

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

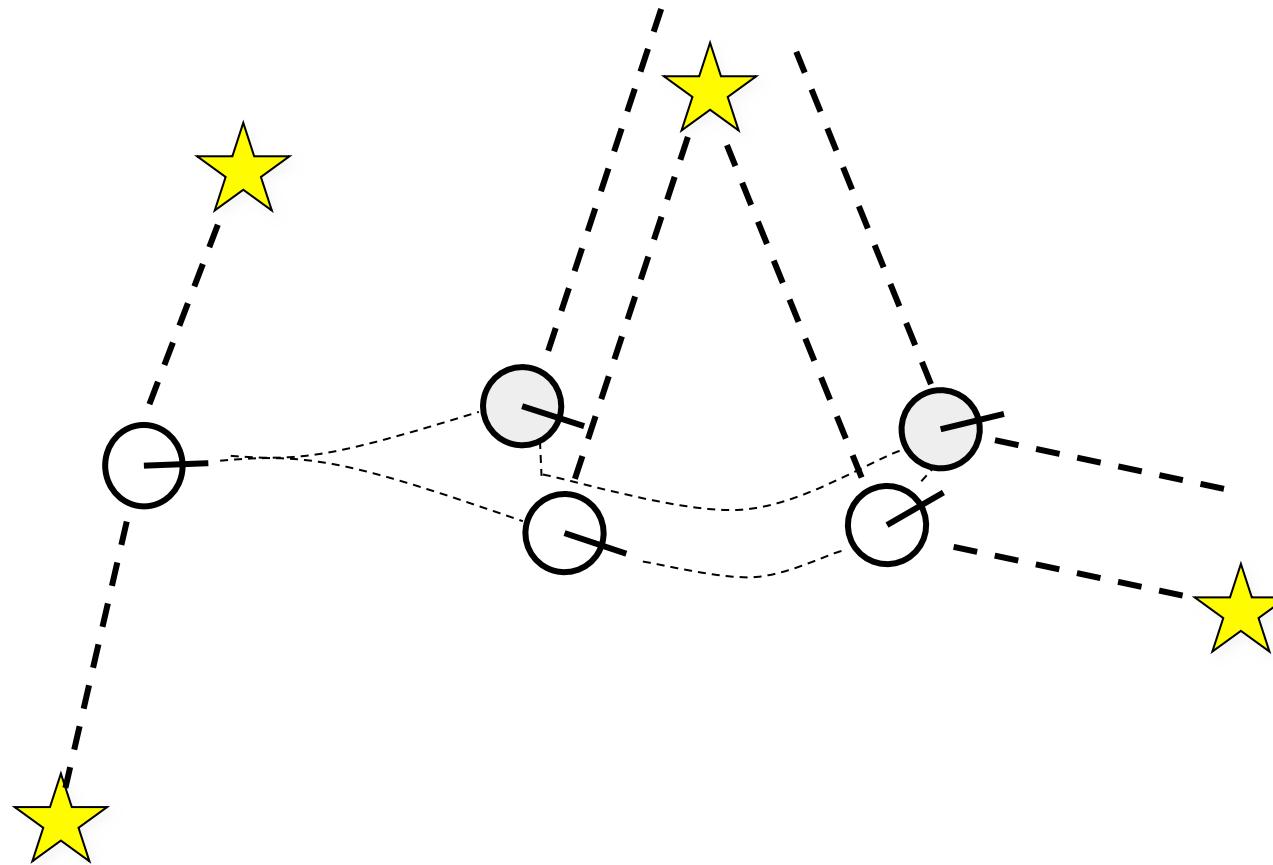
Motion
Planning

What is SLAM?

- Computing the robot's 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

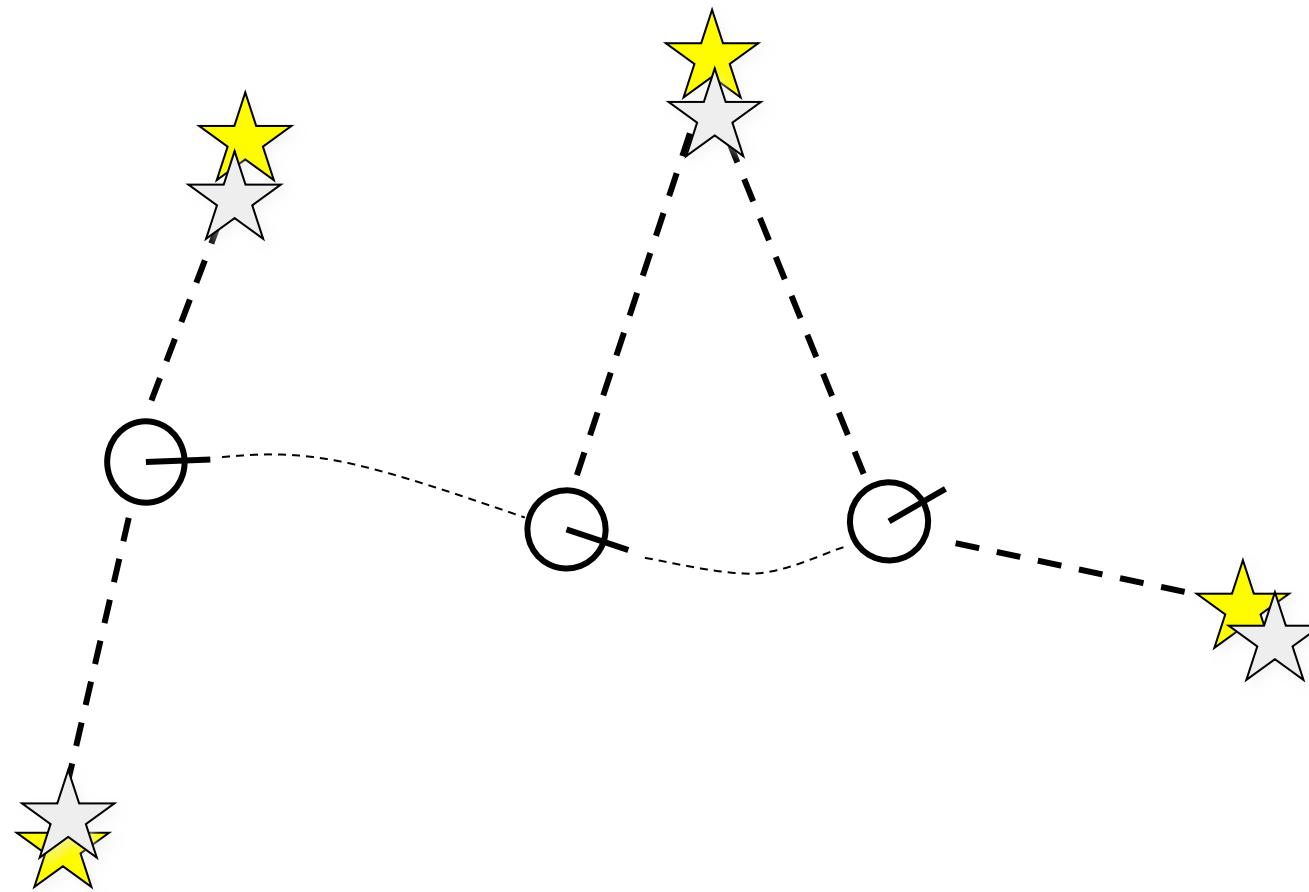
Localization Example

- Estimate the robot's poses given landmarks



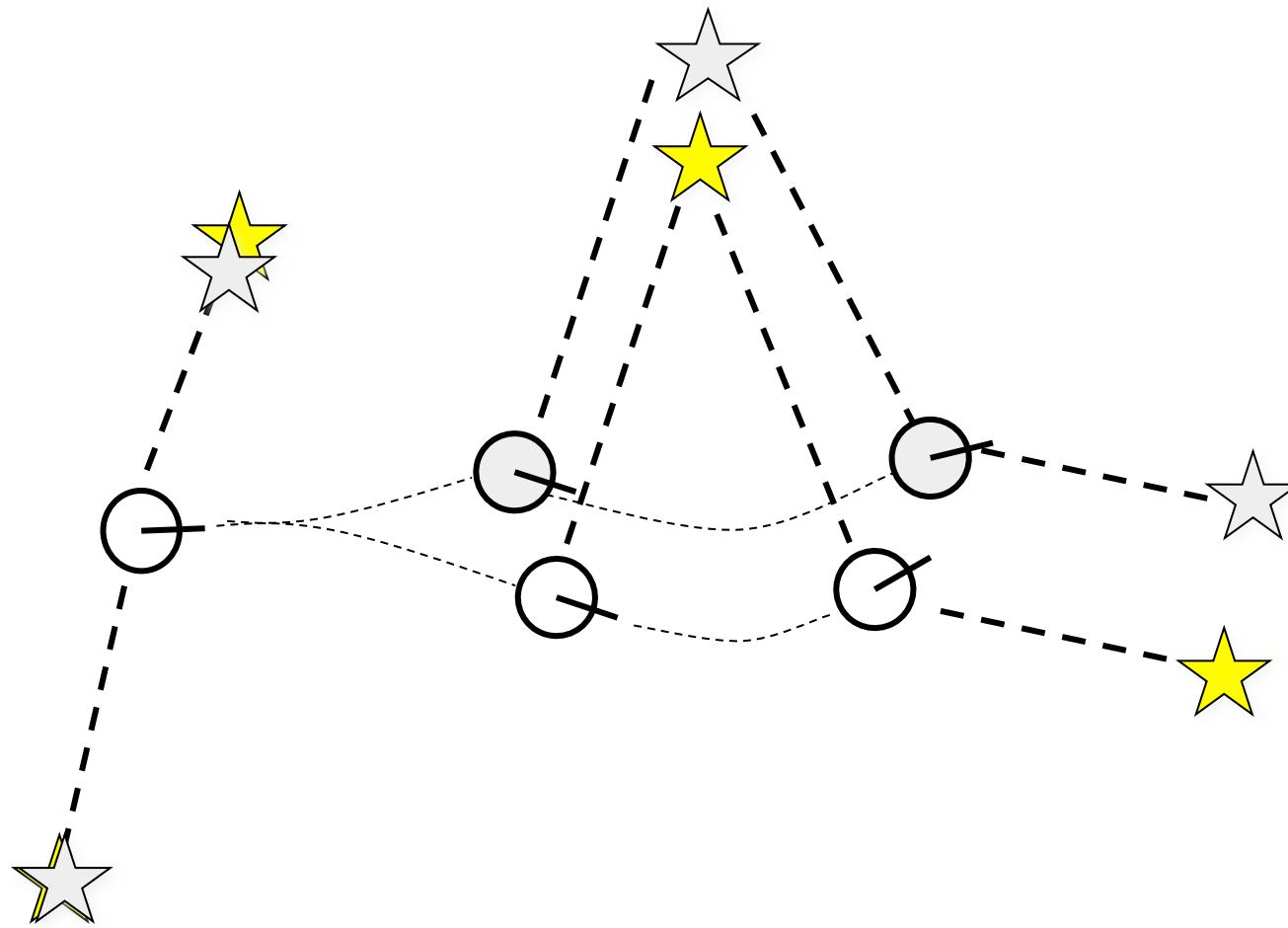
Mapping Example

- Estimate the landmarks given the robot's poses



SLAM Example

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



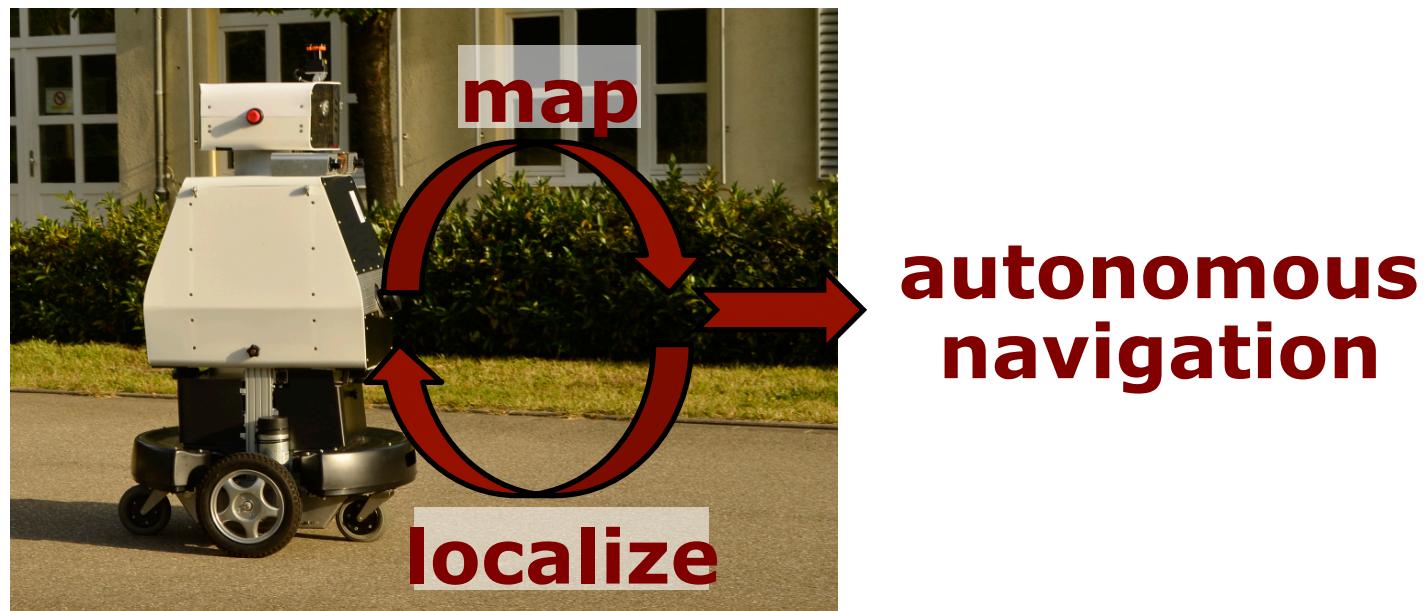
The SLAM Problem

- 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



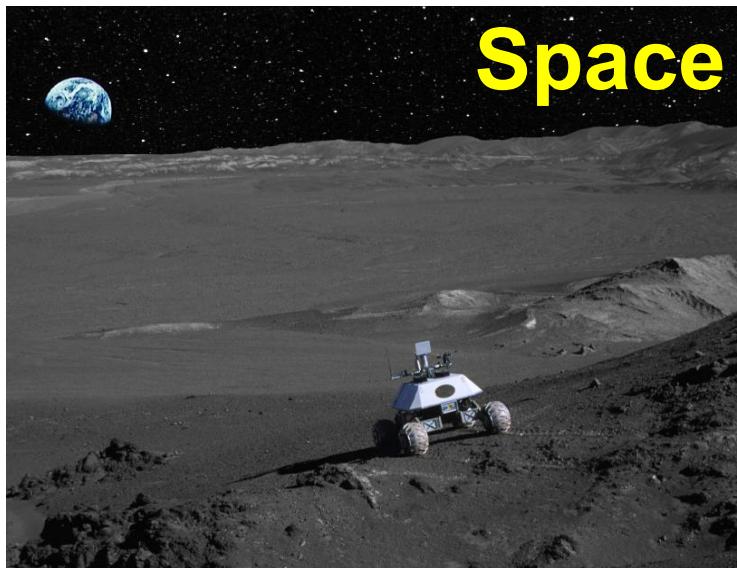
SLAM Applications

- SLAM is central to a range of indoor, outdoor, 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

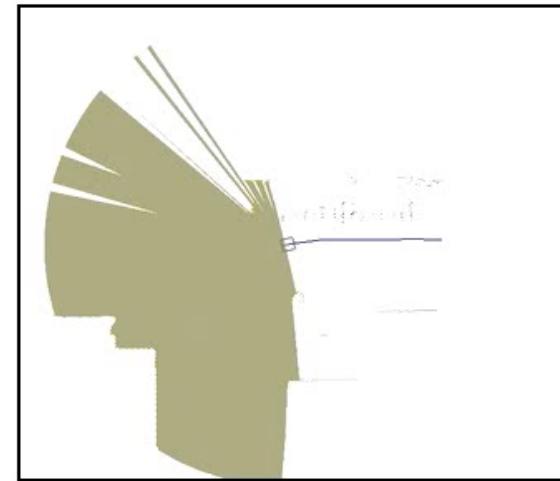


Courtesy of Evolution Robotics (now iRobot)

SLAM Showcase – EUROPA



Mapping Freiburg CS Campus



Definition of the SLAM Problem

Given

- The robot's controls

$$u_{1:T} = \{u_1, u_2, u_3 \dots, u_T\}$$

- Observations

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

Wanted

- Map of the environment

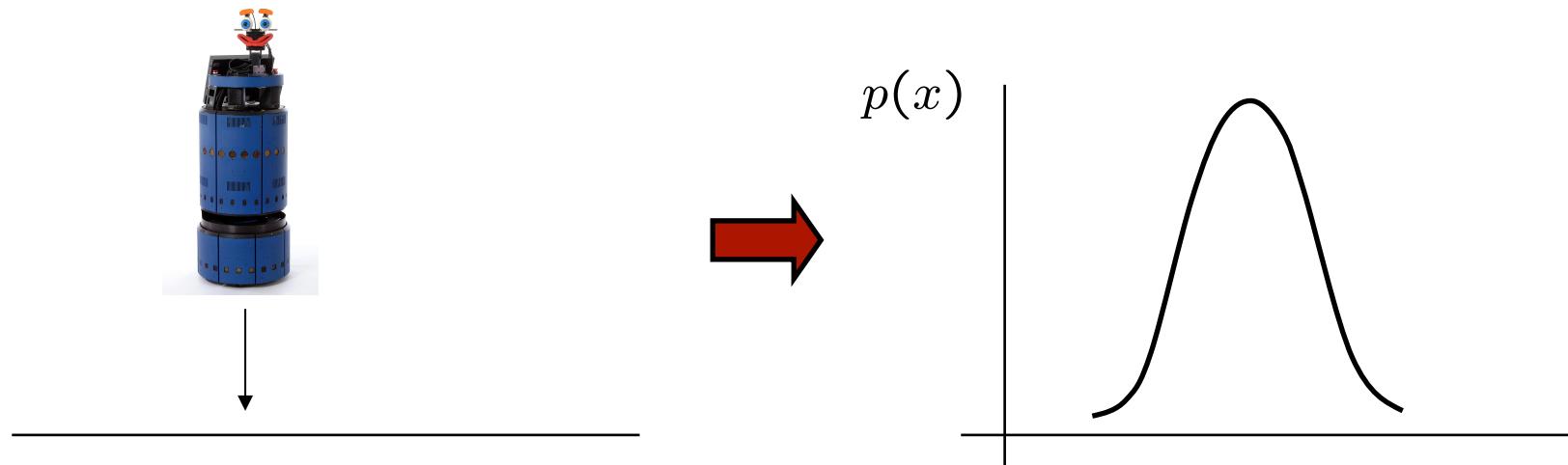
$$m$$

- Path of the robot

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

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

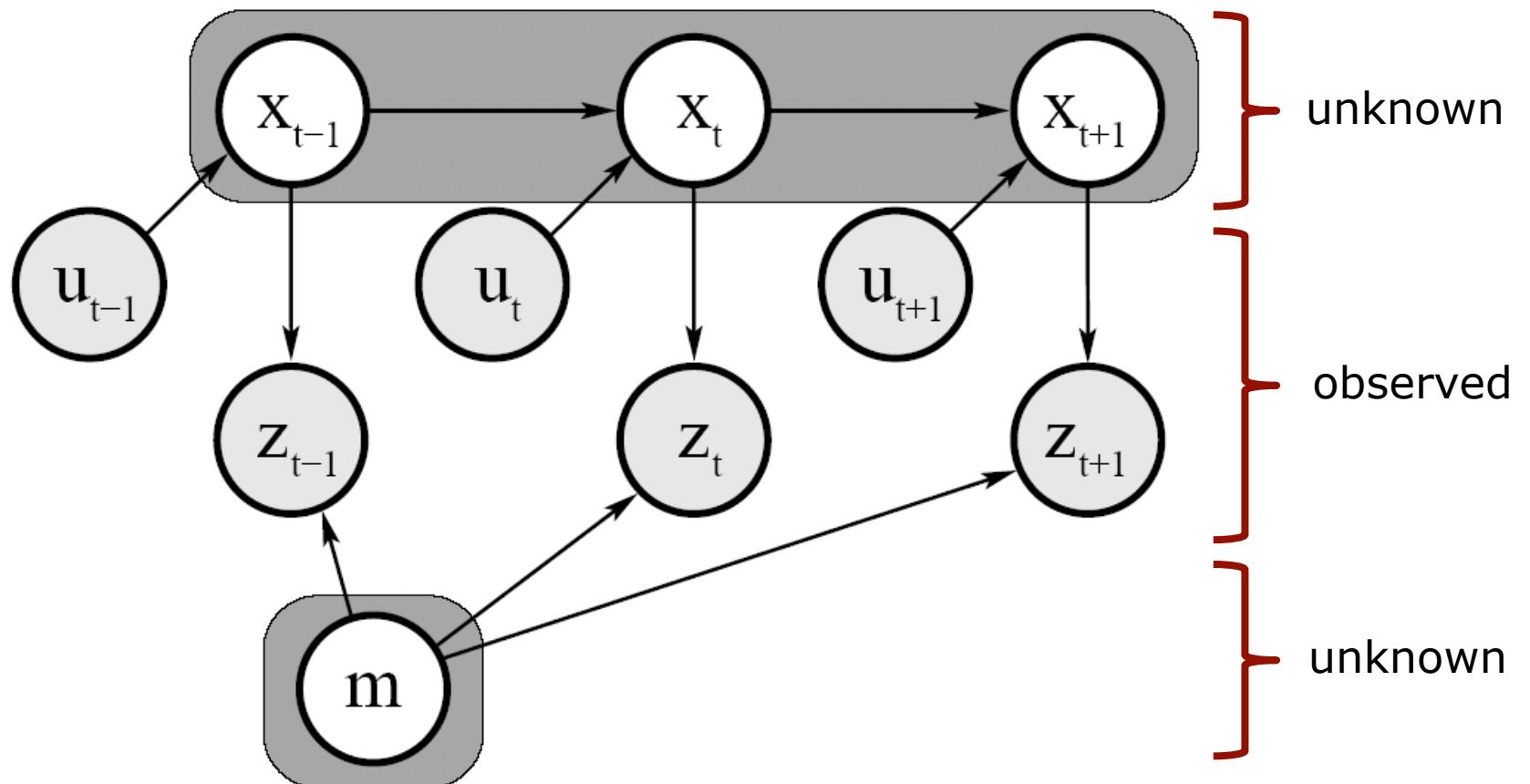
Estimate the robot's path and the map

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

distribution path map given observations controls

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graph TD; A[p(x_{0:T}, m | z_{1:T}, u_{1:T})] --> B[distribution]; A --> C[path]; A --> D[map]; A --> E[given]; A --> F[observations]; A --> G[controls]
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Graphical Model



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

Full SLAM vs. Online SLAM

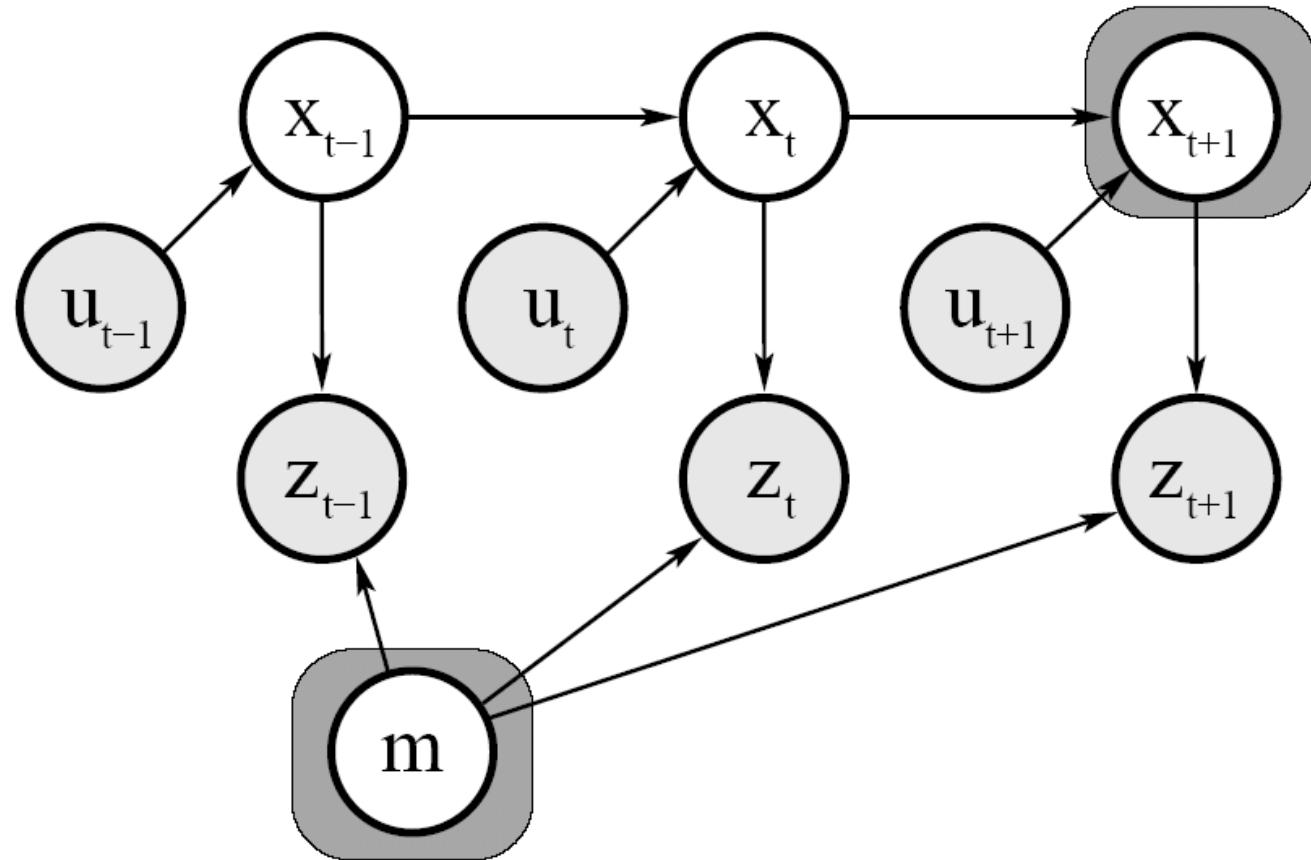
- Full SLAM estimates the entire path

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

- 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



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

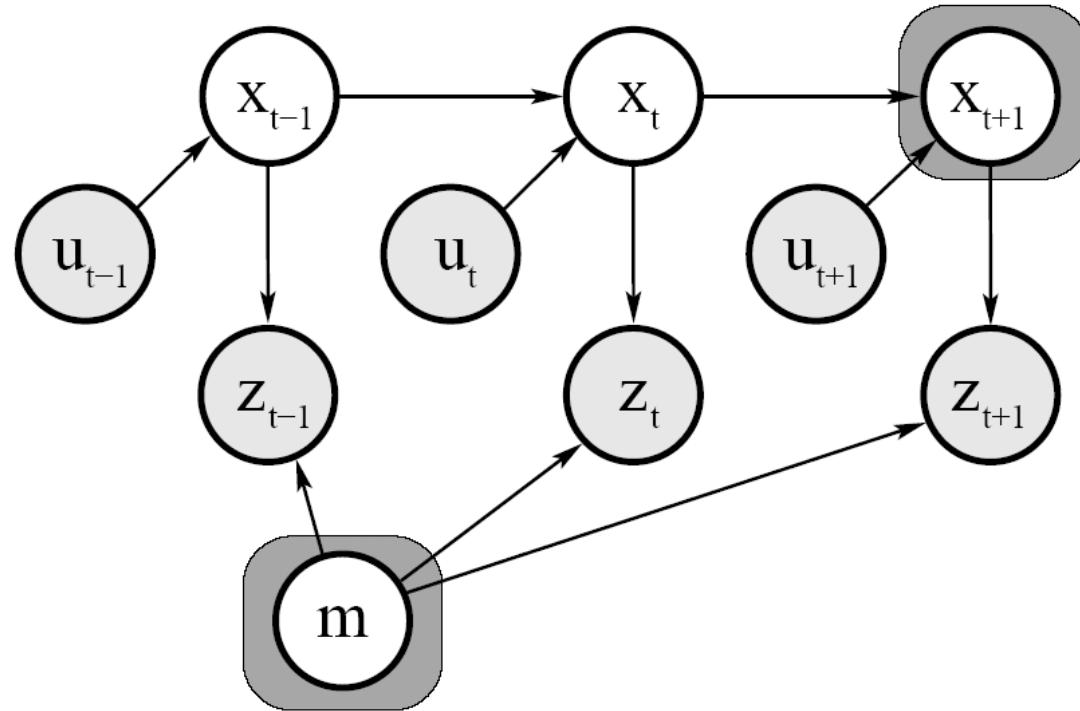
Online SLAM

- Online SLAM means marginalizing out the previous poses

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

- Integrals are typically solved recursively, one at a time

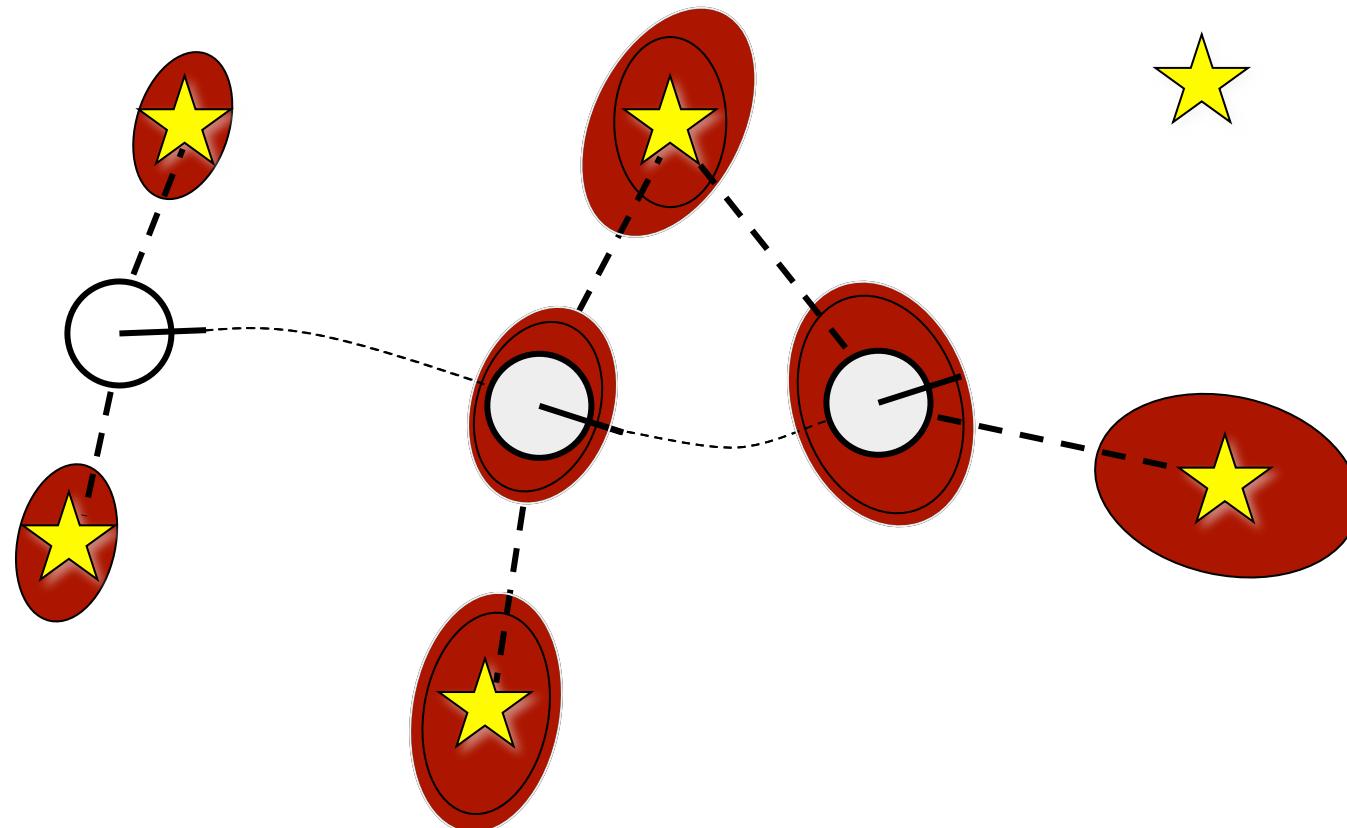
Graphical Model of Online SLAM



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

Why is SLAM a Hard Problem?

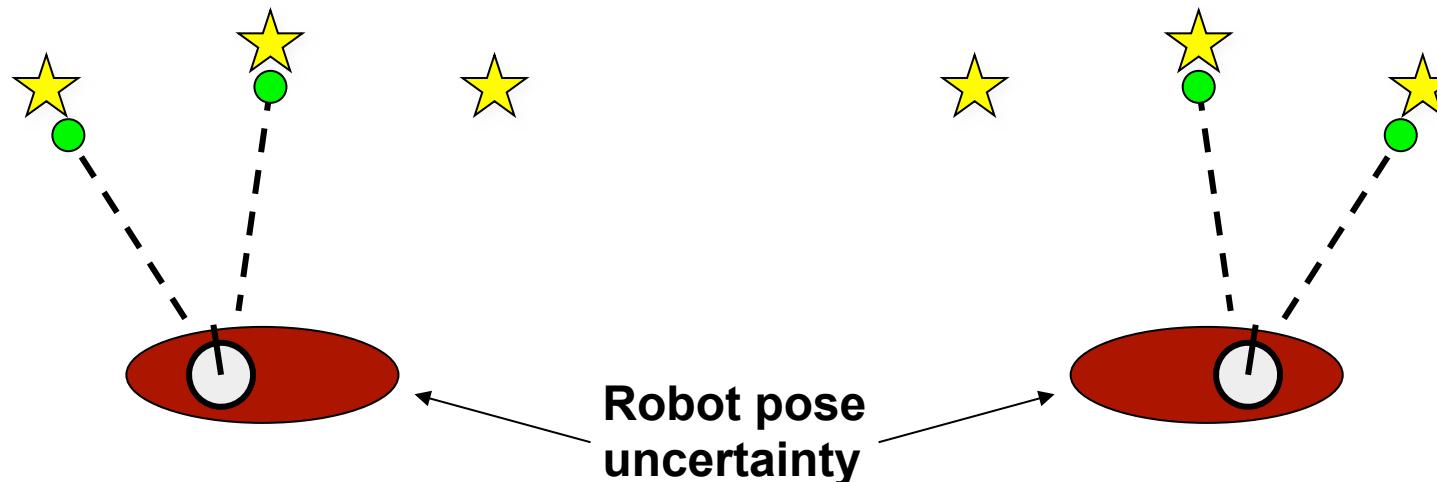
1. Robot path and map are both **unknown**



2. Map and pose estimates correlated

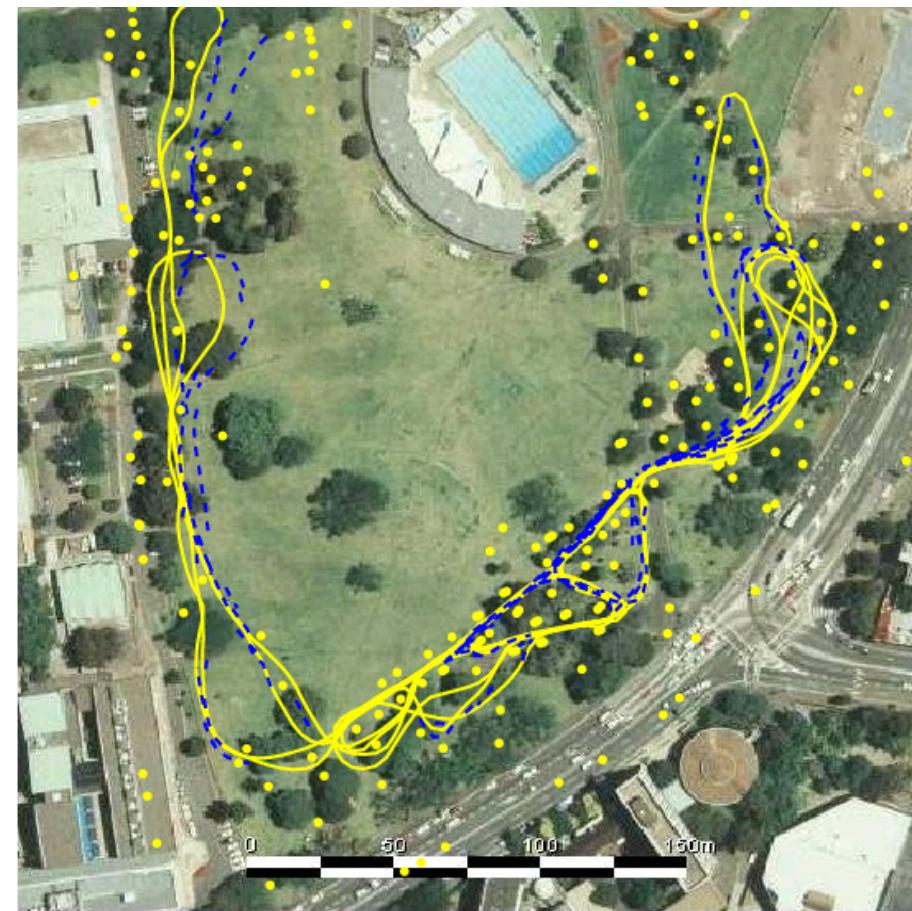
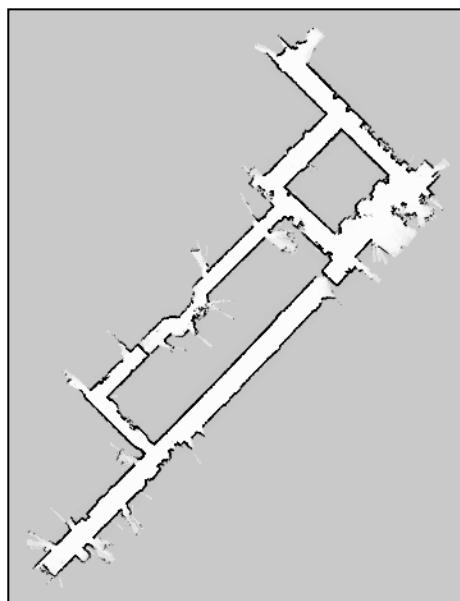
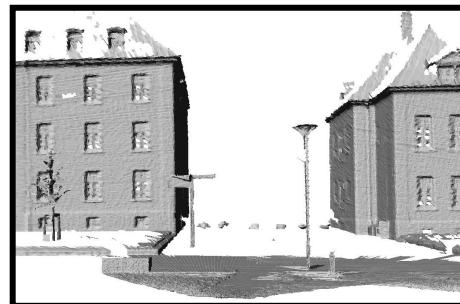
Why is SLAM a Hard Problem?

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



Taxonomy of the SLAM Problem

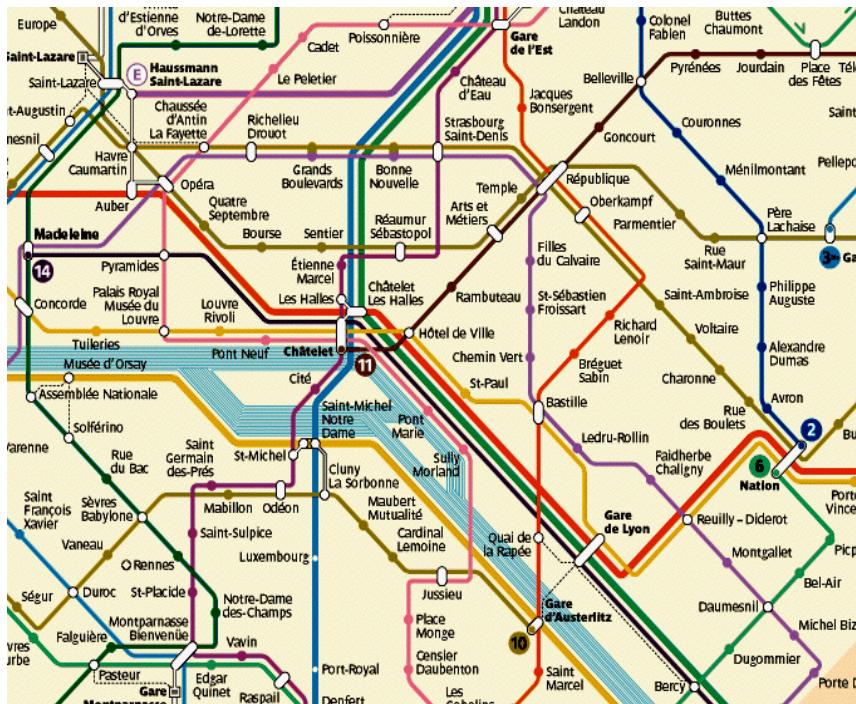
Volumetric vs. feature-based SLAM



Courtesy by E. Nebot

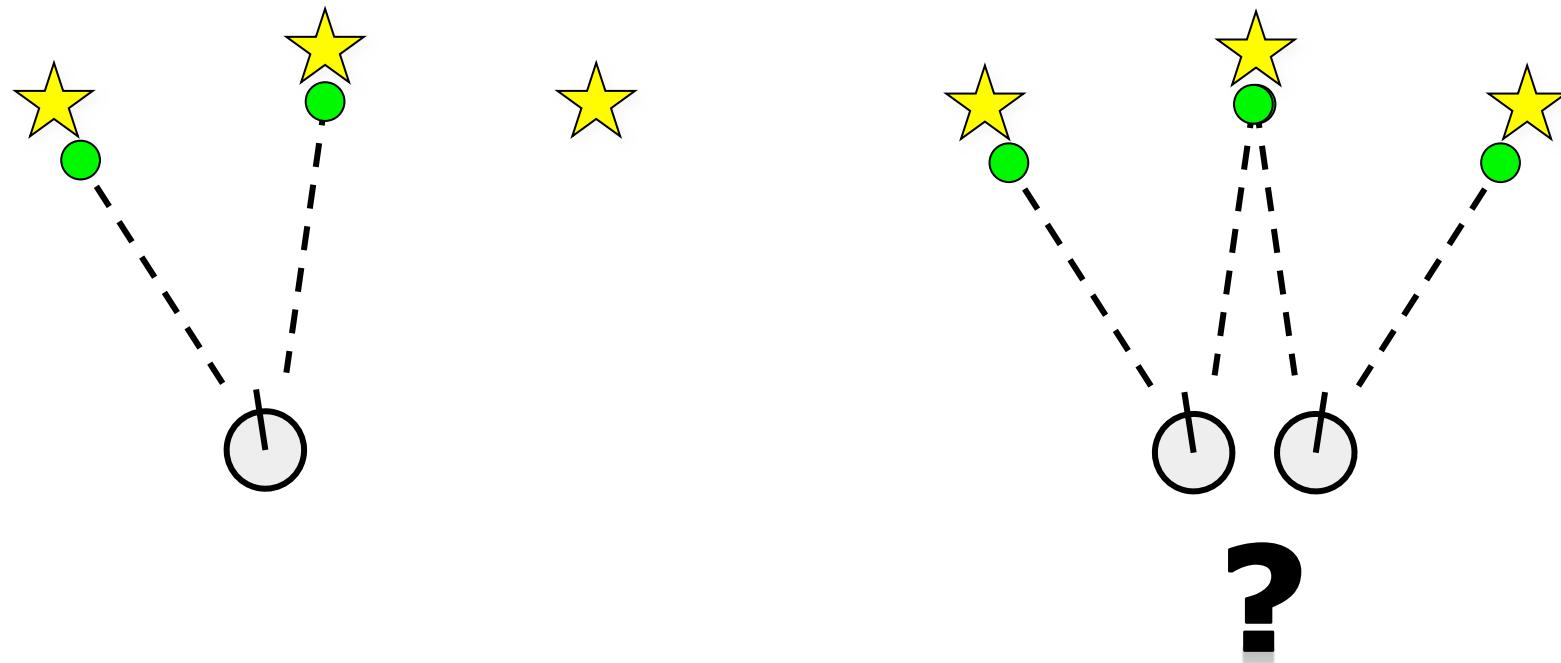
Taxonomy of the SLAM Problem

Topologic vs. geometric maps



Taxonomy of the SLAM Problem

Known vs. unknown correspondence



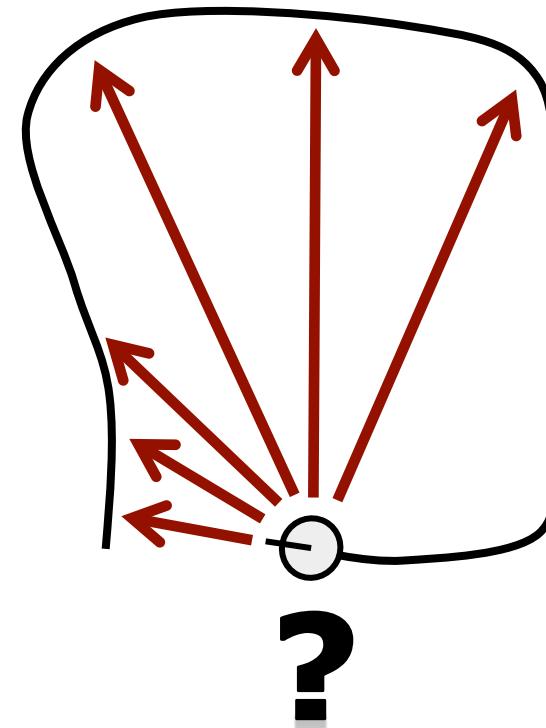
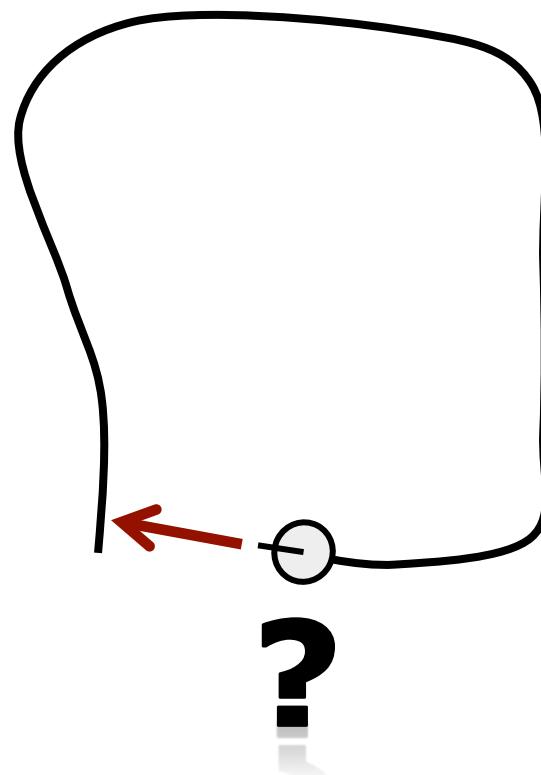
Taxonomy of the SLAM Problem

Static vs. dynamic environments



Taxonomy of the SLAM Problem

Small vs. large uncertainty



Taxonomy of the SLAM Problem

Active vs. passive SLAM

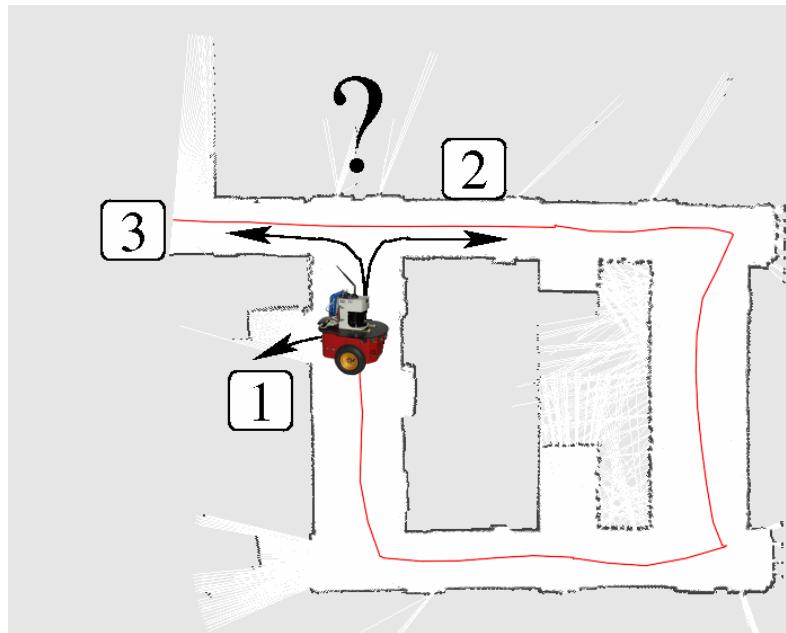


Image courtesy by Petter Duvander

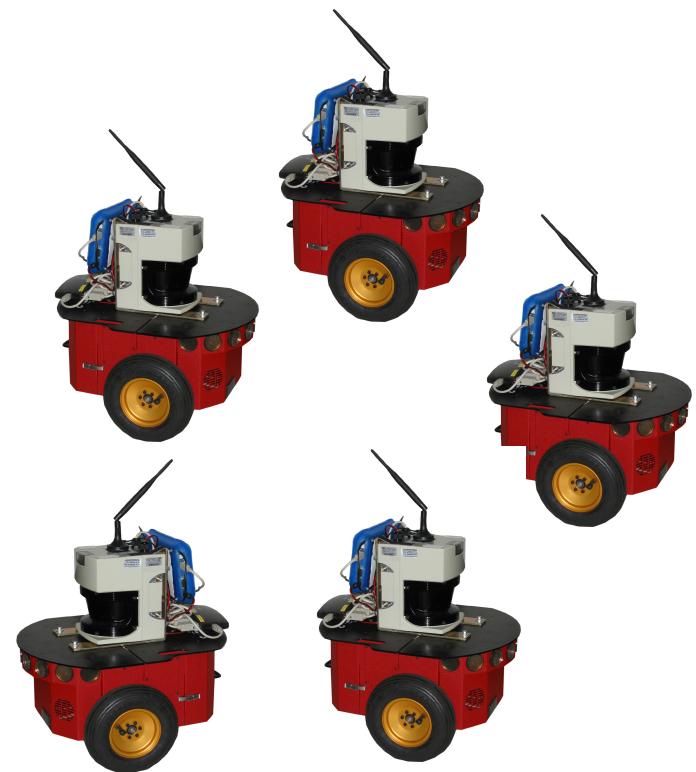
Taxonomy of the SLAM Problem

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 of techniques uses probabilistic concepts
- History of SLAM dates back to the mid-eighties
- Related problems in geodesy and photogrammetry

SLAM History by Durrant-Whyte

- 1985/86: Smith et al. and Durrant-Whyte describe geometric uncertainty and relationships between features or landmarks
- 1986: Discussions at ICRA on how to solve the SLAM problem followed by the 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 real systems
- 2000: Wide interest in SLAM started

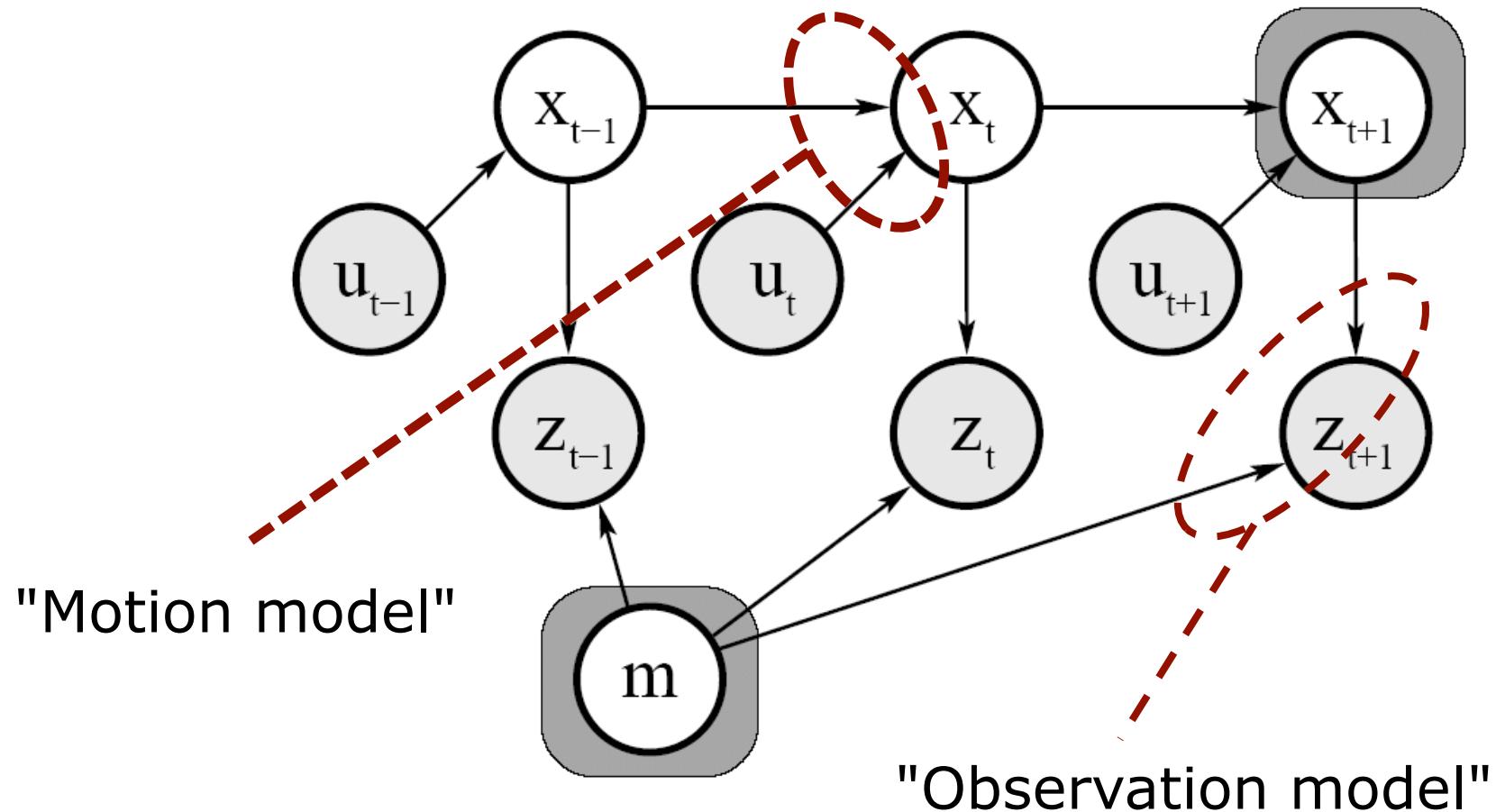
Three Main Paradigms

Kalman
filter

Particle
filter

Graph-
based

Motion and Observation Model



Motion Model

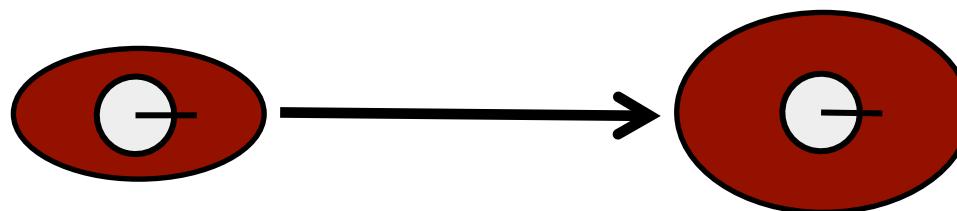
- The motion model describes the relative motion of the robot

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

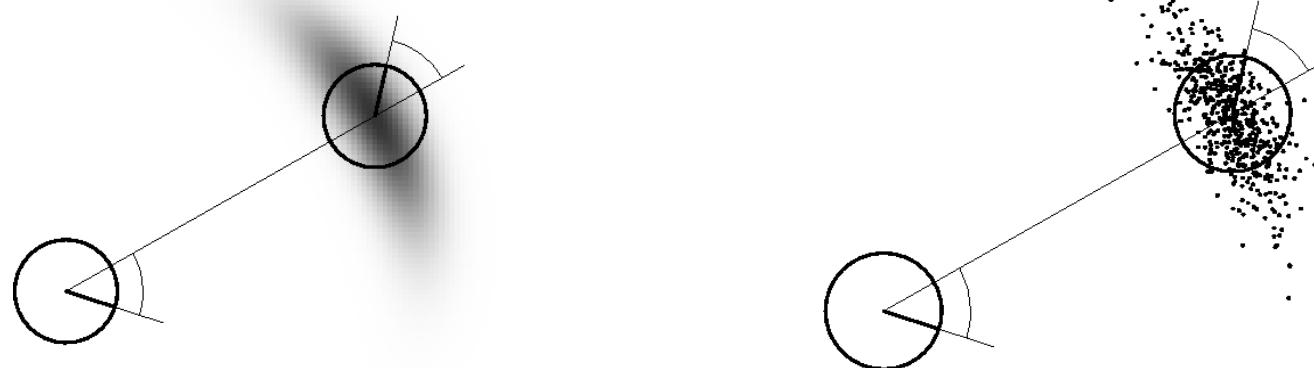
distribution new pose given old pose control

Motion Model Examples

- Gaussian model



- Non-Gaussian model



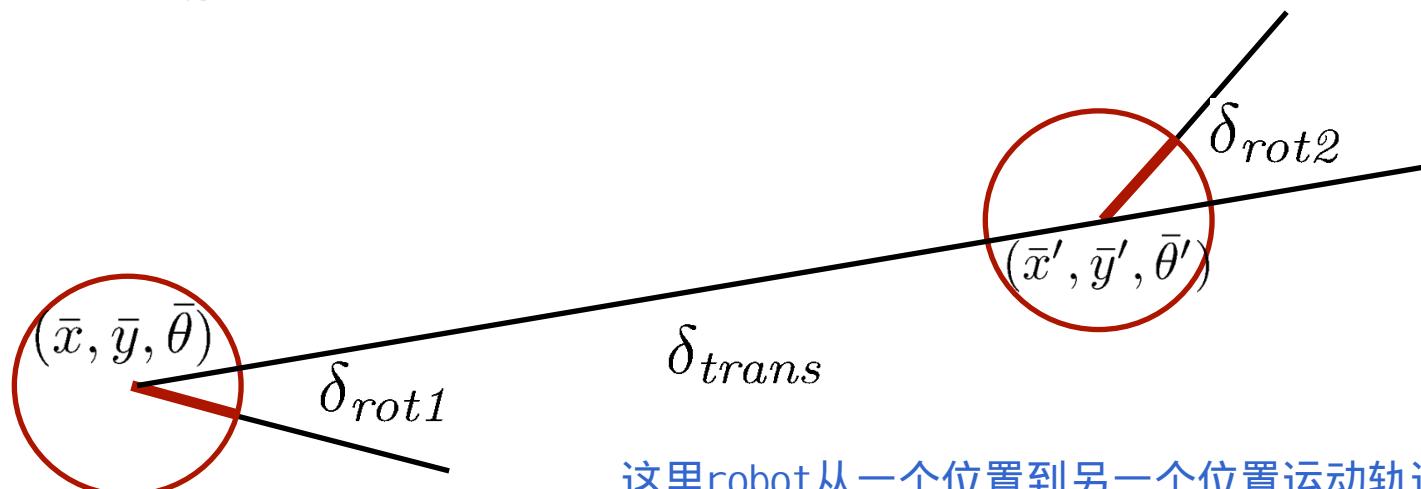
Standard Odometry Model

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

$$\delta_{trans} = \sqrt{(\bar{x}' - \bar{x})^2 + (\bar{y}' - \bar{y})^2}$$

$$\delta_{rot1} = \text{atan2}(\bar{y}' - \bar{y}, \bar{x}' - \bar{x}) - \bar{\theta}$$

$$\delta_{rot2} = \bar{\theta}' - \bar{\theta} - \delta_{rot1}$$



这里robot从一个位置到另一个位置运动轨迹是先旋转rot1, 再走一段位移再旋转一次。

More on Motion Models

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

Observation Model

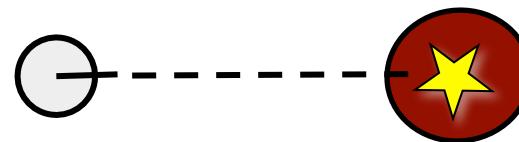
- The observation or sensor model relates measurements with the robot's pose

$$p(z_t | x_t)$$

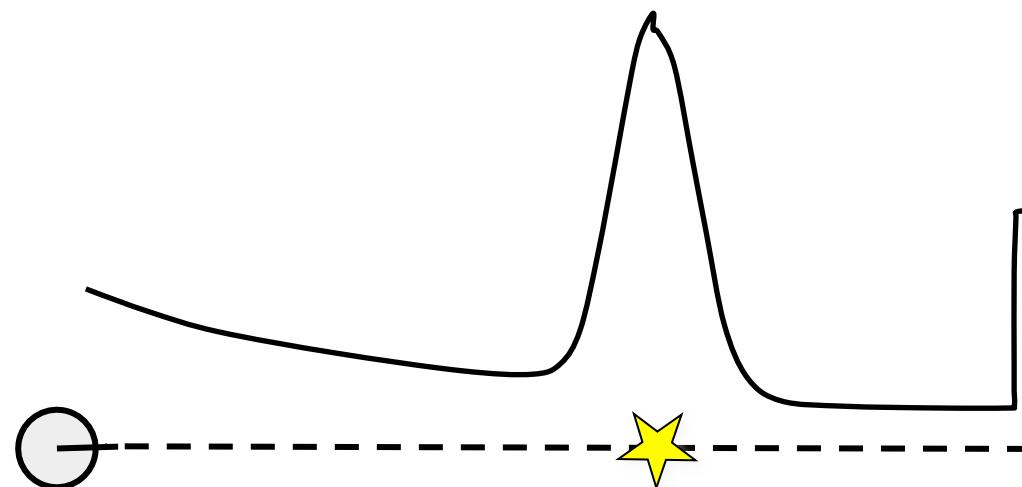
A diagram illustrating the components of the observation model. At the top is the mathematical expression $p(z_t | x_t)$. Below it, four red arrows point upwards from the words "distribution", "observation", "given", and "pose" to the corresponding terms in the expression.

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 (subsection 1 & 2)

On motion and observation models

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