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

Indoors

Undersea

Space

Underground

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
  \[ u_{1:T} = \{ u_1, u_2, u_3 \ldots, u_T \} \]
- 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”

\[ p(x) \]

“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

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

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

- Integrals are typically solved recursively, one at a time
Graphical Model of Online SLAM

\begin{align*}
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 \cdots \, dx_0
\end{align*}
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"

"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

\[
\mathbf{u} = (\delta_{\text{rot}1}, \delta_{\text{trans}}, \delta_{\text{rot}2})
\]

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

\[
\delta_{\text{rot}1} = \text{atan2}(y' - \bar{y}, x' - \bar{x}) - \bar{\theta}
\]

\[
\delta_{\text{rot}2} = \bar{\theta}' - \bar{\theta} - \delta_{\text{rot}1}
\]
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 (subsection 1 & 2)

On motion and observation models

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