Research Theme: Supervised Autonomy

- **Autonomous Navigation in Unstructured Environments**
  - How can we enable robots to plan their own dynamically-feasible motions to successfully navigate in unstructured environments?
- **Task-Level Autonomy**
  - How can we make robots more capable to complete complex tasks on their own?
- **Human-Robot Collaboration**
  - How can we alleviate the cognitive workload placed on human supervisors working with a team of robots?
  - How can the robots interact with their human supervisors to provide feedback and incorporate new objectives?

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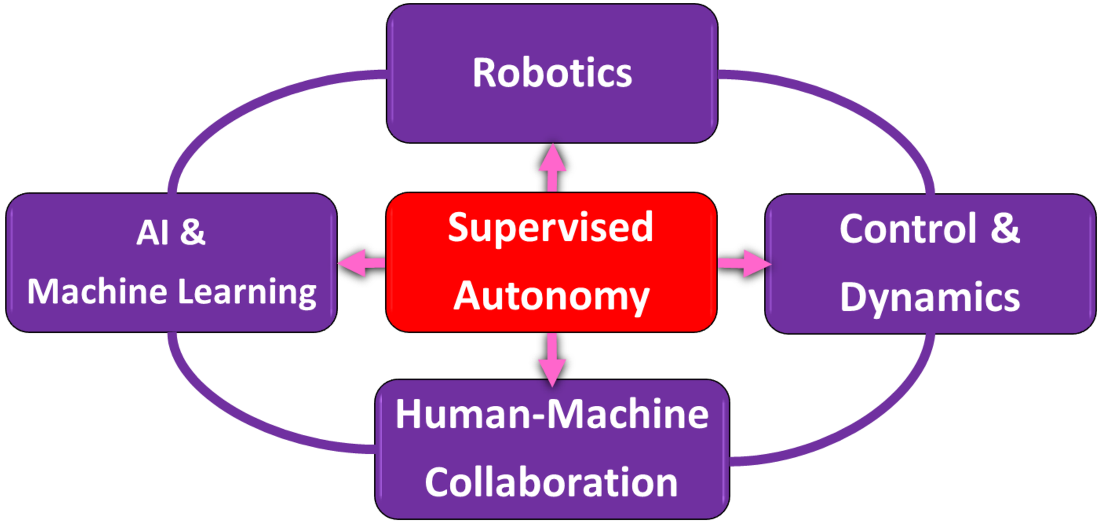
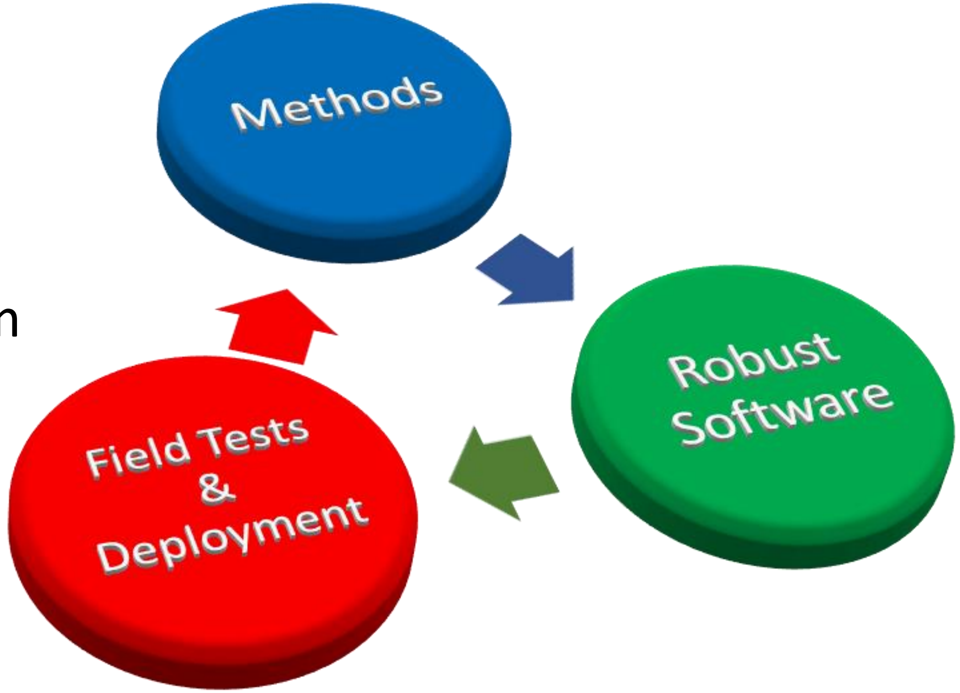
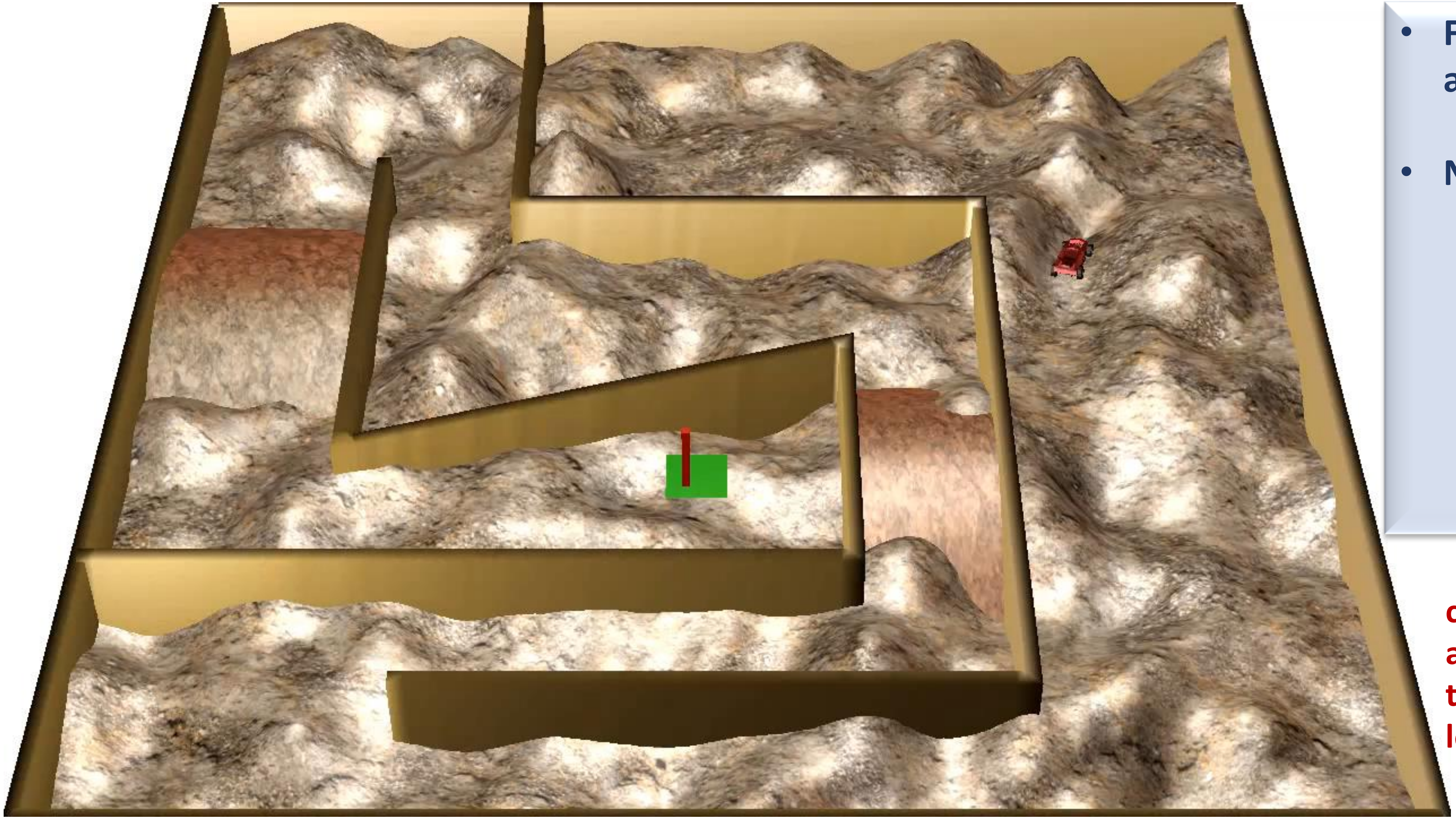




Overview

- Research Theme: Supervised Autonomy
- **Navigation in Unstructured Environments**
- Task-Level Autonomy
- Human-Robot Collaboration
- Highlighted Applications: Marine Robotics, Aerial Robotics
- Other Areas: Medical Robotics, Robot Manipulation, Cyber-Physical Systems
- Discussion

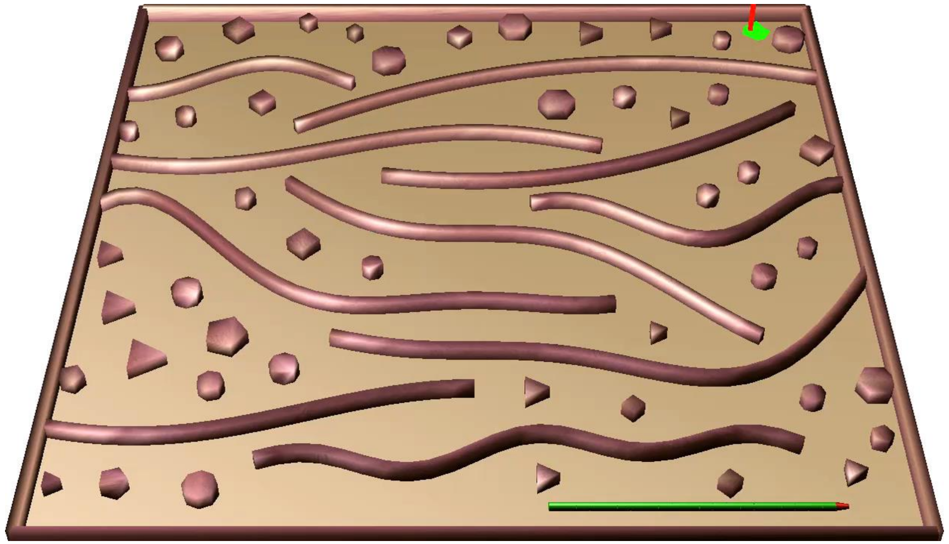
Motion Planning in Unstructured Environments

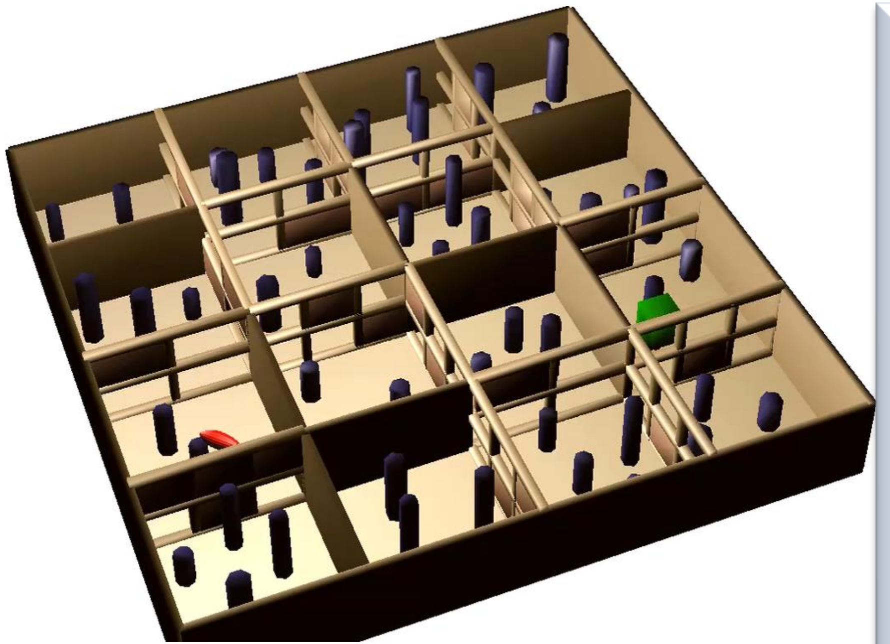


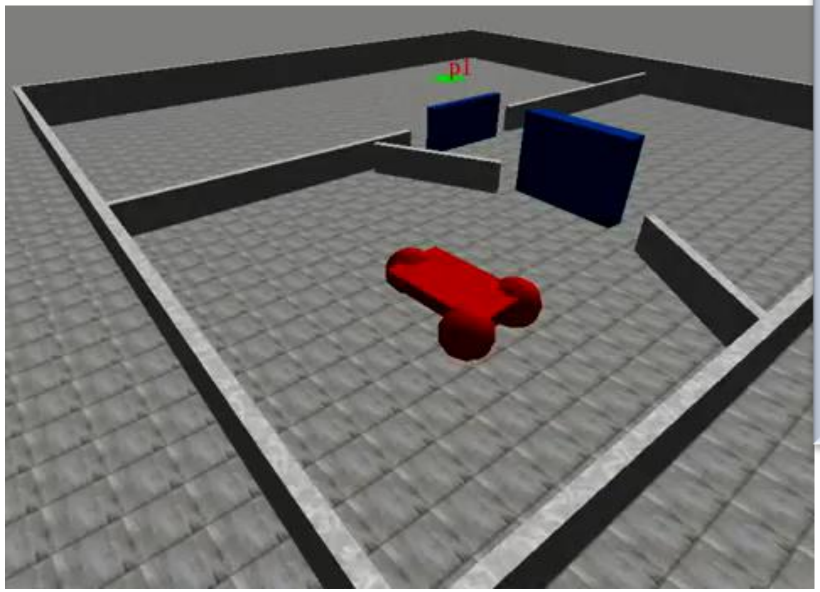
- Fundamental for autonomous robotics
- Numerous applications
  - exploration
  - transportation
  - navigation
  - search-and-rescue
  - video games
  - medical robotics
  - …

compute a collision-free and dynamically-feasible trajectory from the initial location to the goal

Motion Planning Poses Hard Problems





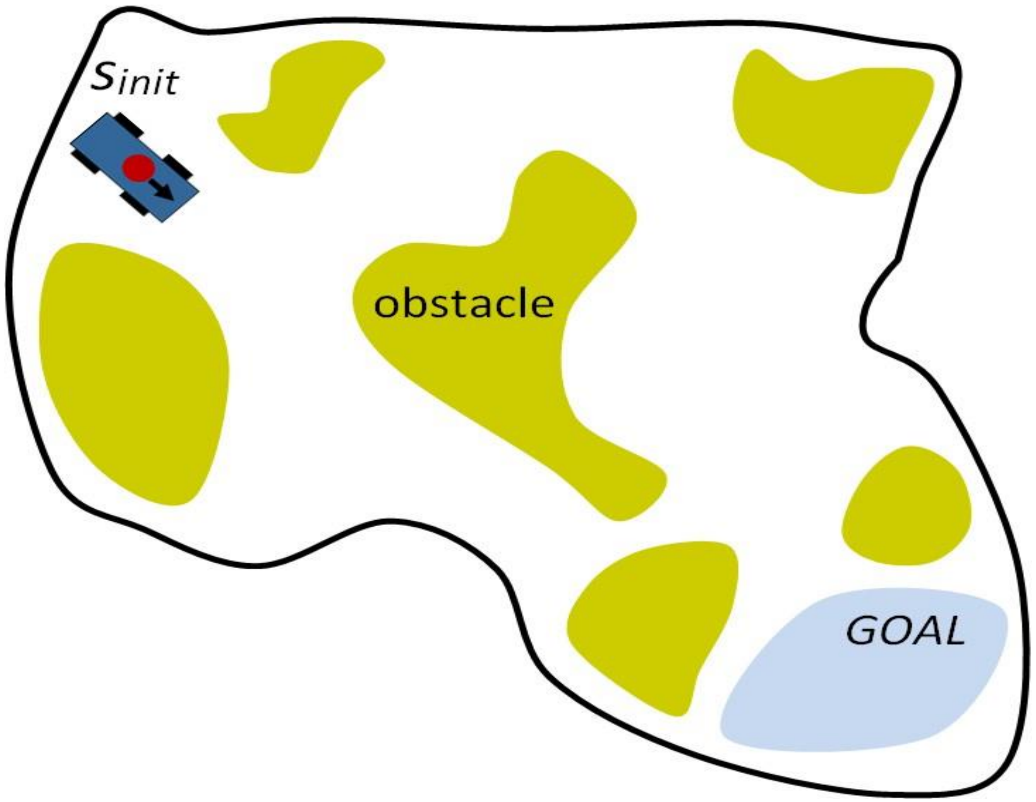


- **High-dimensional continuous state spaces**
- **Obstacle-rich and unstructured environments**
- **Feasible motions constrained by underlying dynamics**
  - **Often nonlinear, nonholonomic, and high-dimensional**
- **PSPACE-complete:** **geometry, no dynamics**
- **Undecidable:** **with dynamics**

Driving Research Questions

- How can we develop motion planners that are generally applicable?
- How can we achieve planning efficiency even for robots with nonlinear dynamics operating in unstructured, obstacle-rich environments?
- How can we improve the solution quality?
- What formal guarantees can we provide?

Sampling-based Motion Planning



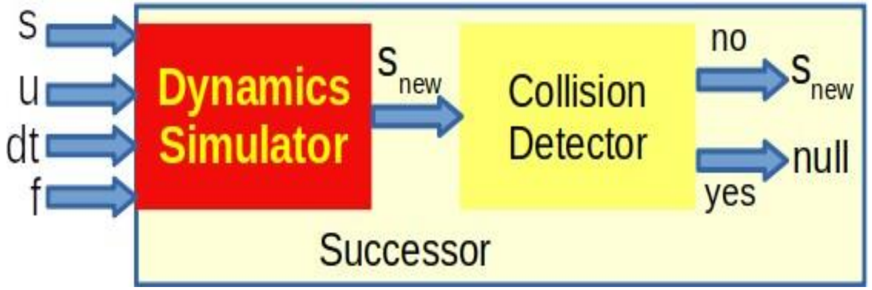
$MP = (s_{init}$, GOAL, SUCCESSOR) : search problem

- accounts for obstacles and dynamics

Expand tree whose branches correspond to collision-free and dynamically-feasible motions

repeat until solution or runtime limit is reached:

- select state from which to expand the tree
- select target position
- generate trajectory from selected state toward target
- add the collision-free portion as new branch to the tree



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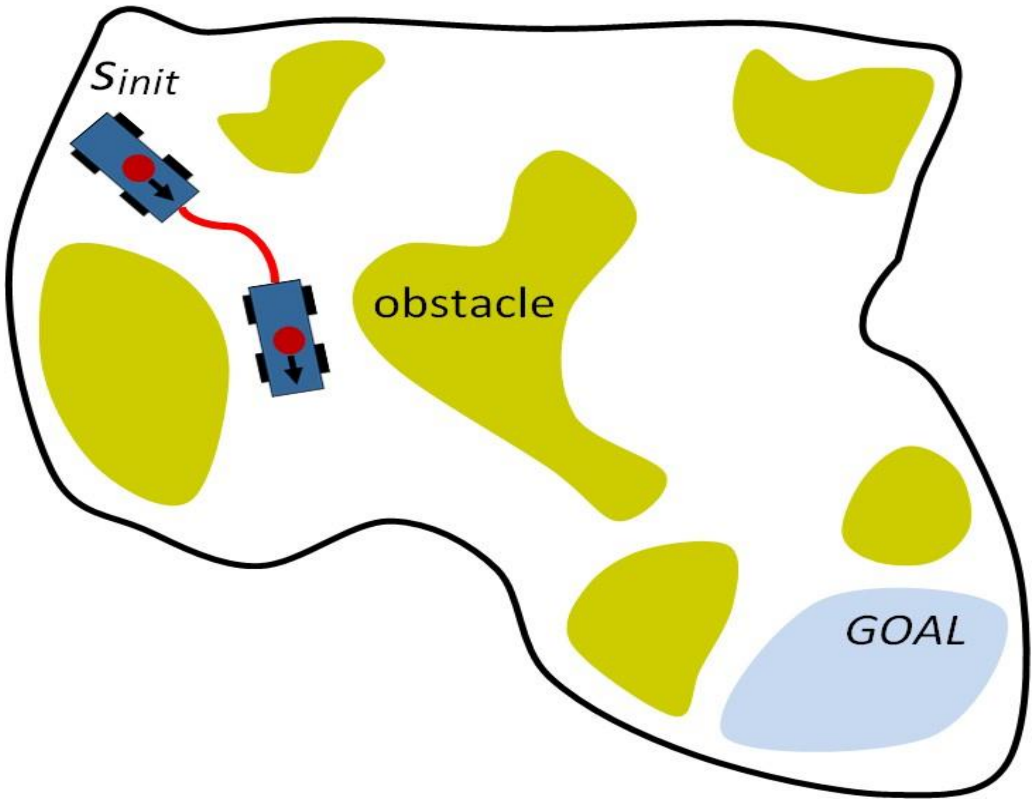

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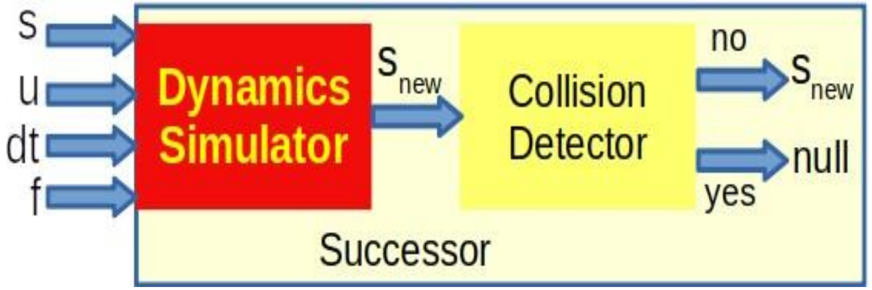

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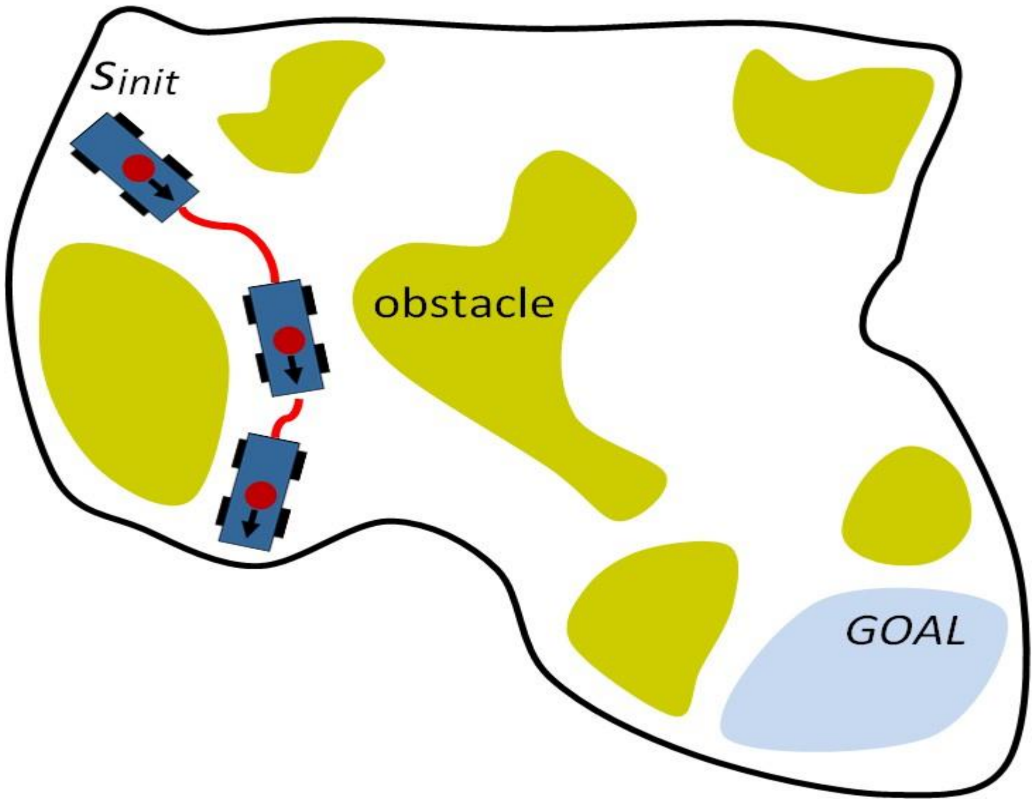

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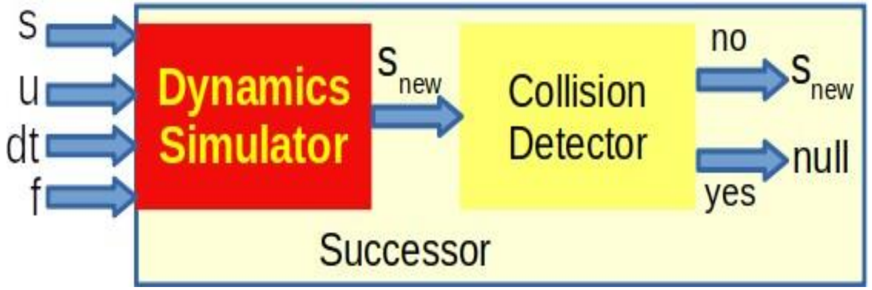

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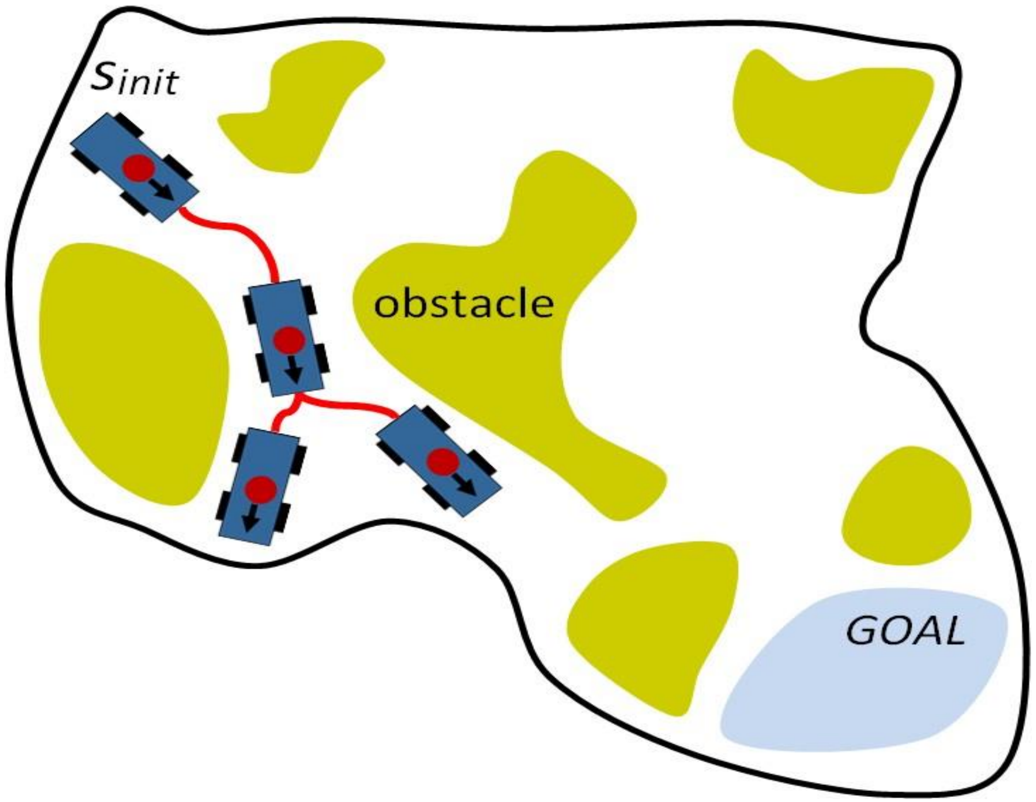

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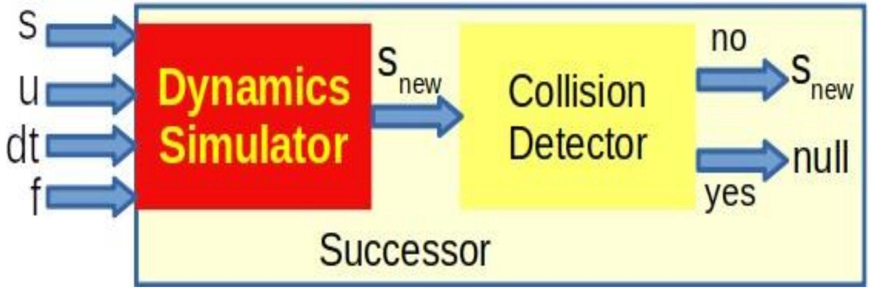

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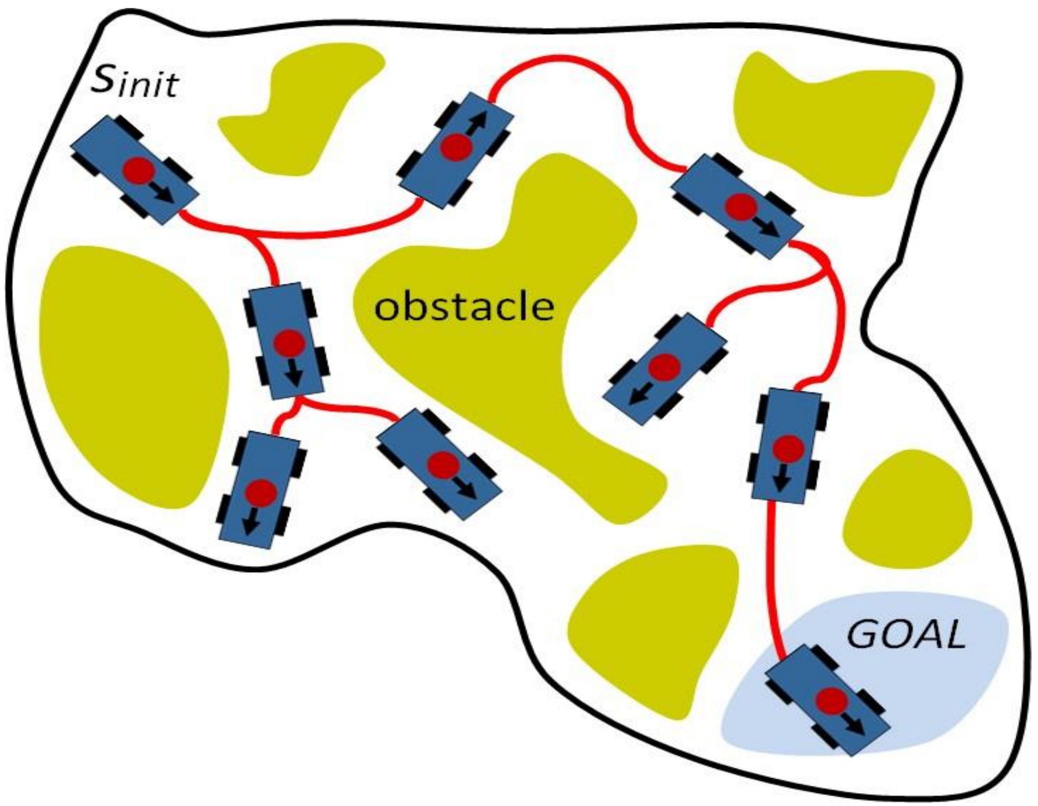

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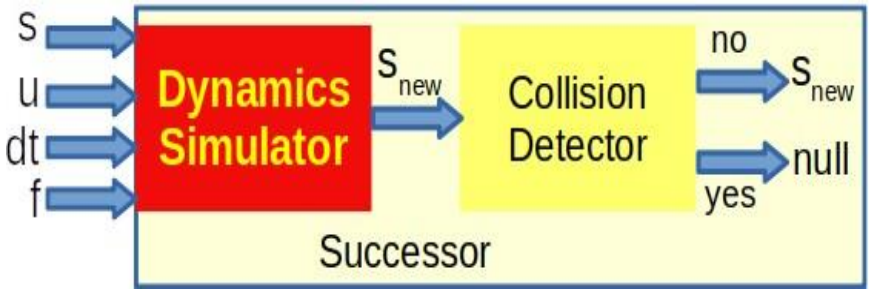

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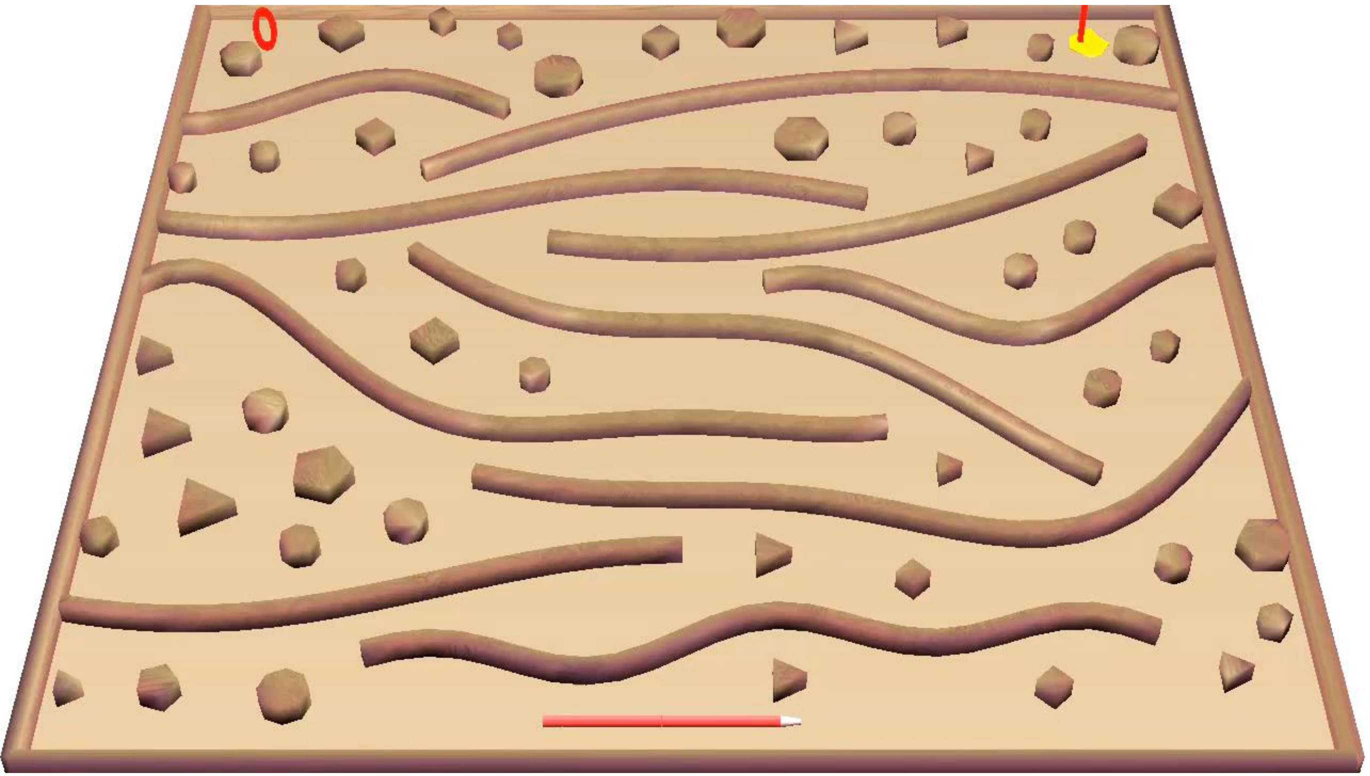
Sampling-based Motion Planning

On difficult problems:

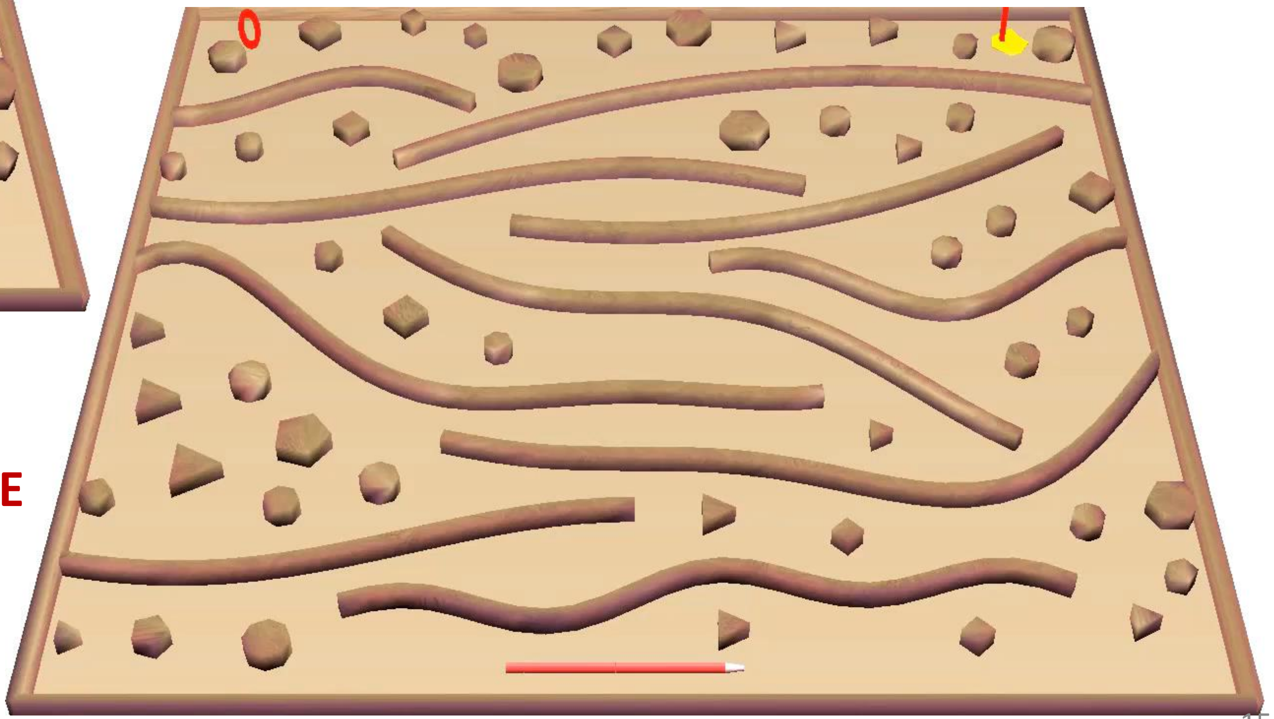
- Expansion frequently gets stuck
- Progress slows down
- Exploration guided by limited information
- Difficult to discover new promising directions



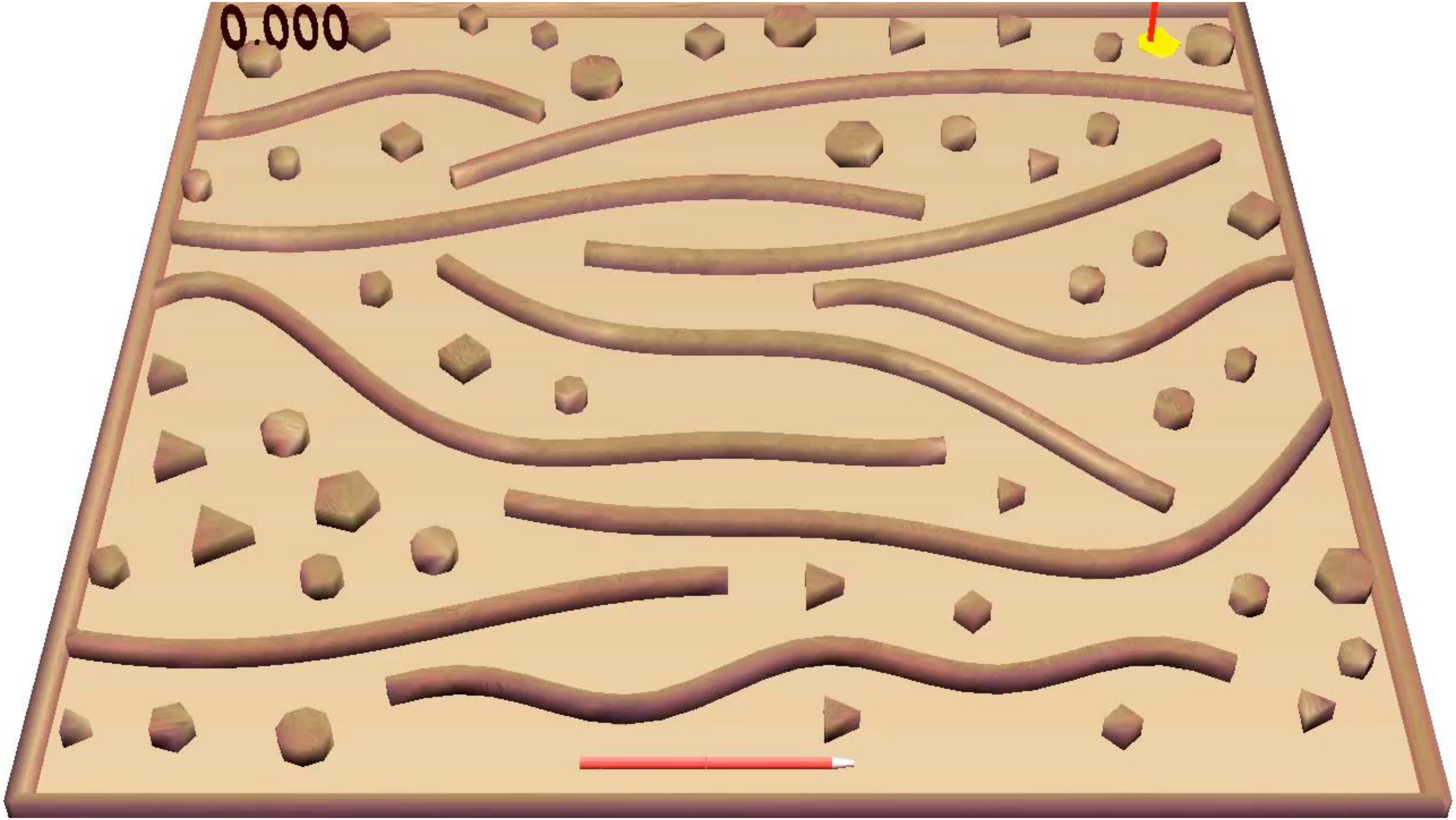
RRT

state-of-the-art motion planners have difficulty solving these challenging problems

KPIECE



Our approach



Framework

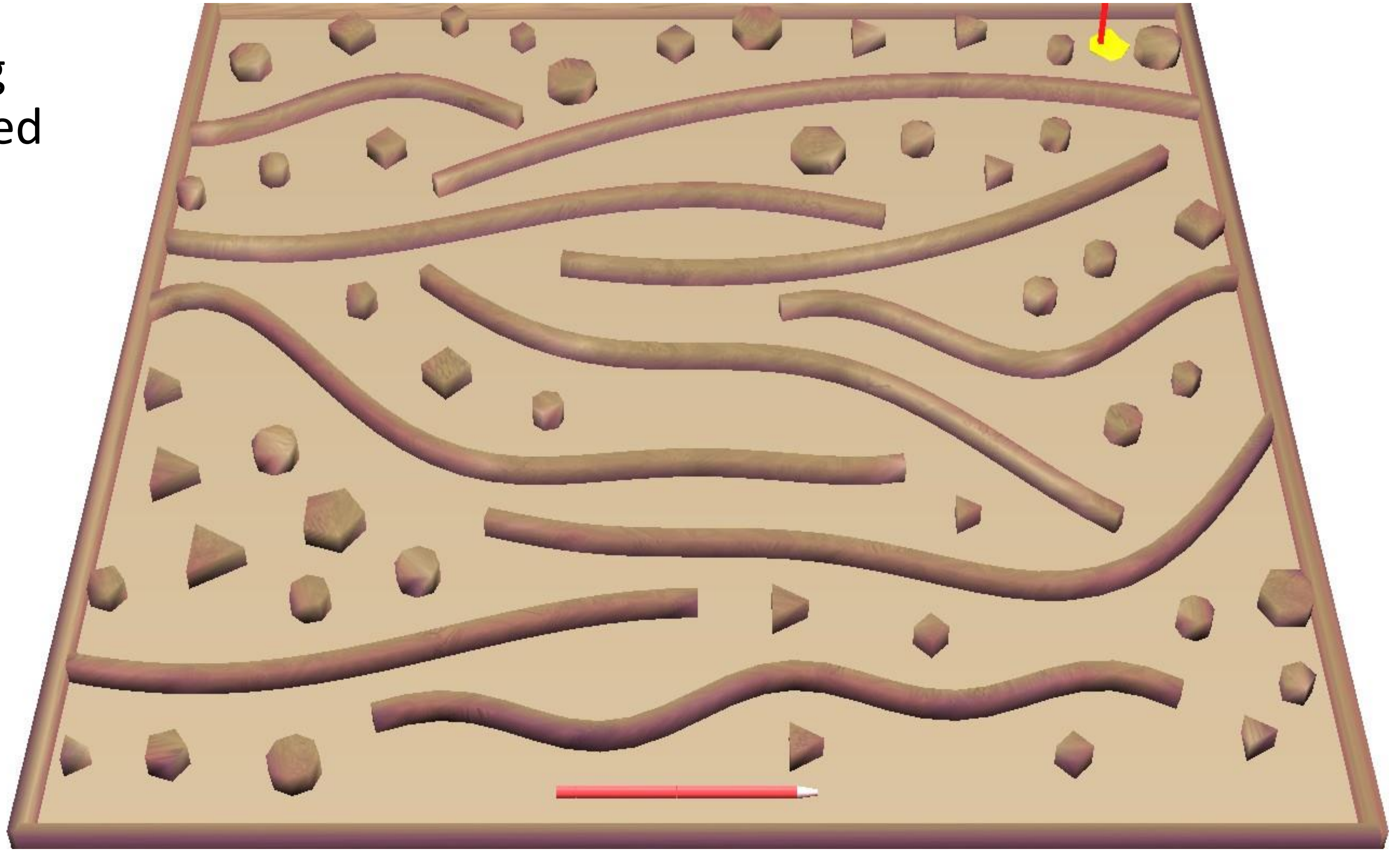
- Pioneered framework to treat motion planning as a ***search*** problem in a ***hybrid*** space composed of ***discrete*** and ***continuous*** components

AI

- High-level reasoning over discrete abstractions
- Provide simplified planning layer
- Guide search in the continuous space

Sampling-Based Motion Planning

- Probabilistic sampling to selectively explore the space of feasible motions
- Expand tree by adding collision-free and dynamically-feasible trajectories as branches



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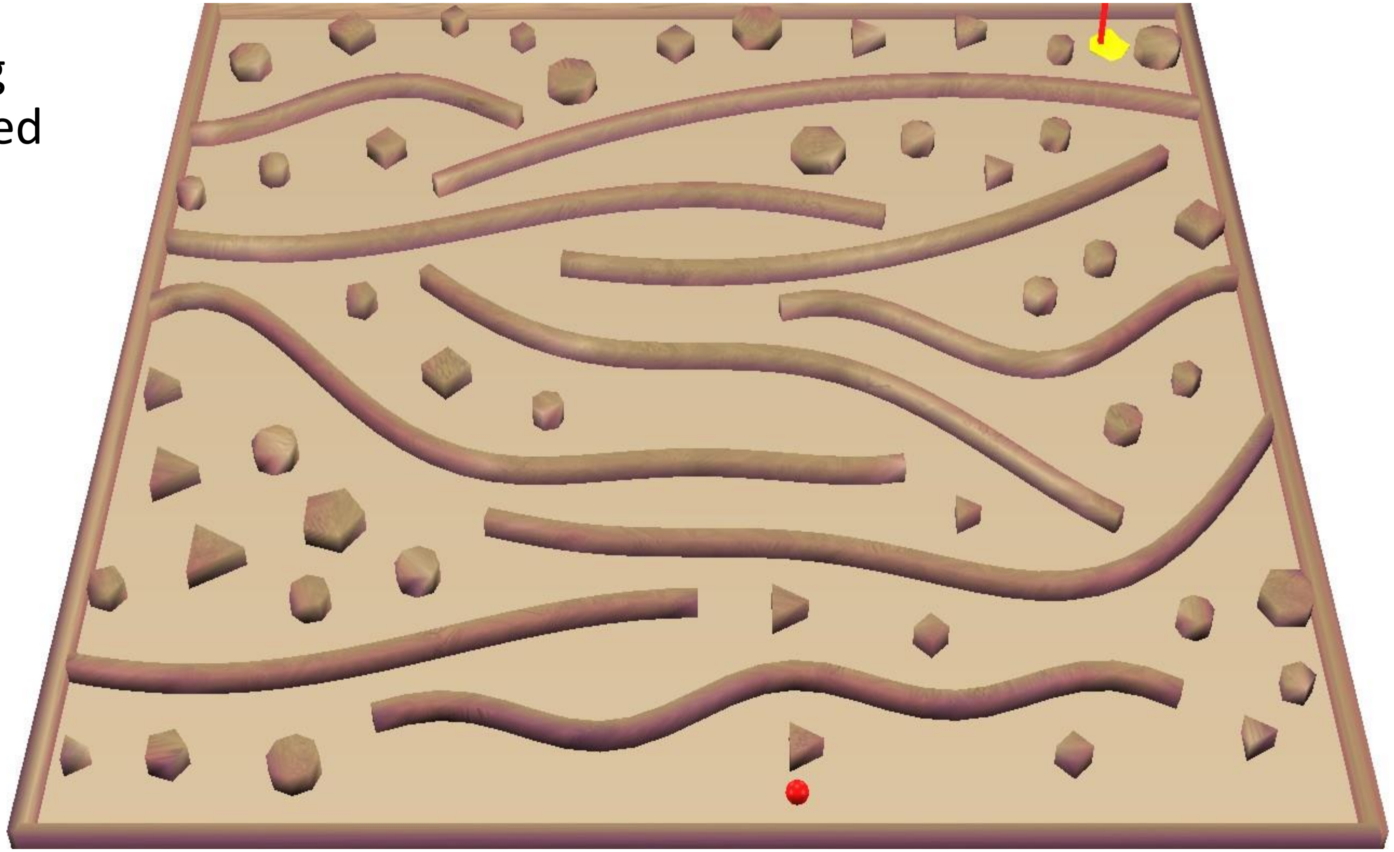

Simplified planning layer

- relaxed problem: no dynamics, point robot

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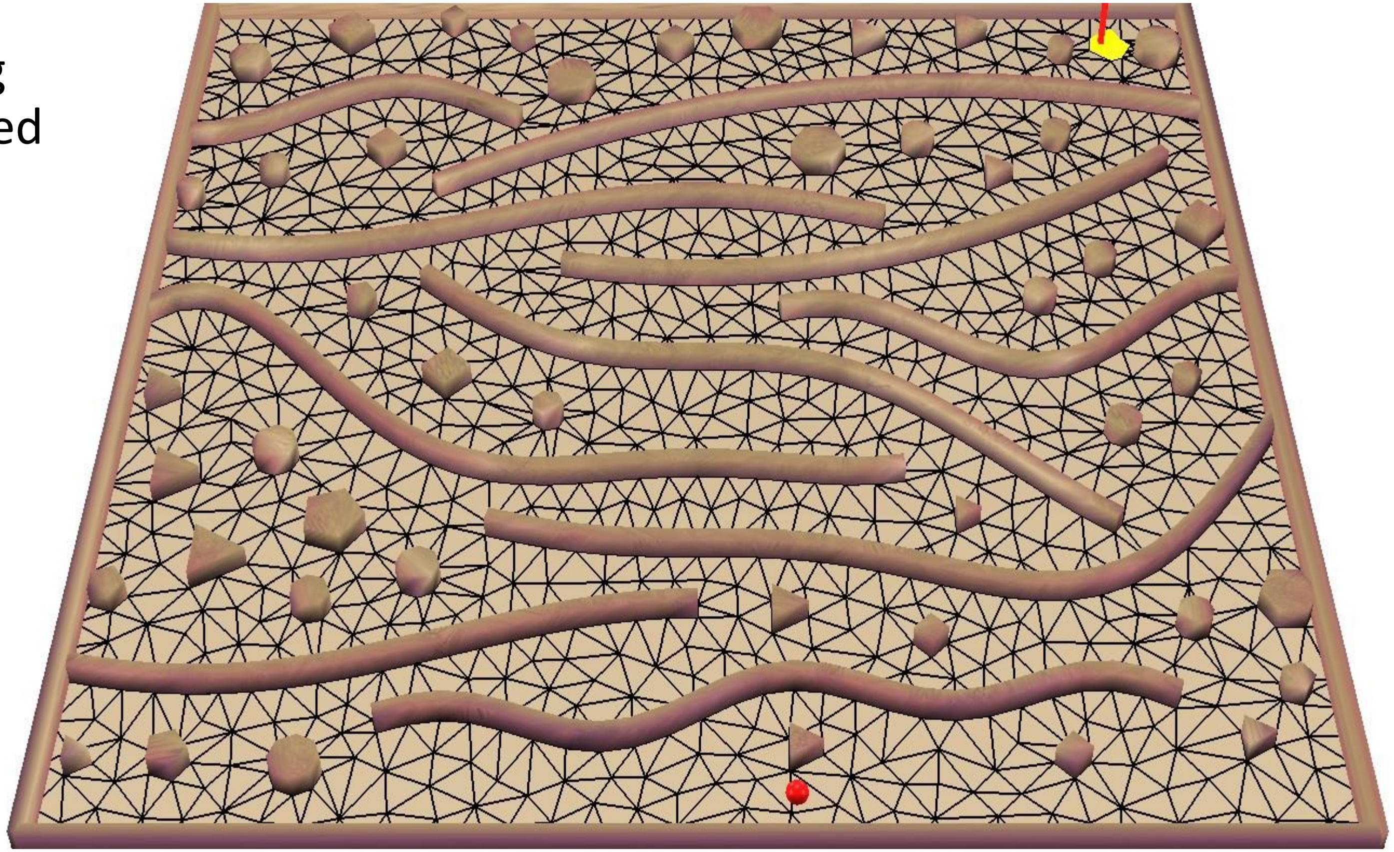

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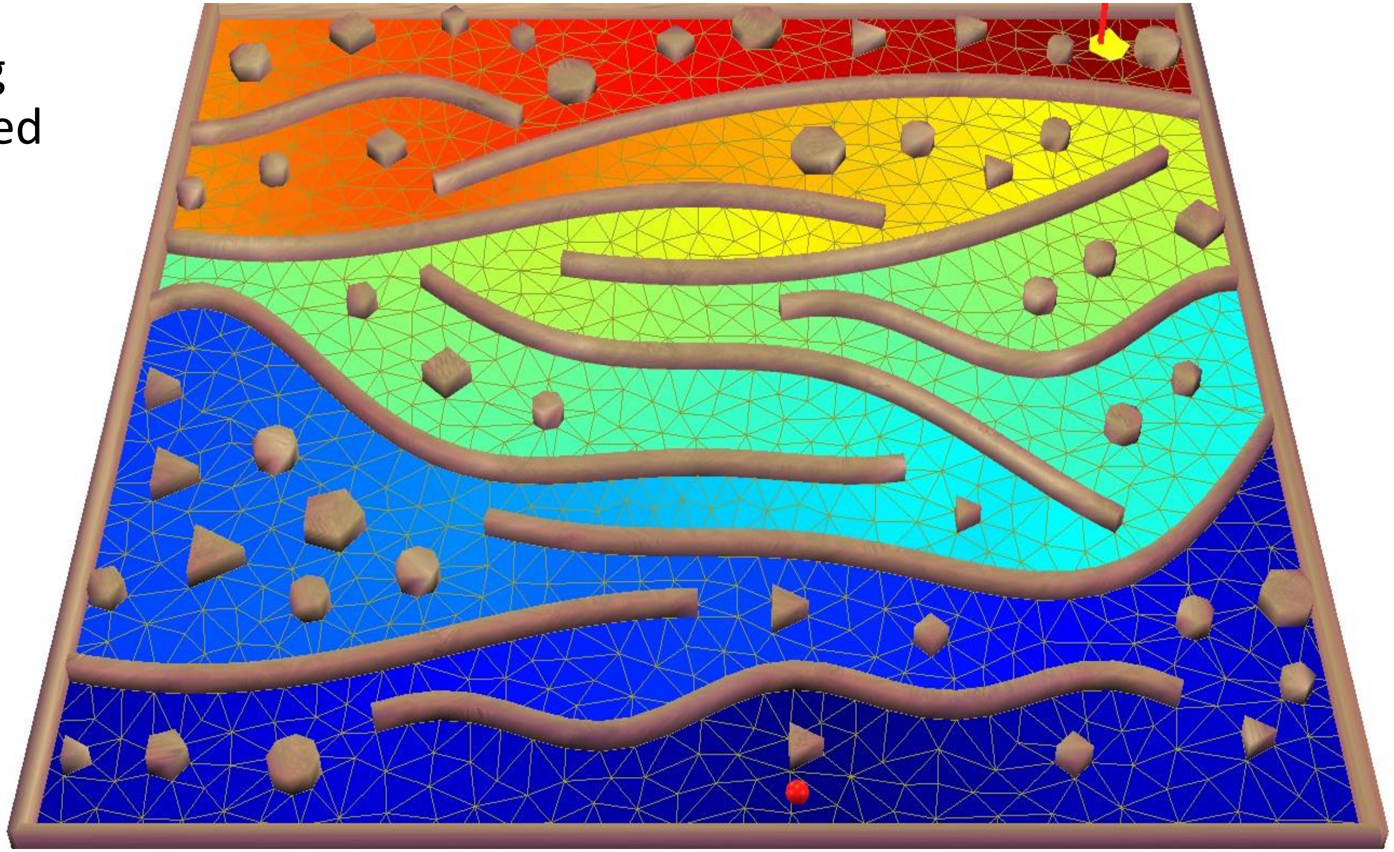

Simplified planning layer

- relaxed problem: no dynamics, point robot
- decomposition, adjacency graph
- shortest-path from each region to goal

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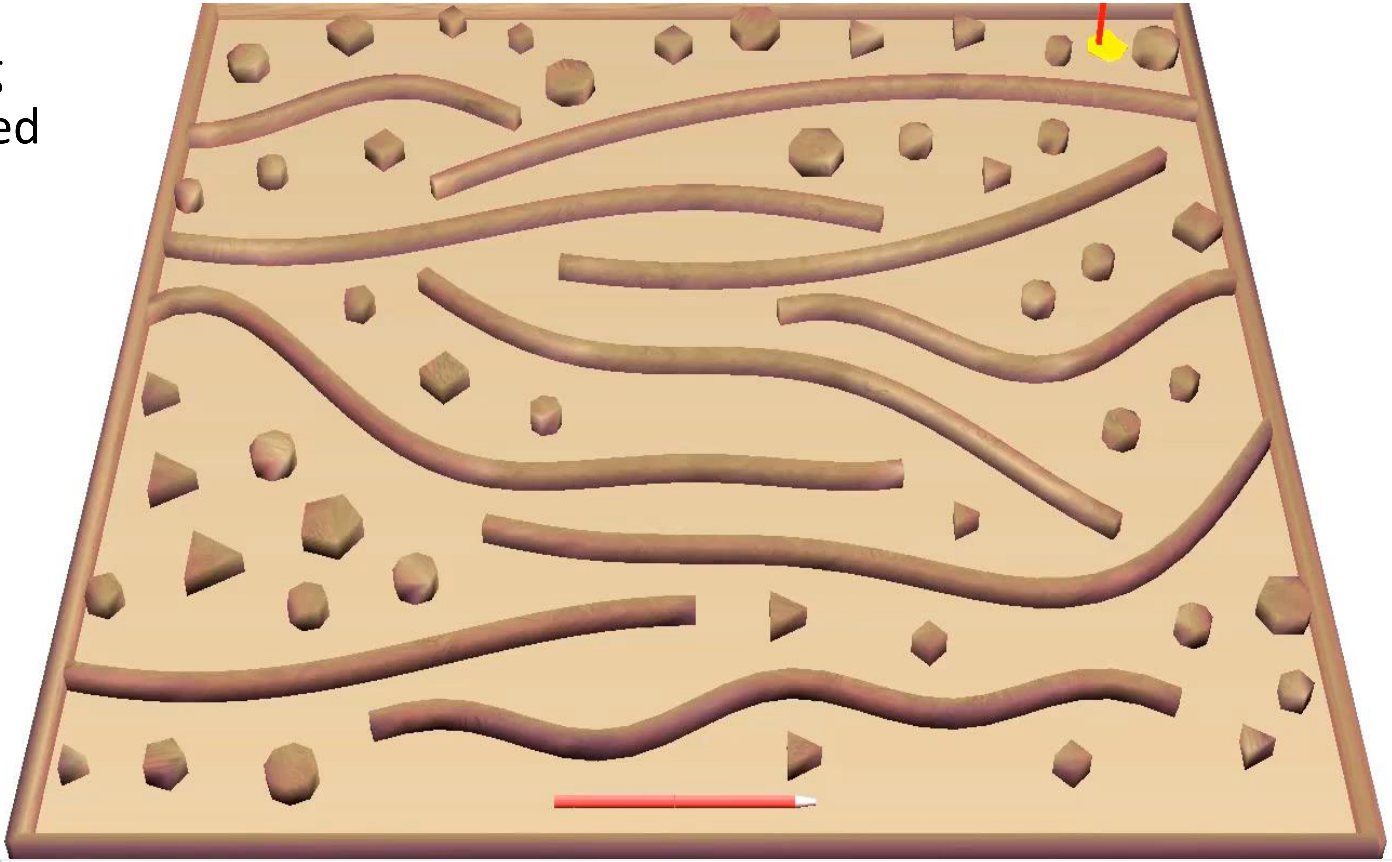
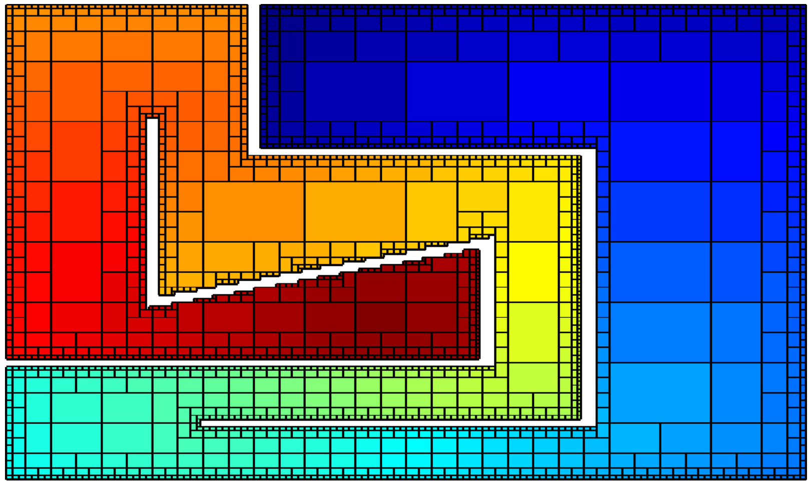
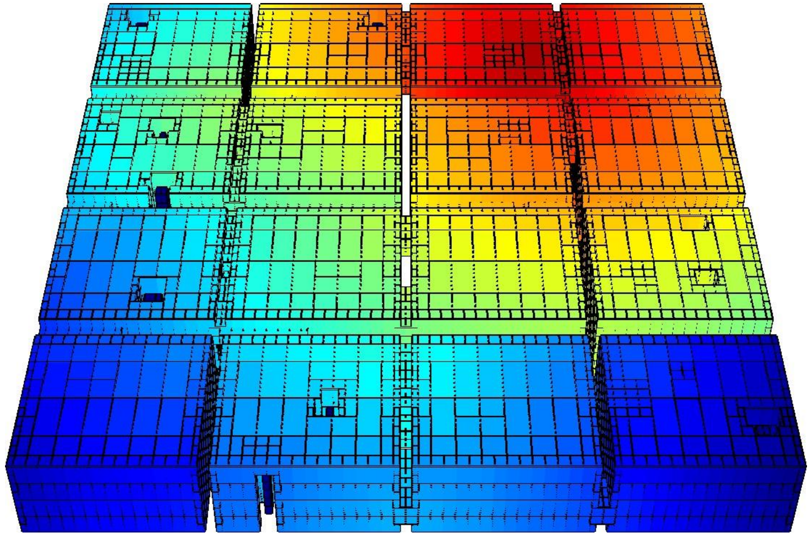


iterate until solution found or runtime limit is reached:

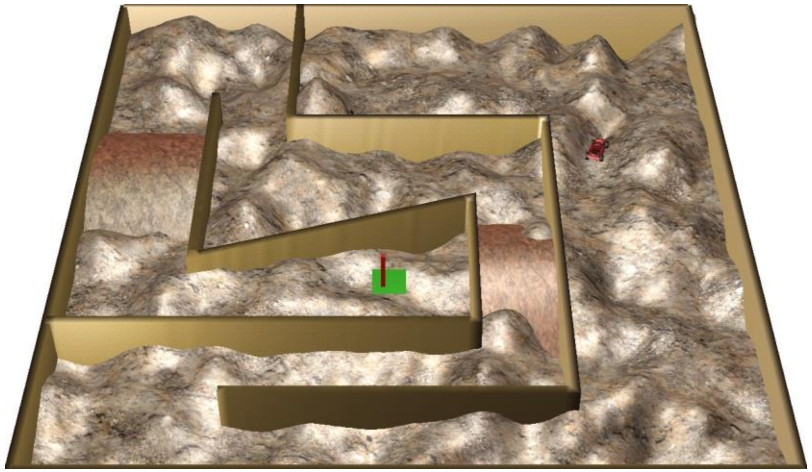
- select non-empty region with maximum weight
- expand motion tree along shortest path
- update weights based on progress made

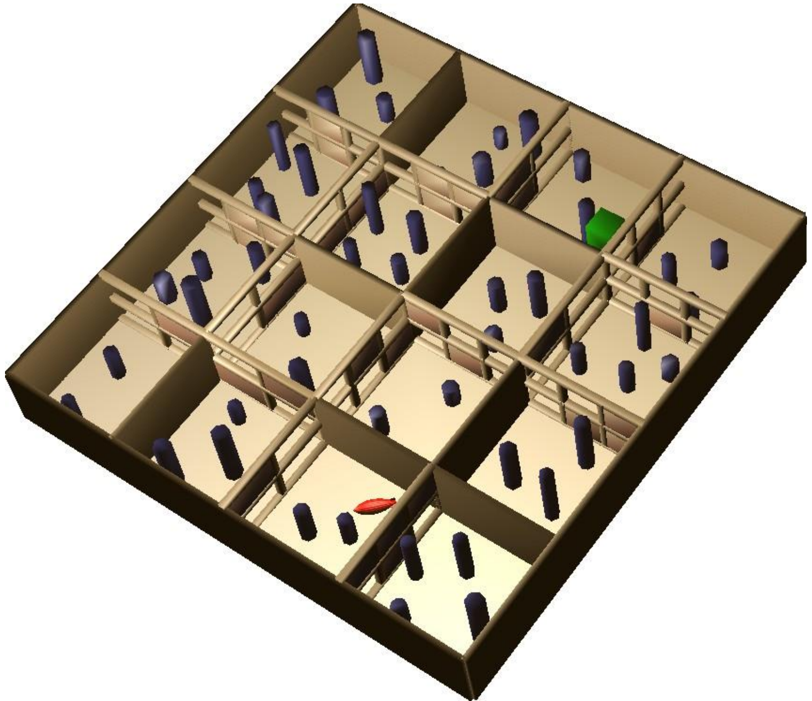
Framework: Enhancements/Improvements





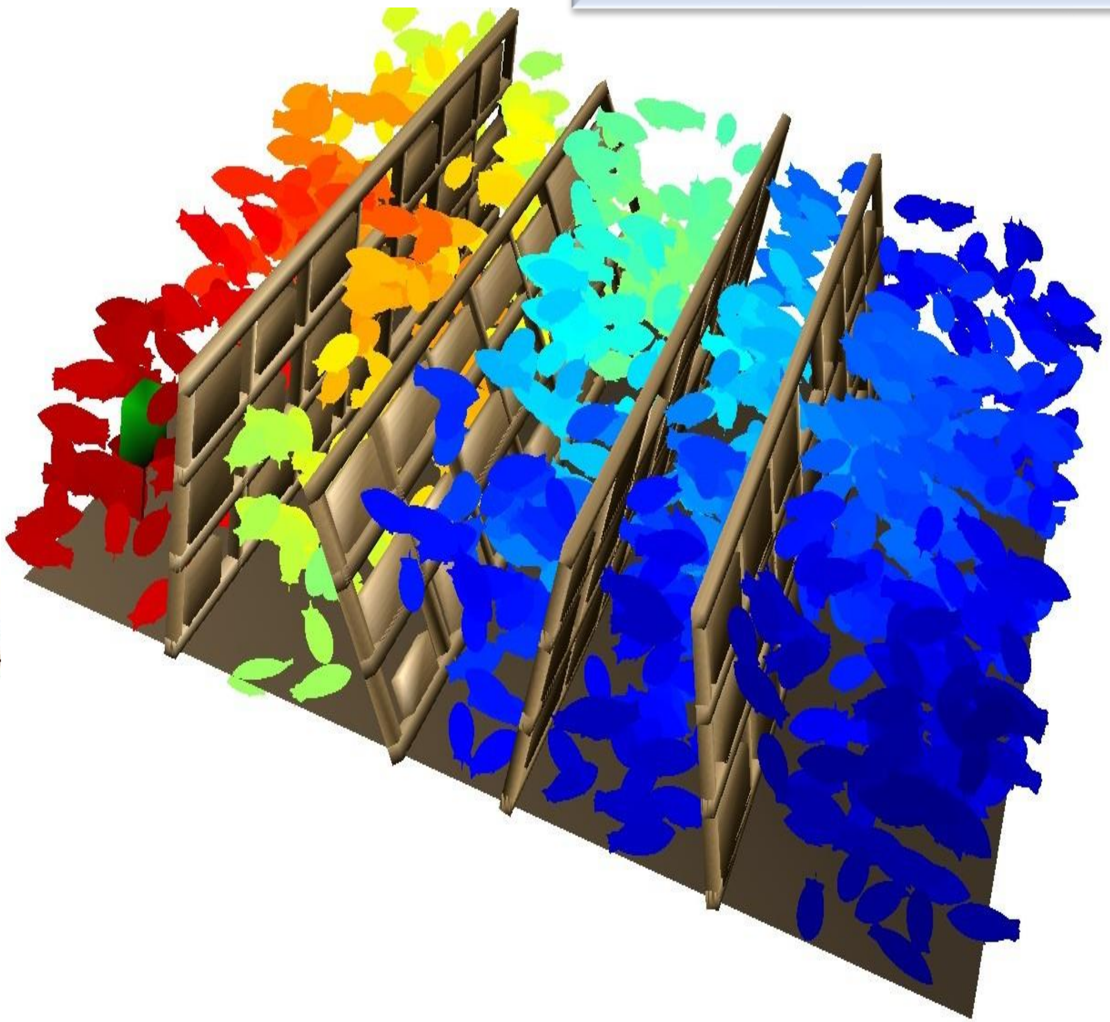
abstractions via subdivisions





Framework: Enhancements/Improvements

abstractions via roadmaps



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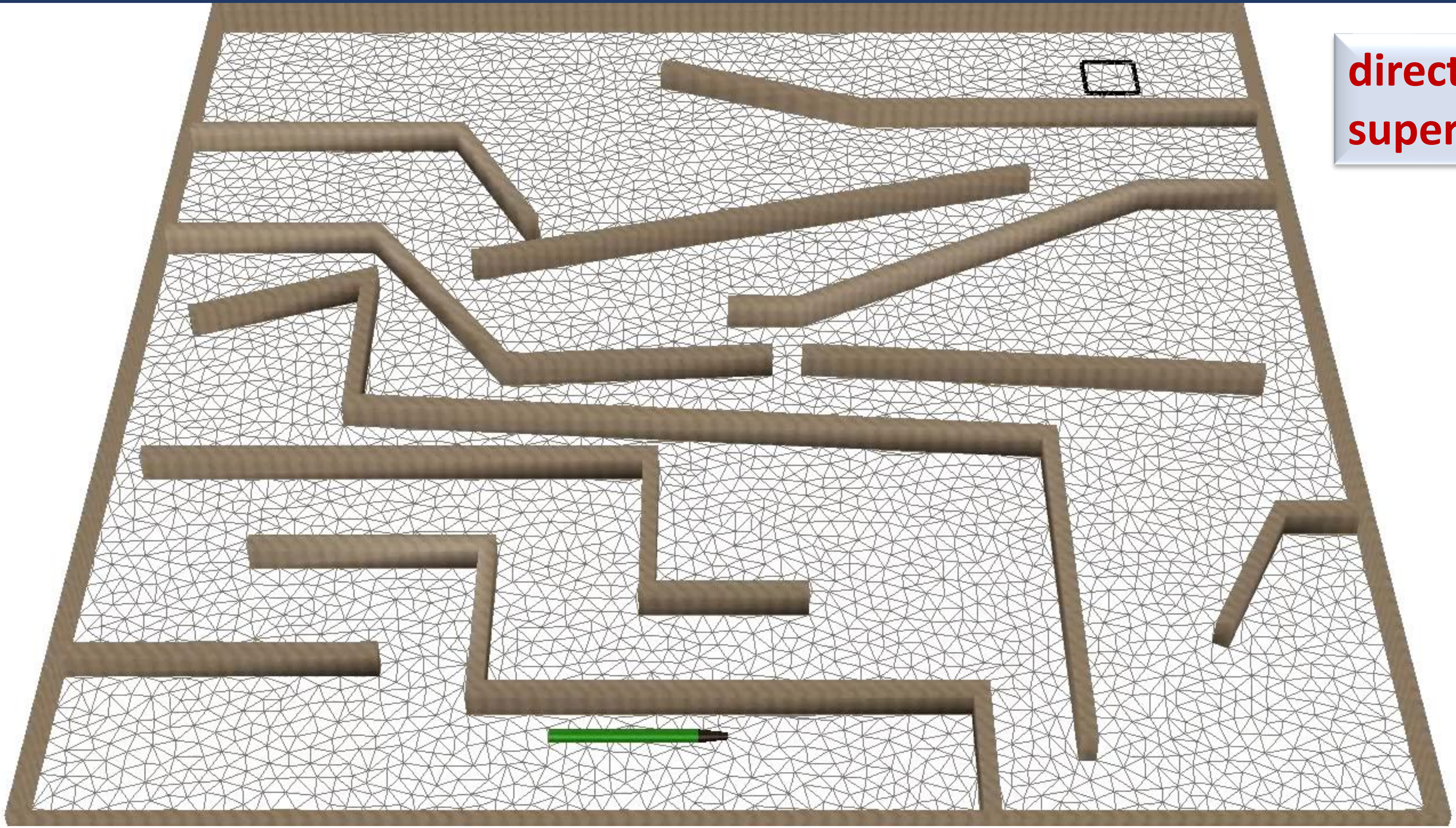
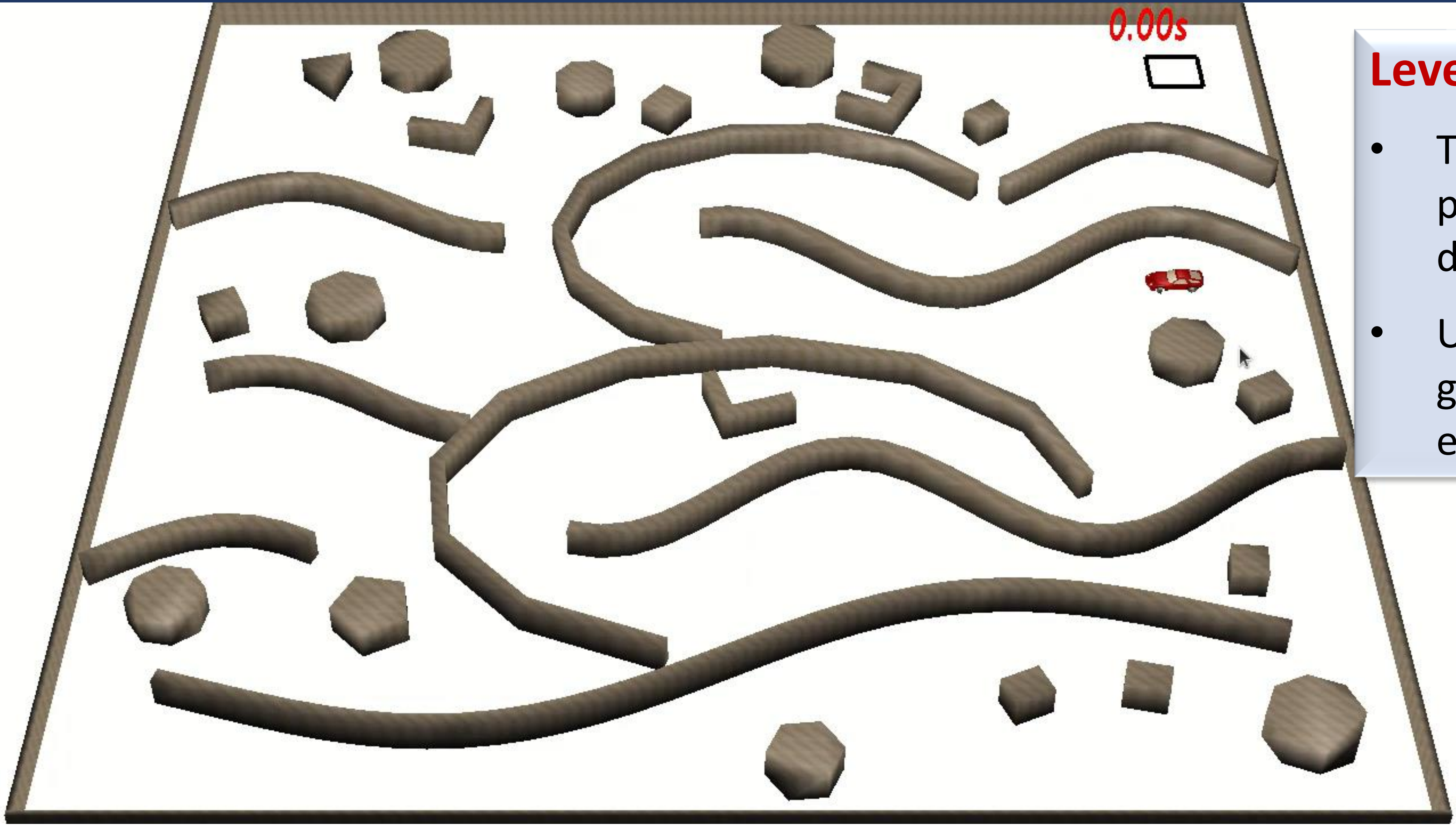


direct path superfacets

Framework: Enhancements/Improvements

clearance-driven motion planning

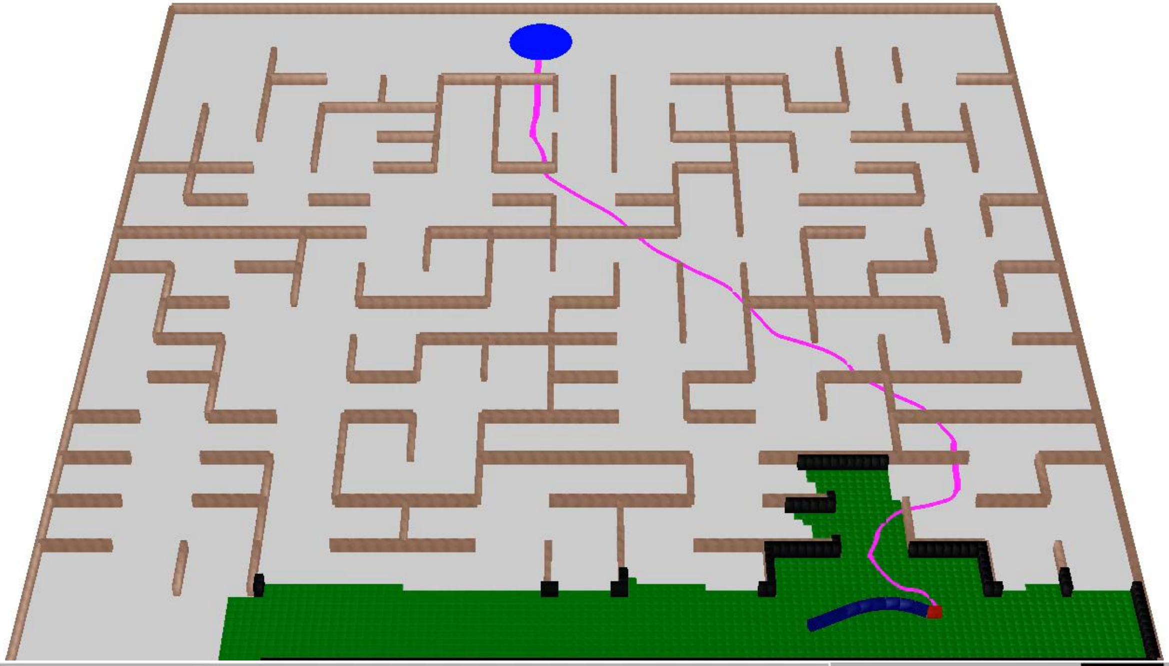
Framework: Enhancements/Improvements

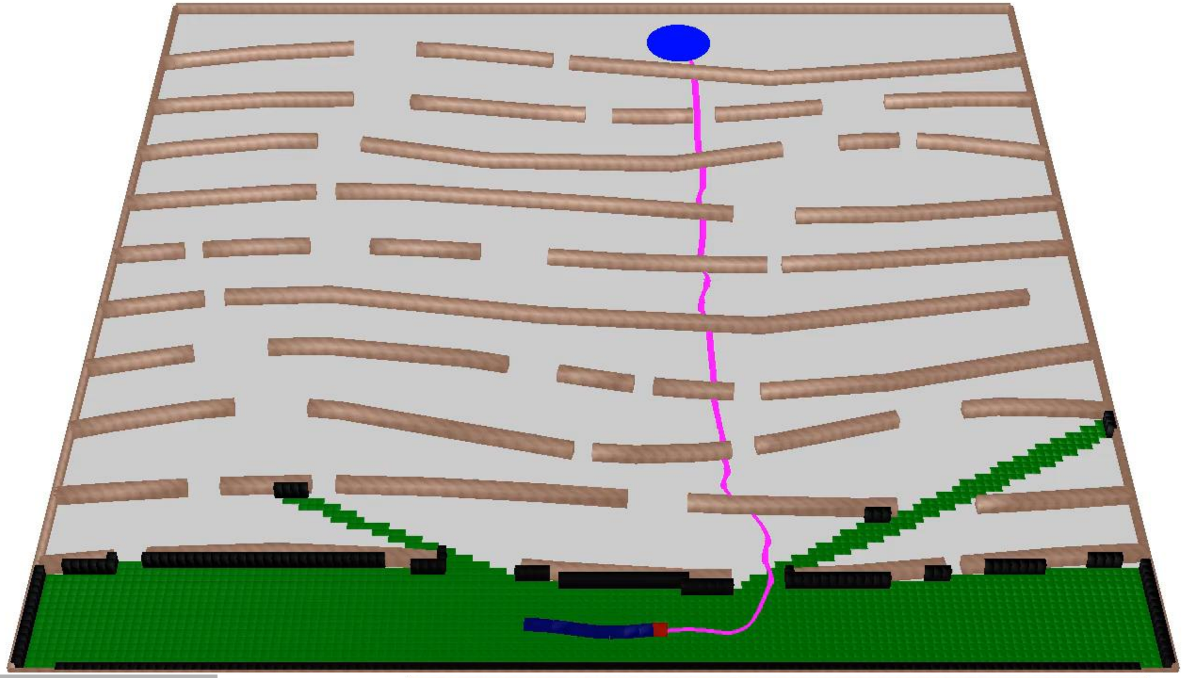


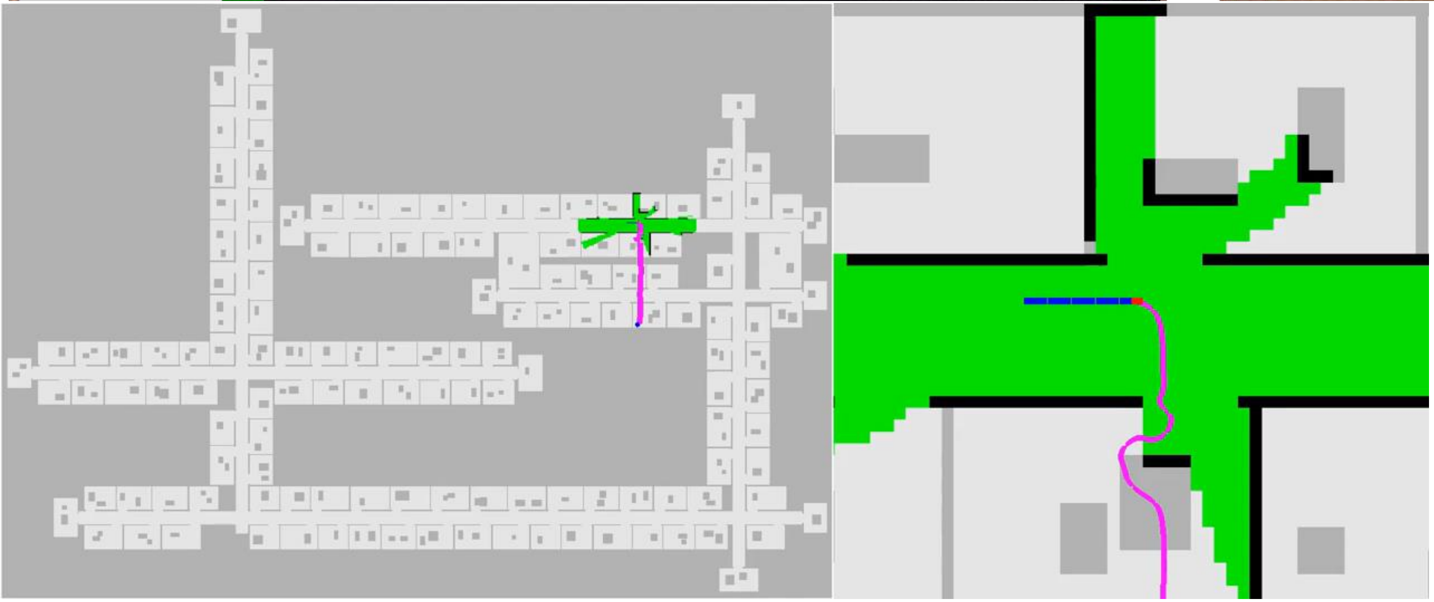
Leveraging ML

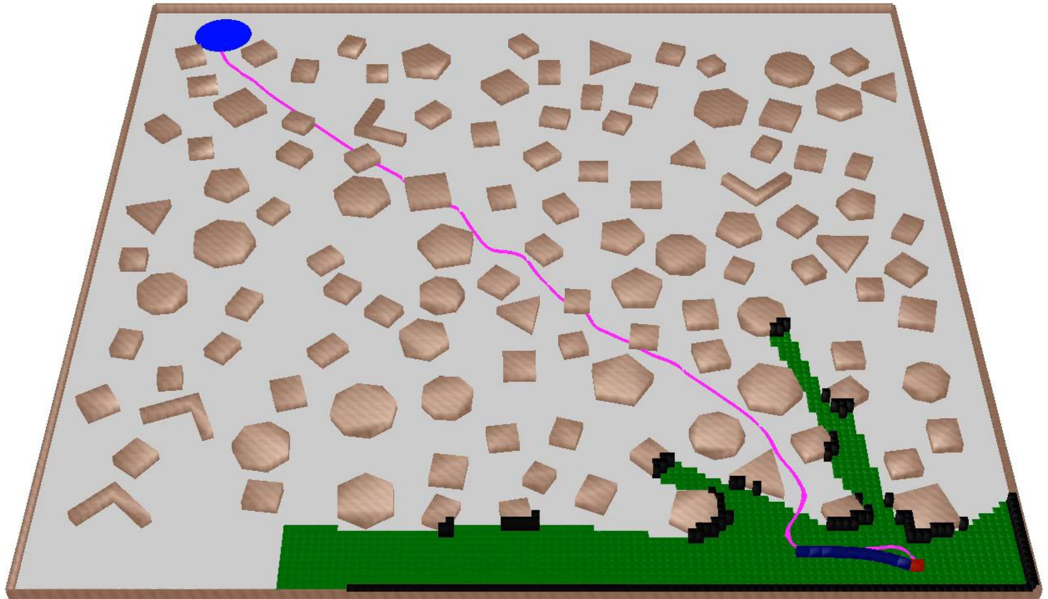
- Train model to predict problem difficulty
- Use predictions to guide motion tree expansion

Motion Planning in Unknown Environments









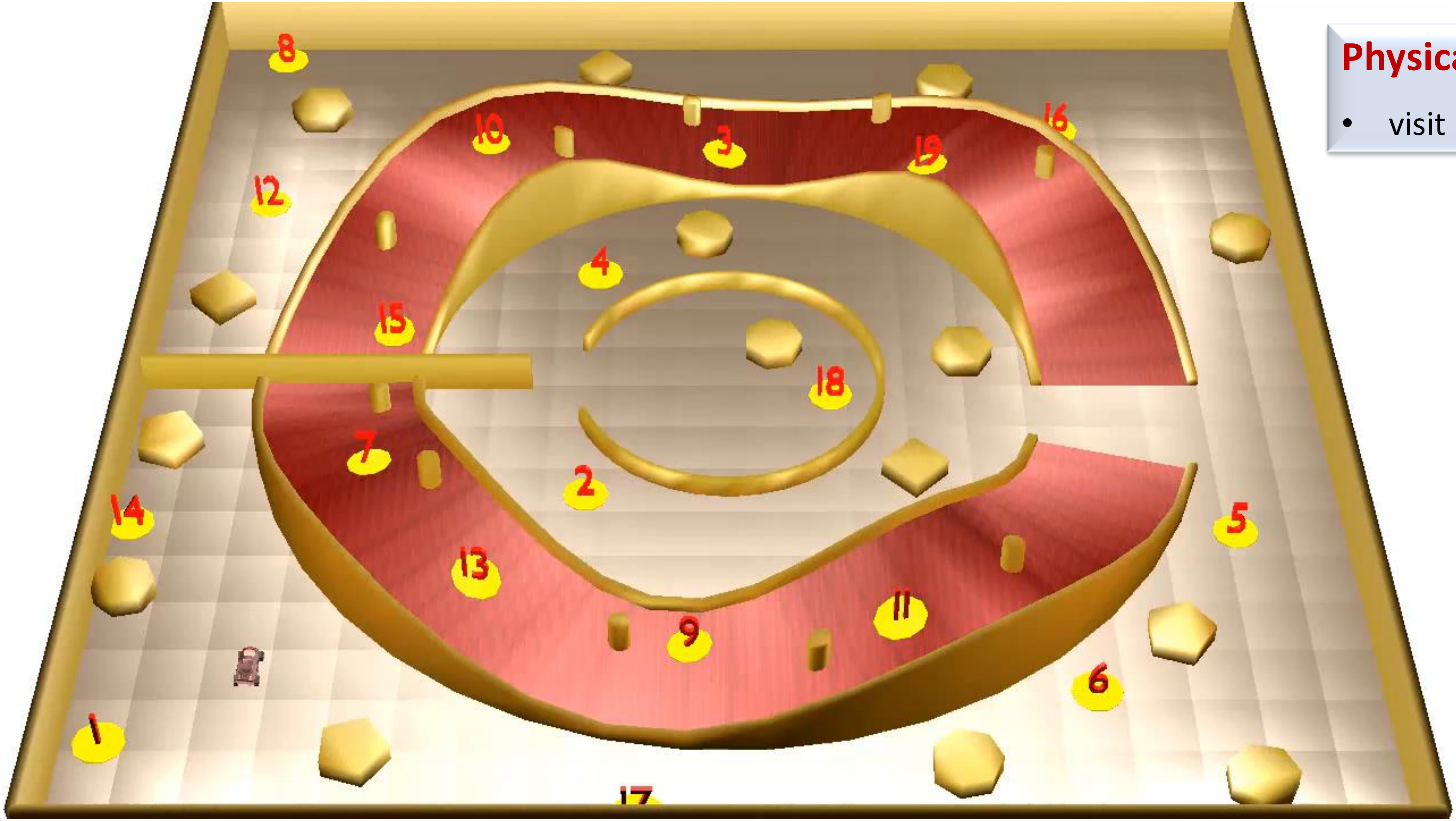
Summary of Motion-Planning Capabilities

- Ground, aerial, and marine robots
- High-dimensional nonlinear dynamics
- Differential equations or physics-based engines
- Unstructured, obstacle-rich, and even unknown environments
- Any cost/risk metric
- Real-time planning
- Speedups of one to two orders of magnitude over related work

Selected Publications for
Motion Planning with Dynamics:

- IEEE Intl Conf on Automation Science and Engineering (CASE), 2023
- IEEE Intl Conf on Intelligent Robots and Systems (ICRA), 2022
- IEEE Intl Conf on Automation Science and Engineering (CASE), 2022
- Robotica, 2018
- IEEE Robotics and Automation Letters (RAL), 2017
- IEEE Trans on Robotics (TRO), 2015
- Springer LNCS Towards Autonomous Robotic Systems, 2015 (**Best Student Paper, my undergrad student**)
- IEEE/RSJ Intl Conf on Intelligent Robots and Systems (IROS), 2014

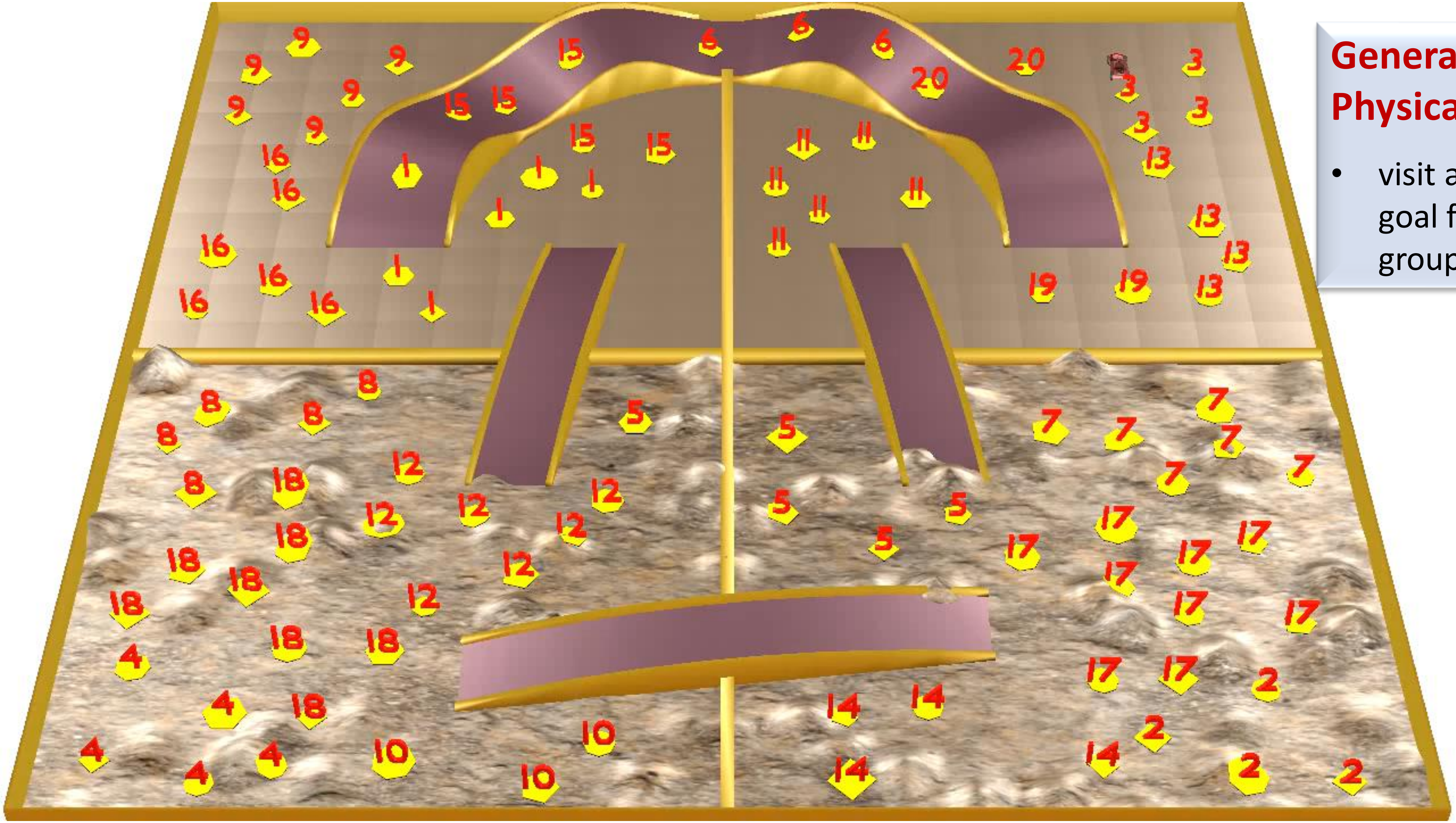
Multi-Goal Motion Planning



Physical TSP

- visit each goal

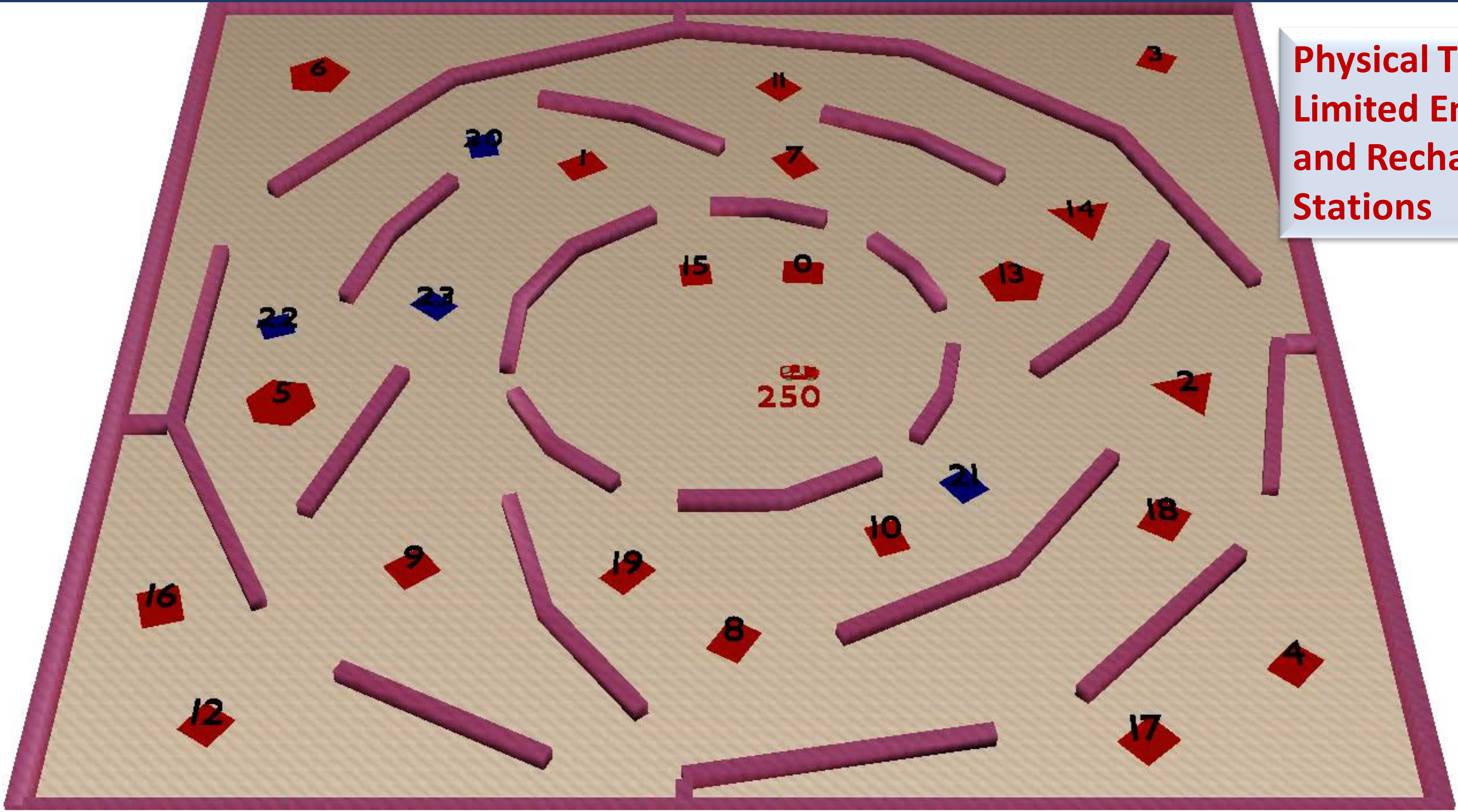
Multi-Goal Motion Planning



Generalized Physical TSP

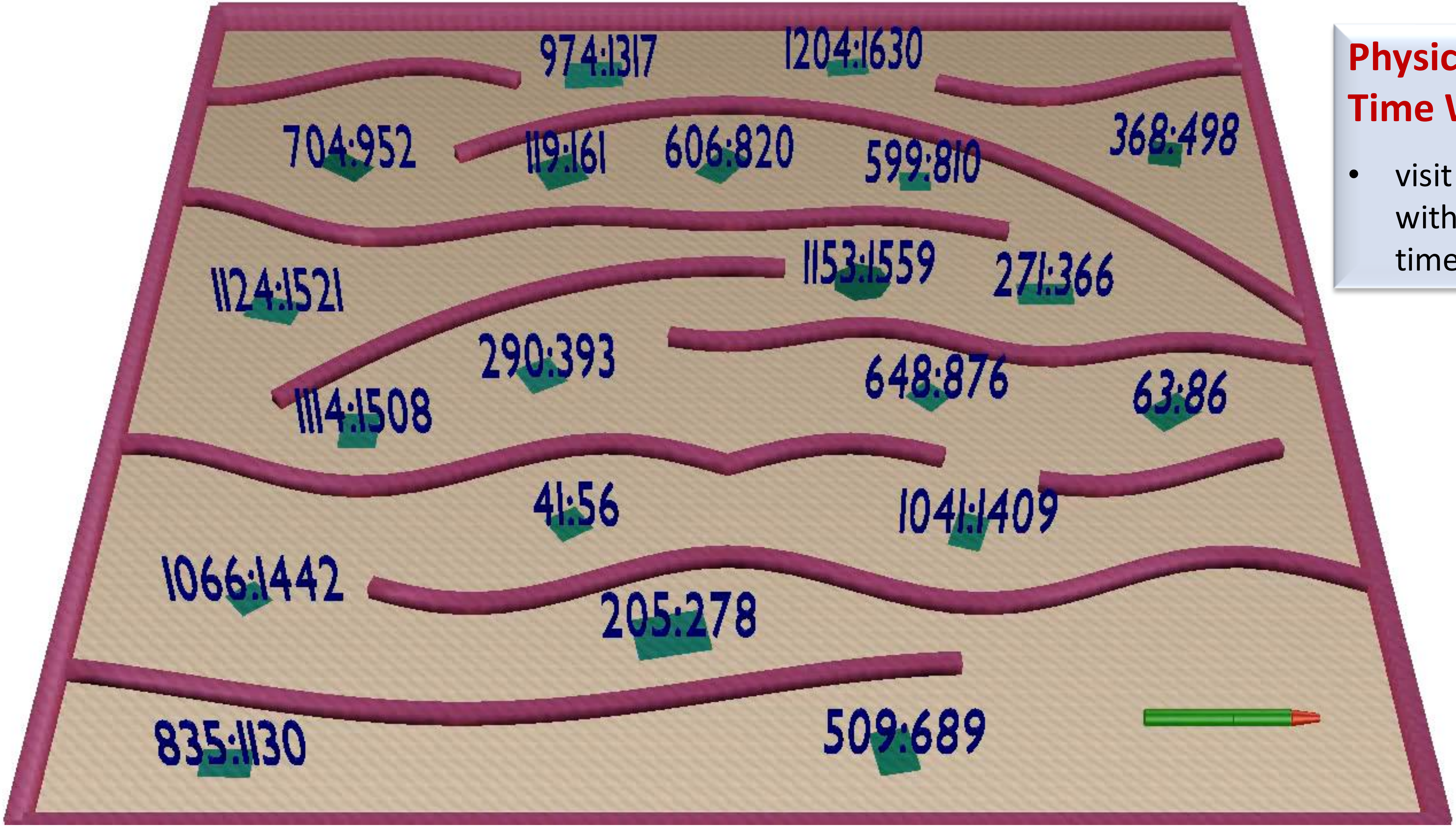
- visit at least one goal from each group

Multi-Goal Motion Planning



Physical TSP with Limited Energy and Recharging Stations

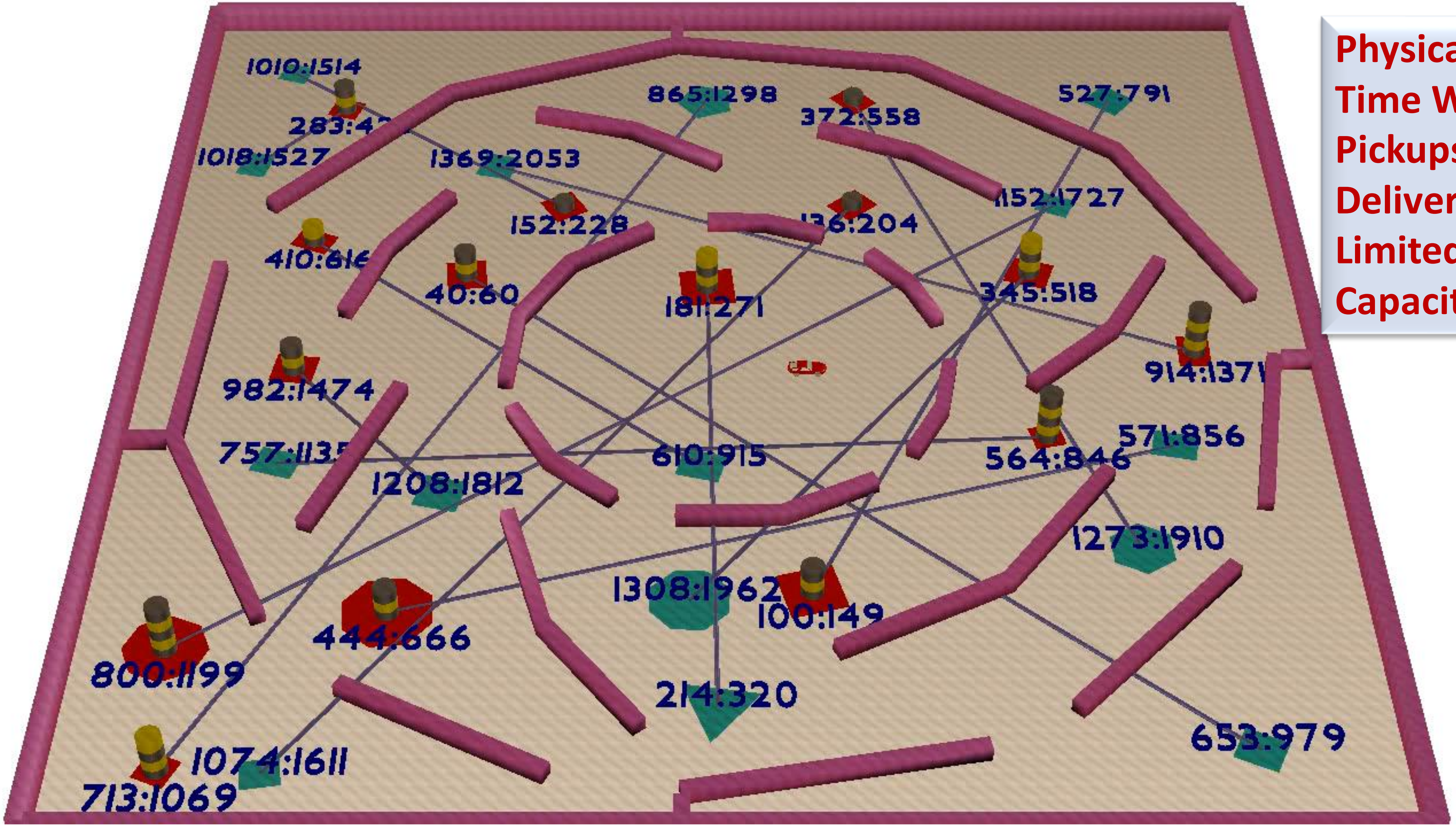
Multi-Goal Motion Planning



Physical TSP with Time Windows

- visit each goal within specified timeframe

Multi-Goal Motion Planning



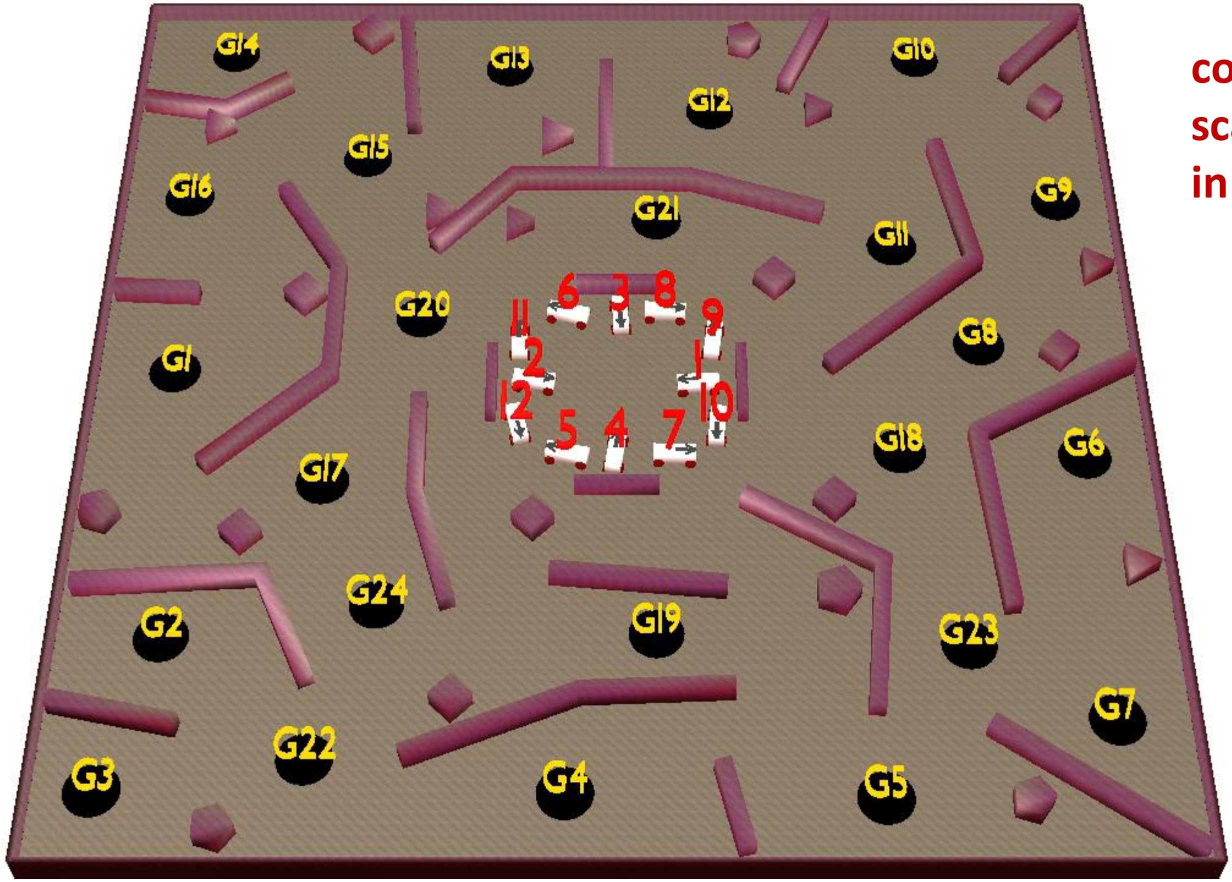
Physical TSP with Time Windows, Pickups, Deliveries, and Limited-Load Capacity

Summary of Multi-Goal Motion Planning

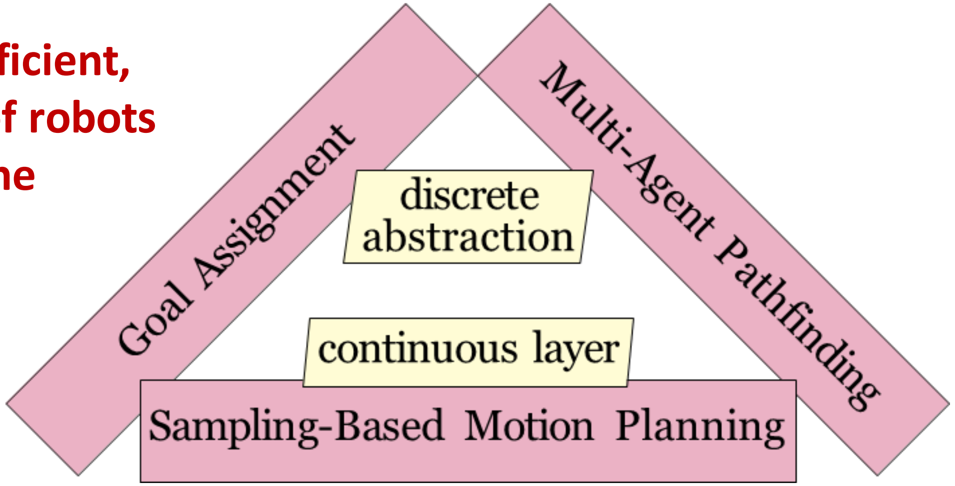
- Physical Traveling Salesman Problem (TSP)
- Generalized TSP
- Physical TSP with Limited Energy and Recharging Stations
- Physical TSP with Time Windows, Pickups, Deliveries, and Limited Load Capacity

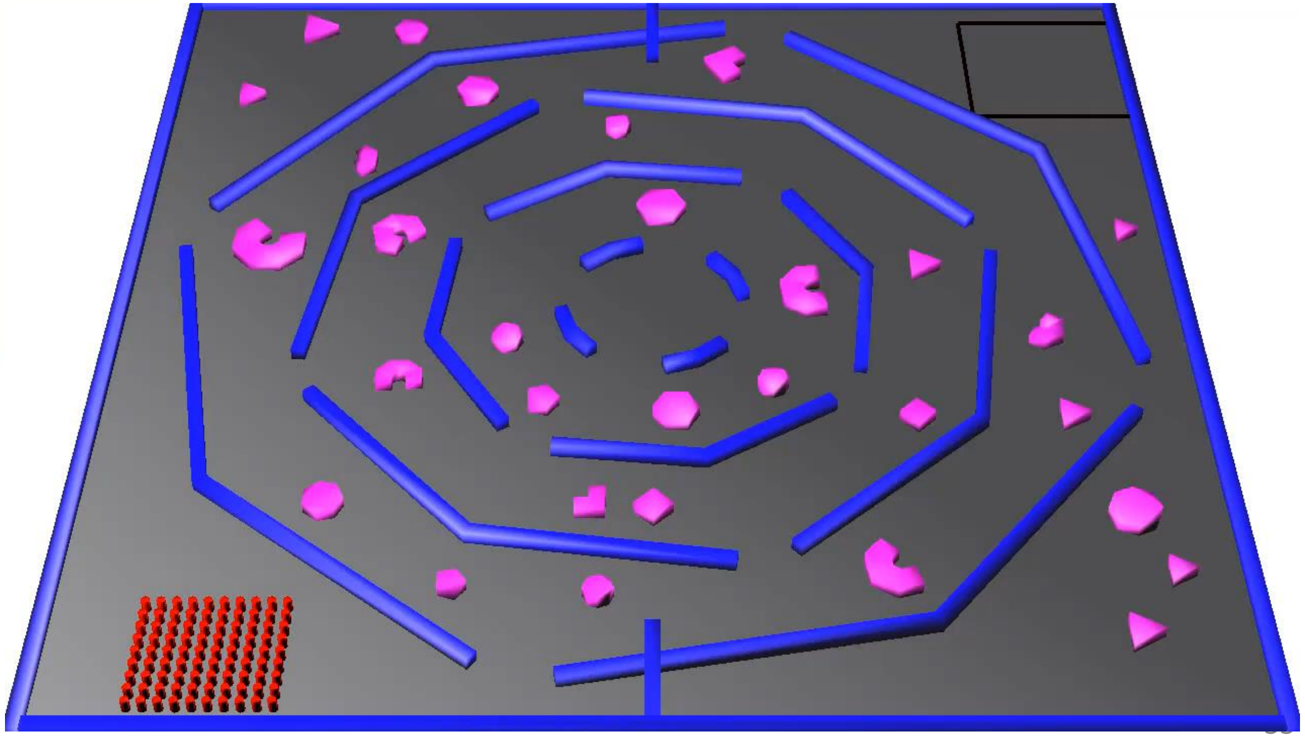
[IEEE Intl Conf on Automation Science and Engineering (CASE), 2020]
[Springer LNCS Advances in AI, 2019]
[IEEE/RSJ Intl Conf on Intelligent Robots and Systems (IROS), 2018]
[IEEE Robotics and Automation Letters, 2017]
[Springer LNCS Towards Autonomous Robotic Systems, 2017]

Multi-Robot Motion Planning



computationally efficient, scaling up to tens of robots in 1-3s planning time





- [IEEE Intl Conf on Robotics and Automation (ICRA), 2021]
- [IEEE Robotics and Automation Letters, 2019]
- [J Artificial Intelligence Research, 2018]
- [Intl Joint Conf on AI, 2018]
- [Intl Conf on Planning and Scheduling, 2017 **(Best Robotics Paper)**]
- [IEEE Trans on Automated Science and Engineering (TASE), 2015]

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Missions via High-Level Languages

Natural Language

- **propositions and predicates to express general statements:** "safe; reached area; measurement taken; object picked up"
- **verbs to express actions relevant to the overall mission:** "move to; inspect; avoid; track; pick up; release"
- **logical connectives to combine multiple objectives:** "and; or; not; if; if and only if"
- **temporal connectives to express objectives along time spans:** "next; always; eventually; until; time intervals"
- **preconditions and postconditions to express effects of actions**
- **sentences formed by combining propositions/predicates/verbs with logical/temporal connectives**

(**always** safe) **and** (**eventually** inspect areas A1, A2, . . . , An **and** (**if** damage detected **then** take pictures or attempt repair)) **and** (next return to the base)

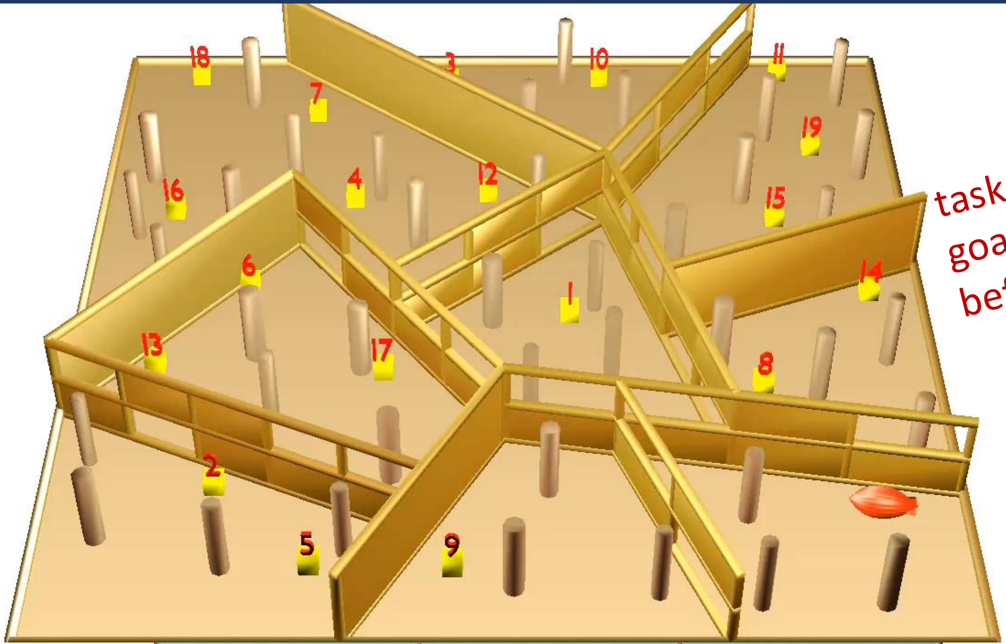
(**for each** package p_i: pickup p_i whose weight is w_i from location P_i within time $[t^{start}, t^{end}]$ **and** deliver to location D_i within time $[T^{start}, T^{end}]$) **and** do not exceed max weight capacity C **and** reduce time to complete deliveries and distance traveled

Formal Models

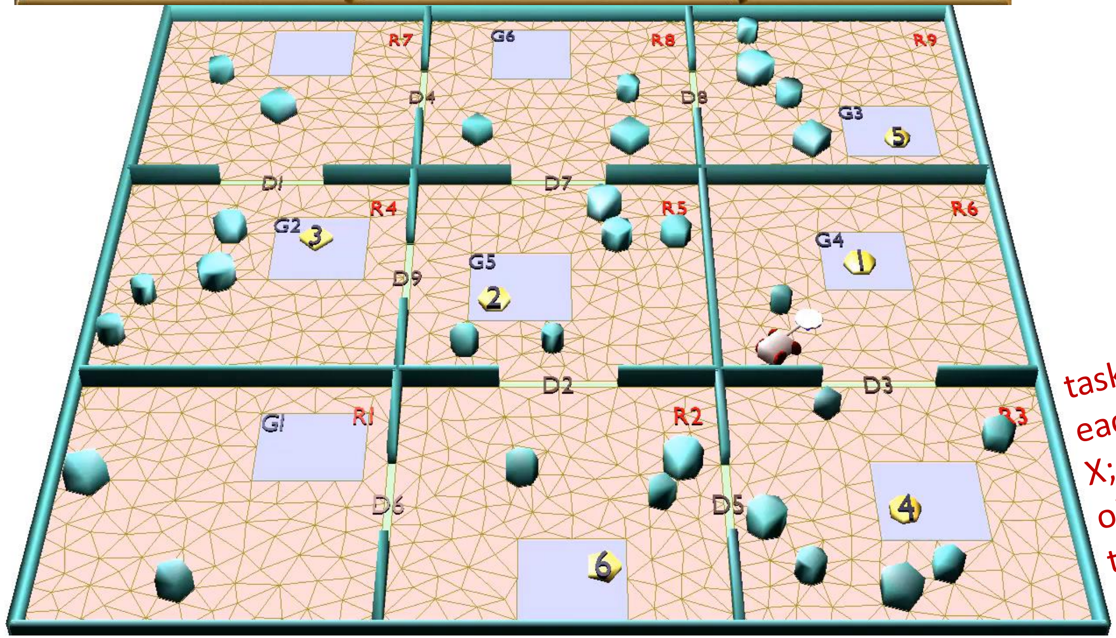
- **Regular Languages (RL)**
- **Linear Temporal Logic (LTL)**
- **Signal Temporal Logic (STL)**
- **Planning-Domain Definition Languages (PDDL)**

Combined Task/Mission and Motion Planning

- Framework tightly couples AI, Motion Planning, and Control
- Enables robots to complete high-level missions on their own
- Missions given by Regular Languages, Linear Temporal Logic, PDDL



task: visit goals 1-10 before 11-20



task: pick and place each object X in goal X; when carrying an object go only through empty rooms

Complex Tasks
- Regular Languages
- Linear Temporal Logic
- AI Languages

Complex Systems
- High-dimensional
- Nonlinear dynamics
- Ground, aerial, marine robots

task specification → PLANNING ← robot model
world model → PLANNING

PLANNING → collision-free and dynamically-feasible trajectory that enables the robot to accomplish its task

Discrete Planning Layer
- High-Level Reasoning
- AI, Logic

SYNERGISTIC COMBINATION

Continuous Planning Layer
- Sampling-based Motion Planning
- Motion Control

[IEEE Trans on Automation Science and Engineering (TASE), 2022]
[IEEE Intl Conf on Automation Science and Engineering (CASE), 2021]
[IEEE Intl Conf on Robotics and Automation (ICRA), 2021]
[Robotica, 2017]
[J of Experimental and Theoretical Artificial Intelligence, 2016]
[AI Communications, 2015] [IEEE/RSJ Intl Conf on Intelligent Robots and Systems (IROS), 2013]

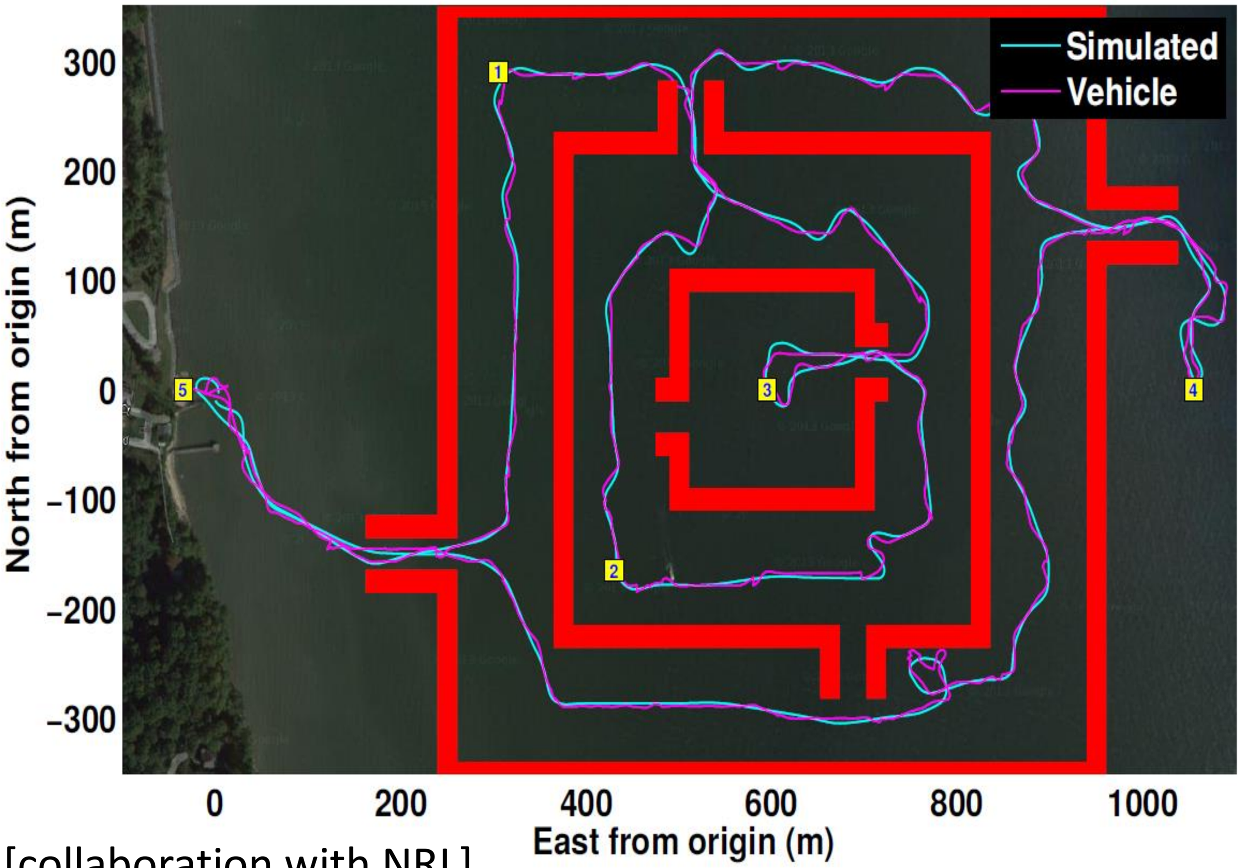
Autonomous Surface and Underwater Vehicles

Pursuing research toward long-endurance missions

Adaptive mission and motion planning to enhance autonomy of marine vehicles

[collaborations with NRL, Australian Defence Science and Technology Group

Complex Missions via Linear Temporal Logic



[collaboration with NRL]

Field Testing at NRL Chesapeake Bay Detachment

- Mission duration ≈ 2 hours

Ocean Server Iver-2

- 55-inch length
- 5.8-inch diameter

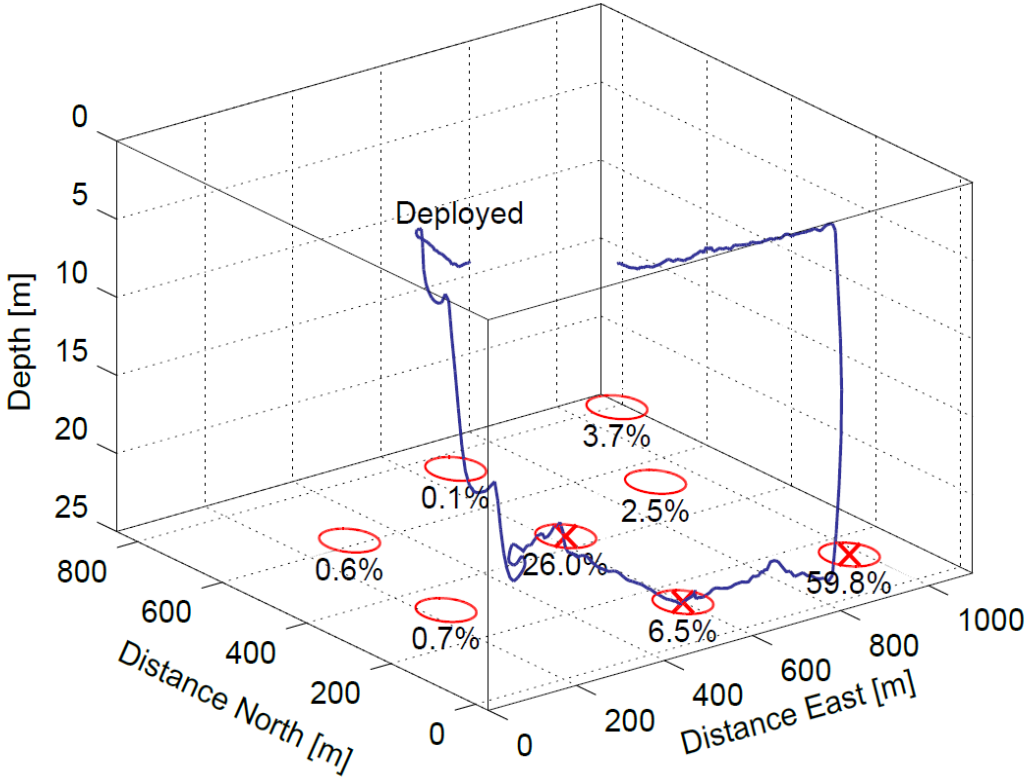
Enable AUV to avoid collisions and complete complex missions given by Linear Temporal Logic

Mission examples:

- Sequencing (goals in order)
- Coverage (goals in any order)
- Partial ordering (some goals before others)
- Group coverage (all goals in a group before moving on to the next group)
- …

[IEEE Journal of Oceanic Engineering, 2016] [NRL Review, 2015] [MTS/IEEE Oceans, 2015] [Springer LNCS Towards Autonomous Robotic Systems, 2014]

Autonomous Data Collection with Limited Time



- **Enable AUV to reach several locations within a given time bound**
- **Each region of interest has a reward associated with it**
- **When not all regions can be reached, maximize overall reward**

Bluefin-21 Heavyweight AUV

- 18-hour endurance at 2.5 kts
- 314-inch length
- 21-inch diameter
- DVL & INS navigation

Field Testing at Boston Harbor

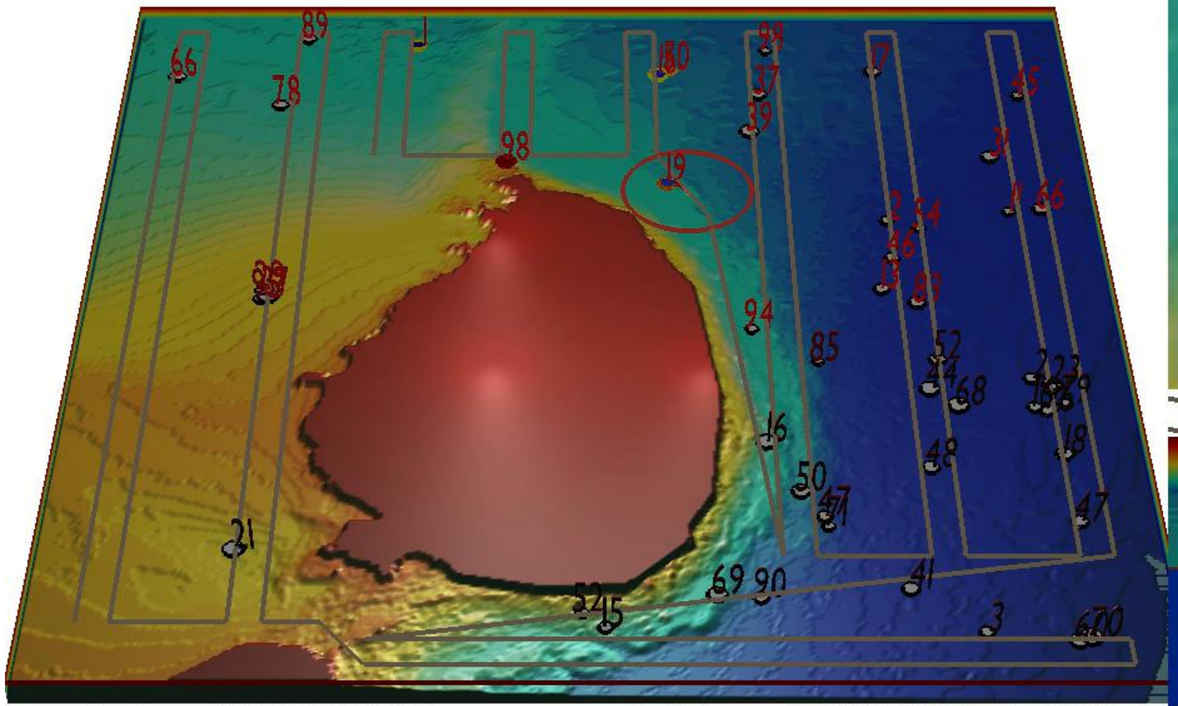
- Upper bound on mission duration is 42 minutes
- Each circle represents a target location
- Reward associated with each target
- Radius represents the distance required to sample data from target

[IEEE Robotics and Automation Letters, 2016]

[collaboration with NRL]

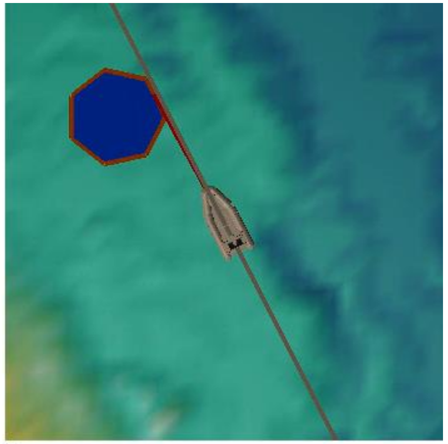
Simultaneous Survey and Inspection with Communication Constraints for Teamed Autonomous Marine Vehicles

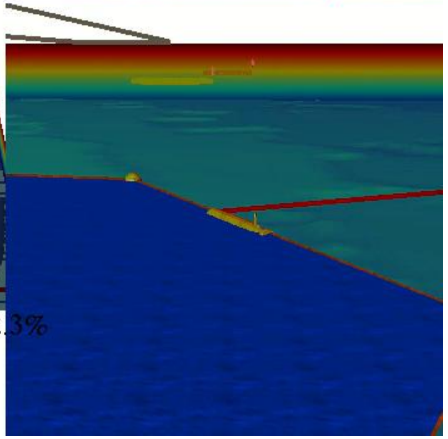
Marine Robotics



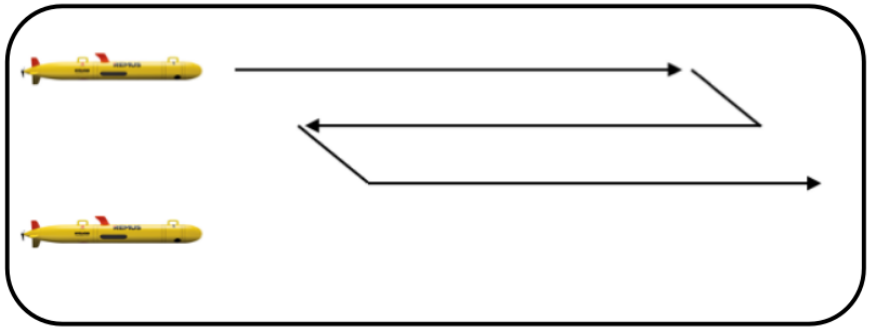
execution time: 22800.8s/25578.5s collected reward: 2213/2397/2397 : 92.3% : 92.3%

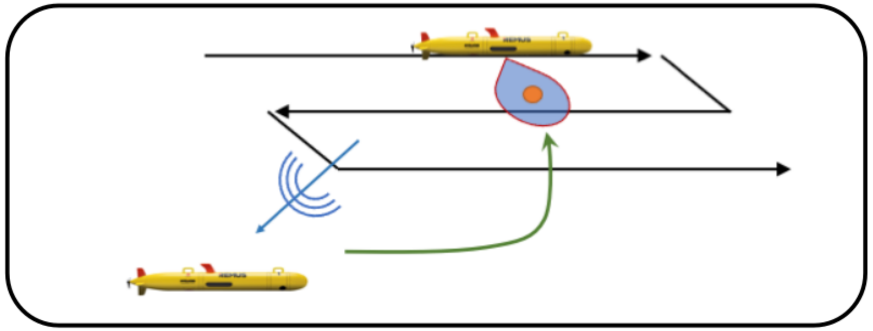
[USV speed: 1m/s] [AUV desired speed: 1.50m/s] [communication range: 130m]

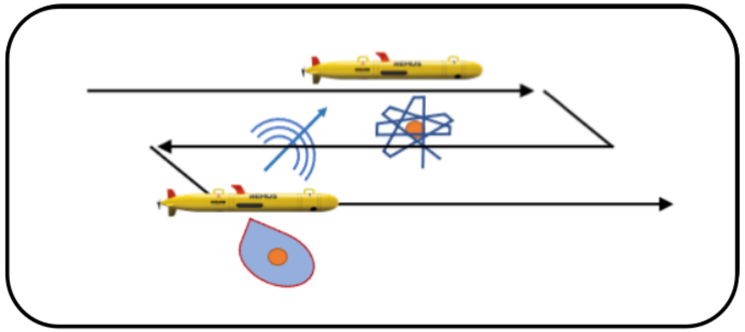




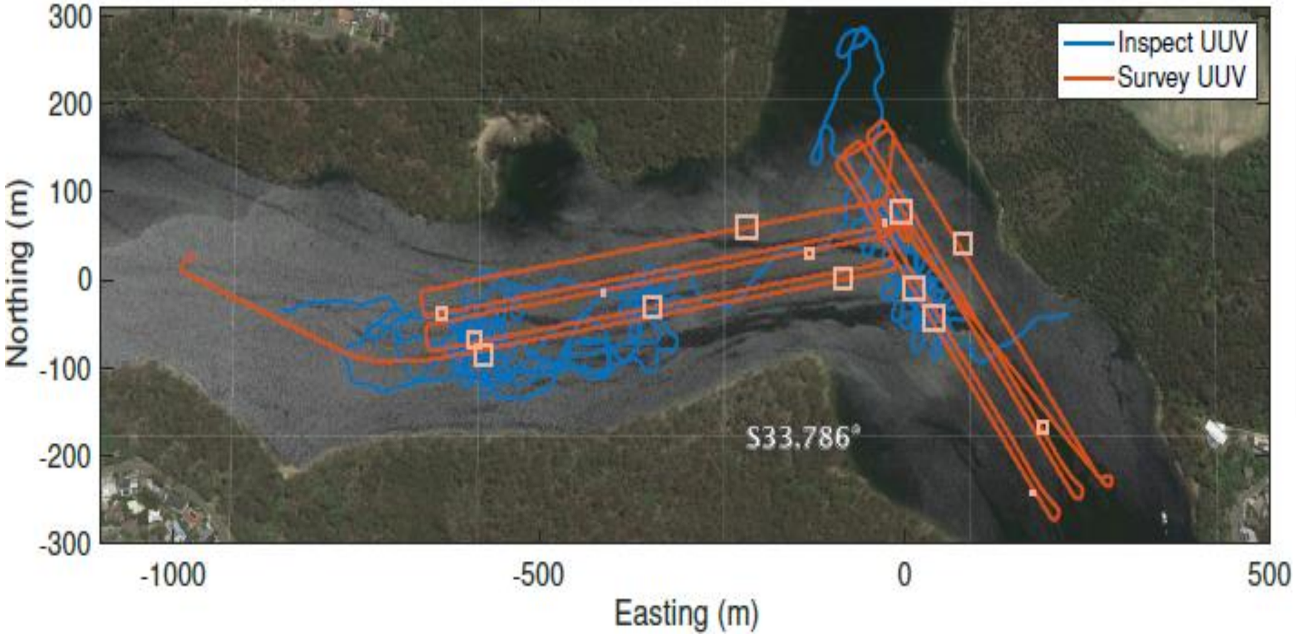
- Survey vehicle
  - moves along pre-planned path
  - uses its on-board sensors to detect objects of interest
  - acoustically communicates locations and rewards to Inspection vehicle
- Inspection vehicle seeks to inspect detected objects, seeking to maximize total reward
- Survey and inspection vehicles must be in communication range at all times



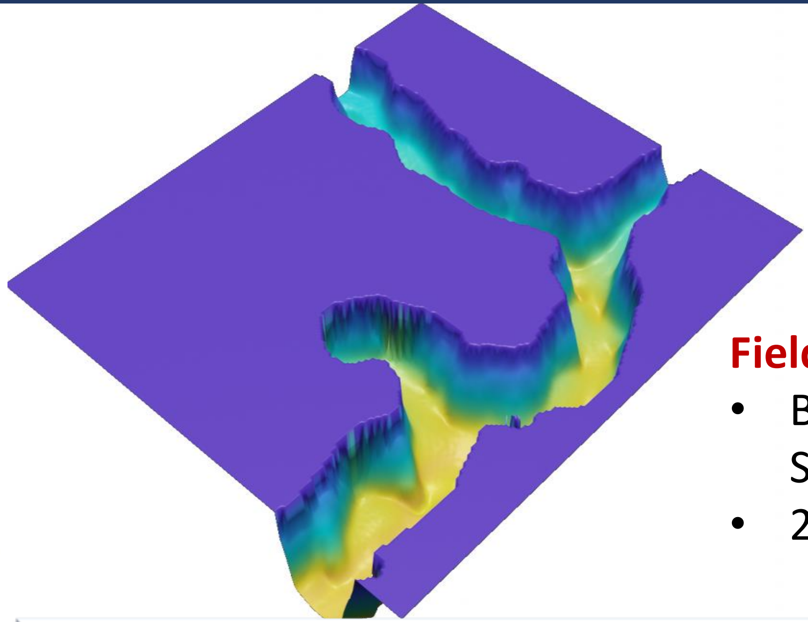




Simultaneous Survey and Inspection with Communication Constraints for Teamed Autonomous Marine Vehicles



[collaboration with NRL and Australian Defence Science and Technology Group]



Field Experiments:

- Bantry Bay within Sydney Harbor
- 2 Remus 100 AUVs

- How can the planner ensure that the Inspection vehicle always stays within the communication range of the Survey vehicle?
- How can the planner determine the order in which to inspect goals as they are detected and reported by the Survey vehicle in real time so as to increase the sum of the rewards?
- How do we plan efficiently to support real-time applications?

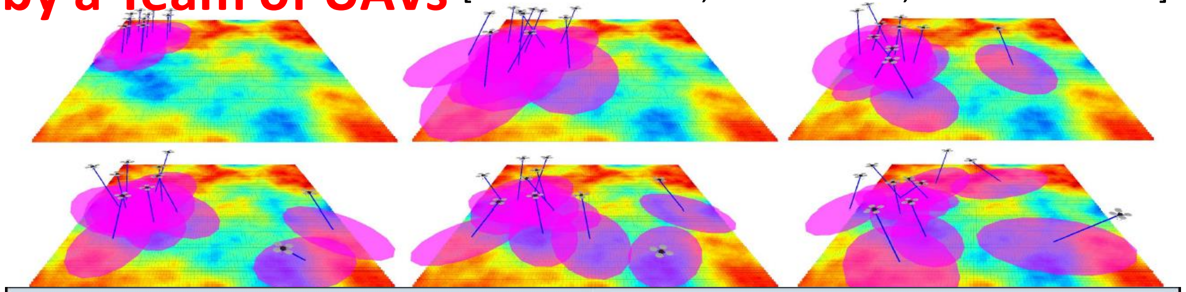
- [IEEE/RSJ Intl Conf on Intelligent Robots and Systems (IROS), 2023]
- [IEEE Trans Automation Science and Engineering (TASE), 2022]
- [IEEE Intl Conf Automation Science and Engineering (TASE), 2021 **(Finalist Best Application Paper)**]
- [IEEE Intl Conf Robotics and Automation (ICRA), 2021]

Autonomous Inspection and Persistent Surveillance

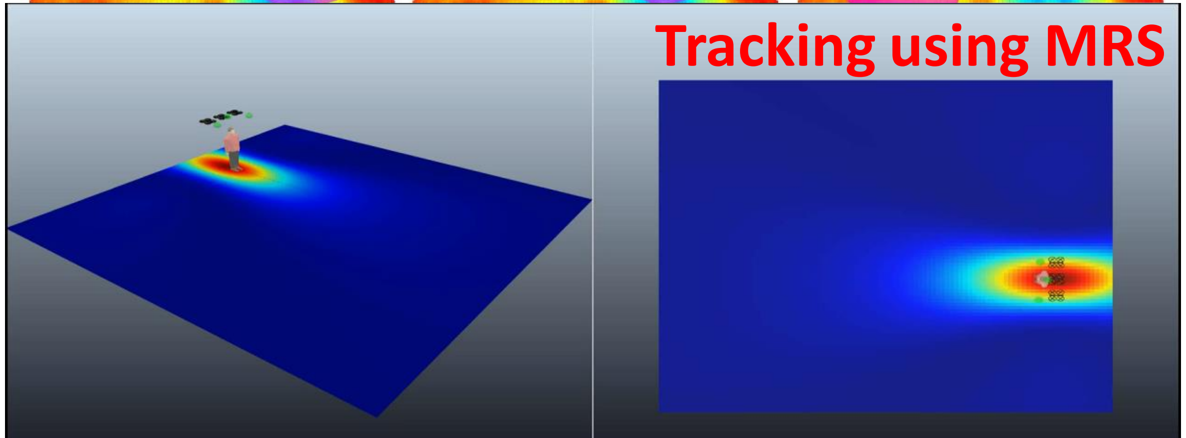
Search-and-find

Persistent Surveillance of Risk-Sensitive Areas by a Team of UAVs

[IEEE TASE 2014; TAROS 2014; Swarm Int 2013]

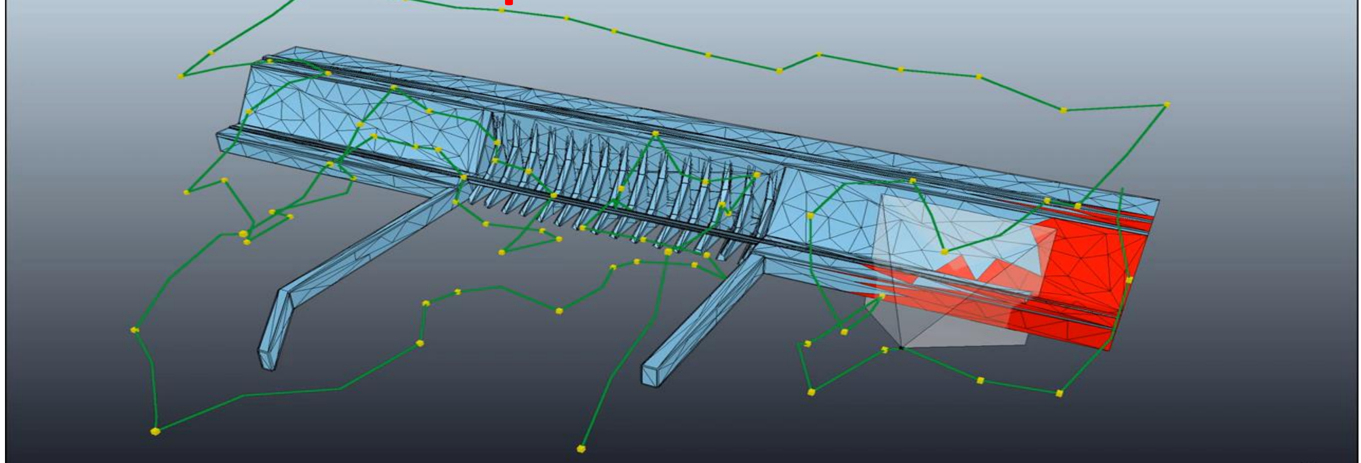


Tracking using MRS



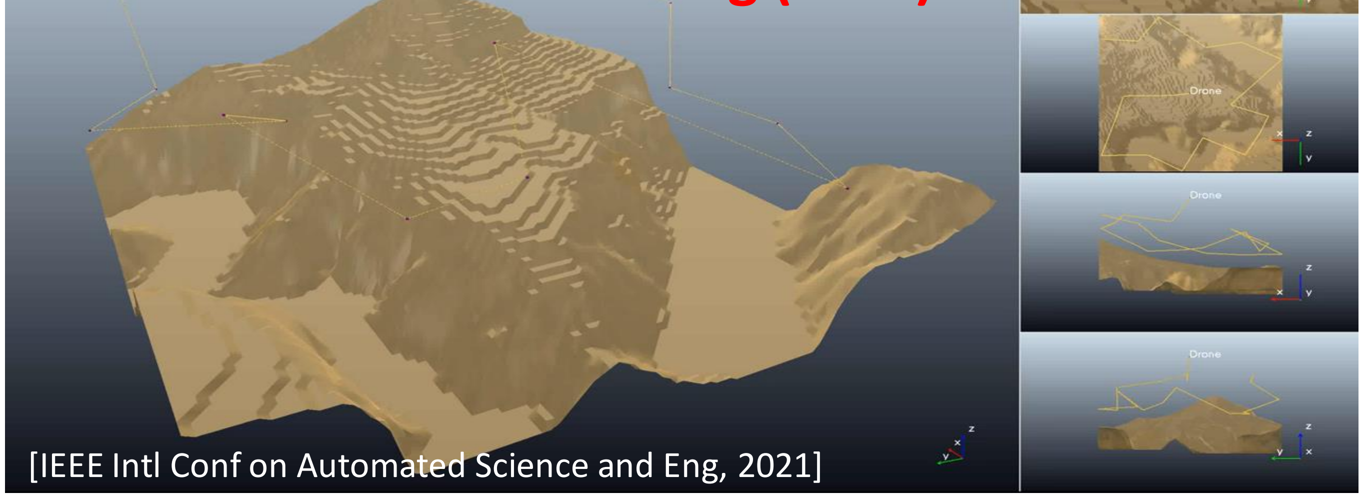
[USNC-URSI National Radio Science, 2017]

Camera-based Inspection of 3D Structures



[Springer LNCS Towards Autonomous Robotic Systems, 2017]

Inspection of Nonflat Terrains via Microwave Remote Sensing (MRS)

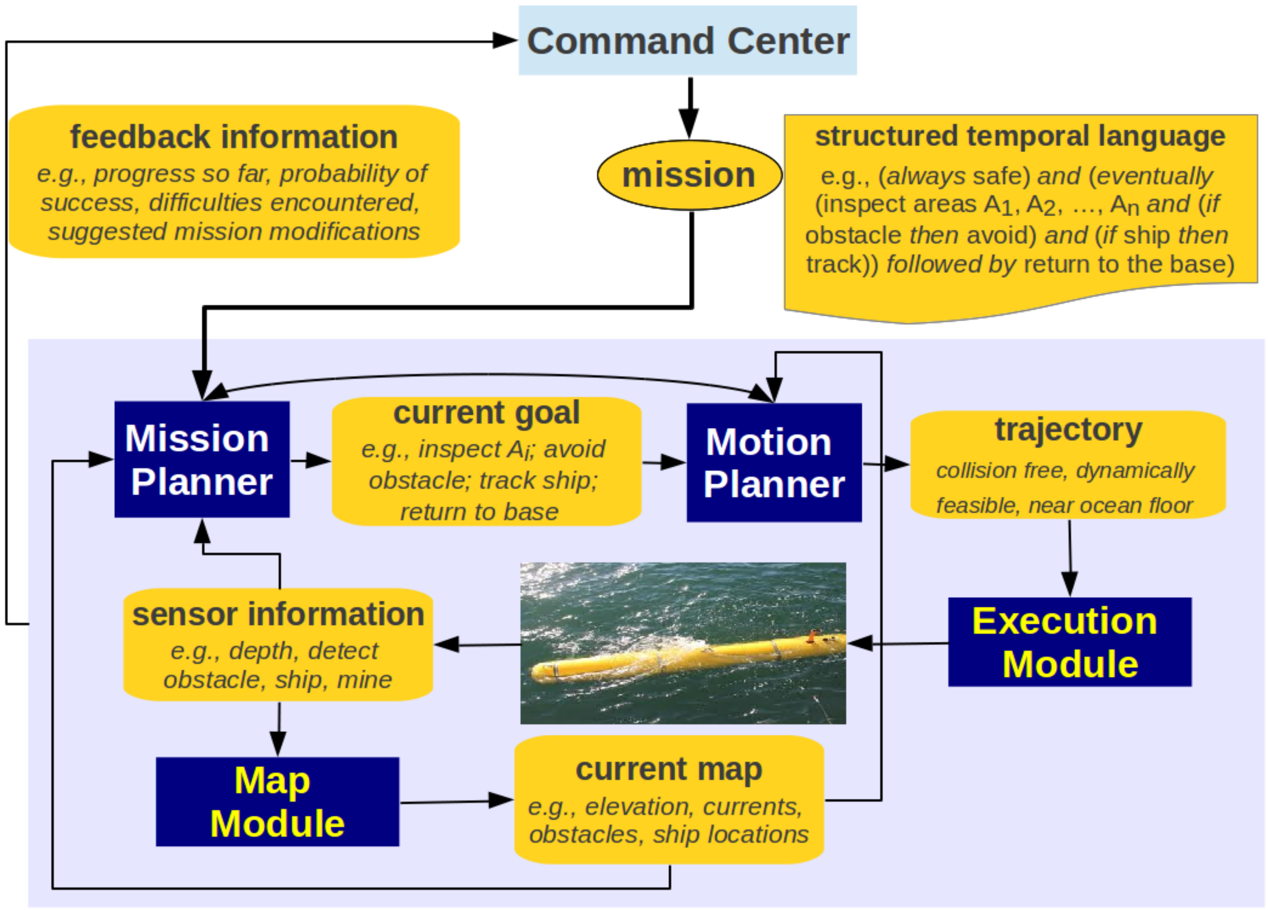


[IEEE Intl Conf on Automated Science and Eng, 2021]

Research Theme: Supervised Autonomy

- **Autonomous Navigation in Unstructured Environments**
  - How can we enable robots to plan their own dynamically-feasible motions to successfully navigate in unstructured environments?
- **Task-Level Autonomy**
  - How can we make robots more capable to complete complex tasks on their own?
- **Human-Machine Collaboration**
  - How can we alleviate the cognitive workload placed on human supervisors working with a team of robots?
  - How can the robots interact with their human supervisors to provide feedback and incorporate new objectives?

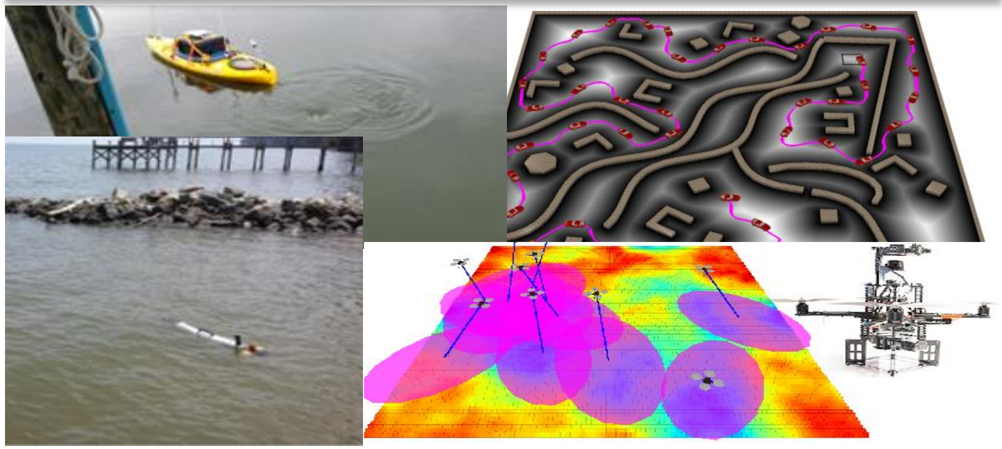
Human-Machine Collaborations



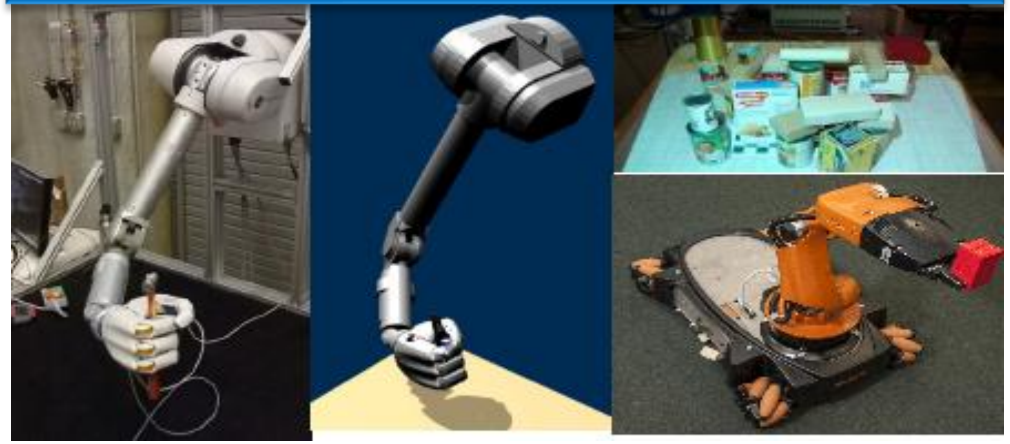
- Interaction with human supervisors: Essential to effectively handle challenges that arise when operating in complex domains
- The robot team will adapt its plans based on difficulties that it encounters or new information that it gathers
- Human supervisors will also be able to modify the overall mission or specify additional tasks based on the feedback information provided by the robot team

Enhancing Autonomy and Providing Assistance in Human-Machine Cooperative Tasks

Ground/Aerial/Marine Robotics



Sensor-based Manipulation



Medical Robotics

Da Vinci Surgical System,
© Intuitive

Cyber-Physical Systems