COE CST Second Annual Technical Meeting:

Autonomous Rendezvous and Docking for Space Debris Mitigation: Rapid Trajectory Generation

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Federal Aviation
Administration

Overview

- Team Members
- Purpose of Task
- Research Methodology
- Results
- Next Steps
- Contact Information

Team Members

- Griffin Francis, PhD Student Mechanical Engineering

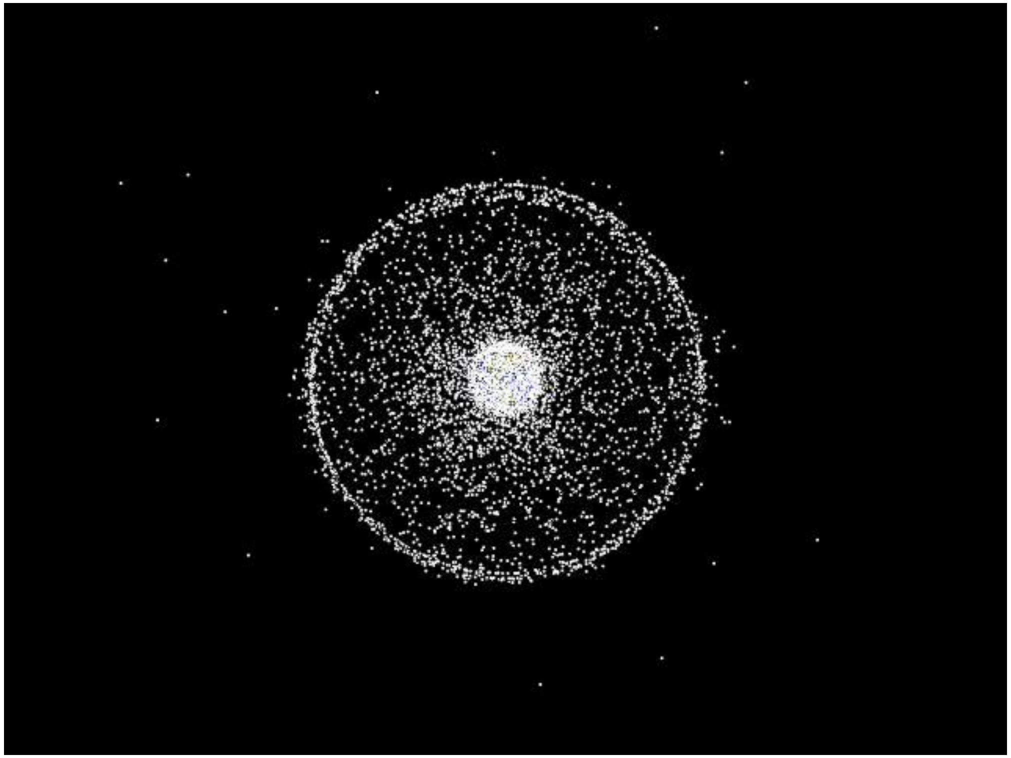
- Aneesh Sharma, PhD Student, Computer Science

- Oscar Chuy, Assistant Scholar Scientist

Purpose of Task

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

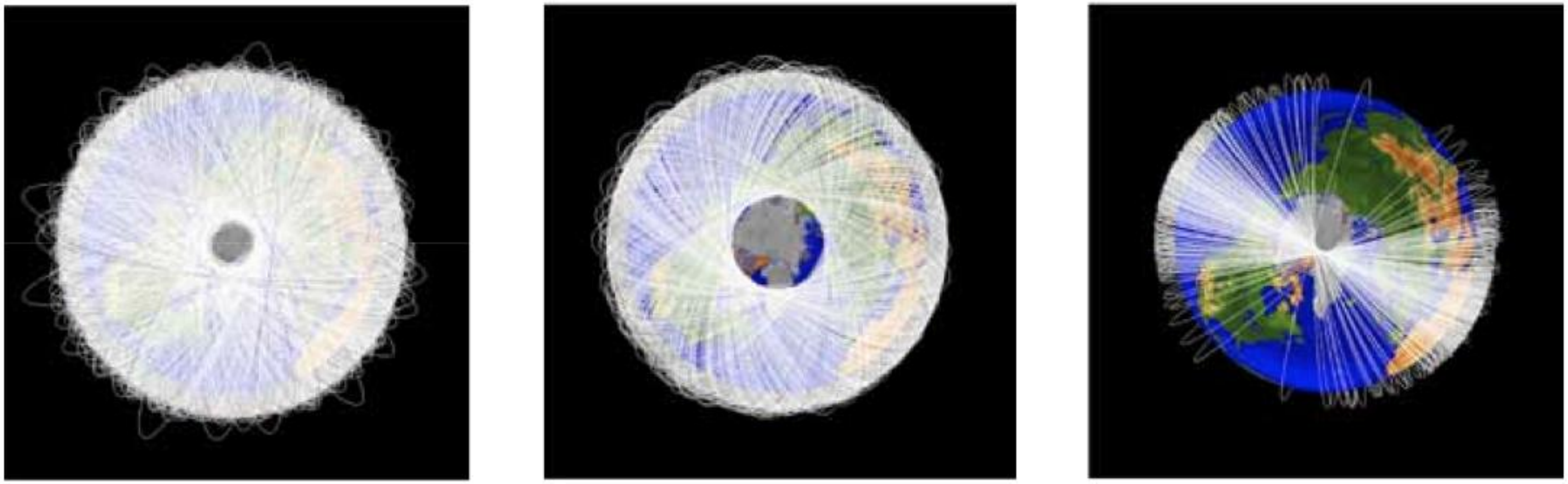
- A promising solution for direct debris removal is the development of a “Space Tow Truck.”
- Requires automated guidance to approach targeted debris.



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 space tow truck to approach debris 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

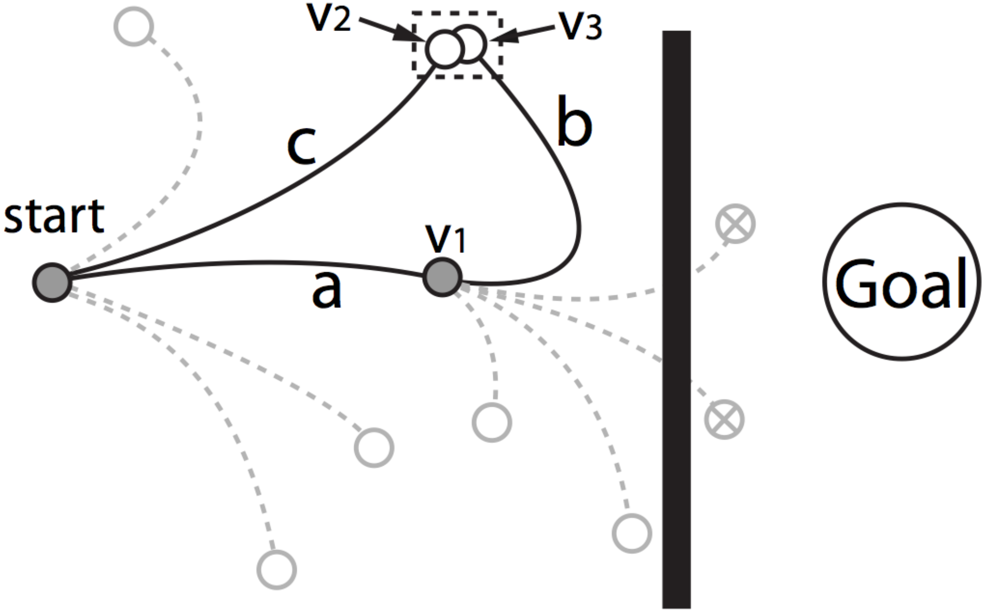
Goals:

1. Develop space tow truck dynamic model to account for actuator characteristics, vehicle momentum, and power consumption.
2. Use the dynamic model to develop trajectories for effective rendezvous of space truck with target space debris.
3. Optimize trajectories based on relevant metrics such as distance, time, and 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

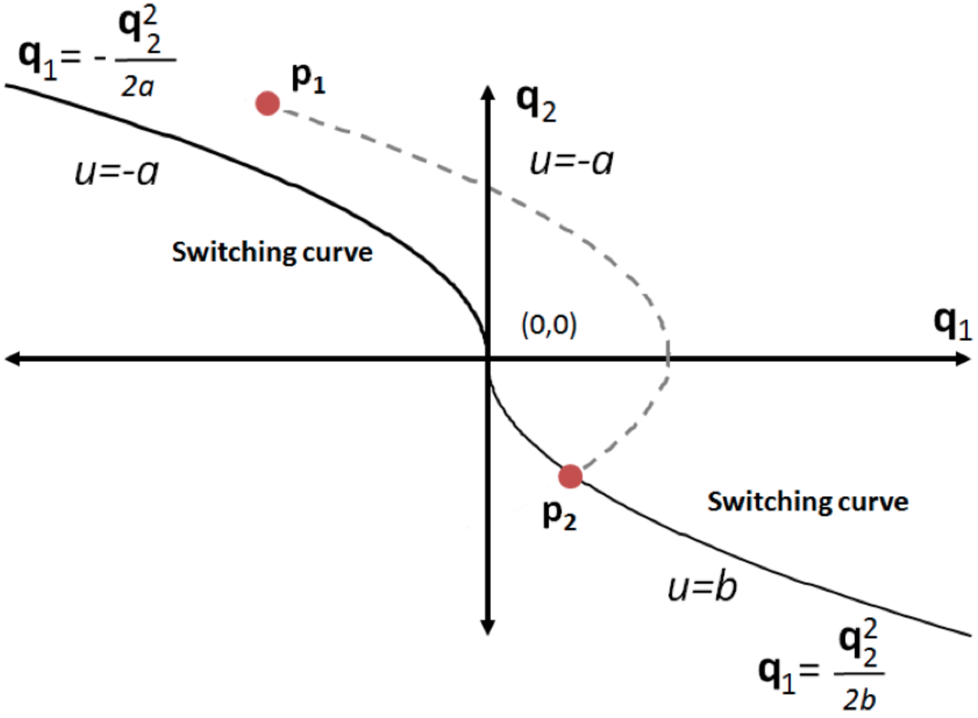
- The primary tool used is Sampling-Based Model Predictive Optimization (SBMPO).
- SBMPO is a graph search method characterized by:
  - Graph that is based on sampling of model inputs;
  - Optimization via A*;
  - Incorporation of dynamic model in planning;
  - Ability to rapidly replan;
  - Generation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



Graph formation: the process of node expansion, node rejection due to collision detection, and output space discretization via an imposed implicit grid encompassing nearby nodes V2 and V3.

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

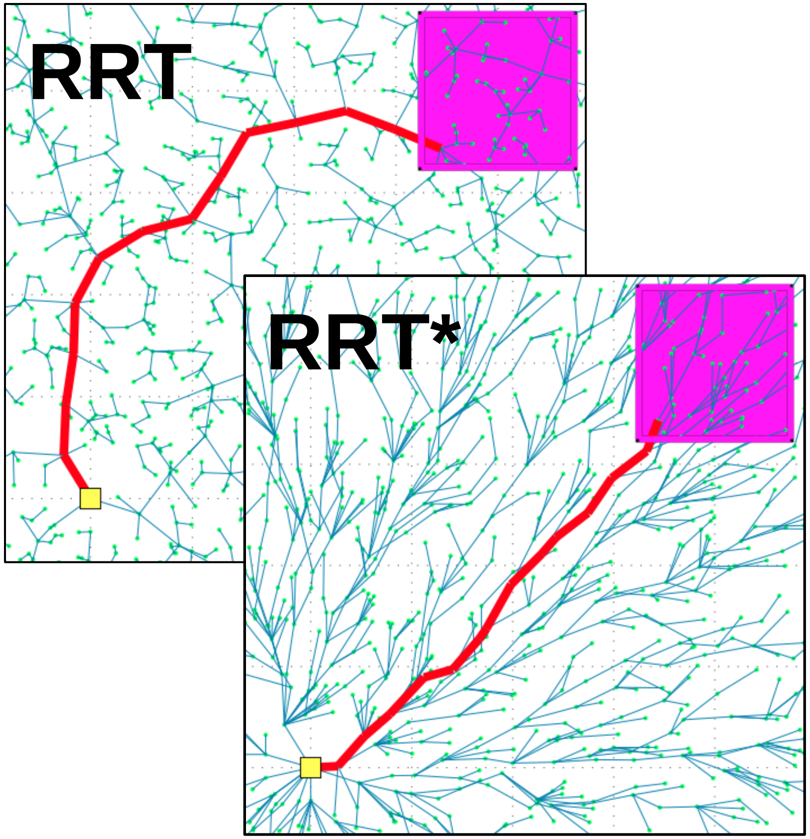
Facilities

- Dedicated in April 2012, research has moved into the new 60,000+ square foot AME (Aerospace, Mechatronics, and Energy) Building.
- The mechatronics laboratories will soon be equipped with a state-of-the-art motion capture system to be used for hardware testing of this research.

Results

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

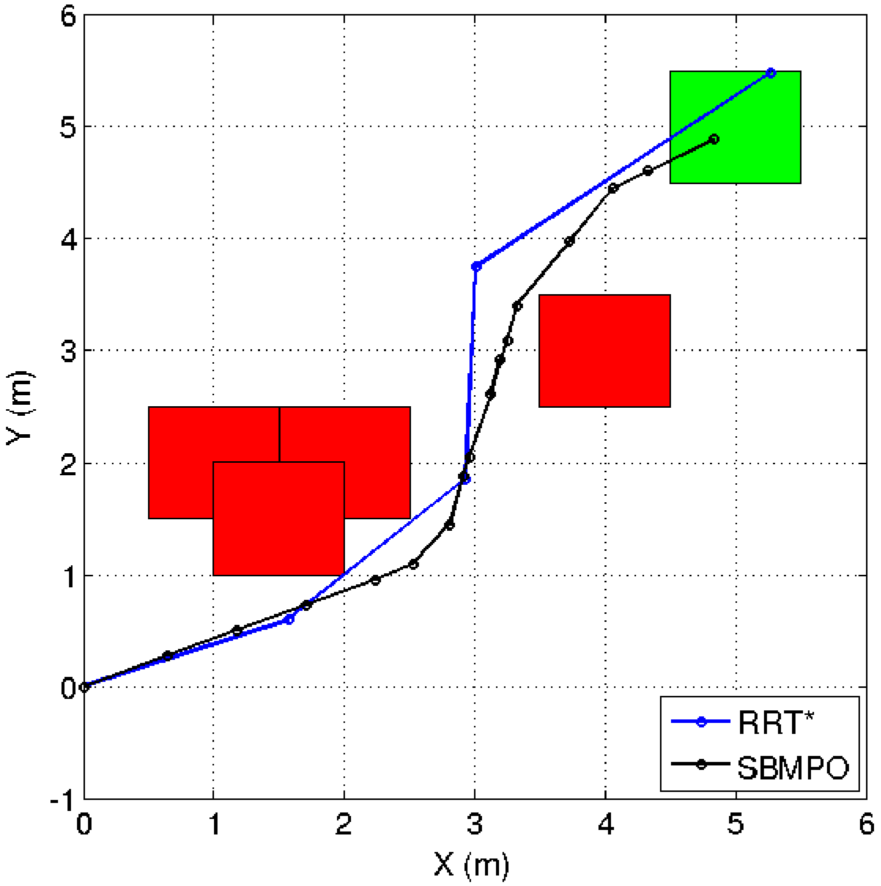
- Among the most popular motion planning methods, RRT* is an improvement of the RRT algorithm.
- Comparable to SBMPO, RRT* utilizes sampling, graph search, and cost-based optimization.
- However, RRT* does not employ prediction to speed up computations.



When compared with RRT (rear), it is clear that RRT* (front) produces a more optimal planning result. In fact, it has been proved 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)



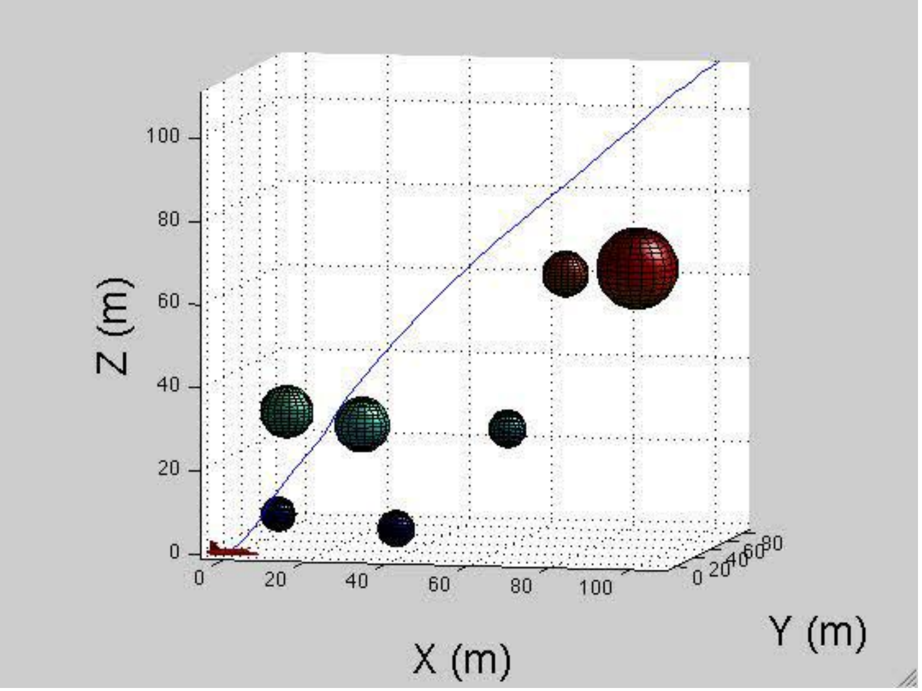
	SBMPO	RRT*
Distance (m)	7.39	8.28
Comp. Time (ms)	1.9	50.0

- 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 for prediction (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).
- Time is optimized. (Similar result obtained minimizing distance.)
- Zero relative velocity at the goal is enforced.
- Route to goal position and orientation is computed in about one second.



- Other approaches compute similar trajectories in 25+ seconds.

Scheduled Milestones

Hardware Integration

- Progress toward on-orbit implementation.
- Laboratory demonstration of planning for aerospace rendezvous.
- Utilize recently acquired quadrotor micro-air vehicles (MAV) as precursor to on-orbit deployment.
    - Complexity of trajectory generation problem is similar to spacecraft despite different dynamics.
- Employ VICON motion capture system for trajectory tracking.

Prominently featured as the standard platform of choice in authoritative autonomous MAV literature, a set of AscTec "Pelican" quadrotors will be used as a precursor for hardware implementation of this trajectory generation research. (AscTec, GmbH)

Next Steps

- Develop a better visualization tool using MATLAB’s Virtual Reality Toolbox.
- Develop an “anytime” version of SBMPO that enables trajectory planning in a fixed time.
- Configure laboratory equipment for hardware implementation and real-world testing.
- Formulate a power consumption model and demonstrate planning of minimum energy trajectories.
- Apply trajectory constraints based on research of Penny Axelrad (U. Colorado).
- Use research of Steve Rock (Stanford) and Norm Fitz-Coy (U. Florida) to determine final pose constraints.

Quad Charts

MAJOR MILESTONES – PAST

- Obstacle Free Trajectory Generation for Rendezvous Using Sampling Based Model Predictive Optimization
- Trajectory Generation with Obstacles
- Algorithmic Extensions of SBMPO to Fast Replanning and State Prediction Errors

MAJOR MILESTONES – FUTURE

- Demonstration (via Simulation)Anytime Version of SBMPO in Rendezvous Maneuver
- Demonstration of Energy Efficient Plannin
- Initial Hardware Demonstration with Quadrotors
- Accommodation of Moving Obstacles
- Extensive Hardware Demonstrations

SCHEDULE

- December 2013
- December 2014
- December 2015
- December 2016
- December 2017

BUDGET

- FY13 - FY14 - FY15 - FY16 - FY17
- $100K -$100K - $100K - $100K - $100K

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