UNIVERSITÉ DE TECHNOLOGIE DE BELFORT-MONTBÉLIARD

Locomotion

RO51 - Introduction to Mobile Robotics

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https://yzrobot.github.io/

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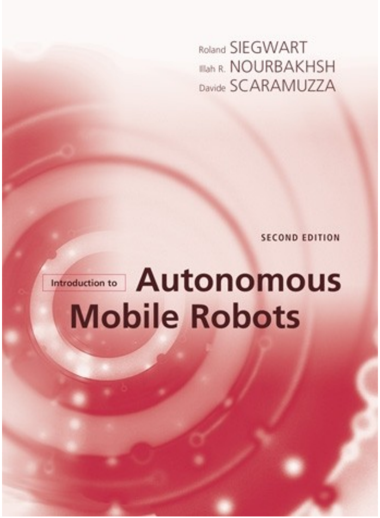
Extended reading

- This lecture is organized according to the textbook *Introduction to Autonomous Mobile Robots, Second Edition*.

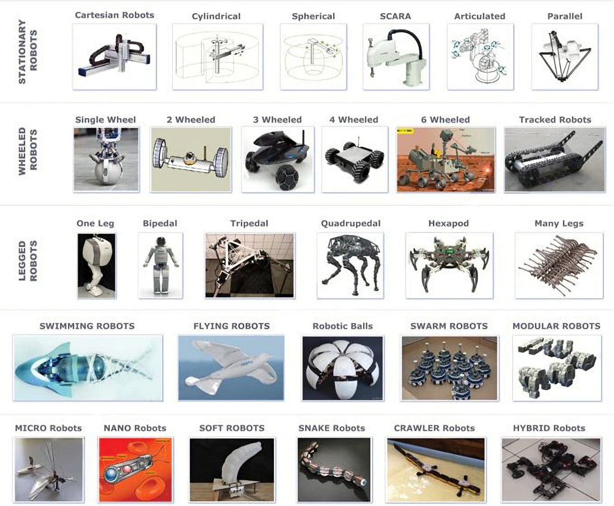


What is locomotion

- Locomotion is the act of moving from place to place.
  - *Fundamentally speaking, no matter which kind of locomotion is adopted, a mobile robot needs to transport itself from one place to another.*
- Locomotion relies on the physical interaction between the robot and its environment.
- Locomotion is concerned with the interaction forces, along with the mechanisms and actuators that generate them.

Types of locomotion

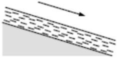
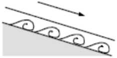
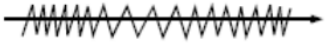
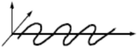
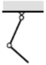
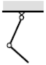
- Robots can roll, walk, fly, swim, and so forth.



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

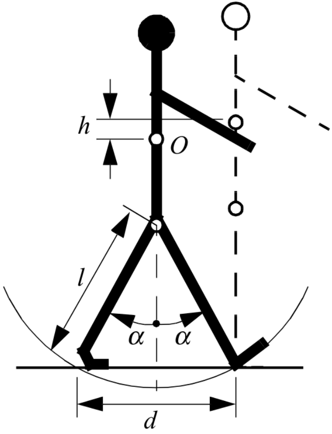
Principles found in nature

- Nature evolved a multitude of locomotion concepts
  - Adaptation to environmental characteristics
  - Adaptation to the perceived environment (e.g. size)
- However, concepts found in nature
  - Difficult to imitate technically
  - Do not employ wheels (nature never invented the wheel)
  - Sometimes imitate wheels (the motion of bipedal walking is close to rolling)
- Most technical systems today use wheels or caterpillars
  - Easy to control and show excellent performance on flat ground
- Legged locomotion is still mostly a research topic
  - But legs offer excellent mobility in rough environments (at the cost of power)

Locomotion concepts

Walking or rolling?

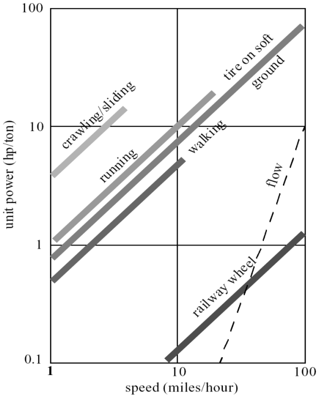
- Bipedal (i.e. two legs) walking mechanism
  - not too far from real rolling when moving on flat ground
  - rolling of a polygon with side length equal to the length of the step (i.e. d)
  - the smaller the step gets, the more the polygon tends to a circle (i.e. wheel)



Locomotion concepts

Walking or rolling?

- number of actuators
- structural complexity
- control expense
- energy efficient
  - terrain (flat, soft, rough, etc.)
  - Cost of transport:
    $COT \triangleq \frac{E}{m \cdot g \cdot d} = \frac{P}{m \cdot g \cdot v}$
    - $E = Energy, P = Power$
    - $m = mass, g = std.\ gravity$
    - $d = distance, v = speed$
- movement of the involved masses
  - walking/running includes up and down movement of center of gravity
  - some extra losses



Specific power versus attainable speed of various locomotion mechanisms

Locomotion concepts

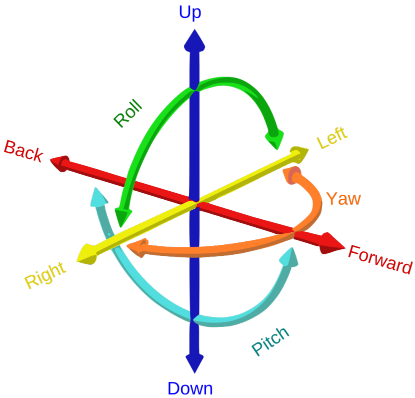
The most important issues

- Stability:
  - number of contact points
  - center of gravity
  - static/dynamic stabilization
  - inclination of terrain (e.g. sloping road)
- Characteristics of contact:
  - contact point or contact area
  - angle of contact
  - friction
- Type of environment:
  - structure
  - medium (e.g. water, air, soft or hard ground)

Locomotion concepts

Degrees of freedom

- In physics, the degrees of freedom (DOF) of a mechanical system is the number of independent parameters that define its configuration or state.



The six degrees of freedom: forward/back, up/down, left/right, yaw, pitch, roll

Wheeled robots

- The wheel has been by far the most popular locomotion mechanism in mobile robotics.
  - Good efficiencies and relatively simple mechanical implementation.
- Even though wheels are the most appropriate solution for many applications, basic wheel layouts are limited to easy terrain.
  - Much work on adapting wheeled robots to hard terrain.
  - Motivation for work on legged robots.
- Three wheels are sufficient to guarantee stability.
  - Two-wheeled robots can also be stable, dynamically.
  - With more than three wheels a (flexible) suspension is required (to allow all wheels to maintain ground contact).
- Selection of wheels depends on the application.

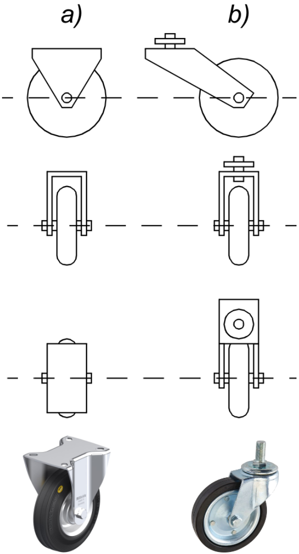
Wheeled robots

- Balance is not a problem.
  - Instead, traction, stability, maneuverability, and control.
- Kinematic parameters come from type and configuration of wheels.
  - Rolling and/or steering.
  - Position relative to chassis.
- Kinematic constraints come from combining all the wheels rolling and steering constraints.
  - Wheels don't like to go sideways.

=> *Discuss mobile robot kinematics in detail in the next lecture.*

Wheeled robots

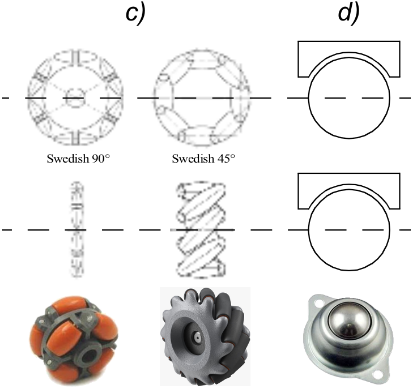
- Standard wheel: Two DOF; rotation around the (motorized) wheel axle and the contact point.
- Caster wheel: Three DOF; rotation around the wheel axle, the contact point and the castor axle.



Wheeled robots

Wheel design

- Swedish/Mecanum wheel: Three DOF; rotation around the (motorized) wheel axle, around the rollers and around the contact point.
- Ball/Spherical wheel: Suspension technically not solved.



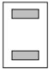
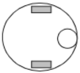
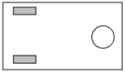
Wheeled robots

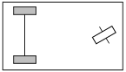
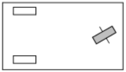
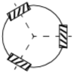
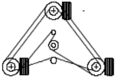
Wheel design

- Sometimes the suspension system of small robots is replaced by soft rubber tires.
  - Require a more dynamic suspension from significantly uneven terrain.
- Bigger wheels allow to overcome higher obstacles.
  - Require higher torque or reductions in the gearbox.
- Most wheel configurations are nonholonomic (c.f. next slides).
  - Require high control effort.

Wheeled robots

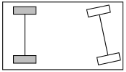
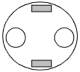
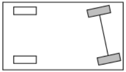
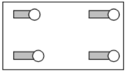
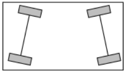
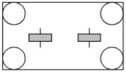
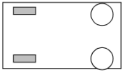
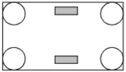
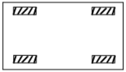
Wheel configurations

# of wheels	Arrangement	Description
2		One steering wheel in the front, one traction wheel in the rear
		Two-wheel differential drive with the center of mass (COM) below the axle
3		Two-wheel centered differential drive with a third point of contact
		Two independently driven wheels in the rear/front, 1 unpowered omnidirectional wheel in the front/rear

# of wheels	Arrangement	Description
3		Two connected traction wheels (differential) in rear, 1 steered free wheel in front
		Two free wheels in rear, 1 steered traction wheel in front
		Three motorized Swedish or spherical wheels arranged in a triangle; omnidirectional movement is possible
		Three synchronously motorized and steered wheels; the orientation is not controllable

Wheeled robots

Wheel configurations

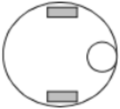
# of wheels	Arrangement	Description	# of wheels	Arrangement	Description
4		Two motorized wheels in the rear, 2 steered wheels in the front; steering has to be different for the 2 wheels to avoid slipping/skidding.	4		Two-wheel differential drive with 2 additional points of contact
		Two motorized and steered wheels in the front, 2 free wheels in the rear; steering has to be different for the 2 wheels to avoid slipping/skidding.			Four motorized and steered castor wheels
		Four steered and motorized wheels	6		Two motorized and steered wheels aligned in center, 1 omnidirectional wheel at each corner
		Two traction wheels (differential) in rear/front, 2 omnidirectional wheels in the front/rear			Two traction wheels (differential) in center, 1 omnidirectional wheel at each corner
		Four omnidirectional wheels			

Wheeled robots

Some examples

Wheeled robots

Some examples



Wheeled robots

Some examples

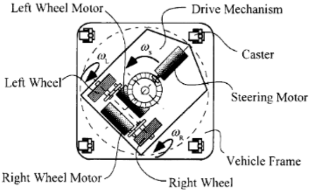
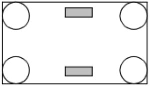


Fig. 1 Omnidirectional vehicle with a dual-wheel caster-drive mechanism



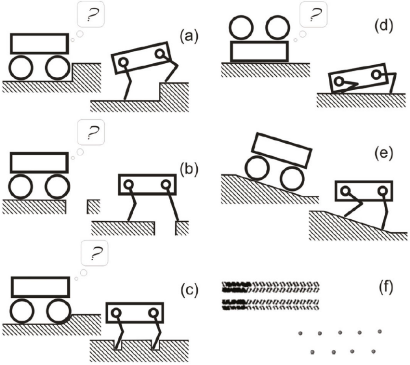
Wheeled robots

Some examples

What about caterpillar robots?

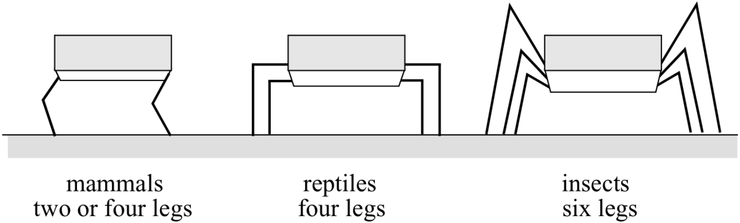
Legged robots

- 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 (power and mechanical complexity);
  - the robot must see detailed elements of the terrain (perception).



Legged robots

- The fewer legs the more complicated locomotion becomes.
  - At least three legs are required for static stability.
- During walking some legs are lifted.
  - Losing stability?
- For static walking at least 6 legs are required.
  - Three of the legs are always in contact with the ground.

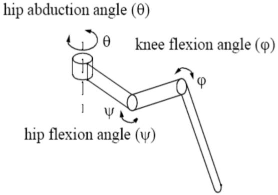


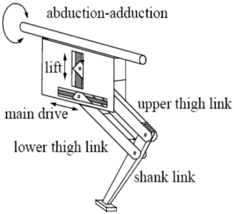
- Legged robotics is a popular research field.
- Few industrial applications, but broad prospects.

Legged robots

Joints

- 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 (see pictured below).
- 4th DOF for the ankle joint (video).
  - Might improve walking and stability.
  - however, additional joint (DOF) increases the complexity of the design and especially of the locomotion control.





Legged robots

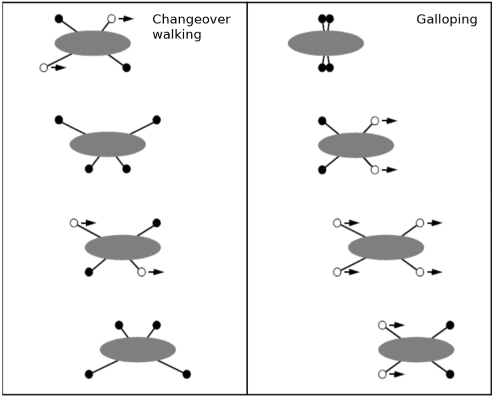
Gaits

- The gait is characterized as the distinct sequence of *lift and release events* of the individual legs.
  - The number of possible gaits depends on the number of legs.
  - The number of possible events N for a walking machine with k legs is: $N = (2k - 1)!$ $\leftarrow$ factorial
- For a biped walker ($k = 2$) the number of possible events N is: $N = (2k - 1)! = 3! = 3 \times 2 \times 1 = 6$
  - 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: $N = 11! = 39\ 916\ 800$

Legged robots

Gaits

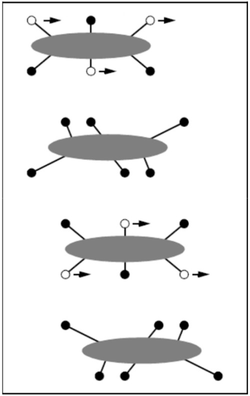
- Most obvious natural gaits with 4 legs are dynamic.



Legged robots

Gaits

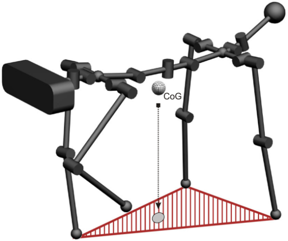
- Most obvious gait with 6 legs is static.



Legged robots

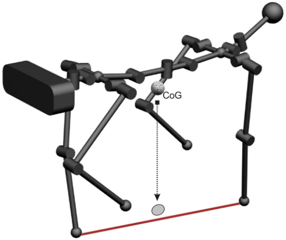
Dynamic walking vs. Static walking

- 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:

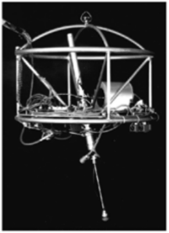
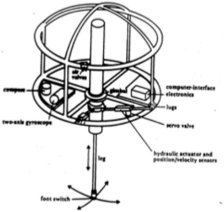


  - The robot will fall if not continuously moving.
  - Less than three legs can be in ground contact.
  - Fast, efficient and demanding for actuation and control. => (video)

Legged robots

Examples: One leg

- MIT's 3D One-Leg Hopper robot (built in about 1983)
  - Pneumatic piston
  - Hydraulic leg "angle" orientation

Legged robots

Examples: Two legs (Humanoid robots)

- ASIMO by Honda (Ver. 2011, the last version)
  - Weight: 48 kg, height: 130 cm
  - Speed 2.7 km/h (walking), 9.0 km/h (running)
  - Autonomy: $\sim$ 1 hour

- Atlas by Boston Dynamics (Ver. 2016, current version)
  - Weight: 89 kg, height: 150 cm
  - Speed: up to 9.0 km/h
  - Autonomy: $\sim$ 1 hour

Legged robots

Fukushima – where no human should go

Legged robots

Examples: Four legs


SpotMini by Boston Dynamics


ANYmal D by ETH Zürich


Aliengo by Unitree


Mini Cheetah by MIT


HyQReal by IIT

Legged robots

Examples: Six legs

- Static stability during walking: easy to control

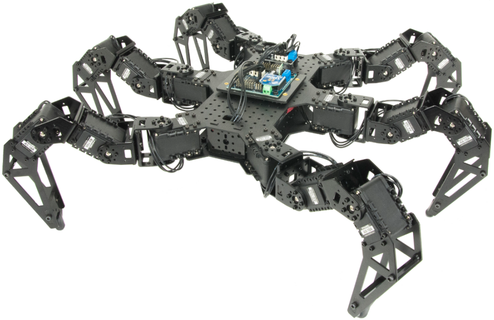


Figure: PhantomX AX Metal Hexapod MK-III Kit

Summary

- This lecture has looked at locomotion, one of the most fundamental aspects of robot design.
- Main distinction: wheeled or legged.
- Within each class there are a number of options: number of wheels/legs, types of wheel/legs (c.f. number of DOF).

The end

Thank you for your attention!

Any questions?