IA712: Mobile Robotics

Lecture 4: Locomotion

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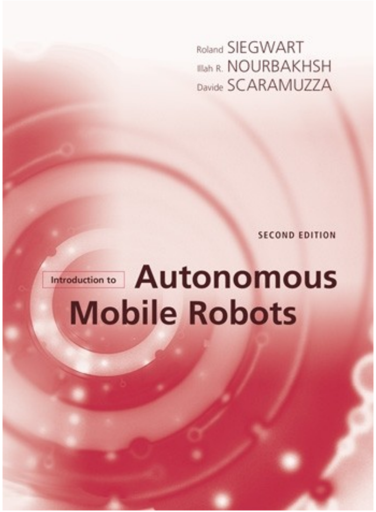
Extended Reading

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



What is Locomotion?

Definition:

Locomotion is the ability of a robot to move from one place to another. It is the **physical realization** of the "Act" component in the Sense-Think-Act cycle.

The choice of a locomotion system is a fundamental **design decision** that determines:

- The environments the robot can traverse (e.g., flat floors, rough terrain, stairs).
- The robot's speed and efficiency.
- Its maneuverability and stability.
- The complexity of its control system.

Key trade-offs:

There is no single "best" locomotion method. The choice always involves trade-offs between the above four items.

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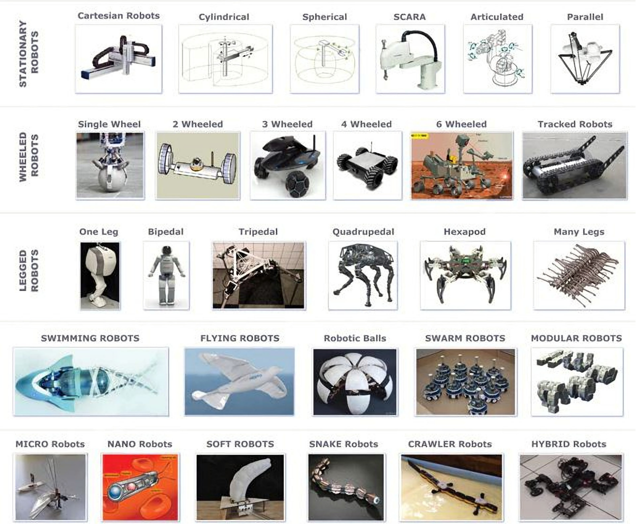
Types of Locomotion

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

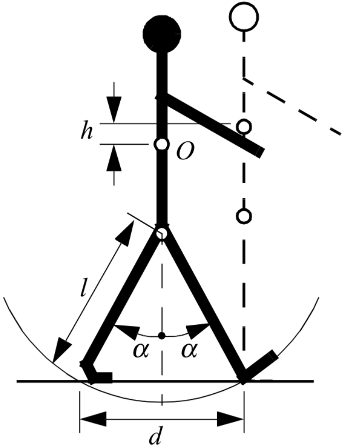
- Concepts found in nature are difficult to imitate technically.
- Most technical systems today use wheels or caterpillars.
- Rolling is very efficient, but not found in nature.
- The motion of bipedal walking is close to rolling.

Locomotion Concepts

Walking or Rolling?

Bipedal (i.e. two legs) walking mechanism:

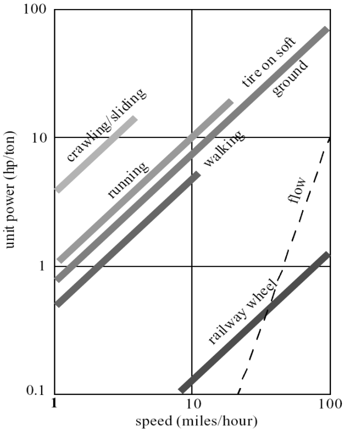
- Not too far from real rolling (flat ground).
- Rolling of a polygon with side length equal to the length of the step (d).
- The smaller the step gets, the more the polygon tends to a circle (wheel).



Locomotion Concepts

Walking or Rolling?

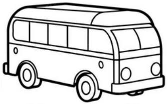
- Number of actuators
- Structural complexity
- Control expense
- Energy efficient
  - Terrain (flat, soft, rough, etc.)
  - Cost of transport
- Movement of the involved masses
  - Walking/running includes up and down movement of center of gravity
  - Some extra losses

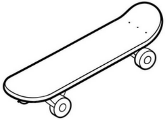


Locomotion Concepts

Important Issues

- 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)





Why Wheels?

Wheels are by far the most common locomotion method in mobile robotics, especially for indoor and structured environments.

Advantages

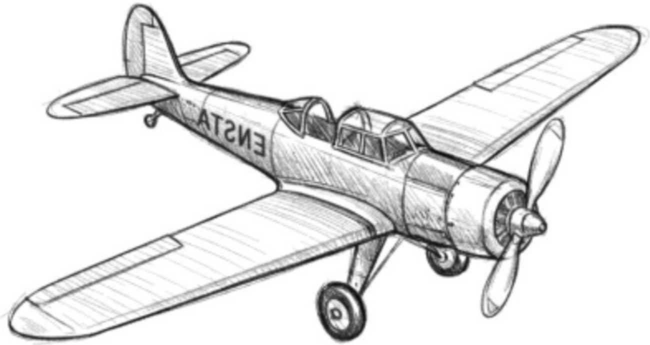
- **High efficiency:** Low friction results in excellent energy efficiency on flat surfaces.
- **Simplicity:** Mechanically and conceptually simple to build and control.
- **Stability:** Provides a stable platform, especially with 3 or more wheels.
- **Speed:** Capable of high speeds.

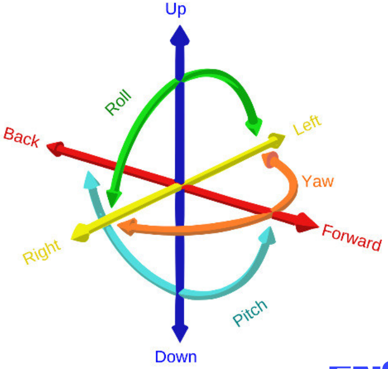
Disadvantages

- **Limited terrain:** Poor performance on rough terrain, stairs, or large obstacles.
- **Requires contact:** Needs continuous contact with the ground.
- **Slippage:** Prone to slipping.

Degrees of Freedom (DOF)

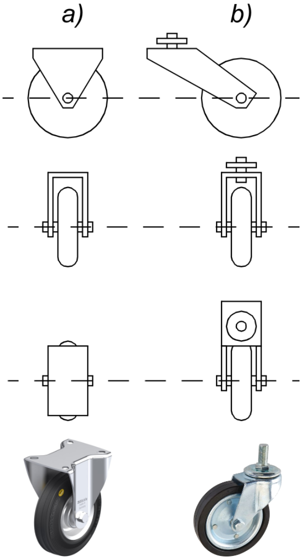
The six degrees of freedom – forward/back, up/down, left/right, yaw, pitch, roll – of an aircraft:





The Four Basic Wheels Types

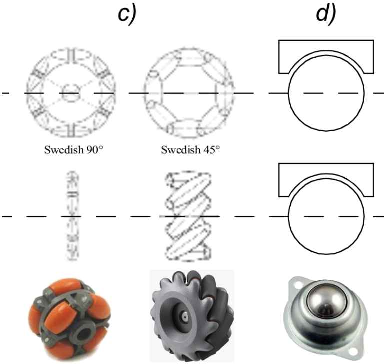
a) Standard wheel: Two DOF; rotation around the (motorized) wheel axle and the contact point.
b) Castor wheel: Three DOF; rotation around the wheel axle, the contact point and the castor axle.



The Four Basic Wheels Types

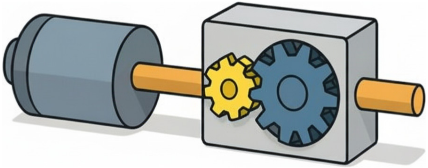
c) Swedish/Mecanum wheel: Three DOF; rotation around the (motorized) wheel axle, around the rollers and around the contact point.

d) Ball/Spherical wheel: Three DOF; suspension technically not solved.



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 gear box.
- Most wheel configurations are nonholonomic.
  - Require high control effort.



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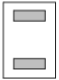
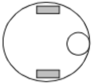
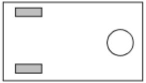
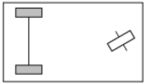
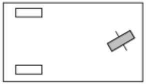
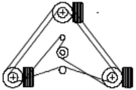
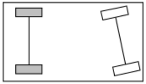
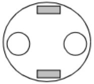
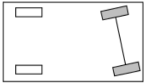
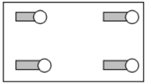
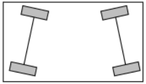
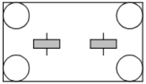
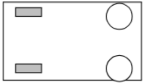
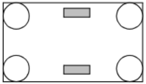
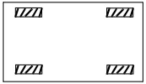
Wheel Configurations

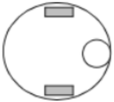
# of wheels	Arrangement	Description
2		One steering wheel in the front, one traction wheel in the rear
		Two-wheel differential drive with the center of mass (COM) below the axle
3		Two-wheel centered differential drive with a third point of contact
		Two independently driven wheels in the rear/front,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

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			

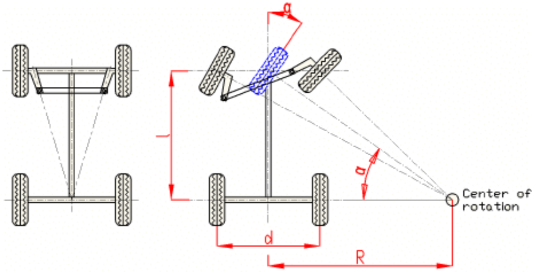
Differential Drive

- **Mechanism:** Two independently driven wheels on a common axis, and one passive castor / ball is used for stability.
  $\Longrightarrow$ One of the simplest and most popular drive mechanisms.
- **Movement features:**
  - **Forward/Backward:** Both wheels turn at the same speed.
  - **Turning:** One wheel turns faster than the other.
  - **Spin in place (zero-radius turn):** Wheels turn at the same speed in opposite directions.
- **Use cases:** Roomba vacuum cleaner, most educational robots (TurtleBot).



Ackermann Steering

- **Mechanism:** Two wheels provide propulsion, and the two front wheels pivot to steer.
  $\implies$ Car-like steering.
- **Movement features:** Stable at high speeds but has a non-zero turning radius (cannot spin in place).
- **Use case:** Autonomous cars, outdoor vehicles.



Omnidirectional (Holonomic)

- **Mechanism:** Uses special wheels (Mecanum or omni-wheels) that have rollers mounted along their circumference.
- **Movement features:** Allows for instantaneous movement in any direction (x, y) and rotation (θ) without needing to reorient first.
  $\Longrightarrow$ This is called holonomic movement.
- **Use case:** Warehouse logistics (Amazon Kiva), robot soccer.

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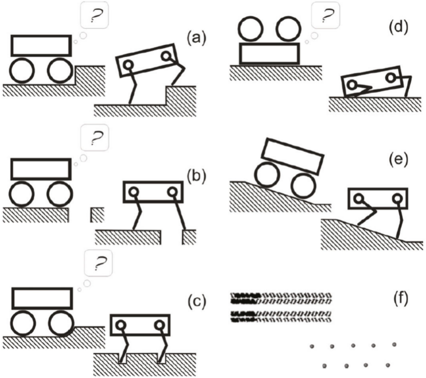
Why Legs?

Legged locomotion mimics biology and is designed to overcome the primary limitation of wheels: discrete obstacles and highly irregular terrain.

Advantages:

- **All-terrain:** Navigates stairs, gaps, and very rough terrain.
- **Discrete contact:** Requires only specific points of contact (unlike a wheel's continuous path).
- **Active suspension:** Adapts to the ground's shape.

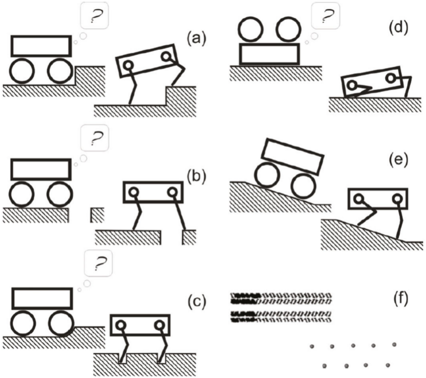


Why Legs?

Controlling a legged robot is vastly more complex than a wheeled one.

Challenges:

- Power needs
- Mechanical complexity
- Kinematic complexity
- Control complexity
- Perceptual complexity



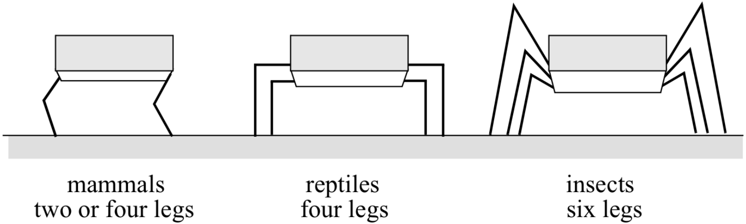
Types of Legged Robots

- **Bipeds (2 legs):**
  - Humanoid robots.
  - Unstable and require constant active balancing (dynamic stability).
  - Complex but can navigate human-centric environments.
- **Quadrupeds (4 legs):**
  - Animal-like robots.
  - Can be statically stable (if CoM is within the support triangle of 3 feet) or dynamically stable (trotting, running).
  - A good balance of stability and agility.
- **Hexapods (6+ legs):**
  - Insect-like robots.
  - Stable and can always keep a tripod of legs on the ground while moving the other three, ensuring static stability.
  - Slower and more mechanically complex, but excellent for careful traversal of unknown terrain.

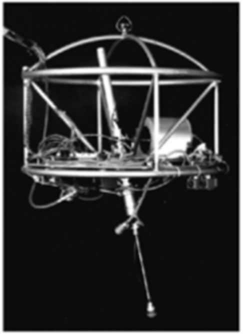
Gaits

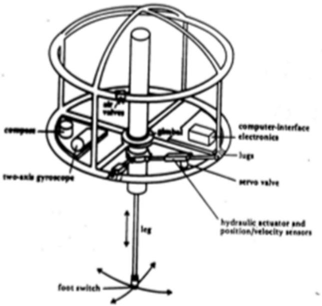
The **gait** is characterized as the distinct sequence of **lift and release events** of the individual legs.

- The number of possible gaits (N) depends on the number of legs (k): $N = (2k - 1)!$
- For a biped walker ($k = 2$): $N = (2k - 1)! = 3! = 3 \times 2 \times 1 = 6$
  $\Longrightarrow$ 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: $N = 11! = 39\ 916\ 800$



Early Legged Robots





Beyond Wheels and Legs

Tracked (tank treads)

- A hybrid approach that creates a continuous, large contact patch with the ground.
- Pros: Excellent traction, distributes weight well, good on soft or loose terrain (sand, mud).
- Cons: Inefficient on flat surfaces, can damage terrain, complex mechanics.
- Example: Bomb disposal robots, some rovers.

Beyond Wheels and Legs

Aerial and aquatic

- **Flying (drones/UAVs):**
  - Use propellers to generate lift.
  - Unmatched for overcoming ground obstacles but have high energy consumption and limited flight time.
- **Swimming (AUVs):**
  - Use thrusters and fins to move in water.
  - A completely different set of challenges related to buoyancy, pressure, and communication.

Questions?

Next: Practical Work 4 - Play with Gazebo