Simultaneous Localization and Mapping (SLAM)

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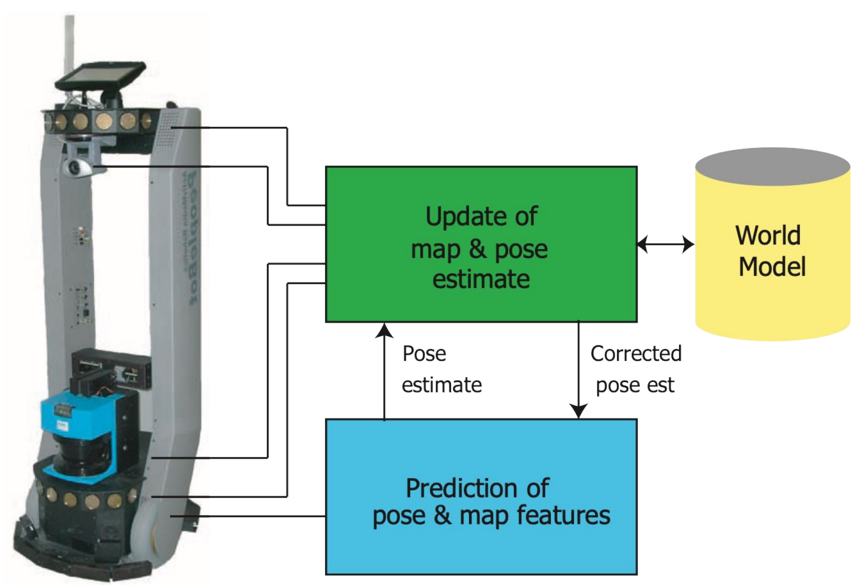
The Robotics Context



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Terminology

Pose	x_r	The robots position and orientation
Path/Trajectory	$X=\{x_r\}_i$	The set of poses the robot has passed through
Landmark/Feature	z_i	A landmarks in the environment used for navigation etc.
Map	$Z=\{z_i\}$	The set of all landmarks
Measurements	f_i	The estimates provided by sensors which are contaminated by noise
Dead reckoning	d_i	Data from the dead reckoning sensors
Estimate	$P(x,z,d,f,\Lambda)$	Estimate of the pose and map information

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Outline

- What is Localization, Mapping and SLAM?
- Management of process uncertainty
- Modeling the environment
- Example use of SLAM
- Summary and Future Challenges

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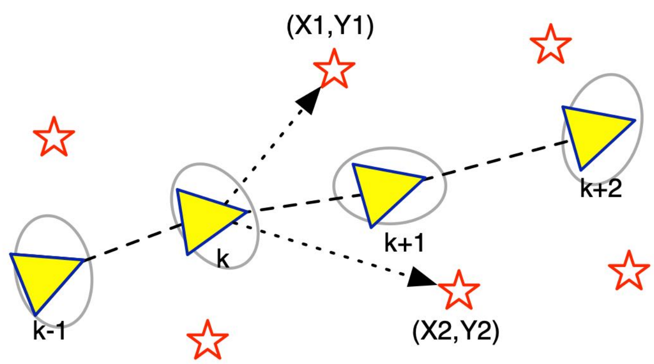
The localization problem



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Localization in robotics

- One of the most common problems in mobile robotics
- Prior Information
  - A model of the environment is available
  - A kinematic/dynamic model for the robot
  - A set of sensors to detect features in the environments
  - A strategy to associate features with the environmental model
- Problem: Estimation of the robot pose (position & orientation)

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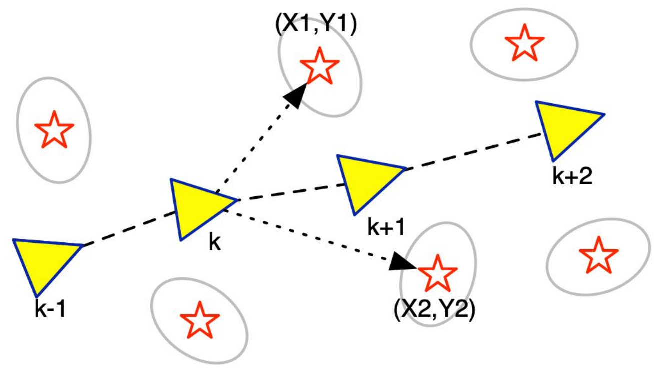
The mapping problem



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Mapping in robotics

- Frequently used in surveying and in perception such as vision
- Prior Information
  - A set of sensors for feature generation
  - A kinematic/dynamic model of the robot
  - A model of uncertainty propagation
  - A data association strategy
  - Knowledge of the trajectory traversed by the robot
- Problem: Estimate the position of features in the environment

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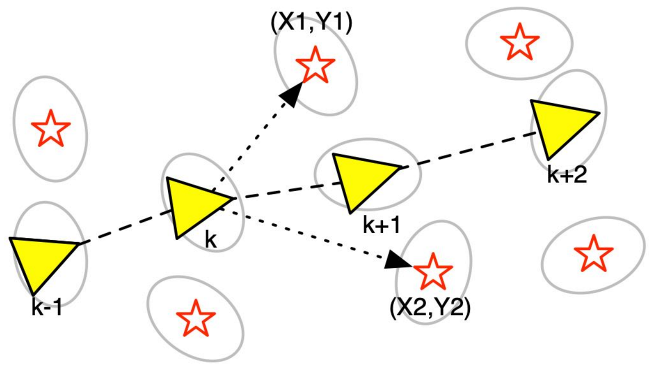
The SLAM problem



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Simultaneous localization and mapping

- Simultaneous estimation of robot location and environmental map / features (SLAM)
- Prior information
  - Kinematic/dynamic model of robot
  - Sensors for feature detection incl model of uncertainty
  - A method for data association
- Problem: Estimate pose for robot and the position of map features while traversing an environment

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Components to the puzzle

- A kinematic/dynamic model for the vehicle
- A strategy to manage uncertainty over time
- Sensors / features for modeling of environment
- A method for data association across

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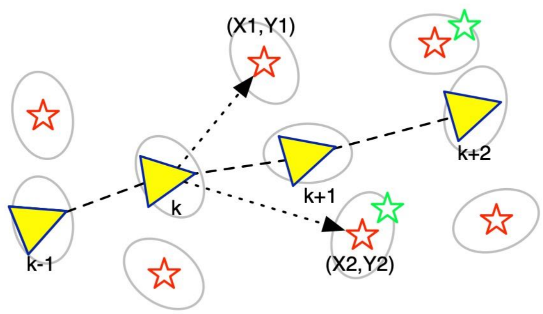
Modeling of uncertainty

- There are several ways to represent uncertainty.
- Close ties to representations and data association.
- Multiple associations => multiple hypotheses



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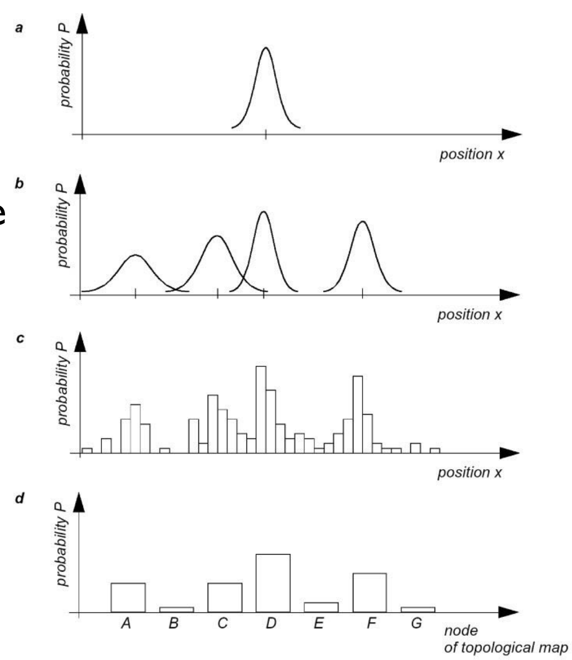
Uncertainty Models

- Uni-Modal
- Multi-Hypotheses (Gaussian Mixture Model)
- Grid Tessellation
- Topological



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Preliminaries on modelling

- Assume a state of $$s_i = \begin{bmatrix} x_r \\ z_1 \\ z_2 \\ \vdots \\ z_n \end{bmatrix}$$
- Using a state space model we can estimate the system evolution

$$\begin{aligned} s_{i+1} &= \mathbf{F}s_i + \mathbf{G}d_i + v_i \\ \{f_{i+1}\} &= \mathbf{H}s_{i+1} + w_{i+1} \end{aligned}$$

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Kalman Filter Model

- Under the assumption of good data association the Kalman provides an optimal LSQ solution to the problem
- The Kalman filter model is a two stage process
  - Prediction of the process evolution
  - Update of the prediction based on measured data

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Kalman Prediction

- The prediction step

$$\begin{aligned} s_{i|i-1} &= \mathbf{F} s_{i-1|i-1} + \mathbf{G} d_i \\ \Sigma_{i|i-1} &= \mathbf{F} \Sigma_{i-1|i-1} \mathbf{F}^T + \mathbf{Q}_i \end{aligned}$$

- The term Σ is the estimate of innovation covariance, and Q is the system noise

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Kalman Updating

- From measurements the prediction can be corrected

$$\begin{aligned} s_{i|i} &= s_{i|i-1} + \mathbf{K}_i (f_i - \mathbf{H} s_{i|i-1}) \\ \mathbf{K}_i &= \Sigma_{i|i-1} \mathbf{H}^T \mathbf{S}_i^{-1} \\ \mathbf{S}_i &= \mathbf{H} \Sigma_{i|i-1} \mathbf{H}^T + \mathbf{R}_i \\ \Sigma_{i|i} &= (\mathbf{I} - \mathbf{K}_i \mathbf{H}) \Sigma_{i|i-1} \end{aligned}$$

- R_i is the measurement noise

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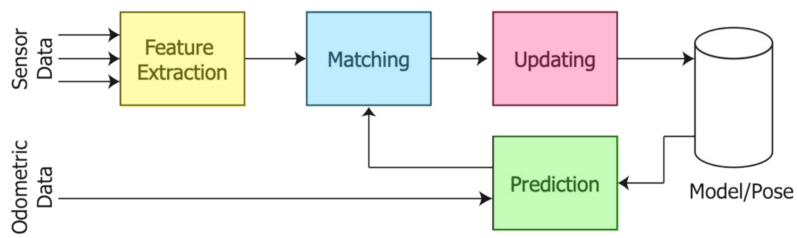
Kalman Example



- Using the above mentioned model it is possible to perform mapping and localization.

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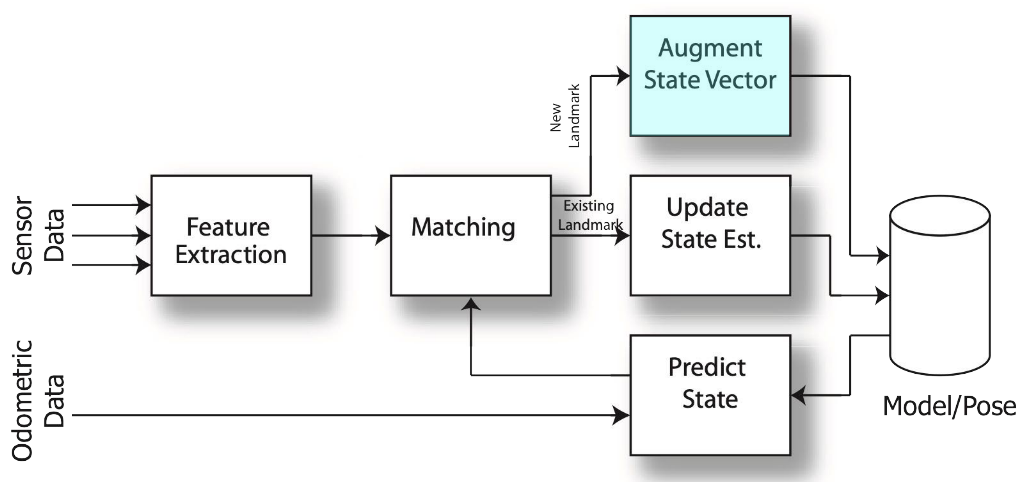
Kalman Example Expanded



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Introduction of new features

- The new feature is added to the state vector
  - Strategy 1: wait until stability established
    - Appropriate for high frequency sensors
  - Strategy 2: establish covariance with other features for initial estimate
    - Appropriate for low frequency sensors
- A simple example of localization

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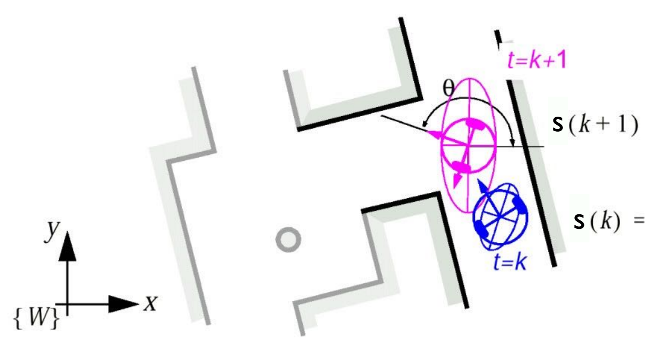
Kalman Example



- Here the robot pose has been predicted based on odometric information

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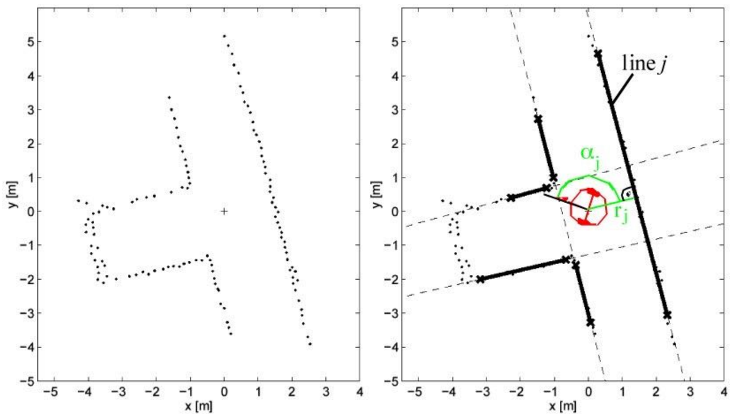
Kalman Example



- From laser data line features are extracted using a least square fit

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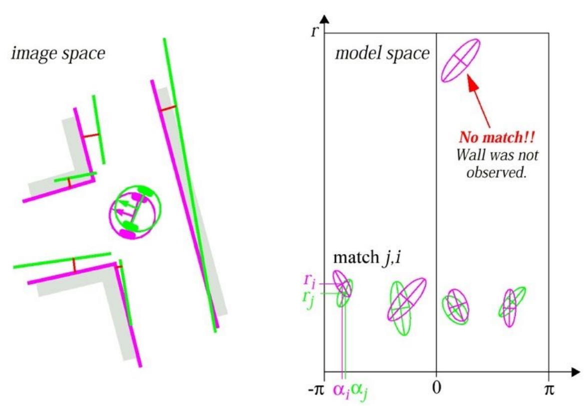
Kalman Example



- The extracted lines are matched the model using similarity in polar space

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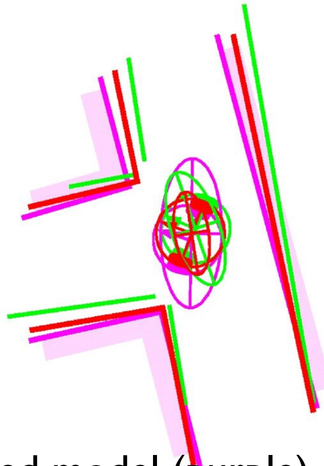
Kalman Example



- The predicted model (purple) and the measured data (green) are combined in the Kalman update step to refine the estimate (red) and the process can be repeated.

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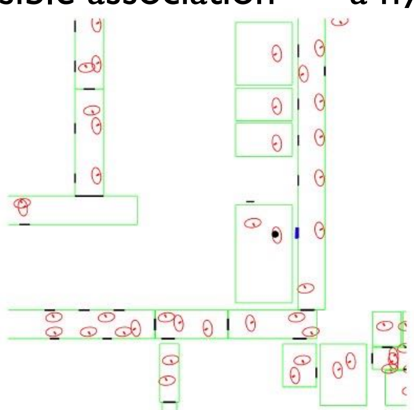
The Multi-Hypothesis Approach

- The Kalman filter assumes that the data association is trivial. In some cases associations are noisy.
- Each possible association => a hypothesis



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Particle Filtering

- In general the probability distribution is not Gaussian or uni-modal
- Particle filters allow approximation of any distribution by sampling
- Idea/intuition:
  - Distribute a number of particles across the world representation, each particle is a hypothesis. The density of particles = the distribution
  - Update particles based on measurement data
  - Too unlikely hypotheses are eliminated
  - Likely hypotheses are “replicated” in local neighborhood
  - The process is repeated until the distributed stabilizes

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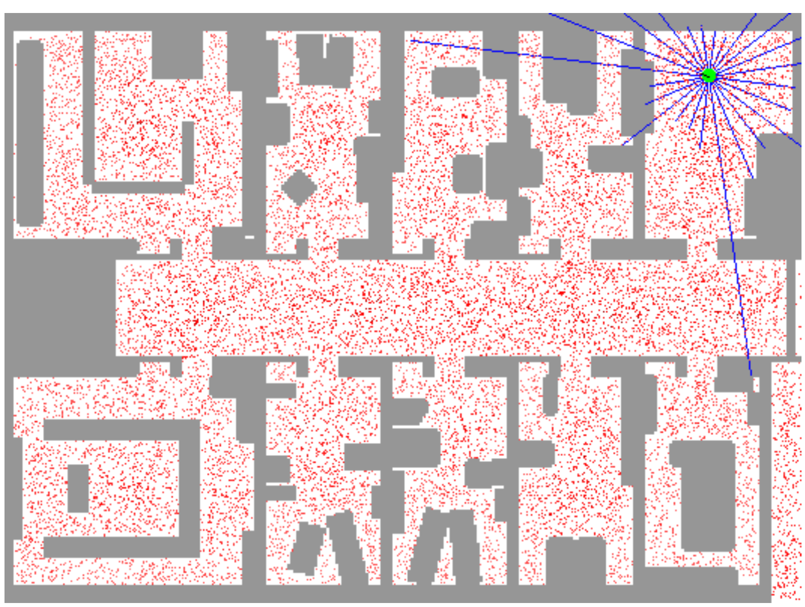
Particle Filtering - Example



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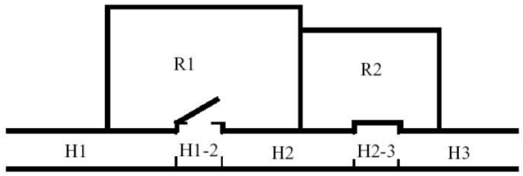
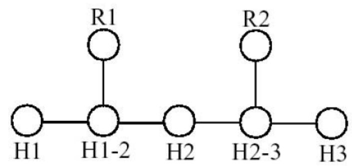
Topological Models





	Wall	Closed door	Open door	Open hallway	Foyer
Nothing detected	0.70	0.40	0.05	0.001	0.30
Closed door detected	0.30	0.60	0	0	0.05
Open door detected	0	0	0.90	0.10	0.15
Open hallway detected	0	0	0.001	0.90	0.50

- Adopted from I. Nourbakhsh, “Dervish”

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Representation of the environment

- A variety of models have been proposed
  - Grid-based tessellation of environment
  - Feature based models
  - Graphical models
  - Topological model of environment
  - Hybrid Models

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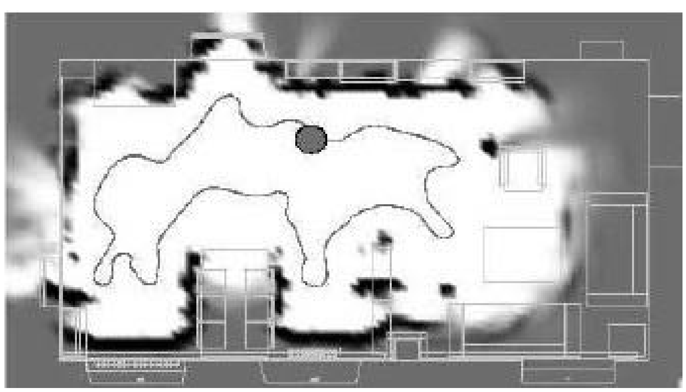
Grid Based Models



$Space$	$\mathcal{O}(D^2)$
$Update$	$\mathcal{O}(R^2)$ $(Local\ region)$
$Represent$	$p_{(x,y)}(occupied \vert F)$

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Feature Based Models

Space	$\mathcal{O}(N)$
Update	$\mathcal{O}(N^2)$
Represent	$p(z_i \mid F)$

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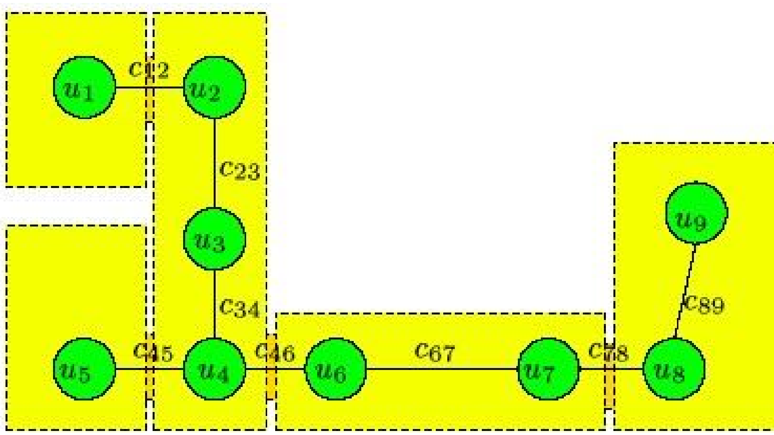
Topological Models



Space	$\mathcal{O}(N \times A)$
Update	$\mathcal{O}(\|A\|)$
Represent	$p(z_i \mid F)$

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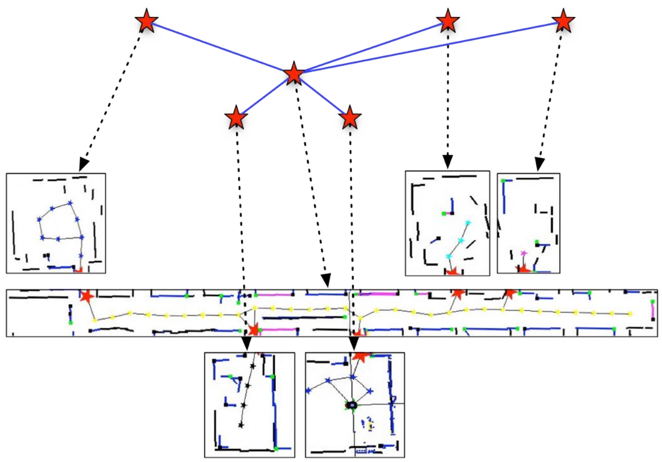
Hybrid Models



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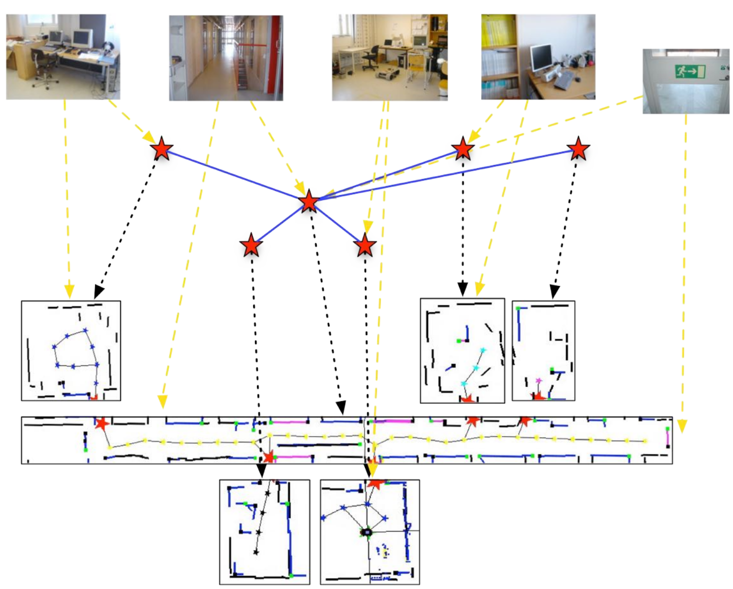
Hybrid Models



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Example Applications

- In-door application for coverage and mapping of an office environment
- Out-door application with a rugged robot for mapping of a small urban area

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Indoor navigation

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The Robot Systems

- Differential Drive Robot
  - Pioneer PeopleBot
- Video and Laser Sensors
  - SICK LMS 221
  - Web camera (VGA)
- Odometric Feedback
- A mixed environmental model

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The Representational Framework

- Representation of environment using
  - Points (high curvature)
  - Line segments (hough transform)
  - Door-ways (pattern matching)
  - Lamps in ceiling (pattern matching)
  - Visual lines in ceiling (lamps, ...)
  - Estimation based on an EKF model with overlaid topological graph model

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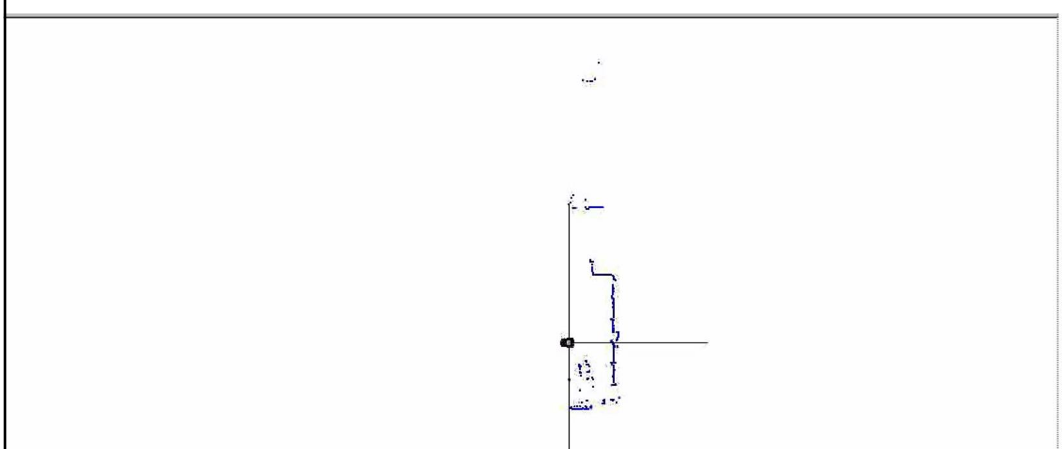
Results from a test run



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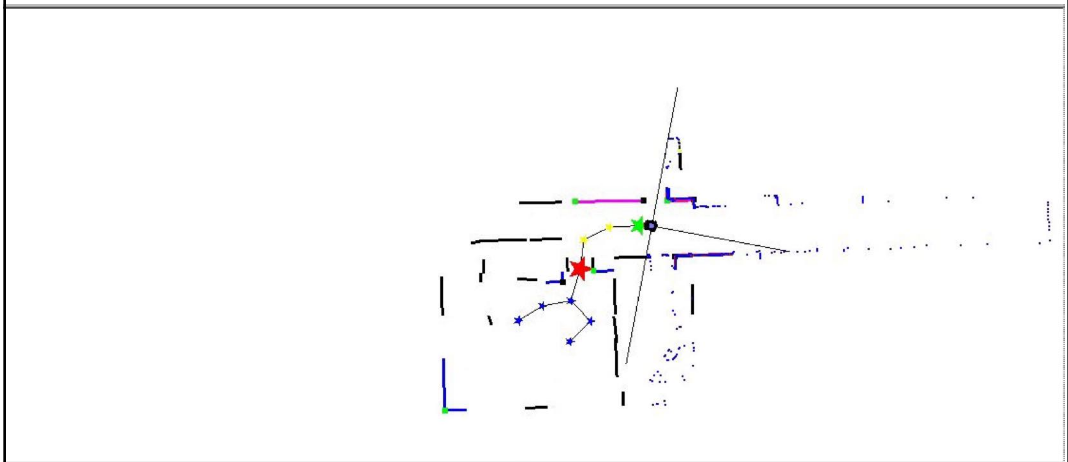
Results from a test run



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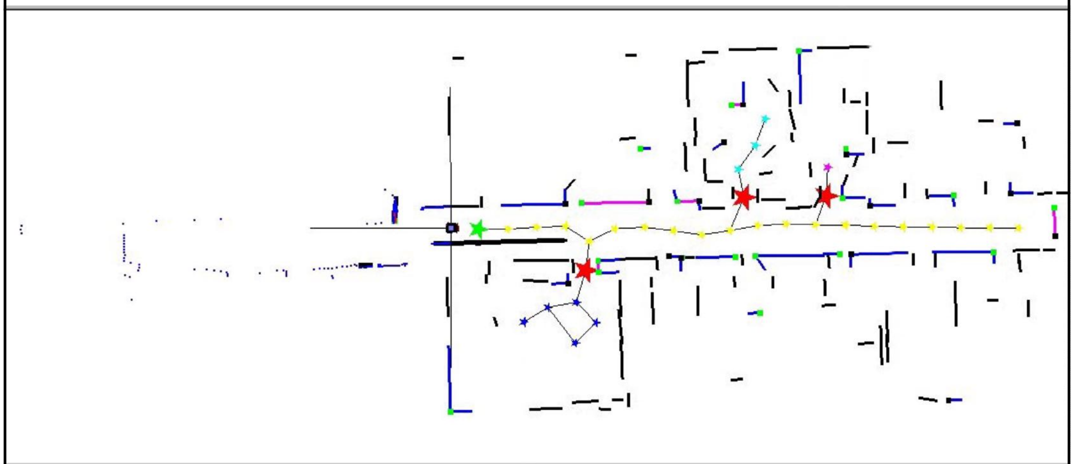
Results from a test run



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Results from a test run

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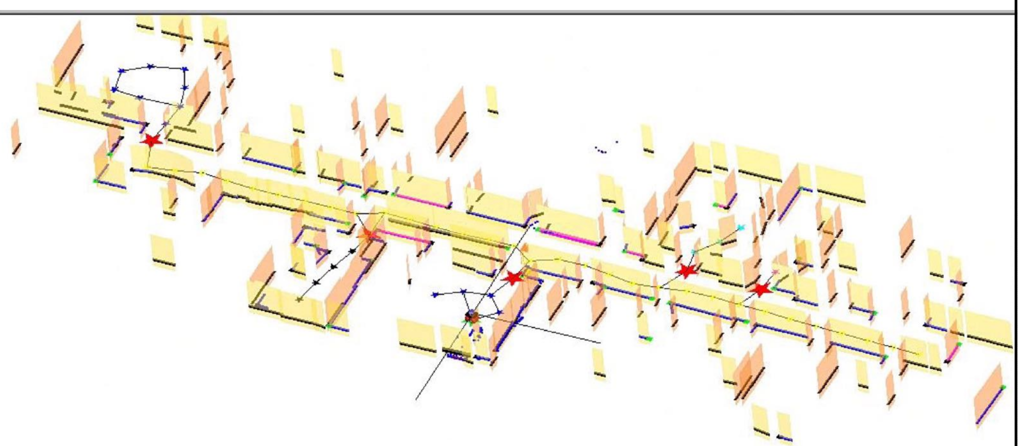
Results from a test run



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Outdoor navigation

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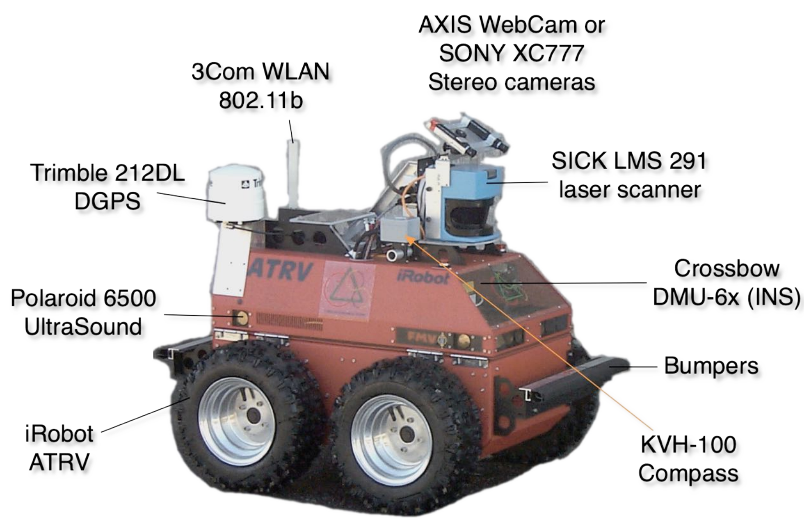
The Robot System



- Line based environmental model
- Evaluated using both a graphical and an EKF approach

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The evaluation environment

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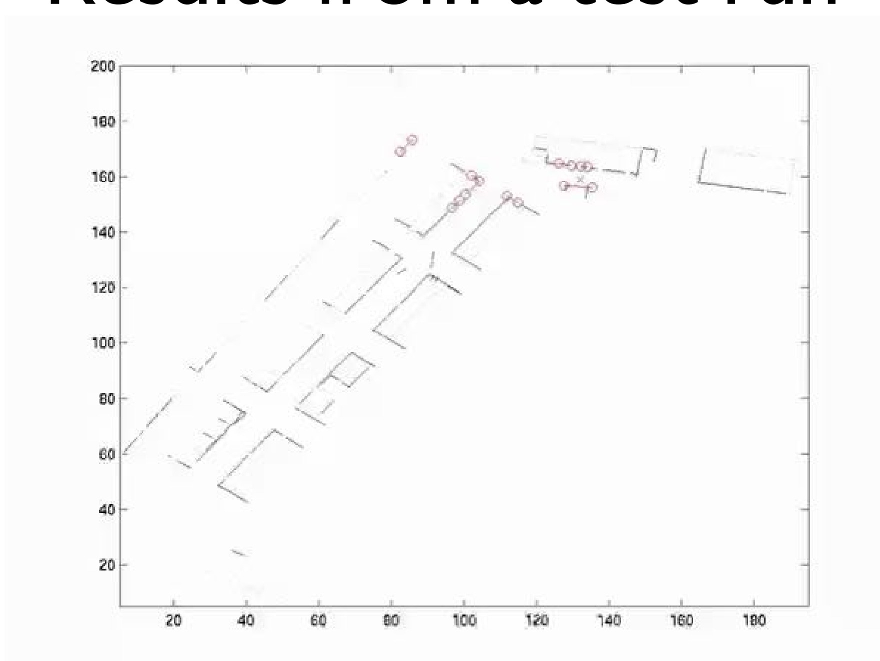
Results from a test run



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Summary

- The underlying theoretical model for SLAM is by now well established
- Graphical models and ways to partition the estimation problem has eliminated or reduced computational challenges
- Mature models for vehicles and sensors are available
- An increasing number of applications with operation of vehicle over extended periods
- SLAM is by now a mature technology

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Future challenges in SLAM

- SLAM for truly unstructured environment
- Extended use of vision for SLAM
- SLAM in noisy environments
- Active exploration of environments
- Integration with other sensor systems

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The End!

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