Robot Locomotion

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

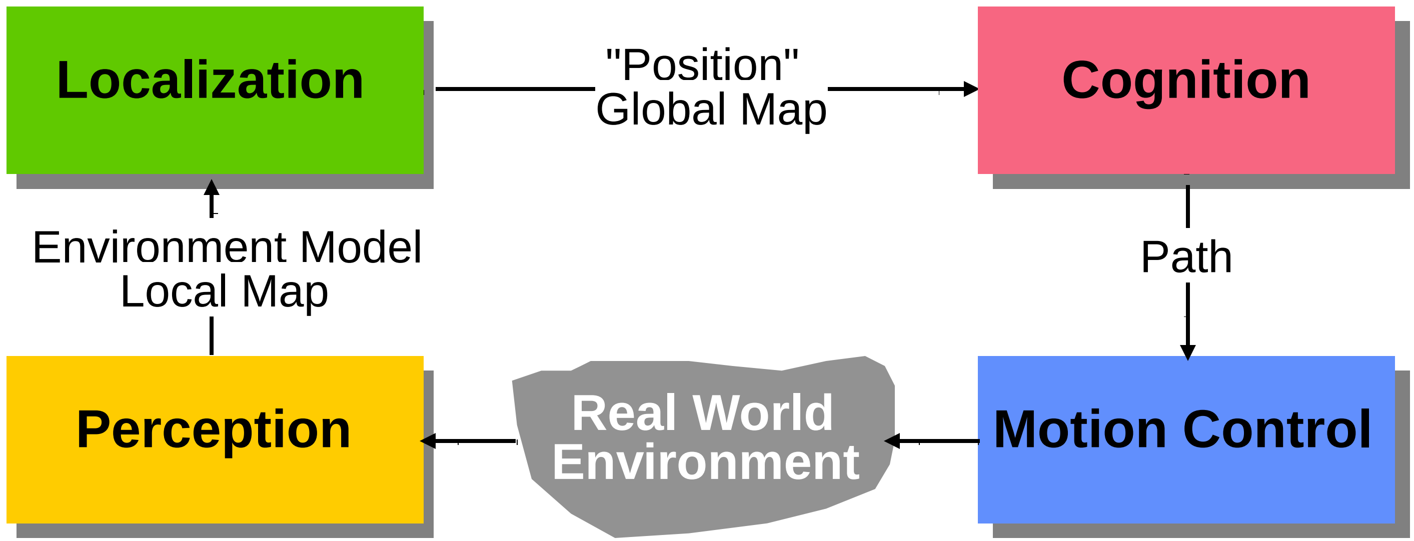
August 28, 2014

Reading Assignments

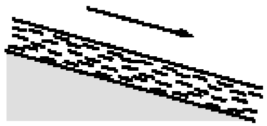
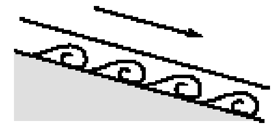
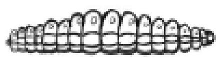
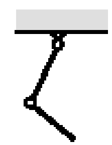
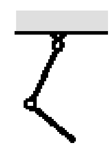
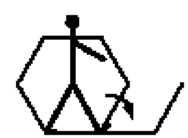
- Today: Chapter 2, sections 2.1-2.3
- Next time:
  - *Chapter 2, section 2.4*
  - *Begin Chapter 3*

Locomotion Concepts

- Concepts
- Legged Locomotion
- Wheeled Locomotion



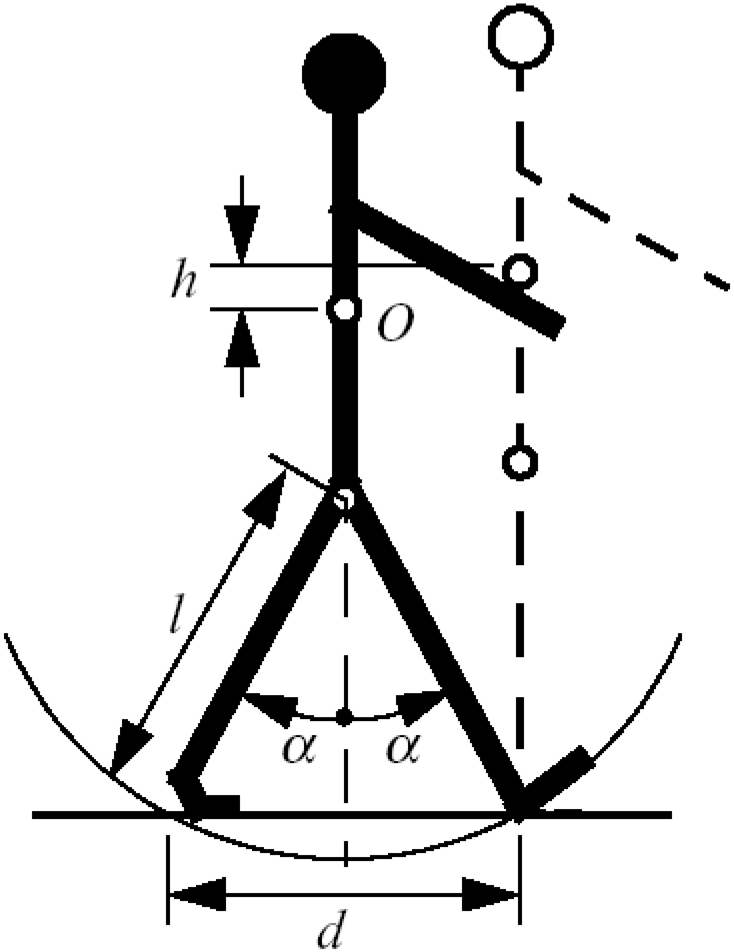
Locomotion Concepts: Principles Found in Nature

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

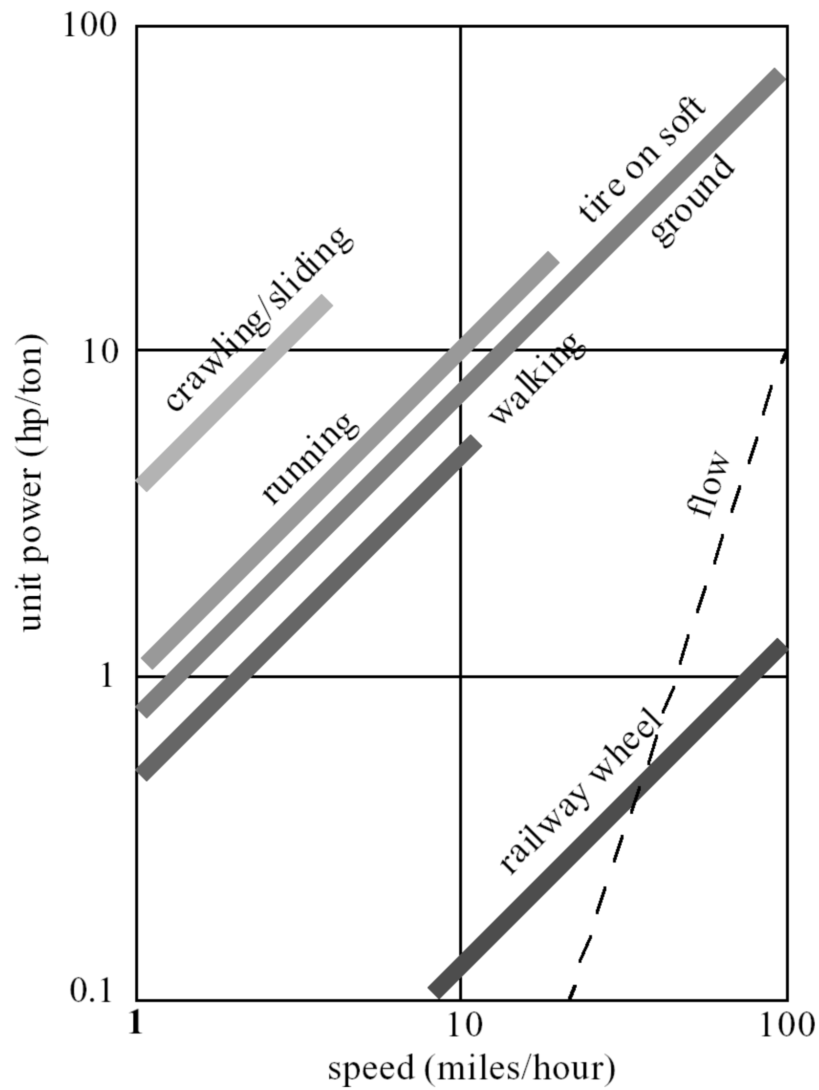
Walking of a Biped



- 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

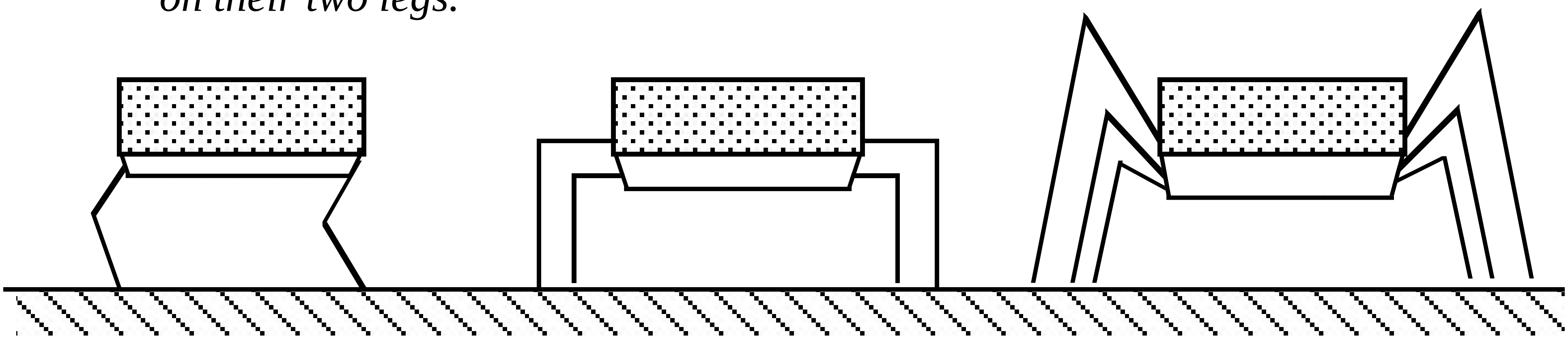
- Locomotion
  - *physical interaction between the vehicle and its environment.*
- Locomotion is concerned with *interaction forces*, and the *mechanisms* and *actuators* that generate them.
- The most important issues in locomotion are:

- 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

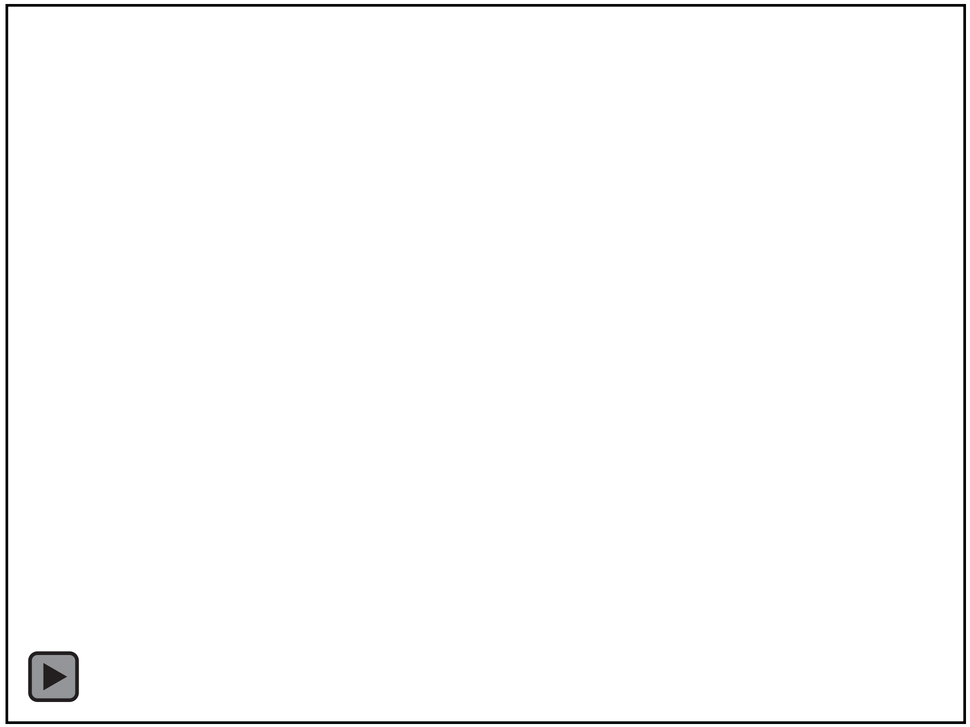
Number of Joints of Each Leg (DOF: degrees of freedom)

- 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.*

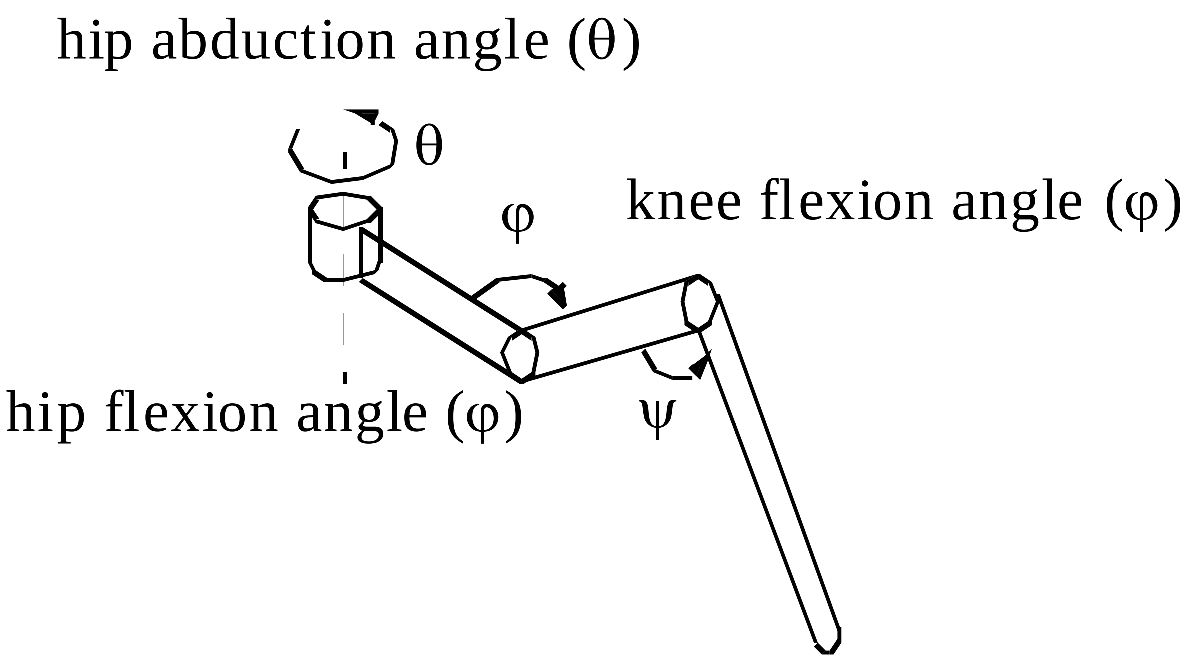
Passive Dynamic Walkers

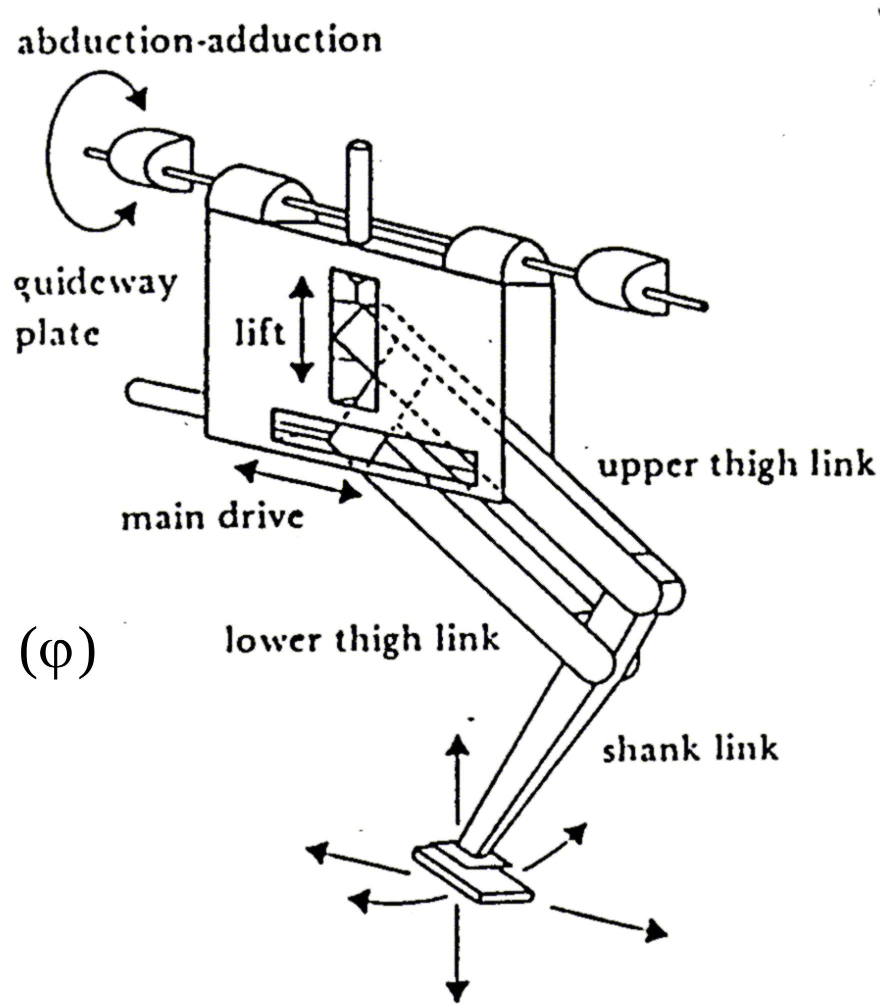
- Efficient walking via natural dynamics of mechanical structure
- Use pendula and springs to generate periodic motions
- Result: passive dynamic walking

Here: Cornell's Ranger robot (2011):



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:*

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

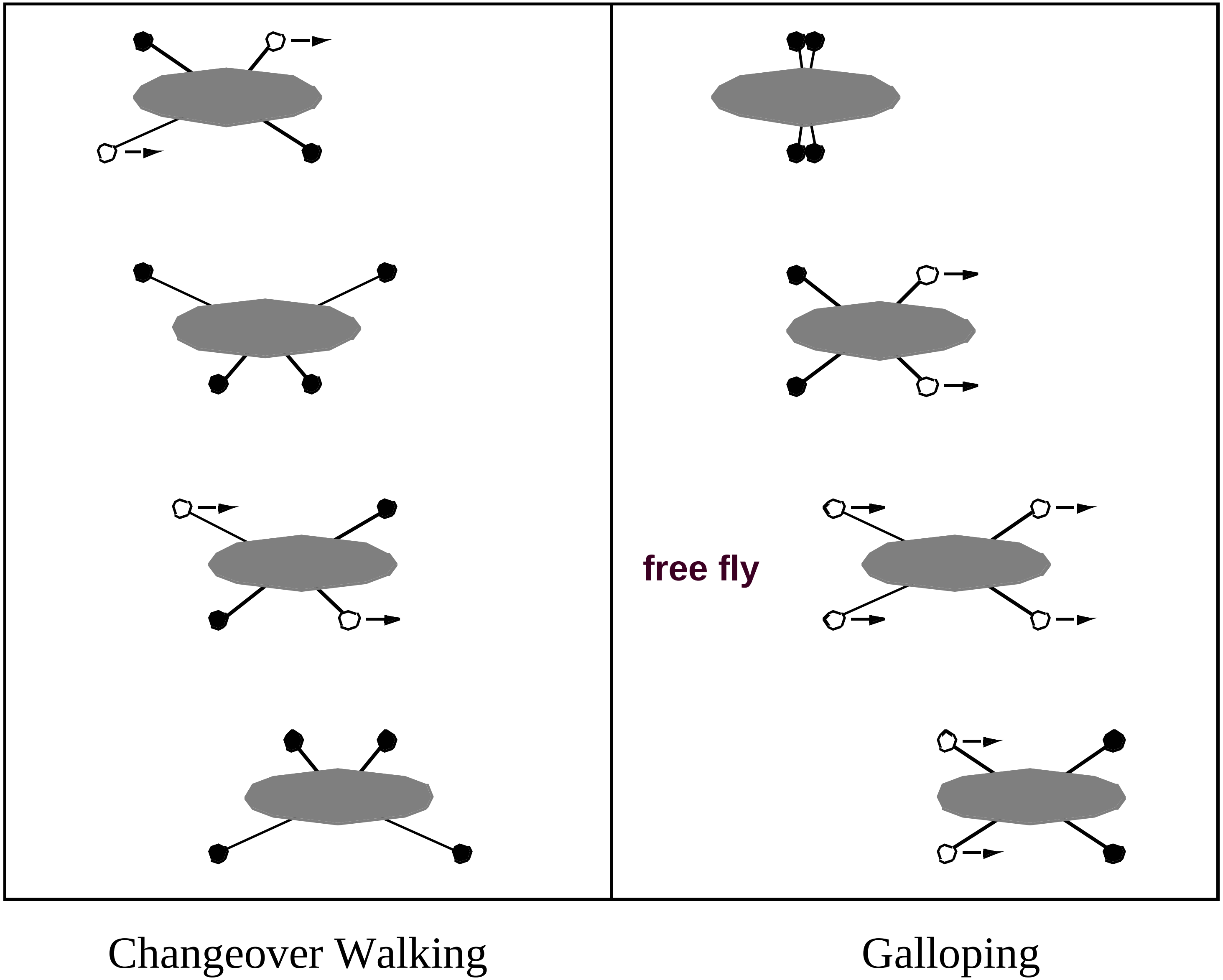
- For a biped walker (k=2) the number of possible events N is:

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

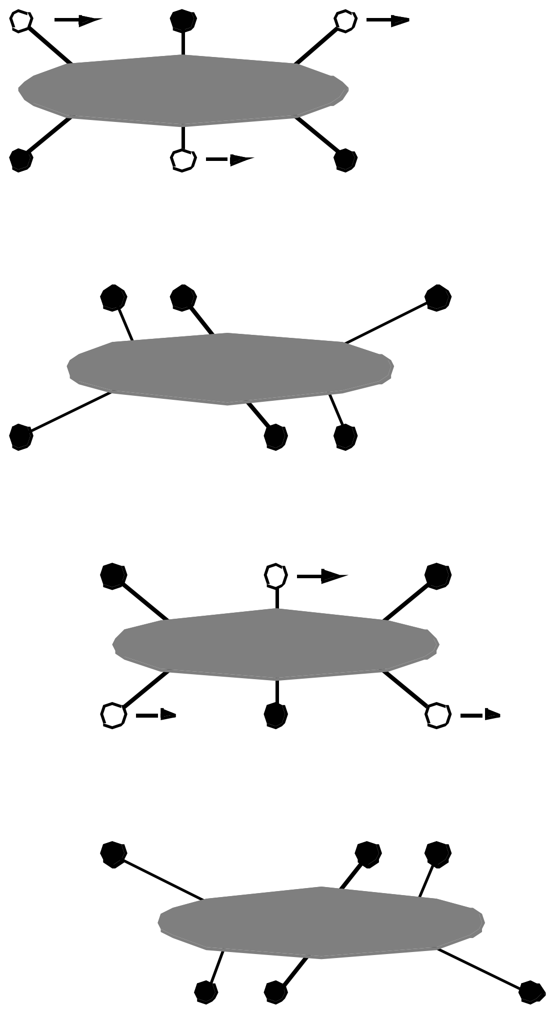
  - *The 6 different events are:*
    lift right leg / lift left leg / release right leg / release left leg / lift both legs together / release both legs together
- For a robot with 6 legs (hexapod) N is already

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

Most Obvious Gaits with 4 legs

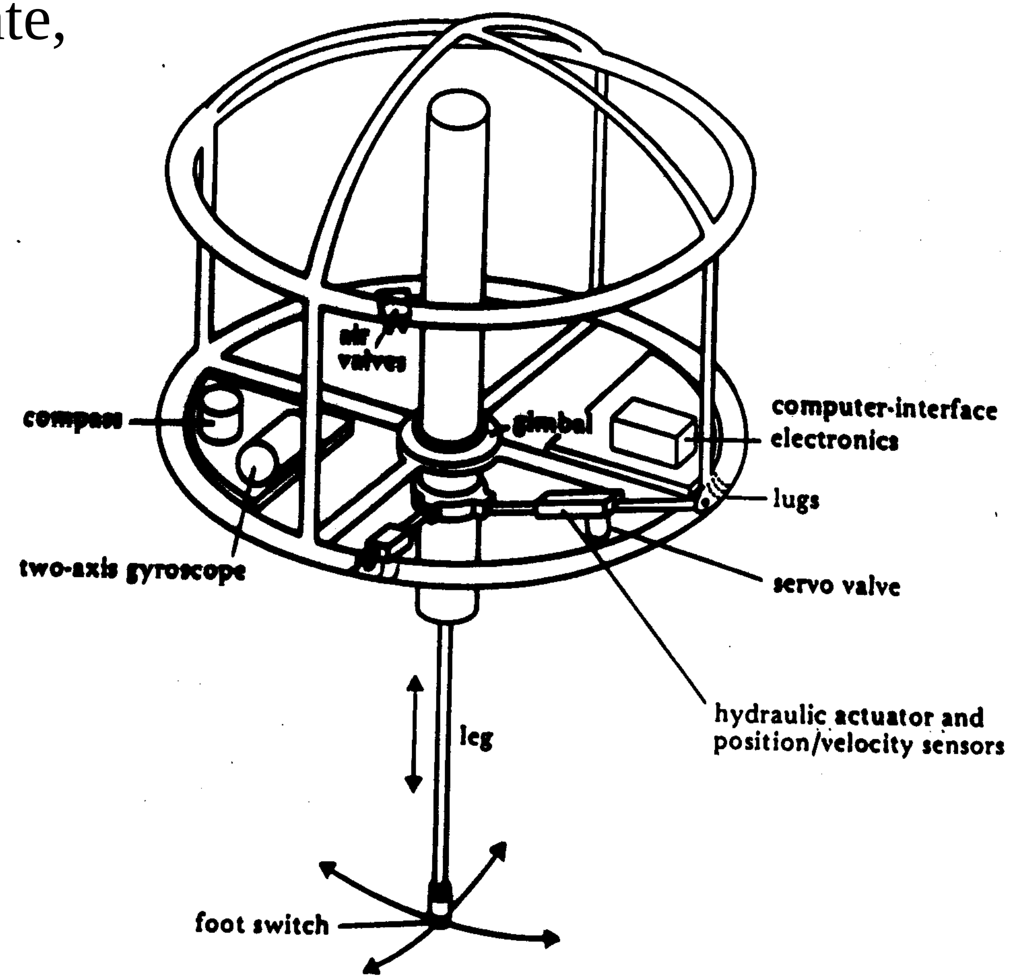


Most Obvious Gait with 6 legs (static)



Examples of Walking Machines

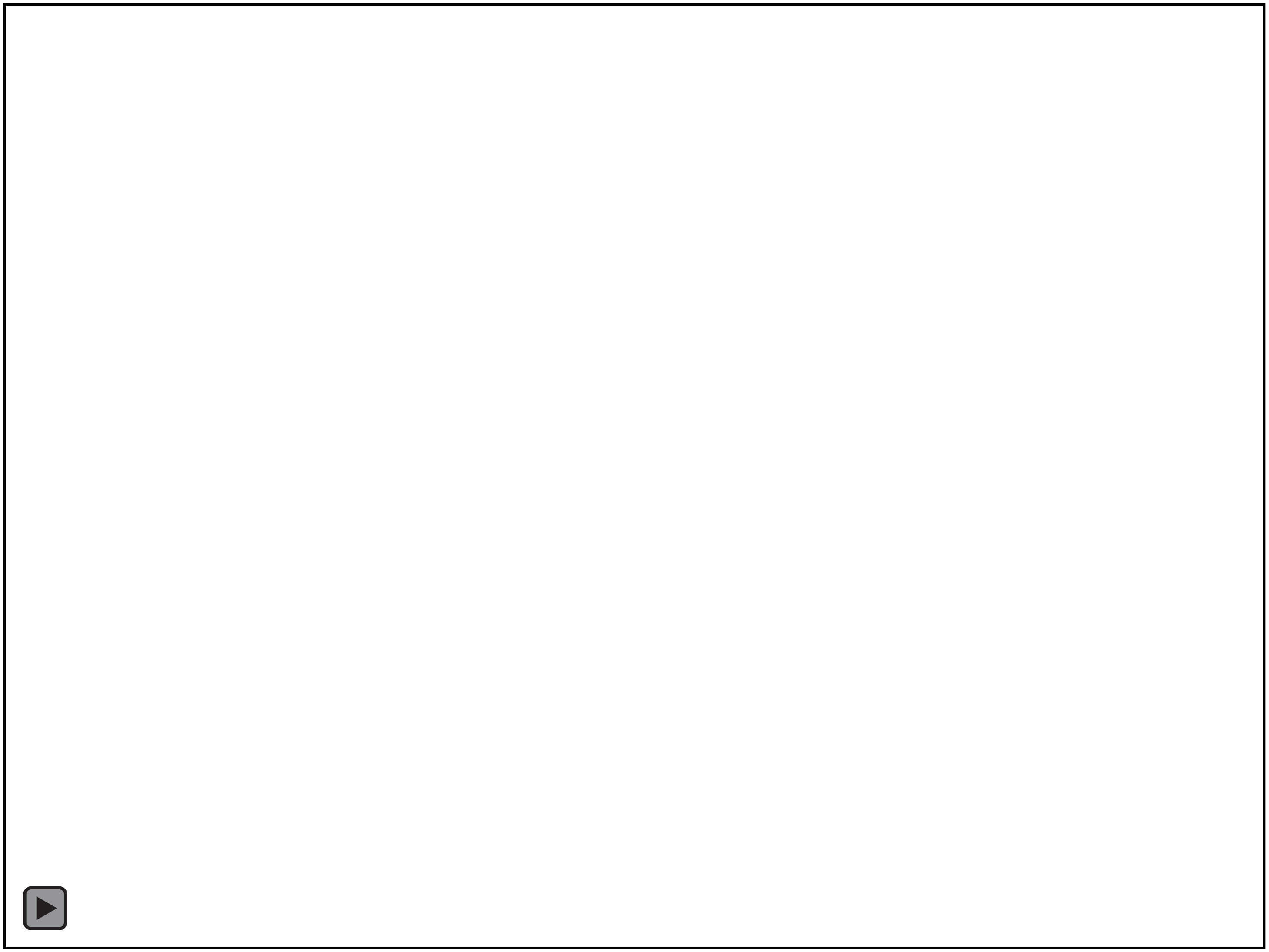
- No industrial applications up to date, but a popular research field



Courtesy of Marc Raibert

The Hopping Machine

Raibert's Hopping Machines



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/

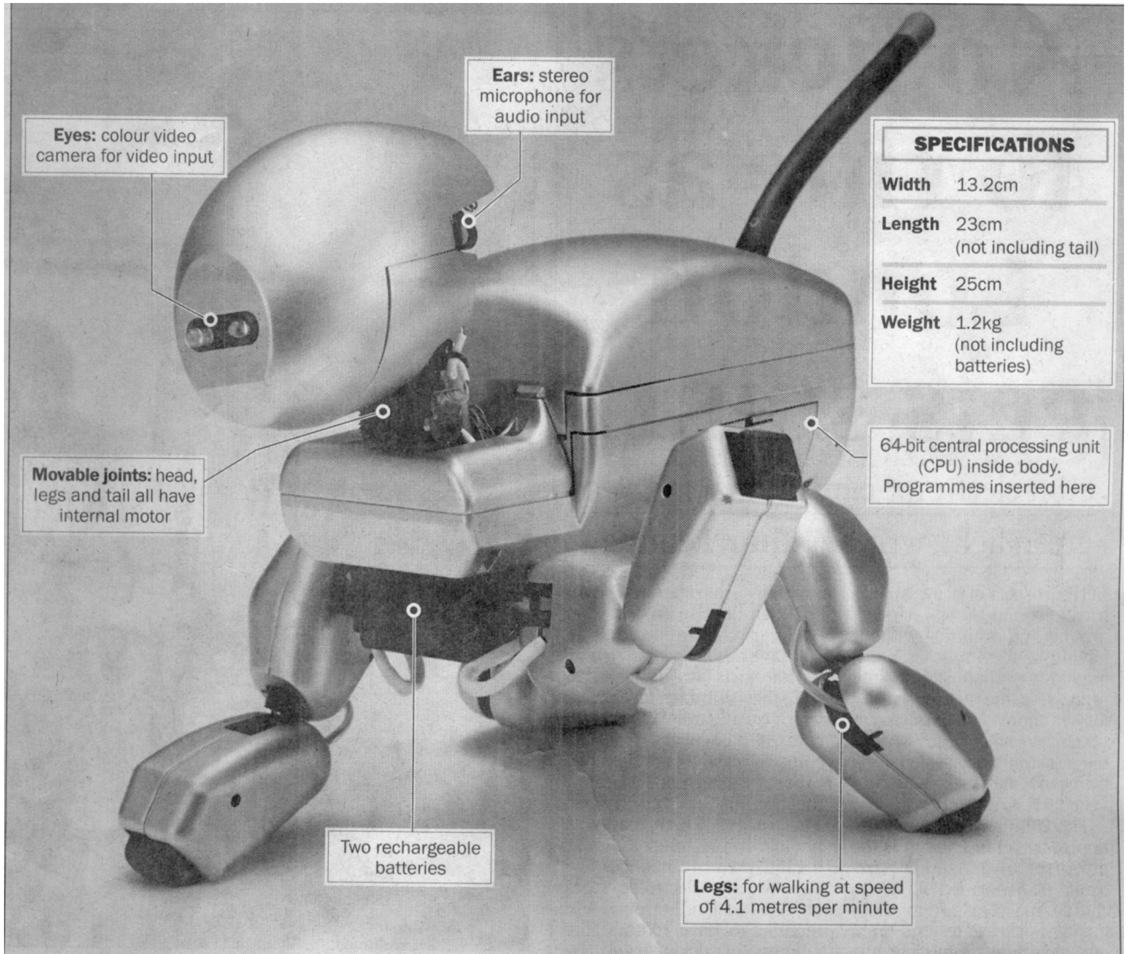
Spring Flamingo, MIT Leg Lab

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

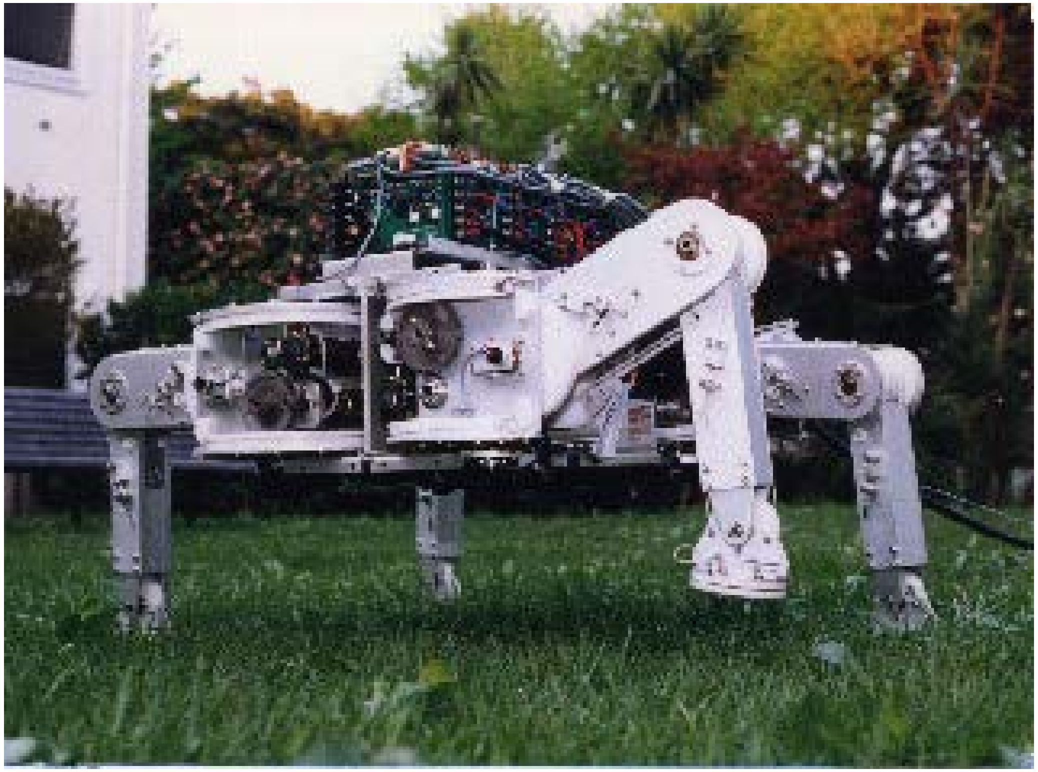


Sony's new computer canine will chase a ball or sit when asked, but cleaning up will be a thing of the past

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*



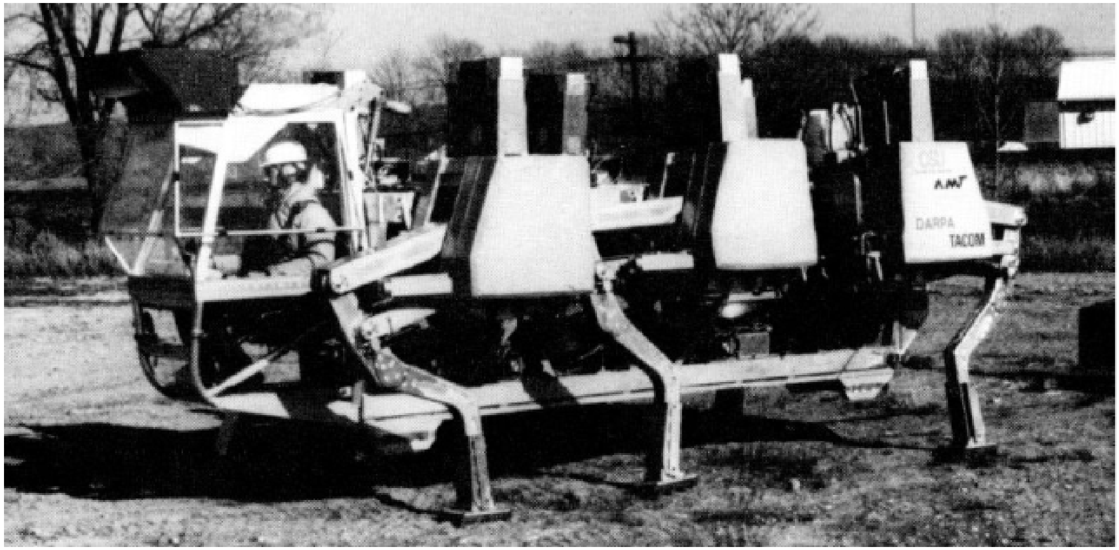
Walking Robots with Four Legs (Quadruped)

- 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)

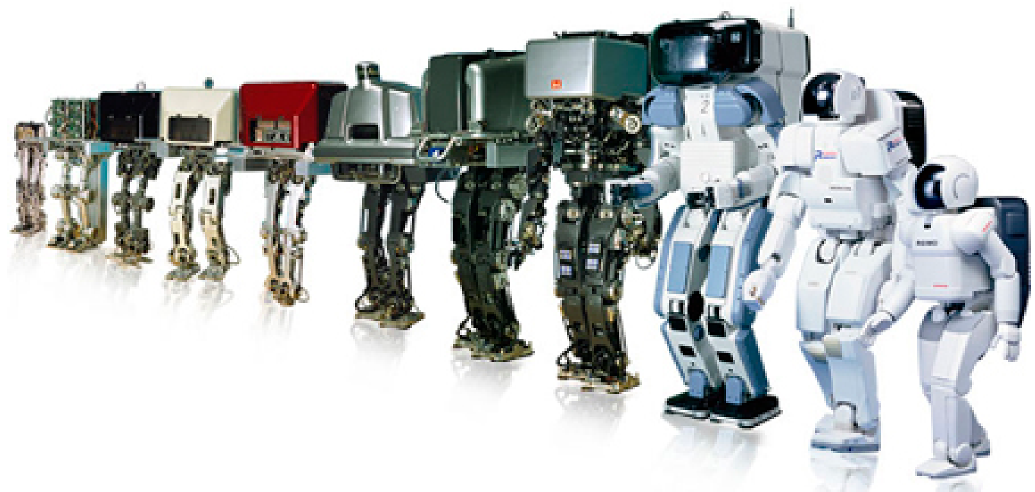
- Lauron II,
  University of Karlsruhe
  - *Maximum Speed: 0.5 m/s*
  - *Weight: 6 kg*
  - *Height: 0.3 m*
  - *Length: 0.7 m*
  - *No. of legs: 6*
  - *DOF in total: 6*3*
  - *Power Consumption: 10 W*

Raibert's Boston Dynamics Robots

Raibert’s Boston Dynamics Robots – Cheetah

Humanoid Robots

- P1-P2-P3-etc. (Asimo) from Honda, Japan
- Latest version:
  - *Walking Speed: 2.7+ km/h*
  - *Running Speed: 9 km/h*
  - *Autonomy: 1+ hour*
  - *Weight: 55 kg*
  - *Height: 1.3 m*
  - *DOF: 57*
    - *Head: 3*
    - *Arm: 2 * 7*
    - *Hand: 2 * 13*
    - *Torso: 2*
    - *Leg DOF: 2*6*



Honda’s Asimo, 2014

NAO Robot

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

Legged Locomotion – Summary of Important Concepts

- Characterized by point contacts with ground
- Key advantages: adaptability and maneuverability
- Key disadvantages: power, mechanical complexity
- Stability:
  - *Generally, more legs provide more stability, more maneuverability*
  - *Static stability versus dynamic stability*
- Legged locomotion loses energy due to friction, periodic acceleration/deceleration, actuators working against each other
- Passive dynamic walking minimizes energy loss via mechanical structure
- 1-legged walking: key challenge is balance
- 2-legged (bipedal) , and 4-legged walking: lots of successful robot examples
- 6-legged walking: can be statically stable

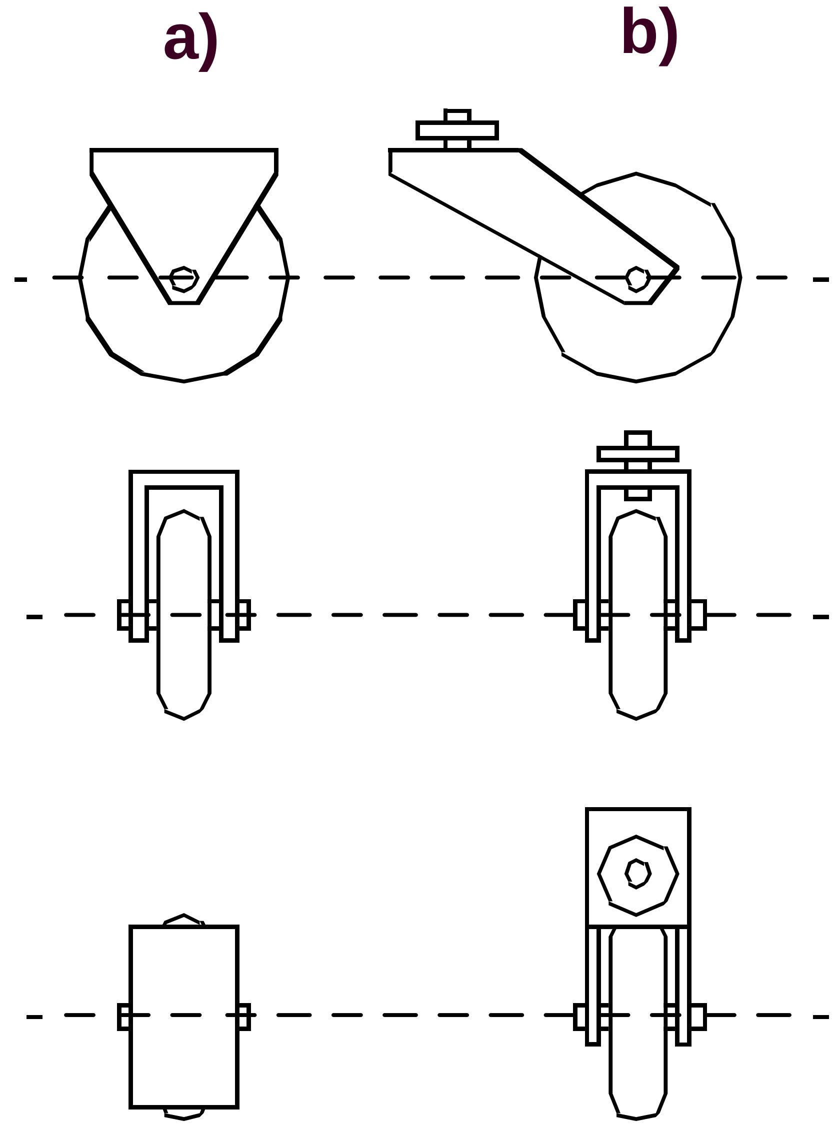
Mobile Robots with Wheels

- 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

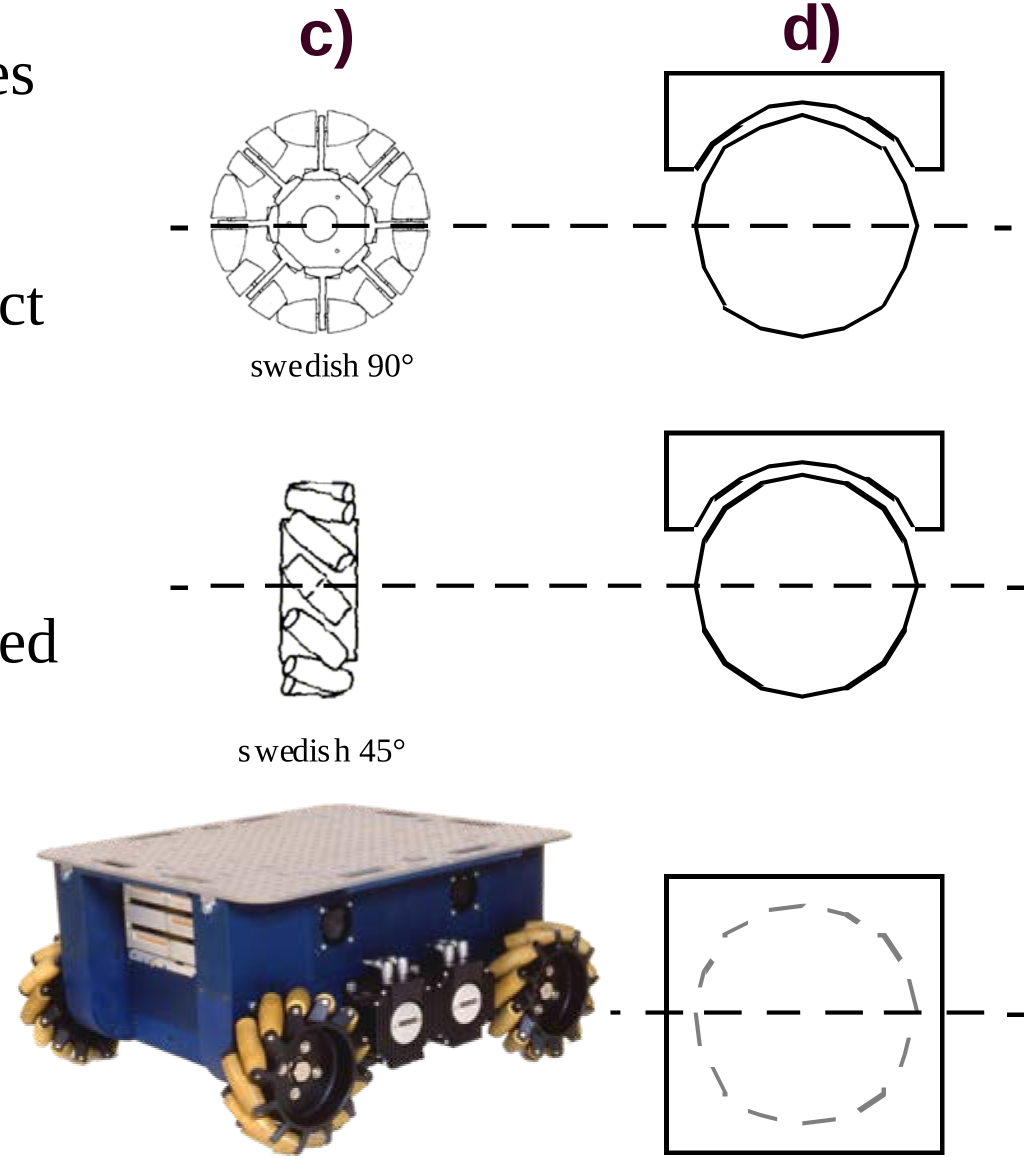
- b) Castor wheel: Three degrees of freedom; rotation around the wheel axle, the contact point and the castor axle



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*

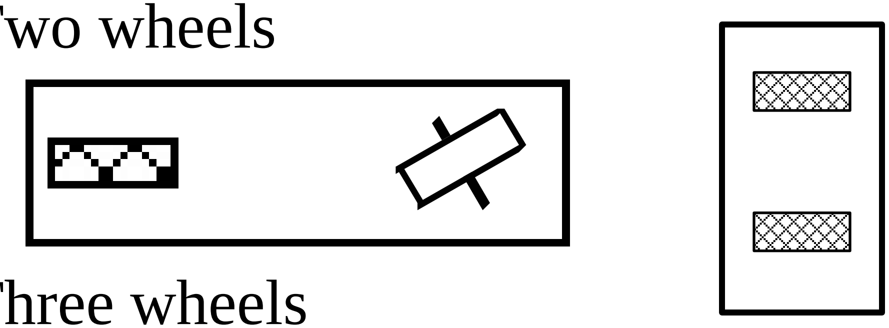
- Controllability
  - *Inversely correlated to maneuverability; how "easy" the robot is to control to achieve the desired motion*

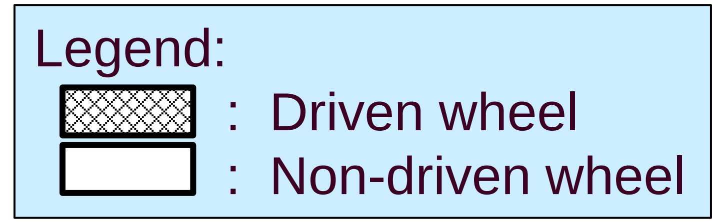
Characteristics of Wheeled Robots and Vehicles

- 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.

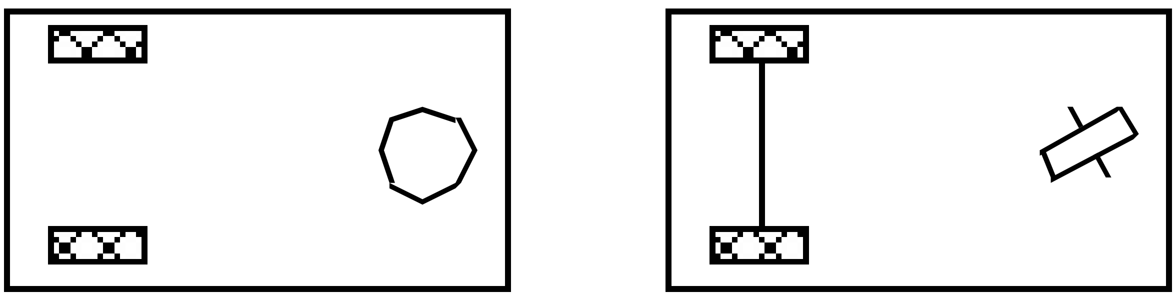
Different Arrangements of Wheels I

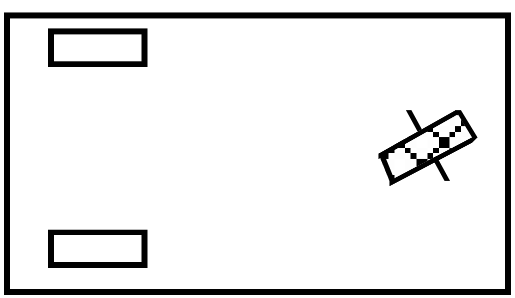
- Two wheels

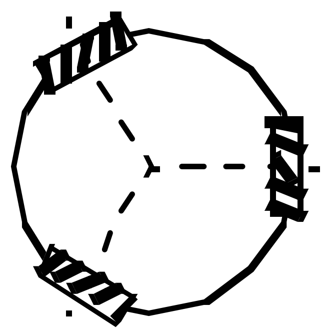




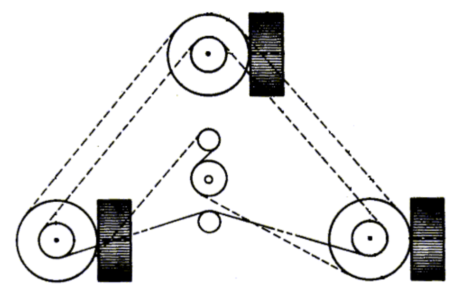
- Three wheels







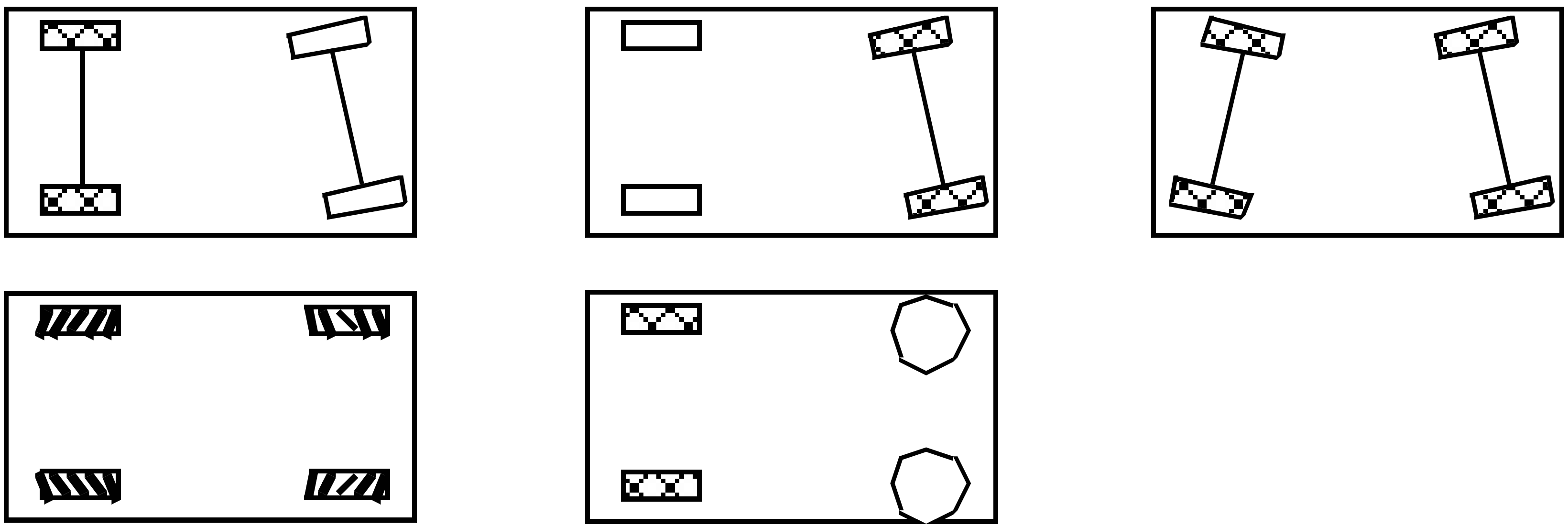
Omnidirectional Drive



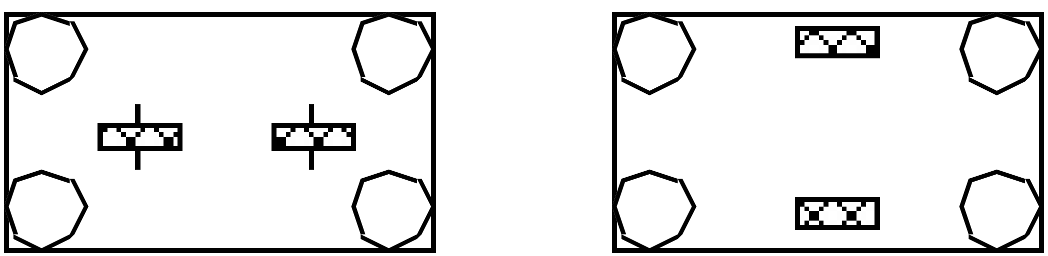
Synchro Drive

Different Arrangements of Wheels II

- Four wheels



- Six wheels

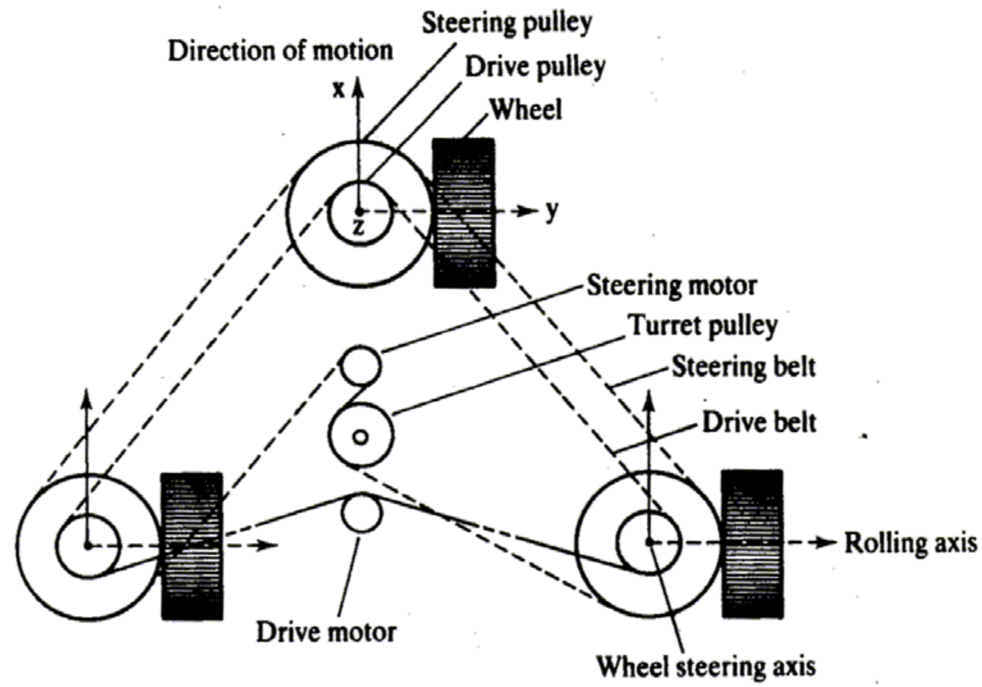


Two wheeled robot can achieve dynamic stability

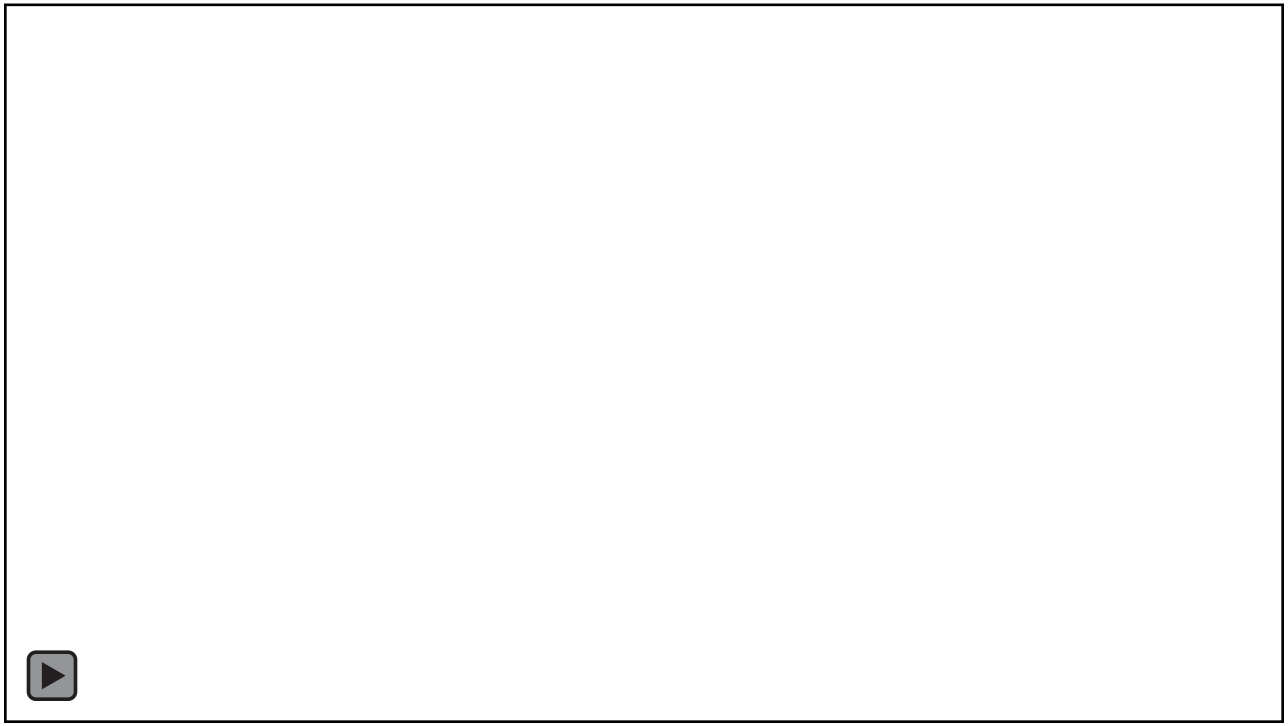
Synchro Drive

- 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.*

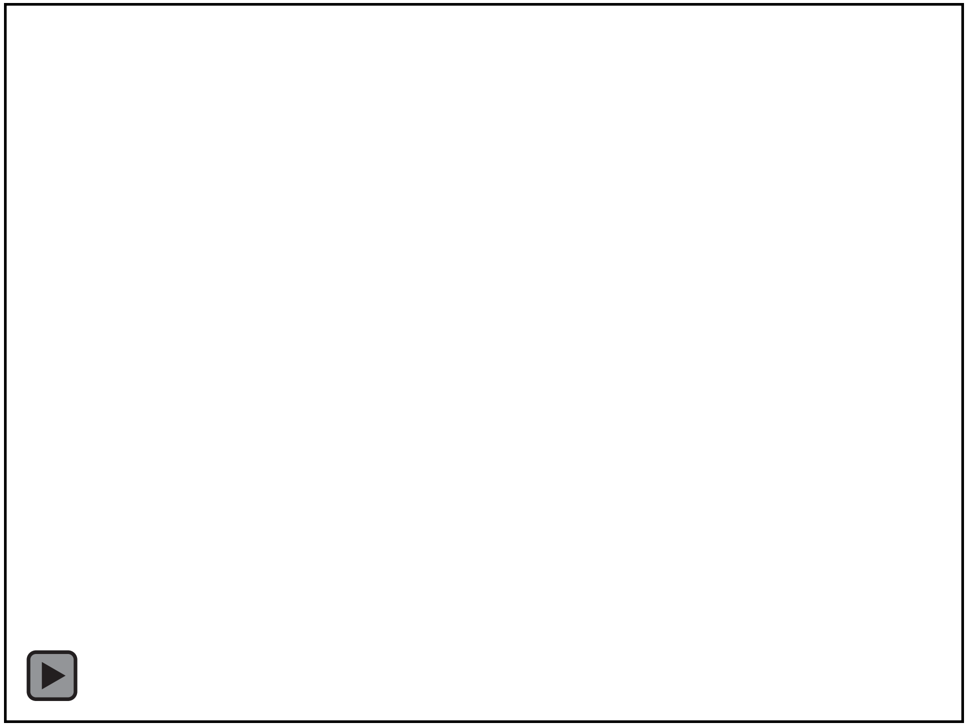


Omnidirectional Robot



Robot balancing on a ball

- From Japan's RIKEN Institute (2010):

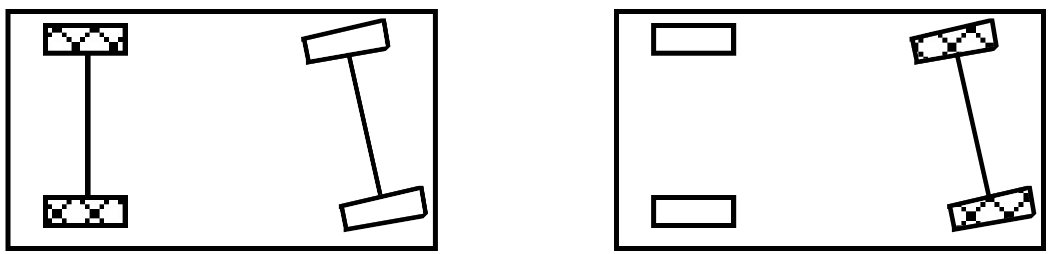


Stability

- 2-wheeled robots:
  - *Can achieve static stability with 2 wheels, if center of mass is below wheel axle*
  - *Generally, static stability with 2 wheels requires large wheel diameters*
  - *Dynamic stability is possible with 2 wheels, via control*
- 3-wheeled robots:
  - *Can achieve static stability easily – center of mass must be within triangle formed by ground contact points of wheels*
- More wheels:
  - *Usually requires flexible suspension on uneven terrain*

Maneuverability

- Omnidirectional robots are highly maneuverable
- Two-wheel differential-drive robot is also highly maneuverable
  - *Use additional castor for stability*
- Standard automobiles use Ackerman steering:



  - *Advantage: high lateral stability in high-speed turns*
  - *Disadvantage: Low maneuverability:*
    - *Large turning diameter*
    - *Sideways moving is difficult (think parallel parking!)*

Controllability

- Generally, an inverse correlation between controllability and maneuverability
- E.g., omnidirectional designs usually require significant processing to convert desired velocities to individual motor commands
- High maneuverability → usually high DOF → accumulation of uncertainty

Is there an "ideal" configuration?

- Unfortunately, no.
- Can't simultaneously maximize stability, maneuverability, controllability
- Each application places unique constraints on the robot design problem
- Designer's task:
  - *Choose most appropriate drive configuration for the application*

Some interesting case studies…

Curiosity Rocker-Bogie Mechanism

Hybrid Walking Wheeled Robot (“Roller-Walker”, 2007)

Whegs – Wheel-leg robot (Case Western Univ., 2009)

Wheeled Locomotion – Summary of Important Concepts

- Stability usually "automatic", since wheels designed to have constant ground contact
- Bigger challenges: traction, maneuverability, control
- 4 major wheel classes: standard, castor, Swedish, ball/spherical
- Wheel choice and geometry affect:
  - *Maneuverability*
  - *Controllability*
  - *Stability*

Next time…

- Locomotion – Aerial robots

- Chapter 3 – Mobile Robot Kinematics