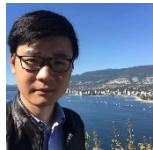




Motion Planning for Mobile Robots



主讲人 Fei Gao

Ph.D. in Robotics
Hong Kong University of Science and Technology
Assistant Professor, Zhejiang University





Outline



1. Introduction



2. Course Outline



3. Typical Planning Methods Overview



4. Map Representation



5. Pre-requirement



6. Homework



Introduction



About this Course

- **This course is about:**
 - Academism (old school) planning pipeline
 - Path finding algorithm
 - Trajectory generation/optimization
 - Real-time software implementation
- **This course is NOT about:**
 - Dynamics Modelling ☹
 - Robot design ☹
 - End-to-end navigation ☹
 - Learning-based method ☹
 - Mathematical/theoretical proof ☹
- **This course may also cover:**
 - Autonomy for mobile robots
 - Paper recommendations
 - Cutting-edge research direction/ethics



Basic Expectation

- Discipline:

- Every researcher has his own taste/style. Since you choose this course, please follow my style.
- Q&A only at appointed office time.
- Finish your homework by yourself.

- Project:

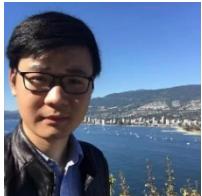
- Basic algorithm validation (MATLAB)
- Sophisticated engineering implementation (ROS/C++)

每位研究者都有自己的风格和品味，如果你们选择了这门课，那请你们在这门课的范围内，尽量 follow我们的风格。我相信，如果大家跟随老师的风格，无论如何，大家最后都会收获很多很多。

我简单说一下我的风格：我的风格一定是实用第一，任何算法如果没有很好的实用价值，那我就认为它在实际的机器人系统上没有太大实际意义。我教给大家的算法，希望不要仅停留在Matlab的数值验证层面，更要在C++或者ROS里面跑起来，在嵌入式系统中跑起来。这就是我的风格！



Teaching Team



Instructor 1: **Fei Gao**

Assistant Professor, ZJU

Ph.D, HKUST

Email: fgaoaa@connect.ust.hk



Instructor 2: **Chaoqun Wang**

Research Professor, SDU

Ph.D, CUHK

Email: zychaoqun@gmail.com



Instructor 3: **Shupeng Lai**

Adjunct Assistant Professor, NUS

Ph.D, NUS

Email: shupenglai@gmail.com



Instructor 4: **Delong Zhu**

Research Engineer, Huawei ADS

Ph.D, CUHK

Email: dlzhu@ee.cuhk.edu.hk



Information

- **Lecture time:**
 - Every Friday night 19:00
- **Course Community:**
 - www.shenlanxueyuan.com/course/315/threads/show
- **Course Website:**
 - www.shenlanxueyuan.com/course/315
- **Course Wechat Group:**
 - Connect the class teacher



Workload

- Expected Student Background:

- Linear algebra
- Probability
- MATLAB programming skills
- C++ programming skills (VERY IMPORTANT)
- Linux
- Love robots ☺

- Workload:

- Attend lectures
- Lots of project work
- Have fun with robots ☺

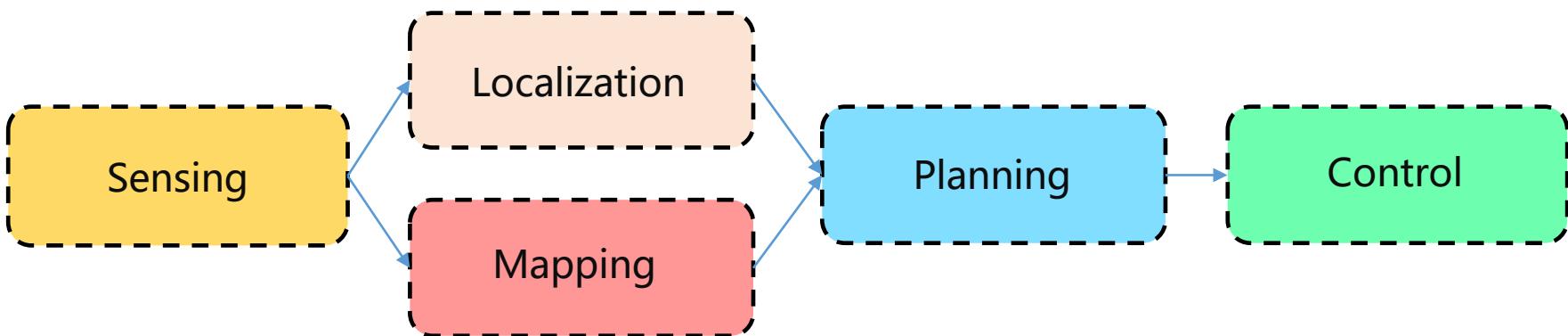


What is autonomous robot

Definition: an autonomous robot is a robot that performs behaviors or tasks with a high degree of autonomy (without external influence).

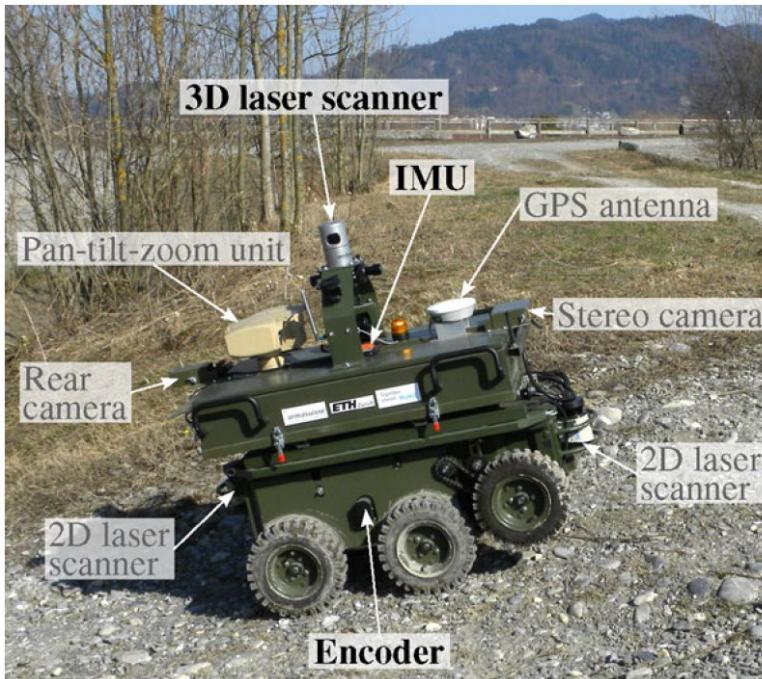
Subjects: Computer Science, Automation, Mechanism, Electronics ...

- Perception-Planning-Control action loop





Autonomous robot: applications





What is autonomous robot

- Estimation

- Low latency
- High accuracy & consistency

- Perception

- 3D sensing & dense perception
- Map fusion & integration for planning

- Planning

- Complex & unknown environments
- Safety & dynamical feasibility
- Limited sensing & computation

- Control

- Aggressive maneuvers
- Smooth trajectory tracking



What is motion planning

- Basic requirements
 - Safety: collision avoidance
 - Smoothness: energy saving, comfort
 - Kinodynamic feasibility: executable, controllable
- Old-school pipeline
 - Front-end path finding
 - Search for an initial safe path
 - Low dimensional
 - Discrete space
 - Back-end trajectory generation
 - Search for an executable trajectory
 - High dimensional
 - Continuous space



How to do robotics research

- **Find a problem**

- ✓ A problem only in your imagination is not a problem at all.
- ✓ A robotician must be an engineer first.
- ✓ Hot topic is just hot.
- ✓ Be honest.

- **Solve a problem**

- ✓ Don't intentionally making things complicated.
- ✓ Simple but effective solution is always preferable.
- ✓ Simulation tells nothing, show everyone real robots.
- ✓ Solve real problems.
- ✓ Solve it 100%, or not.



How to do motion planning

- Overall knowledge of planning
 - ✓ Choose suitable methods for different scenarios.
 - ✓ Design customized strategy.
- Dirty hands
 - ✓ Don't wait, don't just read papers. Do it yourself.
 - ✓ A lot of coding work.
 - ✓ A lot of field work.
- Know the whole system well
 - ✓ Take care every component in your robot.



Groups and Researchers

University of Pennsylvania

- GRASP Lab,Vijay Kumar
Research Interests: planning, control, swarm
Homepage: www.kumarrobotics.org

Massachusetts Institute of Technology

- Jonathan How
Research Interests: modelling, control, planning
Homepage: www.mit.edu/~jhow
- Nicholas Roy
Research Interests: perception, learning
Homepage: groups.csail.mit.edu/rrg

Carnegie Mellon University

- Nathan Michael
Homepage: www.rislab.org
- Sebastian Scherer
Research Interests: perception, planning
Homepage: theairlab.org

University of California, Berkeley

- Markus Mueller
Research Interests: control, planning

ETH Zurich

- ASL Team, Roland Siegwart
Research Interests: perception, control
Homepage: asl.ethz.ch
- Raffaello D'Andrea
Research Interests : control, swarm
Homepage: raffaello.name

University of Zurich

- Davide Scaramuzza
Research Interests : perception, control
Homepage: rpg.ifi.uzh.ch

Hong Kong University of Science Technology

- Shaojie Shen
Research Interests : UAV
Homepage: uav.ust.hk
- Ming Liu
Research Interests : UGV
Homepage: ram-lab.com



Young researchers who most related to me



Helen Oleynikova

helenol.github.io

Graduate at Jan. 2019, from ASL team, ETH

Supervised by Roland Siegwart

Author of **VoxBlox**

Planning and mapping



Sikang Liu

github.com/sikang

Graduate at Aug. 2018, from GRASP Lab, UPenn

Supervised by Vijay Kumar

Planning



Course Outline



Front-end: Path finding

- SEARCH-BASED PATH FINDING

- Graph Search Basis
- Dijkstra and A*
- Jump Point Search
- Homework

- SAMPLING-BASED PATH FINDING

- Probabilistic Road Map
- Rapidly-exploring Random Tree (RRT)
- Optimal Sampling-based Methods
- Advanced Sampling-based Methods
- Homework

- KINODYNAMIC PATH FINDING

- Introduction
- State-state Boundary Value Optimal Control Problem
- State Lattice Search
- Kinodynamic RRT*
- Hybrid A*
- Homework



Back-end: Trajectory Generation

- MINIMUM SNAP TRAJECTORY GENERATION
 - Differential Flatness
 - Minimum Snap Optimization
 - Closed-form Solution to Minimum Snap
 - Time Allocation
 - Implementation in Practice
 - Homework
- SOFT AND HARD CONSTRAINED TRAJECTORY OPTIMIZATION
 - Soft Constrained Trajectory Optimization
 - Hard Constrained Trajectory Optimization
 - Homework



MDP & MPC

- MARKOV DECISION PROCESS-BASED PLANNING
 - Uncertainties in Planning and MDP
 - Minimax Cost Planning and Expected Cost Minimal Planning
 - Value Iteration and Real-Time Dynamic Programming
 - Homework
- MODEL PREDICTIVE CONTROL FOR ROBOTICS PLANNING
 - Introduction
 - Linear MPC
 - Non-linear MPC
 - Homework



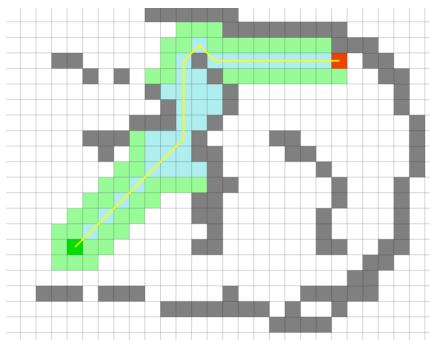
Overview



Front-end: Path Finding

- Sampling-based methods
 - Probabilistic roadmap (PRM)
 - Rapidly exploring random tree (RRT)
 - RRT*, informed RRT*
- Search-based methods
 - General graph search: DFS, BFS
 - Dijkstra and A* search
 - Jump point search

RRT example

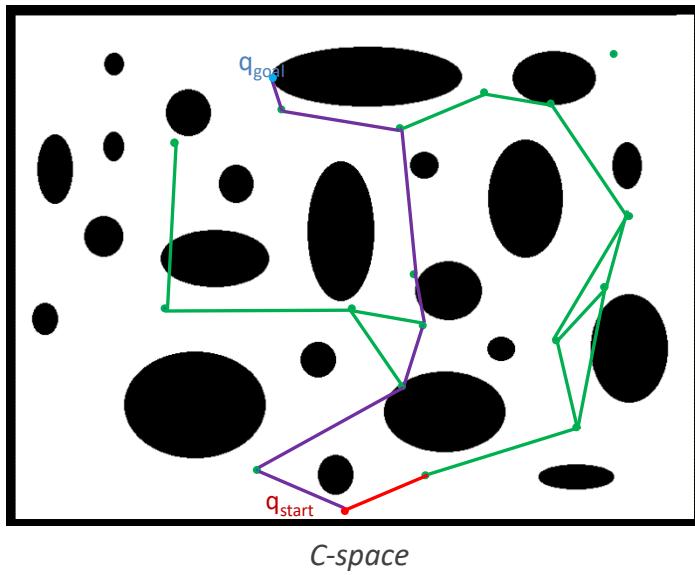


A* search example



Sampling-based Method

Probabilistic Roadmap (PRM)



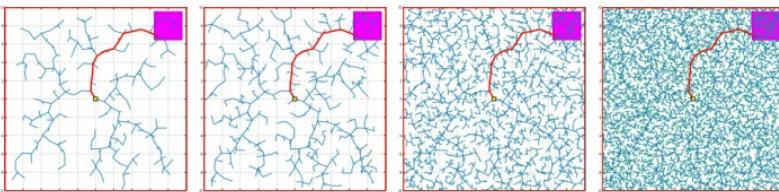
C-space



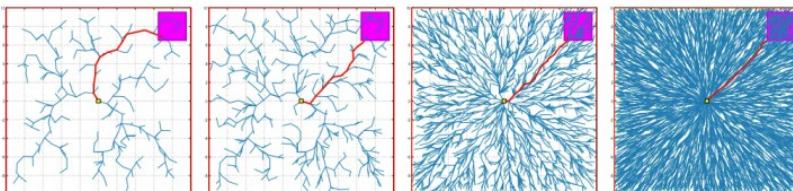
Sampling-based Method

RRT* vs RRT

RRT

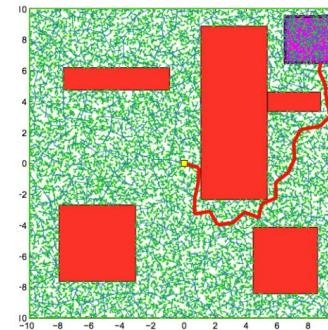


RRT*

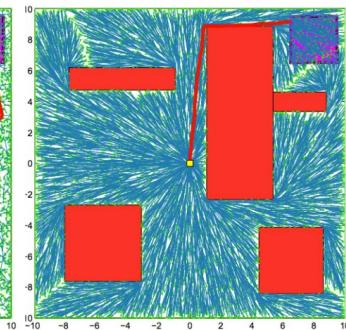


Source: Karaman and Frazzoli

RRT



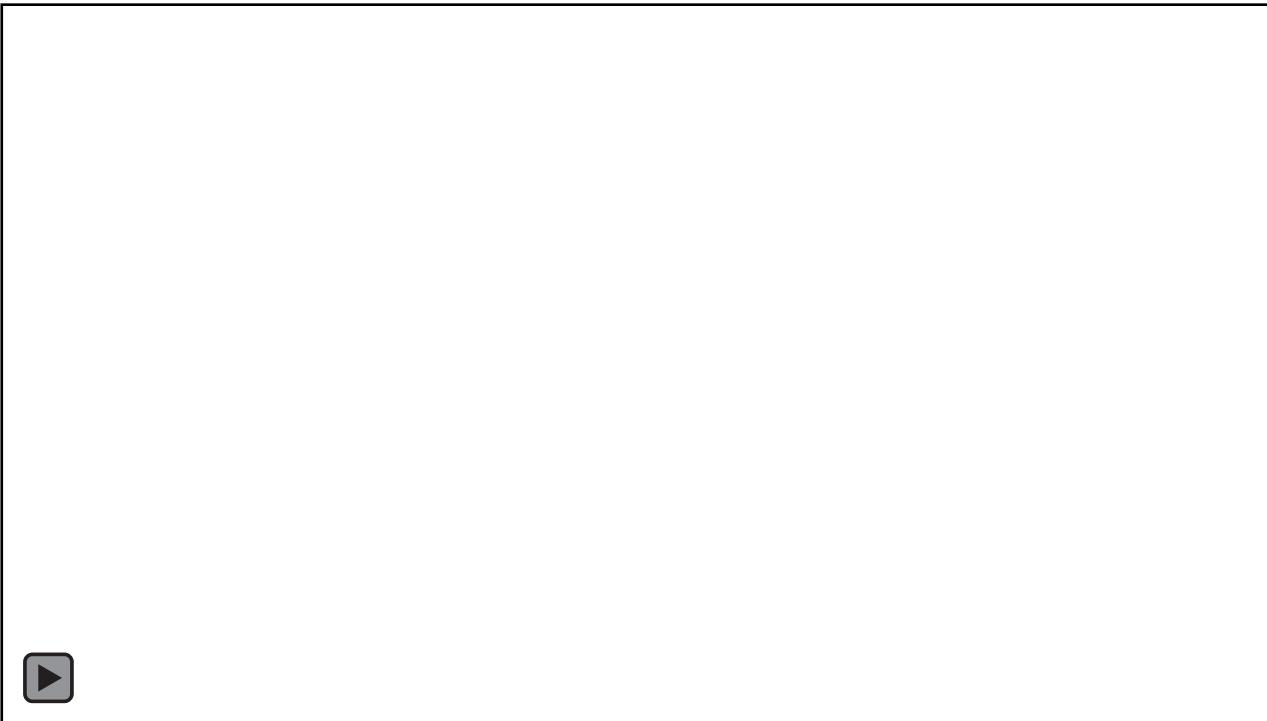
RRT*





Sampling-based Method

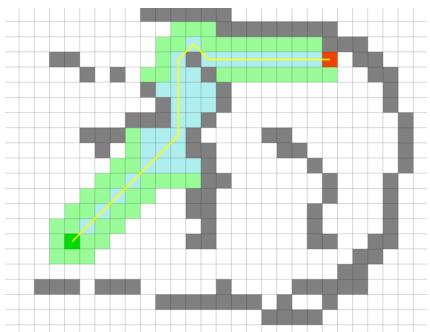
Informed RRT*



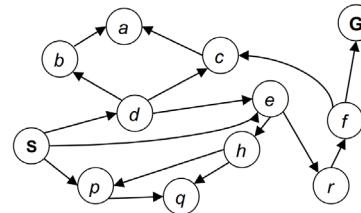


Search-based Method

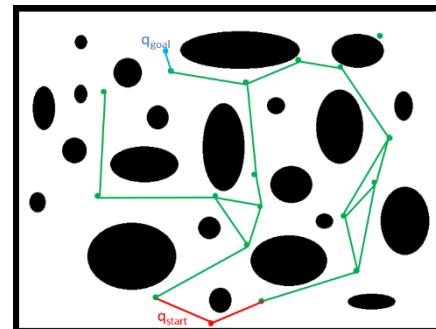
- For every search problem, there's a corresponding state space graph
- Connectivity between nodes in the graph is represented by (directed or undirected) edges



Grid-based graph: use grid as vertices and grid connections as edges



*Ridiculously tiny search graph
for a tiny search problem*



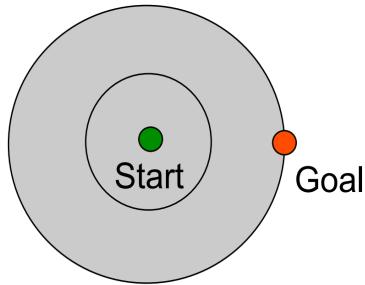
The graph generated by probabilistic roadmap (PRM)



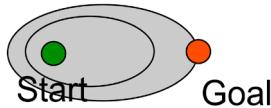
Search-based Method

Dijkstra's vs. A*

- Dijkstra's algorithm expanded in all directions



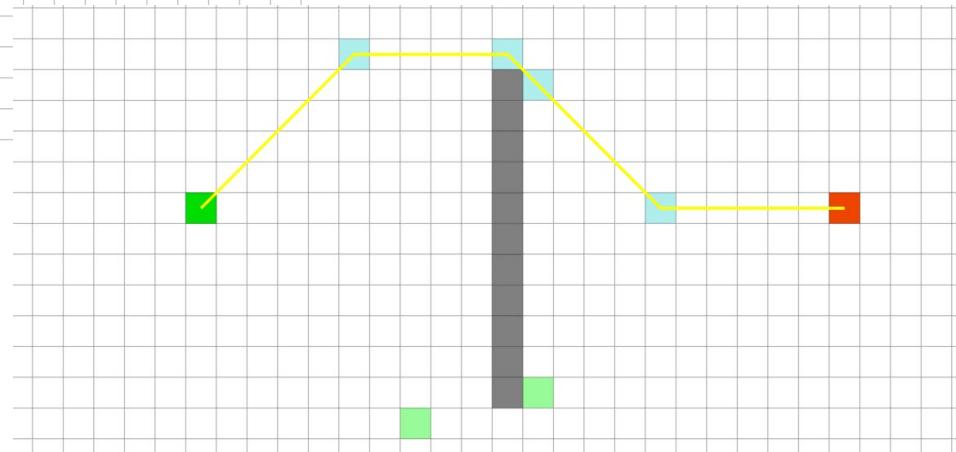
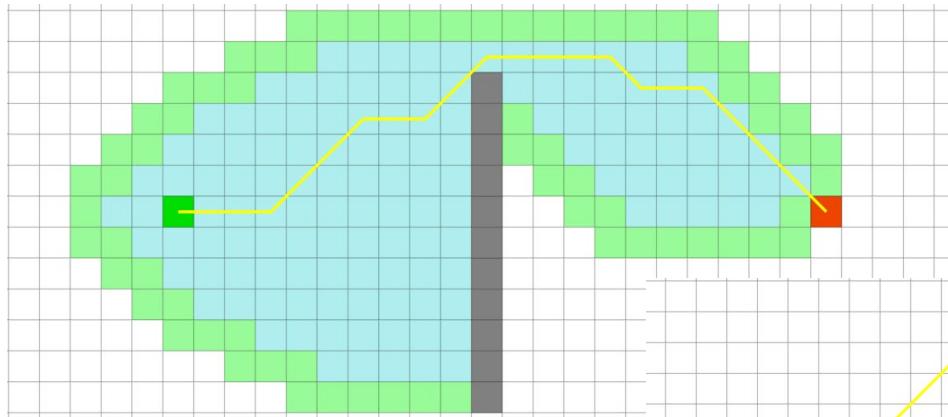
- A* expands mainly towards the goal, but does not hedge its bets to ensure optimality





Search-based Method

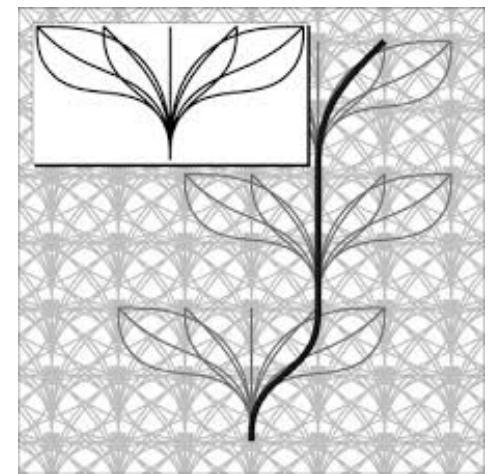
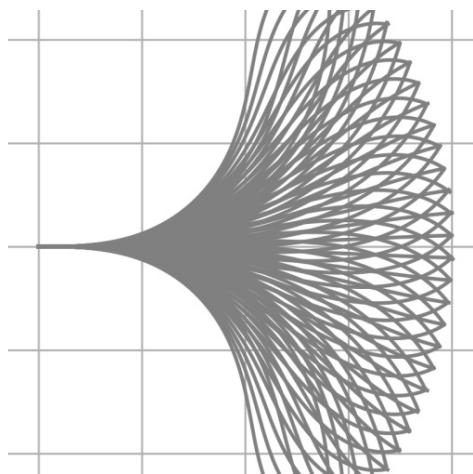
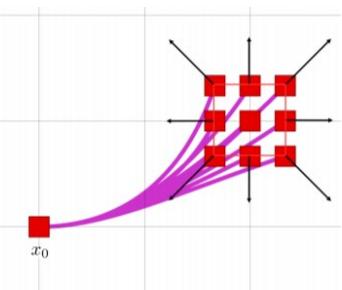
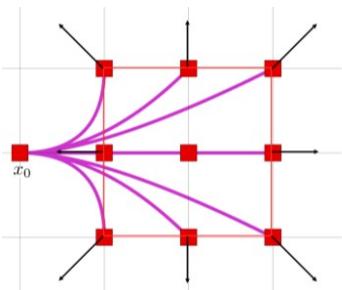
A* vs. JPS





Kinodynamic Path Finding

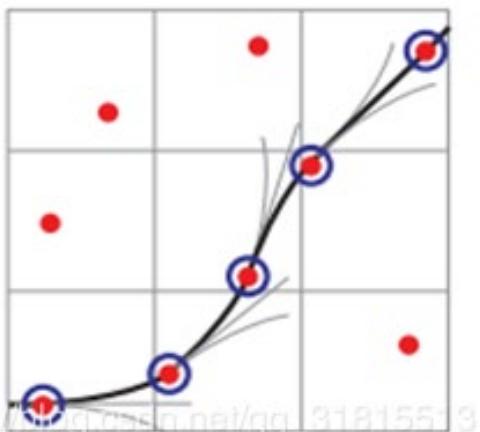
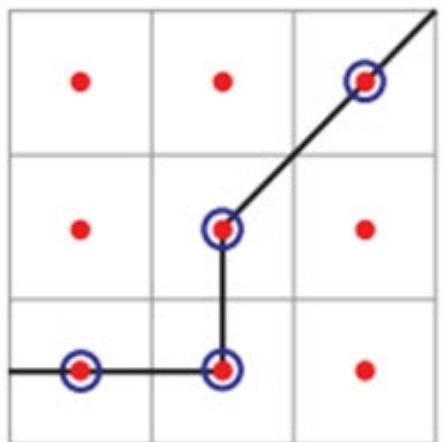
State Lattice Search





Kinodynamic Path Finding

Hybrid A*



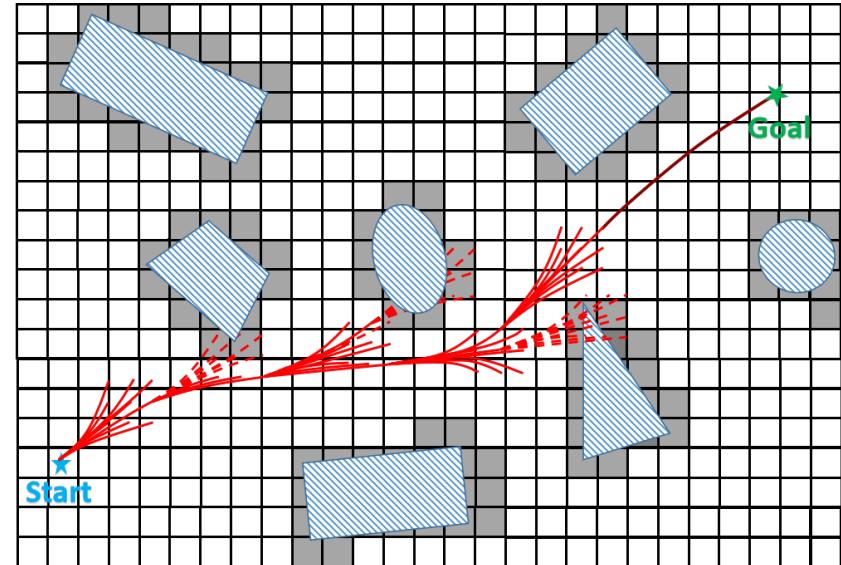
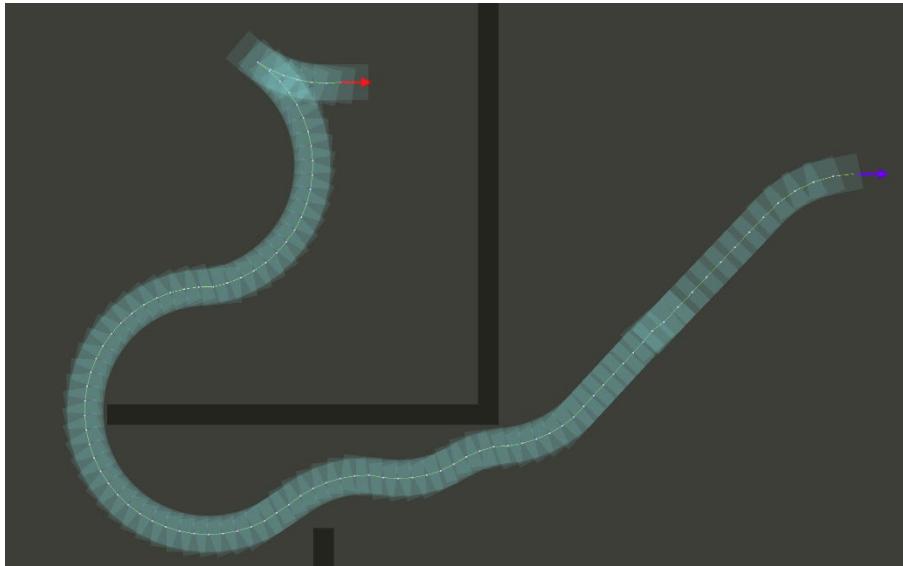
1. Follow A* algorithm
2. Forward simulate states with different discrete control inputs
3. Keep only 1 state in each grid

https://blog.csail.mit.edu/qq_31815513



Kinodynamic Path Finding

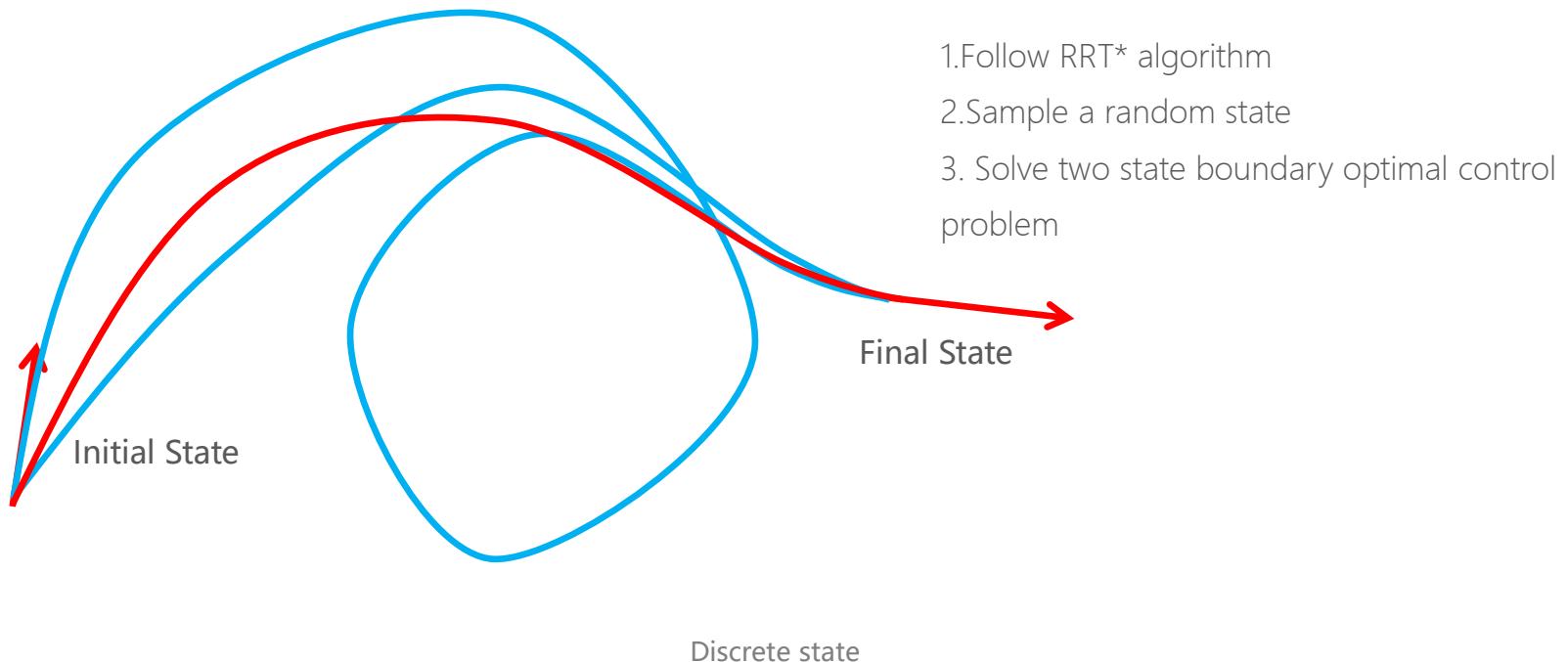
Hybrid A*





Kinodynamic Path Finding

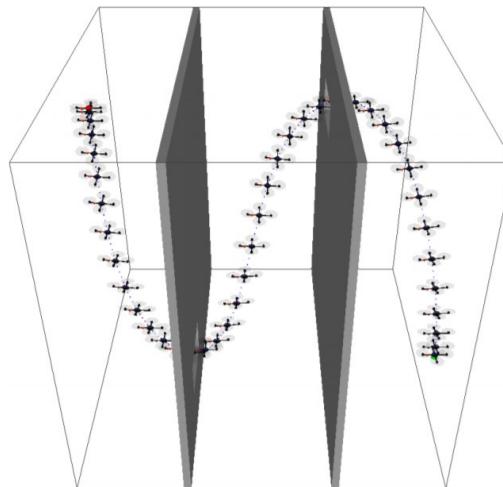
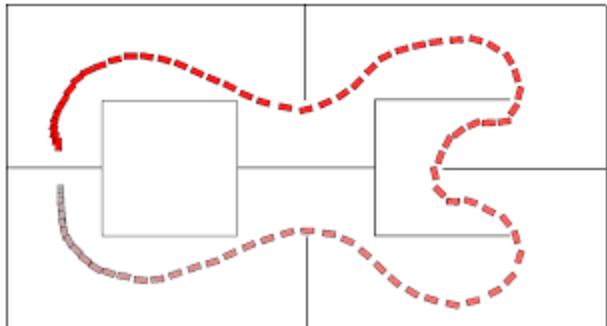
Kinodynamic RRT*





Kinodynamic Path Finding

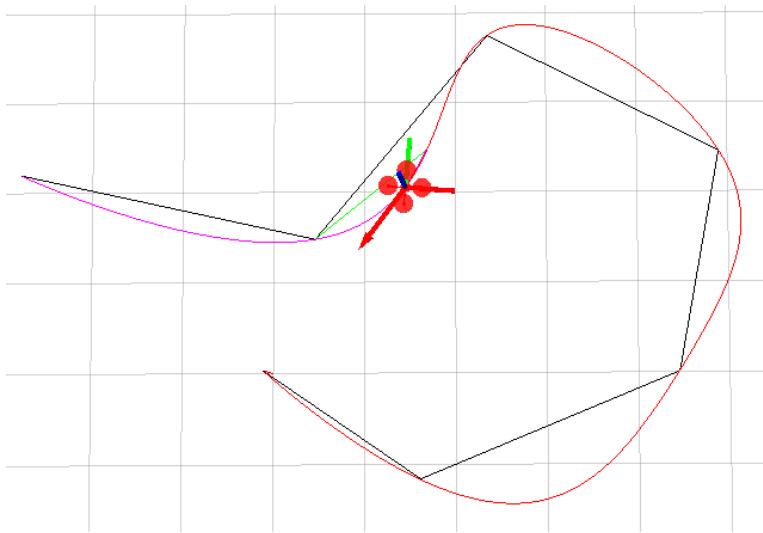
Kinodynamic RRT*





Back-end: Trajectory Optimization

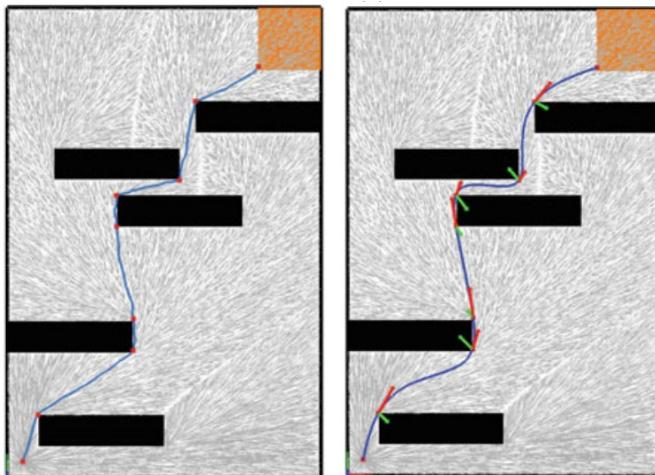
Basic Minimum-snap





Back-end: Trajectory Optimization

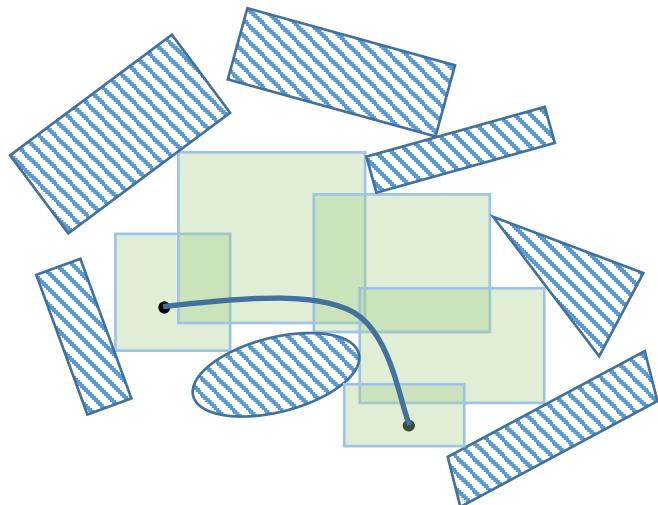
Basic Minimum-snap





Back-end: Trajectory Optimization

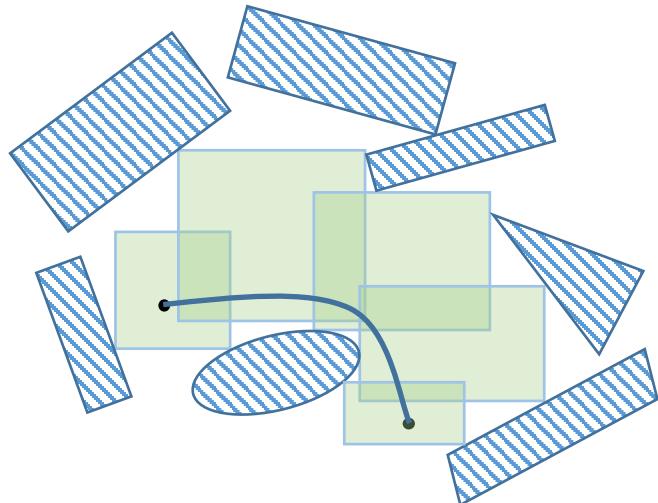
Hard constrained Minimum-snap





Back-end: Trajectory Optimization

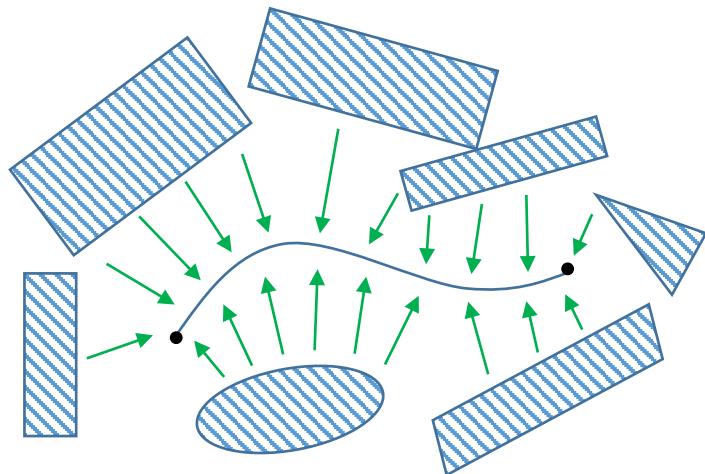
Hard constrained Minimum-snap





Back-end: Trajectory Optimization

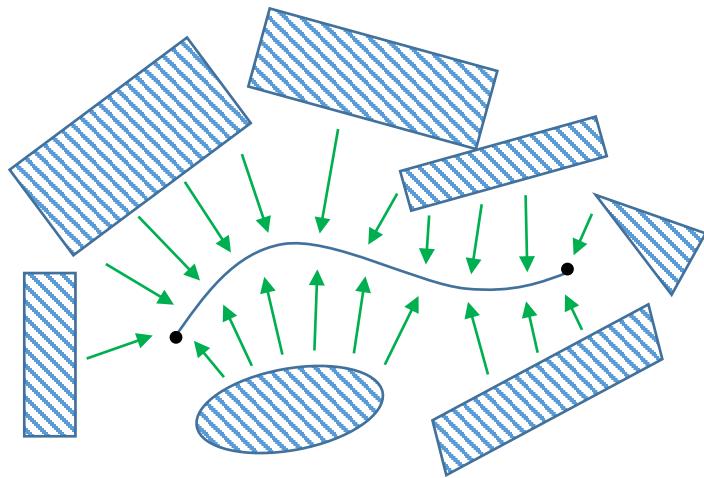
Soft constrained Minimum-snap





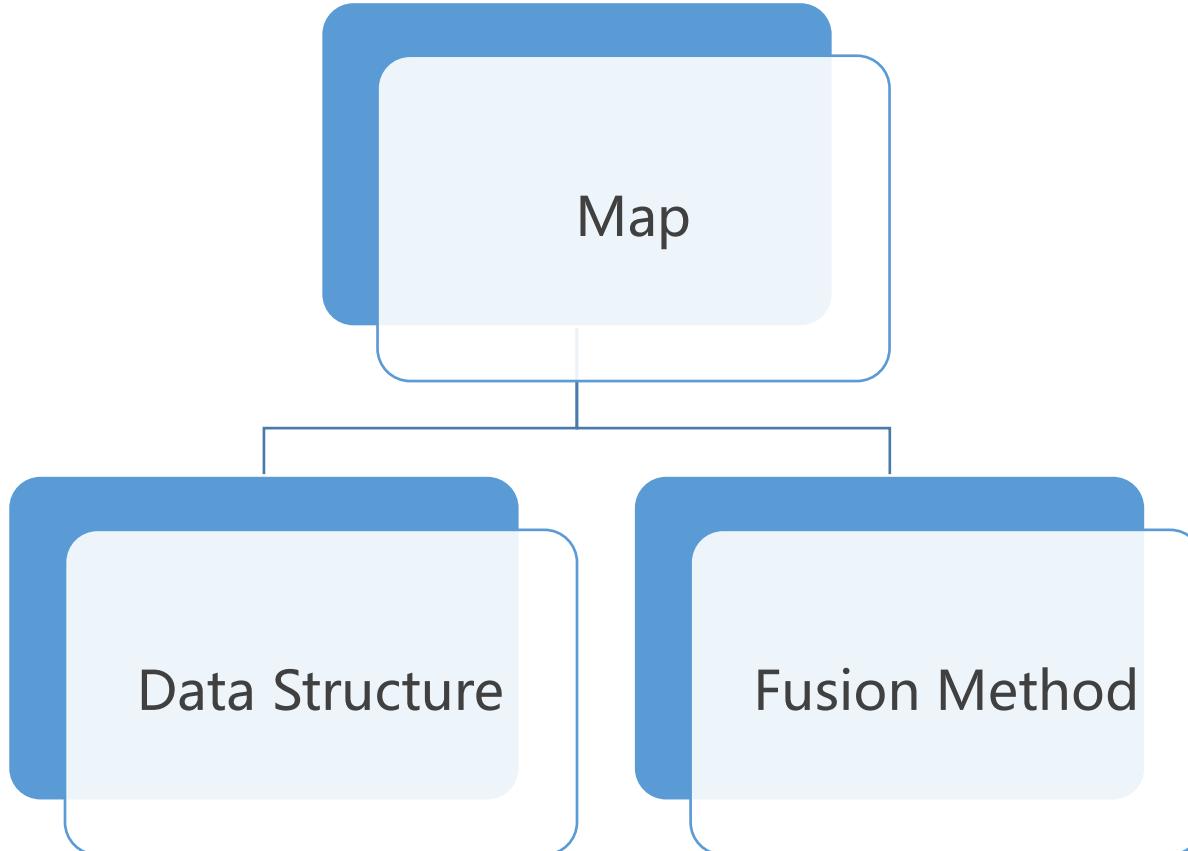
Back-end: Trajectory Optimization

Soft constrained Minimum-snap



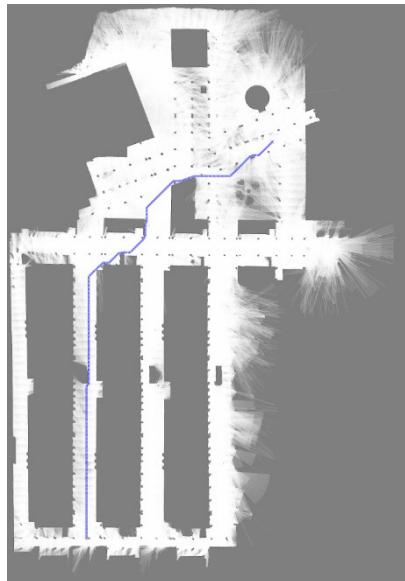
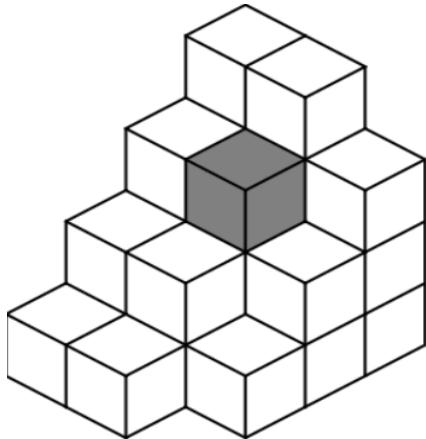


Map Representation

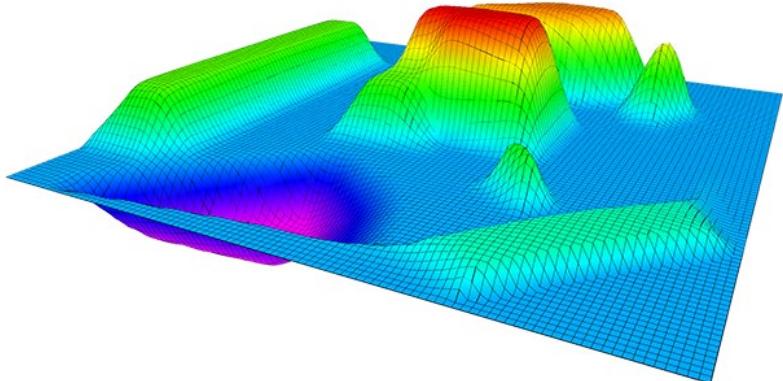




Occupancy grid map



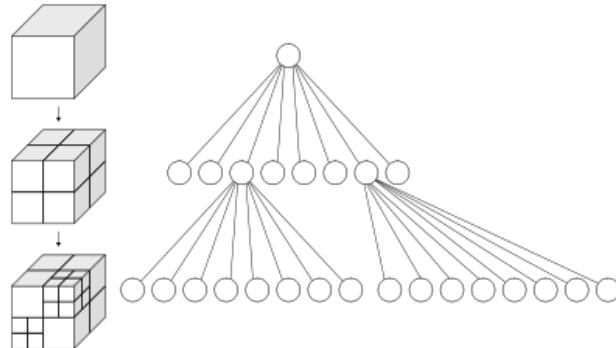
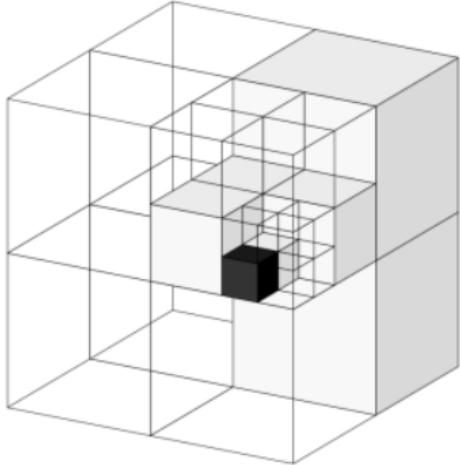
- Most Dense
- Structural
- Direct Index Query



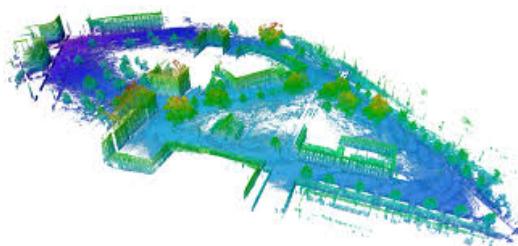
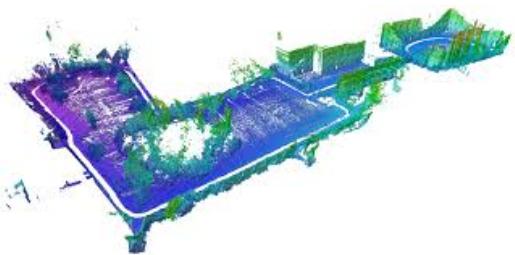
https://github.com/ANYbotics/grid_map



Octo-map



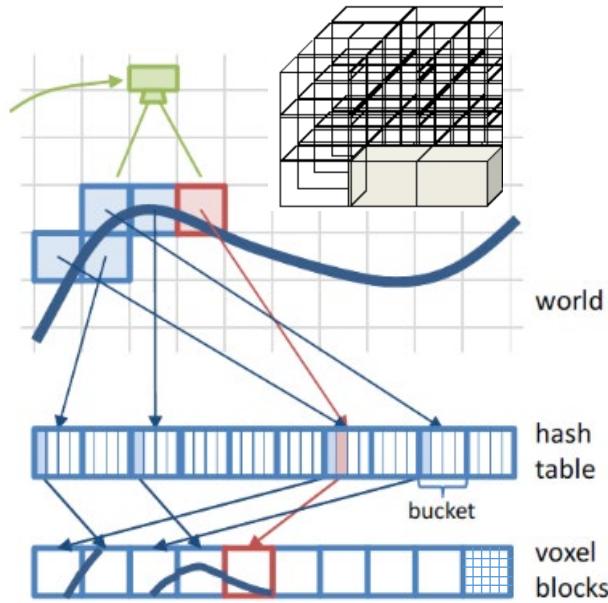
- Sparse
- Structural
- Indirect Index Query



<https://octomap.github.io/>



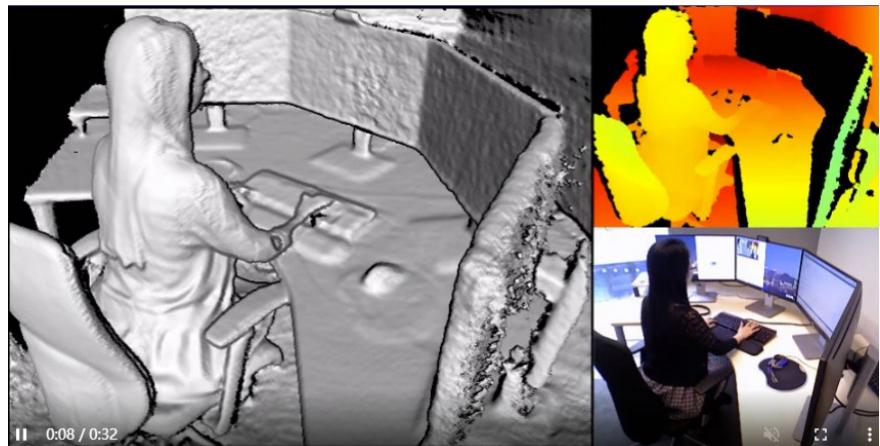
Voxel hashing



Voxel Hashing:

<https://github.com/niessner/VoxelHashing>

- Most Sparse
- Structural
- Indirect Index Query

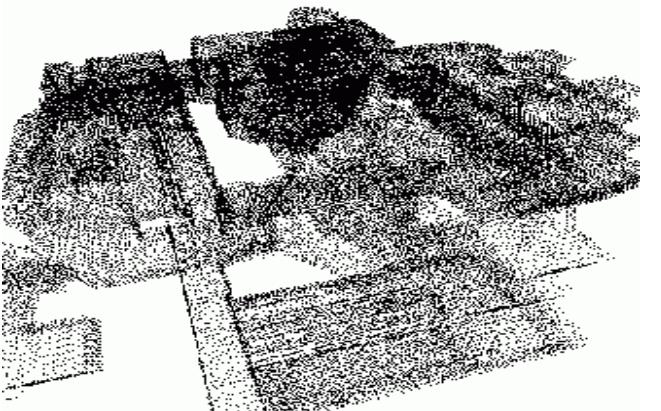


InfiniTAM:

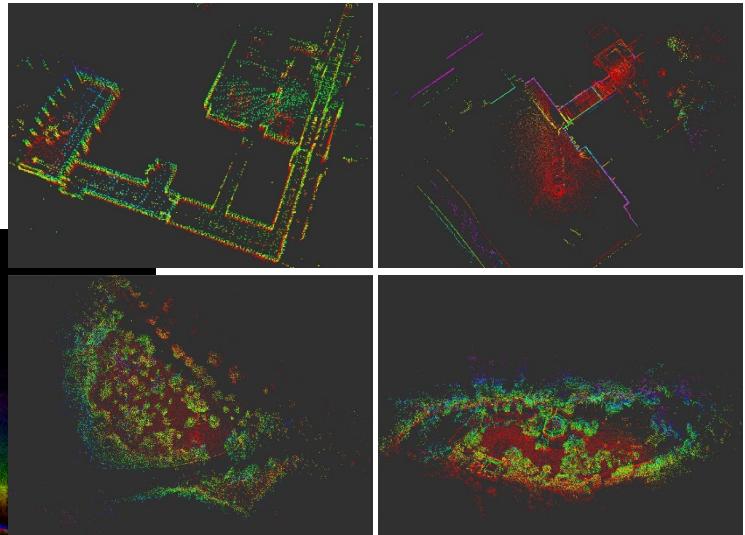
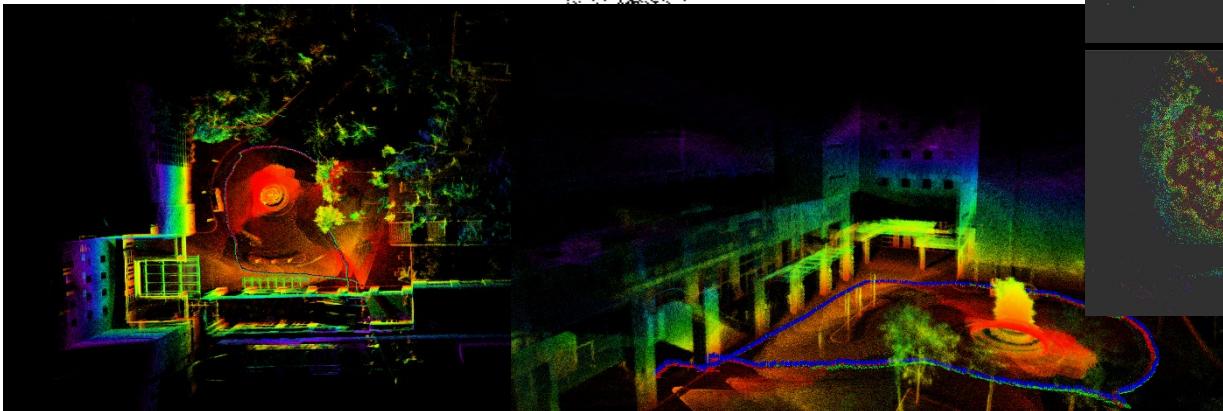
<http://www.robots.ox.ac.uk/~victor/infinitam/>



Point cloud map



- Un-ordered
- No Index Query

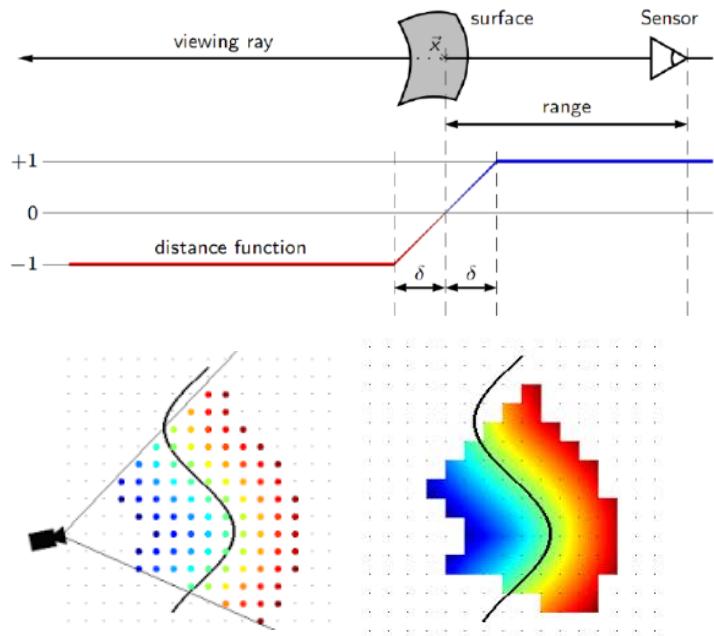


PCL
<http://pointclouds.org/>



TSDF map

Truncated Signed Distance Functions



OpenChisel

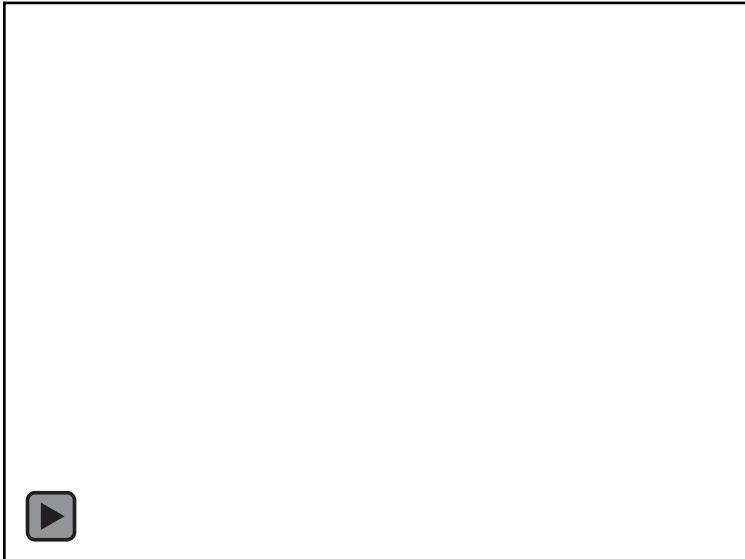
<https://github.com/personalrobotics/OpenChisel>



ESDF map

Euclidean Signed Distance Functions

Incremental Update, Global Map



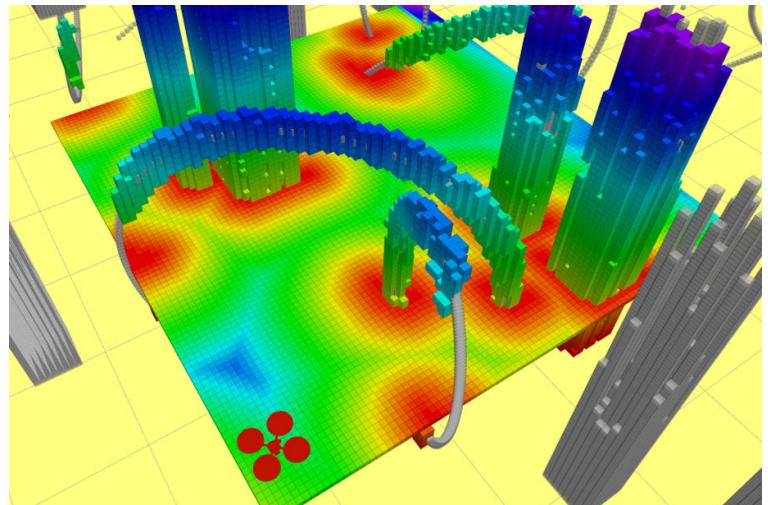
VoxBlox

<https://github.com/ethz-asl/voxblox>

FIESTA

<https://github.com/HKUST-Aerial-Robotics/FIESTA>

Batch Update, Local Map



Distance Transforms of Sampled Functions, PF Felzenswalb

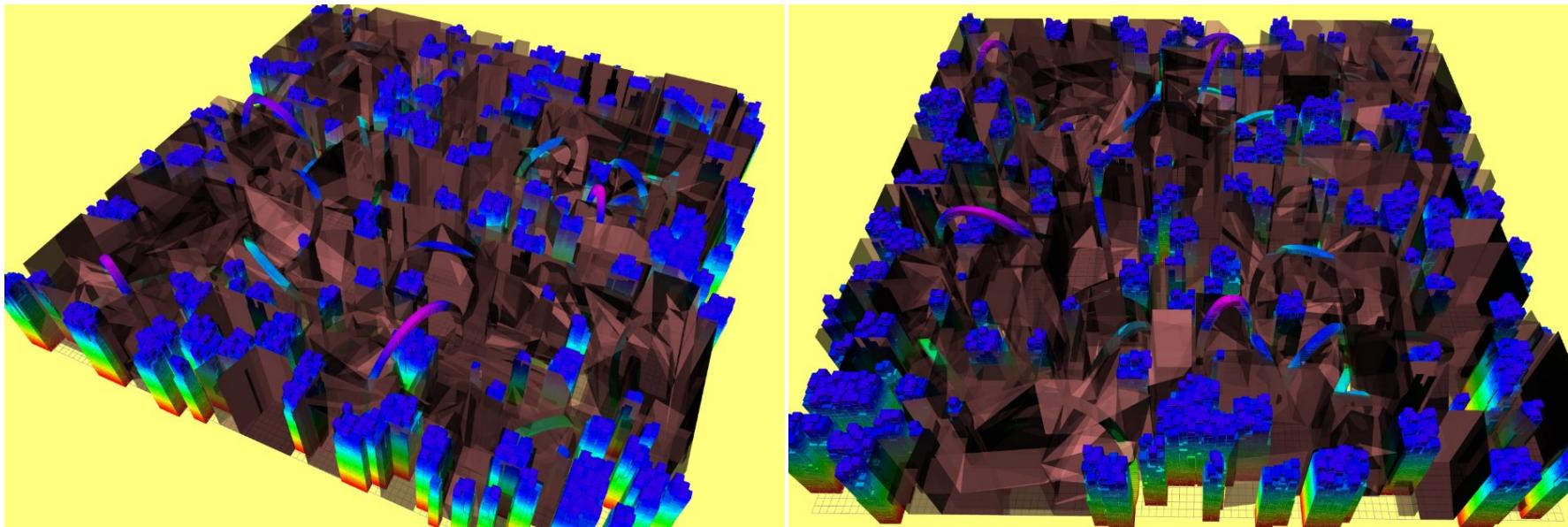
TRR's Local Map

<https://github.com/HKUST-Aerial-Robotics/Teach-Repeat-Replan>



More ?

Free-space Roadmap

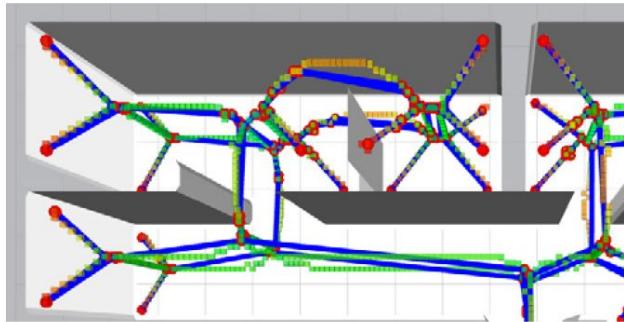


<https://github.com/HKUST-Aerial-Robotics/Teach-Repeat-Replan>

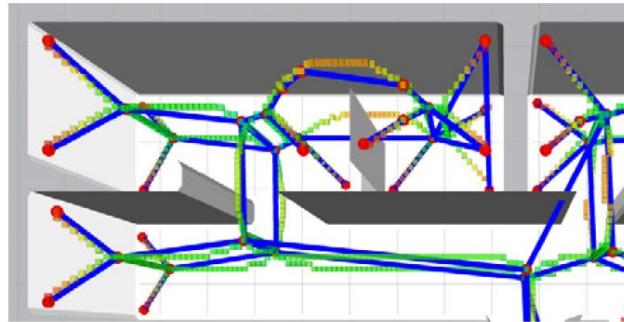


More ?

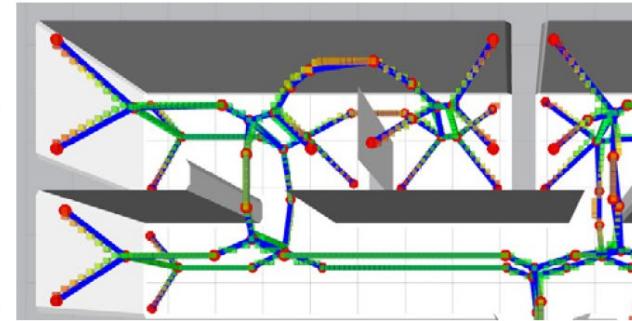
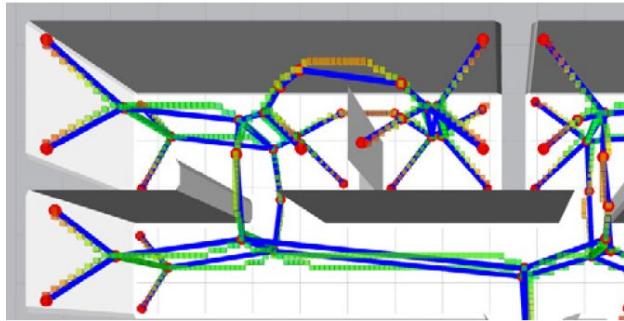
Voronoi Diagram Map



(a)



(b)



https://github.com/ethz-asl/mav_voxblox_planning



Pre-requirement



Linux

- Linux file system
- How to install software in linux
- Useful commands



C++ and GCC Toolchain

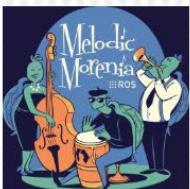
- C with class ?
- Gcc, Makefile, CMakeList
- Write CMakeList
- How to solve problems: google and document



ROS

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Homework



Thanks for Listening!

