Short Introduction to SLAM
(From a Photogrammetry Perspective)

Cyrill Stachniss
5 Minute Preparation for Today

https://www.ipb.uni-bonn.de/5min/
What is SLAM?

- **Localize and map simultaneously**

- **Localization**: estimating the location and headings of the sensor/robot

- **Mapping**: building a map of the environment

- **SLAM**: building a map and localizing the robot simultaneously in that map
Simultaneous Localization and Mapping for Mobile Robots

- A term from the **robotics** community
- Used to build maps that allow robots to **navigate** with
- **Sequences** and not sets of sensor measurements
- Use **whatever sensors** there are (cameras, RGBD, lidars, sonars, …)
- Exploits locomotion constraints
SLAM: Simultaneous Localization and Mapping

- Simultaneously build a map from a mobile platform and localize it in the map build so far
- Arbitrary sensors
- Motion models
- Different environment representations
- Offline vs. online operation
Bundle Adjustment vs. SLAM

**BA**
- Observations are mainly images
- Sets of images
- Minimizes the reprojection error
- Map are 3D point locations (features)
- Least squares approach
- Mostly offline

**SLAM**
- All types of sensors
- Sequences, not sets
- Various error functions exists
- Maps: volumetric, landmarks, point clouds, ...
- Recursive Bayes f. or least squares
- Often online
Bundle Adjustment vs. SLAM

**BA**
- Observations are mainly images
- Sets of images
- Minimizes the reprojection error
- Map are 3D point locations (features)
- Least squares approach
- Mostly offline

**SLAM**
- All types of sensors
- Sequences, not sets
- Various error functions exist
- Maps: volumetric, landmarks, point clouds, ...
- Recursive Bayes f. or least squares
- Often online

**SLAM can be seen as a generalization of bundle adjustment**
SLAM History

- 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
SLAM History

- 1985/86: Smith et al. and Durrant-Whyte describe geometric uncertainty and relationships between features or landmarks.

Bundle adjustment developments started in the 1950ies in photogrammetry.

- 2000: Wide interest in SLAM started.
In the 1950ies...

- Computers?
- Errors in computation?
- Digital cameras?
- Automatic image processing?
- ...
In the 1950ies...

- Computers?
- Errors in computation?
- Digital cameras?
- Automatic image processing?
- ...

Keeping this in mind let’s you appreciate the developments on bundle adjustment even more...
The SLAM Problem
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 for Navigation

- It is considered a fundamental problem for truly autonomous robots
- Online SLAM is the basis for most autonomous 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
- Urban: autonomous cars
- 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: Evolution Robotics, H. Durrant-Whyte, NASA, S. Thrun
Definition of the SLAM Problem

**Given**

- The executed 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
  \[ x_{0:T} = \{x_0, x_1, x_2, \ldots, x_T\} \]
Probabilistic Model

Estimate the 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

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

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

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

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
Data Association Problem

- Mapping between observations and the map is unknown
- Picking wrong data associations can have catastrophic consequences

Courtesy: M. Montemerlo
Three Traditional Paradigms

- Kalman filter
- Particle filter
- Least squares

- EKF SLAM
- Graph-SLAM, BA, …
Motion and Observation Model

"Motion model"

"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
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
- Bundle adjustment = Full SLAM using a camera minimizing the reprojection error of features and no motion model
Reading Material

General SLAM Overview
Springer “Handbook on Robotics”, Chapter on Simultaneous Localization and Mapping, subsection 1 & 2 (see E-Campus)