Autonomous mobile robot | the key questions

- The three key questions in Mobile Robotics
  - Where am I?
  - Where am I going?
  - How do I get there?

- To answer these questions the robot has to
  - have a model of the environment (given or autonomously built)
  - perceive and analyze the environment
  - find its position/situation within the environment
  - plan and execute the movement
Autonomous mobile robot | the see-think-act cycle

- **Localization**
  - Map Building
  - "position" global map

- **Cognition**
  - Path Planning
  - Mission commands

- **Perception**
  - Information Extraction
  - Sensing
  - Raw data

- **Motion Control**
  - Path Execution
  - Actuator commands
  - Acting

**Real World Environment**

Knowledge, data base

Environment model

Local map

Autonomous Mobile Robots
Margarita Chli, Paul Furgale, Marco Hutter, Martin Rufli, Davide Scaramuzza, Roland Siegwart
Motion Control | kinematics and motion control

- Wheel types and its constraints
  - Rolling constraint
  - no-sliding constraint (lateral)

- Motion control

\[
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{\theta}
\end{bmatrix} = f(\phi_1 \cdots \phi_n, \theta, geometry)
\]

\[
\begin{bmatrix}
\dot{\phi}_1 \\
\vdots \\
\dot{\phi}_n
\end{bmatrix} = f(\dot{x}, \dot{y}, \dot{\theta})
\]
Autonomous mobile robot | the see-think-act cycle

- **Localization**
  - Map Building
  - Environment model
  - Local map

- **Sensing**
  - Raw data

- **Information Extraction**
  - Knowledge, data base

- **Path Planning**
  - Cognition
  - Global map
  - Mission commands

- **Path Execution**
  - Motion control
  - Actuator commands

- **Acting**
  - Environment model

**See-think-act cycle**

- **Perception**
  - Raw data

- **Cognition**
  - Path

- **Real World Environment**
Perception | sensing

- Laser scanner
  - time of flight

- Cameras

![Diagram showing laser scanner and cameras with various sensors highlighted.](image-url)
Perception | information extraction

- Keypoint Features
  - features that are reasonably invariant to rotation, scaling, viewpoint, illumination
  - FAST, SURF, SIFT, BRISK, …

- Keypoint matching
  - BRISK example

- Filtering / Edge Detection

Image from [Rosten et al., PAMI 2010]
Autonomous mobile robot | the see-think-act cycle

- **Localization**
  - Map Building
  - Environment model
  - Local map
  - “Position”
  - Global map

- **Perception**
  - Information Extraction
    - Raw data
  - Sensing

- **Cognition**
  - Path Planning
    - Path
    - Mission commands

- **Acting**
  - Path Execution
    - Actuator commands
  - Motion Control

- **Real World Environment**
Localization | where am I?

- **SEE**: The robot queries its sensors → finds itself next to a pillar

- **ACT**: Robot moves one meter forward
  - motion estimated by wheel encoders
  - accumulation of uncertainty

- **SEE**: The robot queries its sensors again → finds itself next to a pillar

- **Belief update (information fusion)**
Autonomous mobile robot | the see-think-act cycle

- **Localization**
  - Map Building
  - Environment model
  - Local map

- **Information Extraction**
  - Raw data

- **Sensing**
  - Knowledge, data base

- **Cognition**
  - Path Planning
  - Global map
  - “Position”

- **Path Execution**
  - Actuator commands
  - Motion control

- **Acting**
  - Mission commands

- **Real World Environment**

**The see-think-act cycle**
Cognition | Where am I going? How do I get there?
Cognition | Where am I going? How do I get there?

- Global path planning
  - Graph search

- Local path planning
  - Local collision avoidance
Autonomous mobile robot | the see-think-act cycle

- **Localization**
  - Map Building
  - “position” global map

- **Cognition**
  - Path Planning
  - path

- **Motion Control**
  - Path Execution
  - actuator commands
  - Acting

- **Real World Environment**

- **Perception**
  - Information Extraction
    - raw data
  - Sensing
    - environment model
    - local map

- **Knowledge, data base**
  - mission commands

- **See-think-act** cycle
Autonomous Mobile Robots | Some recent examples
**Rezero | Wheeled locomotion with single point contact**

- Up to 17° tilt angle
- Up to 3.5 m/s

Wheel design adopted from Kumagai & Ochiai, Tohoku Gakuin University, Japan

http://www.rezero.ethz.ch/
Wheeled locomotion in “3D”

- **Paraswift** - the vortex wall climbing robot
- Fast spinning impeller underneath the robot produces a strong vortex

http://www.paraswift.ethz.ch/
From Perception to Understanding

Places / Situations
A specific room, a meeting situation, …

Servicing / Reasoning

Objects
Doors, Humans, Coke bottle, car, …

Features
Lines, Contours, Colors, Phonemes, …

Navigation

Raw Data
Vision, Laser, Sound, Smell, …

• Functional / Contextual Relationships of Objects
  • imposed
  • learned
  • spatial / temporal/semantic

• Models / Semantics
  • imposed
  • learned

• Models
  • imposed
  • learned

Fusing & Compressing Information

Real World Environment

Motion Control

Cognition

Perception

Localization

“position”
global map

environment model
local map
Probabilistic localization | belief representation

a) Continuous map with single hypothesis probability distribution $p(x)$

b) Continuous map with multiple hypotheses probability distribution $p(x)$

c) Discretized metric map (grid $k$) with probability distribution $p(k)$

d) Discretized topological map (nodes $n$) with probability distribution $p(n)$
Discretizes Map | Grid-Based Metric Approach

- Grid Map of the Smithsonian’s National Museum of American History in Washington DC.
- Markov Localization
- Grid: ~ 400 x 320 = 128’000 points

Courtesy S. Thrun, W. Burgard
Grid-Based SLAM (Simultaneous Localization and Mapping)

- Particle Filter to reduce computational complexity
Probabilistic 3D SLAM

- **raw data**
- decompose space into grid cells
- fill cells with data
- find a plane for every cell using RANSAC
- fuse similar neighboring planes together
- **segmented planar segments**

**raw 3D scan of the same scene**

**one plane per grid cell**

**final segmentation**

*photo of the scene*
Locomotion Concepts

- Legged Locomotion
- Wheeled Locomotion
## Locomotion Concepts: Principles Found in Nature

<table>
<thead>
<tr>
<th>Type of motion</th>
<th>Resistance to motion</th>
<th>Basic kinematics of motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow in Channel</td>
<td>Hydrodynamic forces</td>
<td>Eddies</td>
</tr>
<tr>
<td>Crawl</td>
<td>Friction forces</td>
<td>Longitudinal vibration</td>
</tr>
<tr>
<td>Sliding</td>
<td>Friction forces</td>
<td>Transverse vibration</td>
</tr>
<tr>
<td>Running</td>
<td>Loss of kinetic energy</td>
<td>Oscillatory movement of a multi-link pendulum</td>
</tr>
<tr>
<td>Jumping</td>
<td>Loss of kinetic energy</td>
<td>Oscillatory movement of a multi-link pendulum</td>
</tr>
<tr>
<td>Walking</td>
<td>Gravitational forces</td>
<td>Rolling of a polygon (see figure 2.2)</td>
</tr>
</tbody>
</table>
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)

- Most technical systems today use wheels or caterpillars
  - Legged locomotion is still mostly a research topic
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
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 with point contact- at least three legs are required for static stability
  - Stability with surface contact – at least one leg is required
- During walking some (usually half) of the legs are lifted
  - thus loosing stability?
- For static walking at least 4 (or 6) legs are required
  - Animals usually move two legs at a time
  - Humans require more than a year to stand and then walk on two 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 (as 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.

![Diagram of leg joints](image)

- hip abduction angle ($\theta$)
- knee flexion angle ($\varphi$)
- hip flexion angle ($\psi$)
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:
  \[ N = (2\cdot2 - 1)! = 3! = 3 \cdot 2 \cdot 1 = 6 \]

- For a robot with 6 legs (hexapod) $N$ is already
  \[ N = 11! = 39'916'800 \]
Most Obvious Gait with 6 Legs is Static
Most Obvious Natural Gaits with 4 Legs are Dynamic

- Changeover Walking
- Galloping

- free fly
Dynamic Walking vs. Static Walking

- **Statically stable**
  - Bodyweight 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 ↔ demanding for actuation and control

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Most Simplistic Artificial Gait with 4 Legs is Static

- Titan VIII quadruped robot

C Arikawa, K. & Hirose, S., Tokyo Inst. of Technol.
Walking Robots with Four Legs (Quadruped)

- Artificial Dog Aibo from Sony, Japan
Dynamic Walking Robots with Four Legs (Quadruped)

- Boston Dynamics Big Dog
The number of distinct event sequences for biped:

- With two legs (biped) one can have four different states:
  - 1) Both legs down
  - 2) Right leg down, left leg up
  - 3) Right leg up, left leg down
  - 4) Both leg up

- A distinct event sequence can be considered as a change from one state to another and back.
- So we have the following $N = (2k - 1)! = 6$ distinct event sequences (change of states) for a biped:

1. $1 \rightarrow 2 \rightarrow 1$
   - turning on right leg
   - walking

2. $1 \rightarrow 3 \rightarrow 1$
   - turning on left leg
   - hopping left leg

3. $1 \rightarrow 4 \rightarrow 1$
   - hopping with two legs

4. $2 \rightarrow 3 \rightarrow 2$
   - running

5. $2 \rightarrow 4 \rightarrow 2$
   - hopping right leg

6. $3 \rightarrow 4 \rightarrow 3$
   - hopping left leg
Case Study: Stiff 2 Legged Walking

- P2, P3, and Asimo from Honda, Japan
- **P2**
  - Maximum Speed: 2 km/h
  - Autonomy: 15 min
  - Weight: 210 kg
  - Height: 1.82 m
  - Leg DOF: 2x6
  - Arm DOF: 2x7

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Honda’s ASIMO: Advanced Step in Innovative MObility

- Designed to help people in their everyday lives
- One of the most advanced humanoid robots
  - Compact, lightweight
  - Sophisticated walk technology
  - Human-friendly design
Case Study: Passive Dynamic Walker

- Forward falling combined with passive leg swing
- Storage of energy: potential $\longleftrightarrow$ kinetic in combination with low friction
Efficiency Comparison

- Efficiency = $c_{mt} = \frac{|\text{mech. energy}|}{(\text{weight} \times \text{dist. traveled})}$

- $c_{mt} \approx 1.6$
  
  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
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])
Mobile Robots with Wheels

- Wheels are the most appropriate solution for most applications
- Three wheels are sufficient to guarantee stability
- With more than three wheels an appropriate 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
Characteristics of Wheeled Robots and Vehicles

- **Stability** of a vehicle is guaranteed with 3 wheels
  - If center of gravity is within the triangle which is formed by the ground contact point of the wheels.

- Stability is improved by 4 and more wheels
  - however, this arrangements are hyper static and require a flexible suspension system.

- **Bigger wheels** allow to overcome 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
  - COG below axle

- Three wheels
  - Omnidirectional Drive
  - Synchro Drive
Case Study: Vacuum Cleaning Robots

- iRobot Roomba vs.
- Neato XV-11

Images courtesy http://www.botjunkie.com
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.
Different Arrangements of Wheels II

- Four wheels
Case Study: Willow Garage’s PR2

- Four powered castor wheels with active steering
- Results in omni-drive-like behaviour
- Results in simplified high-level planning (see chapter 6)
CMU Uranus: 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
Wheeled Rovers: Concepts for Object Climbing

**a)** Purely friction based

**b)** Change of center of gravity (CoG)

**c)** Adapted suspension mechanism with passive or active joints
The Personal Rover
Climbing with Legs: EPFL Shrimp

- Passive locomotion concept
- 6 wheels
  - two boogies on each side
  - fixed wheel in the rear
  - front wheel with spring suspension
- Dimensions
  - length: 60 cm
  - height: 20 cm
- Characteristics
  - highly stable in rough terrain
  - overcomes obstacles up to 2 times its wheel diameter
Rover Concepts for Planetary Exploration

- ExoMars: ESA Mission to Mars in 2013, 2015, 2018
  - Six wheels
  - Symmetric chassis
  - No front fork → instrument placement
Caterpillar

- The NANOKHOD II,
  - developed by von Hoerner & Sulger GmbH and Max Planck Institute, Mainz
  - will probably go to Mars
Other Forms of "Locomotion": Traditional and Emerging

- Flying

- Swimming