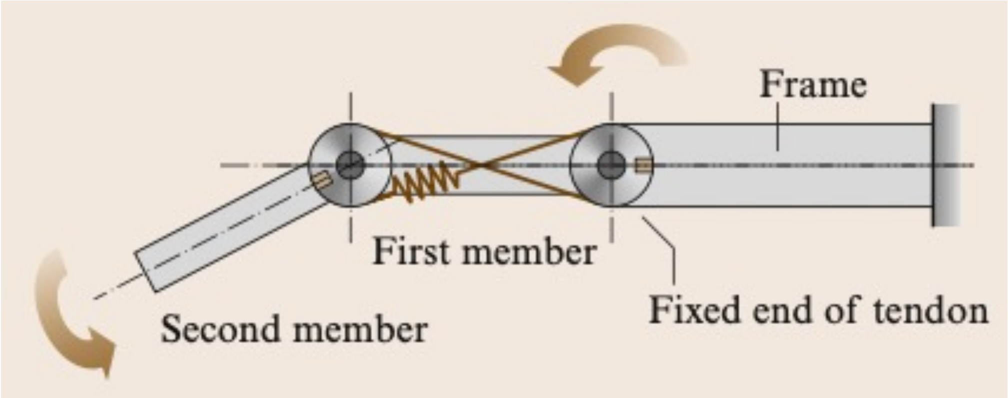


N_Joint > N_actuator

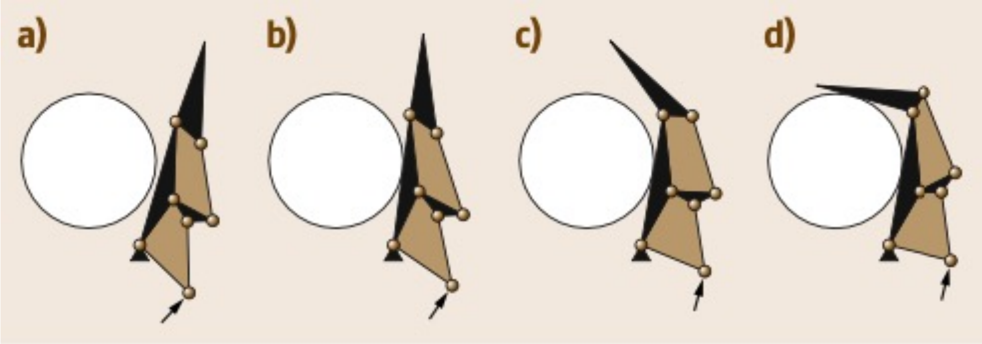
- The joints are selectively actuated by the motor
- The joints are kinematically coupled, in a fixed or variable way

Underactuated hands

- *Underactuated* mechanism: the number of actuators is smaller than the number of degrees of freedom
- Robot hands can be underactuated by applying deformable passive-driven joints
- Will lead the hand's shape adaptation
  - Fingers can envelope the objects and adapt to their shape
- Behavior of the finger is determined by the design parameters



One example of joints coupled in non-fixed way



Grasping a shape with an underactuated mechanism: the finger will passively adapt to the object shape

Example: 3-Finger Adaptive Robot Gripper from Robotiq

3 joints on each finger, but only one control

What are underactuated hands good at and not good at?

https://www.youtube.com/watch?v=ll6JLLQV858

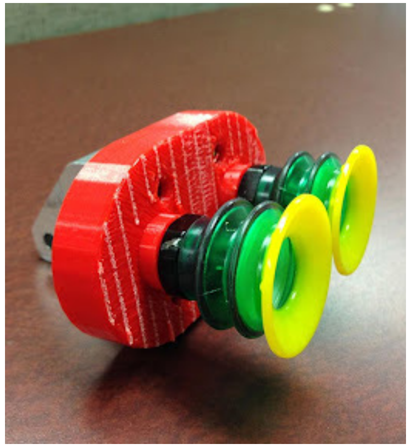
Of course, most people don’t bother to use an anthropic robot hand

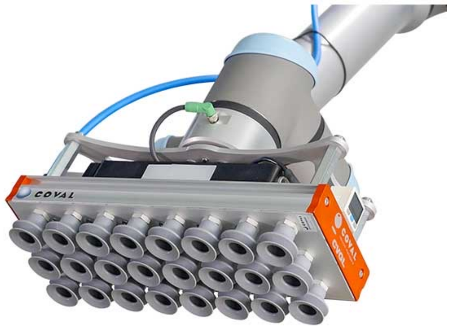
Long-standing popular choice: parallel-jaw grippers

By DH Robotics

By Robotiq

Eureka choice: suction cups





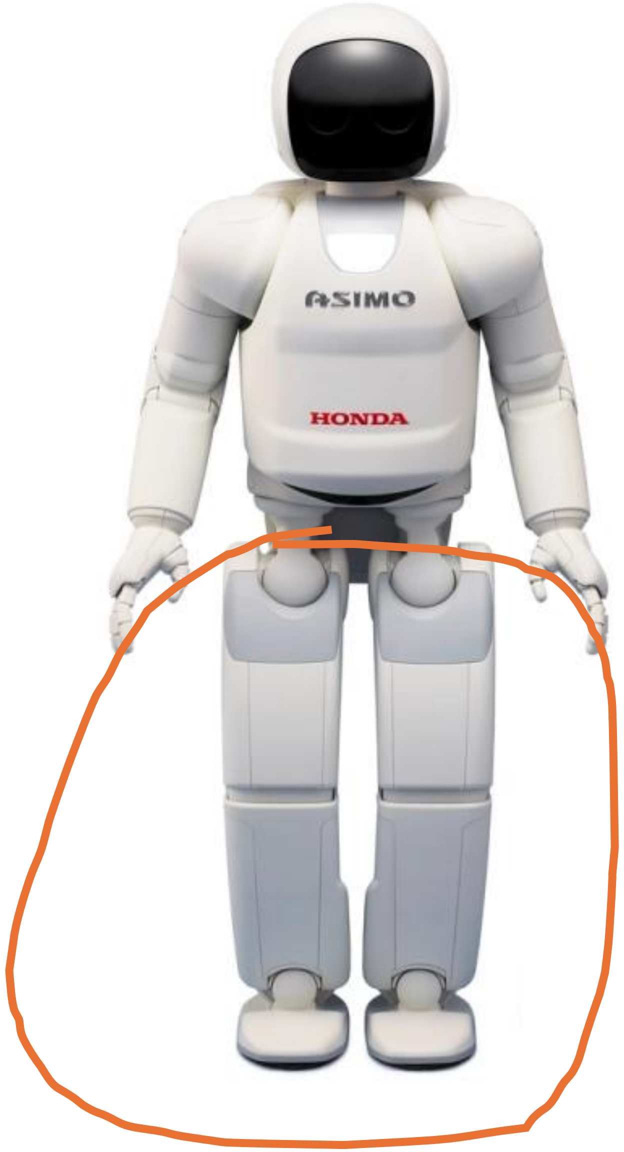
So simple and low-tech, but soooo effective

Suction cups in industry

https://www.youtube.com/watch?v=DxFZ4-z80p4

https://www.youtube.com/watch?v=wI4e7K3_jFU

Getting the robot to move?

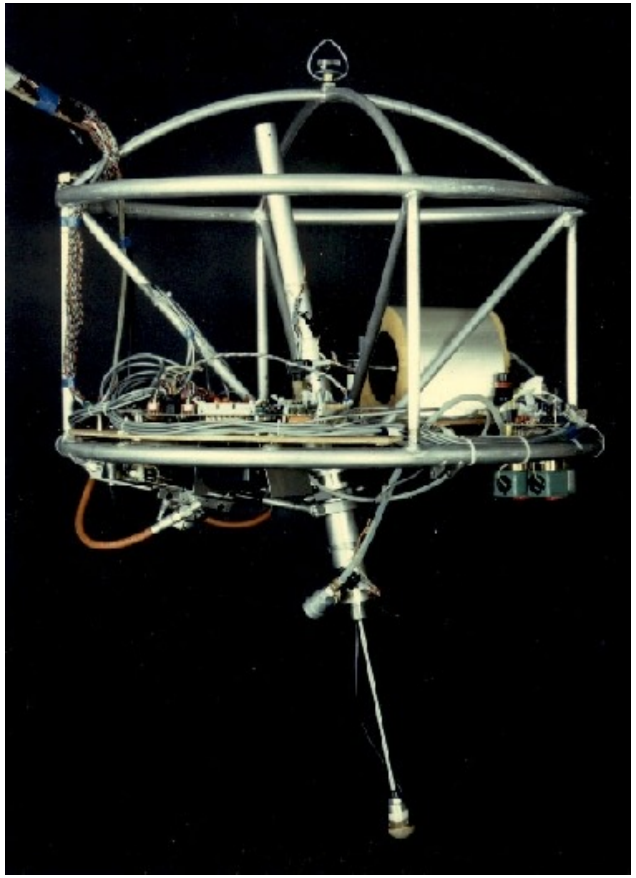


How to move?

- Walk
- Run
- Crawl
- Jump
- Roll on wheels
- ...

The design depends on the functions

3D One-Leg Hooper (1983) from MIT Leg Lab

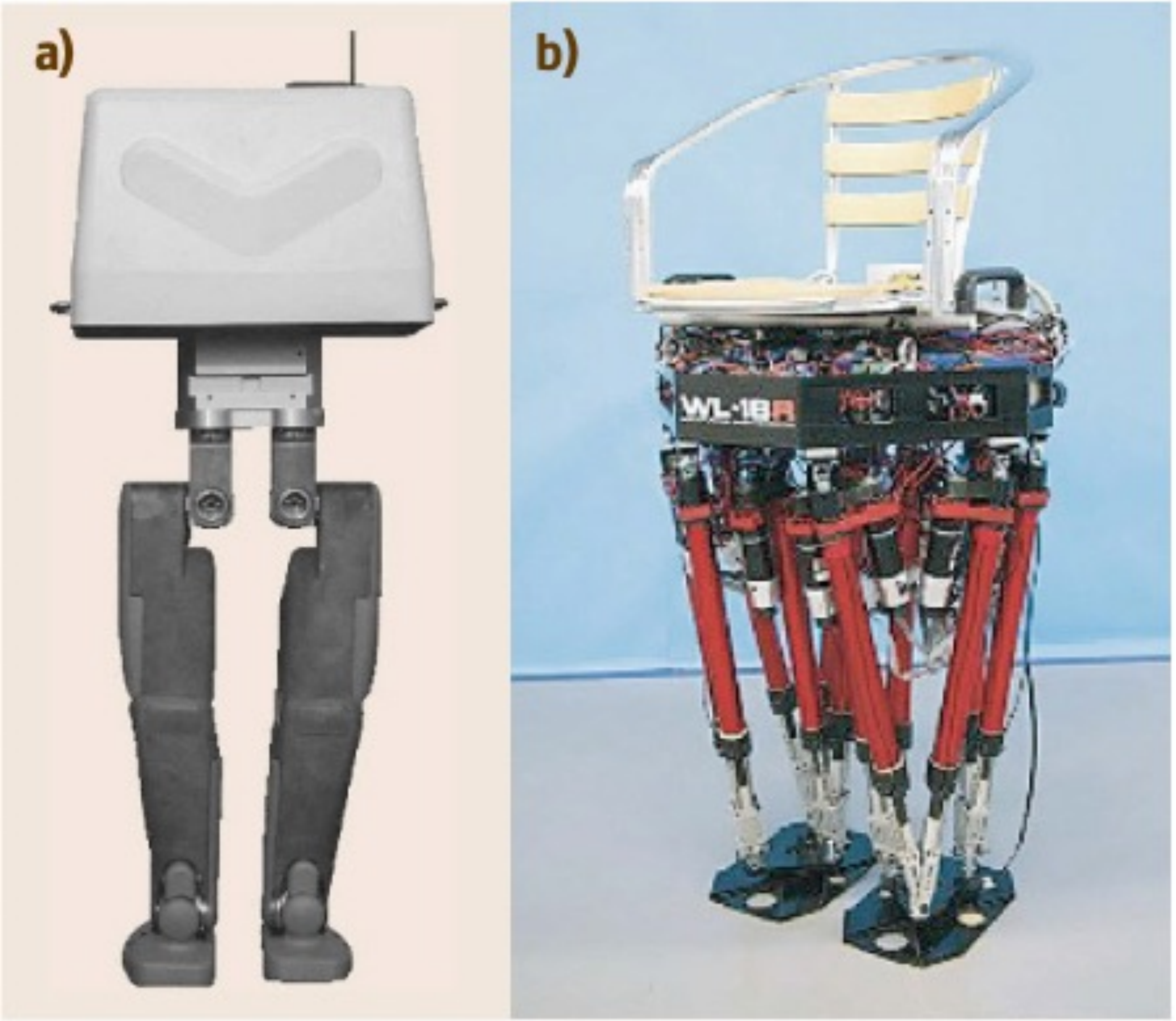


- a leg that changes length; pneumatic actuated
- an actuated 2-axis hip; hydraulic actuated
- a body that carries sensors and interface electronics

https://www.youtube.com/watch?v=XFXj81mvInc

Two legs? – Biped robots

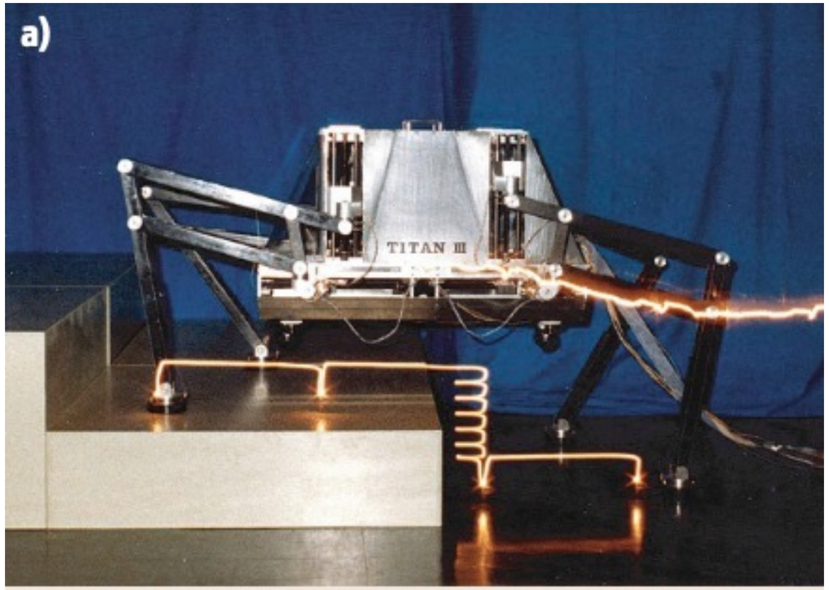
Serial design
3 DoF in the hip
1DoF in the knee
2 DoF in the ankle



HRP-2L (2001) WL-16R (2003)

Parallel design
(Stewart platform))
Each leg consists
of 6 actuators

Multiple legs?

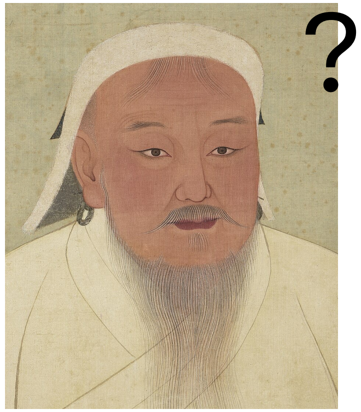


TITAN III (1984)
Each let is a 3D pantograph mechanism driven by 3 linear actuators

BigDog (2005)
Hydraulic driven. For each leg, 3 active joints for hip pitch, hip roll, and kneel; one passive linear pneumatic compliance in the lower leg

Genghis (1989)
Hexapod robot.
Each leg has only 2 DoF. Robust walking in 3D space

Genghis (1989)



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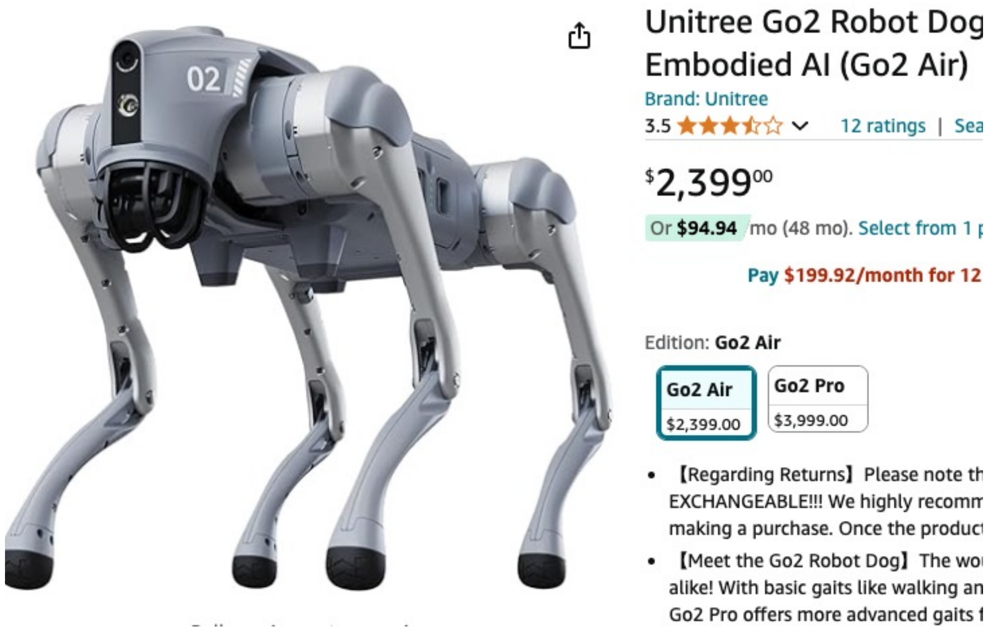
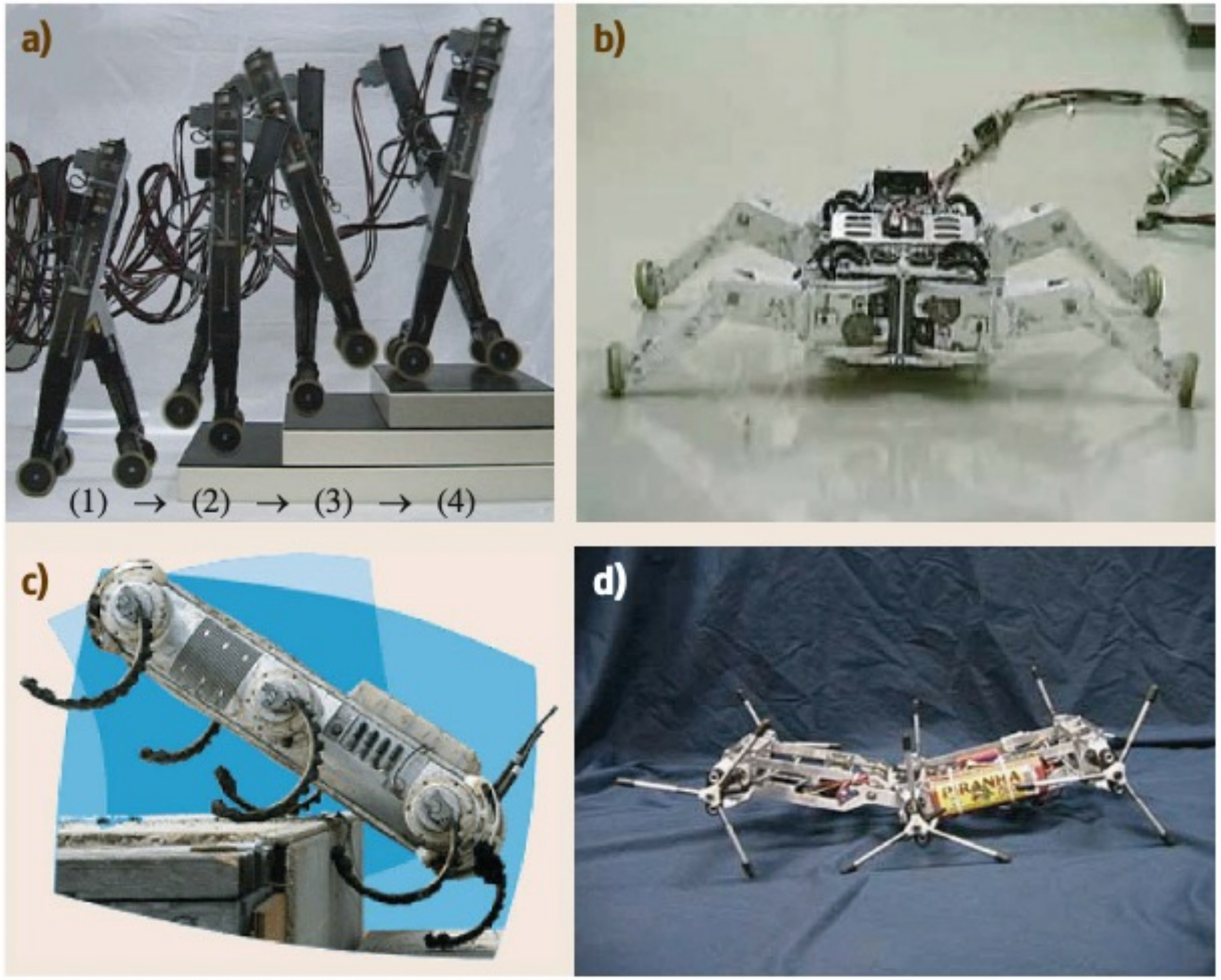
https://www.youtube.com/watch?v=1j6CliOwRng

Quadrupad robots now



Leg-wheel hybrid robots

- Mixing the efficiency of wheels and the flexibility of legs



Biped leg-wheel robot (1998)

Roller walker (1996)

Rhex (2001)

Whegs II (2003)

Leg-wheel hybrid robots

https://vimeo.com/117118178

https://www.youtube.com/watch?v=ISznqY3kESI

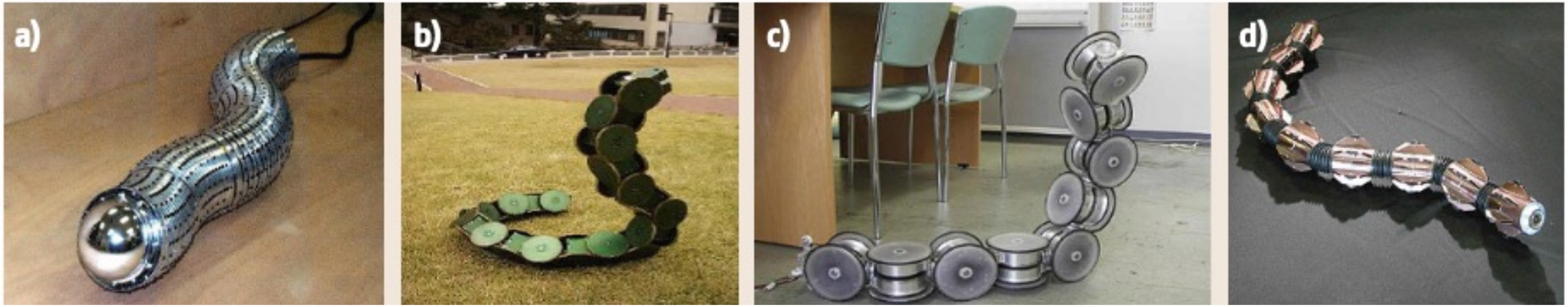
Wall-climbing robots

- Suction cups on the foot

https://www.youtube.com/watch?v=MZGGL20g99A

Why don't just remove legs?

Of course!



Modular-based structures

Choset's Modsnake robot (2007)

https://www.youtube.com/watch?v=8VLjDjXzTiU

What shall you consider when designing a mobile robot?

- We need the robots to move stably
- Terrain requirements
- How to move?
- Hardware design
  - DOF, structure, weight, weight distribution
  - Actuation– Power? Torque? Speed? Compliance?
- Combined with the control framework

Summary

- Actuators
- Transmission
- Robot hand design
- Mobile robots

Reference: Springer Handbook of Robotics, 2nd Edition
Don't buy, too heavy. Check out the electronic version

Chapter 4; 11; 17; 19; 20