Photogrammetry & Robotics Lab

Introduction to SLAM

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Topic of the Course

Simultaneous Localization and Mapping

- Graph-based SLAM using pose graphs
- Graph-based SLAM with landmarks
- Robust optimization in SLAM
- Relative pose estimation using vision

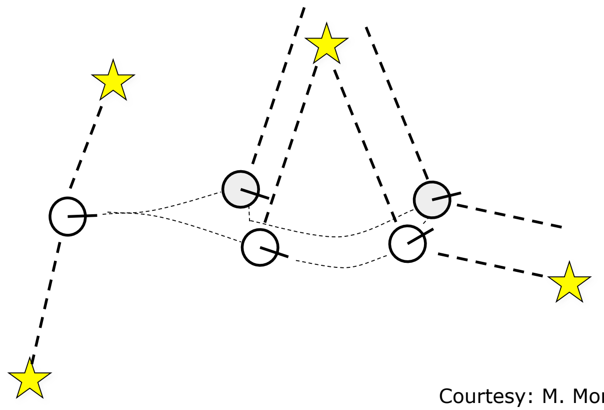
What is SLAM?

- Computing the robot's poses 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 localizing the robot simultaneously

Localization Example

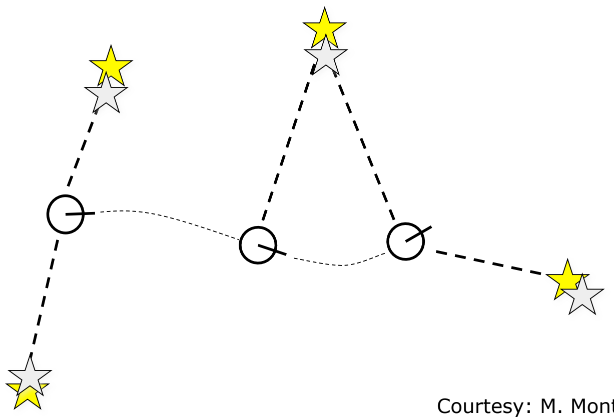
- Estimate the robot's poses given landmarks



Courtesy: M. Montemerlo

Mapping Example

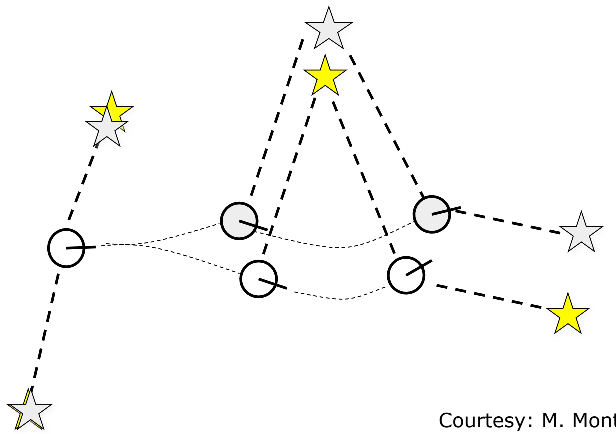
- Estimate the landmarks given the robot's poses



Courtesy: M. Montemerlo

SLAM Example

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



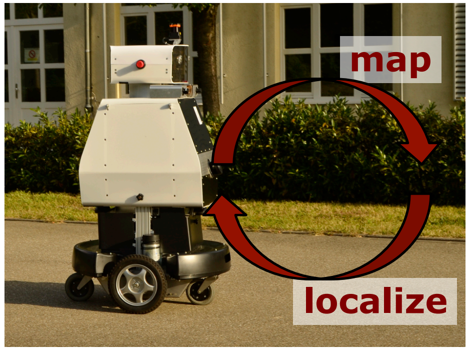
Courtesy: M. Montemerlo

Simultaneous Localization and Mapping or SLAM

- **Build a map** of the environment from a mobile sensor platform
- At the same time, **localize** a mobile sensor platform in the map build so far
- **Online** variant of the bundle adjustment problem for **arbitrary sensors**

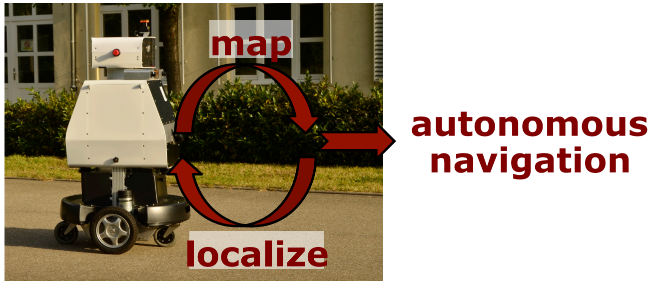
The SLAM Problem

- 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



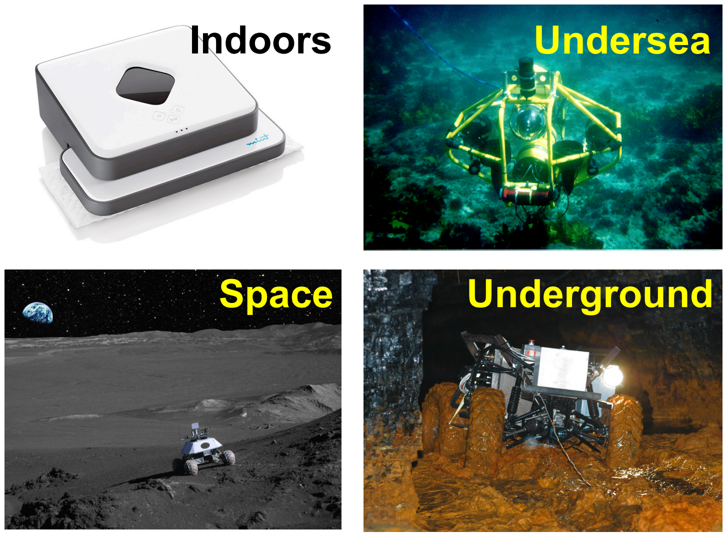
SLAM Applications

- SLAM is central to a range of indoor, outdoor, 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: Evolution Robotics, H. Durrant-Whyte, NASA, S. Thrun

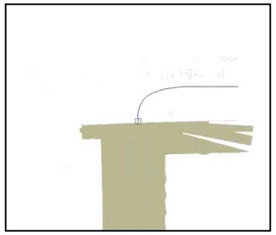
SLAM Showcase – Mint

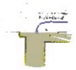
Courtesy: Evolution Robotics (now iRobot)

SLAM Showcase – EUROPA

Courtesy: ZDF

Mapping Freiburg CS Campus





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

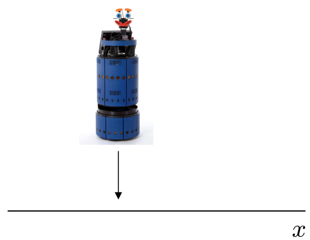
  m

- Path of the robot

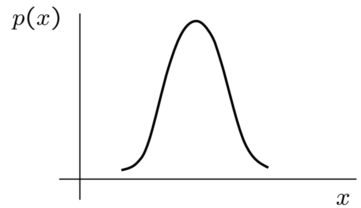
  $x_{0:T} = \{x_0, x_1, x_2, \ldots, x_T\}$

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"

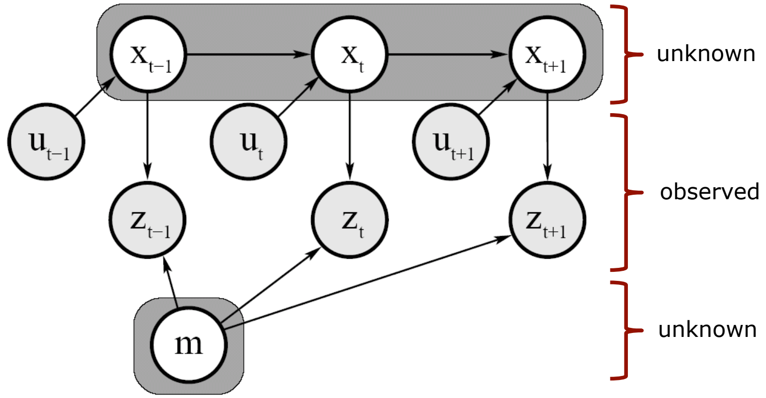
In the Probabilistic World

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



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

Courtesy: Thrun, Burgard, Fox

Full SLAM vs. Online SLAM

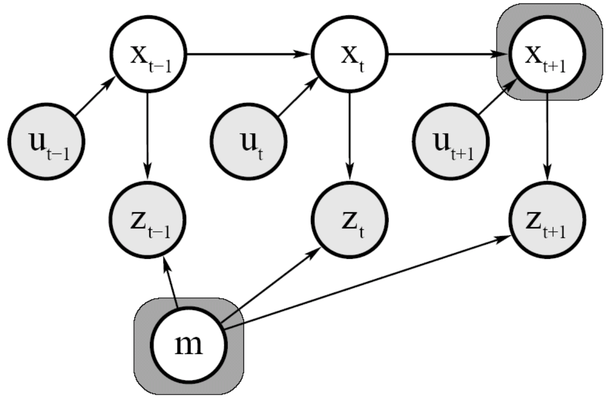
- Full SLAM estimates the entire path

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

- 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



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

Courtesy: Thrun, Burgard, Fox

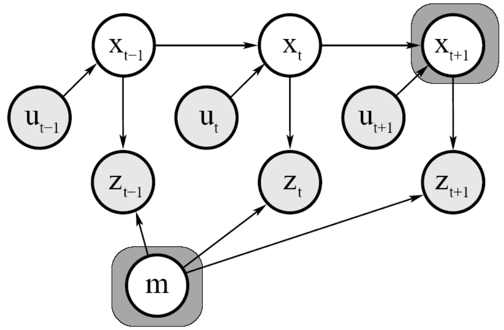
Online SLAM

- Online SLAM means marginalizing out the previous poses

$$p(x_t, m \mid z_{1:t}, u_{1:t}) = \int \dots \int p(x_{0:t}, m \mid z_{1:t}, u_{1:t})\, dx_{t-1} \dots dx_0$$

- Integrals are typically solved recursively, one at at time

Graphical Model of Online SLAM

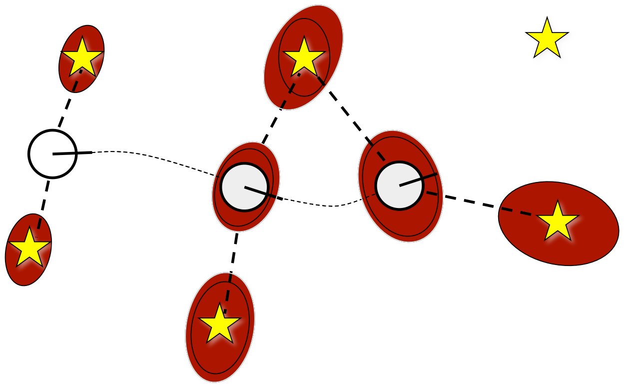


$$p(x_{t+1}, m \mid z_{1:t+1}, u_{1:t+1}) = \int \dots \int p(x_{0:t+1}, m \mid z_{1:t+1}, u_{1:t+1})\, dx_t \dots dx_0$$

Courtesy: Thrun, Burgard, Fox

Why is SLAM a Hard Problem?

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

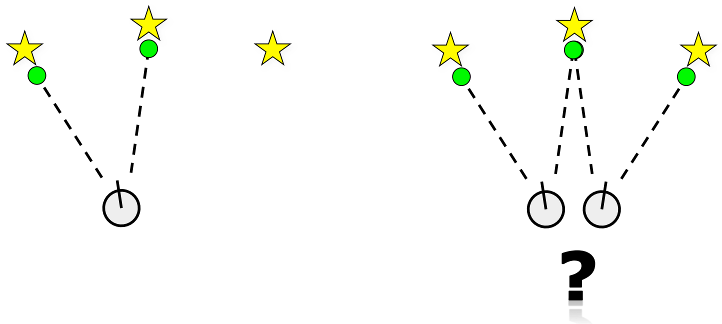


2. Map and pose estimates correlated

Courtesy: M. Montemerlo

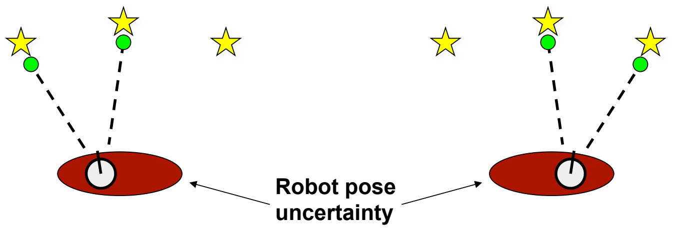
Why is SLAM a Hard Problem?

Known vs. unknown correspondence



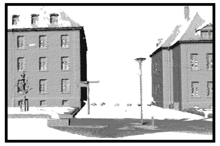
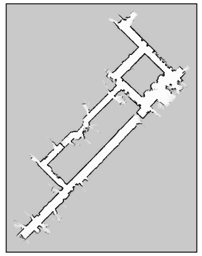
Why is SLAM a Hard Problem?

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

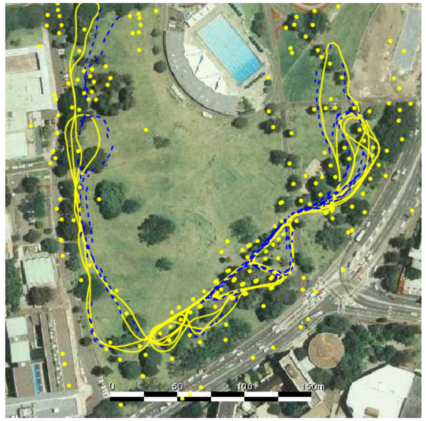


Courtesy: M. Montemerlo

Volumetric vs. Feature-Based SLAM

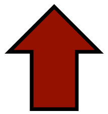
Courtesy: D. Hähnel



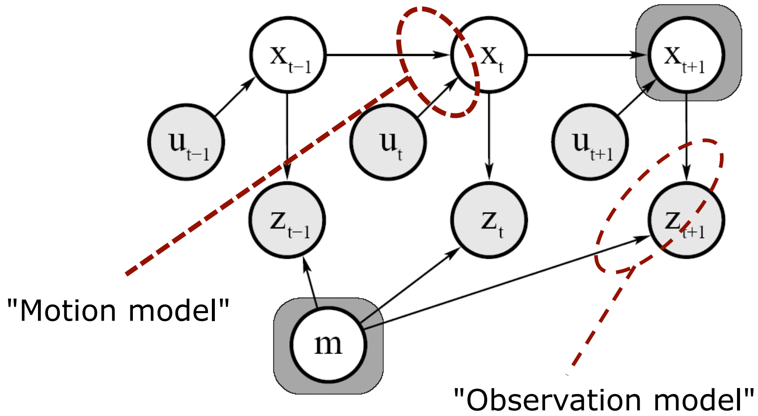
Courtesy: E. Nebot

Three Traditional Paradigms

Kalman filter	Particle filter	Graph-based



Motion and Observation Model



Courtesy: Thrun, Burgard, Fox

Motion Model

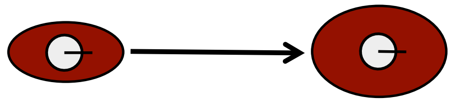
- The motion model describes the relative motion of the robot

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

distribution new pose given old pose control

Motion Model Examples

- Gaussian model



- Non-Gaussian model

Courtesy: Thrun, Burgard, Fox

Observation Model

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

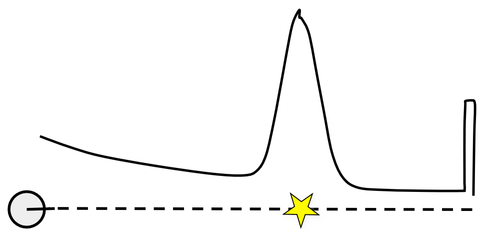
$$p(z_t \mid x_t)$$

distribution observation given pose

Observation Model Examples

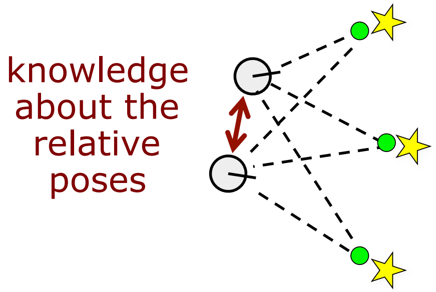
- Gaussian model

- Non-Gaussian model



Model for Virtual Observations

- Relate pairs of poses from which observations have been recorded



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

Reading Material

Read SLAM overview

Springer "Handbook on Robotics", Chapter on Simultaneous Localization and Mapping, subsection 1 & 2
(see E-Campus)

Revisit the math basics slide set

See: sse2-00-background-math-basics.pdf