Mobile Robots | Introduction and Lecture Overview

Autonomous Mobile Robots

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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

- Sensing
  - raw data
  - environment model
  - local map
- Information Extraction
  - knowledge, data base
- Localization
  - Map Building
- Cognition
  - Path Planning
  - “position”
    - global map
- Motion Control
  - Path Execution
  - actuator commands
  - Acting
- Real World Environment

See-think-act cycle:
- Perception
- Cognition
- Motion Control
Motion Control | kinematics and motion control

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

- Motion control

\[
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{\theta}
\end{bmatrix}
= f(\dot{\phi}_1 \ldots \dot{\phi}_n, \theta, \text{geometry})
\]

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

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

- **Information Extraction**
  - Raw data

- **Sensing**
  - Real World Environment

- **Path Planning**
  - Cognition
  - Path

- **Acting**
  - Path Execution
  - Actuator commands

- **Motion Control**
  - Mission commands

- **Perception**
  - Knowledge, data base
Perception | sensing

- Laser scanner
  - time of flight

- Cameras

![Diagram showing components of a robot system including a lens, focal point, focal plane, GPS, IMU, wheel encoders, laser scanners, and omnidirectional camera.](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

Knowledge, data base

Localization
Map Building

Raw data

Environment model
Local map

Sensing

Information Extraction

Path Planning

“position“

global map

Cognition

Mission commands

Path Execution

Actuator commands

Acting

Motion Control

Real World
Environment

Perception
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

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

- **Sensing**
  - Raw data

- **Cognition**
  - Path Planning
    - Path

- **Acting**
  - Path Execution
    - Actuator commands
  - Acting

- **Motion Control**
  - Mission commands

- **Real World Environment**
  - Knowledge, data base

The see-think-act cycle includes:
- **Sensing**
- **Information Extraction**
- **Real World Environment**
- **Localization**
- **Cognition**
- **Acting**

- sensors, sensor fusion, perception
- raw data
- information extraction
- localization, map building
- knowledge, database
- path planning
- path execution, actuator commands
- motion control, real world environment
- see-think-act cycle

"position" global map

ethz Autonomous Systems Lab

Autonomous Mobile Robots
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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

- **Sensing**
  - raw data
  - local map
- **Localization**
  - environment model
- **Map Building**
  - knowledge, data base
- **Information Extraction**
  - “position“ global map
- **Cognition Path Planning**
  - path
  - mission commands
- **Path Execution**
  - actuator commands
- **Acting**

**see-think-act**

**Real World Environment**
Autonomous Mobile Robots | Some recent examples
Rezero | Wheeled locomotion with single point contact

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

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

Member of the ASL / Autonomous Systems Lab

rezero
the ultimate ballbot

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, …
- **Objects**: Doors, Humans, Coke bottle, car, …
- **Features**: Lines, Contours, Colors, Phonemes, …
- **Raw Data**: Vision, Laser, Sound, Smell, …
- **Navigation**
- **Interaction**
- **Servicing / Reasoning**

- **Perception**
  - **Real World Environment**
  - **Localization**
    - "position" global map
    - environment model
    - local map
  - **Motion Control**
  - **Cognition**

- **Fusing & Compressing Information**

- **Relationships of Objects**
  - Functional / Contextual
  - Models / Semantics
    - imposed
    - learned
  - spatial / temporal/semantic

- **Models / Semantics**
  - imposed
  - learned

- **Models**
  - imposed
  - learned
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 $p(n)$
Grid Map of the Smithsonian’s National Museum of American History in Washington DC.

- Markov Localization
- Grid: \( \sim 400 \times 320 = 128'000 \) points

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

- Particle Filter to reduce computational complexity
Probabilistic 3D SLAM

1. Raw data
2. Decompose space into grid cells
   - Fill cells with data
3. Find a plane for every cell
   - Using RANSAC
4. Fuse similar neighboring planes together
5. Segmented planar segments

Photo of the scene

Raw 3D scan of the same scene

One plane per grid cell

Final segmentation
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 a 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 losing 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)
- 4\(^{th}\) 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.
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:

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

- 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
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

- Gyro/IMU
- Hip
- Knee
- Ankle
- Foot
- Heat Exchanger
- Engine/Pump
- Computer
- Actuators
- Leg Spring
- Force Sensor

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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 -> 2 -> 1 (turning on right leg)  
  1 -> 3 -> 1 (turning on left leg)  
  1 -> 4 -> 1 (hopping with two legs)  
  2 -> 3 -> 2 (walking)  
  2 -> 4 -> 2 (hopping right leg)  
  3 -> 4 -> 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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Humanoid Robot: ASIMO

- 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

Video: Honda
Case Study: Passive Dynamic Walker

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

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

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.

![Diagram of gaits](image.png)

- 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

- Three wheels

COG below axle

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

```
Four wheels
```

```
Six 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

Purely friction based

Change of center of gravity (CoG)

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