Carnegie Mellon
THE ROBOTICS INSTITUTE

Robot Localization and Mapping
16-833

Michael Kaess

February 1, 2021

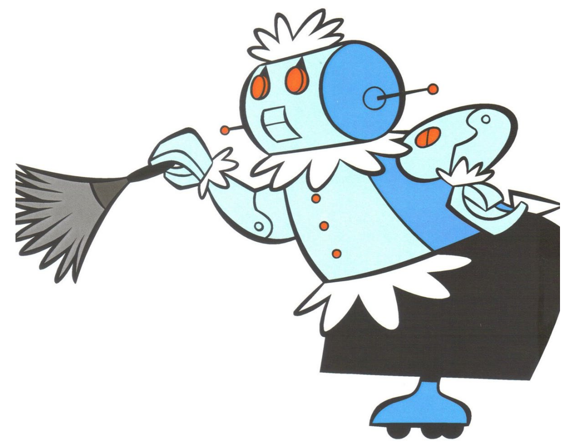
Robot Autonomy Needs Localization & Mapping

Space
[JPL]

Transportation
[ArgoAI]

Drones
[Skydio]

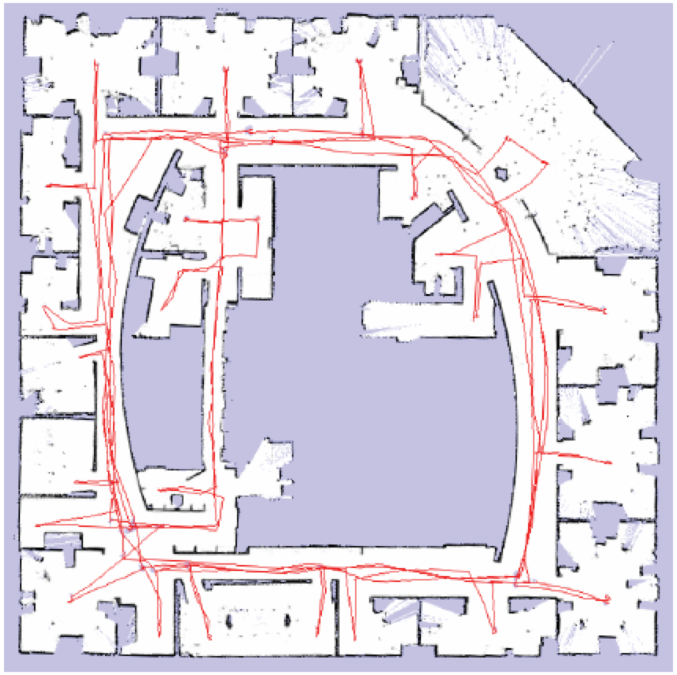
Underwater
[MIT]



Rosie the Robot Maid
[The Jetsons, 1960s]

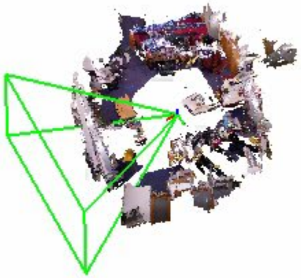
SLAM

- Simultaneous Localization and Mapping
  - CML (Concurrent Mapping and Localization)
  - FBN (Feature-based Navigation)
  - SMAL

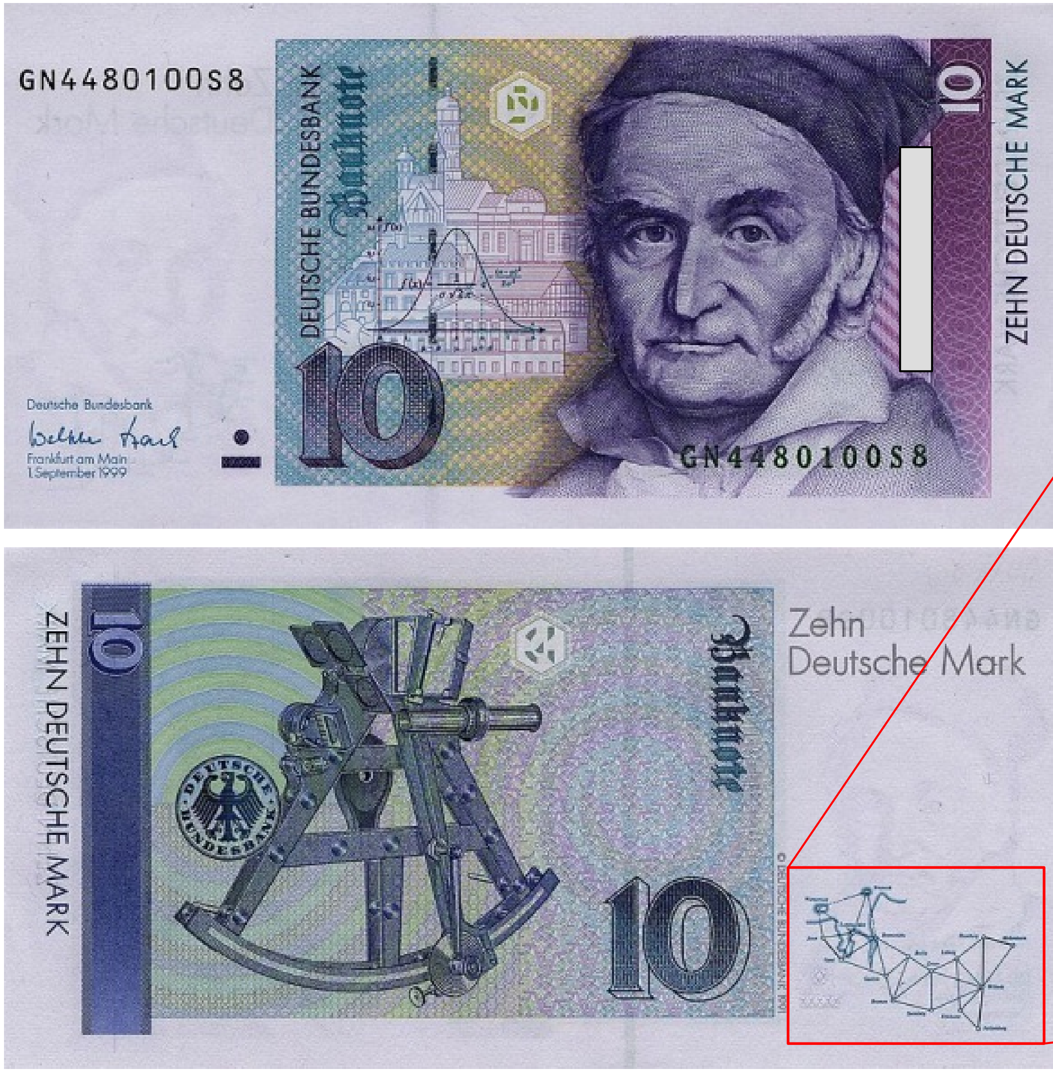


- Chicken-and-egg problem:
  - Given a suitable map it's easy (relatively speaking) to localize
  - Given the exact robot pose, it's easy to build the map

SLAM Example

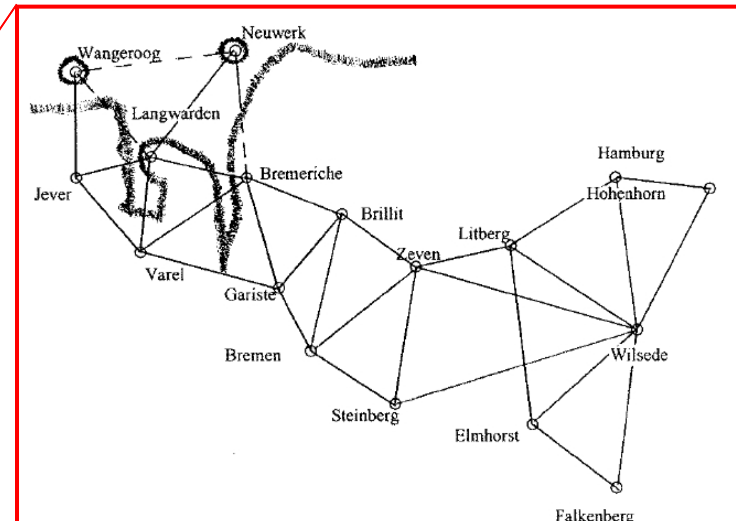


History of SLAM

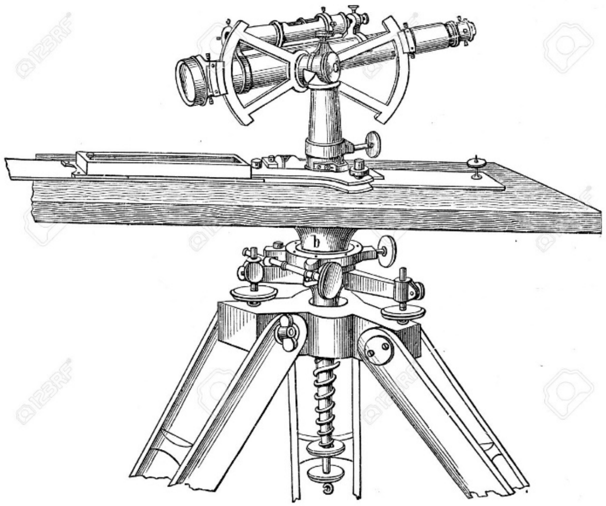


Carl Friedrich Gauss

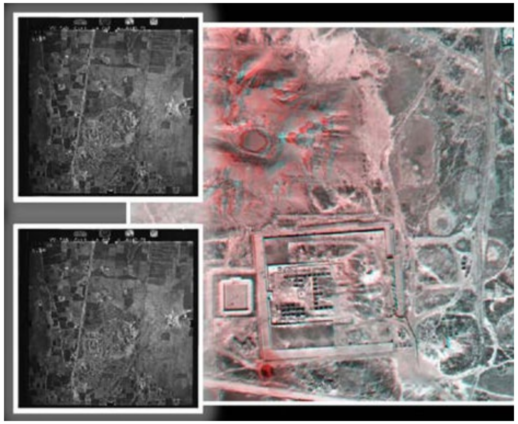
1828: Triangulation of Kingdom of Hanover



A Brief History of SLAM



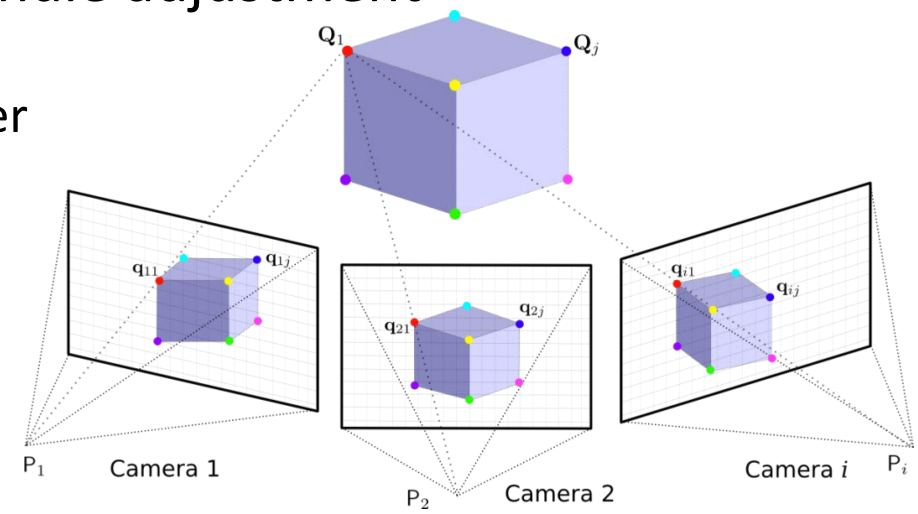
- Geodesy (2000-3000 years old)
  - "Geodesy is the science of accurately measuring and understanding the Earth geometric shape, orientation in space, and gravity field" (NOAA)
  - Using survey tools (now GPS…)



- Photogrammetry (since about 1850)
  - "Photogrammetry is the science of making measurements from photographs, especially for recovering the exact positions of surface points." (Wikipedia)
  - Typically using imagery from satellites or planes

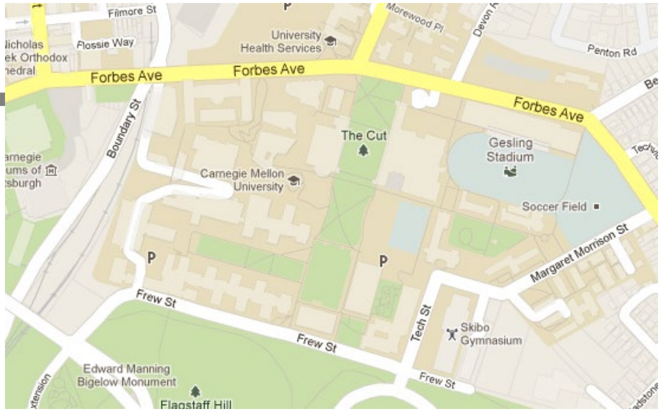
A Brief History of SLAM

- Computer Vision: (traditionally offline)
  - Structure from Motion / Bundle adjustment
    - Brown 1976
    - Bill Triggs 1999: seminal paper



- SLAM in Robotics: (online!)
  - Sonar
    - Several papers around 1989
  - Laser
  - Vision
    - Andrew Davison, PhD thesis 1998 (first real-time)

SLAM – Challenges



- Prior maps not always available (home, search-and-rescue, exploration)
- Environments change over time

- Difficult to map even if GPS is available
  - Google's driverless car uses pre-generated and manually annotated maps
  - Without GPS even more challenging
- High processing requirements for large-scale environments

Robot Localization and Mapping

- Motivation
- **Class Logistics**
- Overview

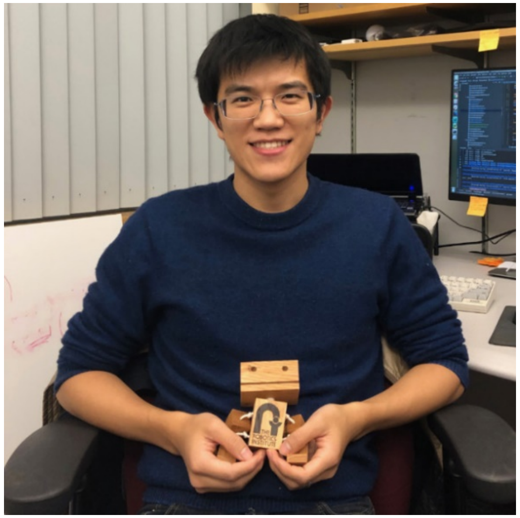
Course Basics

- Lecture: MW 2:20pm - 3:40pm, REMOTE
- TAs: Wei Dong, Ceci Morales, Jay Patrikar
- TA Office Hours: TBD
- Pre-requisits: Python, Matlab?, probability theory, linear algebra
- Resources:
  - Piazza: Discussion
    https://piazza.com/cmu/spring2021/16833a
  - Canvas: Course material, assignments, grades

16-833 TA: Wei Dong

Email:

weidong@andrew.cmu.edu



Advised by:

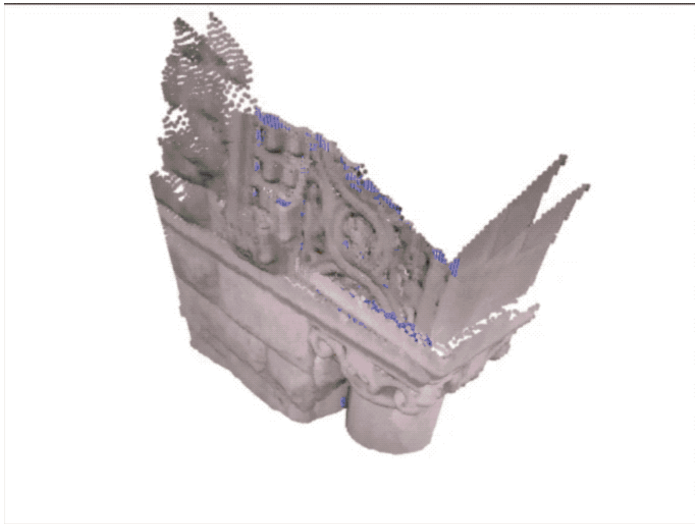
Prof. Michael Kaess

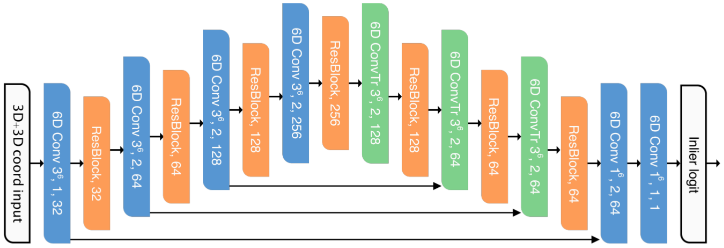
Please post your questions on ***Piazza*** first so that everyone benefits

16-833 TA: Wei Dong

Research Interests

- Dense 3D reconstruction
- Learn to register 3D point clouds
- GPU accelerated 3D perception





16-833 TA: Ceci Morales

Email:

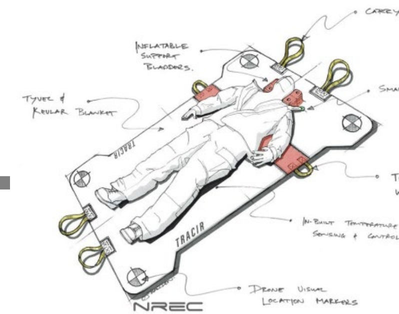
cgmorale@andrew.cmu.edu

Advised by:

Prof. Artur Dubrawski

Please reach out and introduce yourself and your research! I would love to get to know you all ☺

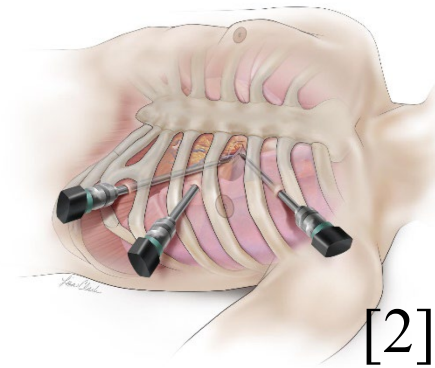
16-833 TA: Ceci Morales



[1]

Research Interests

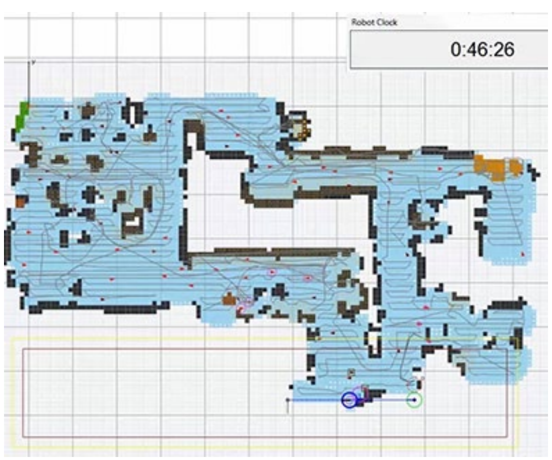
- Diagnosis and treatment of lethal diseases
- Minimally Invasive Surgeries
- Accessible Healthcare



[2]

Professional Experience

- Director of all GT Systems and Lead of a SLAM group at iRobot
  - Please reach out if you have any questions about SLAM in industry



[1] https://www.cmu.edu/news/stories/archives/2019/may/trauma-care-system.html
[2] https://www.sts.org/

16-833 TA: Jay Patrikar

Email:

jpatrika@andrew.cmu.edu

Advised by:

Prof. Sebastian Scherer

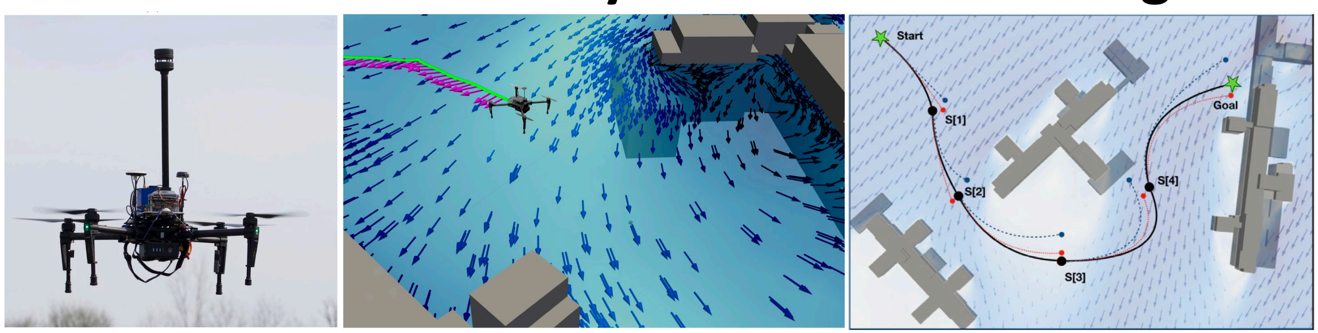
Website: jaypatrikar.me

16-833 TA: Jay Patrikar

Research Interests

- **Long-Range Object Detection and Triangulation**

- **Wind Estimation and Kinodynamic Path Planning for UAVs**



Michael Kaess

Associate Research Professor

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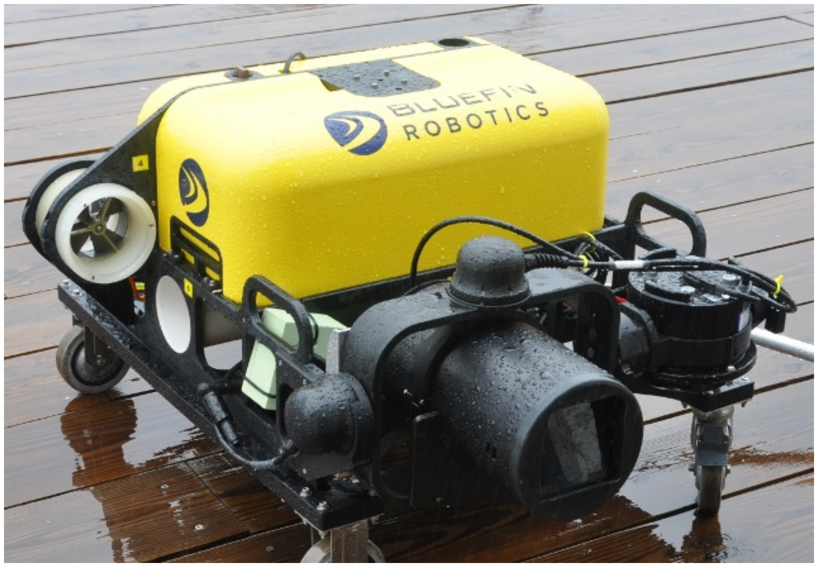
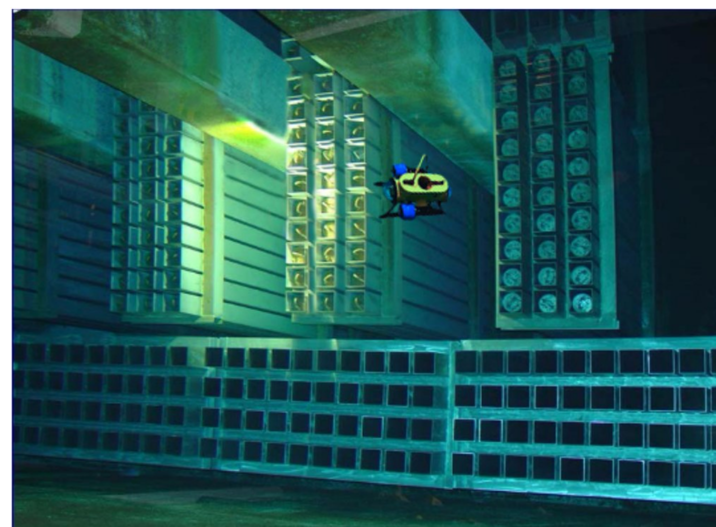
Research Interests:

- Localization and Mapping
- Robust and Large-scale Inference
- Inertial Fusion
- Underwater Robotics

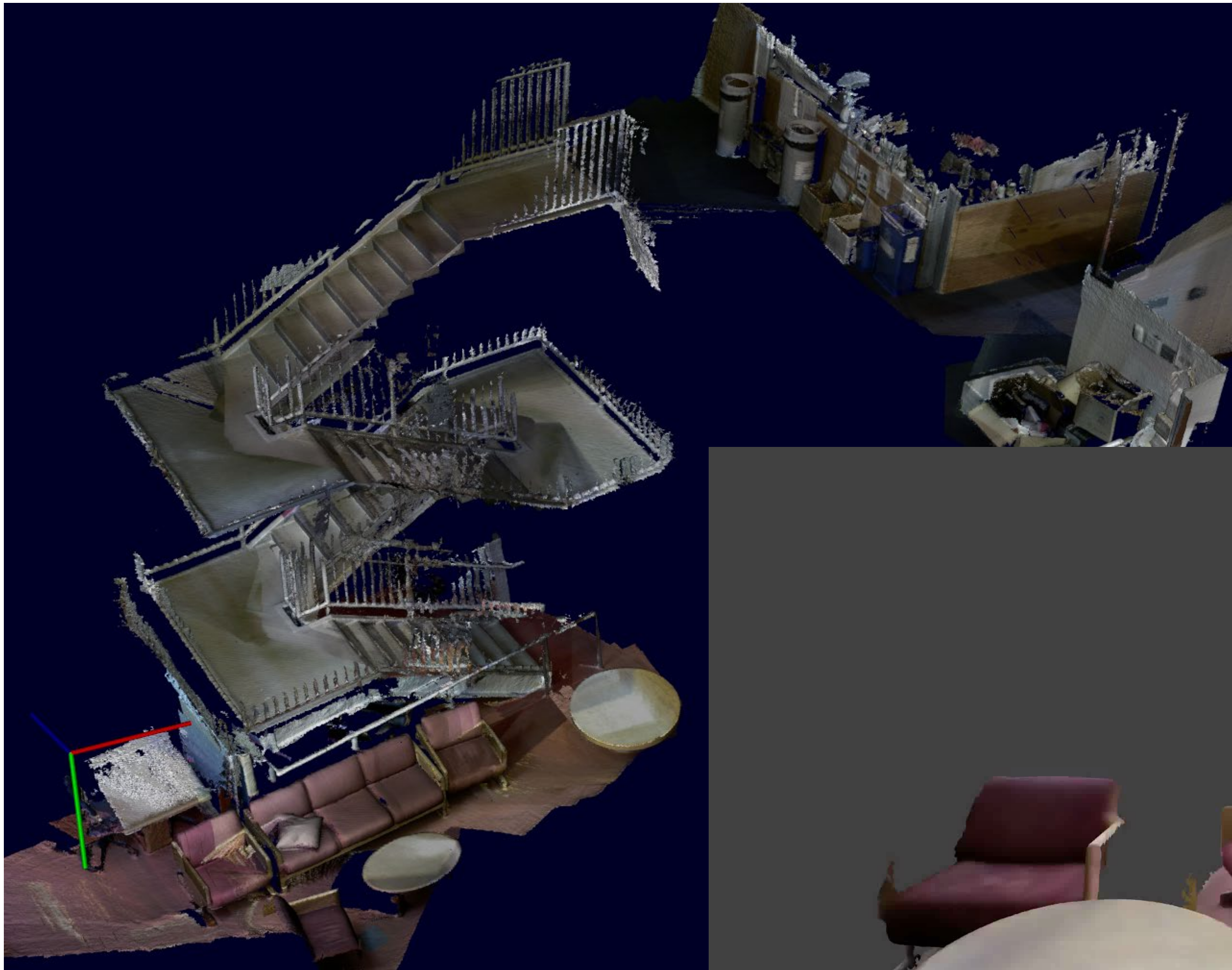
Underwater Robotics

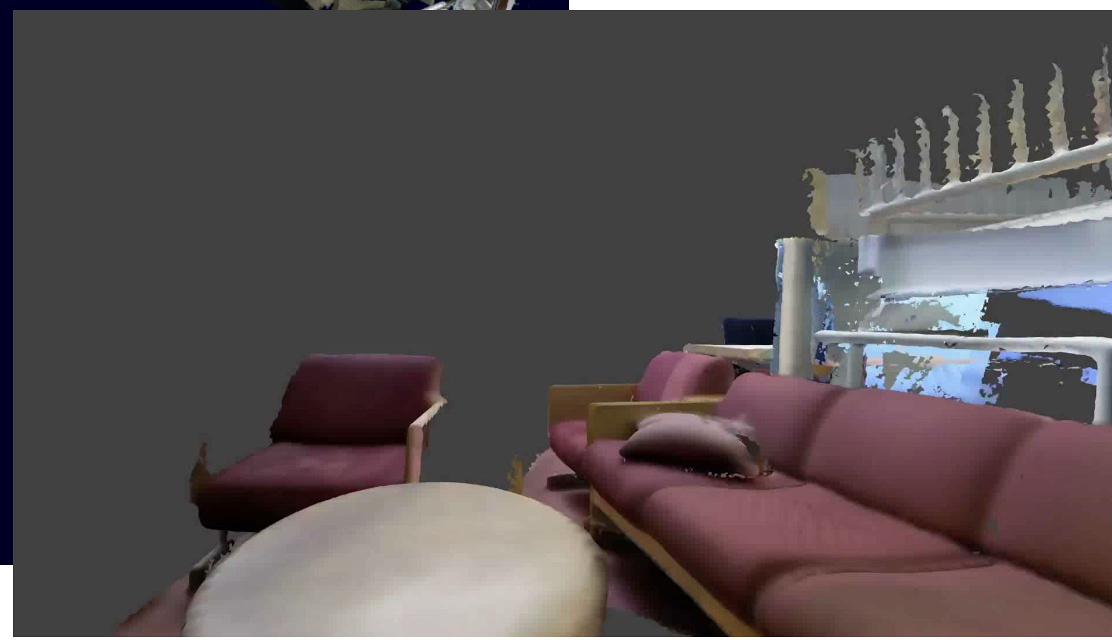
Working in challenging and dangerous environments





Real-time Dense 3D Modeling





GPS-denied Navigation

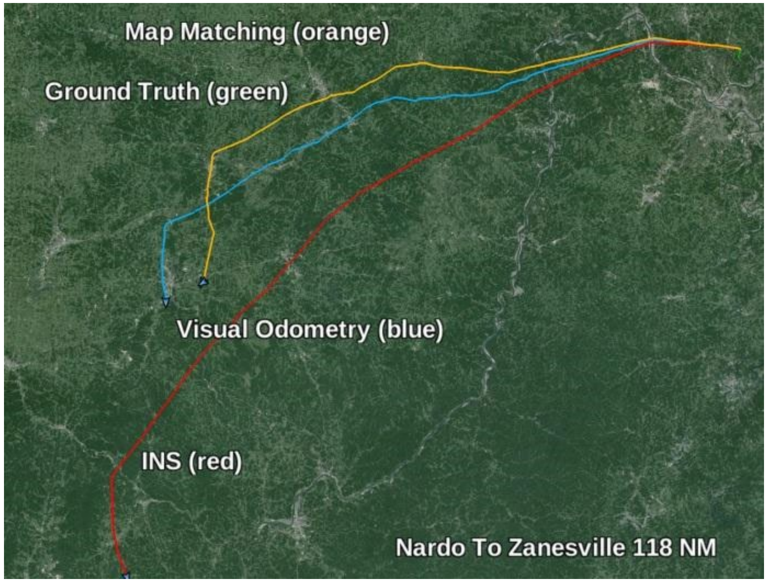
Low and bounded navigation drift without GPS

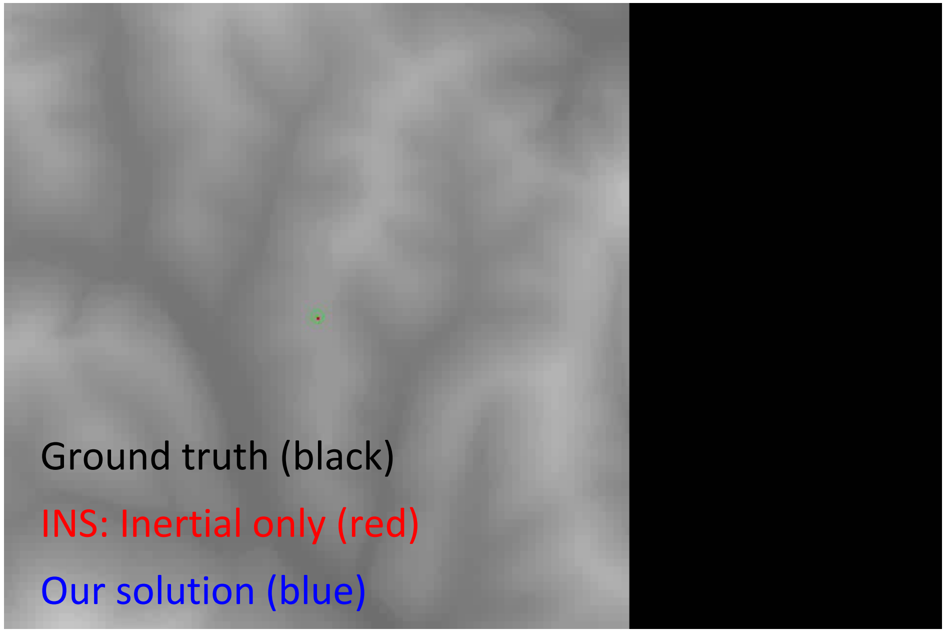
Lidar localization against digital elevation model (DEM)

Fusing with inertial data to provide low drift navigation

Flight distance 118nm = **218km**

Landing position error **< 40m**

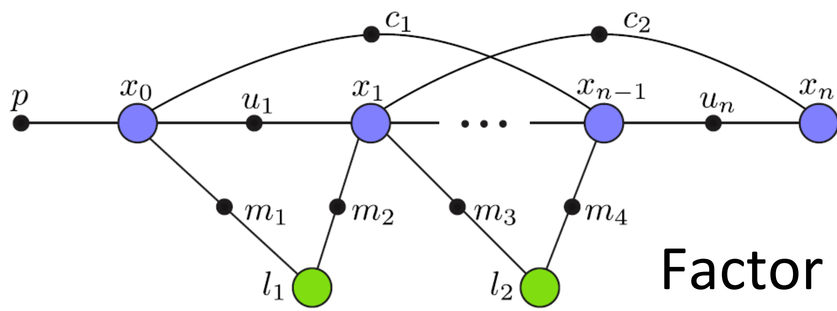




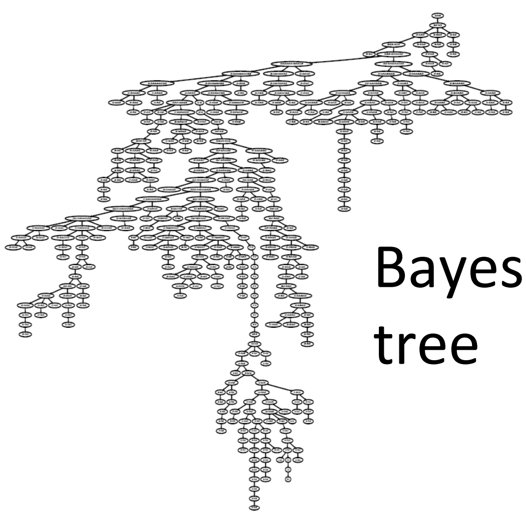
DEM

Lidar

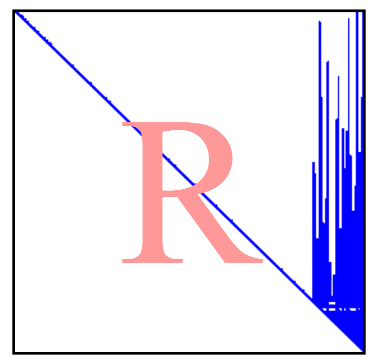
Efficient and Robust Inference



Factor graph



Bayes tree



Sparse QR factorization

Topics

- Probabilities, Gaussians, Covariances
- Particle filter
- Kalman filter, EKF
- Simultaneous localization and mapping
- Least-squares
- Nonlinear least-squares
- Graphical-model-based inference
- Rigid-body transformations and manifolds
- Data association
- SLAM systems including front-ends

Resources

- Book: “Probabilistic Robotics”, Thrun, Burgard, Fox, 2005
- “Factor Graphs for Robot Perception”, Dellaert and Kaess, Foundations and Trends in Robotics, vol. 6, no. 1-2, pp. 1-139, Aug. 2017 (pdf on Canvas)

Assignments

- 60% Four Problem Sets
  - Particle Filters
  - EKF
  - Smoothing / Nonlinear Optimization
  - Dense Mapping
- 10% Participation
  - Quiz (optional)
  - Reading
- 30% Course Project
  - Proposal (5%)
  - Midterm report (5%)
  - Presentation (10%)
  - Report (10%)

Course Project

- The topic of the final project should be closely related to the course. It should be either of the following:
  - An algorithmic or theoretical contribution that extends the current state-of-the-art
  - An implementation of a state-of-the-art algorithm using real-world data and/or robots.
- Team: 3-5 students
- Deliverables:
  - Presentation in class
  - Paper (IEEE style, 6-8 pages)
  - Source code

Programming Language

- Official language of the course is Python
  - Assignments in Python (or Matlab)
  - If you're new to Python (or Matlab), team up with someone more familiar with it
- Course Project
  - Your choice of programming language

Late Submission Policy

- Before deadline: 100% (get some good sleep!)
- Within 48 hours after the deadline: 50%
- After 48 hours: 0% (still must submit something!)

- To help with unexpected situations, you have a total of **4 late days** that can be used on any of the 4 homework assignments

Integrity

- All encouraged to work together BUT you must do your own work (code and write up)
- If you work with someone, please include their name in your write up and inside any code that has been discussed
- If we find highly identical write-ups or code without proper accreditation of collaborators, we will take action according to university policies. **You will fail the course!**
- I reserve the right to use automated software to find duplicate code and writeup in submissions

Health

Take care of yourself. *Do your best to maintain a healthy lifestyle this semester by eating well, exercising, avoiding drugs and alcohol, getting enough sleep and taking some time to relax. This will help you achieve your goals and cope with stress.*

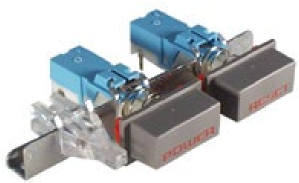
All of us benefit from support during times of struggle. You are not alone. There are many helpful resources available on campus and an important part of the college experience is learning how to ask for help. Asking for support sooner rather than later is often helpful.

If you or anyone you know experiences any academic stress, difficult life events, or feelings like anxiety or depression, we strongly encourage you to seek support. Counseling and Psychological Services (CaPS) is here to help: call 412-268-2922 and visit their website at http://www.cmu.edu/counseling/. Consider reaching out to a friend, faculty or family member you trust for help getting connected to the support that can help.

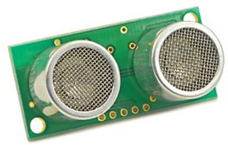
Robot Localization and Mapping

- Motivation
- Class Logistics
- **Overview**

Perception: Sensors



$0.02



$5

$200

$2000

$75000

$4000

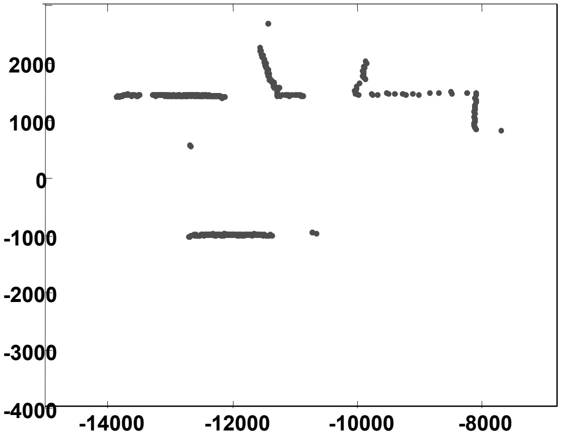
Courtesy E. Olson

Perception: Sensor Data

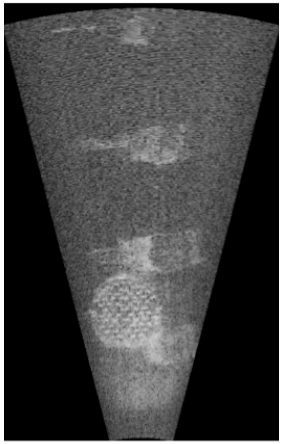
Camera image

RGB-D image

2D laser scan



Multi-beam sonar (profiling and imaging)



Localization and Mapping

- State Estimation
  - Most common example: GPS + Inertial
- Localization
  - Estimating robot's location/orientation given a prior map
- Mapping
  - Building a map given known robot location and orientation
- Simultaneous Localization and Mapping

- Static vs Dynamic
- Tracking

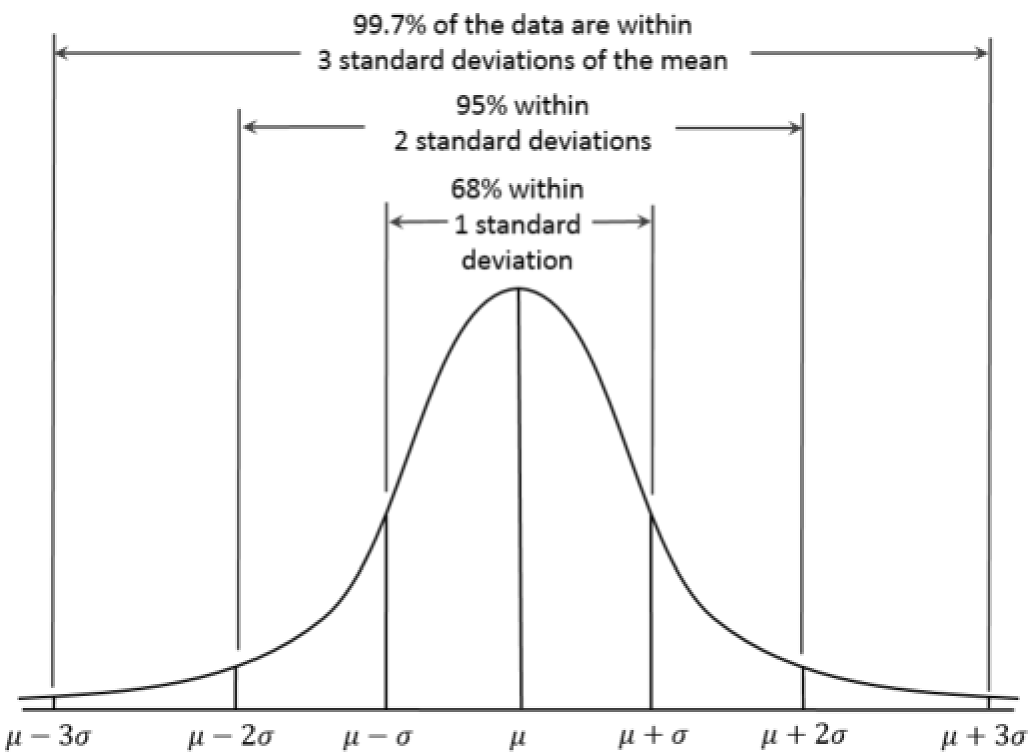
State

- Position
- Orientation
- Velocity
- Sensor calibration

- Current pose vs trajectory
- Discrete vs continuous trajectory
- 2D vs 3D

Uncertainty in State Estimate

- Normal density



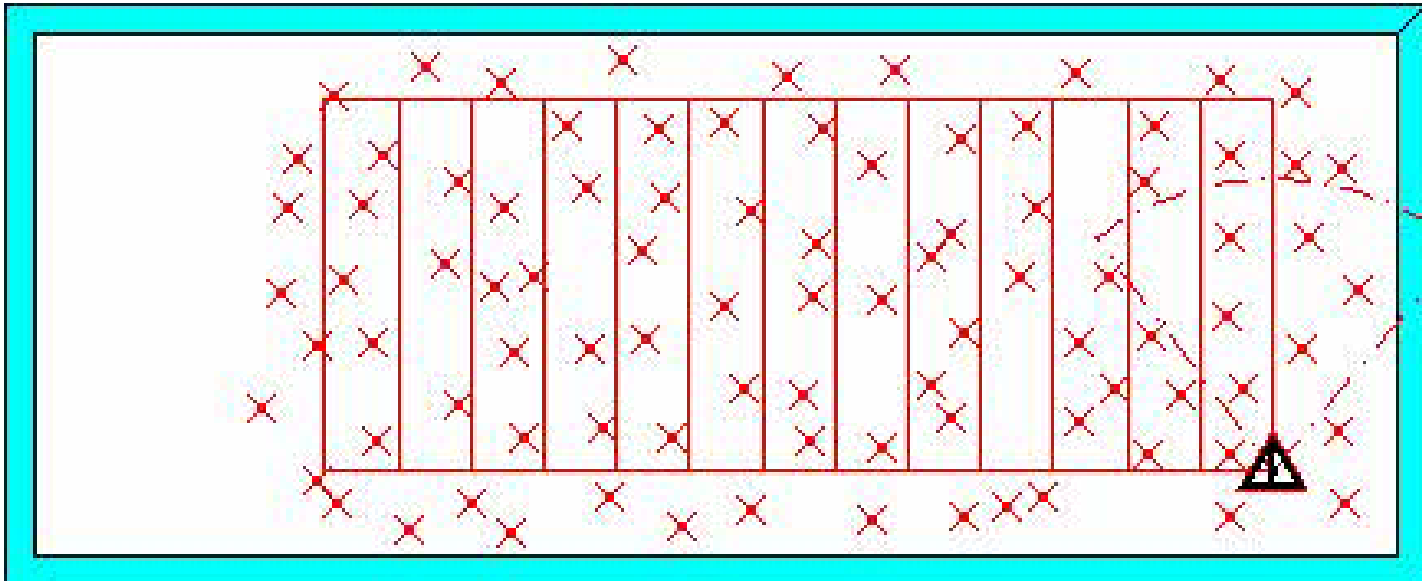
[Wikipedia]

Choices for Map Representation

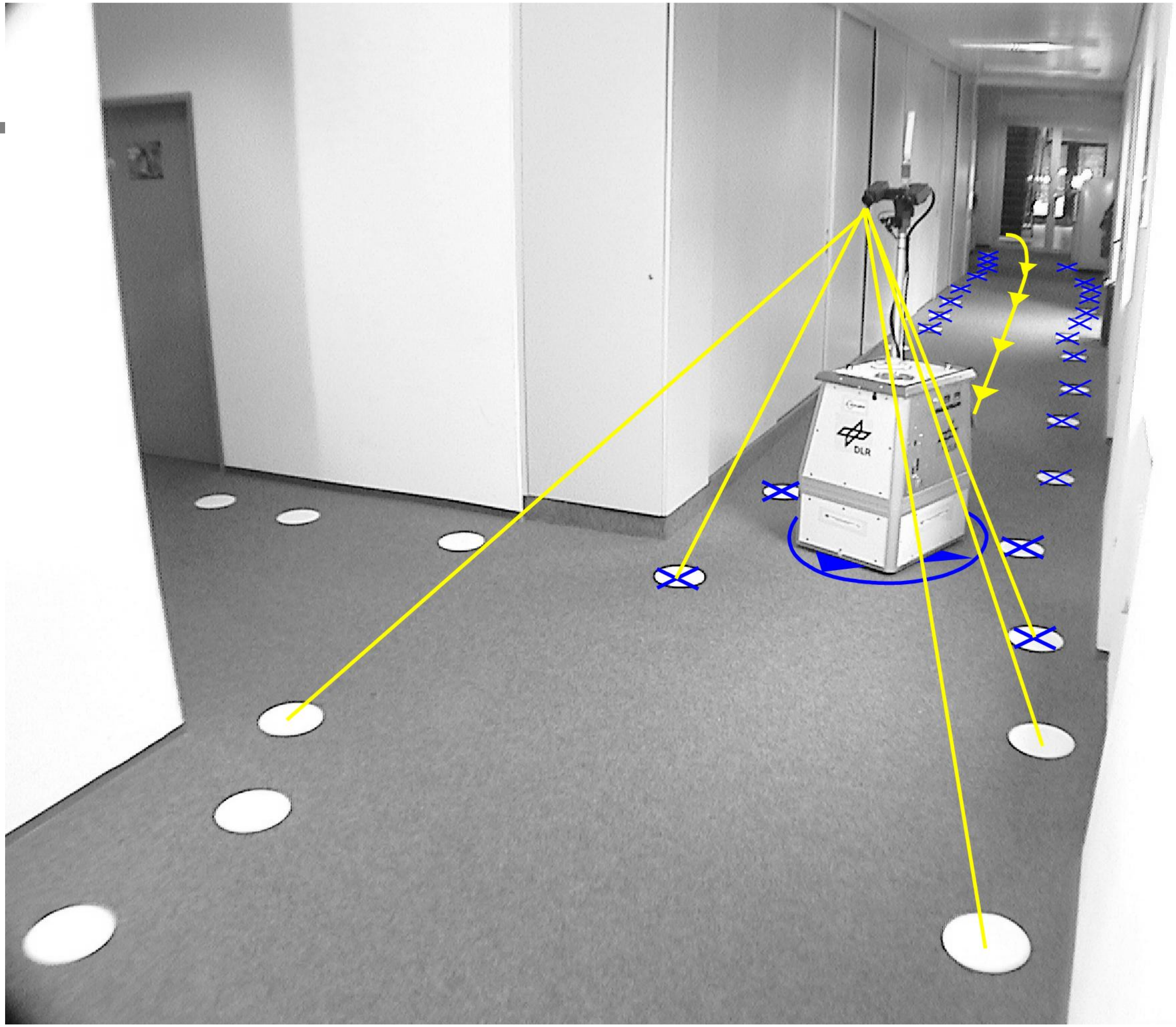
- Features / landmarks
- Occupancy grid
- Poses + raw sensor data
- Point cloud
- Surfaces: triangle mesh, planar patches, implicit representation
- Topological

Feature-based SLAM: Points

- 1. Move
- 2. Sense
- 3. Associate measurements with known features
- 4. Update state estimates for robot and previously mapped features
- 5. Find new features from unassociated measurements
- 6. Initialize new features



Courtesy J. Leonard



http://www.informatik.uni-bremen.de/~ufrese/slamvideos1_e.html Courtesy U. Frese

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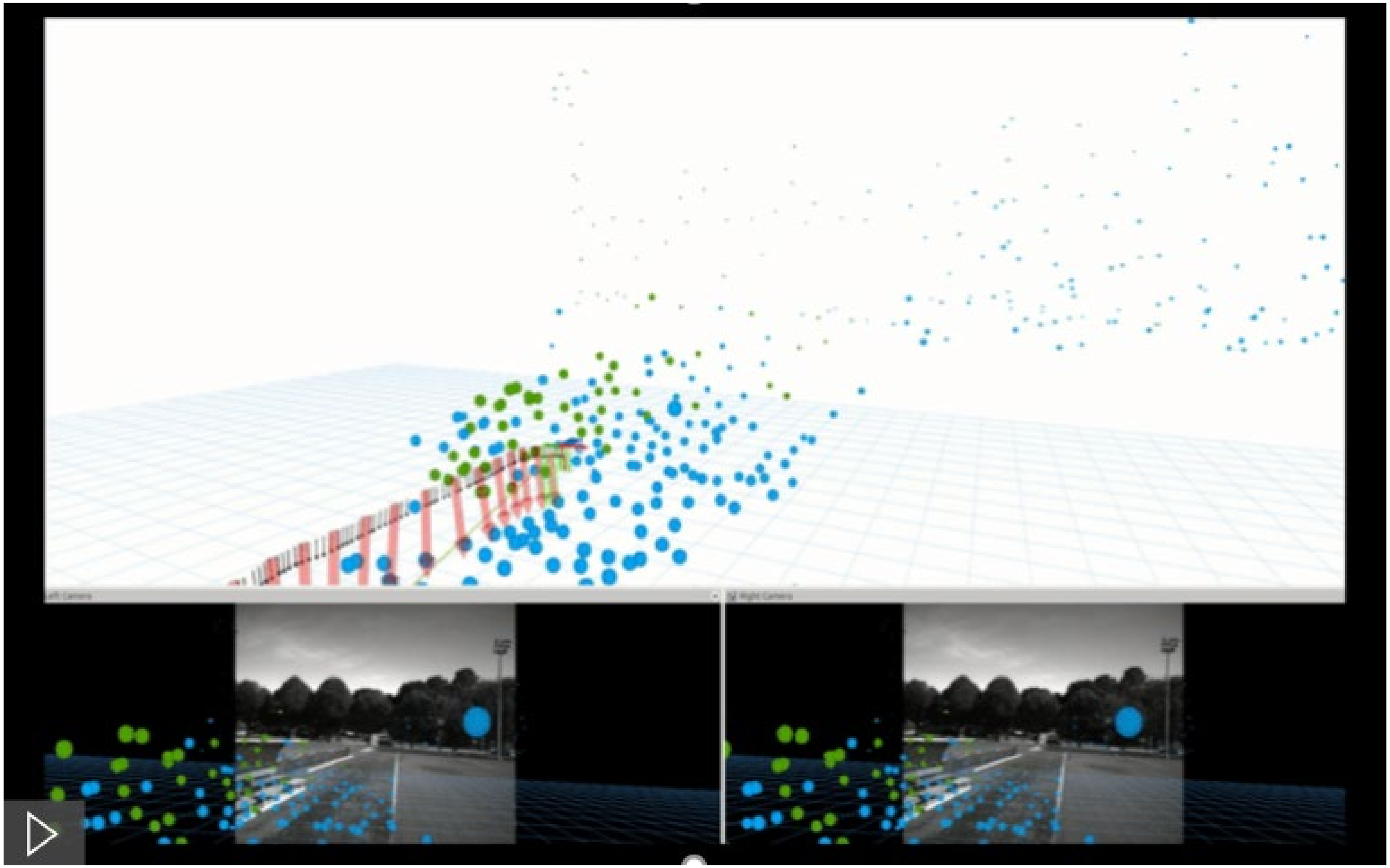
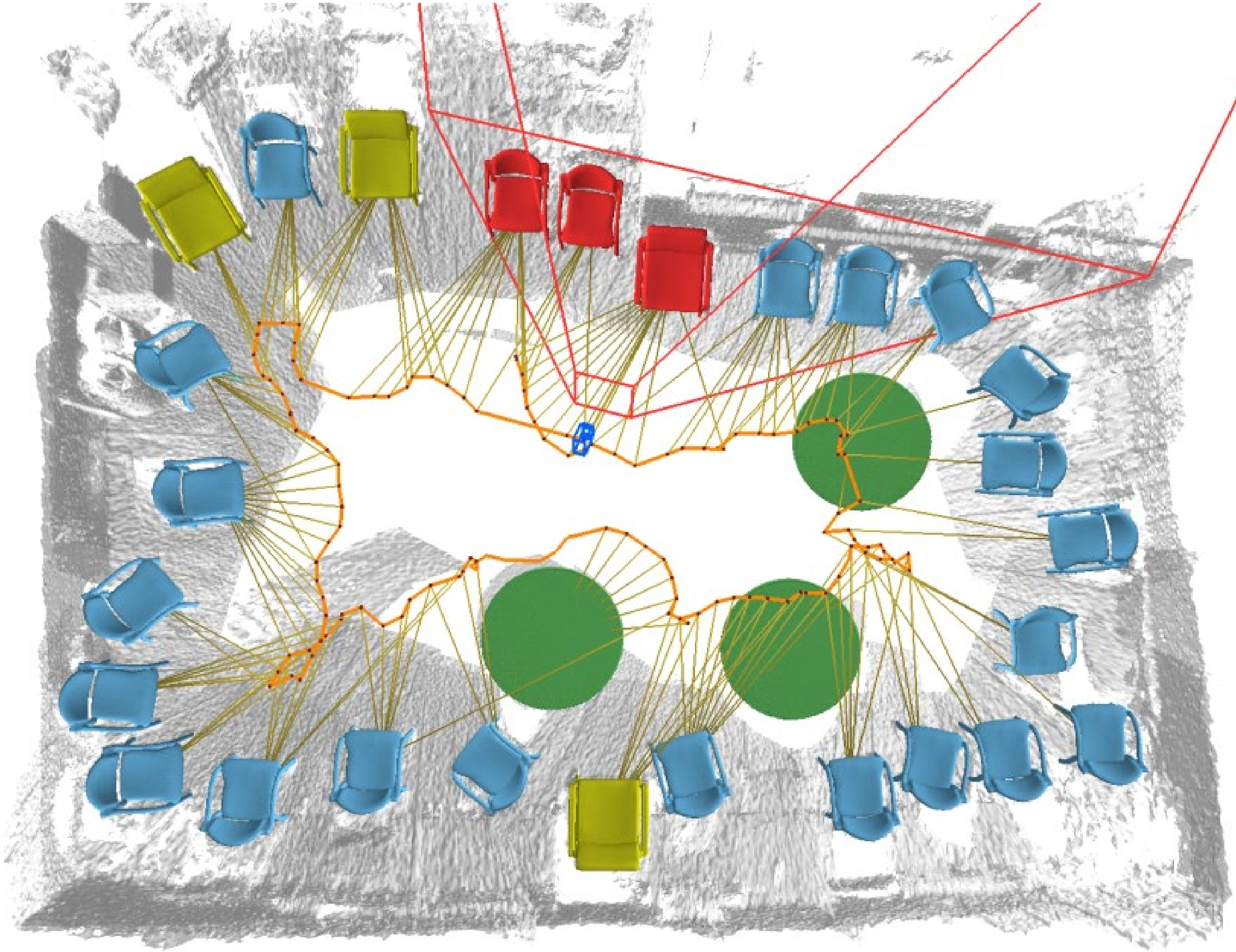
Features: Interest Points from Vision



Features: Chairs



SLAM++, Salas-Moreno et al, CVPR 2013

Choices for Map Representation

- Features / landmarks
- **Occupancy grid**
- Poses + raw sensor data
- Point cloud
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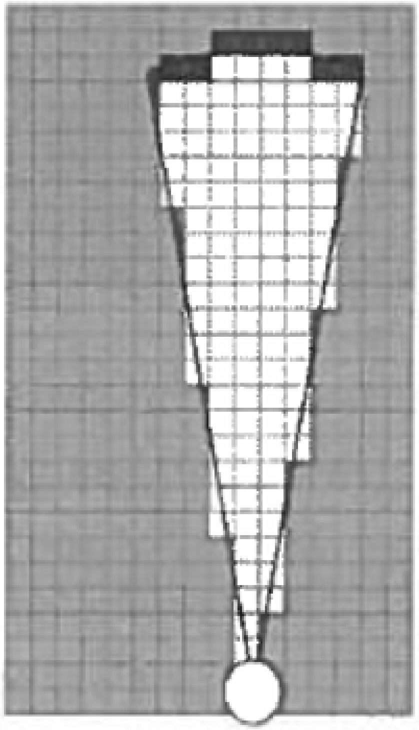
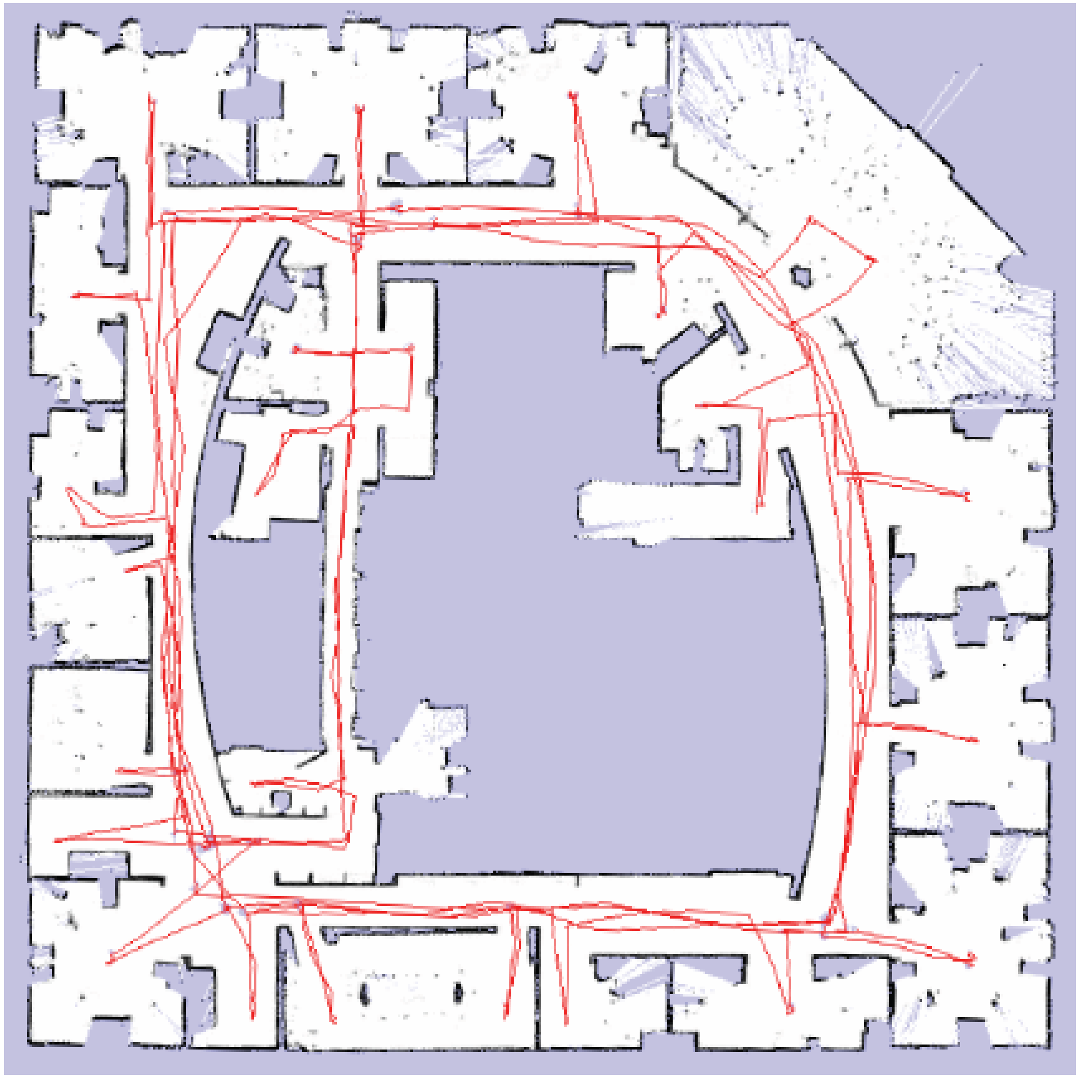
Occupancy Grid Map

- Discretize space into grid cells
- For each cell independently estimate probability of being occupied
- Efficient implementation using “log-odds”



[Moravec, Elfes, “High resolution maps from wide angle sonar”, ICRA 1985]

Occupancy Grid Laser Map



Choices for Map Representation

- Features / landmarks
- Occupancy grid
- **Poses + raw sensor data**
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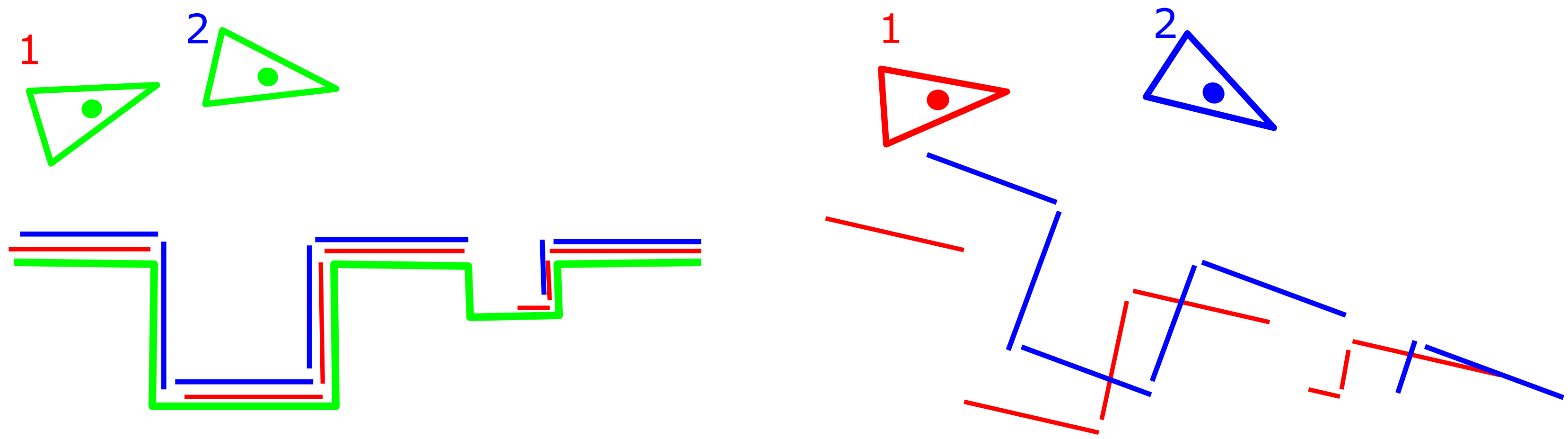
Representation: Poses and Scans

- Robot scans, moves, scans again
- Short-term odometry error causes misregistration of scans
- Scan matching is the process of bringing these scans into alignment



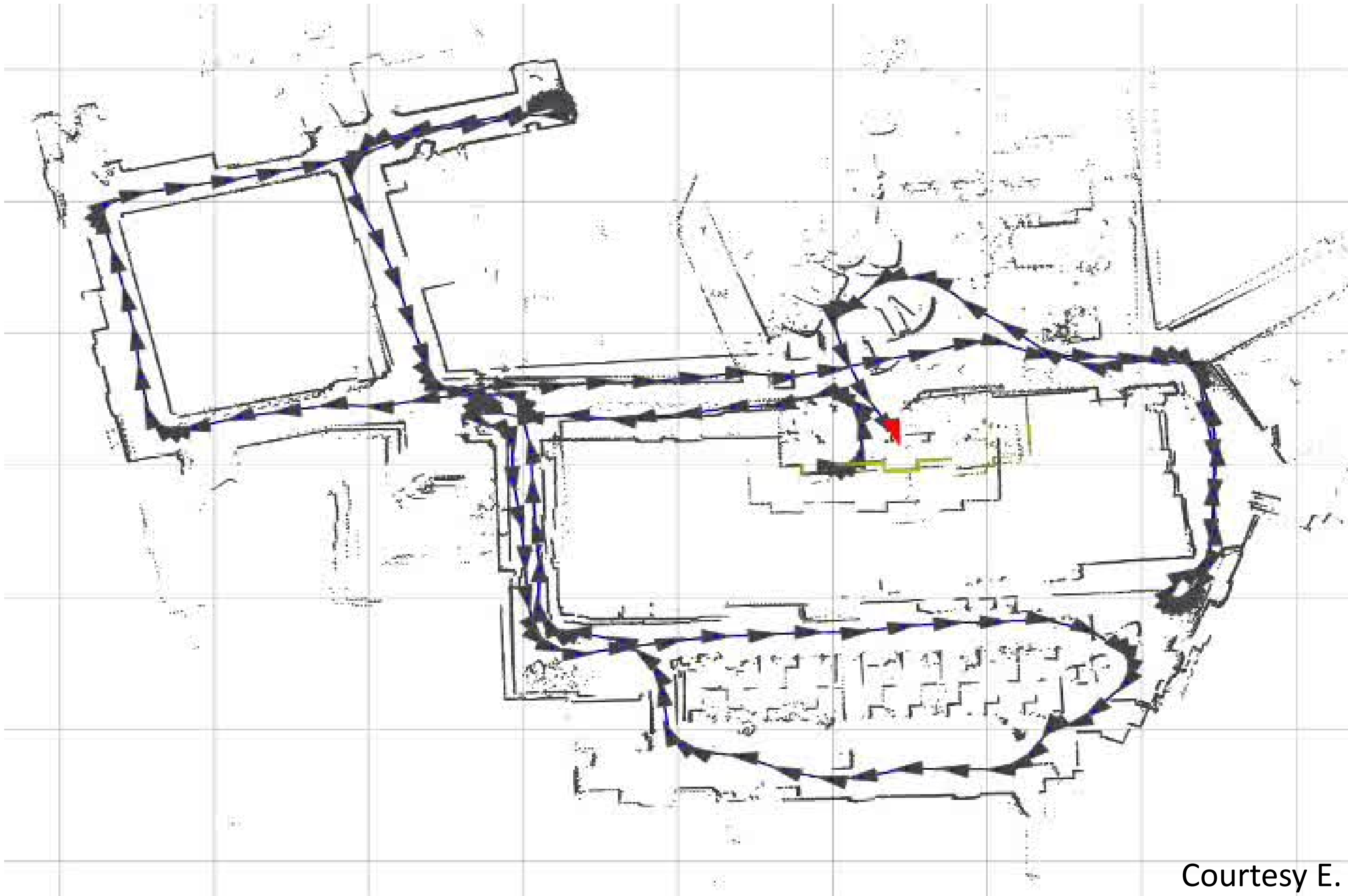
Ground truth (unknown) — Scan from pose 1 — Scan from pose 2

Courtesy J. Leonard

SLAM Based on Laser Scan Matching

Olsen 2005

SLAM Based on Laser Scan Matching



Courtesy E. Olson

Choices for Map Representation

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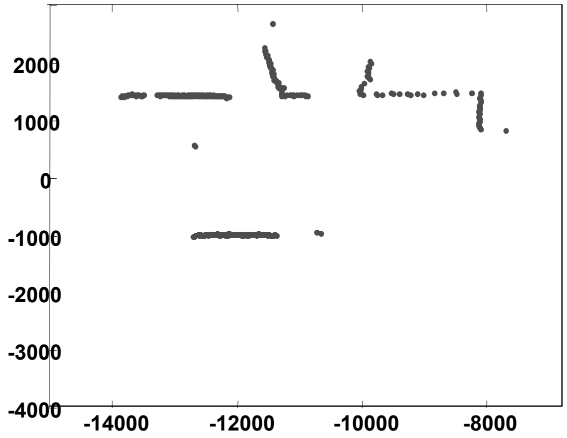
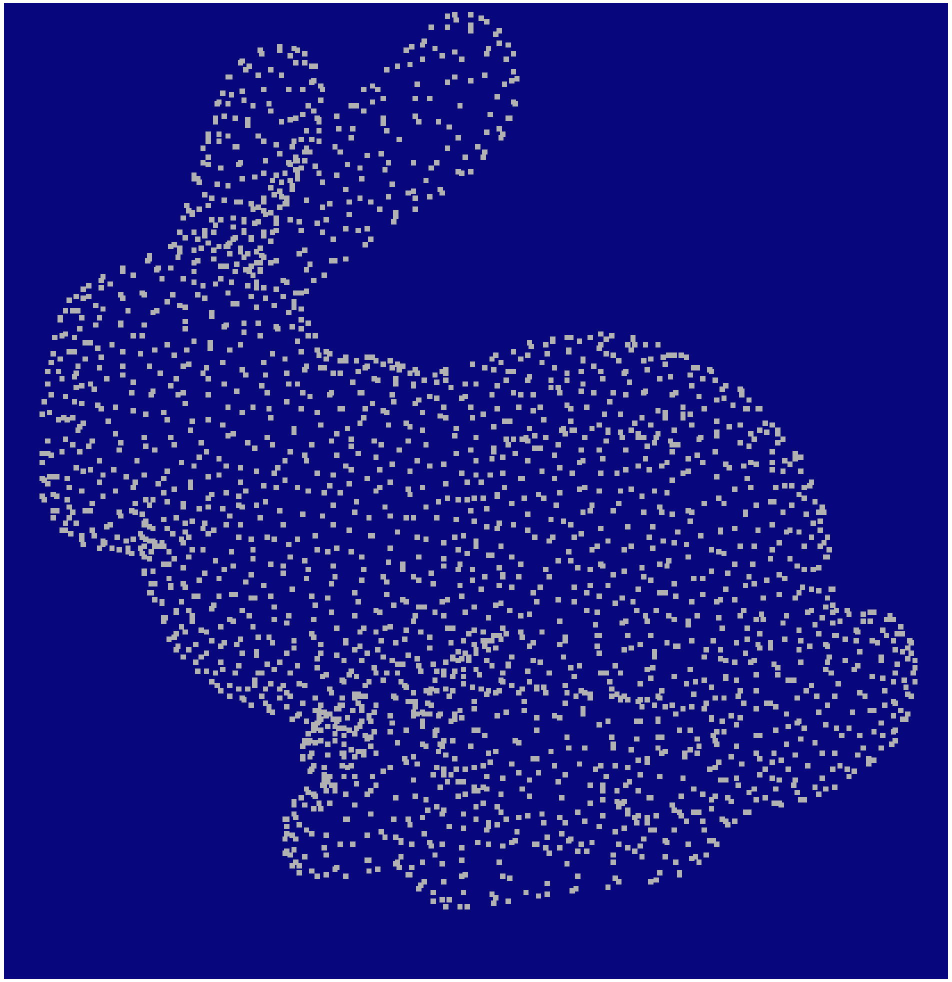
Point Cloud





Point Cloud Example

FRC machine shop, courtesy Ji Zhang

Choices for Map Representation

- Features / landmarks
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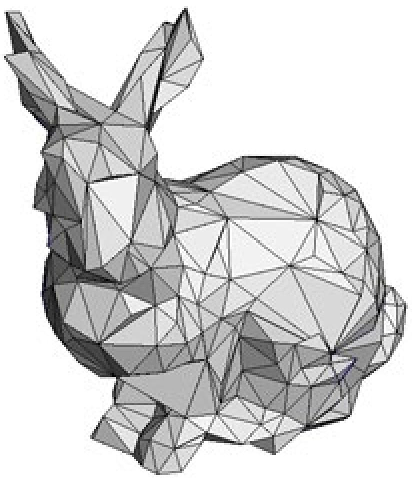
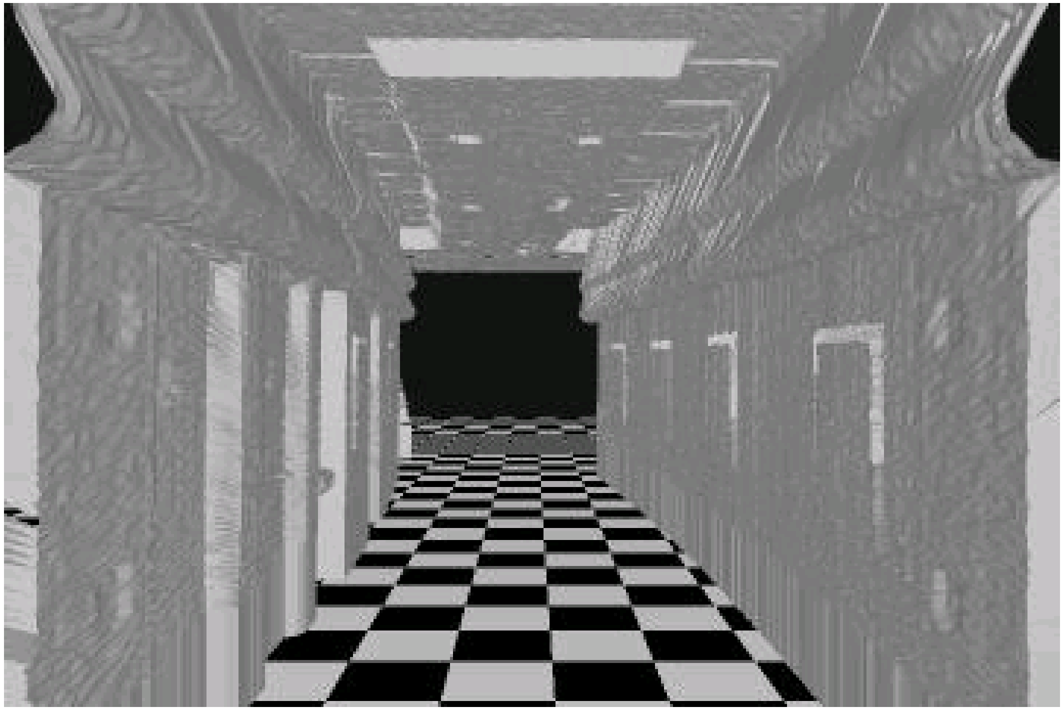
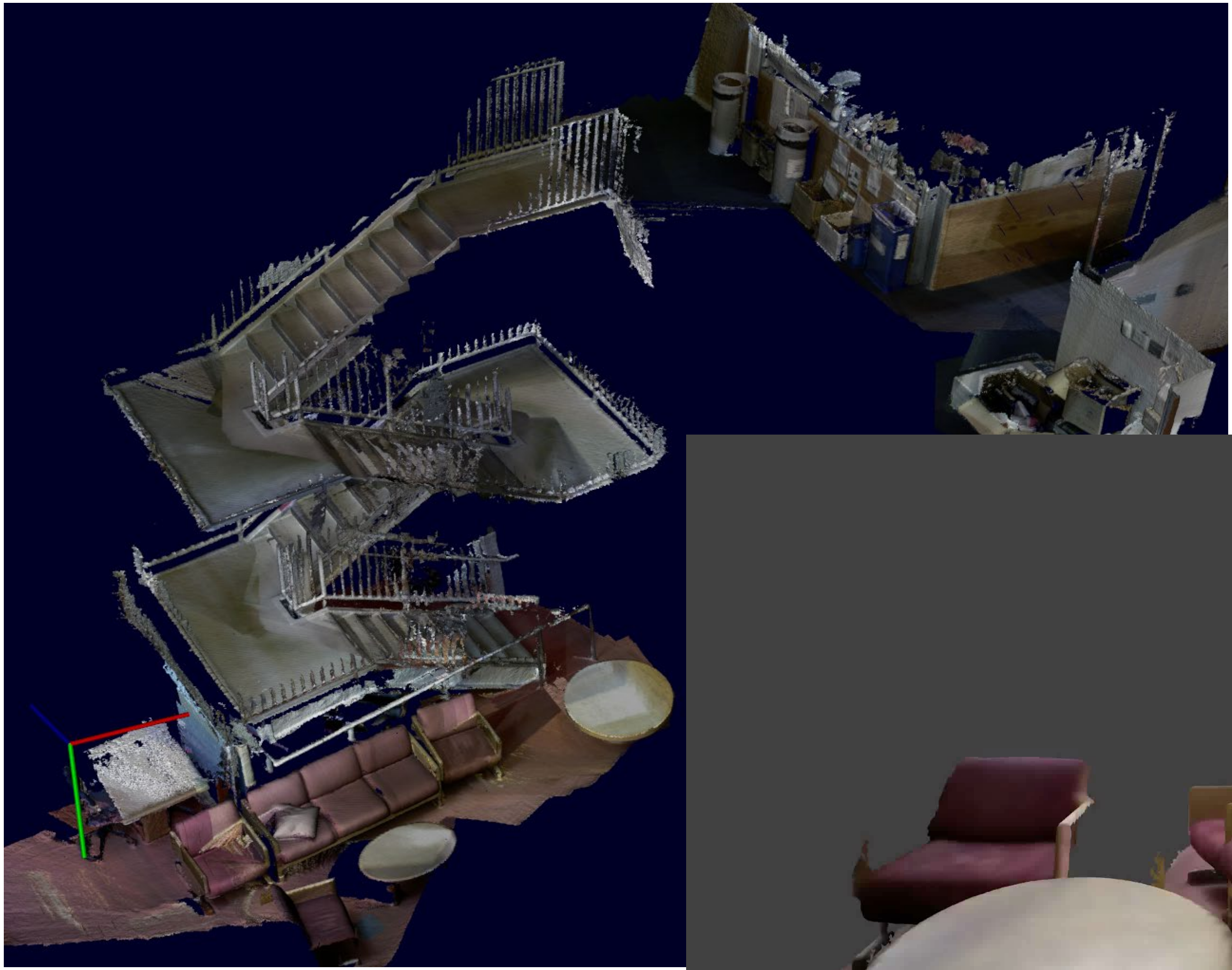
- **Surfaces: triangle mesh, planar patches, implicit representation**
- Topological

Triangle Mesh





Surface Representations: Triangle Mesh



- Handheld RGB-D sensor ($180)
- Real-time with GPU processing

Surface Representations: Implicit and Planar

Implicit (Signed Distance Function)

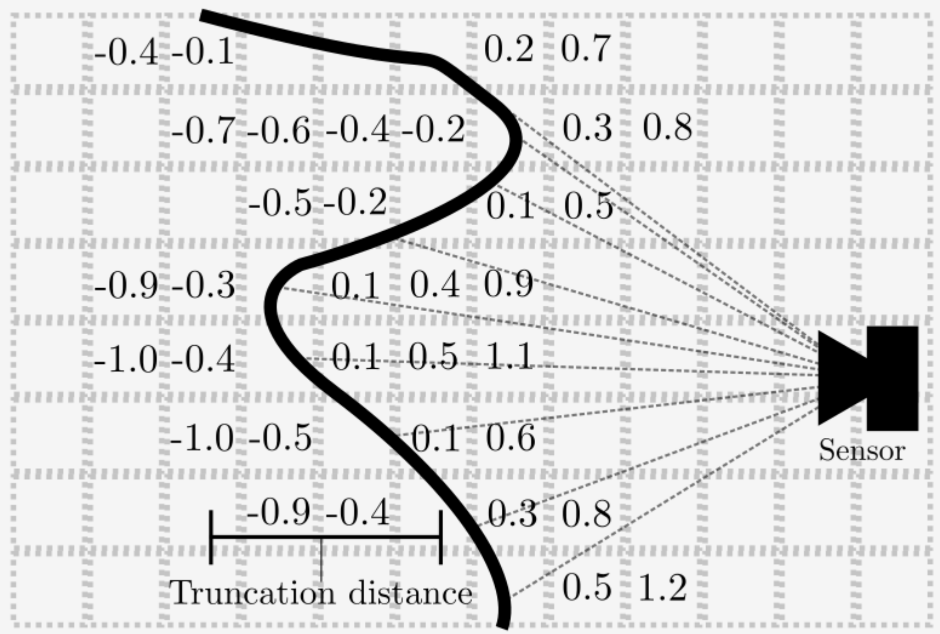
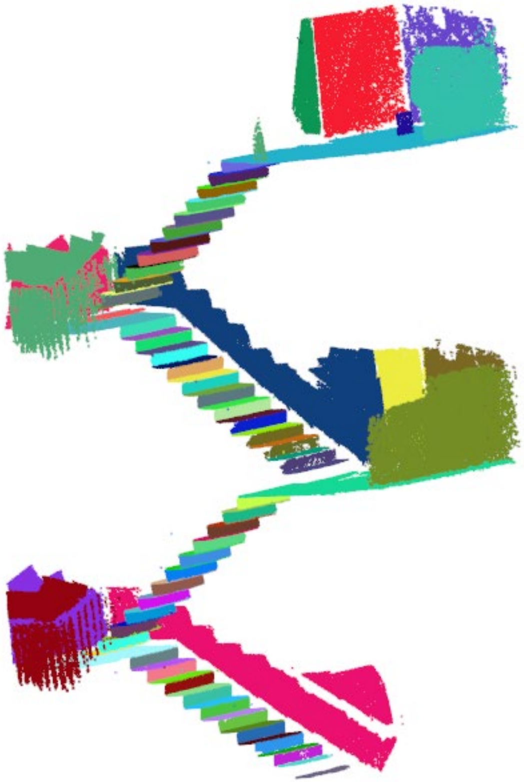


Figure 1: Two dimensional example of the structure of the truncated signed distance function representation of an implicit surface. Shown are example signed distance values stored at voxels within the truncation distance of the observed surface, with rays cast from the observing sensor.

Planar surface patches



Choices for Map Representation

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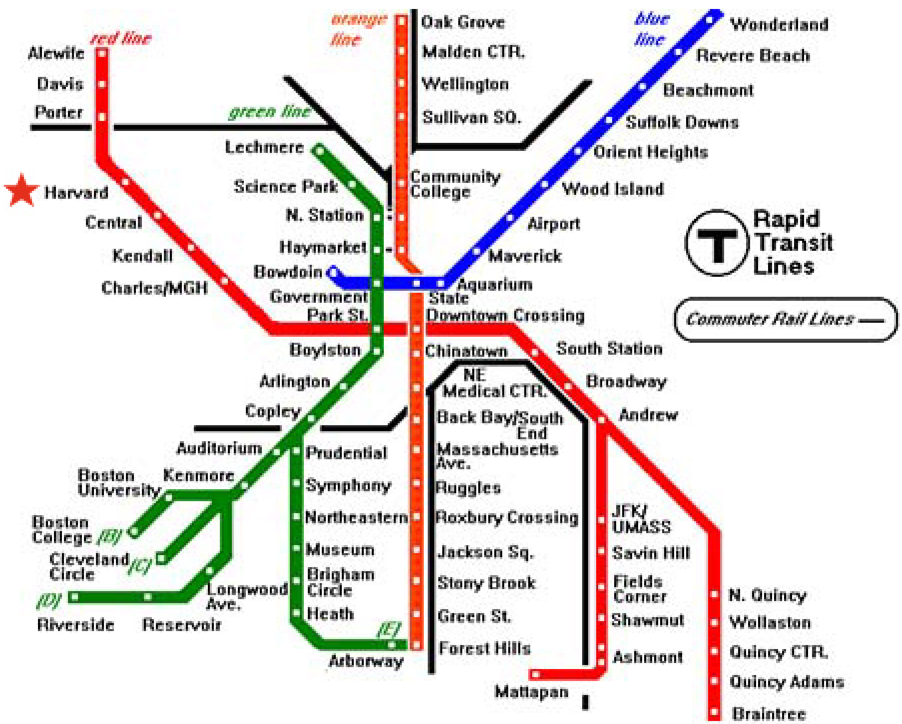
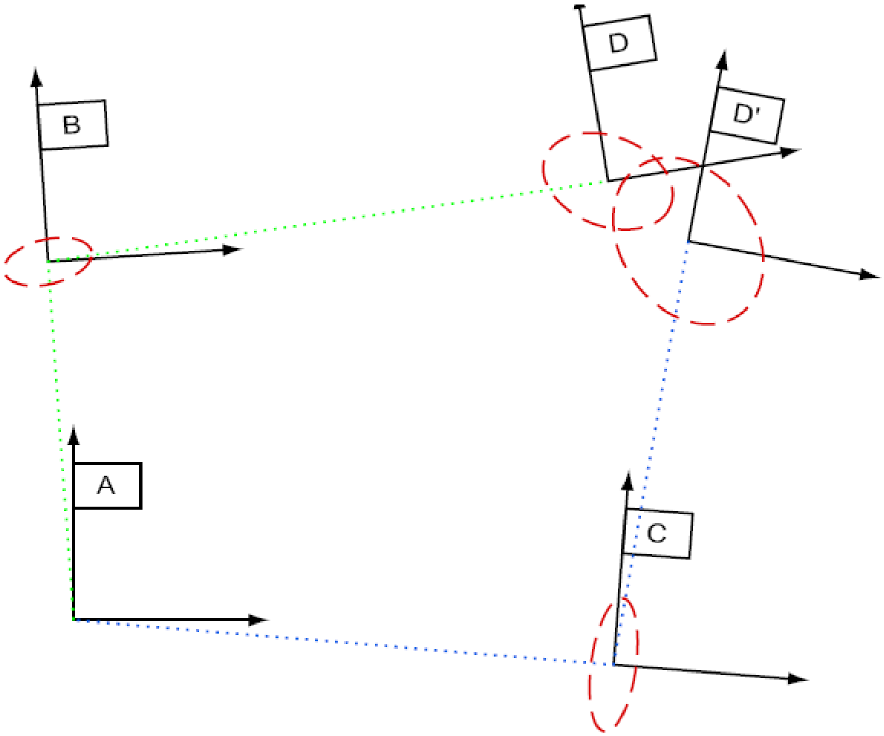
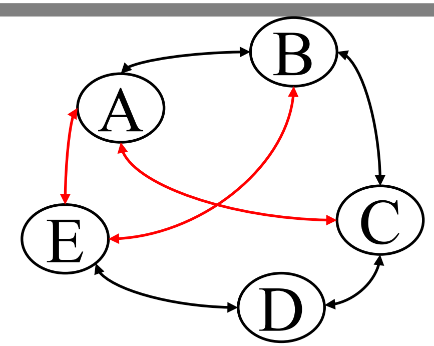
- **Topological**

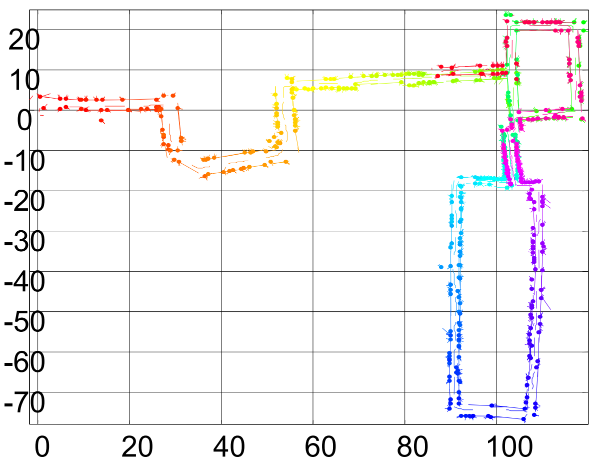
Topologic vs. Geometric Maps



SLAM using Hybrid Metric/Topological Maps



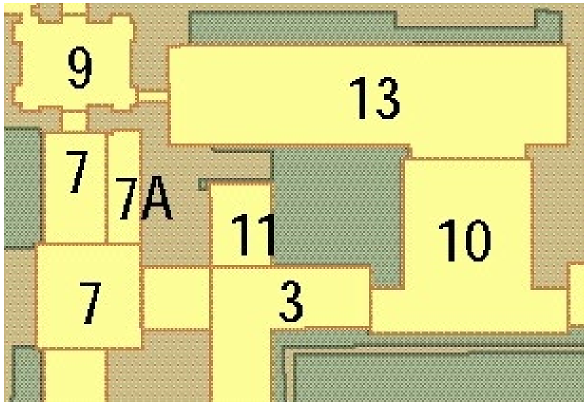


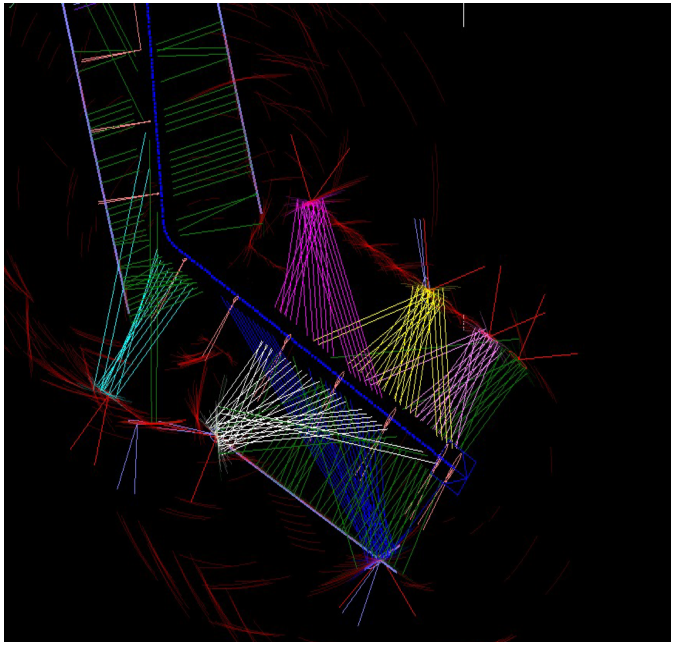


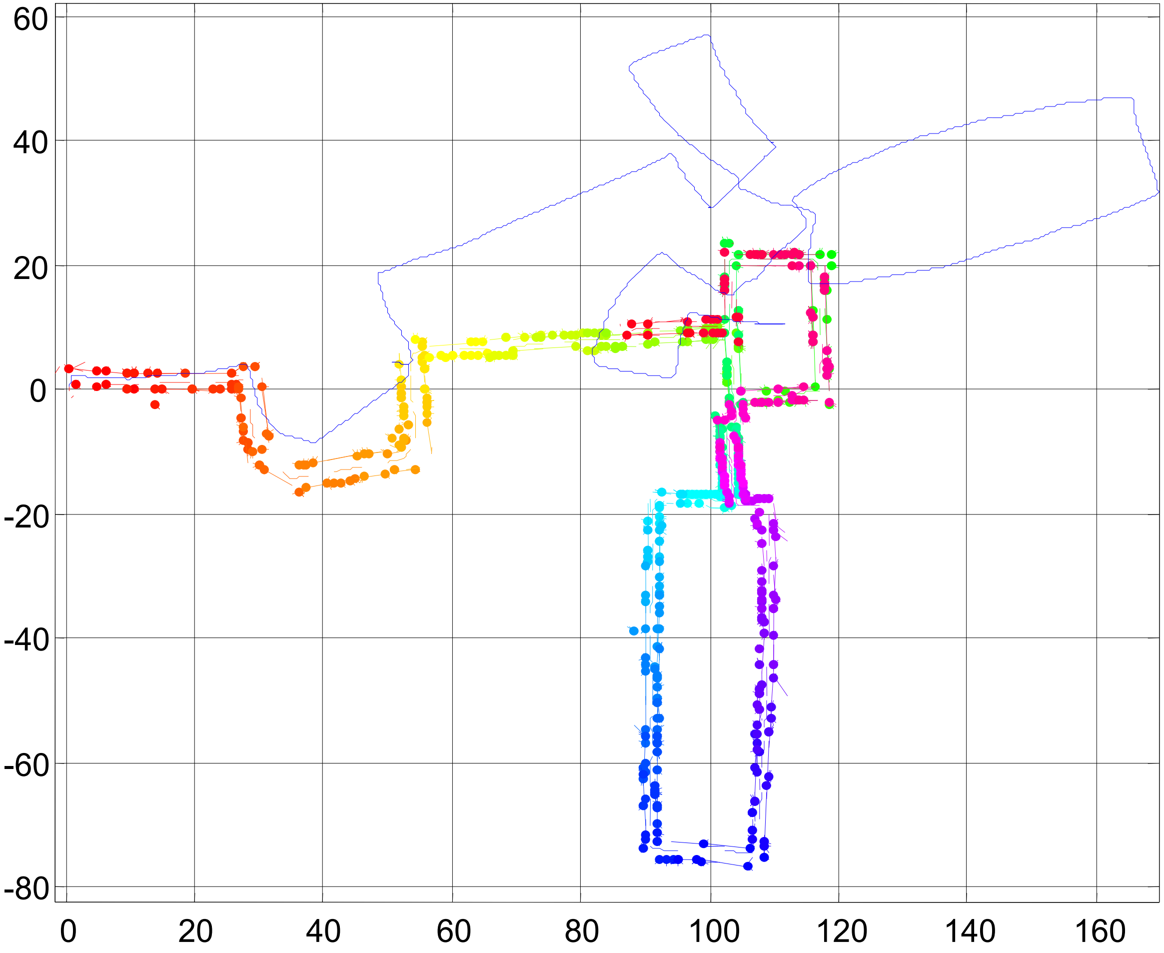
- Geometry: rigid frames, submaps
- Topology: map adjacencies
- Hybrid: uncertain transforms

Bosse, Newman, Leonard & Teller, 2004

Example of a globally optimized map







Bosse, Newman, Leonard & Teller, 2004

Summary

- SLAM is a challenging problem
- Sensors
- State Estimation / Localization / Mapping / SLAM
- Map Representations

Next Lecture

- Probability Review