Mobile Robotics

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Sensors and Sensor Models

Lecture Content

- Sensor Types
- Sensor Models
- Beam-based Sensors
- Scan-Based Sensors
- Image Based Sensors

Sensors and Sensor Models

What?

- Proprioceptive Sensors
  - measure signals internal to the system (robot),
  - e.g. Motor Speed, Battery, Wheel Load
- Exteroceptive Sensors
  - Information about the Robots Environment
  - Distance to Object, orientation of an object, status of object

Exteroceptive Sensors - How?

- Passive Sensors
  - Touch Sensors (Tactile)
  - Camera
- Active Sensors
  - Laser Range Finder
  - Ultrasound
  - Time-of-Flight Camera
  - Structured Light

Sensors and Sensor Models

Touch Sensors

- Simple, Cheap, Reliable
- One Bit of Information per sensor
- Used to activate programmed reaction

Tactile Sensors

- Complex and Expensive Sensors
- Can offer information such as:
  - Direction of Contact,
  - Force of Contact,
  - Size of Contact, and more
- Can be used for complex manipulation tasks, Reactive Grasping

Sensors and Sensor Models

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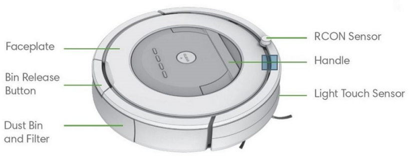

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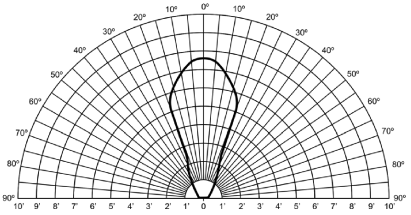
Sensors and Sensor Models

Ultrasound Sensors

- Emit an ultrasound signal
- Receive echo
- Time between transmission and response gives information of distance

PING))) Ultrasonic Distance Sensor

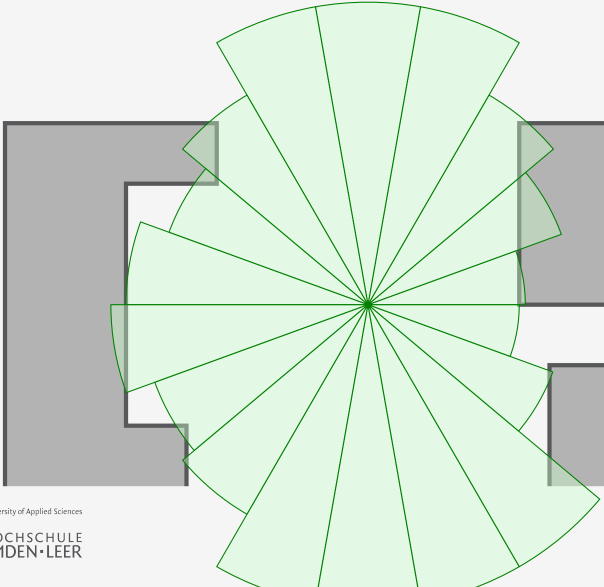


Ping))) Beam Profile

- Ultrasound "Beam" can be quite wide $> 20\,\text{deg}$
- Small Objects may not reflect enough signal
- Soft Objects may absorb sound waves
- Angled Objects may not reflect signal back enough (Specular Reflection)
- Multiple Sensors can have cross

Sensors and Sensor Models

Typical Ultrasonic Scan of a corridor



Sensors and Sensor Models

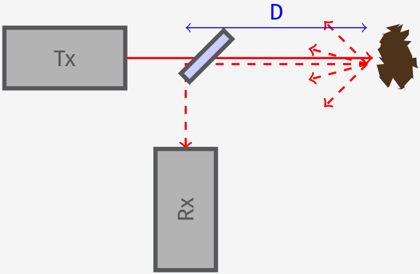
Scan Operation

- Given a 20 degrees opening angle, 18 sensors are needed to cover the whole 360 degrees area around the robot.
- Assume the maximum range we are interested in be 10m.
- The time of flight then is $2 \cdot \frac{10m}{330m/s} = 0.06s$
- A complete scan requires 1.08 s
- To allow frequent updates (necessary for high speed) the sensors have to be fired in parallel.
- This increases the risk of crosstalk

Sensors and Sensor Models

Laser Scanner

- Laser light instead of sound is used
- Transmitted and received beams are coaxial
- Receiver performs time-of-flight measurement:
  - Pulsed Laser
    - measurement of elapsed time directly
    - resolving picoseconds
    - current industry standard
  - Phase Shift Measurement
- Can perform 2D or 3D scans

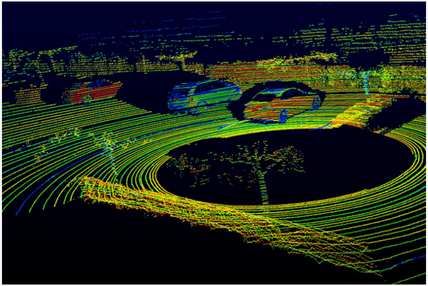


- Transmitted Beam
- Reflected Beam

Sensors and Sensor Models

3D Laser Scanner Example

- Valedyne HDL-64E scans 2.2Million Points per second
- 0.08 deg angular resolution
- $< 2cm$ Accuracy
- 120m Range
- 64 Parallel Channels



Images Courtesy of Valedyne

Sensors and Sensor Models

Time of Flight Camera

- Operates with similar principle to phase measurement Lidar
- Uses a modulated infrared LED to produce a collimated light source
- every pixel of the Photonic Mixer Device (PMD) simultaneously records depth and light intensity

Image Courtesy of Odos imaging

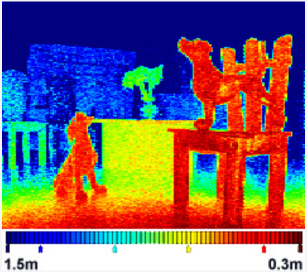


Image Courtesy of Shizuoka

Sensors and Sensor Models

Radar Sensor

- Gaining popularity in Autonomous Car Domain, already used in Adaptive Cruise Control
- Uses Radar at high frequency 76 - 77GHz
- Detection Range: 0.36m to 160m
- Varying Angle from > 40° to < 15°

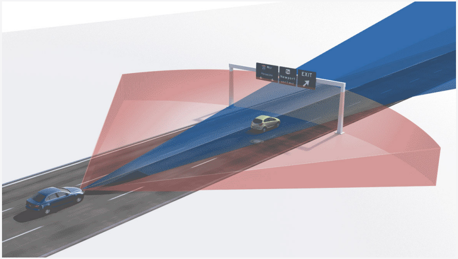


Image Courtesy of Bosch

Sensors and Sensor Models

Distance from Structured Light

- In order to obtain a 3D image with Structured Light, a series of musters is projected onto the target area.
- A normal Camera, specifically at a different angle to the projector, takes images of the object
- The distortion of the projected light, can be used to calculate the geometry of the projected object.

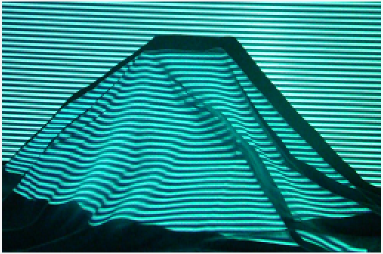
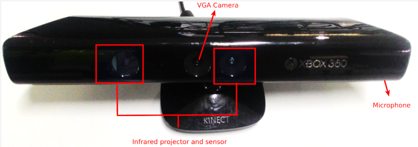


Image Courtesy of Automatic Modelling and Video Mapping Blogspot

Sensors and Sensor Models

Kinect I

- Kinect Projects a speckled pattern in Infrared into the scene.
- This image is detected by the infrared Camera.
- Each Speckle is surrounded by a unique pattern, allowing the projection to be mapped



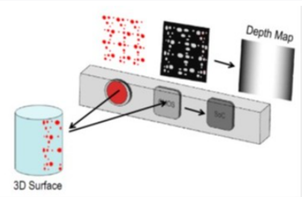


Image Courtesy Microsoft

Sensors and Sensor Models

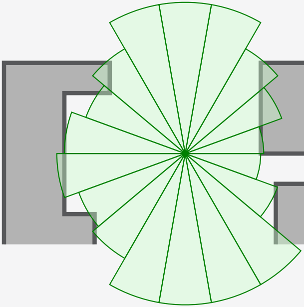
The Challenges in Mobile Robotics Sensing

- Mobile Robot has to perceive, analyse and interpret the state of its environment.
- Measurements in a real world are dynamically changing and prone to error
- Examples:
  - Moving Items
  - Changing Illumination
  - Unknown surface properties, such as reflectivity of items
- Cross Sensitivity of Robot Sensor to Robot Pose and Robot Environment Dynamics
  - very difficult to model, appear as random errors

Sensors and Sensor Models

Proximity Sensors

- The central task is to determine P(z|x), and later P(x|z)
- i.e. The Probability of a Measurement "z", given the robot is at location "x"
- Question: Where do the probabilities come from?



Sensors and Sensor Models

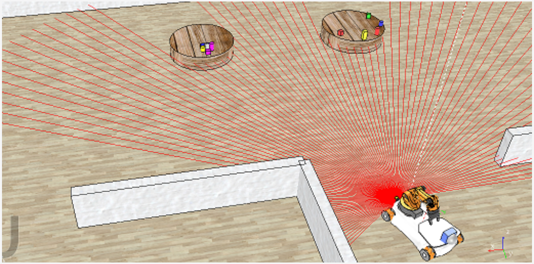
Beam based Sensor Model

- Scan z consists of K Measurements.

$$z = z_1, z_2, z_3, \cdots, z_K \tag{1}$$

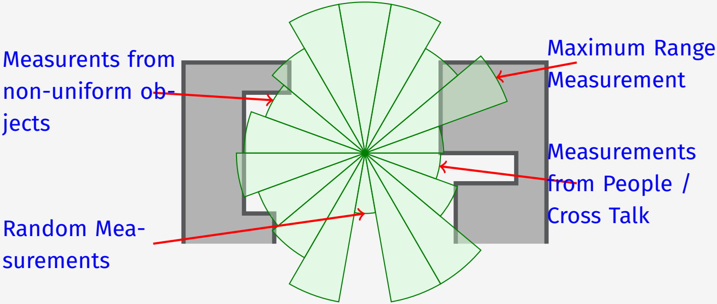
- Individual measurements are independent given the robot position.

$$P(z|x, m) = \prod_{k=1}^{K} P(z_k|x, m) \tag{2}$$



Sensors and Sensor Models

Typical Measurement Errors in Beam Measurements



Sensors and Sensor Models

Measurements can be caused by:

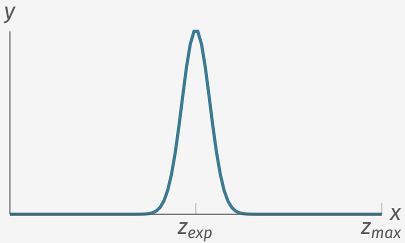
- a known object
- cross-talk
- an unexpected object
  - Furniture
  - Person
  - Part of Robot
  - Other Robot
- missing all objects
  - total reflection (at angle), e.g. Glass
  - total absorbtion

Noise is due to uncertainty:

- in measuring distance to known object
- in position of known object
- in position of additional objects
- in orientation of known object
- whether object is missed

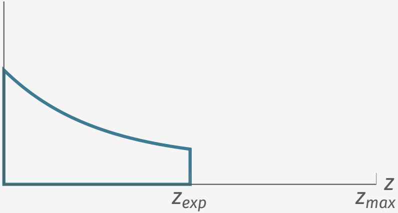
Beam Based Proximity Model

Measurement Noise



$$P_{hit}(z|x,m) = \eta \frac{1}{\sqrt{2\pi b}} e^{-\frac{1}{2}\frac{(z-z_{exp}^2}{b}} \quad (3)$$

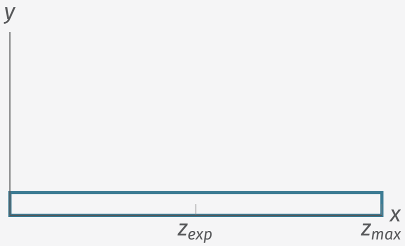
Unexpected Obstacles



$$P_{unexp}(z|x,m) = \begin{cases} \eta\lambda e^{-\lambda z} & z < z_{exp} \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

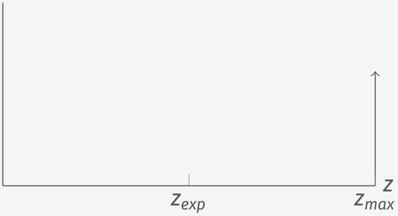
Beam Based Proximity Model

Random Measurement



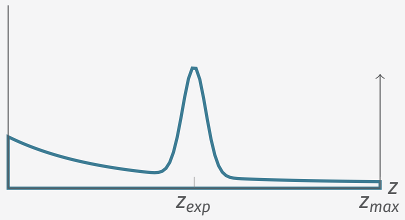
$$P_{rand}(z|x,m) = \eta \frac{1}{z_{max}} \qquad z < z_{max} \quad (5)$$

Maximum Range



$$P_{max}(z|x,m) = \delta(z - z_{max}) \quad (6)$$

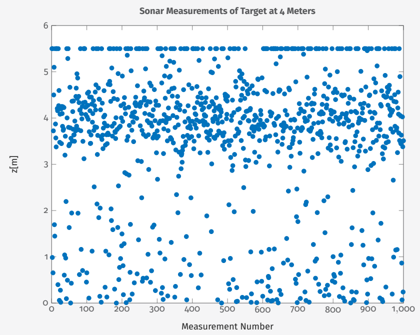
Sensors and Sensor Models

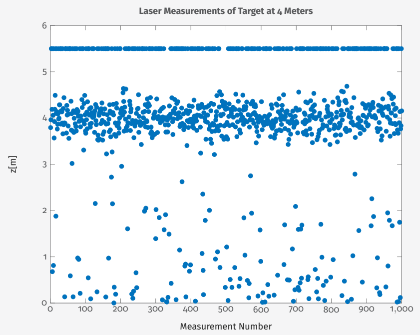


$$P(z|x,m) = \begin{bmatrix} \alpha_{hit} \\ \alpha_{unexp} \\ \alpha_{max} \\ \alpha_{rand} \end{bmatrix}^T \cdot \begin{bmatrix} P_{hit}(z|x,m) \\ P_{unexp}(z|x,m) \\ P_{max}(z|x,m) \\ P_{rand}(z|x,m) \end{bmatrix} \quad (7)$$

How can the model parameters be determined?

Sensors and Sensor Models





Sensors and Sensor Models

Model Approximation

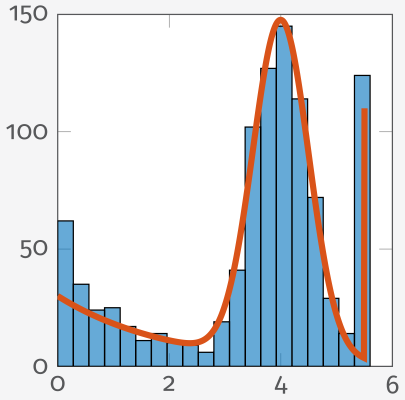
- Maximise Log Likelihood of the data

$$P(z|z_{exp})$$

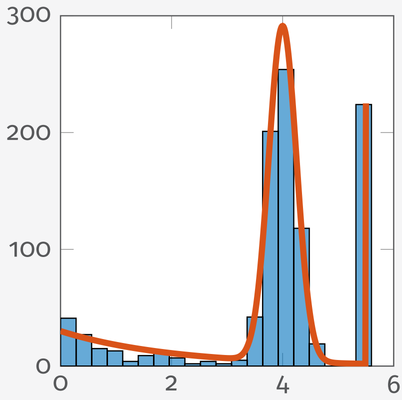
- Search space of n-1 parameters
  - Hill climbing
  - Gradient Descent
  - Genetic Algorithms
  - ...
- Deterministically compute the n-th parameter to satisfy normalisation constraint

Approximation Results

Sonar Measurements



Laser Measurements

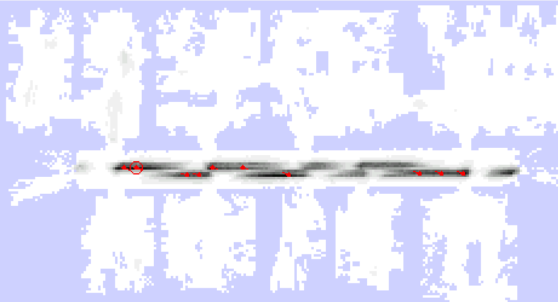


Sensors and Sensor Models

Scan in Building z

Source: Uni Freiburg, Wolfram

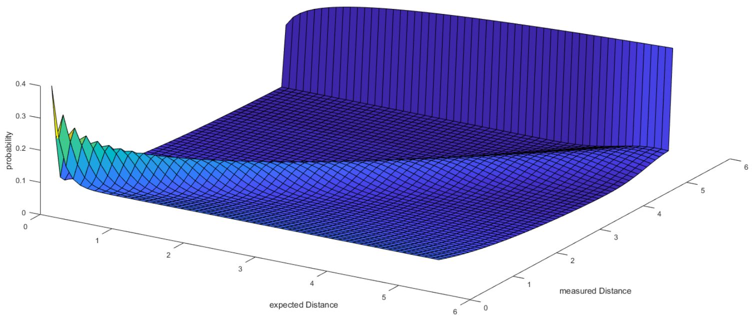
Likelihood of Measurement $P(z|x, m)$



Source: Uni Freiburg, Wolfram

Sensors and Sensor Models

Distribution as function of expected distance



Also as function of angle of incidence.

Sensors and Sensor Models

Summary Beam-based Model

- Assumes independence between beams.
- Mathematical model for different causes for measurement errors
- Assumes no correlation between different causes
- Parameters can be learned from real data.
- Model should be learned for different distances and angles of incidence
- Determine expected distances by ray-tracing.
- Expected distances can be pre-processed for a given map
- Beam Model is not smooth for small obstacles or edges
- Beam Model is not very efficient

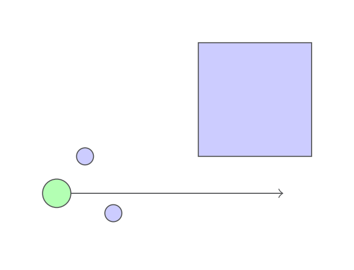
Sensors and Sensor Models

Scan Based Model

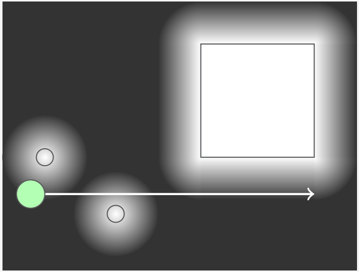
- Scan Based Model calculates a probability based on a mixture of:
  - a Gaussian distribution with mean at distance to closest obstacle,
  - a uniform distribution for random measurements, and
  - a small uniform distribution for max range measurements.
  - Again, independence between different components is assumed.

Sensors and Sensor Models

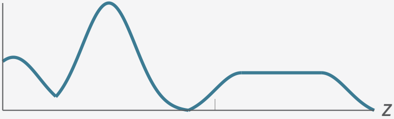
Map m



Likelihood Field



$P(z|x, m)$



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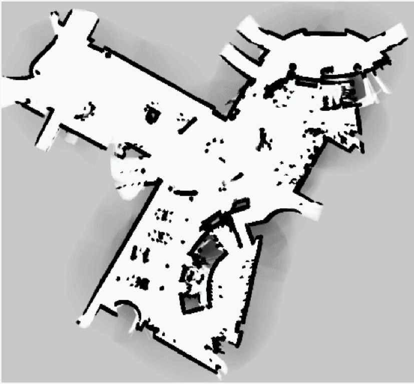
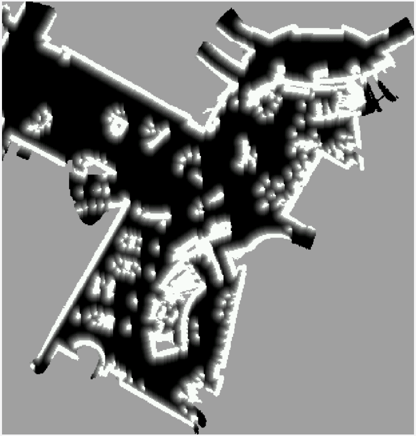
Sensors and Sensor Models

Occupancy Map



Source: Uni Freiberg, Wolfram

Likelihood Map

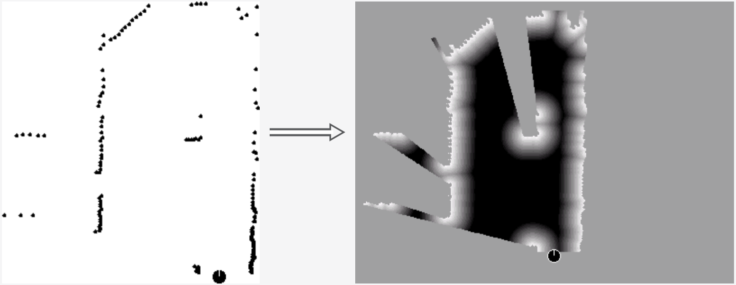


Source: Uni Freiberg, Wolfram

Sensors and Sensor Models

Scan Matching

- Extract Likelihood Map from Scan and use it to match additional scans



Sensors and Sensor Models

Properties of Scan Models

- Highly Efficient, using 2D Tables only
- Smooth w.r.t. to small changes in robot position.
- Allows gradient descent, scan matching.
- Ignores physical properties of beams.
- Will it work for ultrasound sensors?

Sensors and Sensor Models

Additional Models of Proximity Sensors

- **Map matching (sonar, laser)**: generate small, local maps from sensor data and match local maps against global model.
- **Scan matching (laser)**: map is represented by scan endpoints, match scan into this map.
- **Features (sonar, laser, vision)**: Extract features such as doors, hallways from sensor data.

Sensors and Sensor Models

Landmarks

Landmarks

- Active beacons (e.g., radio, GPS)
- Passive (e.g., visual, retro-reflective)
- Standard approach is triangulation
- Sensor provides
  - distance, or
  - bearing, or
  - distance and bearing.

Sensors and Sensor Models

QR Code Markers

Source: IEEE RAS Summer School

Colored Markers

Source: Uni Freiburg, Wolfram

Sensors and Sensor Models

Probabilistic Model

Algorithm for Landmark Detection Model:

$P(z|x, m)$

For Each Measurement of a Target i

$z = \langle d, \alpha \rangle, x = \langle x, y, z \rangle$

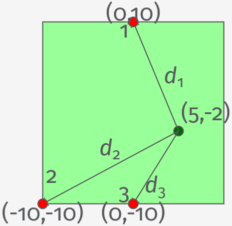
$$\hat{d} = \sqrt{(m_{x_i} - x)^2 + (m_{y_i} - y)^2} \tag{8}$$

$$\hat{\alpha} = atan2(m_{y_i} - y, m_{x_i} - x) - \theta \tag{9}$$

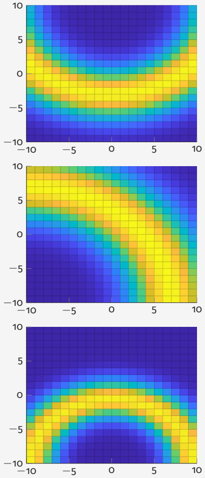
$$P(z|x, m) = \prod^{i} \Phi(\hat{d} - d, \sigma_d) \cdot \Phi(\hat{\alpha} - \alpha, \sigma_\alpha) \tag{10}$$

Distance based Densities

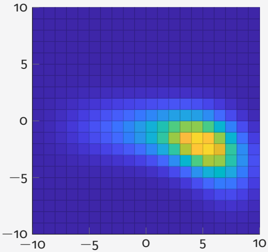
Map



Distance Densities



Combined Probability



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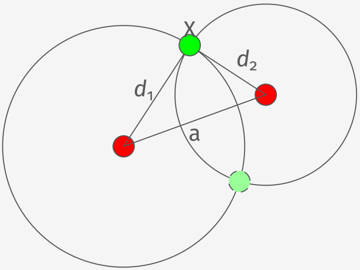
Distance only Calculations



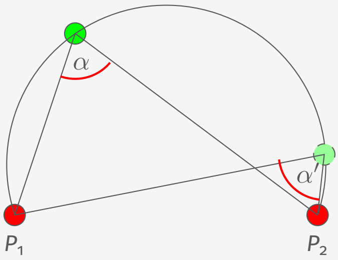
Calculations

Using Trigonometry, including Cosine Rule and coordinates of markers to find intersections of distance circles.

- Beware of Ghost Positions
- Can be removed with multiple markers, odometry readings, or controlled movements

Sensors and Sensor Models

Bearings only no uncertainty



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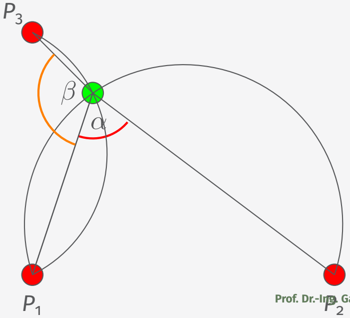
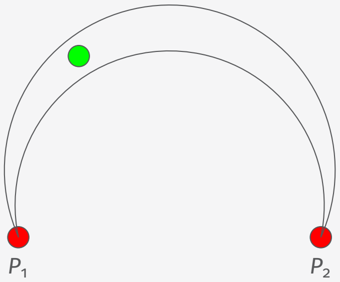
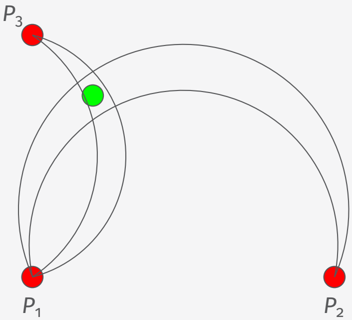


Sensors and Sensor Models

Bearings only with Uncertainty





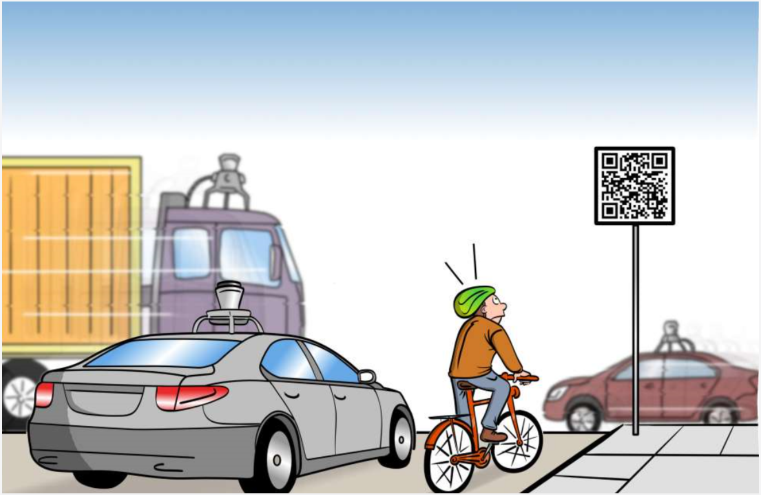
Sensors and Sensor Models

Summary of Sensor Models

- Explicitly modeling uncertainty in sensing is key to robustness.
- In many cases, good models can be found by the following approach:
    - Determine parametric model of noise free measurement.
    - Analyze sources of noise.
    - Add adequate noise to parameters (eventually mix in densities for noise).
    - Learn (and verify) parameters by fitting model to data.
    - Likelihood of measurement is given by "probabilistically comparing" the actual with the expected measurement.
- This holds for motion models as well.
- It is extremely important to be aware of the underlying assumptions!

Sensors and Sensor Models

The Future??



Source: Christian Möller