Robot Mapping

Introduction to Robot Mapping

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What is Robot Mapping?

- **Robot** – a device, that moves through the environment
- **Mapping** – modeling the environment

Related Terms

State Estimation	Localization
Mapping	SLAM
Navigation	Motion Planning

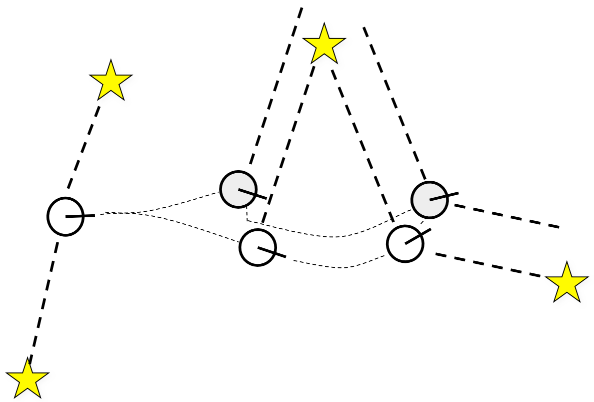
What is SLAM?

- Computing the robot's pose and the map of the environment at the same time

- **Localization:** estimating the robot's location
- **Mapping:** building a map
- **SLAM:** building a map and locating the robot simultaneously

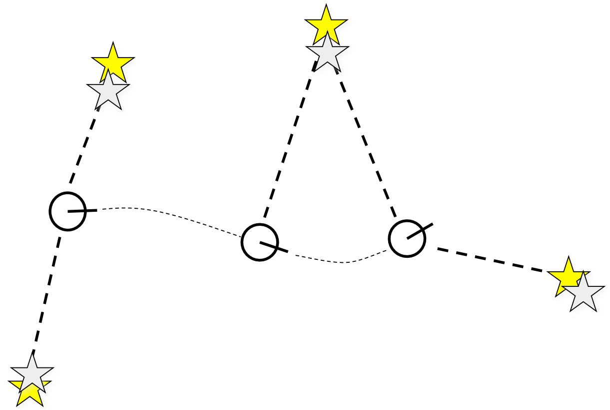
Localization Example

- Estimate the robot's poses given landmarks



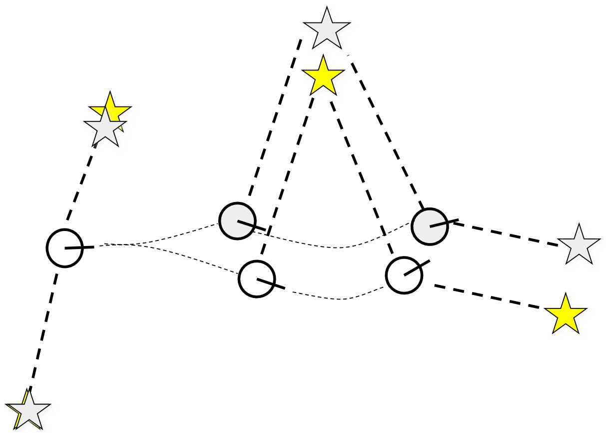
Mapping Example

- Estimate the landmarks given the robot's poses



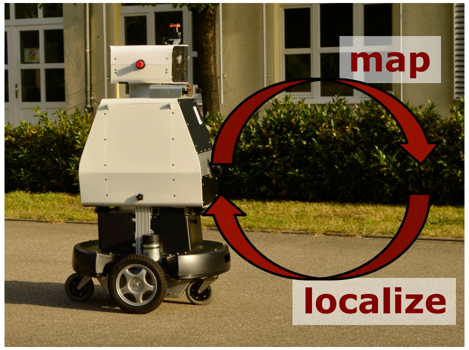
SLAM Example

- Estimate the robot's poses and the landmarks at the same time



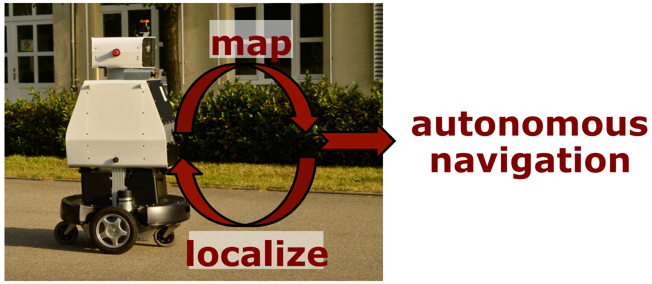
The SLAM Problem

- SLAM is a **chicken-or-egg** problem:
  → a map is needed for localization and
  → a pose estimate is needed for mapping



SLAM is Relevant

- It is considered a fundamental problem for truly autonomous robots
- SLAM is the basis for most navigation systems



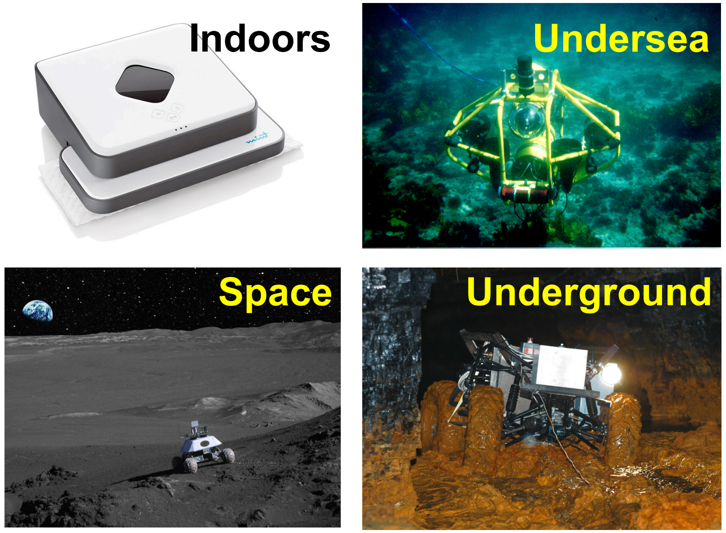
SLAM Applications

- SLAM is central to a range of indoor, outdoor, in-air and underwater applications for both manned and autonomous vehicles.

Examples:

- At home: vacuum cleaner, lawn mower
- Air: surveillance with unmanned air vehicles
- Underwater: reef monitoring
- Underground: exploration of mines
- Space: terrain mapping for localization

SLAM Applications



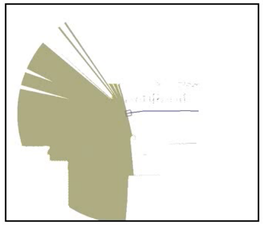
Courtesy of Evolution Robotics, H. Durrant-Whyte, NASA, S. Thrun

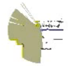
SLAM Showcase – Mint

Courtesy of Evolution Robotics (now iRobot)

SLAM Showcase – EUROPA

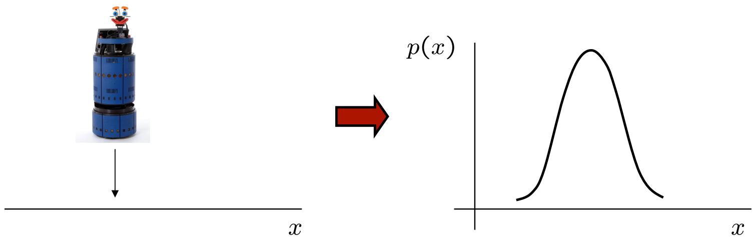
Mapping Freiburg CS Campus





Probabilistic Approaches

- Uncertainty in the robot's motions and observations
- Use the probability theory to explicitly represent the uncertainty



"The robot is exactly here"

"The robot is somewhere here"

Definition of the SLAM Problem

Given

- The robot's controls

  $u_{1:T} = \{u_1, u_2, u_3 \ldots, u_T\}$
- Observations

  $z_{1:T} = \{z_1, z_2, z_3 \ldots, z_T\}$

Wanted

- Map of the environment

  m
- Path of the robot

  $x_{0:T} = \{x_0, x_1, x_2 \ldots, x_T\}$

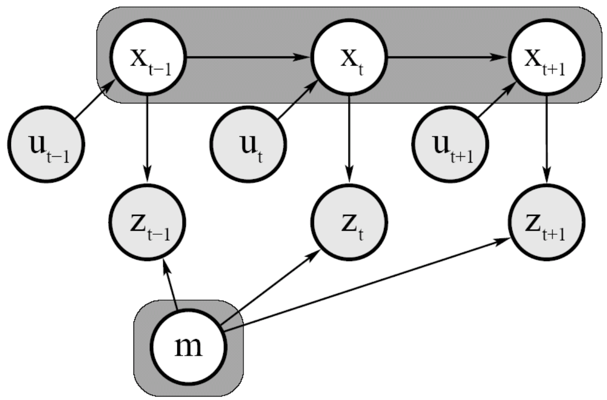
In Probabilistic Terms

Estimate the robot's path and the map

$$p(x_{0:T}, m \mid z_{1:T}, u_{1:T})$$

distribution path map given observations controls

Graphical Model



$$p(x_{0:T}, m \mid z_{1:T}, u_{1:T})$$

Full SLAM vs. Online SLAM

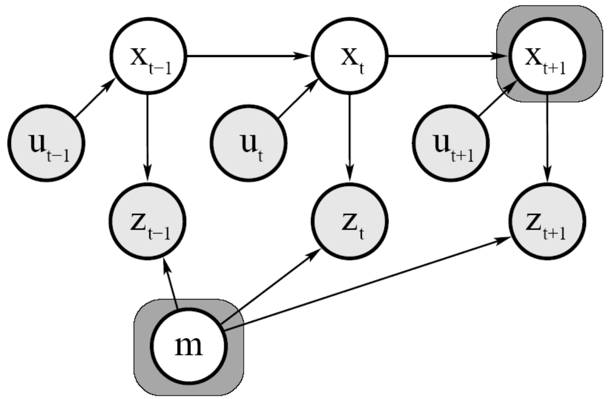
- Full SLAM estimates the entire path

$$p(x_{0:T}, m \mid z_{1:T}, u_{1:T})$$

- Online SLAM seeks to recover only the most recent pose

$$p(x_t, m \mid z_{1:t}, u_{1:t})$$

Graphical Model of Online SLAM



$$p(x_{t+1}, m \mid z_{1:t+1}, u_{1:t+1})$$

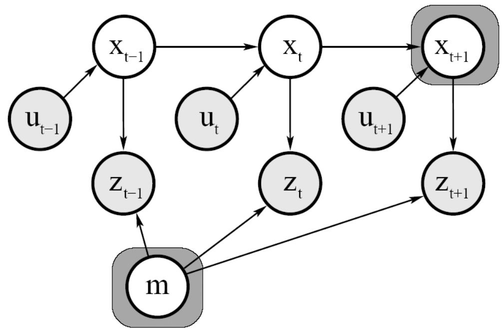
Online SLAM

- Online SLAM means marginalizing out the previous poses

$$p(x_t, m \mid z_{1:t}, u_{1:t}) = \int_{x_0} \cdots \int_{x_{t-1}} p(x_{0:t}, m \mid z_{1:t}, u_{1:t})\, dx_{t-1} \ldots dx_0$$

- Integrations are typically done recursively, one at at time

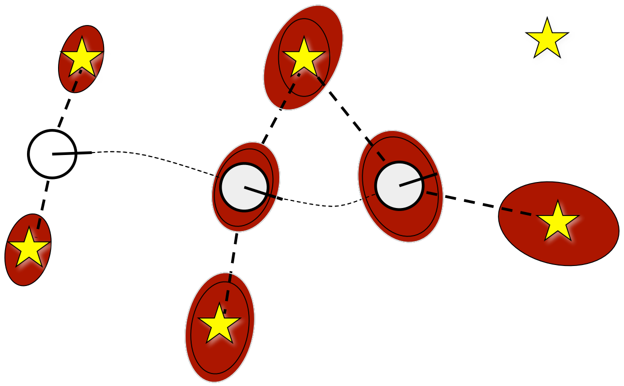
Graphical Model of Online SLAM



$$p(x_{t+1}, m \mid z_{1:t+1}, u_{1:t+1}) = \int_{x_0} \cdots \int_{x_t} p(x_{0:t+1}, m \mid z_{1:t+1}, u_{1:t+1})\, dx_t \ldots dx_0$$

Why is SLAM a hard problem?

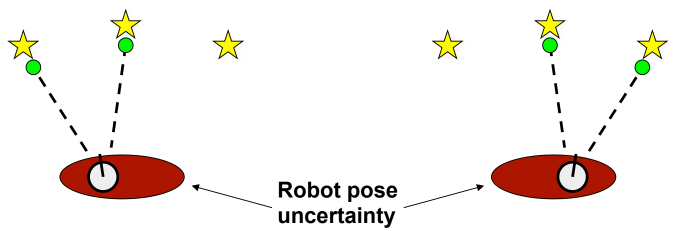
1. Robot path and map are both **unknown**



2. Map and pose estimates correlated

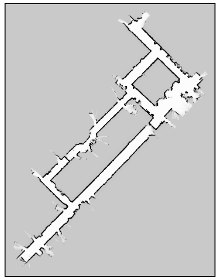
Why is SLAM a hard problem?

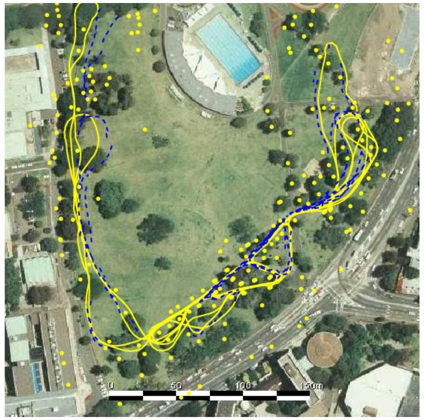
- The **mapping between observations and the map is unknown**
- Picking **wrong** data associations can have **catastrophic** consequences (divergence)



Taxonomy of the SLAM Problem

Volumetric vs. feature-based SLAM

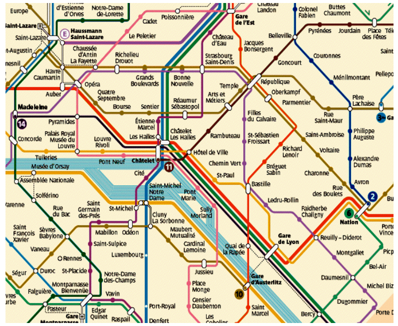




Courtesy by E. Nebot

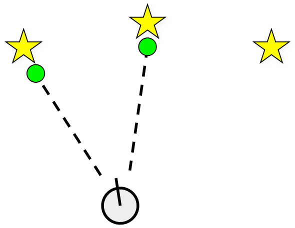
Taxonomy of the SLAM Problem

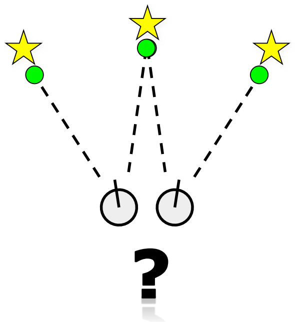
Topologic vs. geometric maps



Taxonomy of the SLAM Problem

Known vs. unknown correspondence



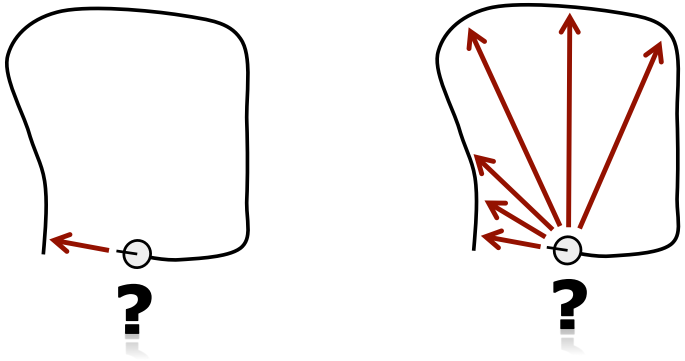


Taxonomy of the SLAM Problem

Static vs. dynamic environments

Taxonomy of the SLAM Problem

Small vs. large uncertainty



Taxonomy of the SLAM Problem

Active vs. passive SLAM

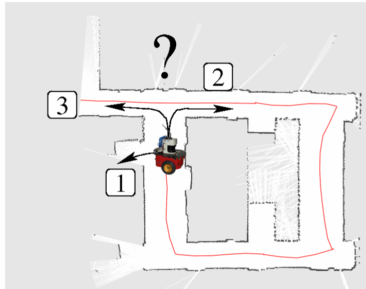


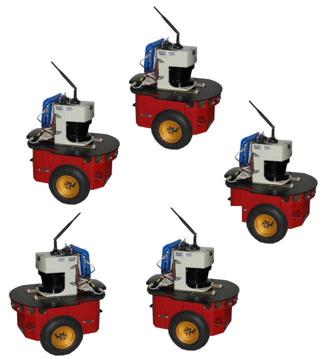
Image courtesy by Petter Duvander

Taxonomy of the SLAM Problem

Any-time and any-space SLAM

Taxonomy of the SLAM Problem

Single-robot vs. multi-robot SLAM



Approaches to SLAM

- Large variety of different SLAM approaches have been proposed
- Most robotics conferences dedicate multiple tracks to SLAM
- The majority uses probabilistic concepts
- History of SLAM dates back to the mid-eighties

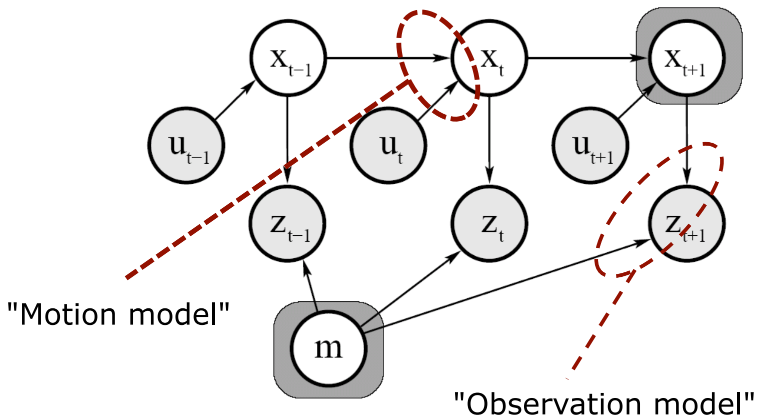
SLAM History by Durrant-Whyte

- 1985/86: Smith et al. and Durrant-Whyte describe geometric uncertainty and relationships between features or landmarks
- 1986: Discussions on how to do the SLAM problem at ICRA; key paper by Smith, Self and Cheeseman
- 1990-95: Kalman-filter based approaches
- 1995: SLAM acronym coined at ISRR'95
- 1995-1999: Convergence proofs & first demonstrations of systems
- 2000: Wide interest in SLAM started

Three Main Paradigms

Kalman filter	Particle filter	Graph-based

Motion and Observation Model



Motion Model

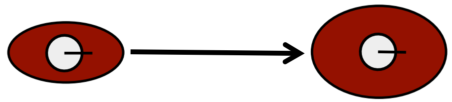
- The motion model describes the relative motion of the robot

$$p(x_t \mid x_{t-1}, u_t)$$

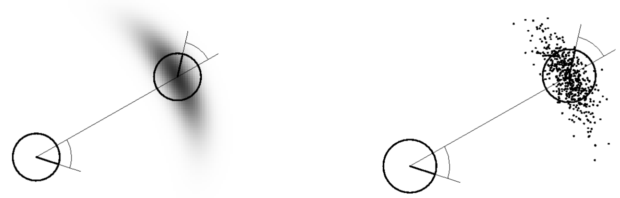
distribution new pose given old pose control

Motion Model Examples

- Gaussian model



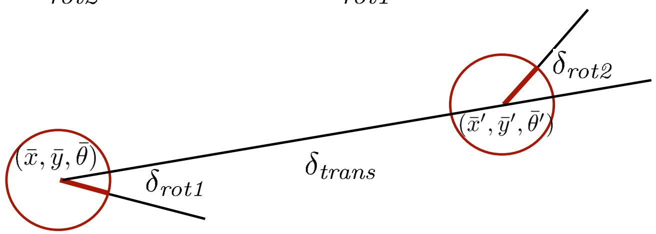
- Non-Gaussian model



Standard Odometry Model

- Robot moves from $(\bar{x}, \bar{y}, \bar{\theta})$ to $(\bar{x}', \bar{y}', \bar{\theta}')$
- Odometry information $u = (\delta_{rot1}, \delta_{trans}, \delta_{rot2})$

$$\begin{aligned}\delta_{trans} &= \sqrt{(\bar{x}' - \bar{x})^2 + (\bar{y}' - \bar{y})^2} \\ \delta_{rot1} &= \operatorname{atan2}(\bar{y}' - \bar{y}, \bar{x}' - \bar{x}) - \bar{\theta} \\ \delta_{rot2} &= \bar{\theta}' - \bar{\theta} - \delta_{rot1}\end{aligned}$$



More on Motion Models

- Course: Introduction to Mobile Robotics, Chapter 6
- Thrun et al. "Probabilistic Robotics", Chapter 5

Observation Model

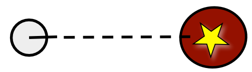
- The observation or sensor model relates measurements with the robot's pose

$$p(z_t \mid x_t)$$

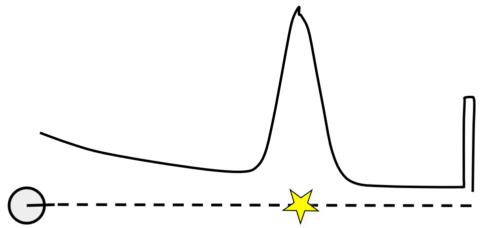
distribution observation given pose

Observation Model Examples

- Gaussian model



- Non-Gaussian model



More on Observation Models

- Course: Introduction to Mobile Robotics, Chapter 7
- Thrun et al. "Probabilistic Robotics", Chapter 6

Summary

- Mapping is the task of modeling the environment
- Localization means estimating the robot's pose
- SLAM = simultaneous localization and mapping
- Full SLAM vs. Online SLAM
- Rich taxonomy of the SLAM problem

Literature

SLAM Overview

- Springer "Handbook on Robotics", Chapter on Simultaneous Localization and Mapping (1st Ed: Chap. 37.1-37.2)

On motion and observation models

- Thrun et al. "Probabilistic Robotics", Chapters 5 & 6
- Course: Introduction to Mobile Robotics, Chapters 6 & 7