Perception I: Sensors

Roland Siegwart, Margarita Chli, Martin Rufli
Mobile Robot Control Scheme

- Knowledge, database
- Localization
  - Map Building
  - Environment model
  - Local map
- Information Extraction
  - Raw data
- Sensing
- Perception
- Cognition
  - Path Planning
  - "Position" global map
  - Path
- Motion Control
  - Path Execution
    - Actuator commands
  - Acting

See-think-act

Real World Environment

- Perception I - Sensors
- 13.03.2017
- Roland Siegwart, Margarita Chli, Martin Rufli
Robotics | challenges and technology drivers

- The challenges
  - Seeing, feeling and understanding the world
  - Dealing with uncertain and only partially available information
  - Act appropriately onto the environment

- Technology drivers
  - Technology evolutions enable robotics revolutions
  - Laser time-of-flight sensors
  - Cameras and IMUs combined with required calculation power
  - Torque controlled motors, “soft” actuation
  - New materials
Perception is hard!

- "In robotics, the easy problems are *hard* and the *hard* problems are easy"

beating the world’s chess master: EASY

create a machine with some “common sense”: very HARD

13.03.2017
Perception for Mobile Robots

Raw Data
Vision, Laser, Sound, Smell, …

Features
Corners, Lines, Colors, Phonemes, …

Objects
Doors, Humans, Coke bottle, car, …

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

Servicing / Reasoning

Interaction

Navigation

Compressing Information
Shakey the Robot (1966-1972), SRI International

- **Operating environment**
  - Indoors
  - Engineered

- **Sensors**
  - Wheel encoders
  - Bumb detector
  - Sonar range finder
  - Camera
University of Bonn

- Operating environment
  - Indoors (Museum: unstructured and dynamic)

- Sensors
  - Wheel encoders
  - Ring of sonar sensors
  - Pan-tilt camera
Indoors and outdoors
Onroad only

Sensors
- Wheel encoders
- Bumper
- IR sensors
- Laser range finder
- 3D nodding laser range finder
- Inertial measurement unit
- Pan-tilt stereo camera with texture projector (active)
- Pressure sensor and accelerometer inside hands
- ...

https://www.youtube.com/watch?v=gy5g33S0Gzo
50x speed
Classification of Sensors

- **What:**
  - Proprioceptive sensors
    - measure values internally to the system (robot),
    - e.g. motor speed, wheel load, heading of the robot, battery status
  - Exteroceptive sensors
    - information from the robots environment
    - distances to objects, intensity of the ambient light, unique features.

- **How:**
  - Passive sensors
    - Measure energy coming from the environment; very much influenced by the environment
  - Active sensors
    - emit their proper energy and measure the reaction
    - better performance, but some influence on environment
# General Classification (1)

<table>
<thead>
<tr>
<th>General classification (typical use)</th>
<th>Sensor System</th>
<th>PC or EC</th>
<th>A or P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tactile sensors</td>
<td>Contact switches, bumpers</td>
<td>EC</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>Optical barriers</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Noncontact proximity sensors</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td>Wheel/motor sensors</td>
<td>Brush encoders</td>
<td>PC</td>
<td>P</td>
</tr>
<tr>
<td>(wheel/motor speed and position)</td>
<td>Potentiometers</td>
<td>PC</td>
<td>P</td>
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<tr>
<td></td>
<td>Synchros, resolvers</td>
<td>PC</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Optical encoders</td>
<td>PC</td>
<td>A</td>
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<tr>
<td></td>
<td>Magnetic encoders</td>
<td>PC</td>
<td>A</td>
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<tr>
<td></td>
<td>Inductive encoders</td>
<td>PC</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Capacitive encoders</td>
<td>PC</td>
<td>A</td>
</tr>
<tr>
<td>Heading sensors</td>
<td>Compass</td>
<td>EC</td>
<td>P</td>
</tr>
<tr>
<td>(orientation of the robot in relation to a fixed reference frame)</td>
<td>Gyroscopes</td>
<td>PC</td>
<td>P</td>
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<tr>
<td></td>
<td>Inclinometers</td>
<td>EC</td>
<td>A/P</td>
</tr>
</tbody>
</table>

A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.
# General Classification (2)

<table>
<thead>
<tr>
<th>General classification (typical use)</th>
<th>Sensor System</th>
<th>PC or EC</th>
<th>A or P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-based beacons (localization in a fixed reference frame)</td>
<td>GPS</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Active optical or RF beacons</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Active ultrasonic beacons</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Reflective beacons</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td>Active ranging (reflectivity, time-of-flight, and geometric triangulation)</td>
<td>Reflectivity sensors</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Ultrasonic sensor</td>
<td>EC</td>
<td>A</td>
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<tr>
<td></td>
<td>Laser rangefinder</td>
<td>EC</td>
<td>A</td>
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<tr>
<td></td>
<td>Optical triangulation (1D)</td>
<td>EC</td>
<td>A</td>
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<td></td>
<td>Structured light (2D)</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td>Motion/speed sensors (speed relative to fixed or moving objects)</td>
<td>Doppler radar</td>
<td>EC</td>
<td>A</td>
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<tr>
<td></td>
<td>Doppler sound</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td>Vision-based sensors (visual ranging, whole-image analysis, segmentation, object recognition)</td>
<td>CCD/CMOS camera(s)</td>
<td>EC</td>
<td>P</td>
</tr>
<tr>
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<td>Visual ranging packages</td>
<td></td>
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<td></td>
<td>Object tracking packages</td>
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</tbody>
</table>
Encoders

- **Definition:**
  - electro-mechanical device that converts linear or angular position of a shaft to an analog or digital signal, making it an linear/angular transducer
Wheel / Motor Encoders

- **Use cases**
  - measure position or speed of the wheels or steering
  - integrate wheel movements to get an estimate of the position -> odometry
  - optical encoders are proprioceptive sensors
  - typical resolutions: 64 - 2048 increments per revolution.
  - for high resolution: interpolation

- **Working principle of optical encoders**
  - regular: counts the number of transitions but cannot tell the direction of motion
  - quadrature: uses two sensors in quadrature-phase shift. The ordering of which wave produces a rising edge first tells the direction of motion. Additionally, resolution is 4 times bigger
  - a single slot in the outer track generates a reference pulse per revolution
Wheel / Motor Encoders (2)
2. Main Characteristics

- The four fields on the scanning reticle are shifted in phase relative to each other by one quarter of the grating period, which equals $360^\circ/(\text{number of lines})$
- This configuration allows the detection of a change in direction
- Easy to interface with a micro-controller
Wheel / Motor Encoders

Notice what happens when the direction changes:
Heading Sensors

- **Definition:**
  - Heading sensors are sensors that determine the robot’s orientation and inclination with respect to a given reference.

- Heading sensors can be proprioceptive (gyroscope, accelerometer) or exteroceptive (compass, inclinometer).

- Allows, together with an appropriate velocity information, to integrate the movement to a position estimate.

- This procedure is called **deduced reckoning** (ship navigation).
**Compass**

- Used since before 2000 B.C.
  - when Chinese suspended a piece of natural magnetite from a silk thread and used it to guide a chariot over land.

- Magnetic field on earth
  - absolute measure for orientation (even birds use it for migrations (2001 discovery))

- Large variety of solutions to measure magnetic or true north
  - mechanical magnetic compass
  - direct measure of the magnetic field (Hall-effect, magneto-resistive sensors)
  - Gyrocompass (non-magnetic, finds true north by using fast-spinning wheel and friction forces in order to exploit the rotation of the Earth) -> used on ships

- Major drawback of magnetic solutions
  - weakness of the earth field (30 μTesla)
  - easily disturbed by magnetic objects or other sources
  - bandwidth limitations (0.5 Hz) and susceptible to vibrations
  - not suitable for indoor environments for absolute orientation
  - useful indoor (only locally)
Gyroscope

- **Definition:**
  - Heading sensors that preserve their orientation in relation to a fixed reference frame
  - They provide an absolute measure for the heading of a mobile system.

- **Two categories, the mechanical and the optical gyroscopes**
  - **Mechanical Gyroscopes**
    - Standard gyro (angle)
    - Rate gyro (speed)
  - **Optical Gyroscopes**
    - Rate gyro (speed)
Mechanical Gyroscopes

- Concept:
  - Inertial properties of a fast spinning rotor
  - Angular momentum associated with a spinning wheel keeps the axis of the gyroscope inertially stable.
- No torque can be transmitted from the outer pivot to the wheel axis
  - Spinning axis will therefore be space-stable
  - However, friction in the axes bearings will introduce torque and so drift - >precession
- Quality: 0.1° in 6 hours (a high quality mech. gyro costs up to 100,000 $)
Rate gyros

- Same basic arrangement shown as regular mechanical gyroscopes
  - But: gimbals are restrained by torsional springs
    - Enables to measure angular speeds instead of the orientation.
Optical Gyroscopes

- Optical gyroscopes are based on the Sagnac effect
  - angular speed (heading) sensors using two monochromic light (or laser) beams from the same source.
  - One is traveling in a fiber clockwise, the other counterclockwise around a cylinder
- Laser beam traveling in direction opposite to the rotation
  - experiences slightly shorter path
  - phase shift of the two beams is proportional to the angular velocity \( W \) of the cylinder
  - In order to measure the phase shift, coil consists of as much as 5Km optical fiber
- New solid-state optical gyroscopes based on the same principle are built using microfabrication technology.
Mechanical Accelerometer

- Accelerometers measure all external forces acting upon them, including gravity
- Accelerometer acts like a spring–mass–damper system

\[ F_{\text{applied}} = F_{\text{inertial}} + F_{\text{damping}} + F_{\text{spring}} = m\ddot{x} + c\dot{x} + kx \]

Where \( m \) is the proof mass, \( c \) the damping coefficient, \( k \) the spring constant

- at steady-state: \( a_{\text{applied}} = \frac{kx}{m} \)
Other Accelerometers

- Modern accelerometers use Micro Electro-Mechanical Systems (MEMS) consisting of a spring-like structure with a proof mass. Damping results from the residual gas sealed in the device.

- In capacitive accelerometers the capacitance between a fixed structure and the proof mass is measured.

- Piezoelectric accelerometers are based on the property exhibited by certain crystals to generate a voltage when a mechanical stress is applied to them.
Factsheet: MEMS Accelerometer (1)

1. Operational Principle
The primary transducer is a vibrating mass that relates acceleration to displacement. The secondary transducer (a capacitive divider) converts the displacement of the seismic mass into an electric signal.

2. Main Characteristics
- Can be multi-directional
- Various sensing ranges from 1 to 50 g

3. Applications
- Dynamic acceleration
- Static acceleration (inclinometer)
- Airbag sensors (+- 35 g)
- Control of video games (Wii)

<http://www.mems.sandia.gov/>
Inertial Measurement Unit (IMU)

- **Definition**
  - An inertial measurement unit (IMU) is a device that uses measurement systems such as gyroscopes and accelerometers to estimate the relative position \((x, y, z)\), orientation \((\text{roll, pitch, yaw})\), velocity, and acceleration of a moving vehicle with respect to an inertial frame.
  - In order to estimate motion, the gravity vector must be subtracted. Furthermore, initial velocity has to be known.

![Diagram of IMU process](image-url)
Ground-Based Active and Passive Beacons

- “Elegant” way to solve the localization problem in mobile robotics
- **Beacons are signaling guiding devices with a precisely known position**
- Beacon base navigation is used since the humans started to travel
  - Natural beacons (landmarks) like **stars, mountains or the sun**
  - Artificial beacons like **lighthouses**
- The recently introduced Global Positioning System (GPS) revolutionized modern navigation technology
  - Key sensors for outdoor mobile robotics
  - For indoor robots GPS is not applicable,
- **Major drawback with the use of beacons in indoor:**
  - Beacons require changes in the environment -> costly.
  - Limit flexibility and adaptability to changing environments.
Motion-Capture Systems

- Vicon and Optitrack
  - System of several cameras that track the position of reflective markers
  - >300 fps
  - <1 mm precision
  - Suitable for ground-truth comparison, control strategies, (e.g., quadrotors)
  - Indoor or outdoor application
  - Require preinstallation and precalibration of the cameras (done with a special calibration rig moved by the user)
Global Positioning System (GPS)

- **Facts**
  - Became accessible for commercial applications in 1995
  - Initially there were 24 satellites orbiting the earth every 12 hours at a height of 20.190 km.
  - 4 satellites were located in each of 6 orbits with 60 degrees orientation between each other.

- **Working Principle**
  - Location of any GPS receiver is determined through a *time of flight measurement* (satellites send orbital location (ephemeris) plus time; the receiver computes its location through *trilateration and time correction*).

- **Technical challenges:**
  - Time synchronization between the satellites and the GPS receiver
  - Real time update of the exact location of the satellites
  - Precise measurement of the time of flight
  - Interferences with other signals
Global Positioning System (GPS)
Global Positioning System (GPS)

- **Time synchronization:**
  - atomic clocks on each satellite
  - monitoring them from different ground stations.
- Ultra-precision time synchronization is extremely important
  - electromagnetic radiation propagates at light speed
- **Light travels roughly 0.3 m per nanosecond**
  - position accuracy proportional to precision of time measurement
- **Real time update of the exact location of the satellites:**
  - monitoring the satellites from a number of widely distributed ground stations
  - master station analyses all the measurements and transmits the actual position to each of the satellites
- **Exact measurement of the time of flight**
  - quartz clock on the GPS receivers are not very precise
  - the range measurement with four satellite allows to identify the three values (x, y, z) for the position and the clock correction $\Delta T$
- Commercial GPS receivers have nominal position accuracy of 3 meters
Global Positioning System (GPS)

Satellite coverage

Multipath problem
Differential Global Positioning System (dGPS)

- DGPS requires that a GPS receiver, known as the **base station**, be set up on a **precisely known location**. The base station receiver calculates its position based on satellite signals and compares this location to the known location. The difference is applied to the GPS data recorded by the roving GPS receiver.

- **Position accuracies in sub-meter to cm range**
Range sensors

- Sonar
- Laser range finder
- Time of Flight Camera
- Structured light
Range Sensors (time of flight)

- Large range distance measurement \(\rightarrow\) thus called range sensors

- Range information:
  - key element for localization and environment modeling

- Ultrasonic sensors as well as laser range sensors make use of propagation speed of sound or electromagnetic waves respectively.

- The traveled distance of a sound or electromagnetic wave is given by
  \[
  d = c \cdot t
  \]
  - \(d\) = distance traveled (usually round-trip)
  - \(c\) = speed of wave propagation
  - \(t\) = time of flight.
Range Sensors (time of flight)

- It is important to point out
  - Propagation speed of sound: 0.3 m/ms
  - Propagation speed of electromagnetic signals: 0.3 m/ns
  - Electromagnetic signals travel one million times faster.
  - 3 meters
    - Equivalent to 10 ms for an ultrasonic system
    - Equivalent to only 10 ns for a laser range sensor
    - Measuring time of flight with electromagnetic signals is not an easy task
    - laser range sensors expensive and delicate

- The quality of time of flight range sensors mainly depends on:
  - Inaccuracies in the time of flight measurement (laser range sensors)
  - Opening angle of transmitted beam (especially ultrasonic range sensors)
  - Interaction with the target (surface, specular reflections)
  - Variation of propagation speed (sound)
  - Speed of mobile robot and target (if not at stand still)
Factsheet: Ultrasonic Range Sensor

1. Operational Principle
An ultrasonic pulse is generated by a piezo-electric emitter, reflected by an object in its path, and sensed by a piezo-electric receiver. Based on the speed of sound in air and the elapsed time from emission to reception, the distance between the sensor and the object is easily calculated.

\[ d = \frac{v \cdot \Delta t}{2} \]

2. Main Characteristics
- Precision influenced by angle to object (as illustrated on the next slide)
- Useful in ranges from several cm to several meters
- Typically relatively inexpensive

3. Applications
- Distance measurement (also for transparent surfaces)
- Collision detection

<http://www.robot-electronics.co.uk/shop/Ultrasonic_Rangers1999.htm>
Ultrasonic Sensor (time of flight, sound) (2)

- typical frequency: 40kHz - 180 kHz
  - Lower frequencies correspond to longer maximal sensor range
- generation of sound wave via piezo transducer
  - transmitter and receiver can be separate or integrated in the same unit
- Range between 12 cm up to 5 m
- Resolution of ~ 2 cm
- Relative error 2%
- sound beam propagates in a cone (approx.)
  - opening angles around 20 to 40 degrees
  - regions of constant depth
  - segments of an arc (sphere for 3D)
Ultrasonic Sensor (time of flight, sound) (3)

- Other problems for ultrasonic sensors
  - soft surfaces that absorb most of the sound energy
  - surfaces that are far from being perpendicular to the direction of the sound → specular reflections

a) 360° scan

b) results from different geometric primitives
Laser Range Sensor (time of flight, electromagnetic)

- Laser range finder are also known as Lidar (Light Detection And Ranging)

SICK

Hokuyo
Laser Range Sensor (time of flight, electromagnetic)

- **Phase-Shift Measurement**

\[ D' = 2D = \frac{\theta}{2\pi} \lambda \]

Where:
- \( c \): is the speed of light; \( f \) the modulating frequency; \( D' \) the distance covered by the emitted light.
- For \( f = 5 \text{ MHz} \) (as in the A.T&T. sensor), \( \lambda = 60 \text{ meters} \)
Laser Range Sensor (time of flight, electromagnetic)

- Operating Principles:
  - Pulsed laser (today the standard)
    - measurement of elapsed time directly
    - resolving picoseconds
  - Phase shift measurement to produce range estimation
    - technically easier than the above method
“Seeing” | Laser-based 3D mapping

scan t₁

scan t₂

scan matching

Mapping & Localization
Today | 3D laser sensors → map based navigation

- **Google Self-Driving Car Project (status summer 2015)**
  - > 20 vehicles in use
  - > 2.7 mio km, 1.5 mio km in autonomous mode
  - > 11 accidents
    - No people insured
    - None of them caused by car control algorithm

Expensive, complex and cumbersome

https://www.youtube.com/watch?v=eJCR2TaSFc
Laser Triangulation (1D)

- Principle of 1D laser triangulation:

\[ D = f \frac{L}{x} \]
Structured Light (vision, 2D or 3D)

- Eliminate the correspondence problem by projecting structured light on the scene.
- Slits of light or emit collimated light (possibly laser) by means of a rotating mirror.

![Diagram of structured light setup](image)
Microsoft Kinect I

- Developed by Israeli company PrimeSense in 2010

- Major components
  - IR Projector
  - IR Camera
  - VGA Camera
  - Microphone Array
  - Motorized Tilt
  - Field of view: 57.5 deg (horizontal) – 43.5 (vertical)
  - Camera resolution: 640x480 pixels
Video Out

- 30 fps
- 57 degree
- 8 bit VGA RGB 640x480
Time of Flight / Projected Light Patterns
e.g. Kinect 2.0 & Intel RealSense

- Typical characteristic
  - Resolution 1920x1080 pixels
  - Field of view: 70 deg (H), 60 deg (V)
  - Claimed accuracy: 1 mm
  - Claimed max range: 6 meters

https://www.youtube.com/watch?v=yvgPrZnp4So
“Seeing” | Visual-Inertial Motion Estimation

https://www.youtube.com/watch?v=yvgPrZNp4So
Autonomous Cars Today

- Detection and tracking of ...
  - Lanes,
  - street signs,
  - other cars,
  - ...

https://www.youtube.com/watch?v=aGW4nRzx8lw
Multimodal detection and tracking

Pedestrians

- Rich info
- Inexpensive
- Noise
- No distance

Cars

- High prec
- Light independent
- Low info
Detection and tracking displayed on camera data

What the robot sees: laser projected on image

Detection and tracking displayed on laser data

Autonomous Mobile Robots
Roland Siegwart, Margarita Chli, Martin Rufli

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