



Motion Planning for Mobile Robots



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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:**

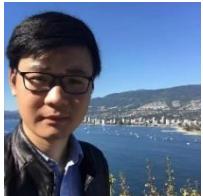
- Every researcher has his own taste/style. Since you choose this course, please follow my style.
- Q&A only at appointed office time.
- Finish your homework by yourself.

- **Project:**

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



Teaching Team



Instructor 1: **Fei Gao**

Assistant Professor, ZJU

Ph.D, HKUST

Email: fgaooa@connect.ust.hk



Instructor 2: **Chaoqun Wang**

Research Fellow, CUHK

Ph.D, CUHK

Email: zychaoqun@gmail.com



Instructor 3: **Shupeng Lai**

Research Fellow, NUS

Ph.D, NUS

Email: shupenglai@gmail.com



Instructor 4: **Delong Zhu**

Ph.D candidate, CUHK

Email: dlzhu@ee.cuhk.edu.hk



Information

- **Lecture time:**
 - Every Friday night 19:00, except October 4th
- **Course Community:**
 - www.shenlanxueyuan.com/course/188/threads/show
- **Course Website:**
 - www.shenlanxueyuan.com/course/188
- **Course Wechat Group:**
 - Connect the class teacher(Wechat: shenlancas)



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 ☺

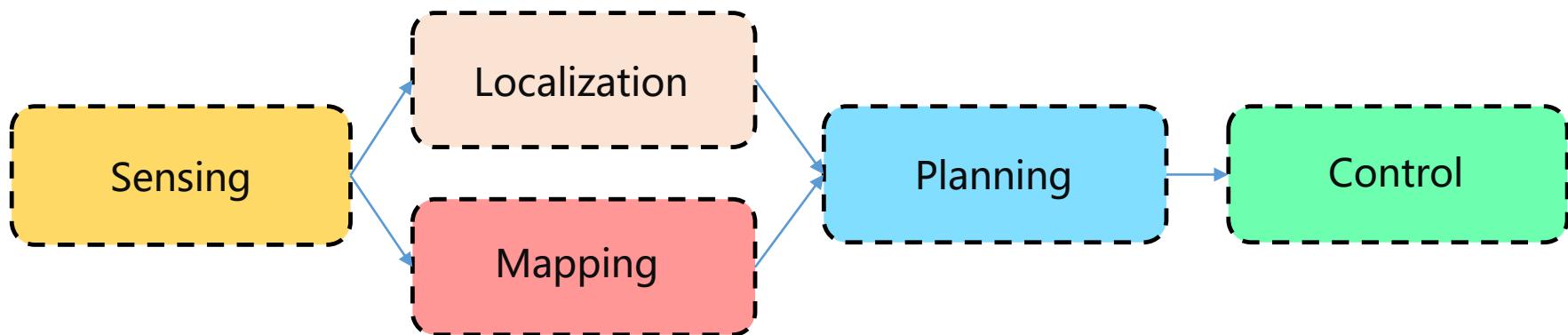


What is autonomous robot

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

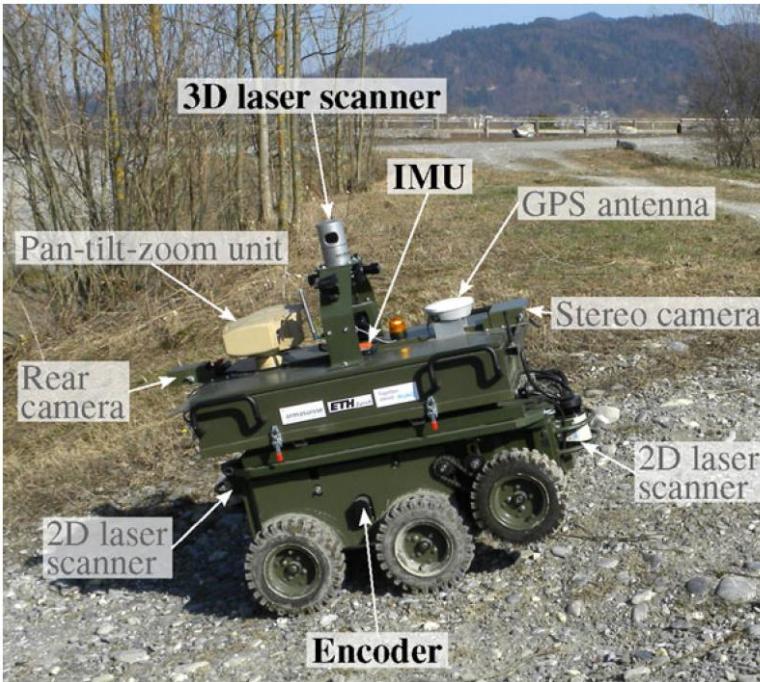
Subjects: Computer Science, Automation, Mechanism, Electronics ...

- Perception-Planning-Control action loop





Autonomous robot: applications

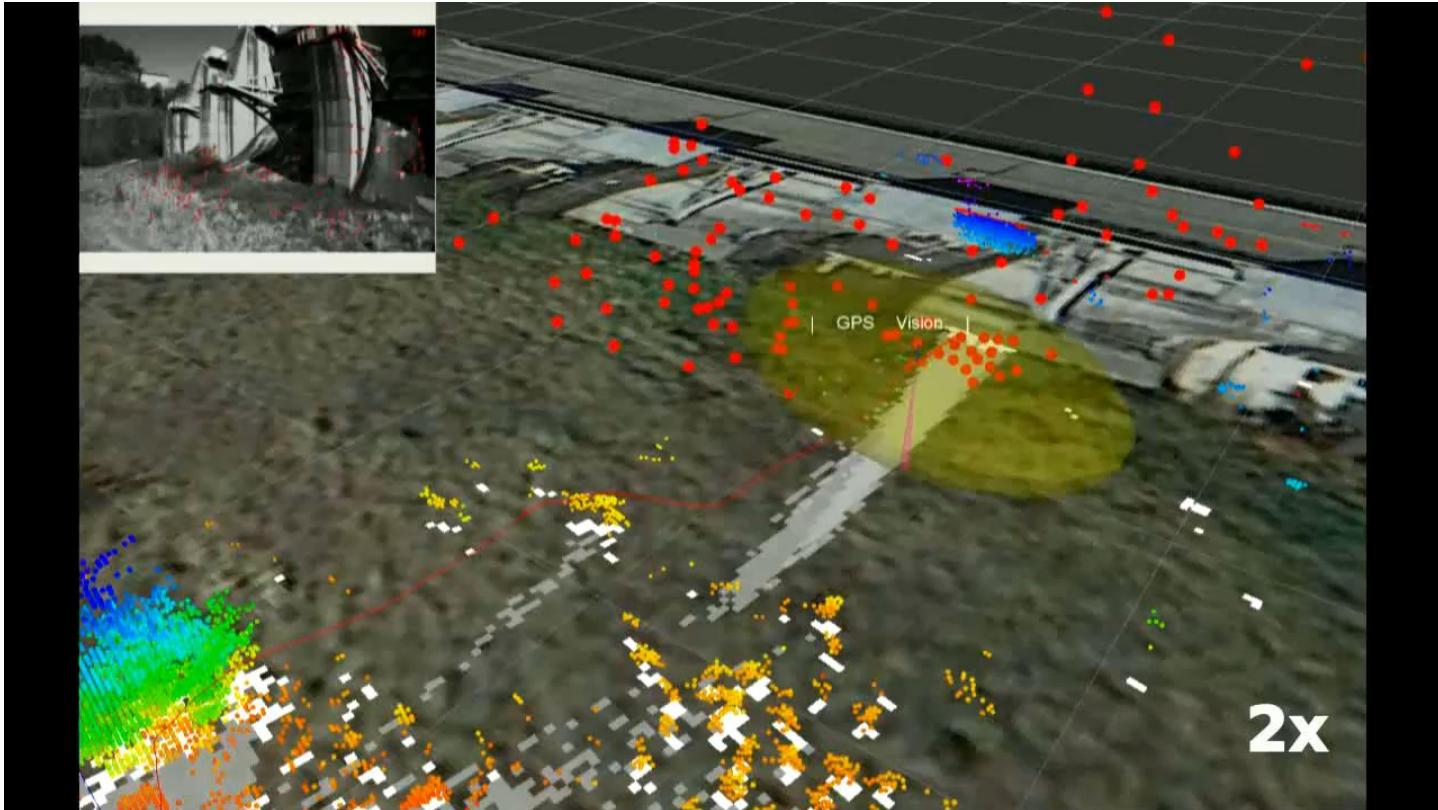




Aerial Robots



Dam Inspection



Shen, et al, 2014



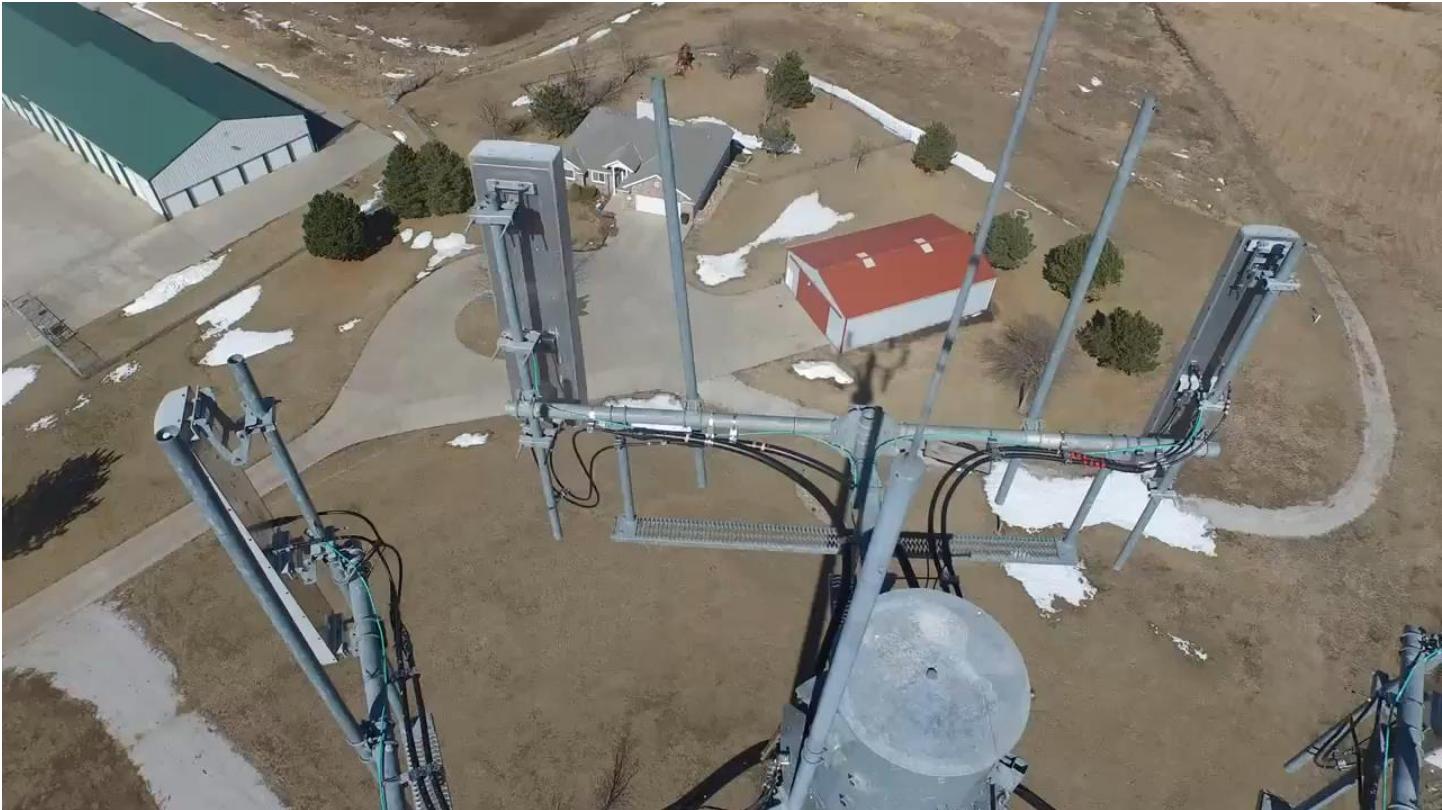
Dam Inspection



Ozaslan, et al, 2014



Cellular Tower Inspection





Precision Farming

2X



Delivery





Ground Robots



Search and Rescue





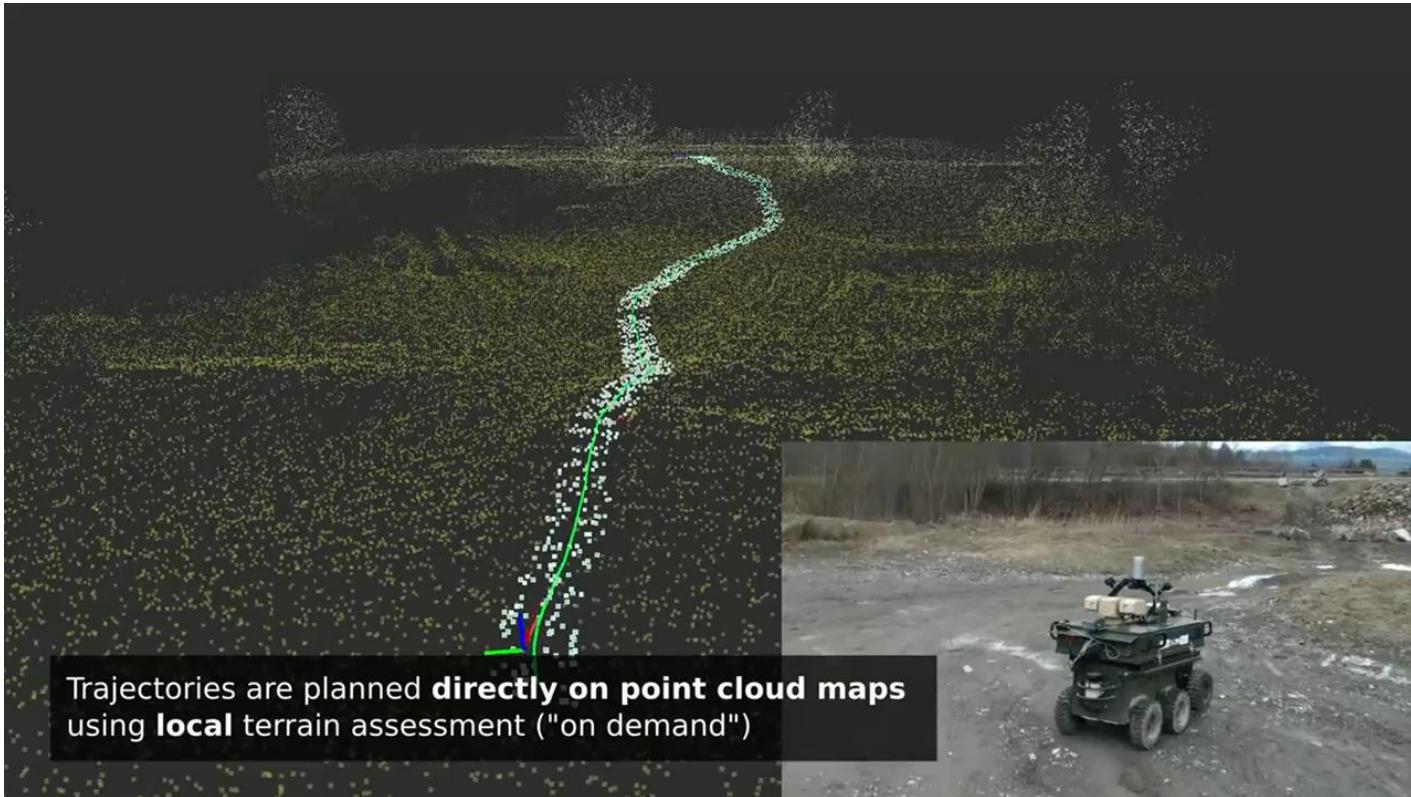
Housekeeping



iRobot®

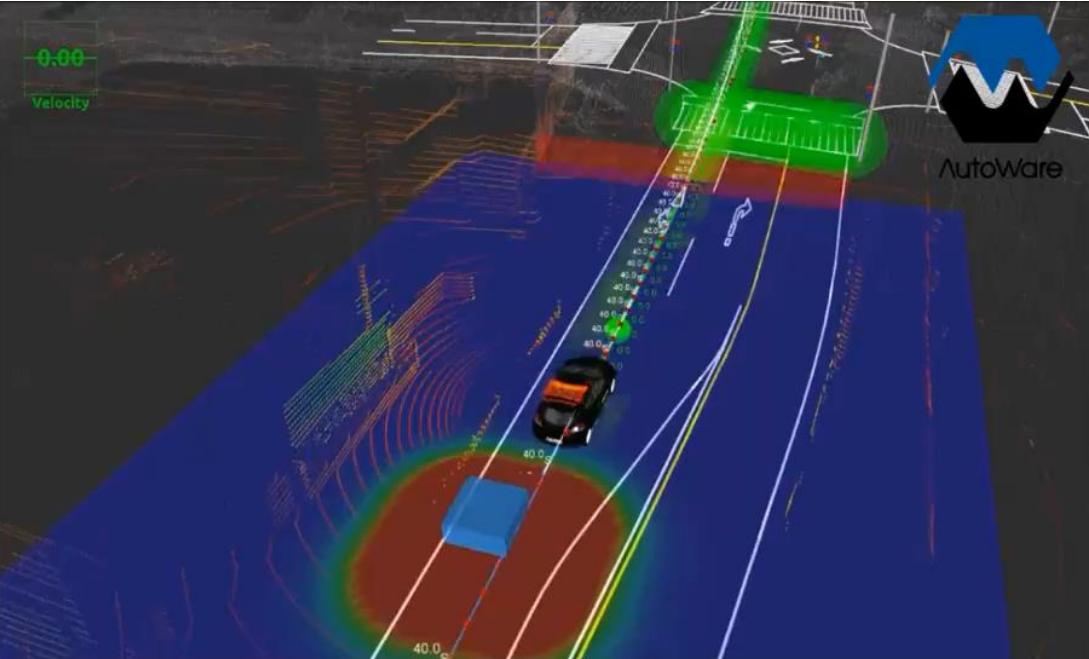


Hills Driving





Urban Driving



Tier IV
Intelligent Vehicle

アイサンテクノロジー株式会社 **AXE**



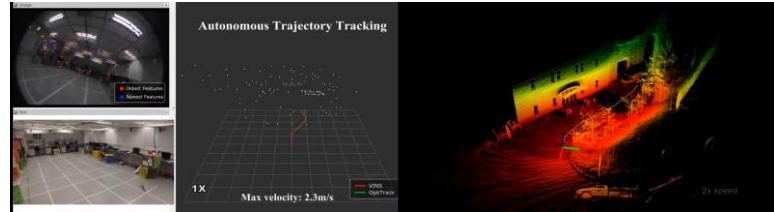
Crowd Driving



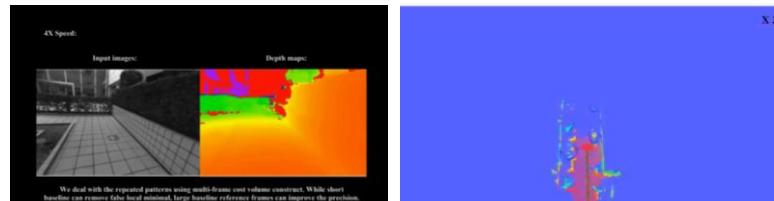


What is autonomous robot

- Estimation
 - Low latency
 - High accuracy & consistency



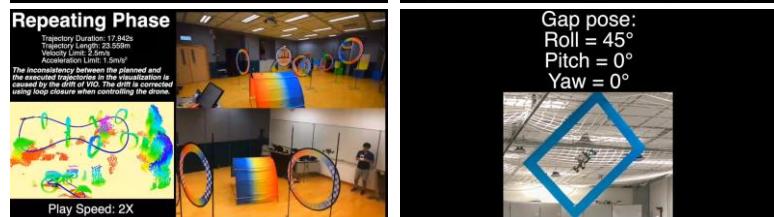
- Perception
 - 3D sensing & dense perception
 - Map fusion & integration for planning



- 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



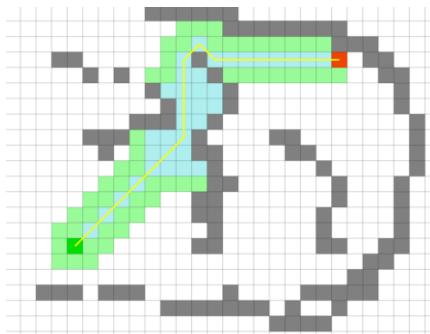
Overview



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

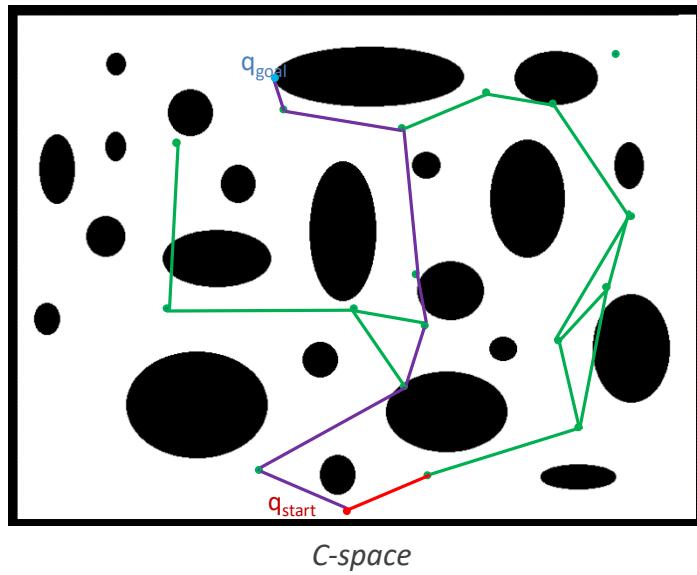


A* search example



Sampling-based Method

Probabilistic Roadmap (PRM)

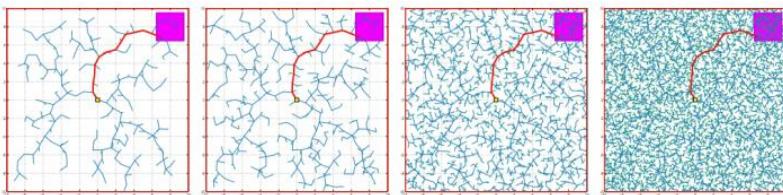




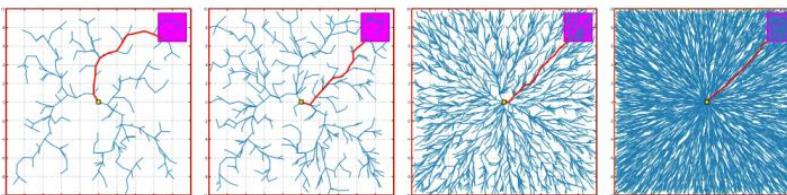
Sampling-based Method

RRT* vs RRT

RRT

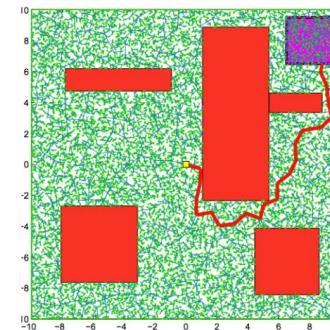


RRT*

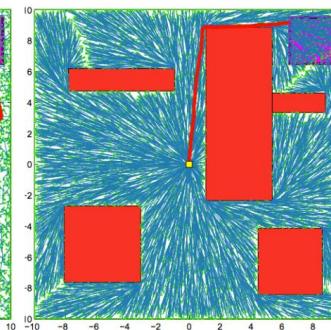


Source: Karaman and Frazzoli

RRT



RRT*

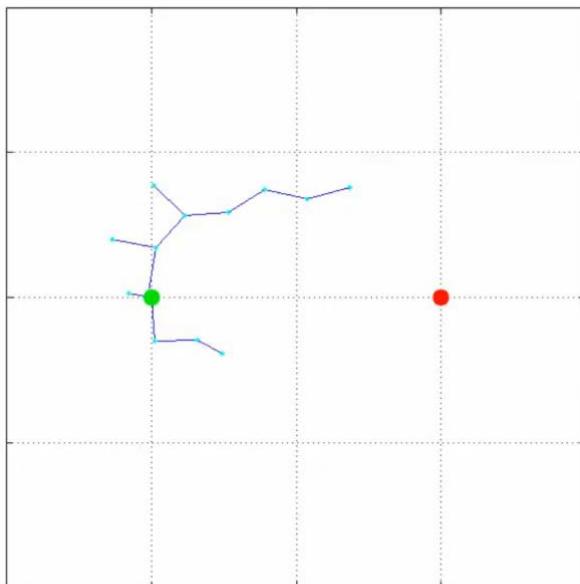




Sampling-based Method

Informed RRT*

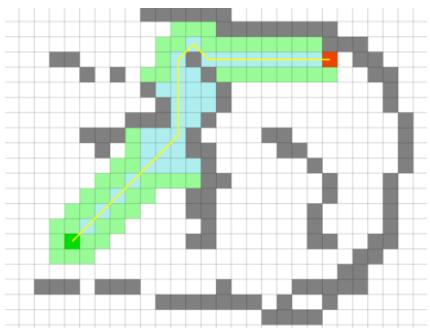
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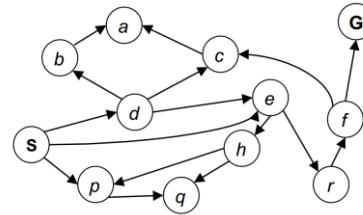


Search-based Method

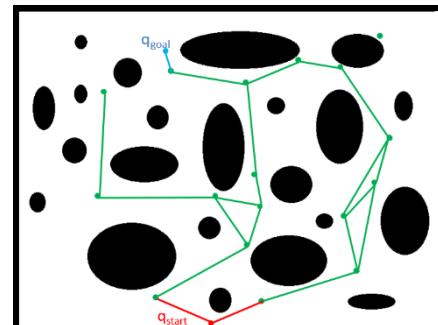
- For every search problem, there's a corresponding state space graph
- Connectivity between nodes in the graph is represented by (directed or undirected) edges



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



*Ridiculously tiny search graph
for a tiny search problem*



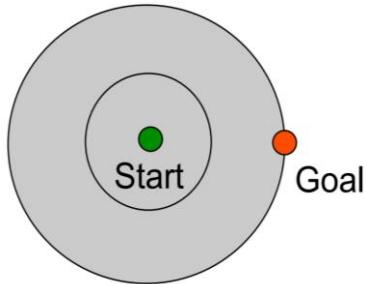
The graph generated by probabilistic roadmap (PRM)



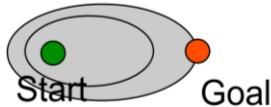
Search-based Method

Dijkstra's vs. A*

- Dijkstra's algorithm expanded in all directions



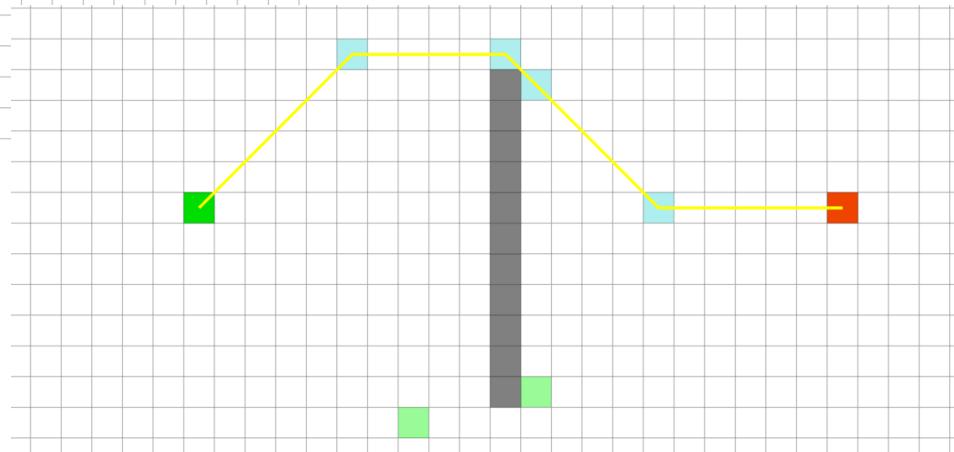
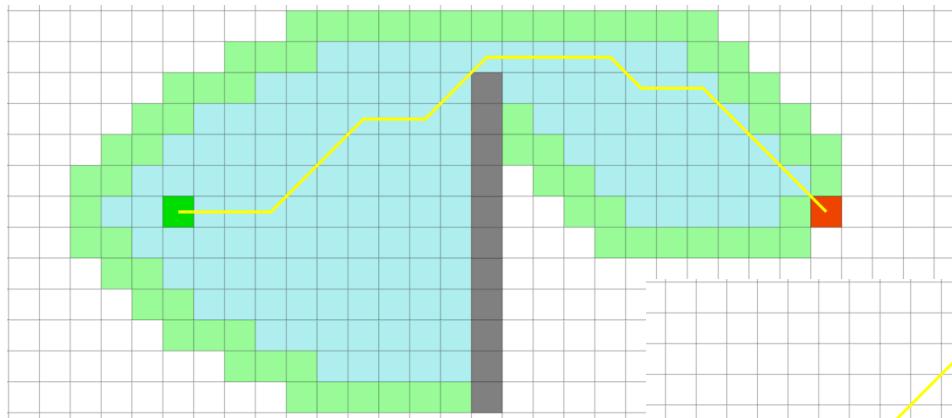
- A* expands mainly towards the goal, but does not hedge its bets to ensure optimality





Search-based Method

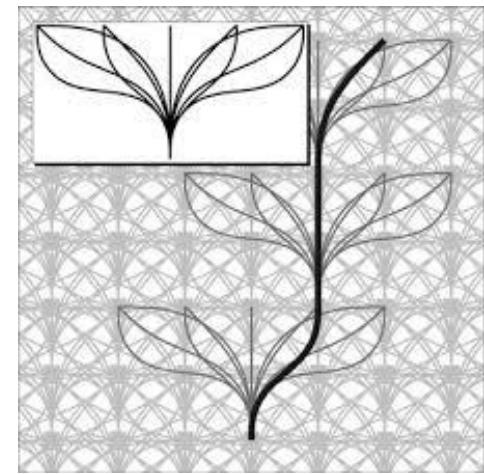
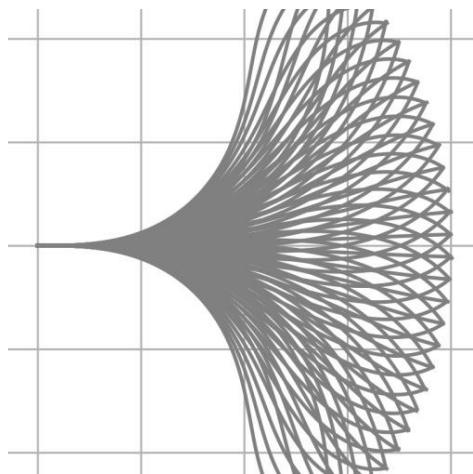
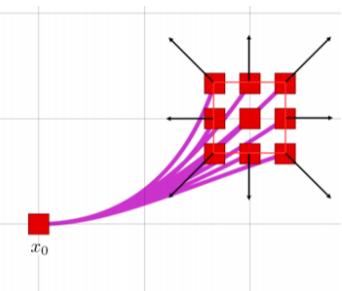
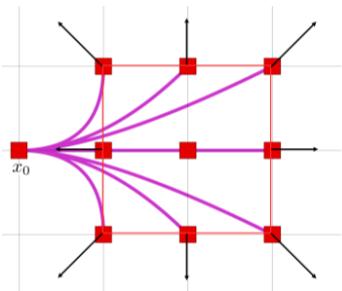
A* vs. JPS





Kinodynamic Path Finding

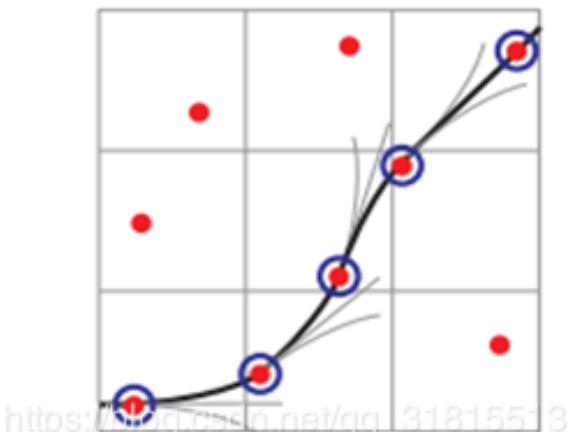
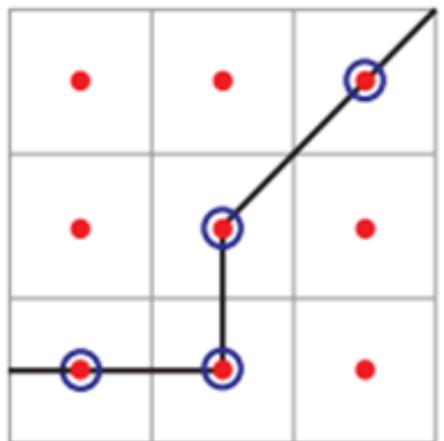
State Lattice Search





Kinodynamic Path Finding

Hybrid A*



<https://blog.csail.mit.edu/cjq/318155/> 3

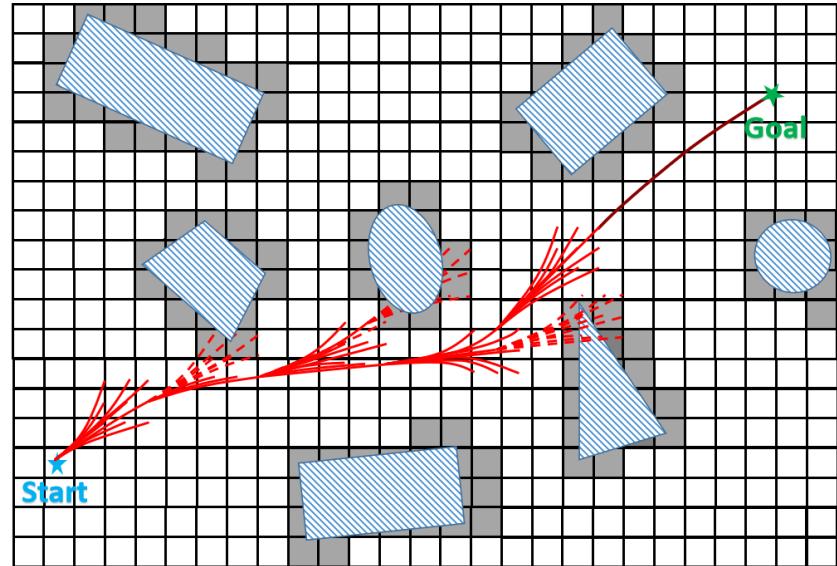
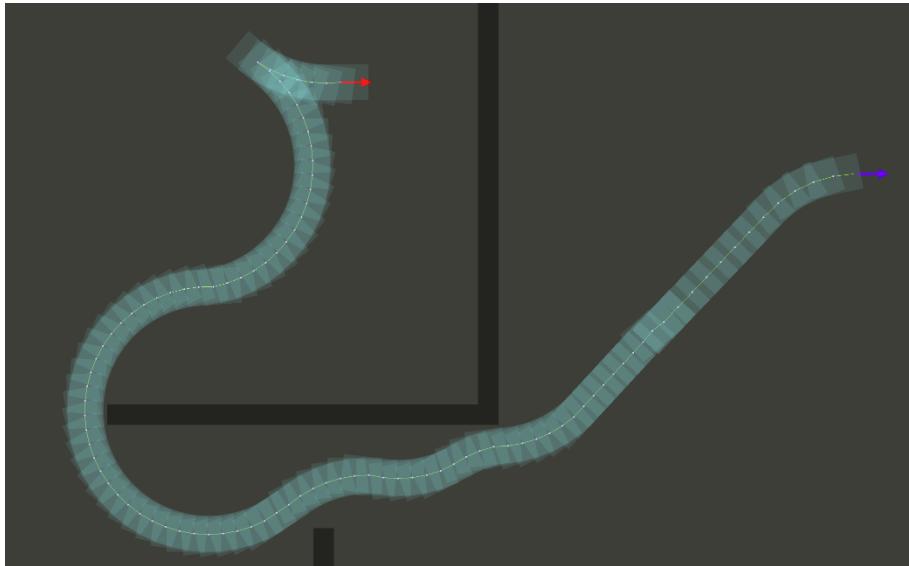
1. Follow A* algorithm
2. Forward simulate states with different discrete control inputs
3. Keep only 1 state in each grid

Discrete control



Kinodynamic Path Finding

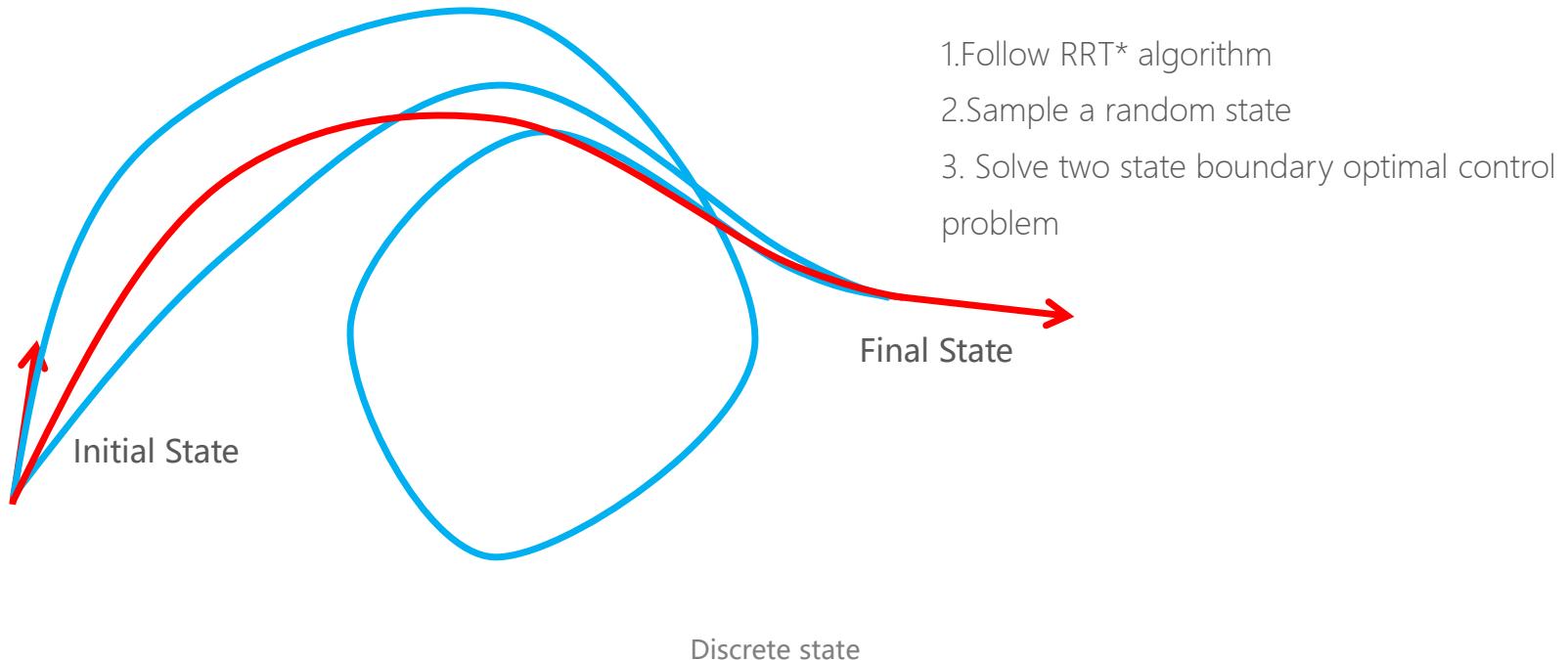
Hybrid A*





Kinodynamic Path Finding

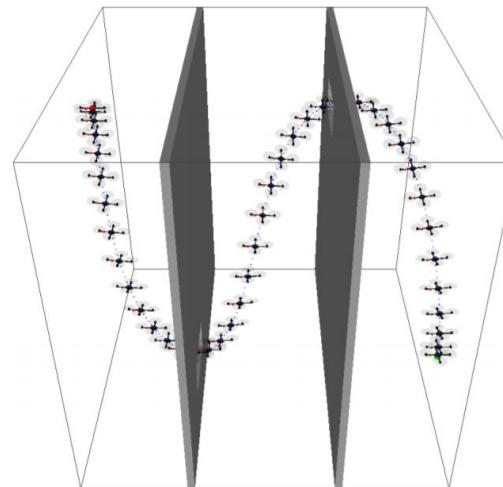
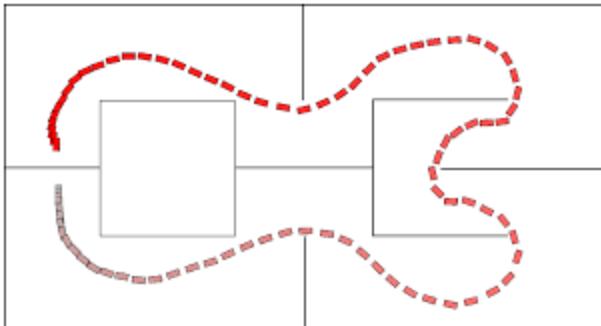
Kinodynamic RRT*





Kinodynamic Path Finding

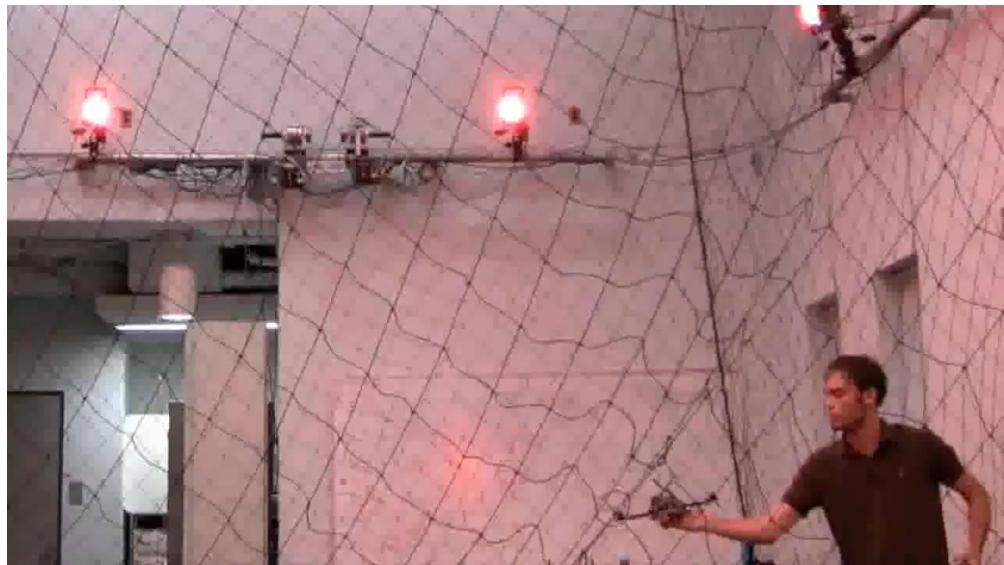
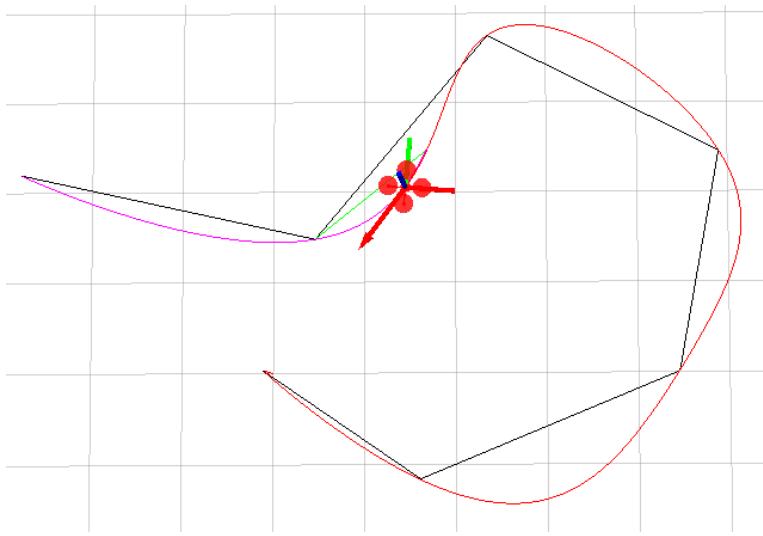
Kinodynamic RRT*





Back-end: Trajectory Optimization

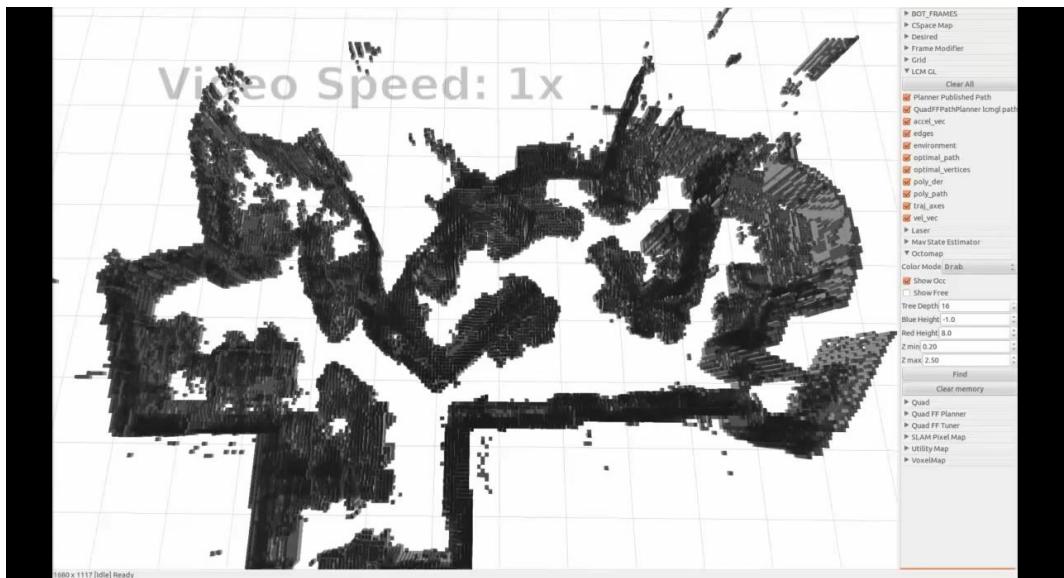
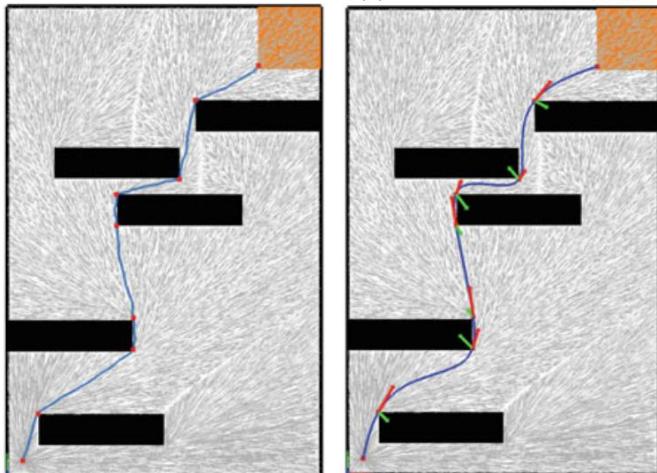
Basic Minimum-snap





Back-end: Trajectory Optimization

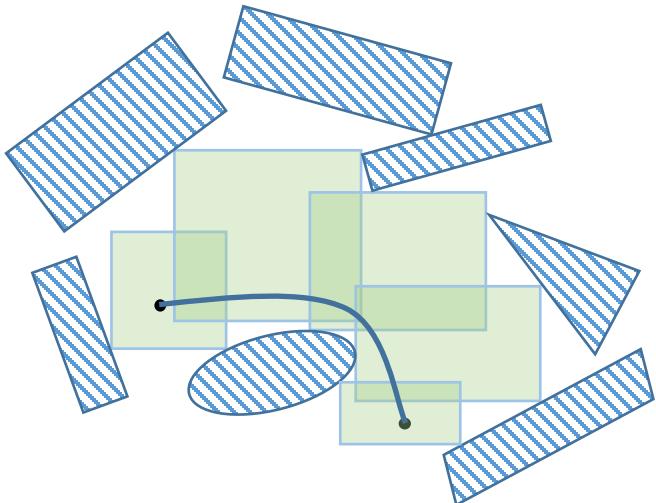
Basic Minimum-snap





Back-end: Trajectory Optimization

Hard constrained Minimum-snap



**Blue curve : trajectory
in execution horizon**

**Red curve :
current trajectory**

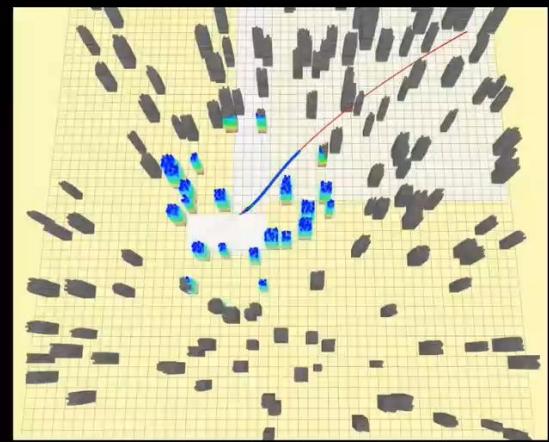
**White cube :
flight corridor**

**Colorful voxels :
mapped obstacles**

**Grey voxels :
un-mapped obstacles**

Green arrow : velocity

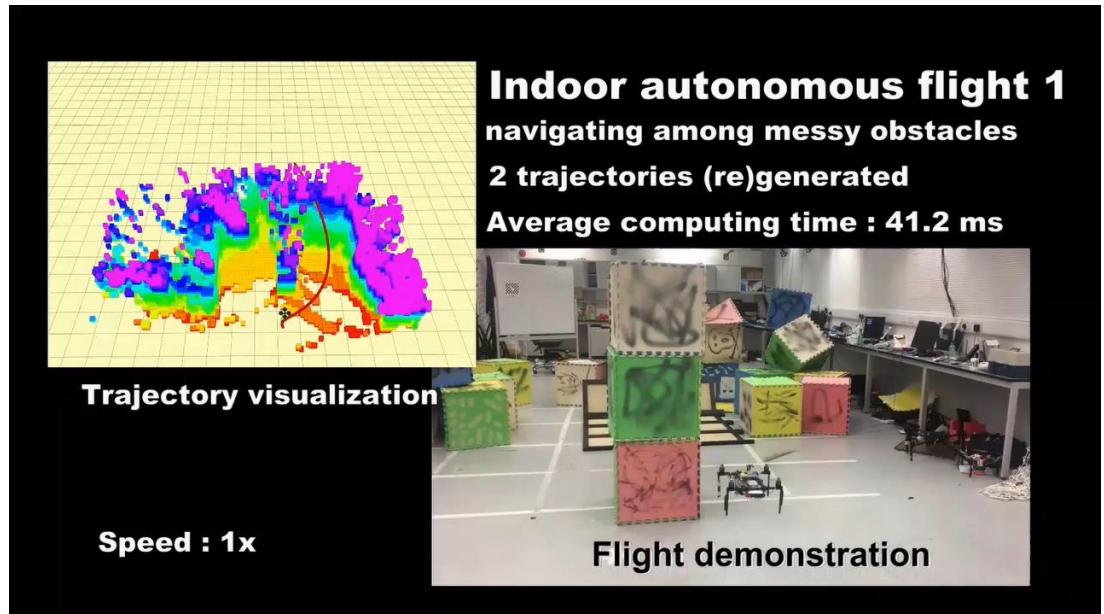
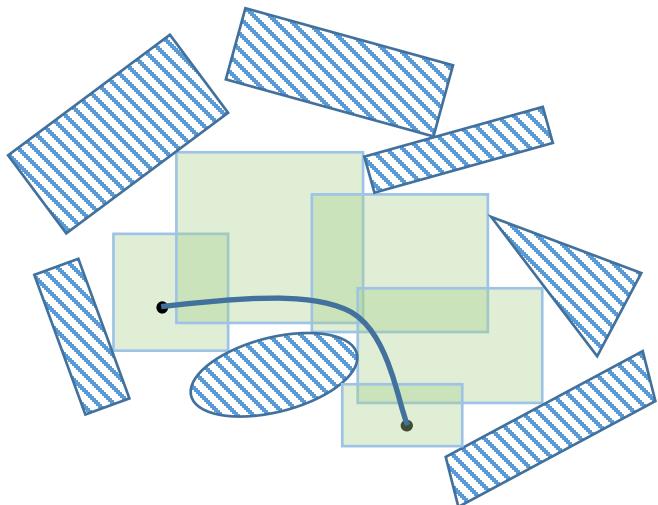
Yellow arrow : acceleration





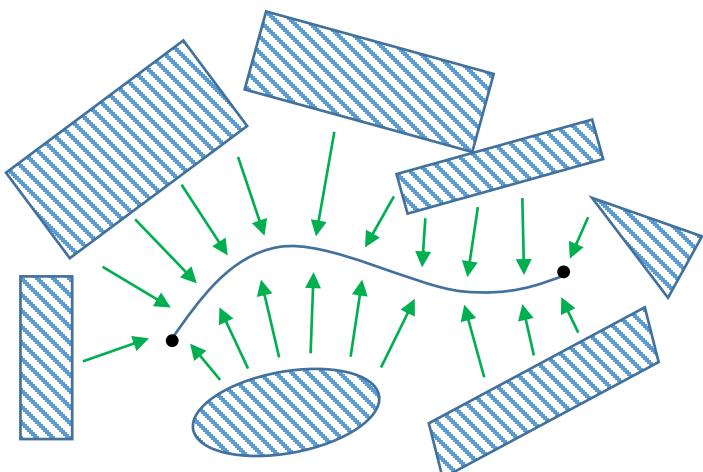
Back-end: Trajectory Optimization

Hard constrained Minimum-snap

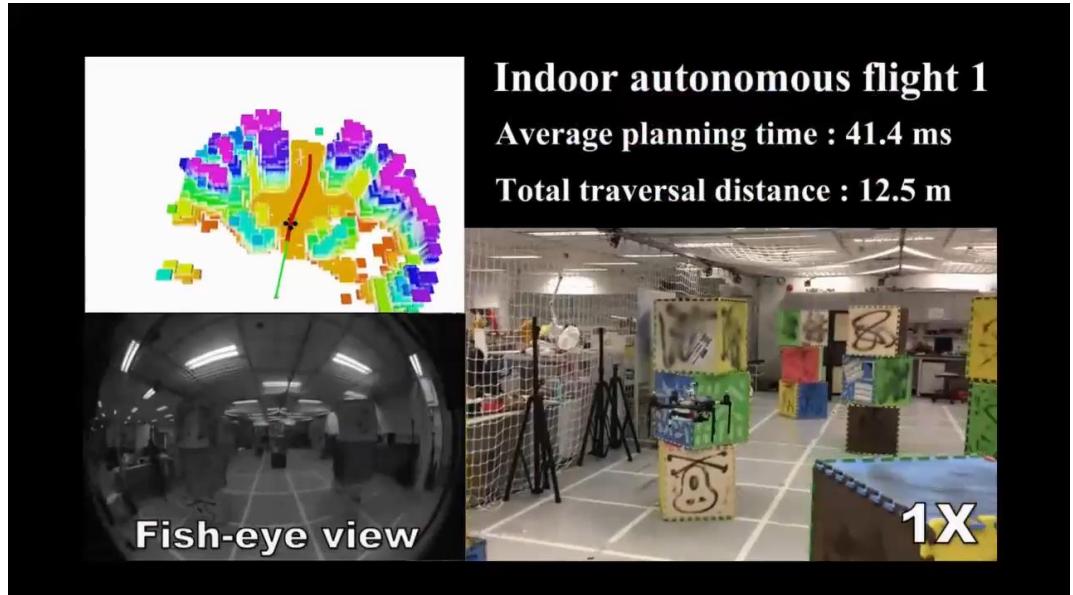




Back-end: Trajectory Optimization

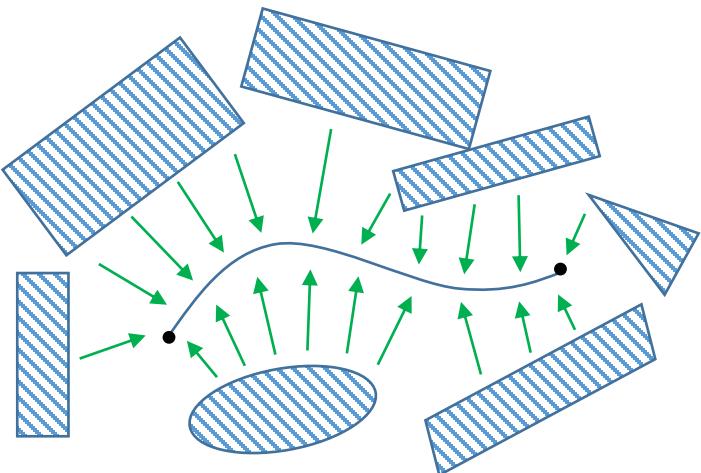


Soft constrained Minimum-snap

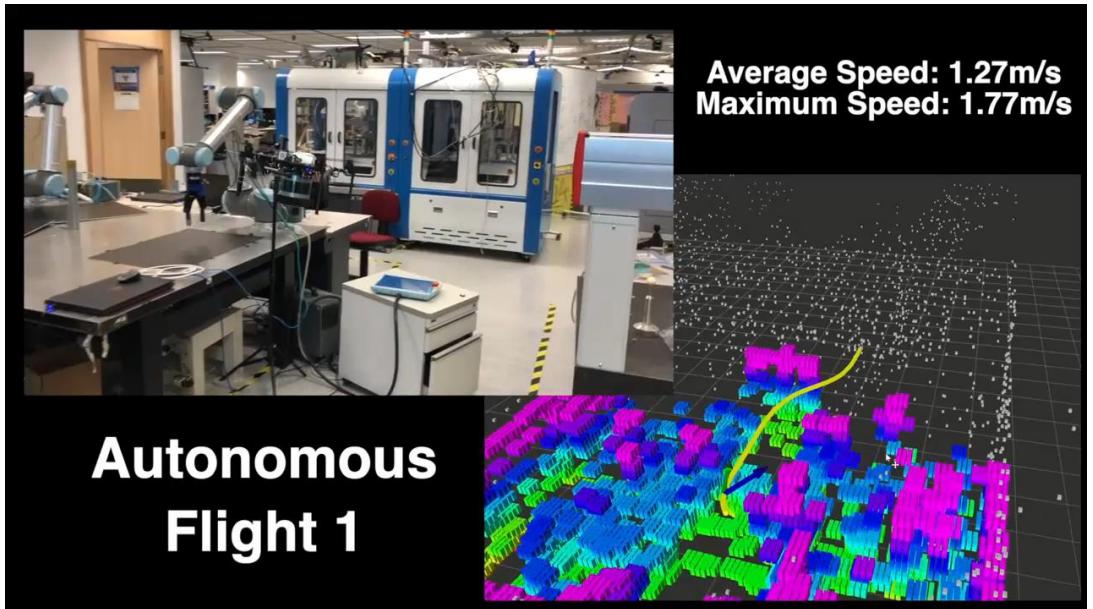




Back-end: Trajectory Optimization

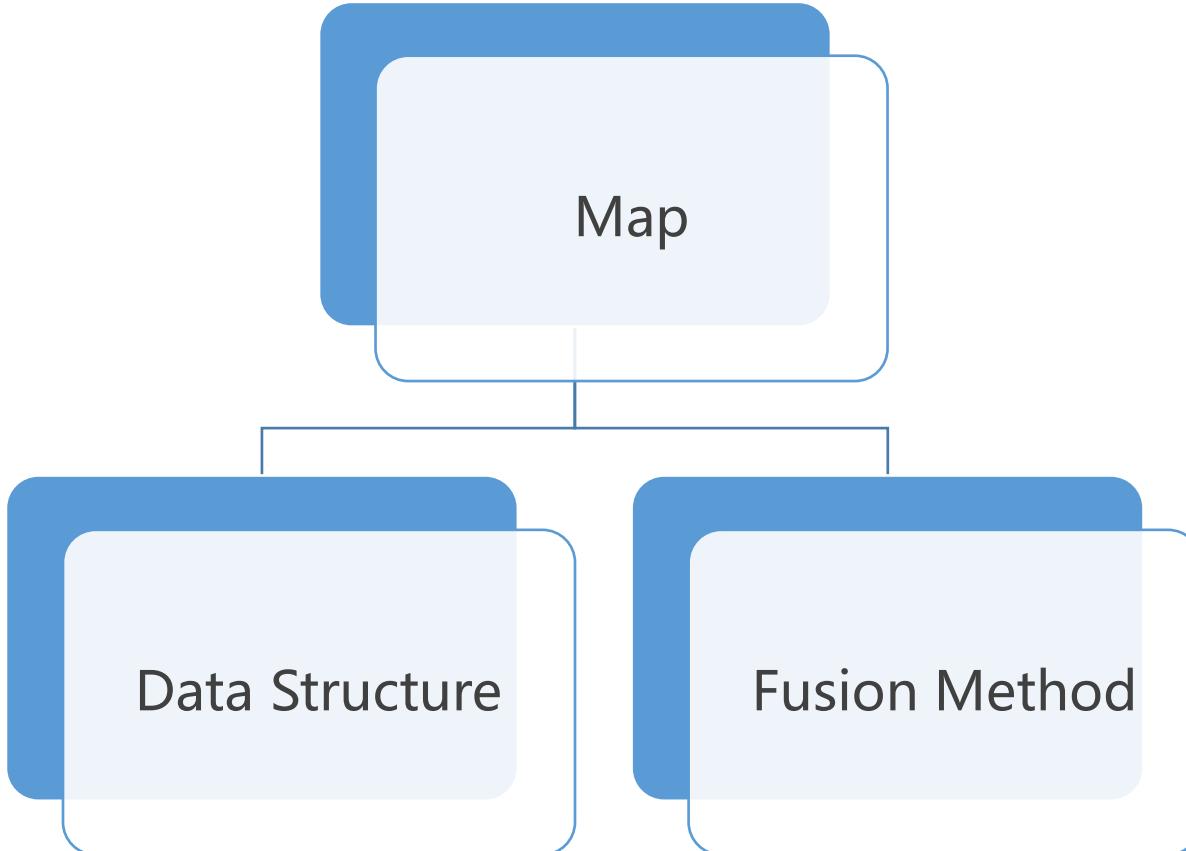


Soft constrained Minimum-snap



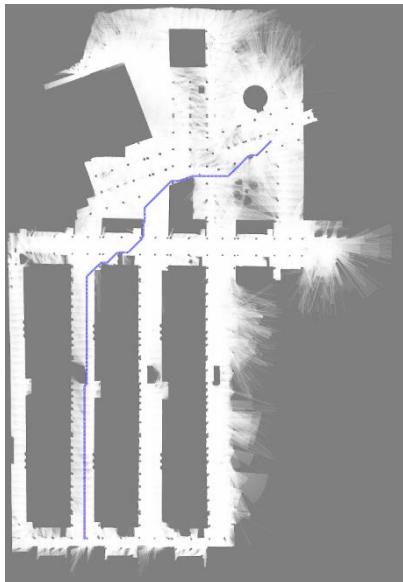
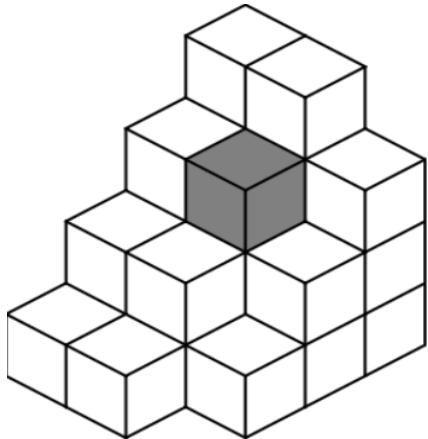


Map Representation

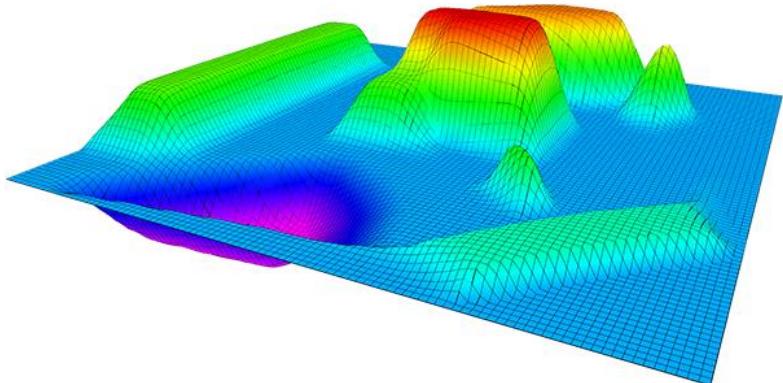




Occupancy grid map



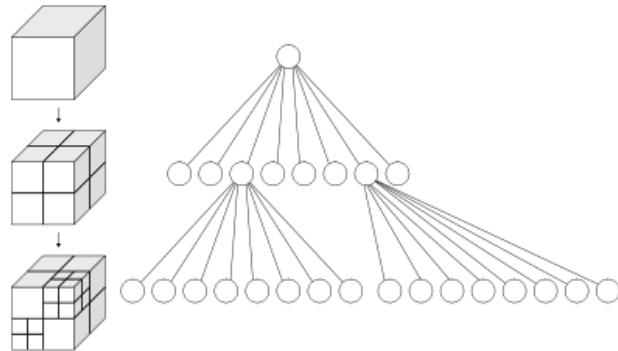
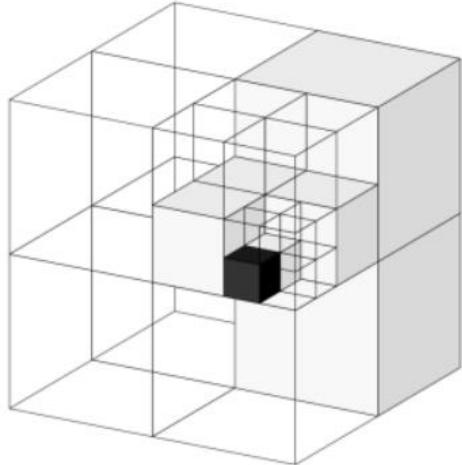
- Most Dense
- Structural
- Direct Index Query



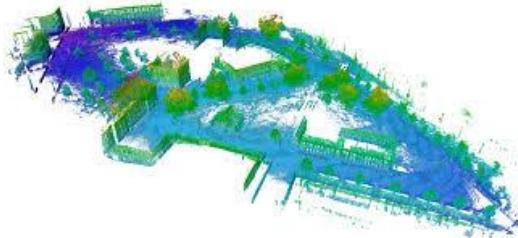
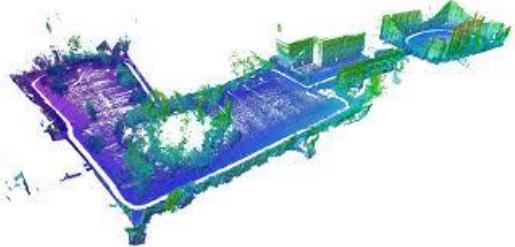
https://github.com/ANYbotics/grid_map



Octo-map



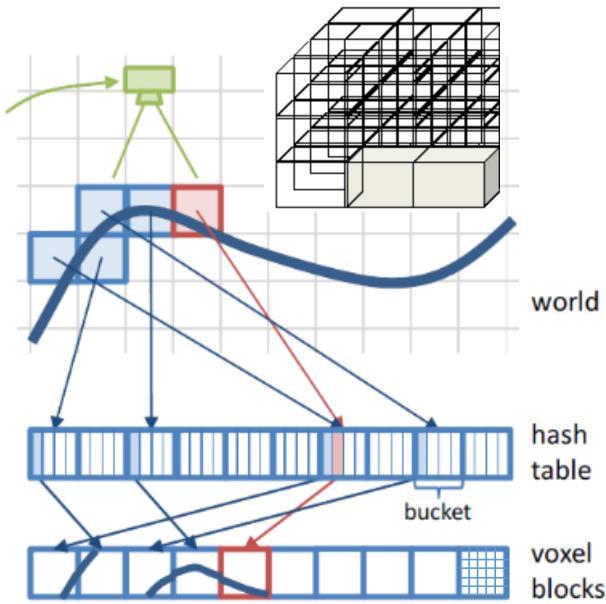
- Sparse
- Structural
- Indirect Index Query



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



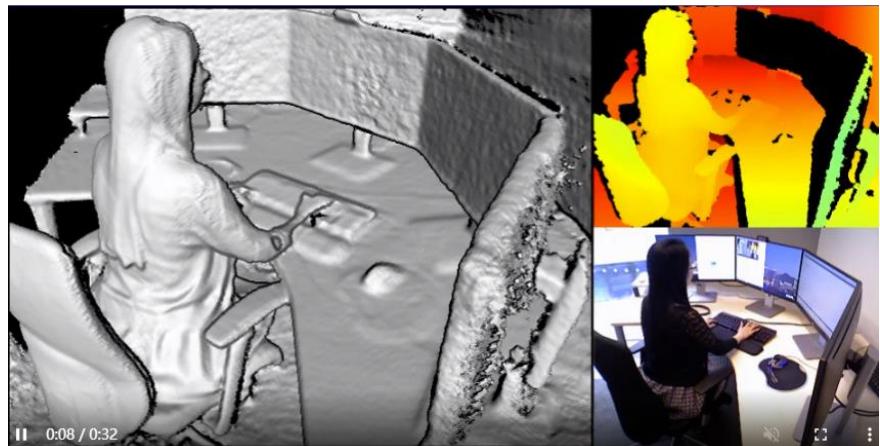
Voxel hashing



Voxel Hashing:

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

- Most Sparse
- Structural
- Indirect Index Query

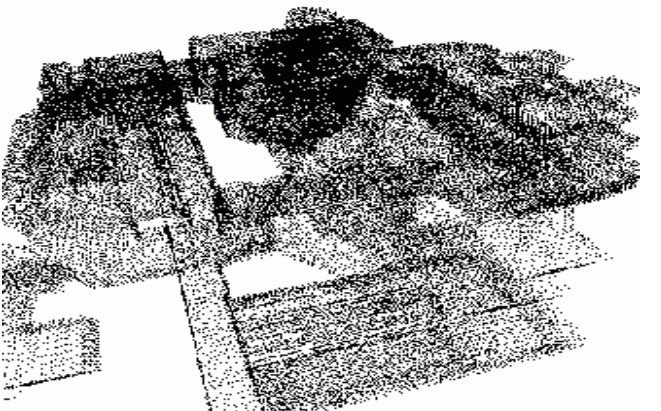


InfiniTAM:

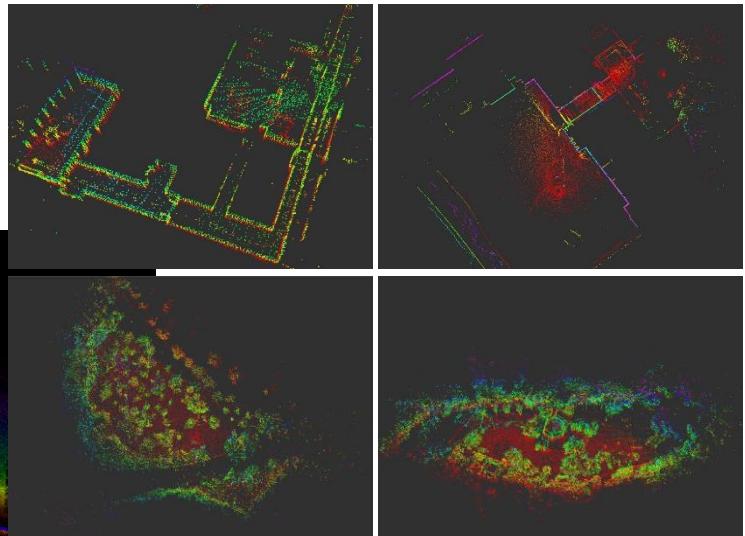
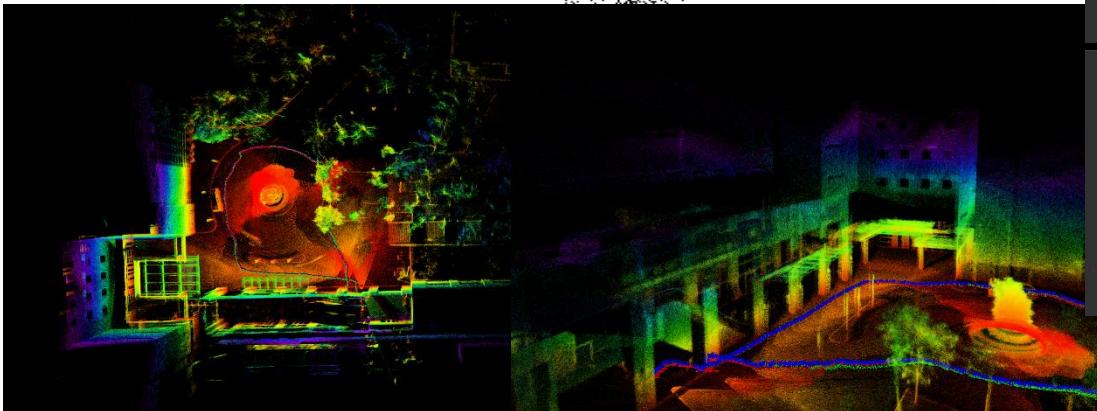
<http://www.robots.ox.ac.uk/~victor/infinitam/>



Point cloud map



- Un-ordered
- No Index Query

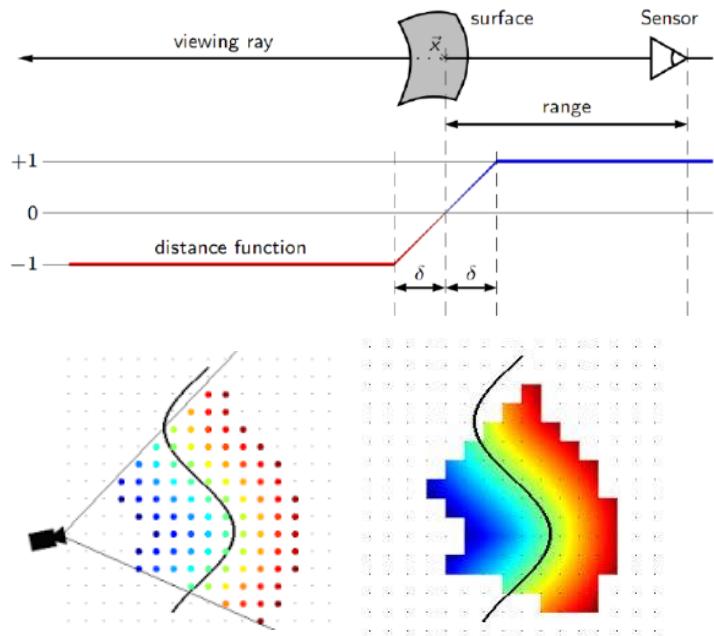


PCL
<http://pointclouds.org/>



TSDF map

Truncated Signed Distance Functions



OpenChisel

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



ESDF map

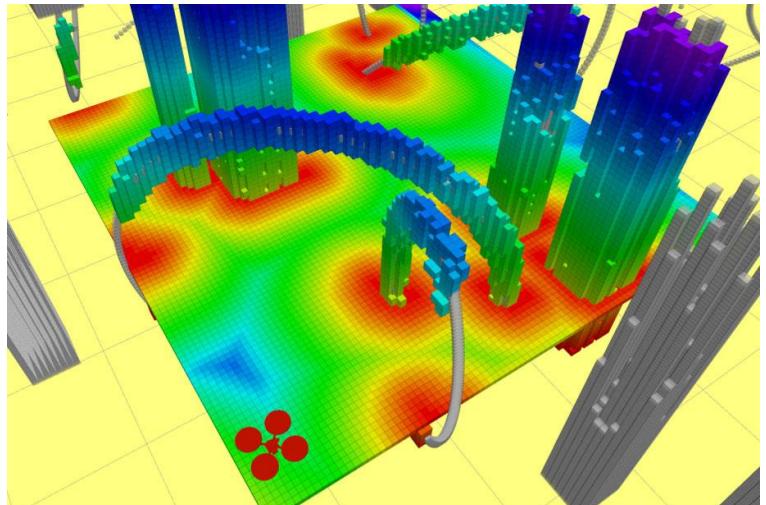
Euclidean Signed Distance Functions
Incremental Update, Global Map

Running the Cow_and_Lady Dataset[1]
Compare with Voxblox[2]

[1] <https://projects.asl.ethz.ch/datasets/doku.php?id=iros2017/>

[2] Helen Olynikova, Zachary Taylor, Marius Fehr, Juan Nieto, and Roland Siegwart, "Voxblox: Building 3D Signed Distance Fields for Planning", In IEEE Int. Conf. on Intelligent Robots and Systems (IROS), October 2017.

Batch Update, Local Map



Distance Transforms of Sampled Functions, PF Felzenswalb

VoxBlox

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

FIESTA

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

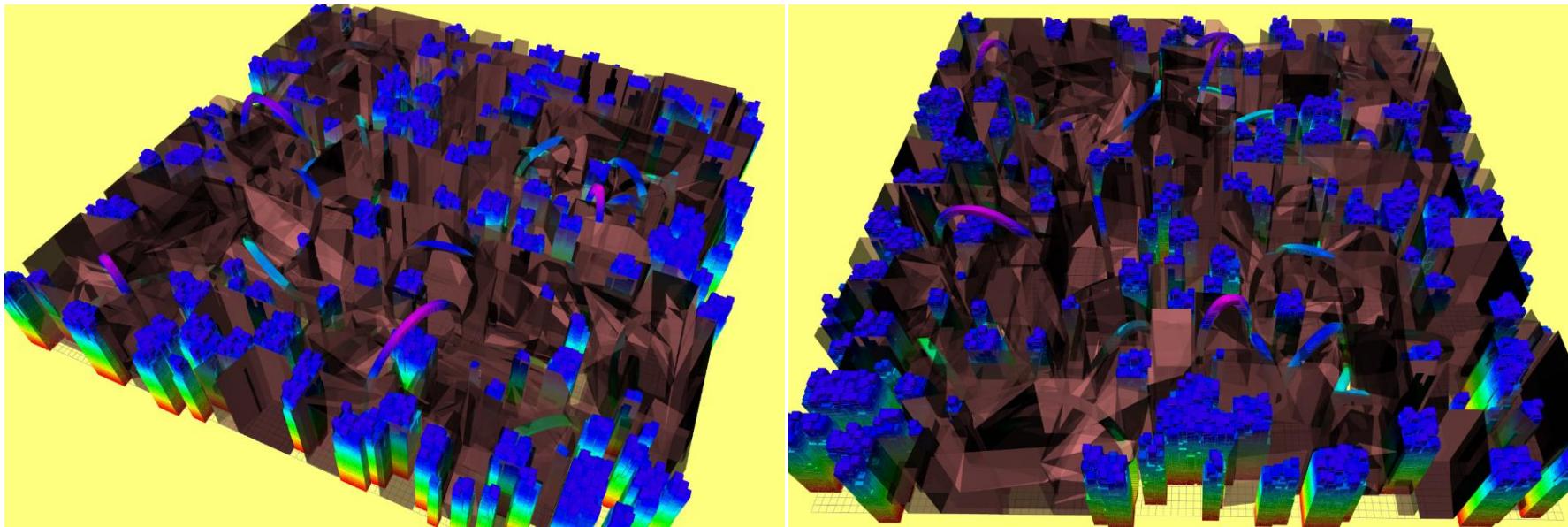
TRR's Local Map

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



More ?

Free-space Roadmap

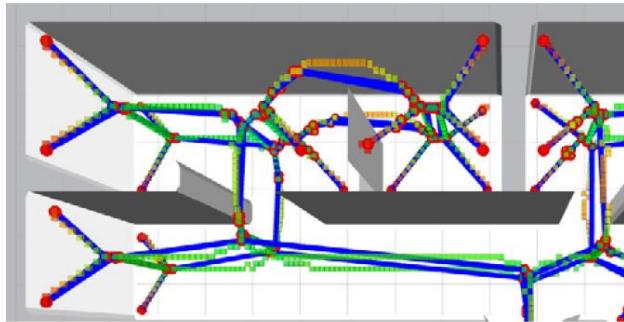


<https://github.com/HKUST-Aerial-Robotics/Teach-Repeat-Replan>

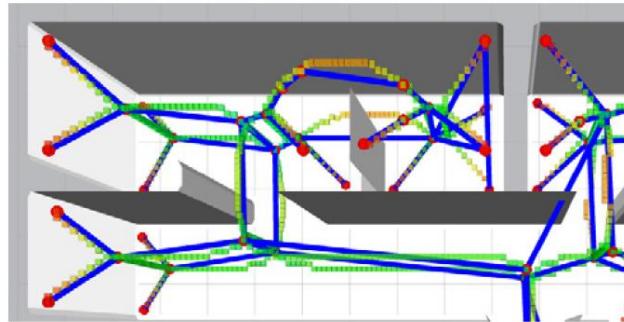


More ?

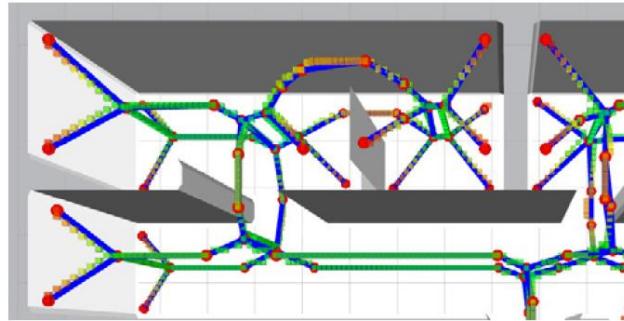
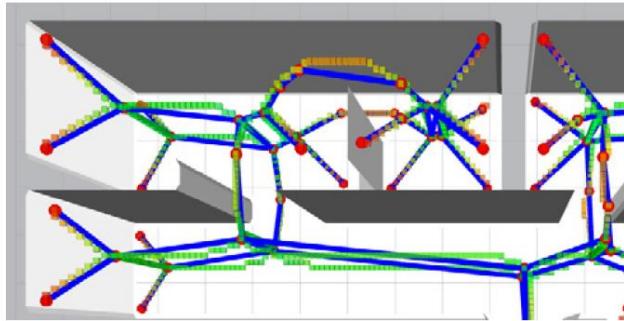
Voronoi Diagram Map



(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

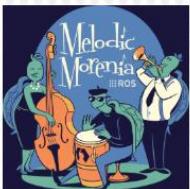
- C with class ?
- Gcc, Makefile, CMakeList
- Write CMakeList
- How to solve problems: google and document



ROS

ROS

About Why ROS? Getting Started Get Involved Blog



ROS Melodic Morenia
Melodic Morenia is the 12th official ROS release. It is supported on Ubuntu Artful and Bionic, along with Debian Stretch. Get Melodic Morenia now!

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- Ubuntu 16.04 + ros kinetic is recommended



Matlab

- Please install Matlab



Homework



Thanks for Listening!

