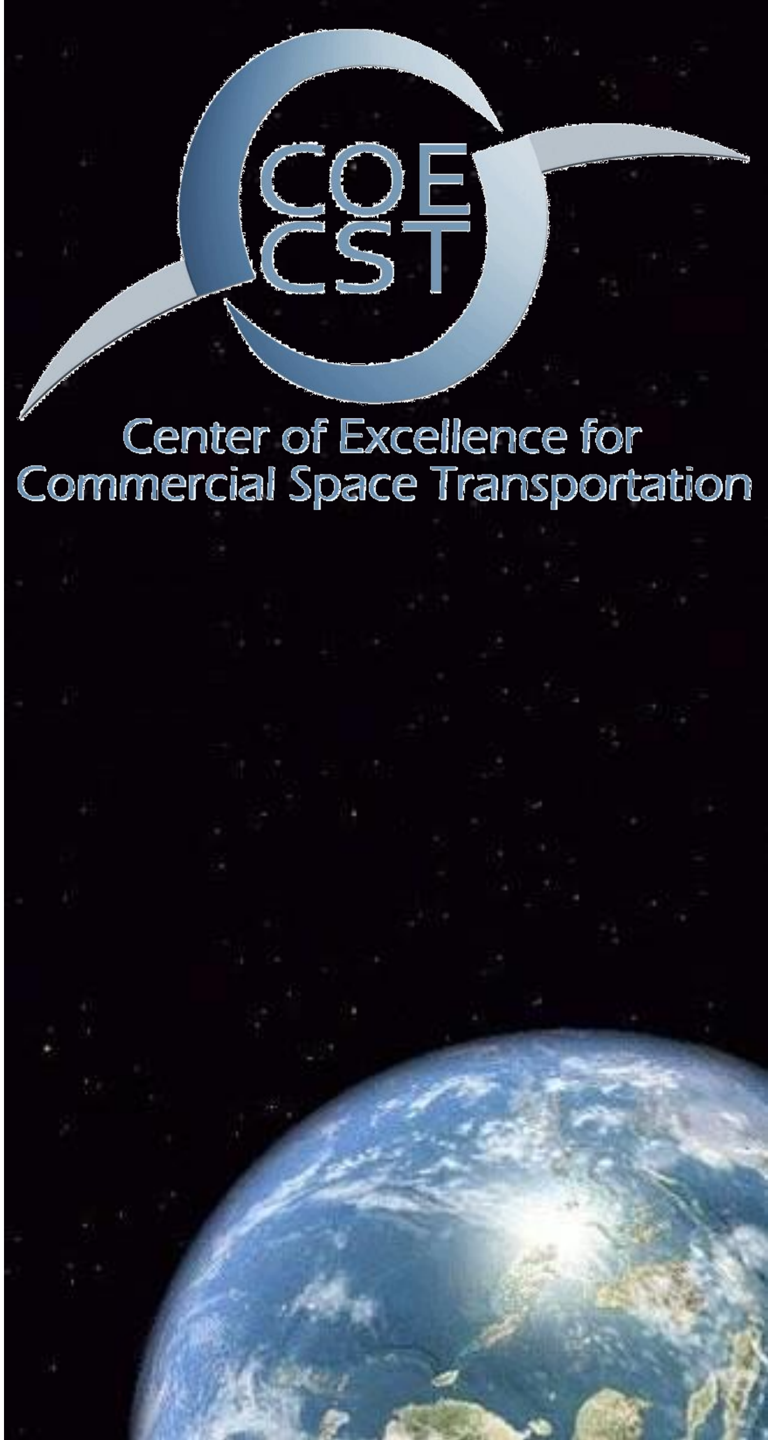
COE CST Fourth Annual Technical Meeting

Autonomous Rendezvous and Docking: Rapid Trajectory Generation

Griffin Francis
Emmanuel Collins, PI
Florida State University

October 29-30, 2014
Washington, DC



Team Members

- Emmanuel Collins, PI
- Griffin Francis, PhD Student, Mechanical Engineering
- Aneesh Sharma, PhD Student, Computer Science
- Oscar Chuy, Scholar Scientist, Mechanical Engineering




Center for Intelligent Systems, Control, and Robotics

Task Description

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.

Potential Applications:

- Resupply of unmanned and manned commercial orbital platforms
- On-orbit repair, recovery, or removal of a disabled commercial supply vehicle;
- De-orbit services (incl. debris mitigation) – by establishing guidelines for markings and docking

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 Goals

USA Today, 04/14/2014

Debris Mitigation as Commercial Application:
As indicated by recent NASA study, there is an immediate need to develop orbital debris mitigation technology.

- Analogous to traditional industry: Waste Management
  - Not "sexy," but should be a sustainable commercial enterprise.
- Large scale efforts warrant the use of automated guidance to approach targeted debris.

SPACE STATION TAKES ACTION TO DODGE ROCKET DEBRIS

The International Space Station had to dodge space junk again — the second time in less than three weeks.

NASA said the station fired its thrusters Thursday afternoon, moving up about half a mile, to avoid some parts from an old Ariane 5 rocket. The European Space Agency launches Ariane rockets out of South America.

The junk would have come within 1,040 feet of the outpost. NASA said the six-man crew was never in danger.

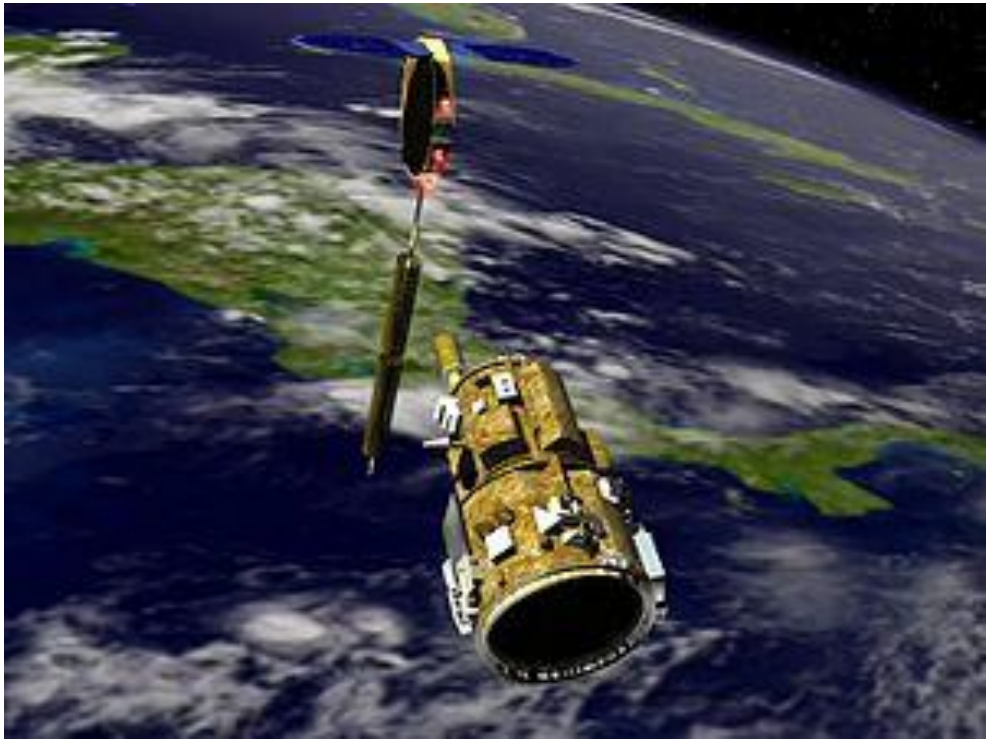
NASA spokesman Kelly Humphries said the space agency has had to consider sidestepping space junk dozens of times since the outpost was launched in 1998, sometimes canceling the orbital dodge at the last moment.

The station moved on March 16 to avoid an old Russian weather satellite part.

Research Goals

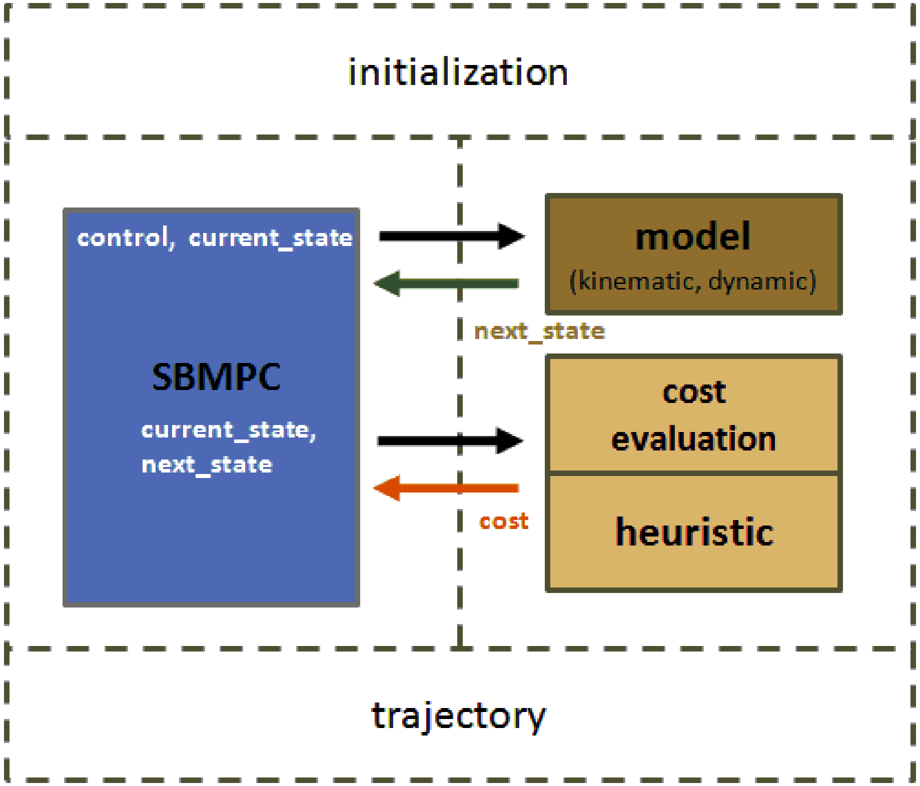
Technical Goals:

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, and/or energy.
4. Rapidly replan trajectories as new information becomes available.



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.

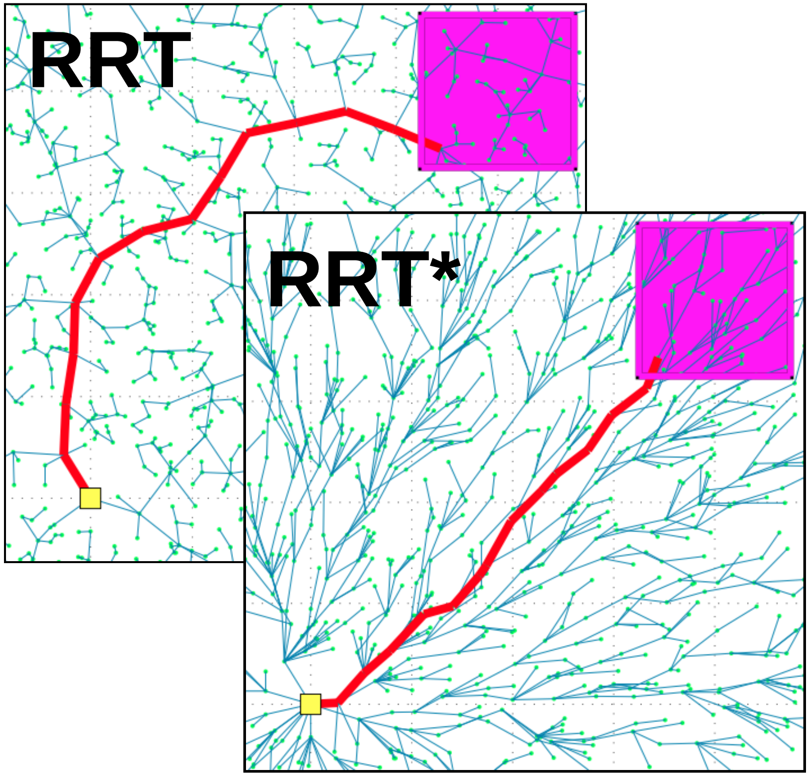


Fundamental Components of SBMPO: Uses kinematic & dynamic models to compute cost optimal trajectories.

Results

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

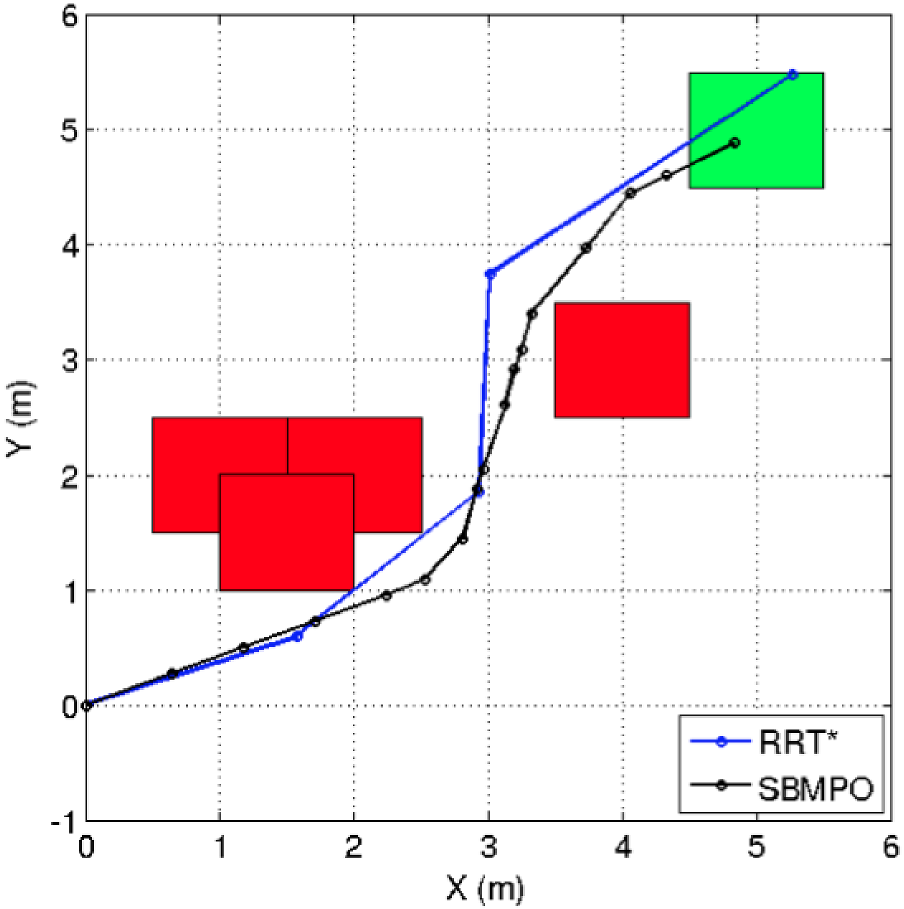
- Among the most popular motion planning methods, RRT* is an improvement of the RRT algorithm.
- Comparable to SBMPO, RRT* utilizes sampling, graph search, and cost-based optimization.
- However, RRT* does not employ prediction to speed up computations.



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)



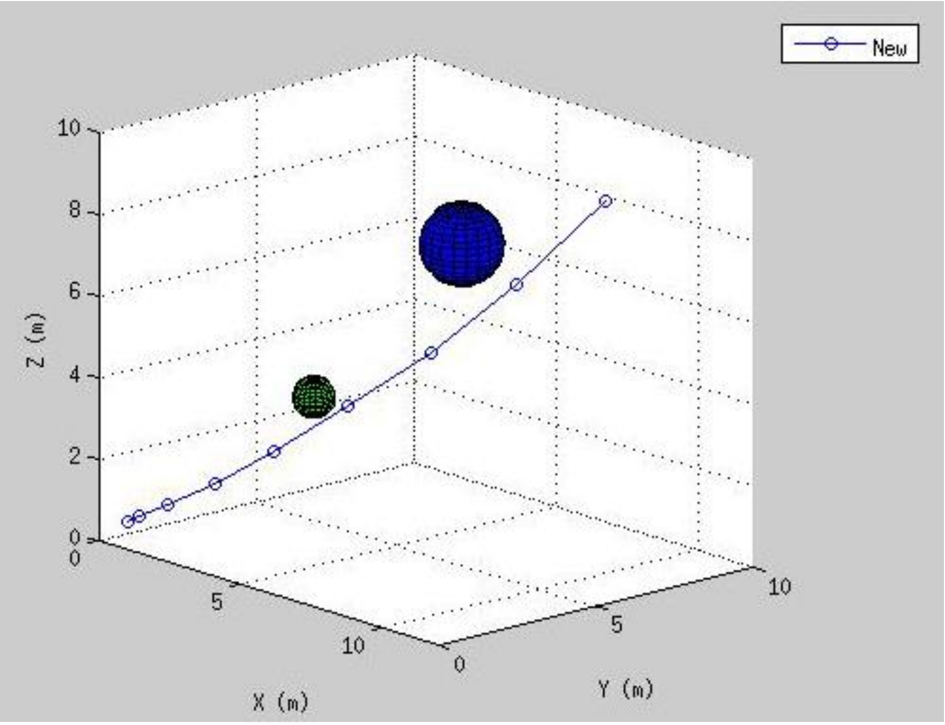
	SBMPO	RRT*
Distance (m)	7.39	8.28
Comp. Time (ms)	1.9	50.0

- 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.

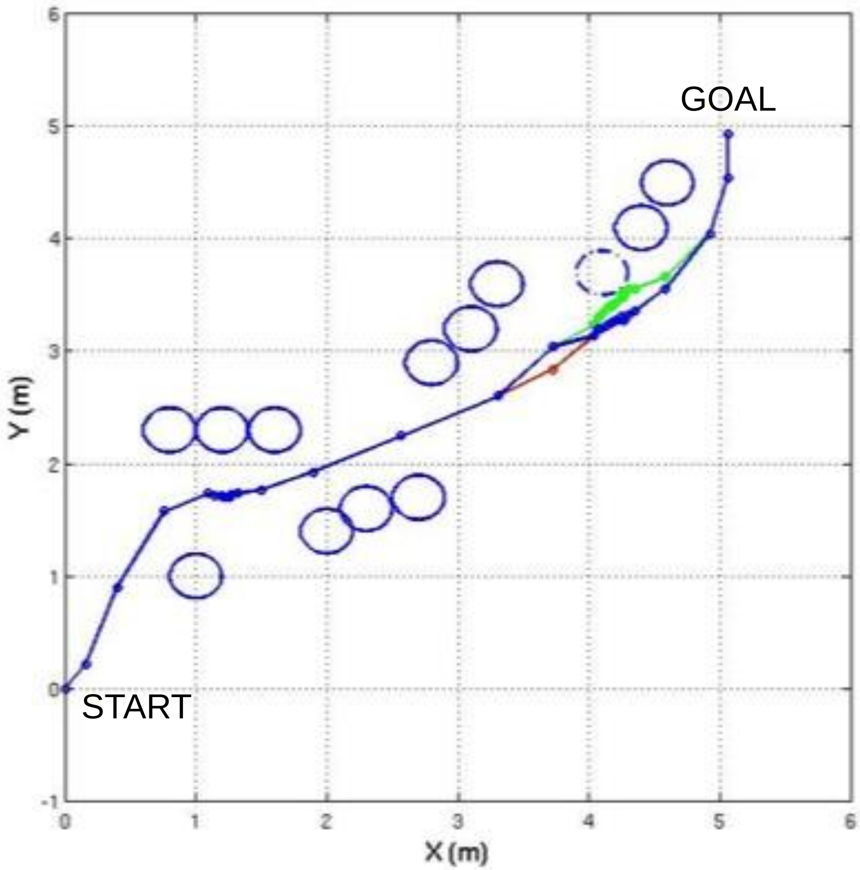


VIDEO

- Other approaches compute similar trajectories in 25+ seconds.

Results

Efficient Replanning via Lifelong Planning A* (LPA*)



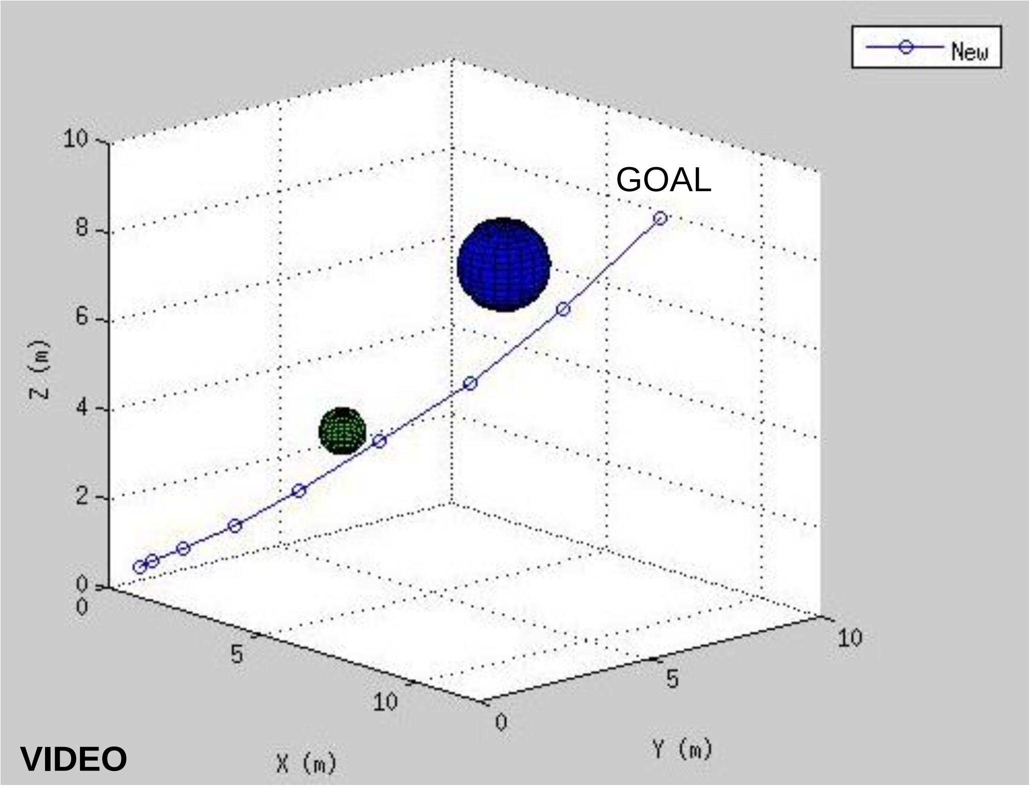
	Initial	Modified	
	SBMPO	w/ LPA*	SBMPO
Distance (m)	7.33	7.34	7.33
Comp. Time (ms)	887	13.6	653

- …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.

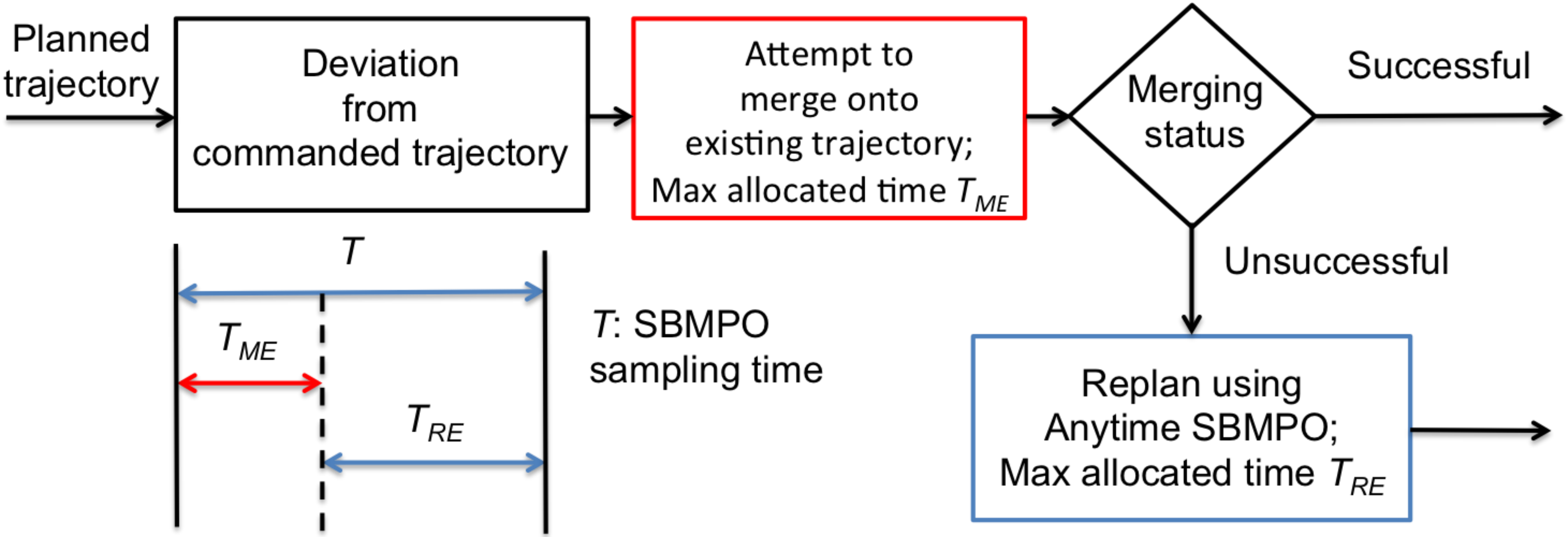


	Computation Time (ms)
w/ Replanning	44.1
w/o Replanning	531.3

Results

Trajectory Merging and Error Correction

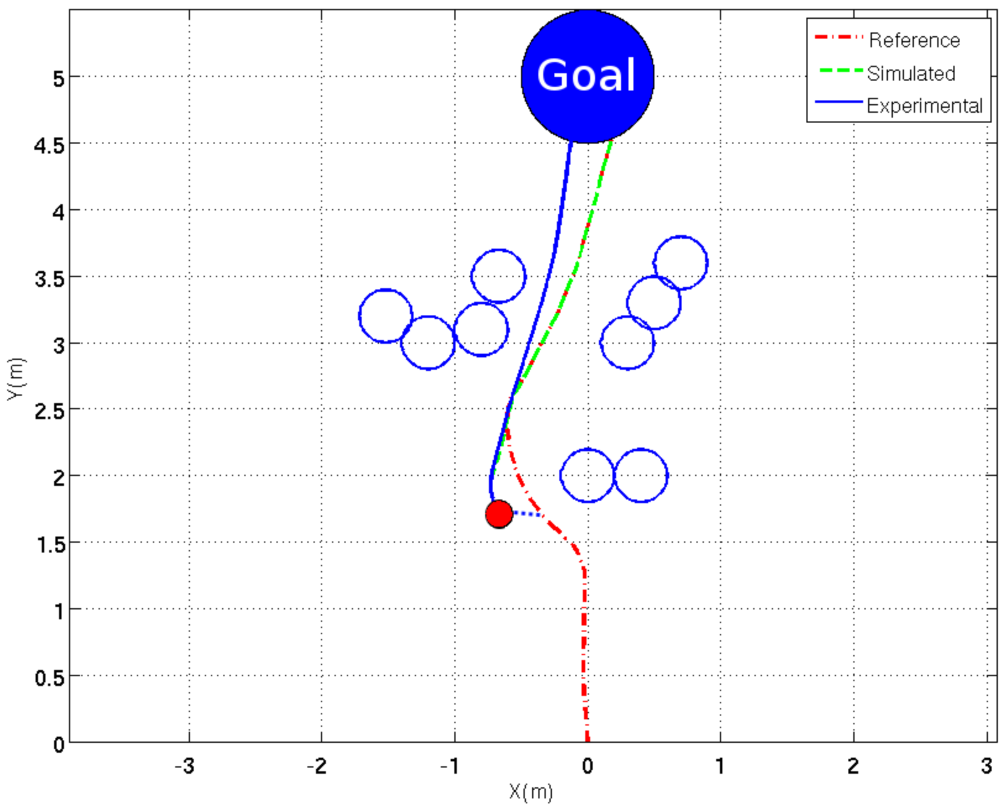
- Mitigate effects of trajectory drift via efficient course correction.
- Resample inputs in attempt to quickly merge back onto solution trajectory.



Results

Trajectory Merging and Error Correction

- When the vehicle is observed to have deviated from the original trajectory, this method computes a merging solution over a fixed time horizon.
  - The max. time for merging is computed such that replanning may occur within the SBMPO sampling time interval if merging fails.
- As a result, this approach is very effective when merging is more efficient than replanning.



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.

A. Sharma, C. Ordonez, and E. Collins, "Robust Sampling-Based Trajectory Tracking for Autonomous Vehicles," 2014 IEEE International Conference on Systems, Man, and Cybernetics, San Diego, CA, Oct 5 – 8, 2014.

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*.

Conclusions and Future Work

Summary:

- There are several applications of AR&D, including removal of orbital debris, which poses an immediate and ongoing threat to our various space endeavors.
- The demonstrated research provides an efficient approach to navigation for autonomous space vehicles.
- This research paves the way for commercially-viable autonomous rendezvous in cluttered space environments.

Upcoming:

- Extend trajectory merging approach to 3D scenarios.
- Synergize iterative and anytime planning paradigms to improve algorithm efficiency in dynamic environments.
- Implement additional planning constraints that may be encountered in a realistic application (i.e., thruster deadzone, solar avoidance of sensors, prevention of plume impingement).

QUESTIONS?