COE CST Third Annual Technical Meeting:

Autonomous Rendezvous and Docking: Rapid Trajectory Generation

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COE CST
Center of Excellence for Commercial Space Transportation

Overview

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Team Members

- Emmanuel Collins, PI
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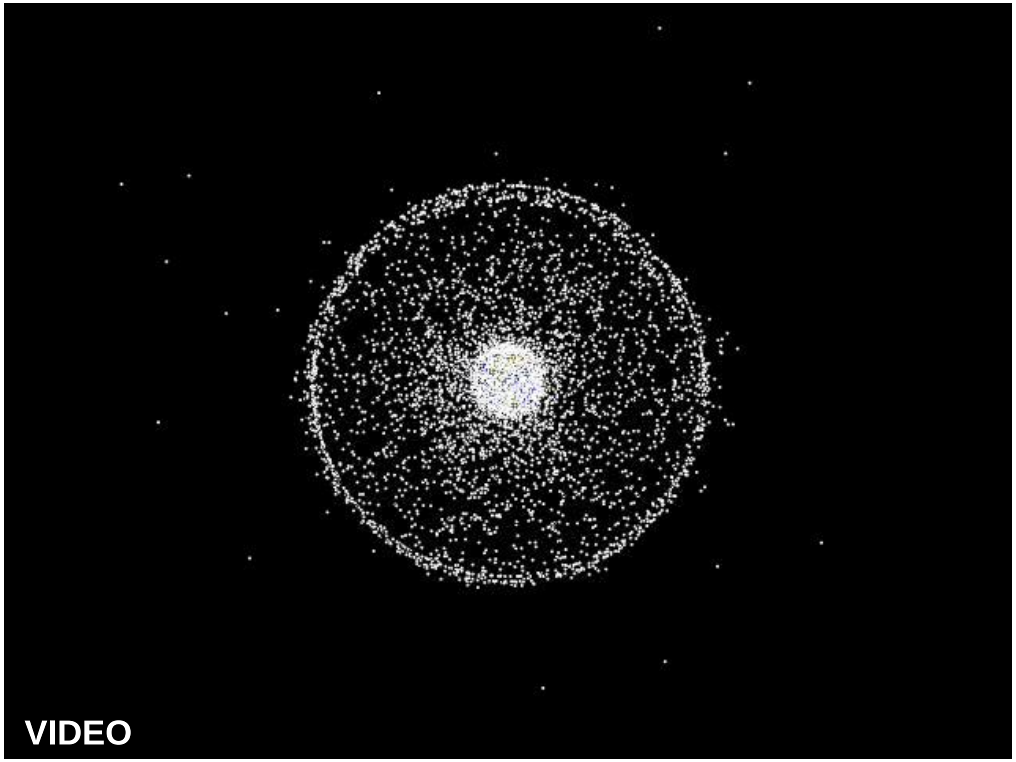
Center for Intelligent Systems, Control, and Robotics

Purpose of Task

Purpose: As indicated by recent NASA study, there is an immediate need to develop orbital debris mitigation technology.

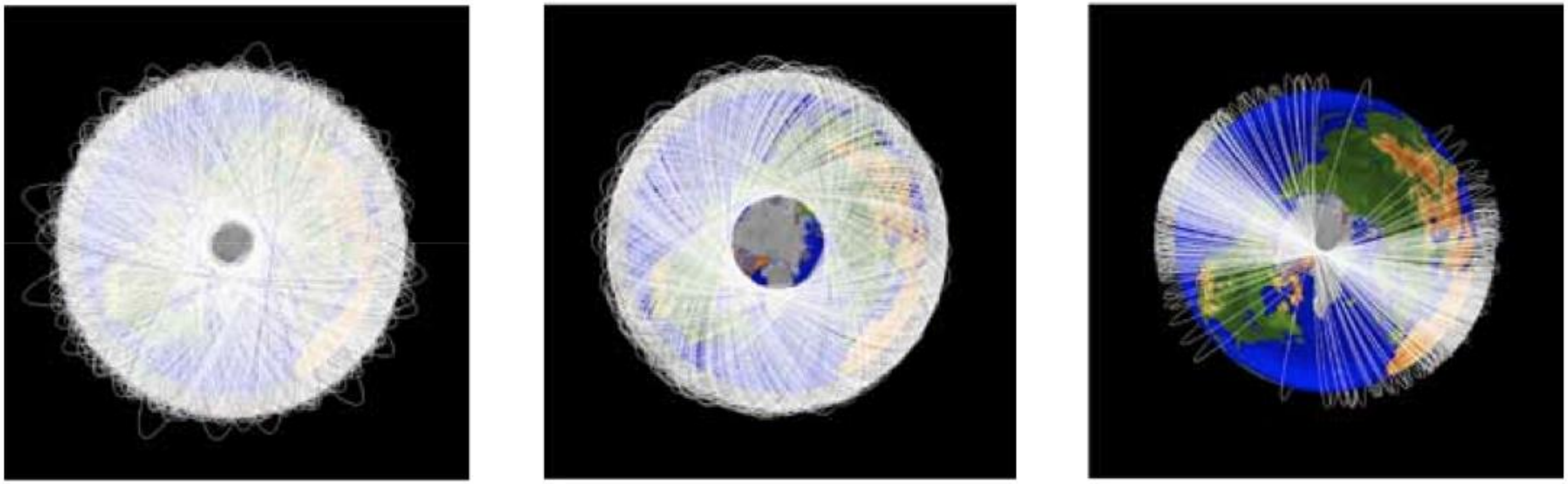
- A promising solution for direct debris removal is the development of a "Space Tow Truck."
- Requires automated guidance to approach targeted debris.



Debris in motion: about 95% of these currently tracked objects in orbit are debris and not functional satellites. (NASA Orbital Debris Program Office)

Purpose of Task

Objective: Develop the technology for rapid (within a few seconds), onboard generation of dynamically feasible trajectories that enable a spacecraft to approach a target for docking.



Impact of unmitigated debris: the profiles of three major debris clouds resulting from the January 2007 destruction of the Chinese Fengyun-1C (left) spacecraft and the February 2009 collision between the Russian Cosmos 2251 (middle) and U.S. Iridium 33 (right) spacecraft. (NASA Orbital Debris Program Office)

Purpose of Task

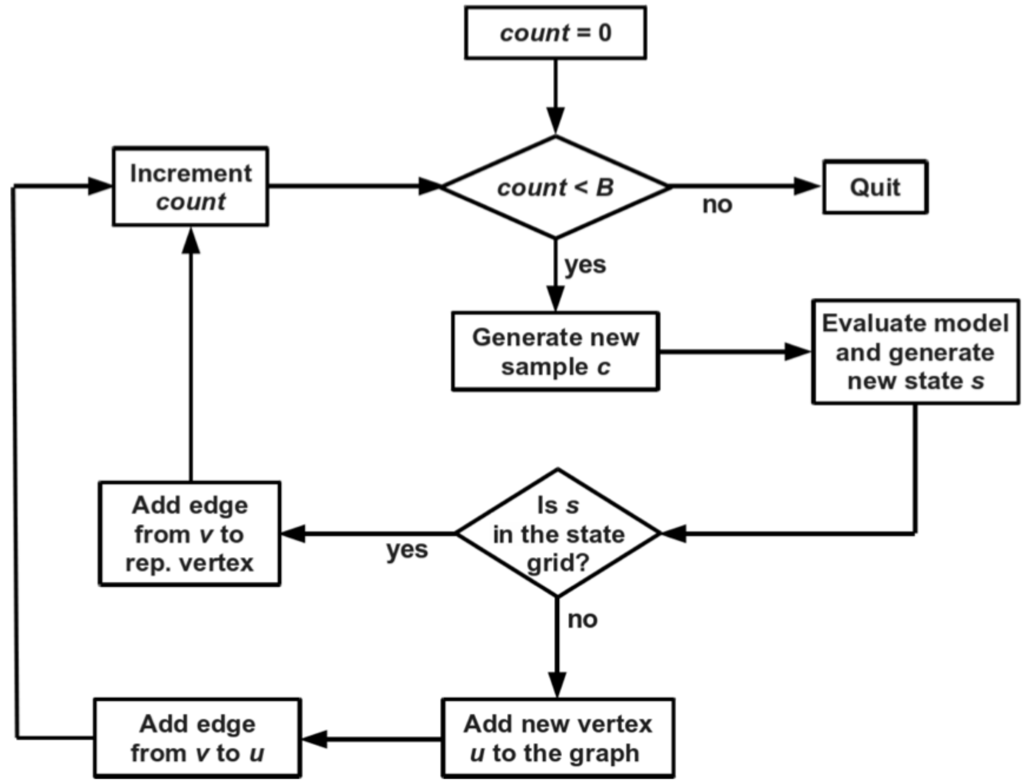
Goals:

1. Develop spacecraft dynamic model for the planner to account for actuator characteristics, vehicle momentum, and power consumption.
2. Use the dynamic model to develop trajectories for effective rendezvous with targets.
3. Optimize trajectories based on relevant metrics such as distance, time, or energy.
4. Rapidly replan trajectories as new information becomes available.

Targeting debris: artistic conceptualization illustrating the challenge of navigating to pursue an object in an orbital environment that is densely occupied. (R. Harris/SPL)

Research Methodology

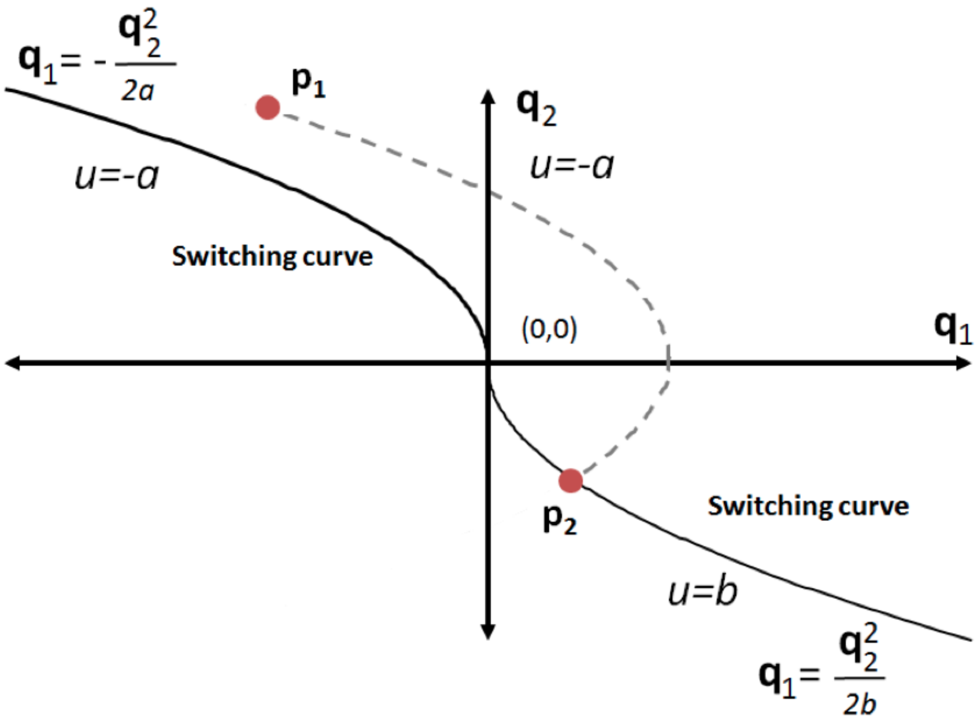
- The primary tool used is **Sampling-Based Model Predictive Optimization (SBMPO)**.
- SBMPO is a graph search method characterized by:
  - Graph that is based on sampling of model inputs;
  - Optimization via A*;
  - Incorporation of dynamic model in planning;
  - Ability to rapidly replan;
  - Generation of trajectories, not simply paths.



Fundamental Steps of SBMPO: (1) Select highest priority vertex in queue. (2) Sample input space. (3) Add new vertex to graph. (4) Evaluate new vertex cost. (5) Repeat 2-4 for defined number of successors. (6) Repeat 1-5 until stopping criteria is achieved.

Research Methodology

- The key to fast computations with SBMPO is the judicious selection of an optimistic heuristic.
  - Optimistic A* heuristic: a rigorous lower bound on the cost from the current node to the goal.
- For example, in a planning scenario requiring a specified velocity at the goal, a heuristic for minimum time optimization can be based upon the solution to the a “simple” time optimal control problem.



Derived from Pontryagin’s Maximum Principle, this minimizing control curve corresponds to the solution of the time optimal control problem.

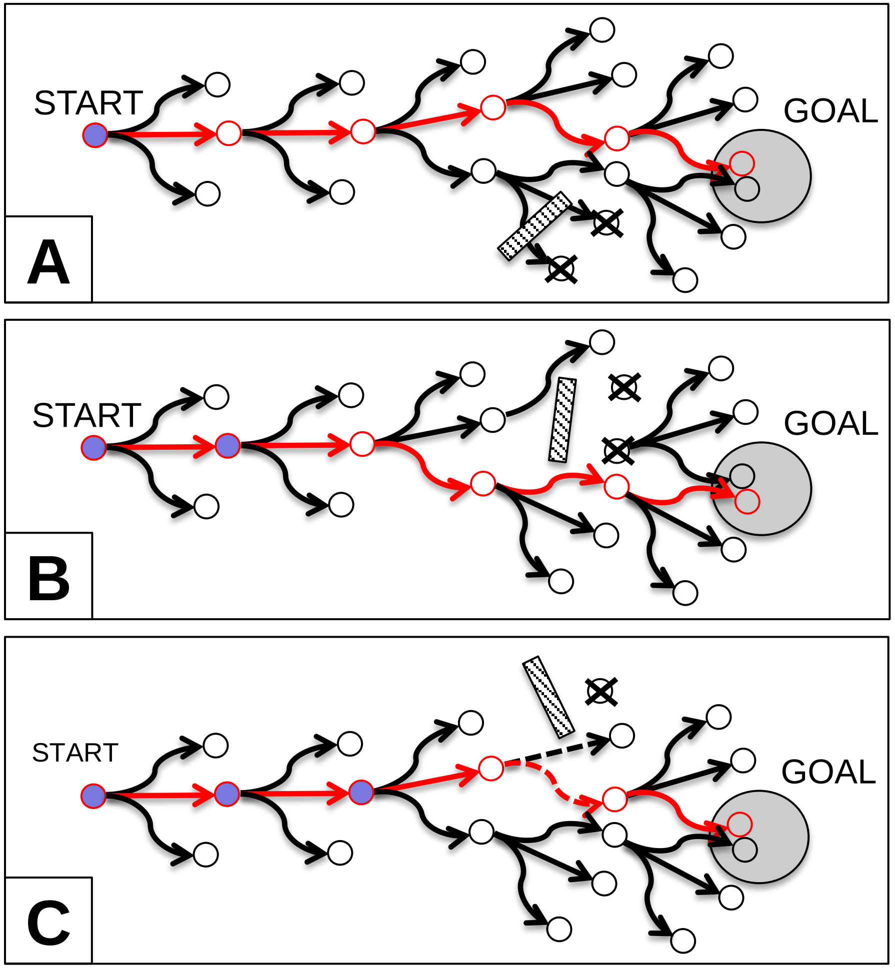
Research Methodology

Incremental Replanning:

(A) Algorithm forms initial graph and plans optimal trajectory.

(B) The graph is restored but the initial plan is violated due to obstacle movement. Invalid edges are removed and the trajectory is replanned.

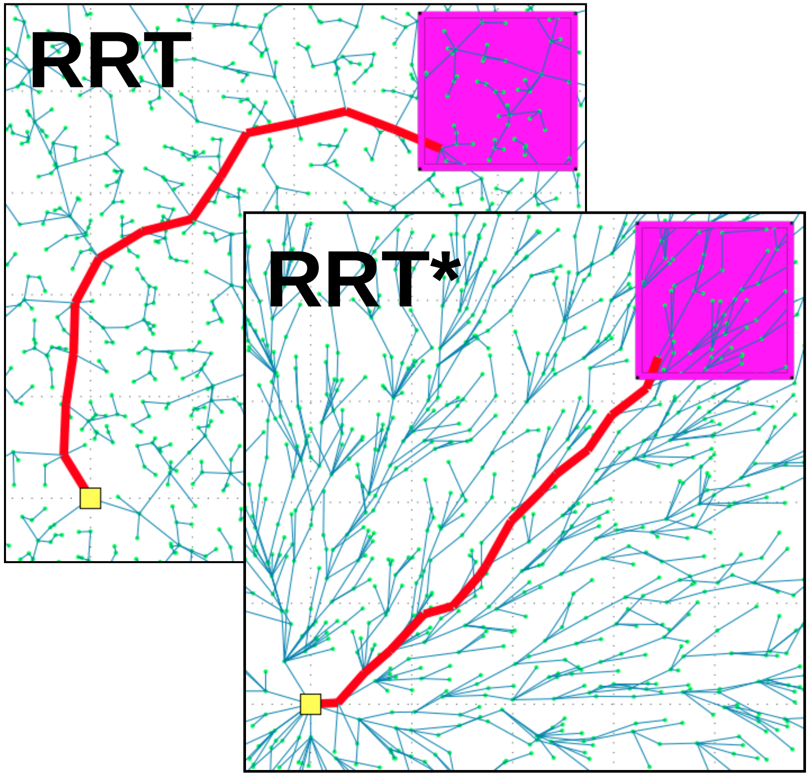
(C) The updated graph is restored but a more optimal trajectory is now achievable. Connectivity is restored and the trajectory is replanned.



Results

Introduction to Optimal Rapidly-Exploring Random Trees (RRT*)

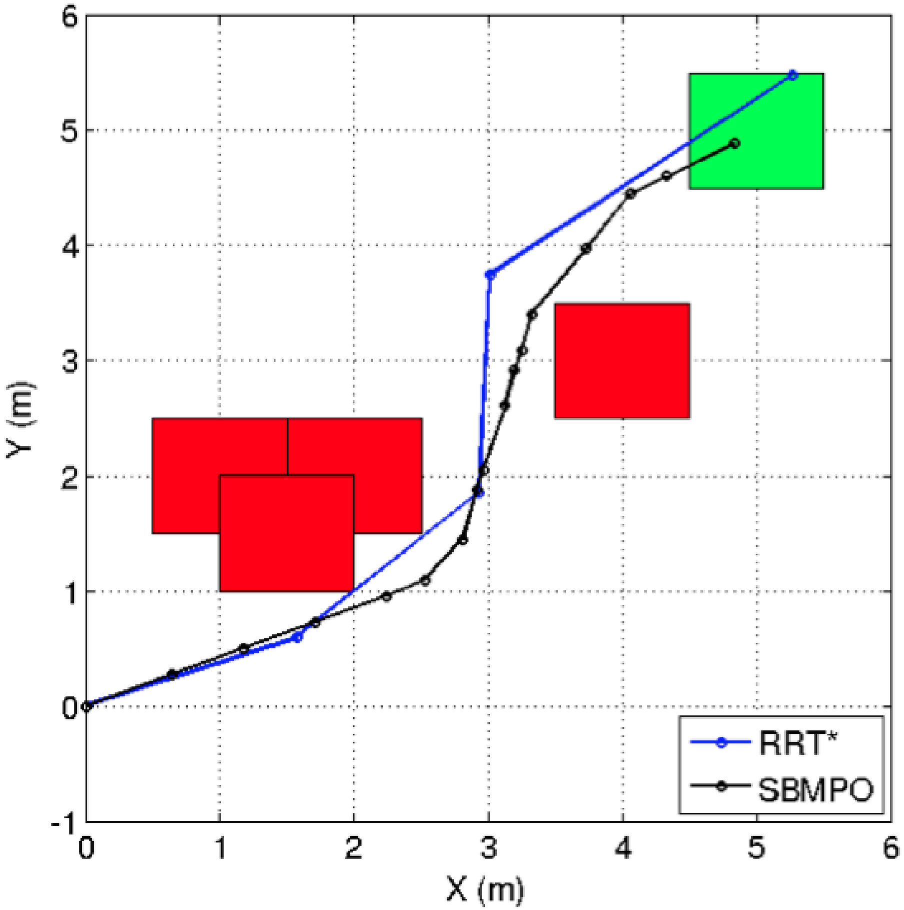
- Among the most popular motion planning methods, RRT* is an improvement of the RRT algorithm.
- Comparable to SBMPO, RRT* utilizes sampling, graph search, and cost-based optimization.
- However, RRT* does not employ prediction to speed up computations.



When compared with RRT (rear), it is clear that RRT* (front) produces a more optimal planning result. In fact, it has been proven that RRT* guarantees an asymptotically optimal solution. (*Sampling-Based Algorithms for Optimal Motion Planning*, Karaman and Frazzoli)

Results

Comparison of SBMPO with RRT* (Typical Result)



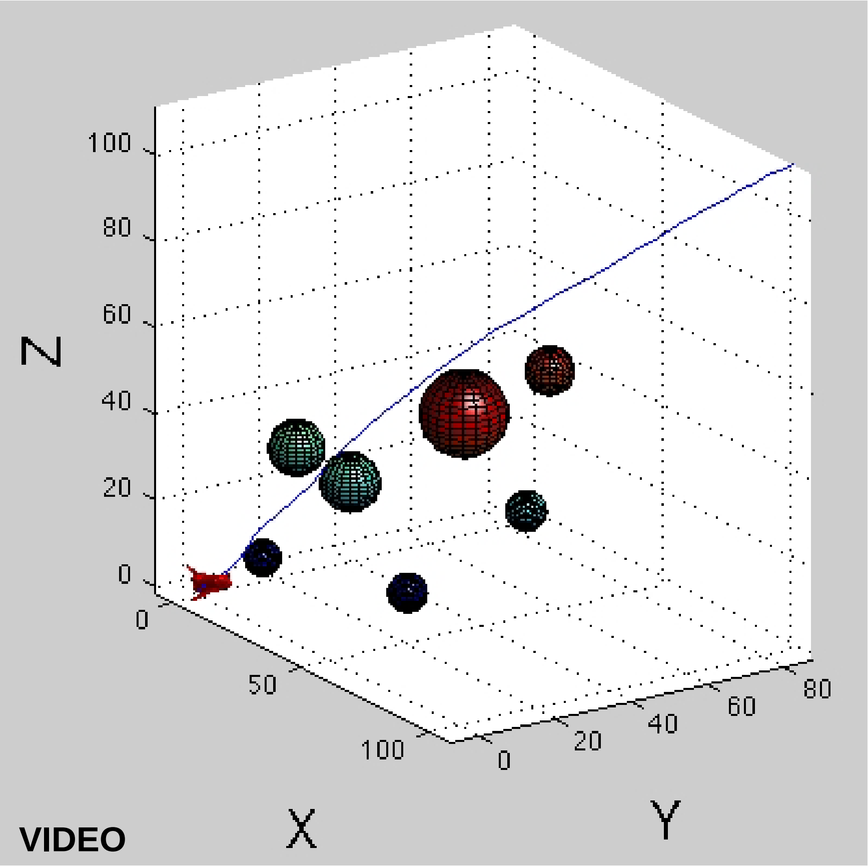
	SBMPO	RRT*
Distance (m)	7.39	8.28
Comp. Time (ms)	1.9	50.0

- Similar trajectories are determined, but SBMPO performs the calculation more than one order of magnitude faster.
- In complicated planning scenarios, this discrepancy in computation time prohibits the use of RRT* and similar approaches.
- As shown in this simple comparison, the use of a heuristic (in SBMPO) facilitates rapid computation.

Results

3D Trajectory Generation in Cluttered Space

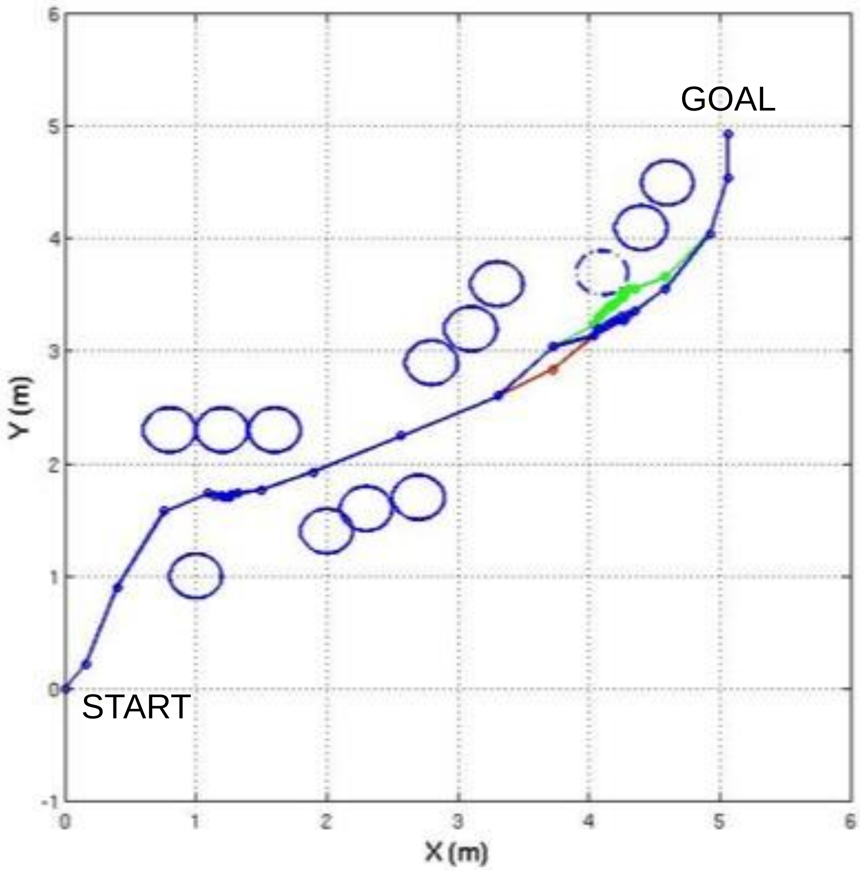
- Spacecraft is disoriented and trailing the target. Several nearby obstacles are detected.
- SBMPO sampled thrusters and rotation wheels aligned to the body axes (6 inputs).
- Maneuver time is optimized (similar result obtained minimizing distance).
- Zero relative velocity at the goal is enforced.
- Route to target is computed in less than one second.



- Other approaches compute similar trajectories in 25+ seconds.

Results

Efficient Replanning via Lifelong Planning A* (LPA*)



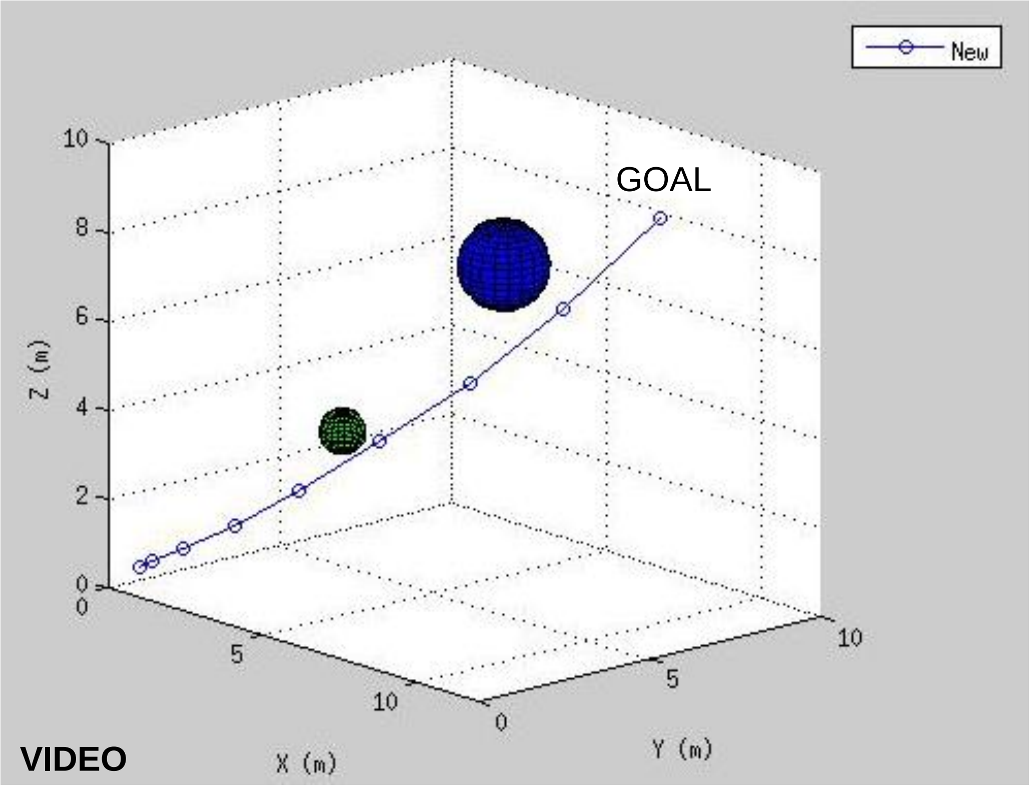
	Initial	Modified	
	SBMPO	w/ LPA*	SBMPO
Distance (m)	7.33	7.34	7.33
Comp. Time (ms)	887	13.6	653

- …A* algorithm as a substitute for traditional A*, the planner is able to utilize past trajectory data.
  - In terms of computation time, LPA* is much more effective when obstacle motion is likely.
- By enabling rapid replanning, LPA* essentially paves the way for an incremental version of SBMPO.
  - Crucial step for hardware implementation.

Results

3D Replanning in a Non-deterministic Environment

- Obstacle field changes as vehicle progresses to the goal.
- Route to target is replanned when changes in obstacle characteristics are detected.
- By using previous graph information and managing graph connectivity, minimal nodes are added.



	Computation Time (ms)
w/ Replanning	44.1
w/o Replanning	531.3

Results

Publications

G. Francis, E. Collins, O. Chuy, and A. Sharma, "Sampling-Based Trajectory Generation for Autonomous Spacecraft Rendezvous and Docking," in *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, Boston, MA, August 19-22, 2013.

G. Francis, E. Collins, O. Chuy, and A. Sharma, "Rapid Trajectory Generation for Autonomous Spacecraft in Stochastic Environments" (in preparation), for submission to *Journal of Guidance, Control, and Dynamics*.

Future Work

- Integrate state-estimation error correction within SBMPO to accommodate minor course corrections without replanning.
- Continue development of an "anytime" version of SBMPO that enables trajectory planning over a fixed amount of time.
- Progress toward on-orbit implementation.
- Laboratory demonstration of planning for aerospace rendezvous.

- Utilize recently acquired quadrotor as precursor to on-orbit deployment.
- Employ VICON motion capture system for trajectory tracking.

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