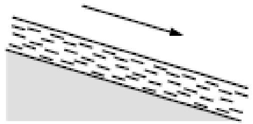
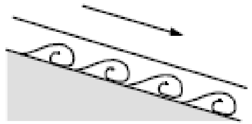
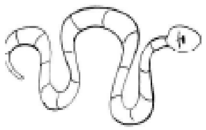
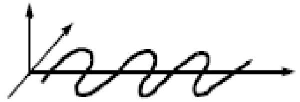
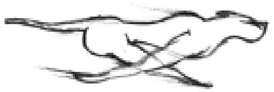
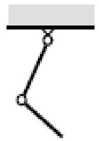
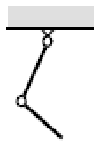
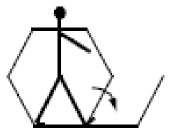

# Locomotion Concepts
## - rolling, walking, flying, swimming

Roland Siegwart, Margarita Chli, Juan Nieto, Nick Lawrance

# Locomotion Concepts: Principles Found in Nature

- On ground

| 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 | Oscillatory movement of a multi-link pendulum  |
| Jumping  | Loss of kinetic energy | Oscillatory movement of a multi-link pendulum  |
| Walking  | Gravitational forces | Rolling of a polygon (see figure 2.2)  |

# Locomotion Concepts

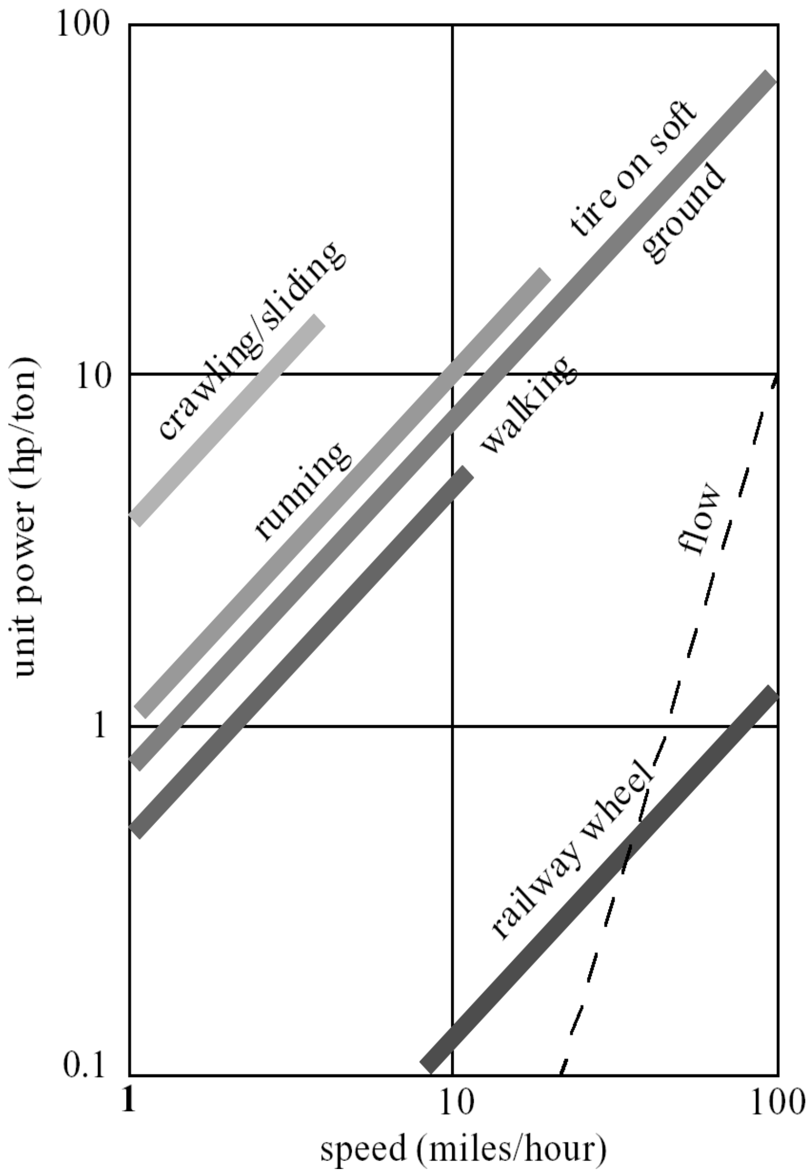
- Nature came up with a multitude of locomotion concepts
  - Adaptation to environmental characteristics
  - Adaptation to the perceived environment (e.g. size)

- Concepts found in nature
  - Difficult to imitate technically
  - Do not employ wheels
  - Sometimes imitate wheels (bipedal walking)
  - The smaller living creatures are, the more likely they fly

- Most technical systems today use wheels or caterpillars
  - Legged locomotion is still mostly a research topic

# Walking or rolling?

- number of actuators
- structural complexity
- control expense
- energy efficient
  - terrain (flat ground, soft ground, climbing..)
- movement of the involved masses
  - walking / running includes up and down movement of COG
  - some extra losses



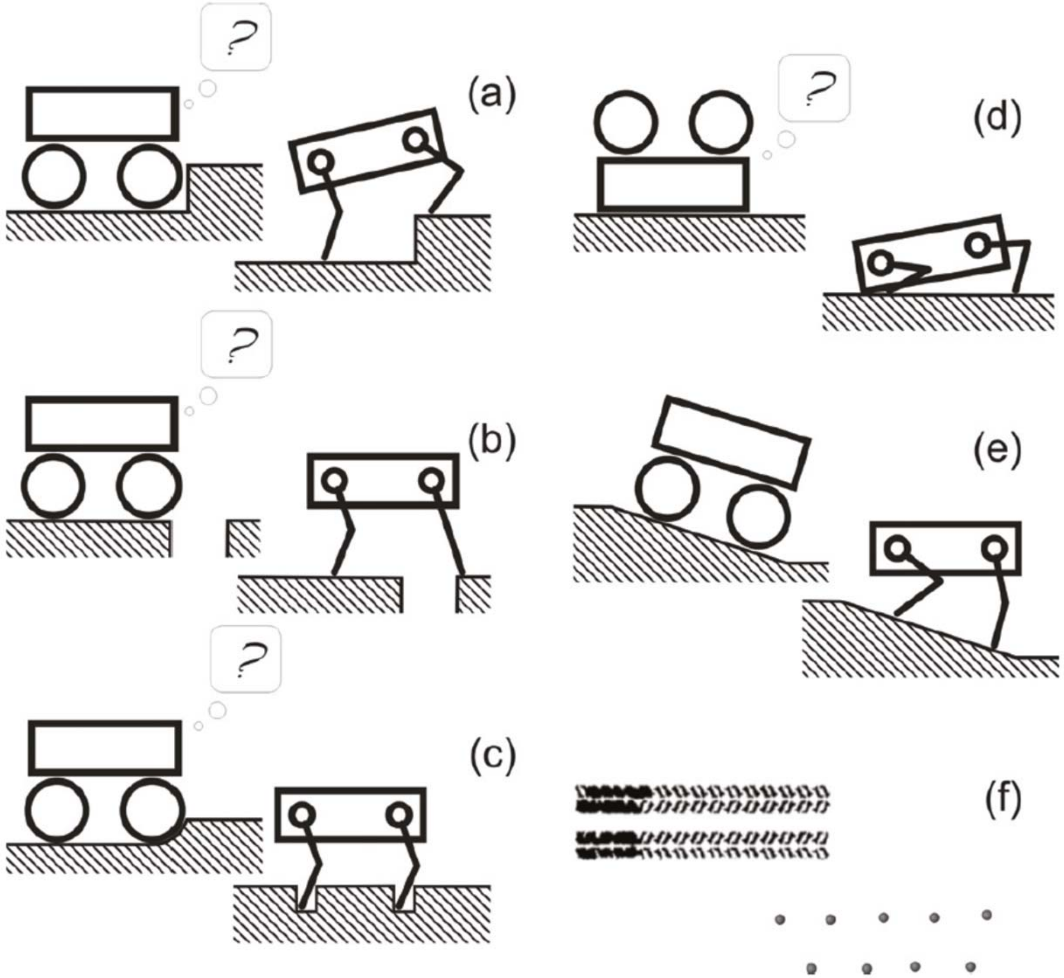
# Characterization of locomotion concept

- Locomotion
  - physical interaction between the vehicle and its environment.
- Locomotion is concerned with interaction forces, and the mechanisms and actuators that generate them.
- The most important issues in locomotion are:
  - **stability**
    - number of contact points
    - center of gravity
    - static/dynamic stabilization
    - inclination of terrain
  - **characteristics of contact**
    - contact point or contact area
    - angle of contact
    - friction
  - **type of environment**
    - structure
    - medium (water, air, soft or hard ground)

# Walking Robots

# Why legged robots?

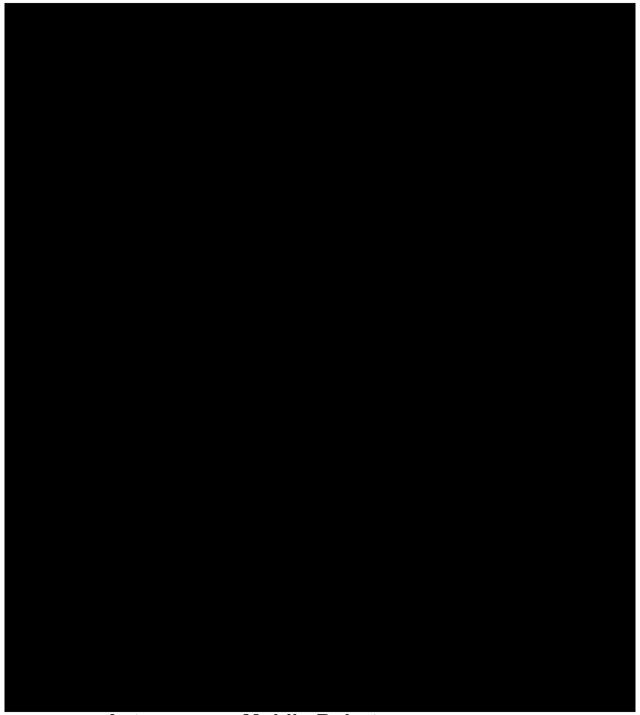
- Legged systems can overcome many obstacles, that are not reachable by wheeled systems!

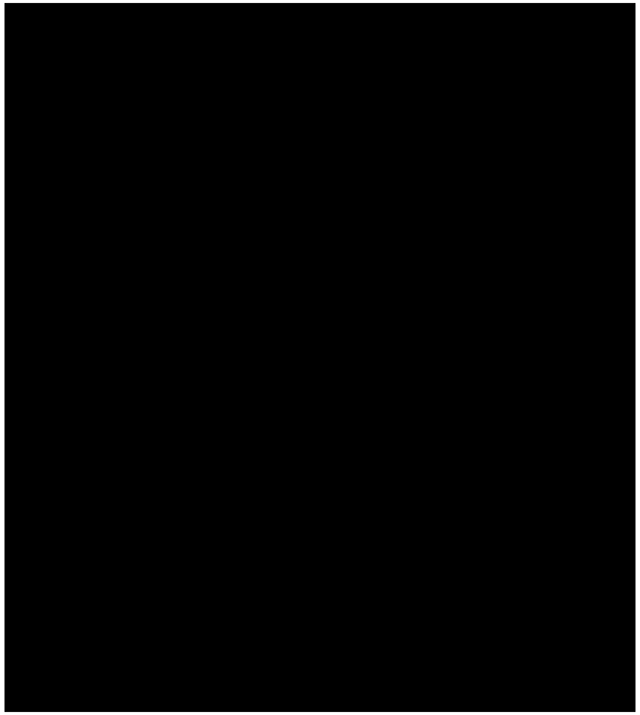


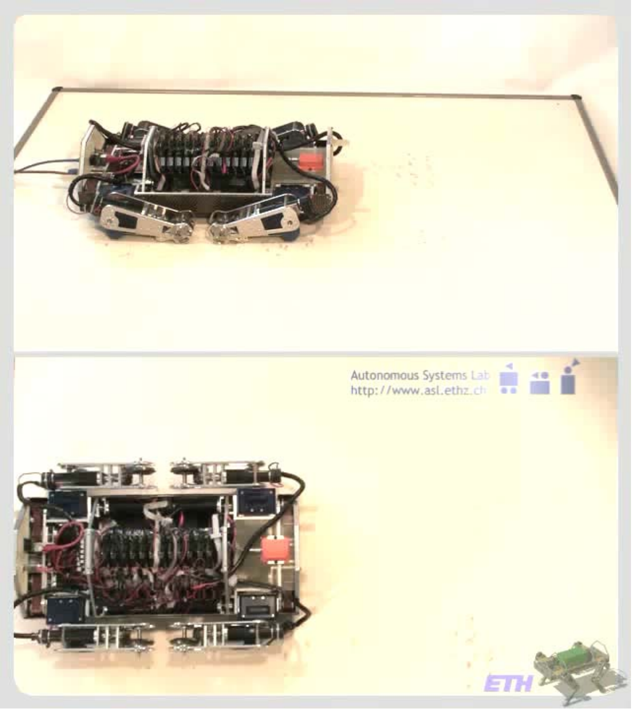

- But it is quite hard to achieve this since
  - many DOFs must be **controlled** in a coordinated way
  - the robot must **see** detailed elements of the terrain

# Legged Robotics | Impressive Mobility
# ALoF – The Quadruped Robot I (ETH)

- Highly integrated leg design
- large range of leg motion
  allowing for complex maneuvers
- “static” walking

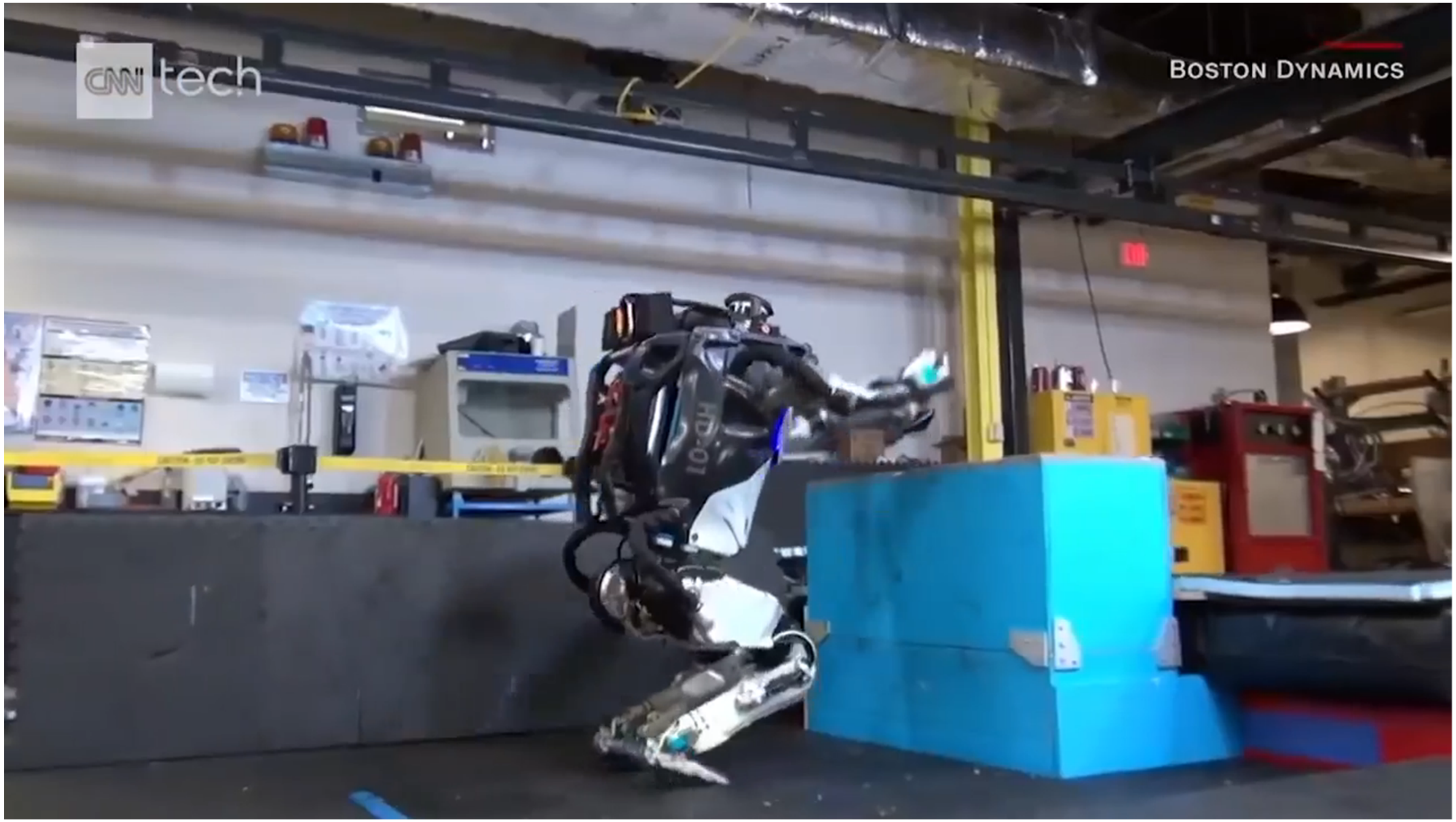






# **Legged Robotics** | Impressive Mobility

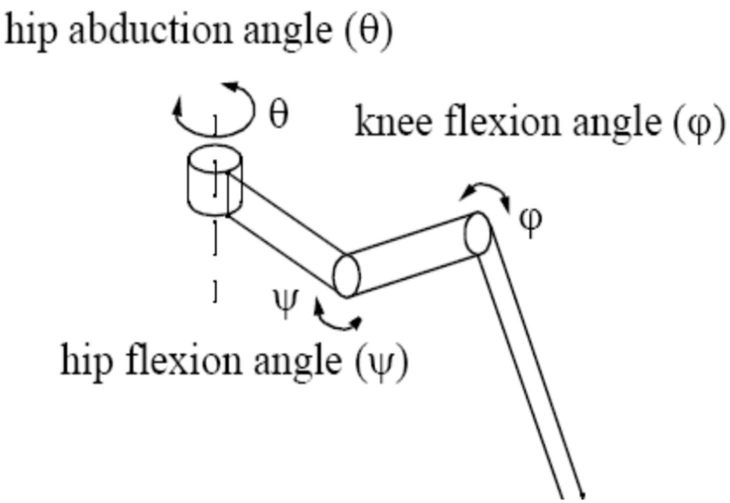
## Atlas from Boston Dynamics

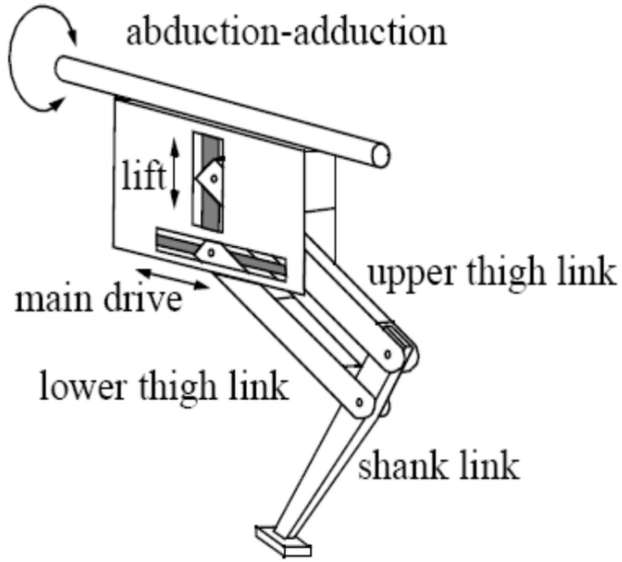



https://www.youtube.com/watch?v=knoOXBLFQ-s

# Number of Joints of Each Leg (DOF: degrees of freedom)

- A minimum of two DOF is required to move a leg forward
  - a *lift* and a *swing* motion.
  - Sliding-free motion in more than one direction not possible
- Three DOF for each leg in most cases (e.g. pictured below)
- 4th DOF for the ankle joint
  - might improve walking and stability
  - additional joint (DOF) increases the complexity of the design and especially of the locomotion control.



# The number of distinct event sequences (gaits)

- The gait is characterized as the distinct sequence of ***lift and release events*** of the individual legs
  - it depends on the number of legs.
  - the number of possible events N for a walking machine with k legs is:

$$N=(2k-1)!$$

- For a biped walker (k=2) the number of possible events N is:

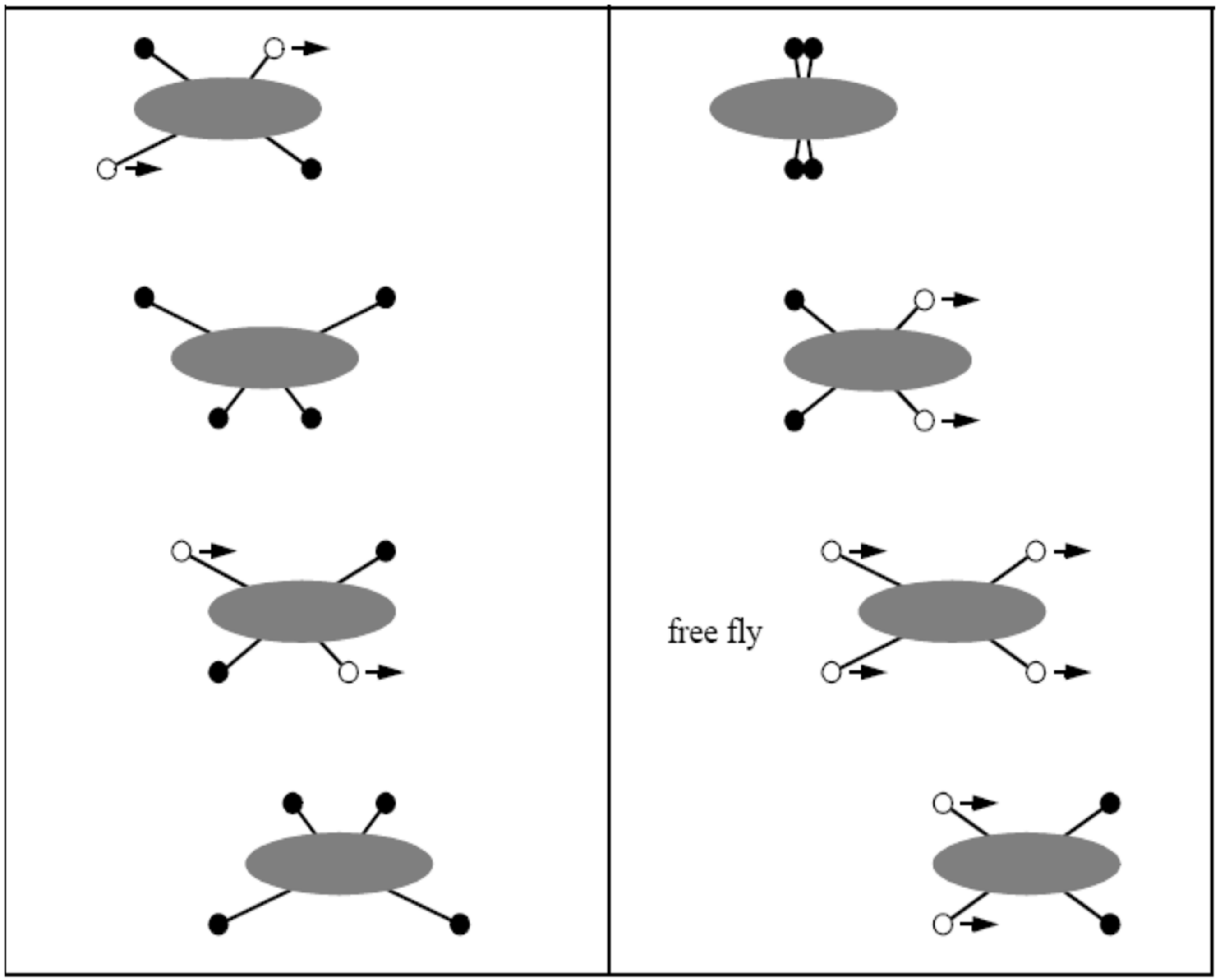
$$N=(2k-1)!=3!=3\cdot 2\cdot 1=6$$

- For a robot with 6 legs (hexapod) N is already

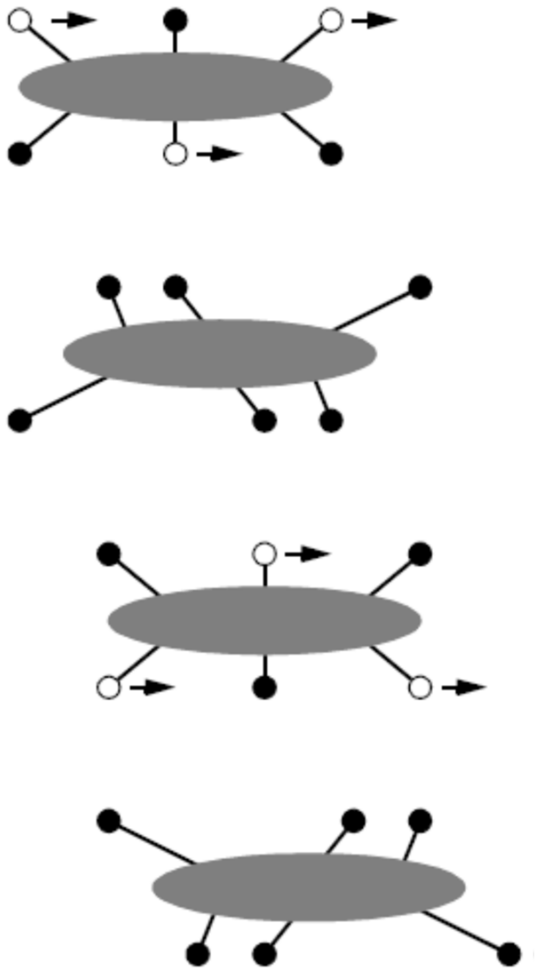
$$N=11!=39'916'800$$

# Most Obvious Natural Gaits with 4 Legs are Dynamic

- Changeover Walking
- Galloping

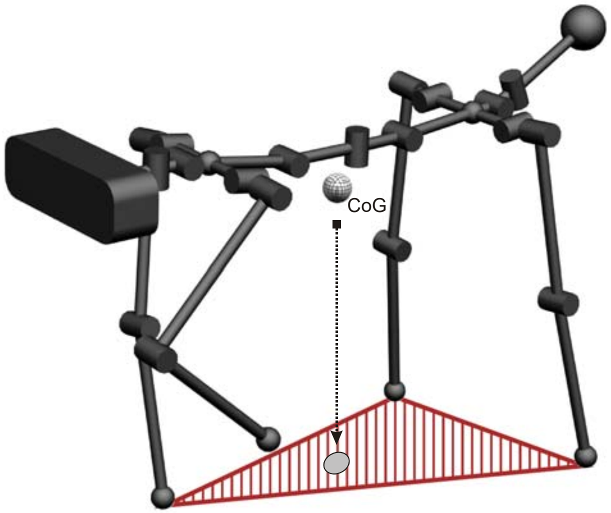


# Most Obvious Gait with 6 Legs is Static



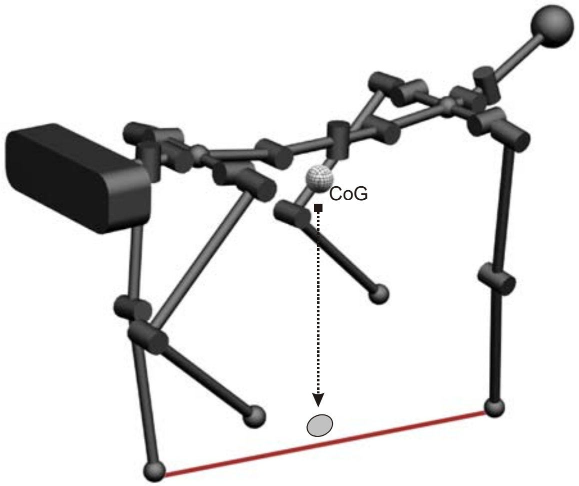
# Dynamic Walking vs. Static Walking

- Statically stable



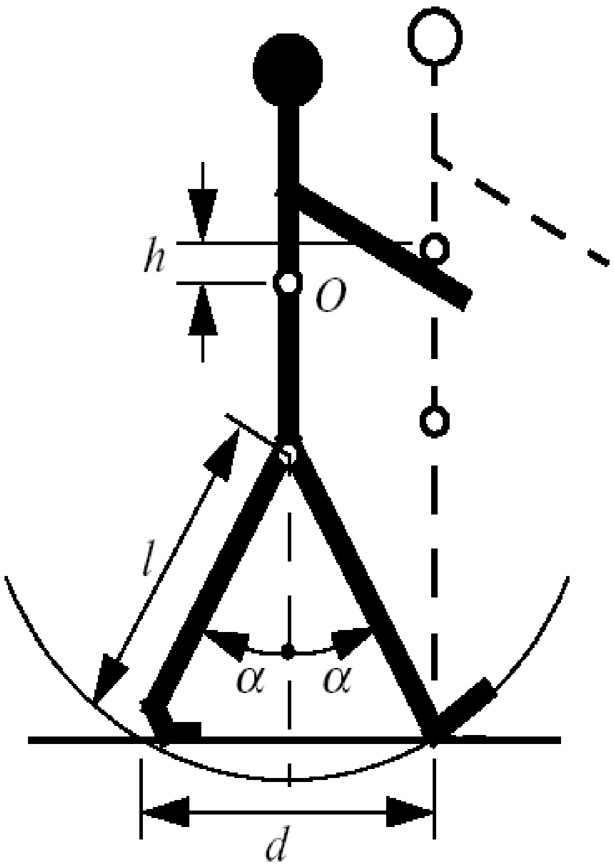

  - body weight supported by at least three legs
  - even if all joints 'freeze' instantaneously, the robot will not fall
  - safe, slow and inefficient

- Dynamic walking




  - the robot will fall if not continuously moving
  - less than three legs can be in ground contact
  - fast, efficient and demanding for actuation and control

# Biped Walking

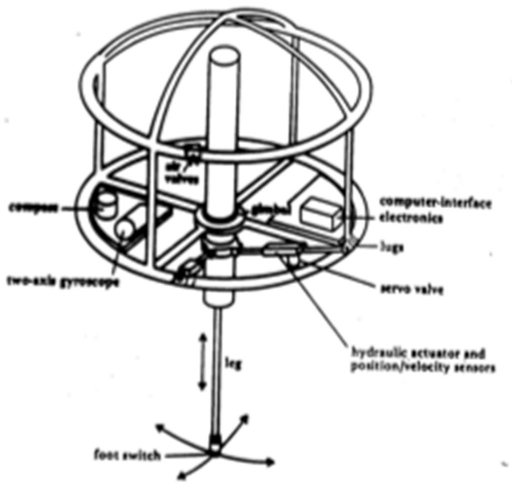



- Biped walking mechanism
  - not too far from real rolling
  - rolling of a polygon with side length equal to the length of the step
  - the smaller the step gets, the more the polygon tends to a circle (wheel)
- But…
  - rotating joint was not invented by nature
  - work against gravity is required
  - more detailed analysis follows later in this presentation

# Dynamic Locomotion

## SLIP Principles in Robotics

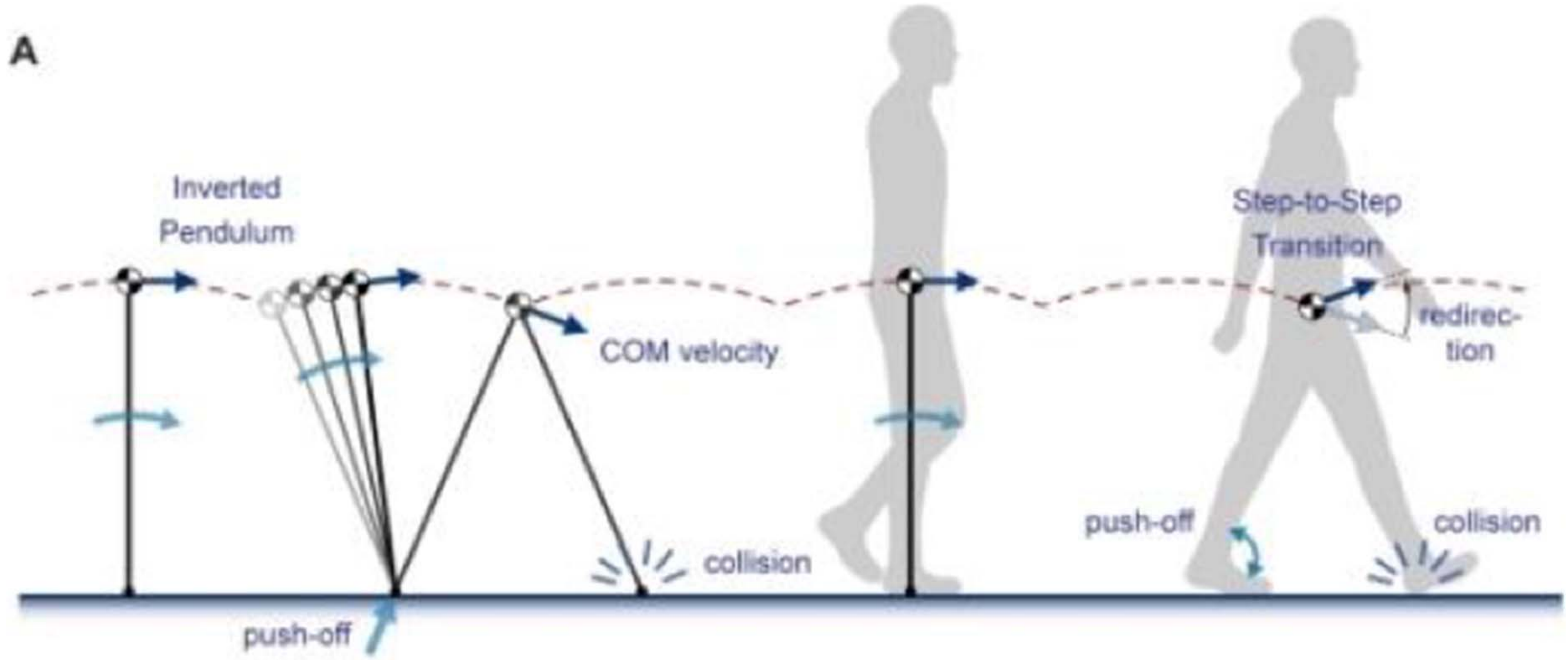
- Pneumatic piston
- Hydraulic leg “angle” orientation




Early Raibert hoppers (MIT Leg Lab), 1983

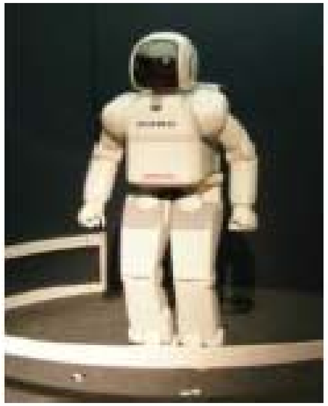
# Modeling Legged Locomotion
## Inverted Pendulum

- Walking can be represented by an inverted pendulum



# Efficiency Comparison

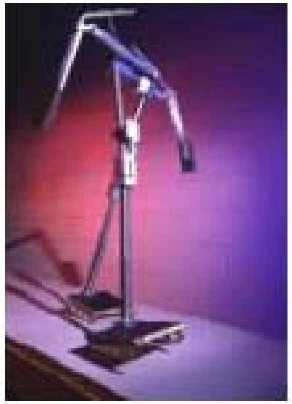
- Efficiency = $c_{mt}$ = |mech. energy| / (weight x dist. traveled)



$c_{mt}^{est.} \approx 1.6$

Collins *et al.* 2005

$c_{mt} \approx 0.31$



$c_{mt} \approx 0.055$

Collins *et al.* 2005

C J. Braun, University of Edinburgh, UK

# Case Study: Passive Dynamic Walker

- Forward falling combined with passive leg swing
- Storage of energy: potential ←→ kinetic in combination with low friction

C youtube material

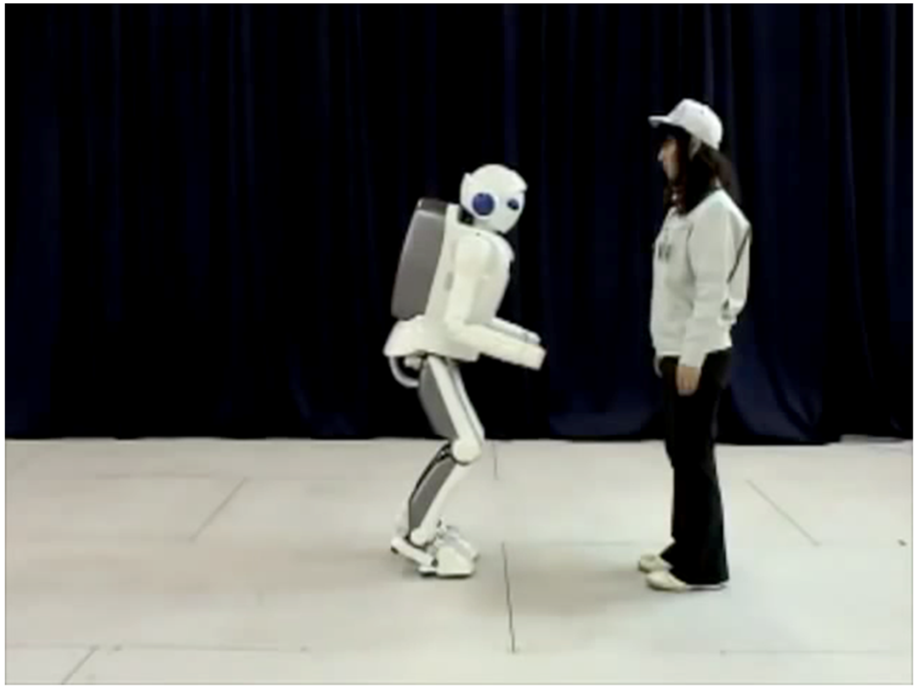
# Static walking principles
## Inverted Pendulum

- Static walking can be represented by inverted pendulum
- Exploit this in so-called passive dynamic walkers
- Add small actuation to walk on flat ground

| **Cornell Ranger** | |
|---|---|
| Total distance: | 65.24 km |
| Total time: | 30:49:02 |
| Power: | 16.0 W |
| COT: | 0.28 |

# Legged Robotics
## Walking Mechanism – Theo Jansen

# History of Legged Robotics
## Humanoid Robots After 2000

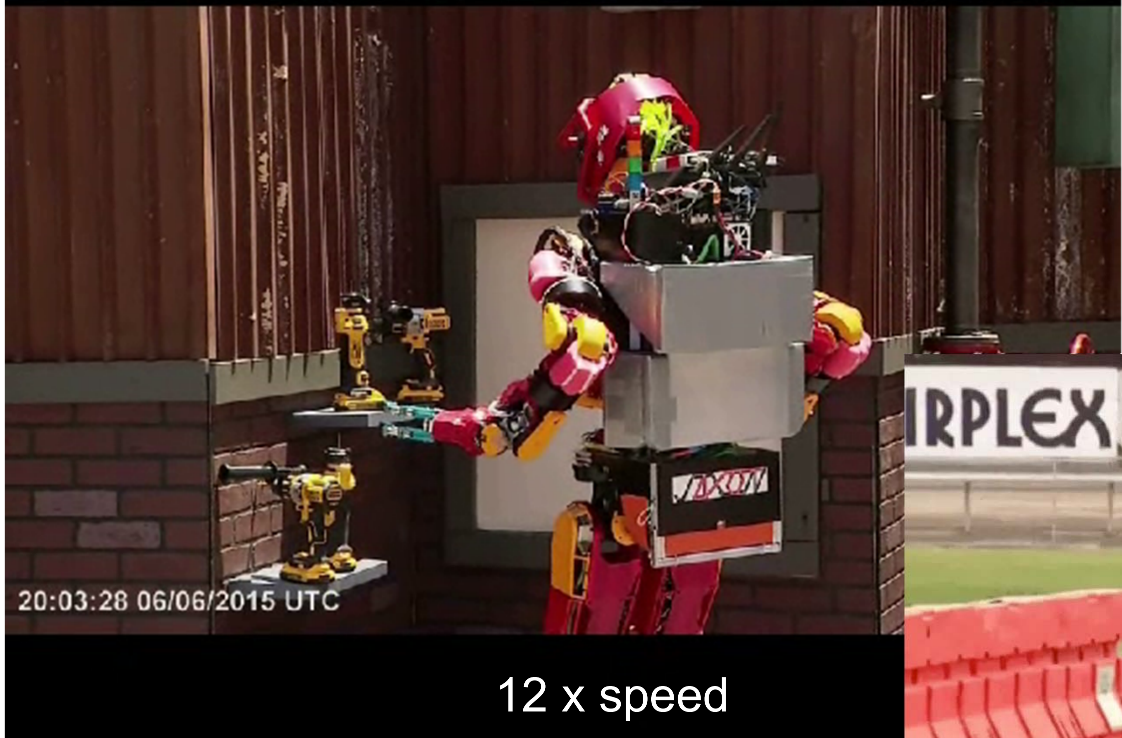
# Fukushima – where no human should go

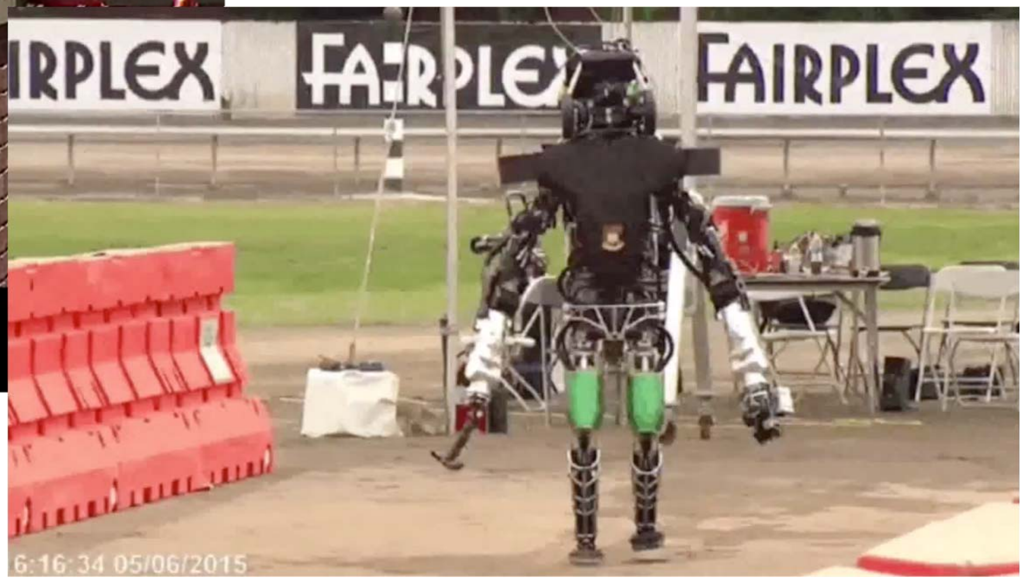
Fukushima, 2011

DARPA Robotics Challenge, 2012

# DARPA Robotics Challenge
## … and a thing we learned after the DRC Finals

- Walking is still difficult



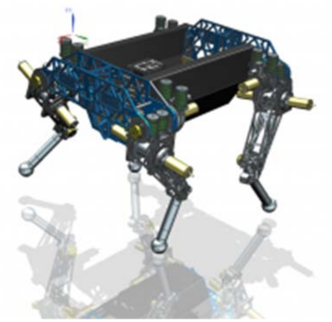
# **Legged Robotics Today |** Finally, a breakthrough?

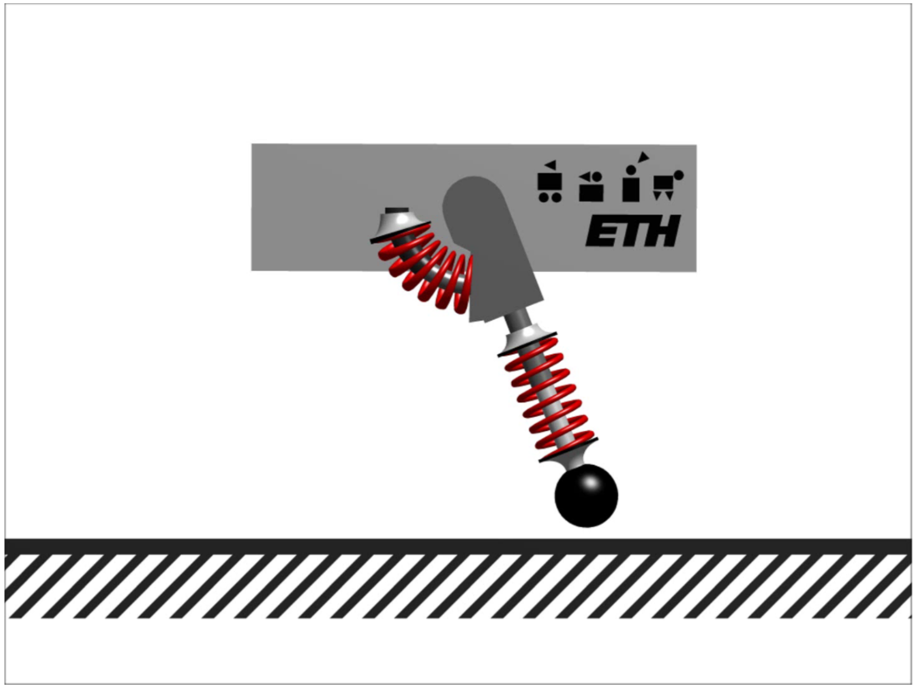
- Example: Boston Dynamics

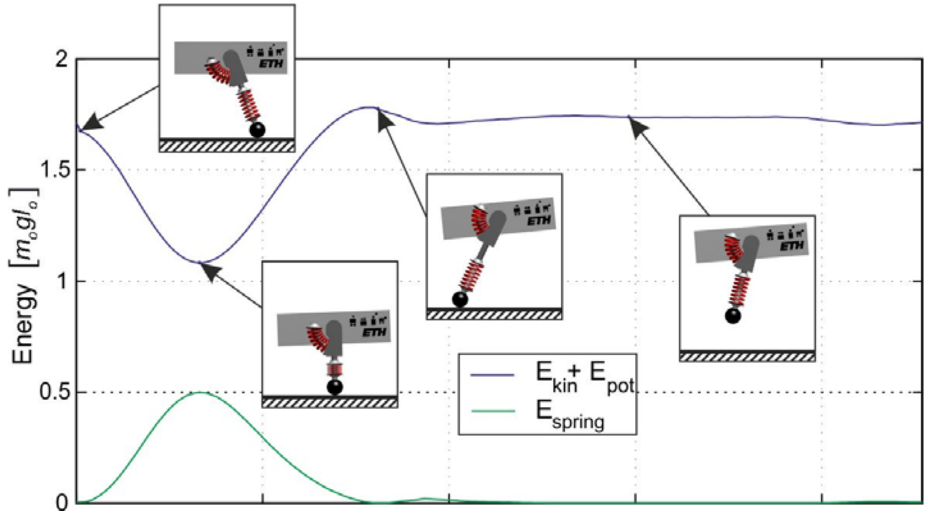
# Towards Efficient Dynamic Walking: Optimizing Gaits

C Structure and motion laboratory
University of London

# Efficient Walking and Running | serial elastic actuation



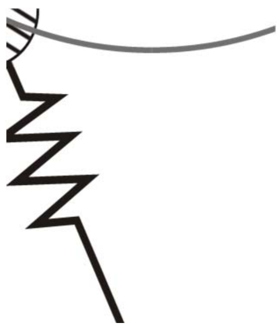


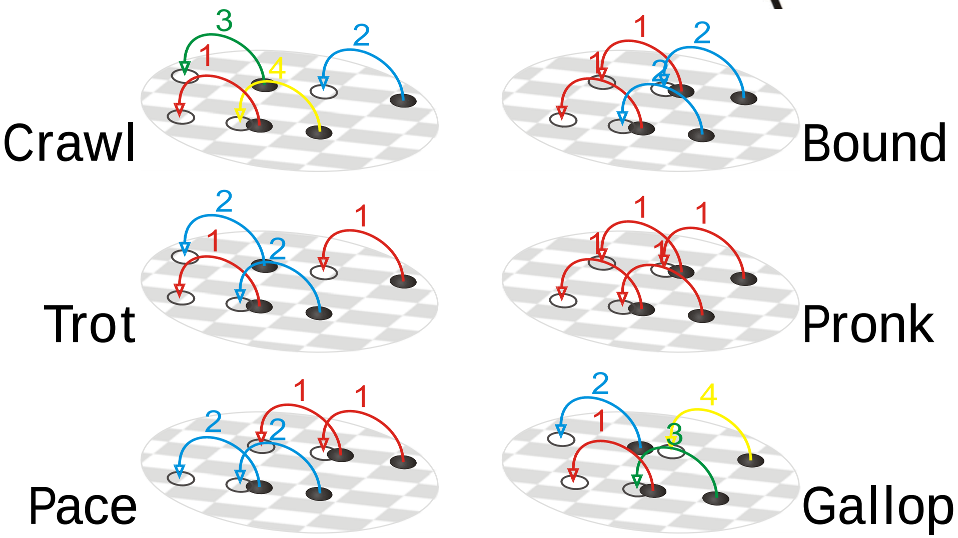



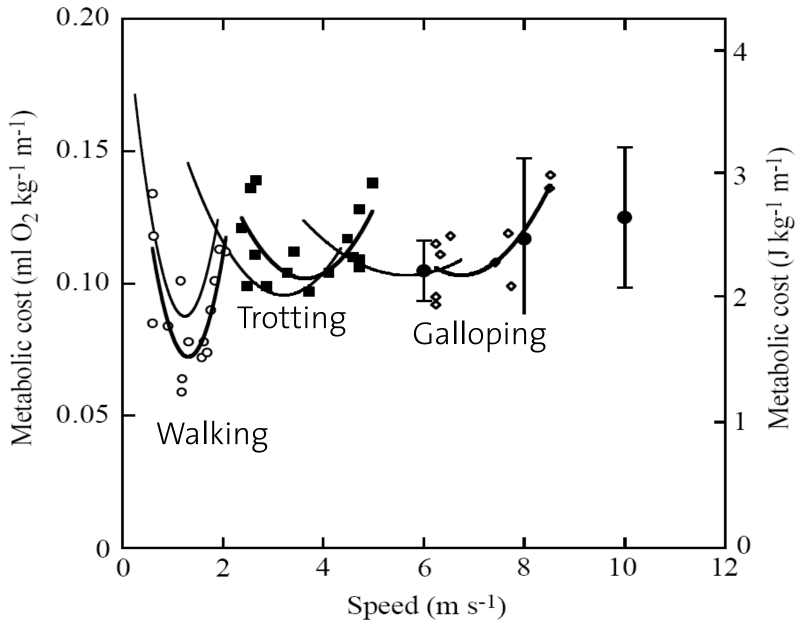

https://www.youtube.com/watch?v=6igNZiVtbxU

# Towards Efficient Dynamic Walking: Optimizing Gaits

- Nature optimizes its gaits
- Storage of “elastic” energy
- To allow locomotion at varying frequencies and speeds, different gaits have to utilize these elements differently





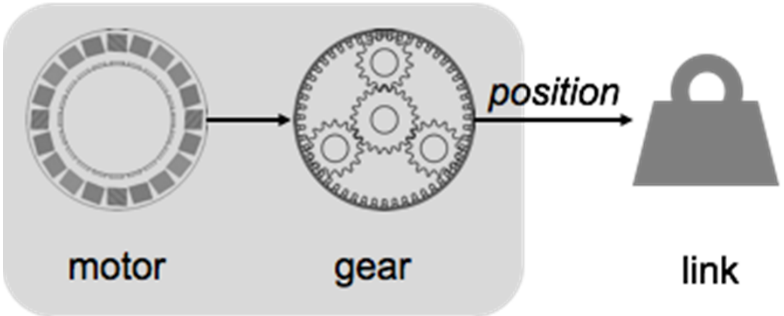




- The energetically most economic gait is a function of desired speed.
(Figure [Minetti et al. 2002])

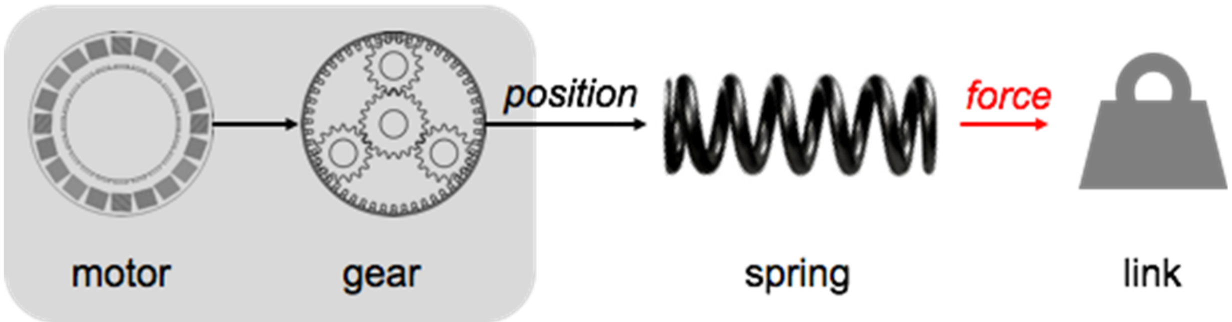
# Series Elastic Actuators

## From Position to Force Controlled Systems

- Kinematic, position control

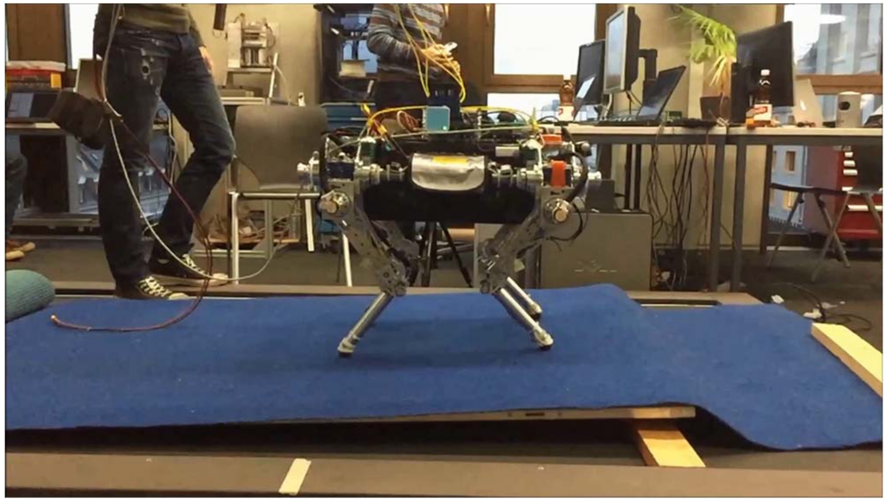


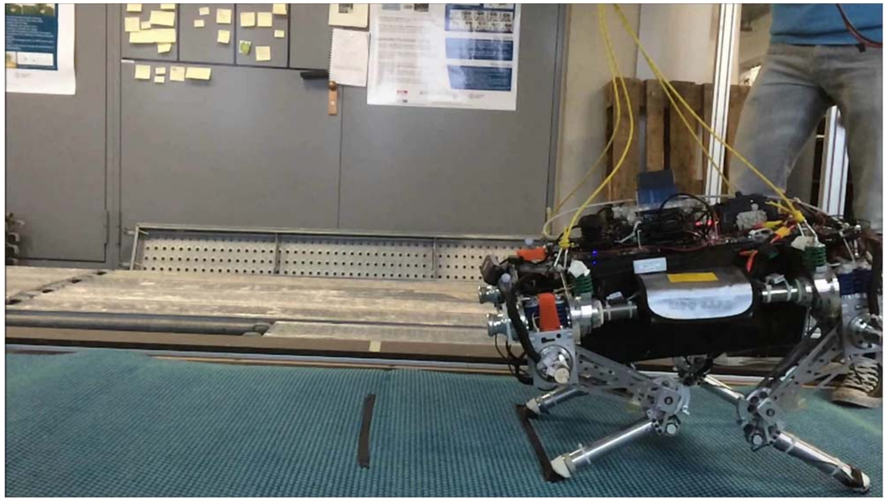

- Dynamic, force control



# StarlETH – “serial elastic actuation”

https://www.youtube.com/watch?v=IO_sZ6FBAwQ
https://www.youtube.com/watch?v=Tj1wreifYhU

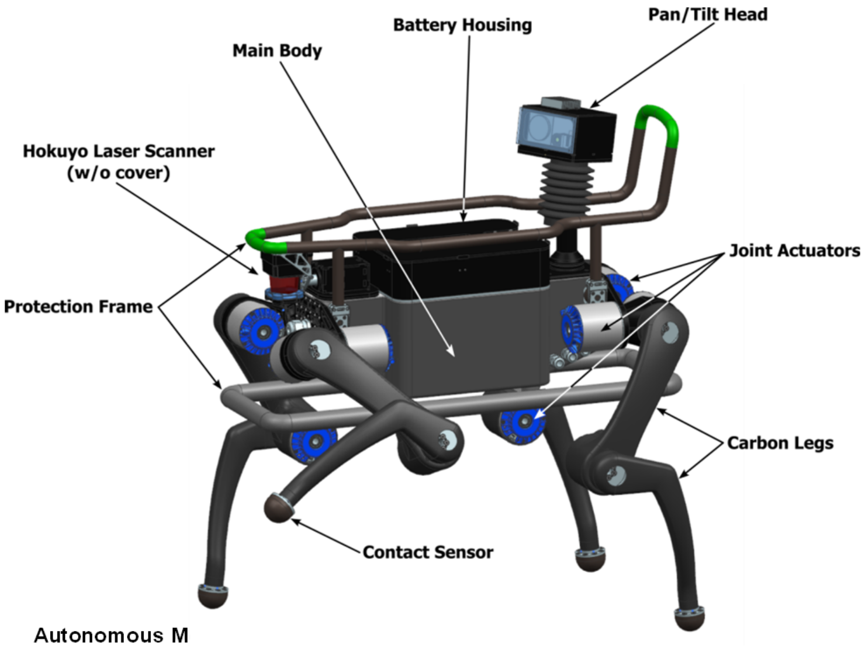


# ANYmal
## an electrically actuated dog for real-world scenarios

Robotic Systems Lab
Prof. Marco Hutter

- High mobility
  - *“to go where today only humans can go”*
- 10 kg of payload
- 2 h of continuous operations

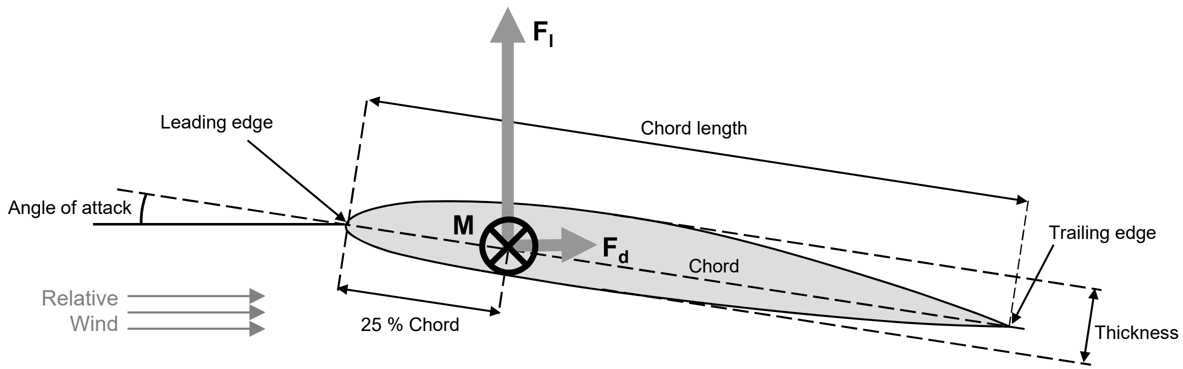



https://www.youtube.com/watch?v=ZdeRi_5xK5U&feature=youtu.be

# Flying Robots

# Flying « Locomotion »

- Forces acting on a profile with relative wind speed
  - Lift force
  - Drag force
  - Moment




$$F_l = C_l \frac{\rho}{2} S v^2$$

$$F_d = C_d \frac{\rho}{2} S v^2$$

$$M = C_m \frac{\rho}{2} S v^2 \cdot chord$$

with
- $\rho$ : Density of fluid (air)
- $S$ : Wing area
- $v$ : Flight speed (relative to surrounding fluid)
- $C_L$ : Lift coefficient
- $C_D$ : Drag coefficient
- $C_M$ : Moment coefficient

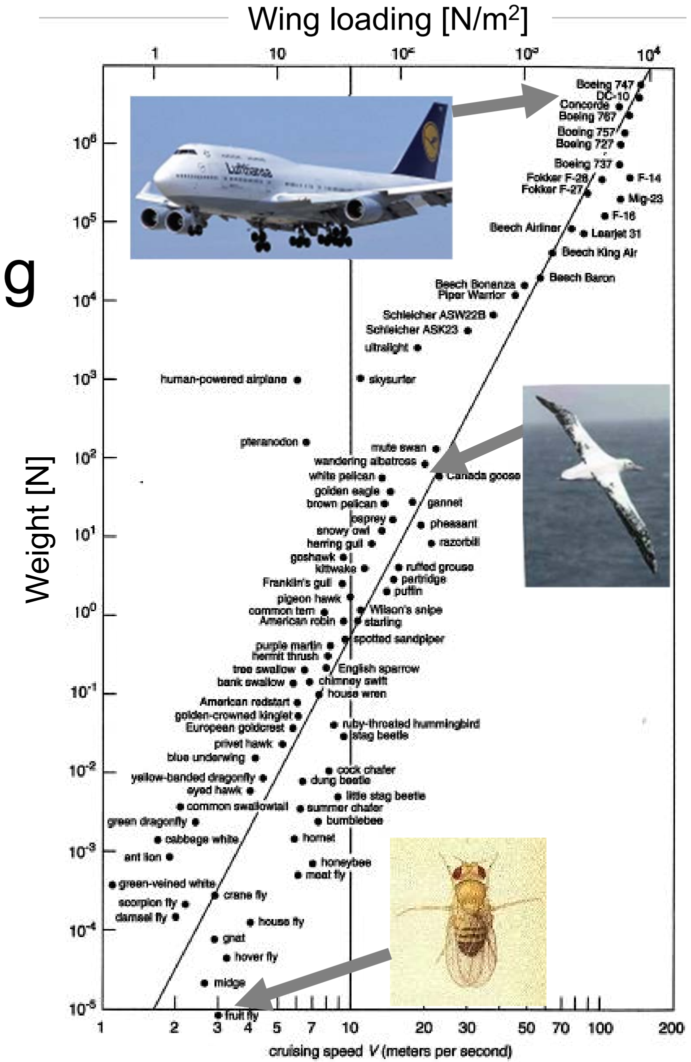
# **Scaling**| Structural Load

- All flying objects follows the square-cube law of scaling

$$W = L = mg \approx b^3 \qquad W\text{: weight}$$
$$S \approx b^2 \qquad S\text{: wing area}$$
$$W / S \approx b$$
$$W / S = k_1 \cdot W^{\frac{1}{3}}$$

- Possible Wing loading as function of weight

$$\boxed{W / S = 47 \cdot W^{1/3}}$$

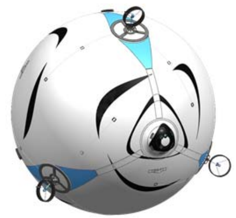



Tennekes H (1996) *The Simple Science of Flight, From Insects to Jumbo Jets*, MIT Press, Cambridge

Tennekes H (1996) ***The Simple Science of Flight, From Insects to Jumbo Jets***, MIT Press, Cambridge

# How to Fly (Unmanned Aerial Vehicles) | flight concepts

- Helicopters: (video Prof. D'Andrea ETH)
  - < 20 minutes
  - Highly dynamic and agility
- Fixed Wing Airplanes:
  - > some hours; continuous flights possib
  - Non-holonomic constraints
- Blimp: lighter-than-air
  - > some hours (dependent on wind conditions);
  - Sensitive to wind
  - Large size (dependent on payload)
- Flapping wings
  - < 20 minutes; gliding mode possible
  - Non-holonomic constraints
  - Very complex mechanics



Festo BionicOpter

# **Service Robots** – flying robots for challenging tasks

## **wingtra** – developed by students

| the VTOL UAV

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


## AtlantikSolar

| 81 hours non-stop in summer 2015

| 5.64 m, 6.2 kg

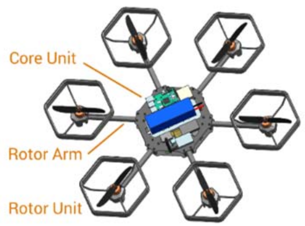
https://www.youtube.com/watch?v=8m4_NpTQn0E

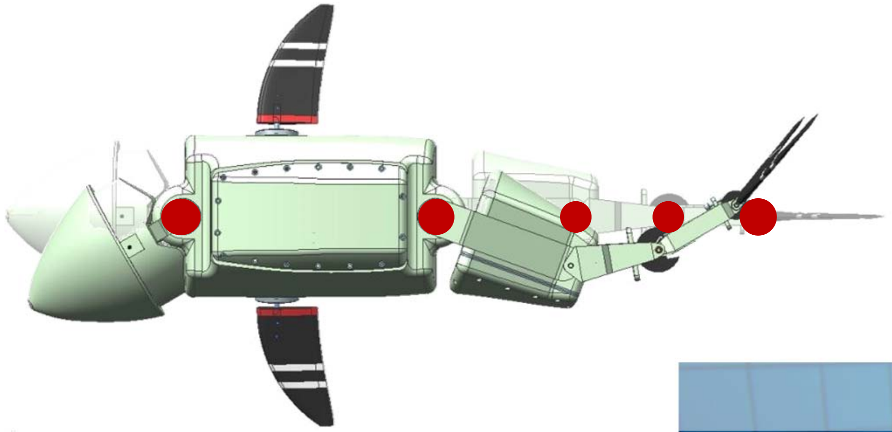
https://www.youtube.com/watch?v=wyS6W1t_ryQ

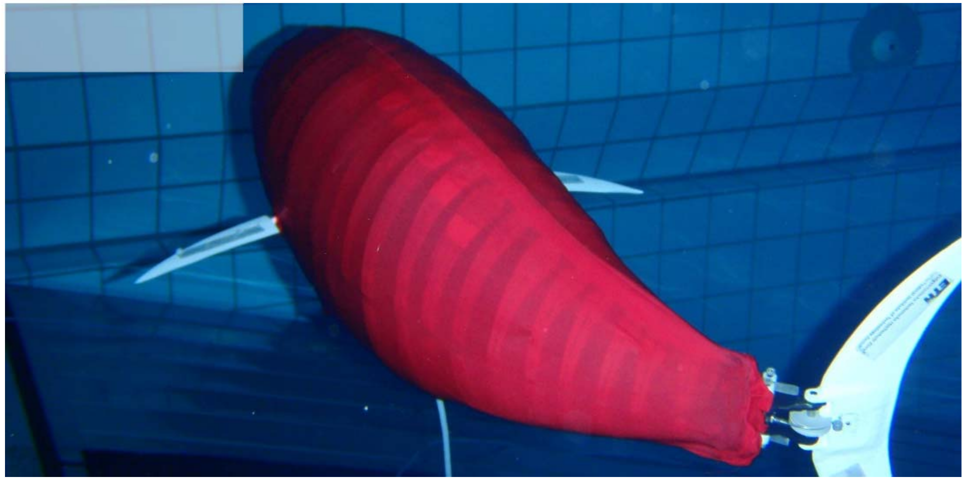
## **Voliro** – developed by students

| the omni-directional multi-copter

https://www.youtube.com/watch?v=9FJn_t-YCwM

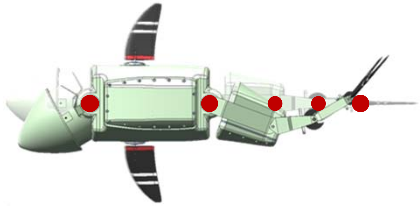


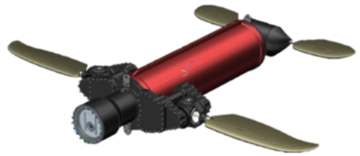


# Swimming Robots

# Underwater Robots
## – designed by ETH students



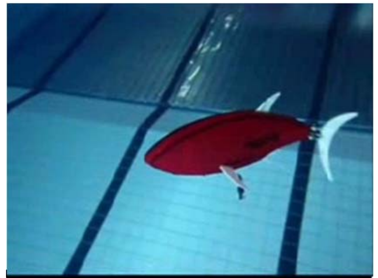
**Naro** (2009)
| the tuna robot
https://www.youtube.com/watch?v=L61O2CmZCc4

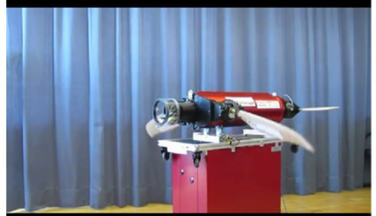


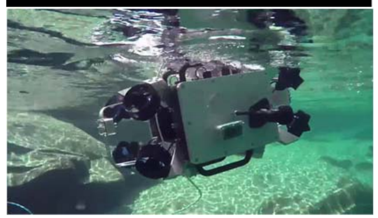
**Taratuga** (2012)
| the turtle robot
https://www.youtube.com/watch?v=pqy_NSHcGLs

**Sepios** (2014, with Disney)
| the Kalmar robot
https://www.youtube.com/watch?v=GeCLL2RWV1c

**Scubo** (2016, with Disney)
| the agile underwater robot
https://www.youtube.com/watch?v=-g2O8e1j3fw







# The end