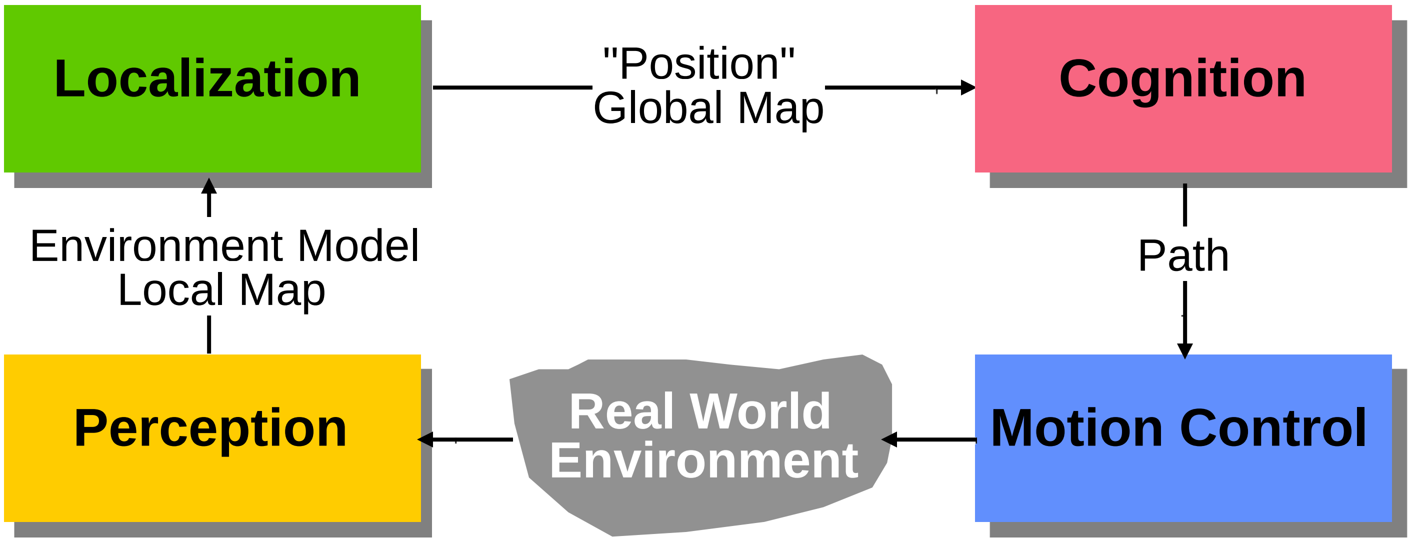
Robot Locomotion

(slides mostly from authors of Autonomous Mobile Robots, MIT Press)

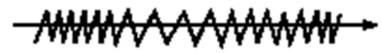
August 30, 2011

Locomotion Concepts

- Concepts
- Legged Locomotion
- Wheeled Locomotion



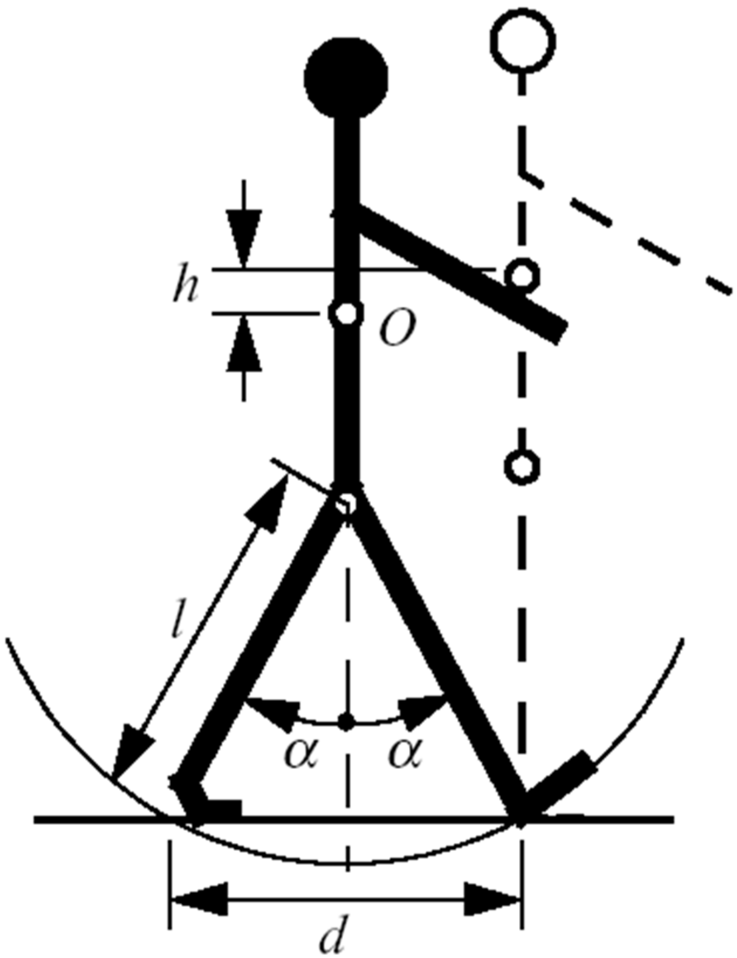
Locomotion Concepts: Principles Found in Nature

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

- Concepts found in nature
  - *difficult to imitate technically*
- Most technical systems use wheels or caterpillars
- Rolling is most efficient, but not found in nature
  - *Nature never invented the wheel !*
- However, the movement of a walking biped is close to rolling

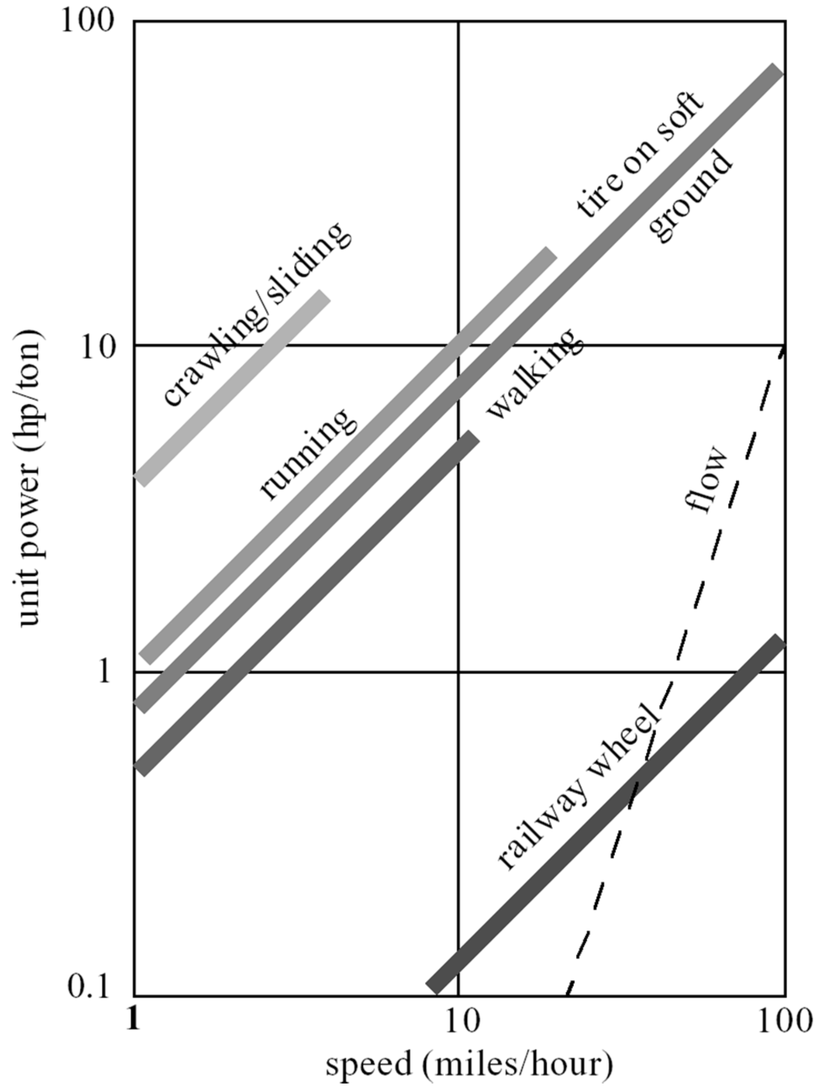
Walking of a Biped



- 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).*
- However, fully rotating joint was not developed in nature.

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*



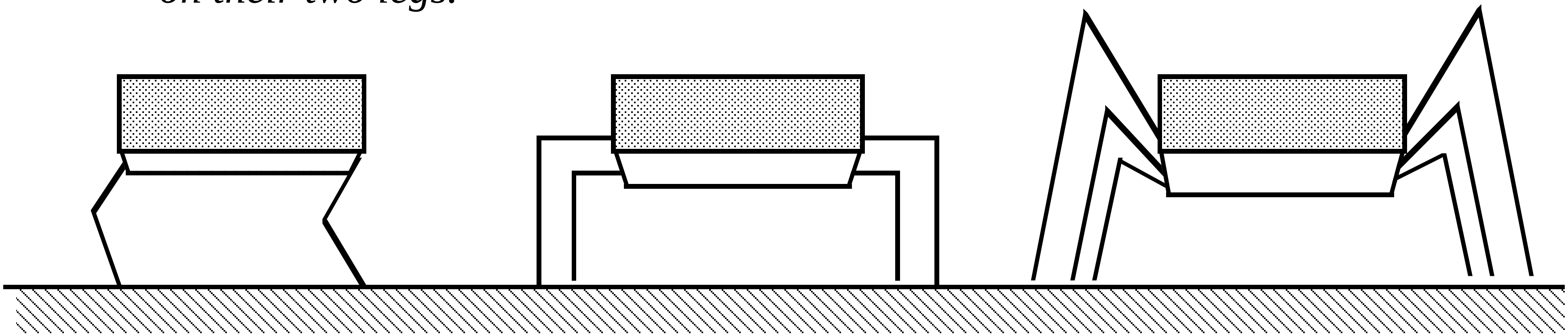
Characterization of locomotion concept

- 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)*

Mobile Robots with legs (walking machines)

- The fewer legs, the more complicated becomes locomotion
  - *stability, at least three legs are required for static stability*
- During walking some legs are lifted
  - *thus loosing stability?*
- For static walking at least 6 legs are required
  - *babies have to learn for quite a while until they are able to stand or even walk on their two legs.*



mammal
four legs (two)

reptiles
four legs

insects
six legs

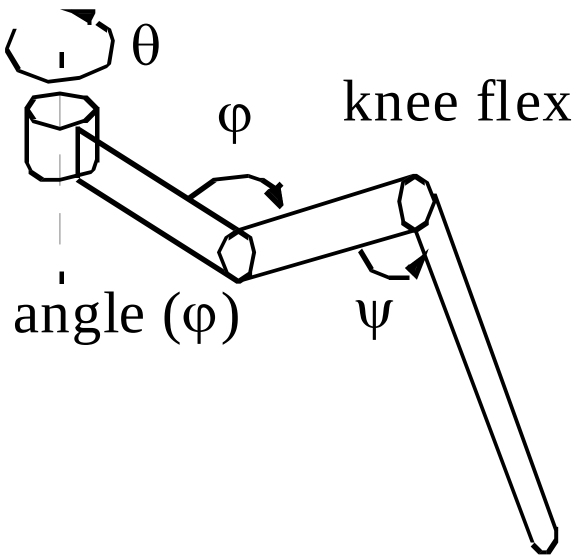
Number of Joints of Each Leg (DOF: degrees of freedom)

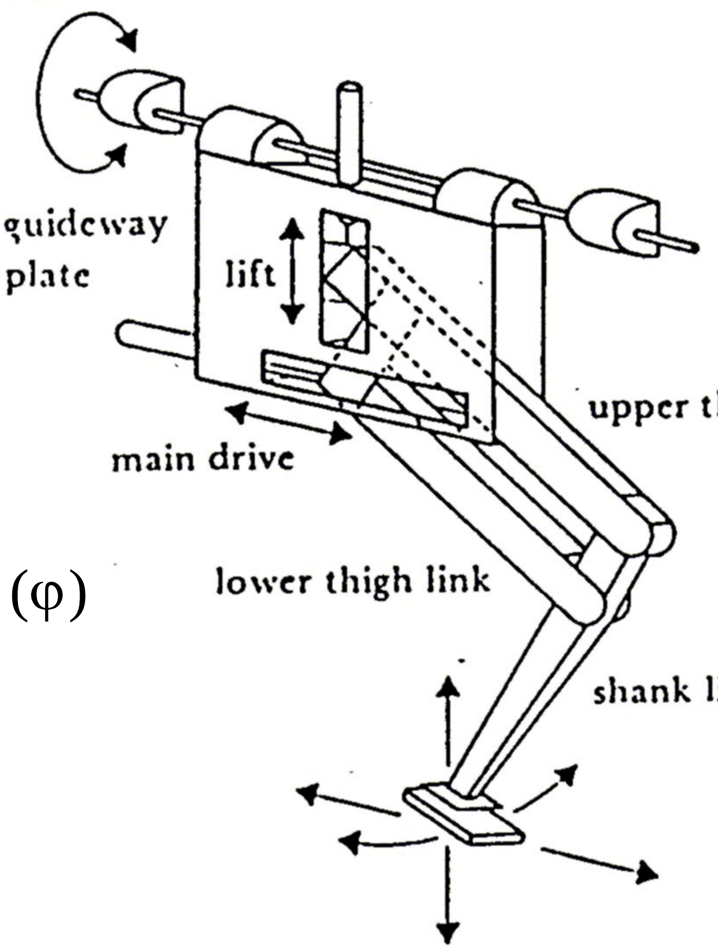
- A minimum of two DOF is required to move a leg forward
  - *a* lift *and a* swing *motion.*
  - *sliding free motion in more than one direction not possible*

- Three DOF for each leg in most cases

- Fourth DOF for the ankle joint
  - *might improve walking*
  - *however, additional joint (DOF) increases the complexity of the design and especially of the locomotion control.*

Examples of Legs with 3 DOF





The number of possible gaits

- The gait is characterized as the 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:*

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

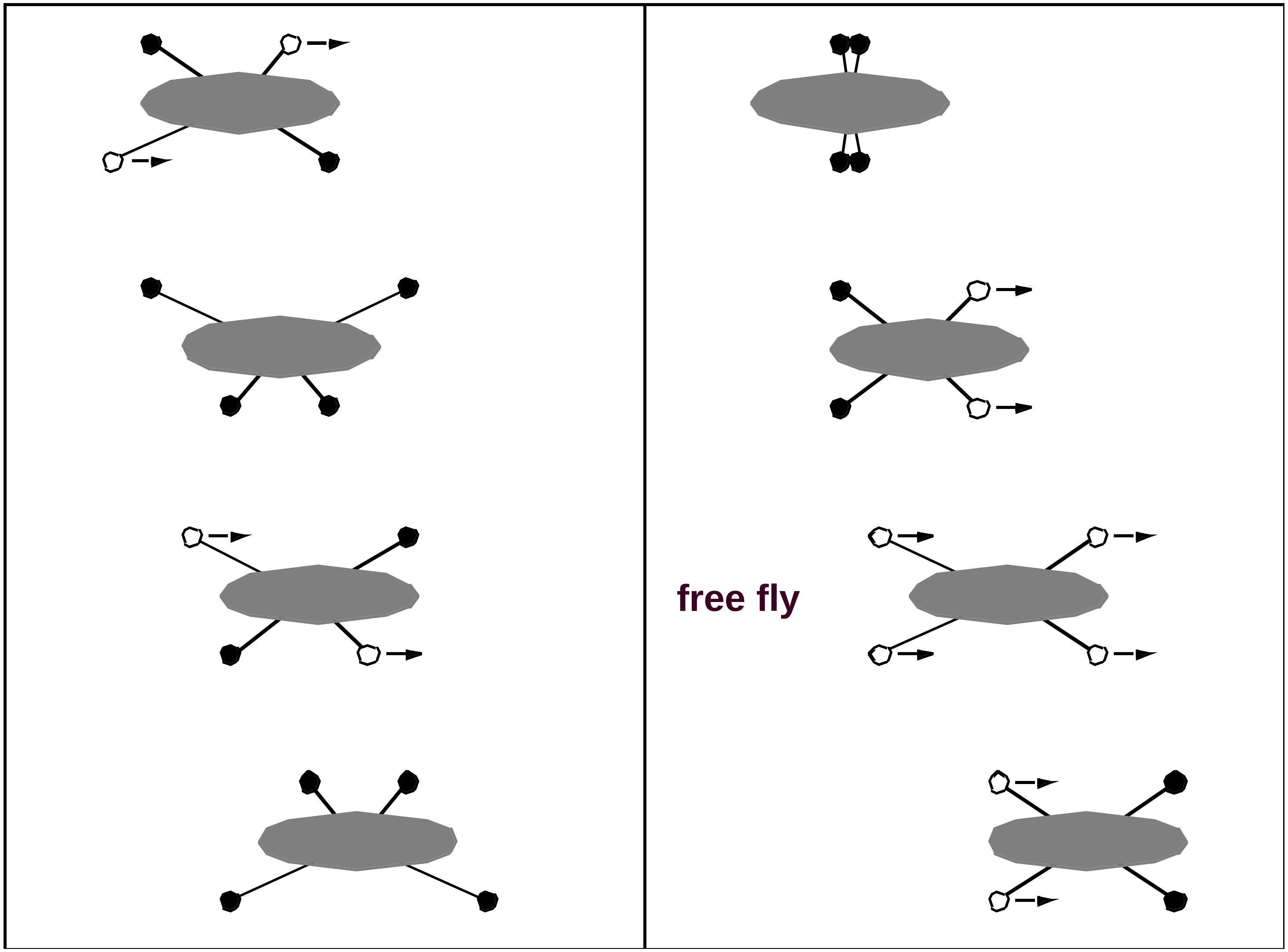
- For a biped walker (k=2) the number of possible events N is:

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

  - *The 6 different events are:*
    lift right leg / lift left leg / release right leg / release left leg / lift both legs together / release both legs together
- For a robot with 6 legs (hexapod) N is already

$$N = 11! = 39{,}916{,}800$$

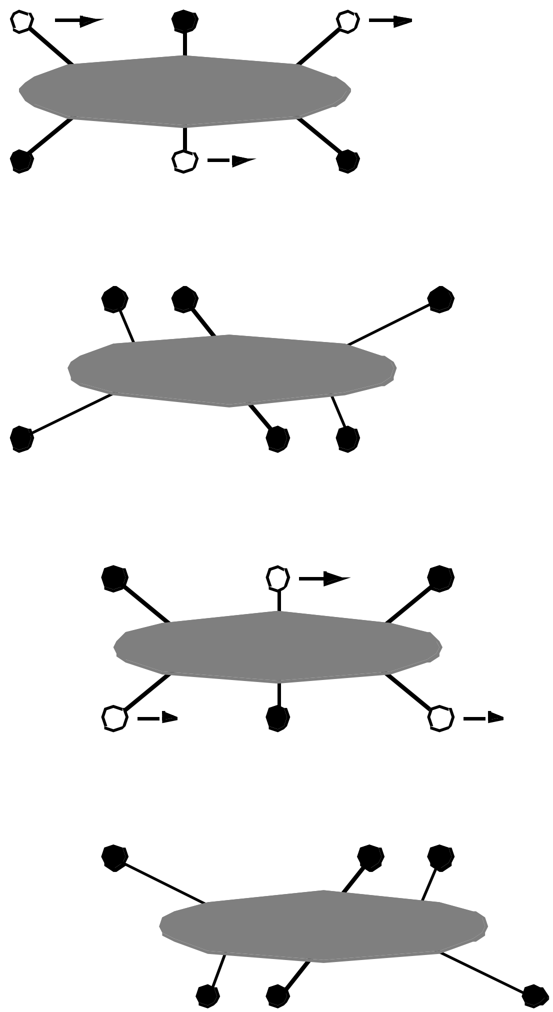
Most Obvious Gaits with 4 legs



Changeover Walking

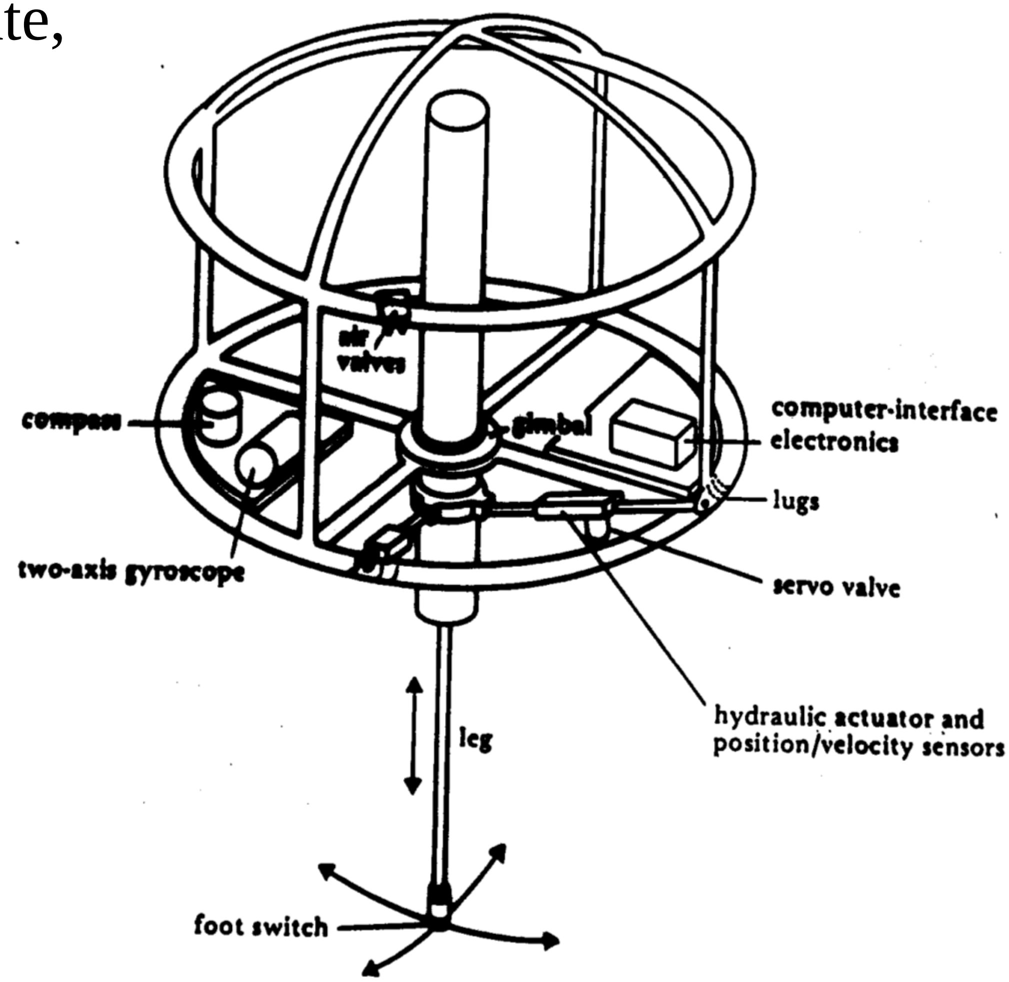
Galloping

Most Obvious Gait with 6 legs (static)



Examples of Walking Machines

- No industrial applications up to date, but a popular research field



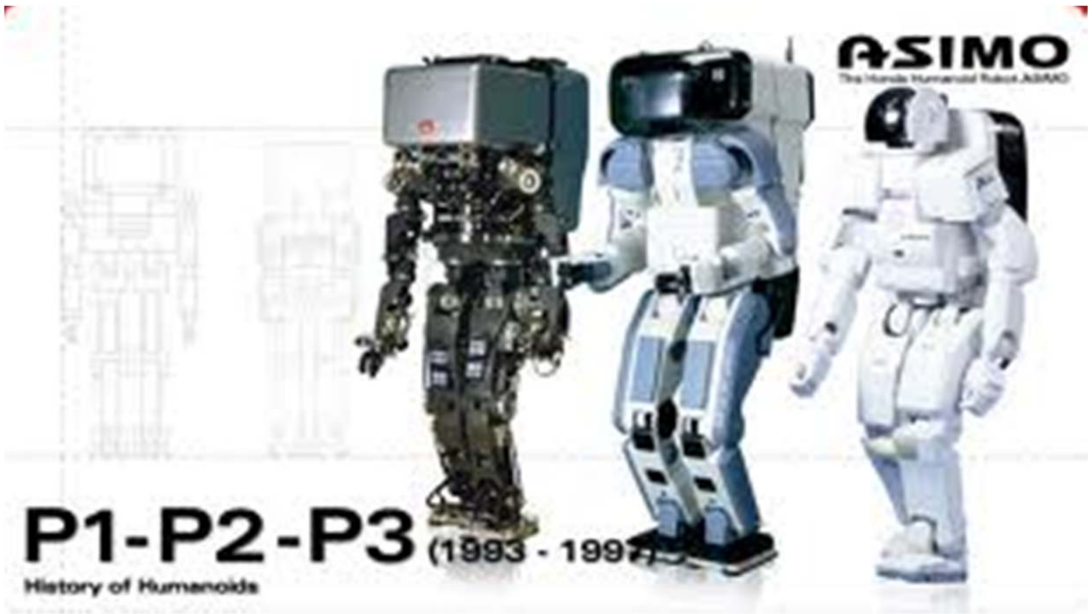
The Hopping Machine

Courtesy of Marc Raibert

Humanoid Robots

- P1-P2-P3 (Asimo) from Honda, Japan

  - *Maximum Speed: 2 km/h*
  - *Autonomy: 15 min*
  - *Weight: 210 kg*
  - *Height: 1.82 m*
  - *Leg DOF: 2*6*
  - *Arm DOF: 2*7*



Humanoid Robots

- Wabian build at Waseda University in Japan
  - *Weight: 107 kg*
  - *Height: 1.66 m*
  - *DOF in total:* ***43***

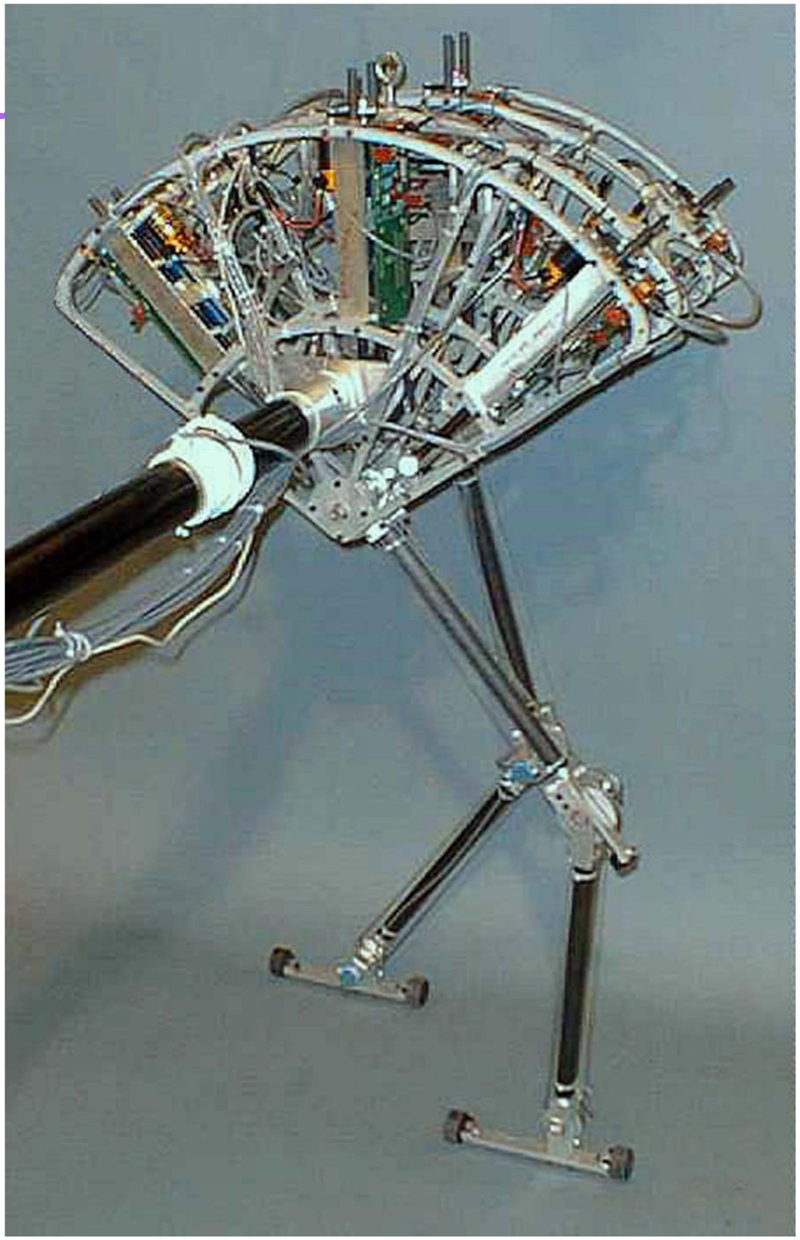
NAO Robot

- Developed by Alderbaran (French company)
- Designed especially for education

Bipedal Robots

- Leg Laboratory from MIT
  - *Spring Flamingo the bipedal running machine*
  - *“Troody” Dinosaur like robot*
  - *“M2” Humanoid robot*

more infos : http://www.ai.mit.edu/projects/leglab/

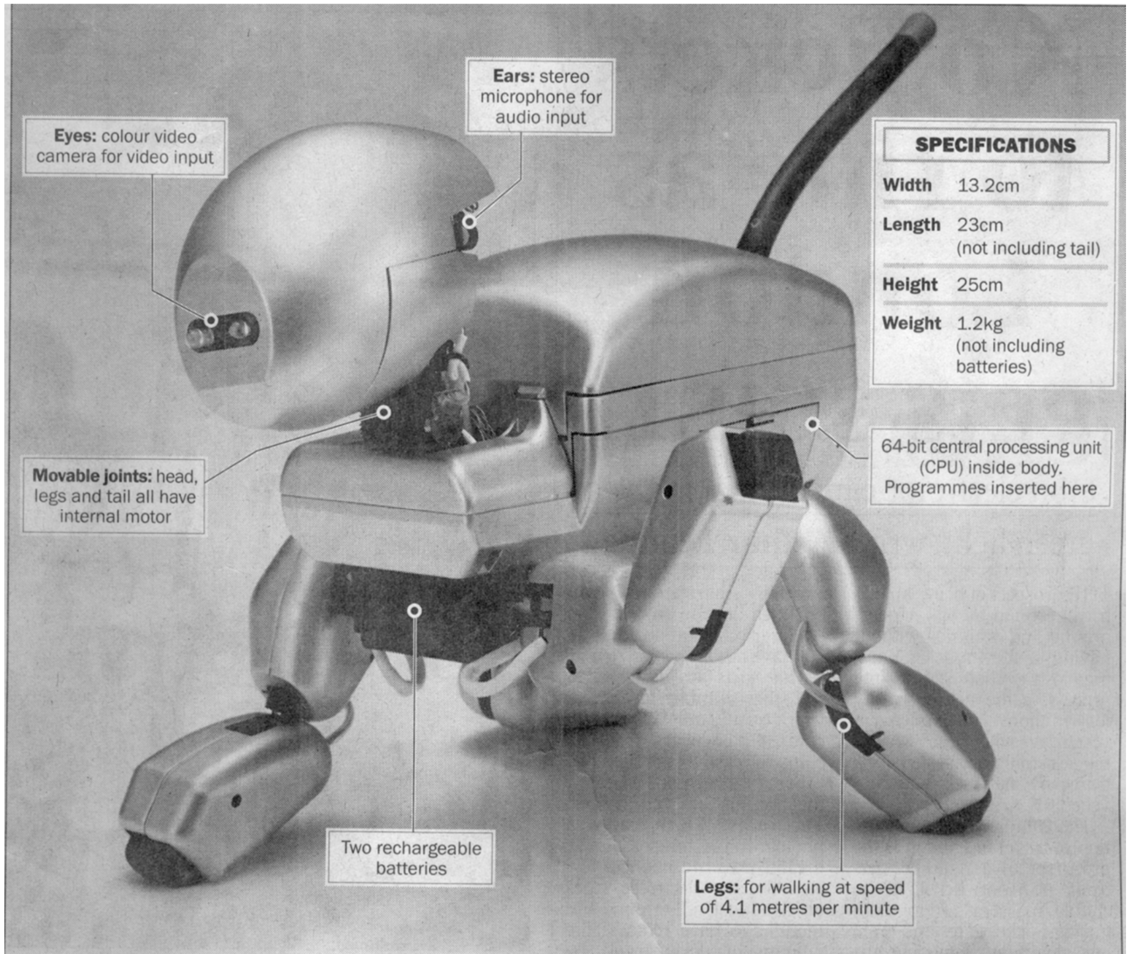


Genghis Robot

- Developed in late 1980s by Rodney Brooks
- Illustration of “elephants don’t play chess”!
- Demonstration of behavior-based robotics
- Used subsumption architecture

Walking Robots with Four Legs (Quadruped)

- Artificial Dog Aibo from Sony, Japan

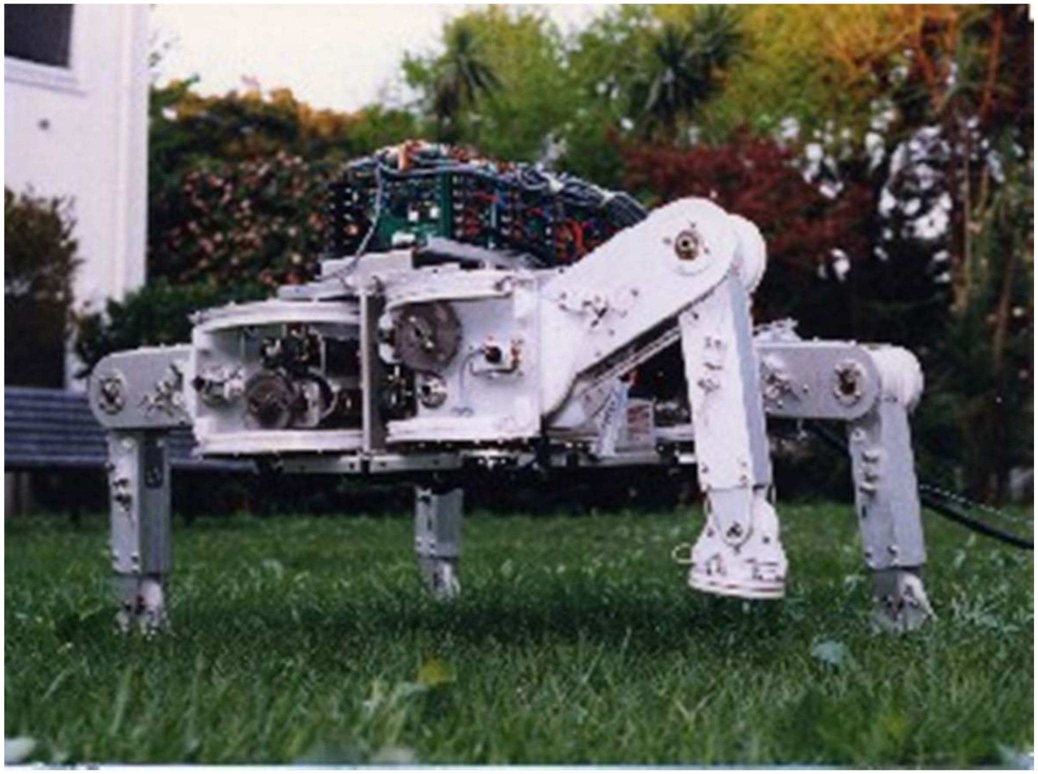


Sony's new computer canine will chase a ball or sit when asked, but cleaning up will be a thing of the past

Walking Robots with Four Legs (Quadruped)

- Titan VIII, a quadruped robot, Tokyo Institute of Technology

  - *Weight: 19 kg*
  - *Height: 0.25 m*
  - *DOF: 4*3*



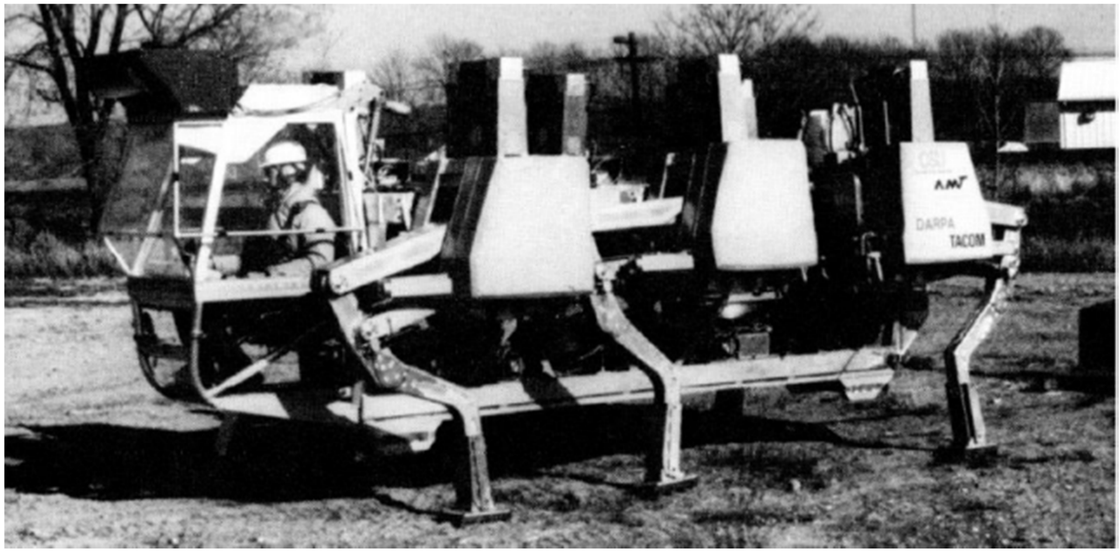
Walking Robots with Four Legs (Quadruped)

- Big Dog, Little Dog: Boston Dynamics

Walking Robots with Six Legs (Hexapod)

- Most popular because static stable walking possible

- The human guided hexapod of Ohio State University
  - *Maximum Speed: 2.3 m/s*
  - *Weight: 3.2 t*
  - *Height: 3 m*
  - *Length: 5.2 m*
  - *No. of legs: 6*
  - *DOF in total: 6*3*



Walking Robots with Six Legs (Hexapod)

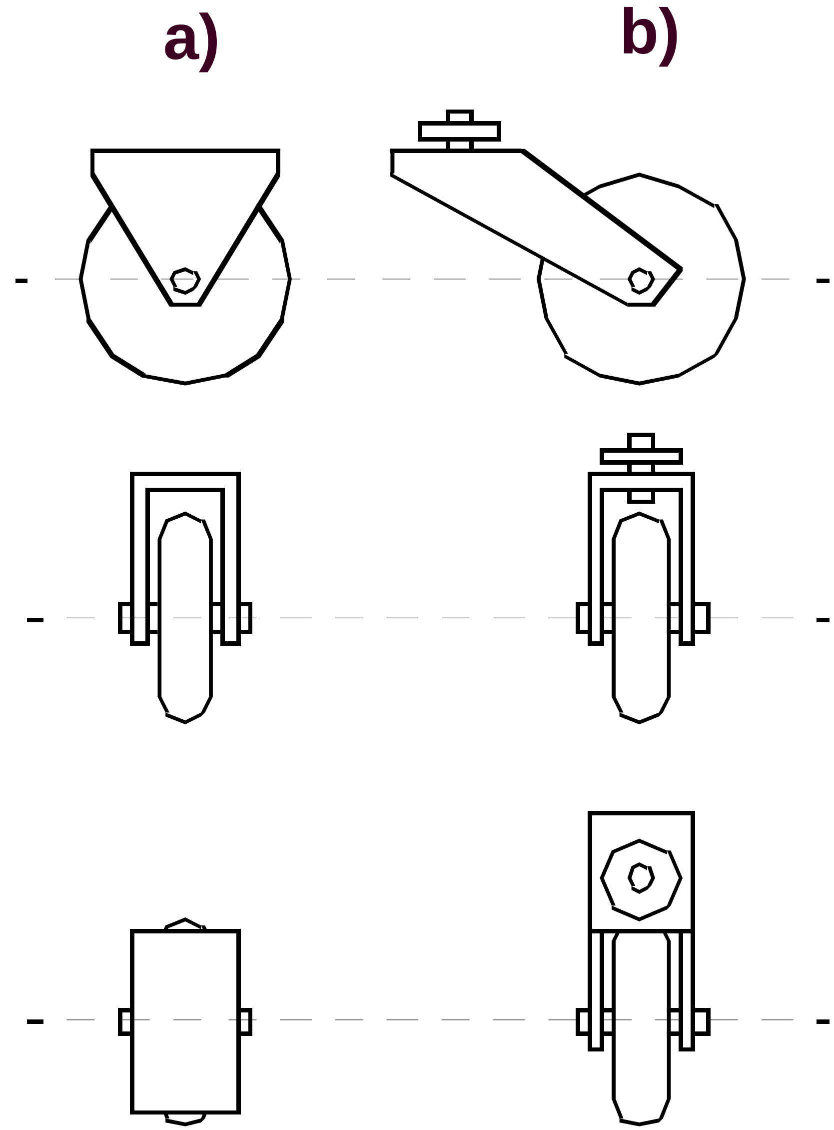
- Lauron II,
  University of Karlsruhe
  - *Maximum Speed: 0.5 m/s*
  - *Weight: 6 kg*
  - *Height: 0.3 m*
  - *Length: 0.7 m*
  - *No. of legs: 6*
  - *DOF in total: 6*3*
  - *Power Consumption: 10 W*

Mobile Robots with Wheels

- Wheels are the most appropriate solution for many applications
- Three wheels are sufficient to guarantee stability
- With more than three wheels a flexible suspension is required
- Selection of wheels depends on the application

The Four Basic Wheels Types

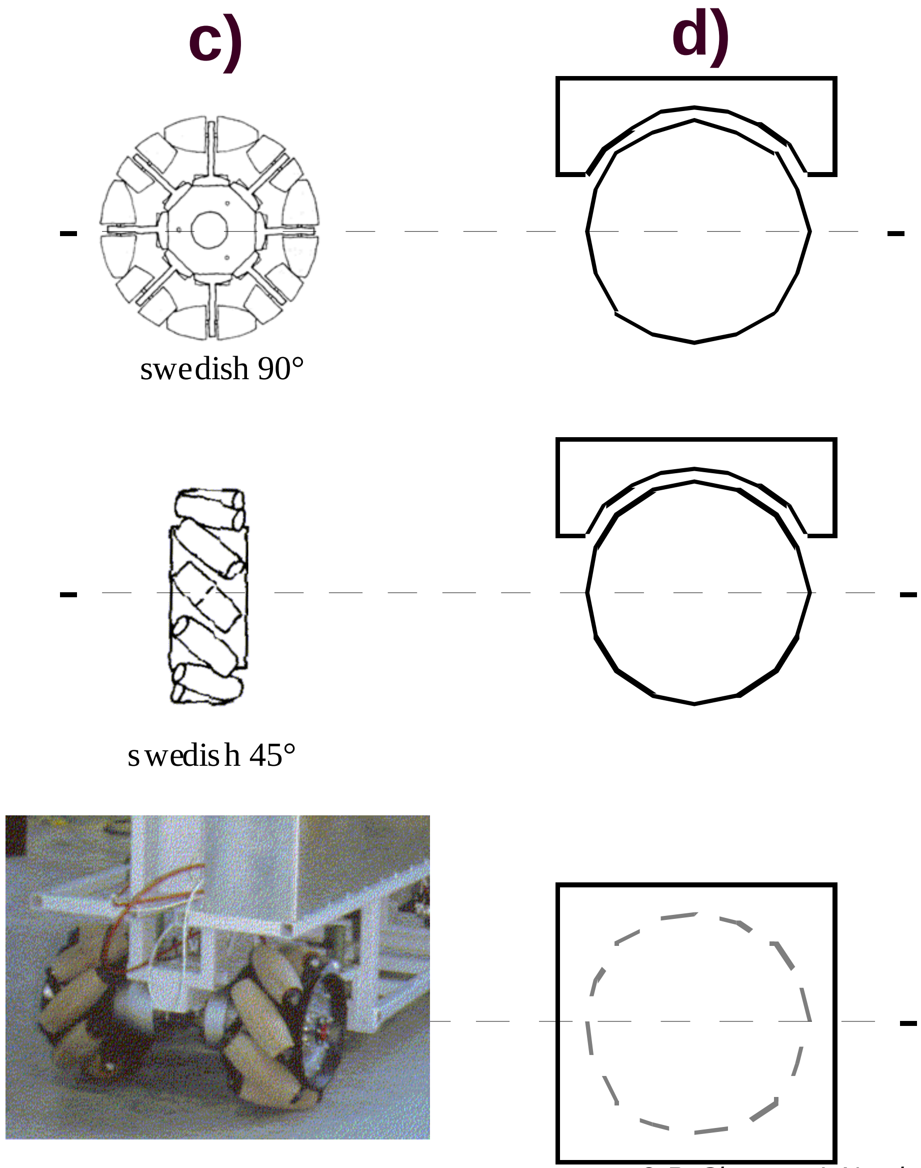
- a) Standard wheel: Two degrees of freedom; rotation around the (motorized) wheel axle and the contact point
- b) Castor wheel: Three degrees of freedom; rotation around the wheel axle, the contact point and the castor axle



The Four Basic Wheels Types

- c) Swedish wheel: Three degrees of freedom; rotation around the (motorized) wheel axle, around the rollers and around the contact point

- d) Ball or spherical wheel: Suspension technically not solved



Trade-Offs

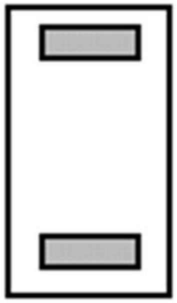
- Stability
  - *A statically-stable robot is one whose center of gravity lies inside the support pattern*
- Maneuverability
  - *How many degrees of freedom a robot can manipulate*
- Controllability
  - *Inversely correlated to maneuverability; how "easy" the robot is to control to achieve the desired motion*

Characteristics of Wheeled Robots and Vehicles

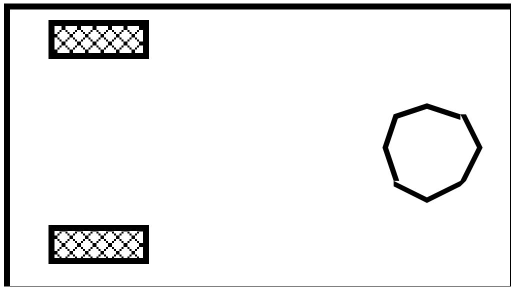
- Stability of a vehicle is guaranteed with 3 wheels
  - *center of gravity is within the triangle formed by the ground contact point of the wheels.*
- Stability is improved by 4 or more wheels
  - *however, these arrangements are hyperstatic and require a flexible suspension system.*
- Bigger wheels allow overcoming higher obstacles
  - *but they require higher torque or reductions in the gear box.*
- Most arrangements are non-holonomic (see chapter 3)
  - *require high control effort*
- Combining actuation and steering on one wheel makes the design complex and adds additional errors for odometry.

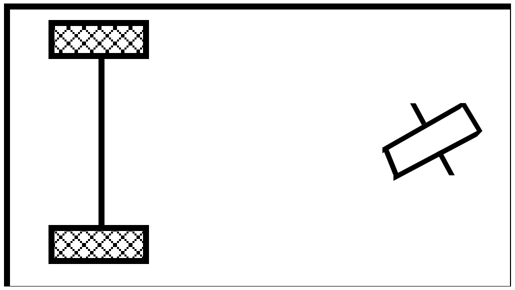
Different Arrangements of Wheels I

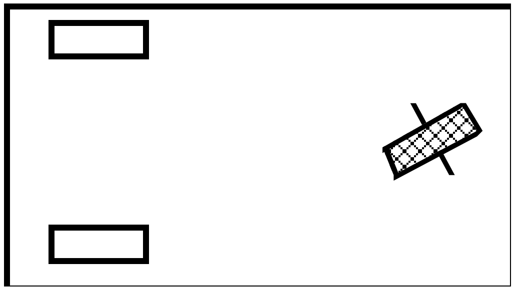
- Two wheels

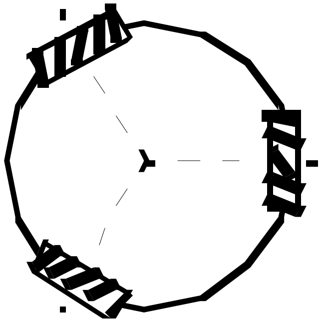


- Three wheels

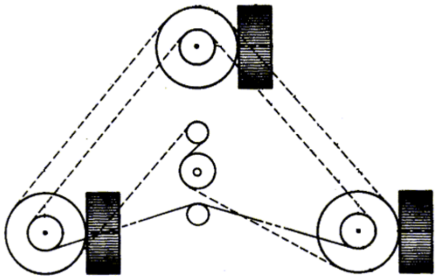








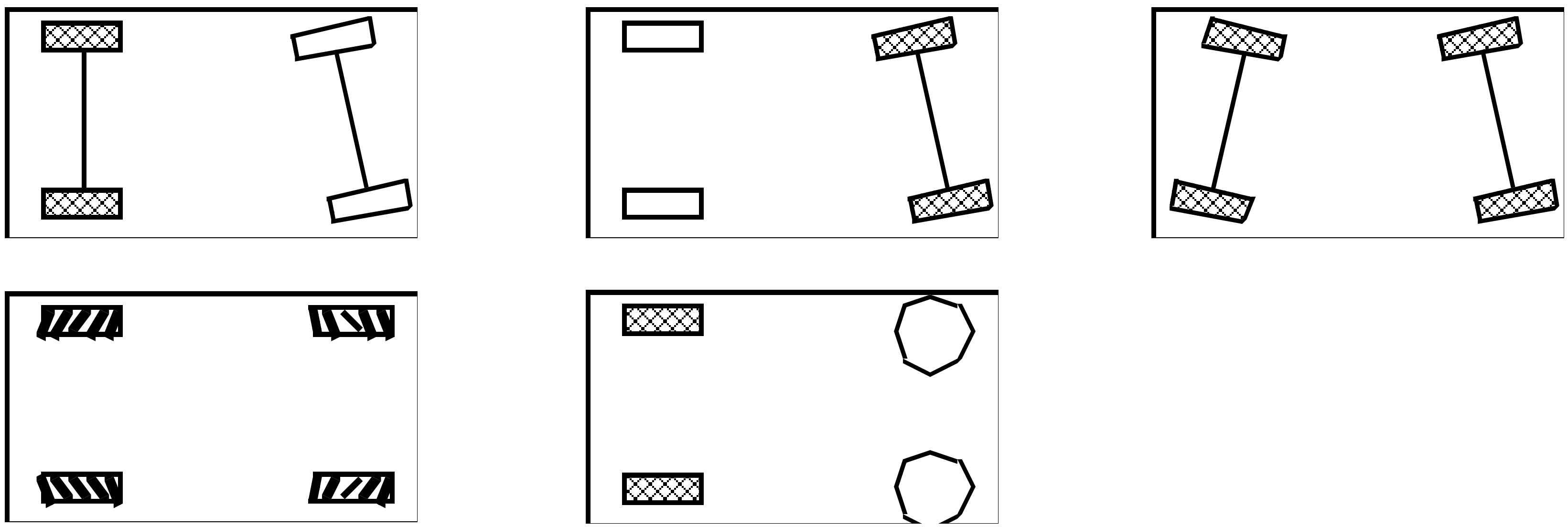
Omnidirectional Drive



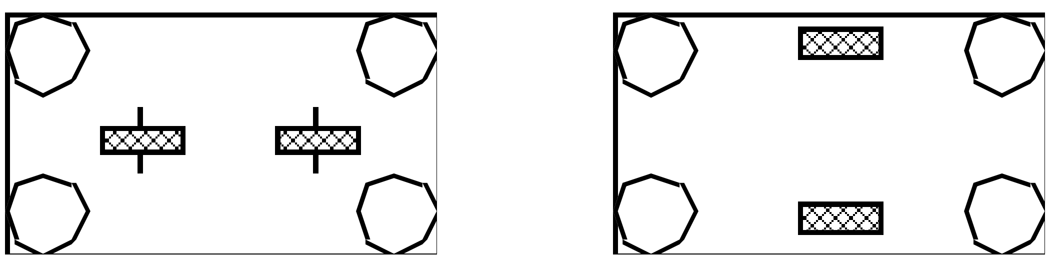
Synchro Drive

Different Arrangements of Wheels II

- Four wheels



- Six wheels



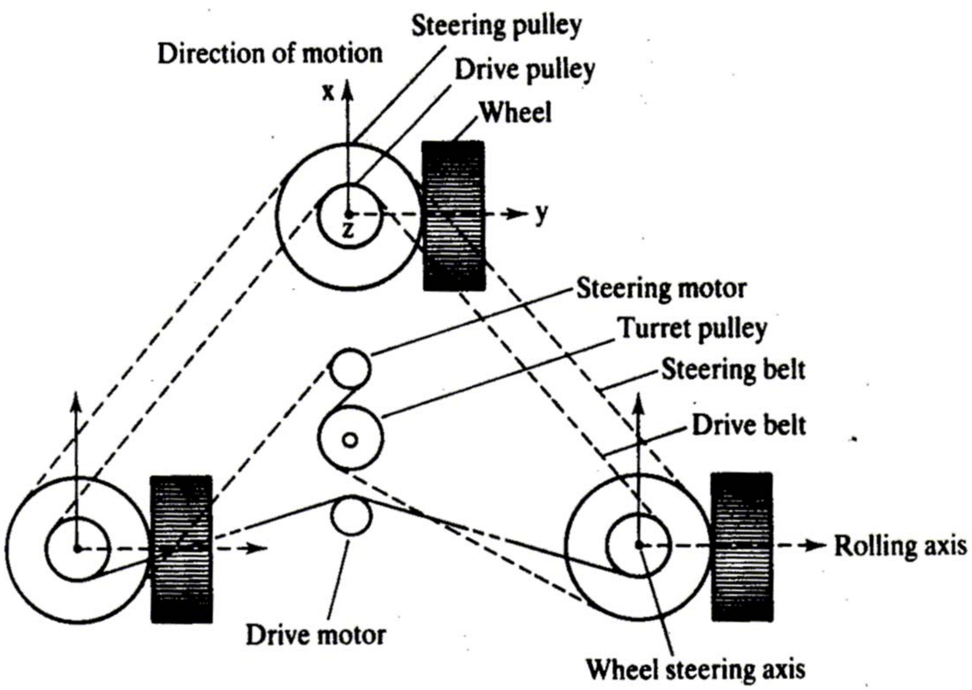
Cye, a Two Wheel Differential Drive Robot

- Cye, a commercially available domestic robot that can vacuum and make deliveries in the home, is built by Probotics, Inc.

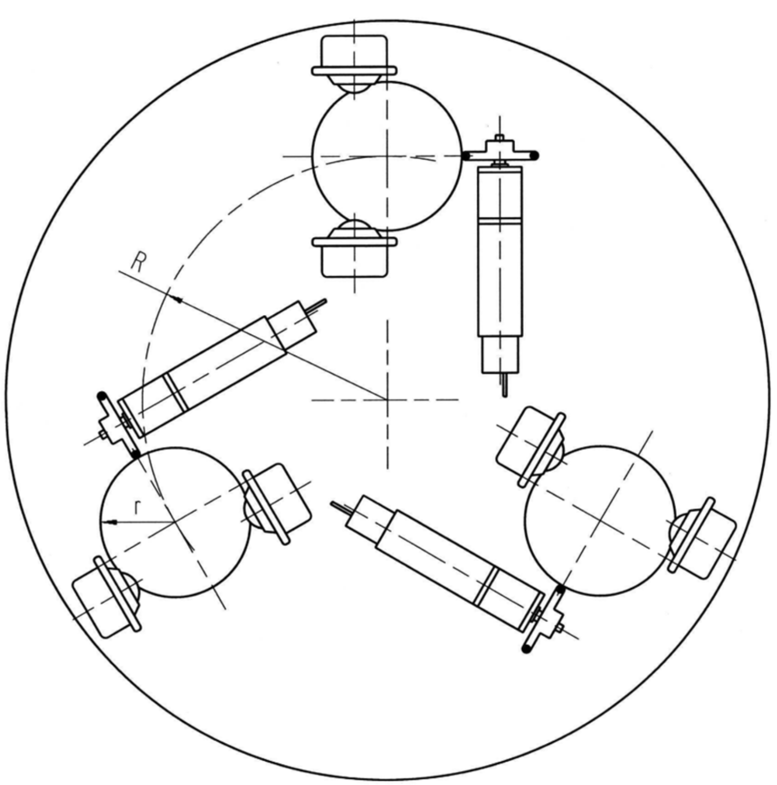
Synchro Drive

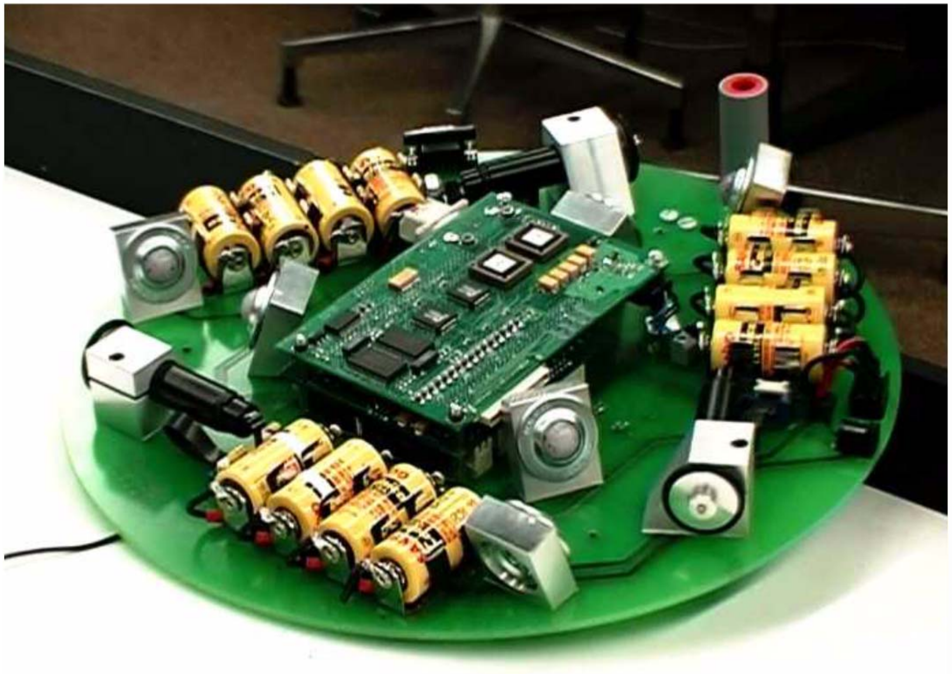
- All wheels are actuated synchronously by one motor
  - *defines the speed of the vehicle*
- All wheels steered synchronously by a second motor
  - *sets the heading of the vehicle*

- The orientation in space of the robot frame will always remain the same
  - *It is therefore not possible to control the orientation of the robot frame.*



Tribolo, Omnidirectional Drive with 3 Spheric Wheels

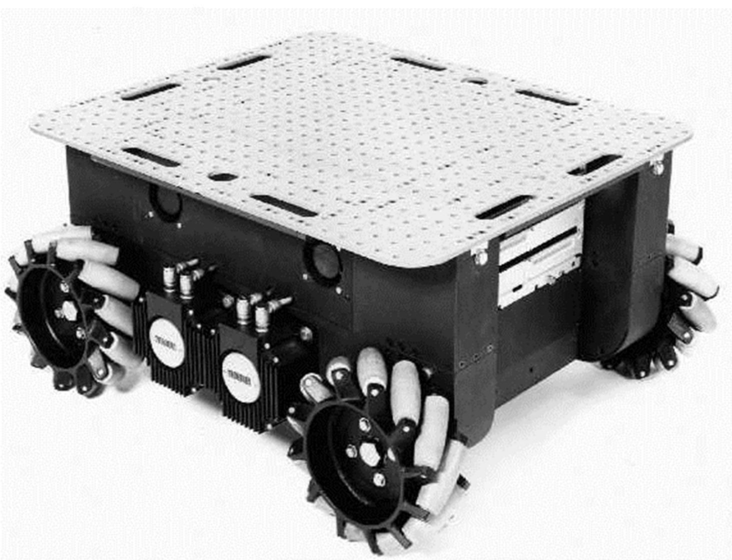


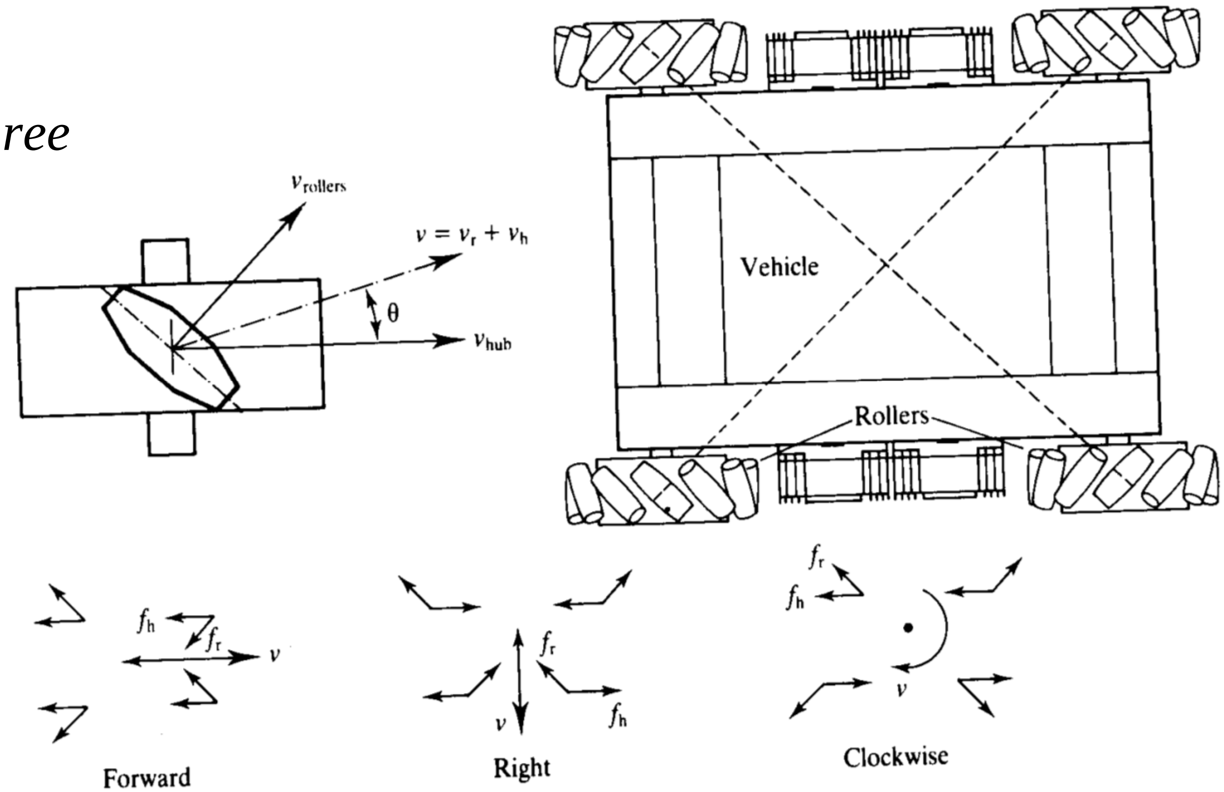


EPFL

Uranus, CMU: Omnidirectional Drive with 4 Wheels

- Movement in the plane has 3 DOF
  - *thus only three wheels can be independently controlled*
  - *It might be better to arrange three swedish wheels in a triangle*





Caterpillar

- The NANOKHOD II, developed by von Hoerner & Sulger GmbH and Max Planck Institute, Mainz for European Space Agency (ESA), designed for Mars

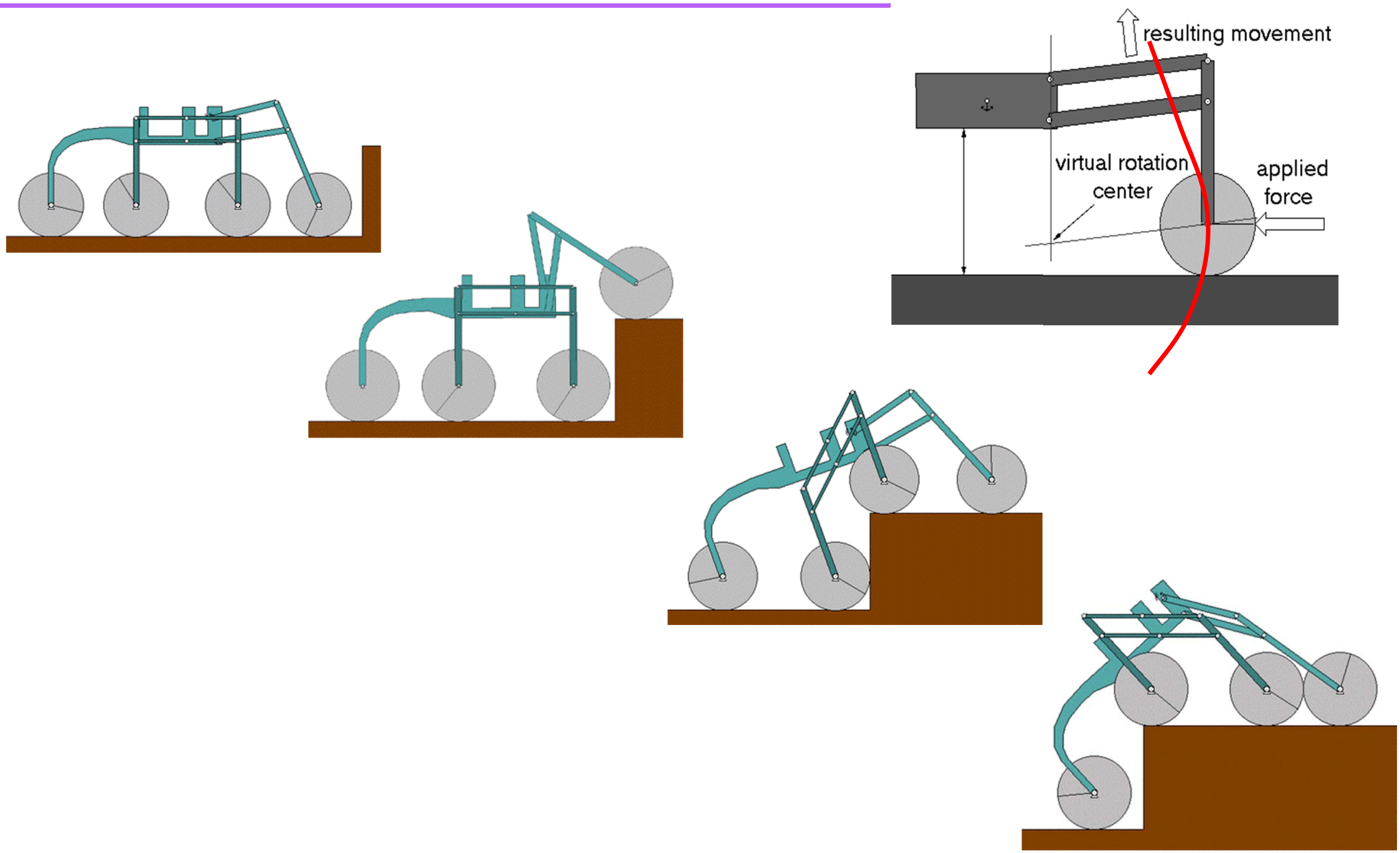
Stepping / Walking with Wheels

- SpaceCat, and micro-rover for Mars, developed by Mecanex Sa and EPFL for the European Space Agency (ESA)

SHRIMP, a Mobile Robot with Excellent Climbing Abilities

- Objective
  - *Passive locomotion concept for rough terrain*
- Results: The Shrimp
  - *6 wheels*
    - *one fixed wheel in the rear*
    - *two boogies on each side*
    - *one front wheel with spring suspension*
  - *robot sizing around 60 cm in length and 20 cm in height*
  - *highly stable in rough terrain*
  - *overcomes obstacles up to 2 times its wheel diameter*

The SHRIMP Adapts Optimally to Rough Terrain



The Personal Rover