# Sampling-Based Spacecraft Motion Planning

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## Objectives

Develop robust and efficient autonomous control algorithms for spacecraft operating in cluttered, rapidly-changing environments

**Key idea:** approximate, “anytime” algorithms for provably safe trajectory control

## The Need for Spacecraft Autonomy

From precision Earth-orbit satellite formations, to deep space missions too distant for remote operation, robust and reliable autonomous control algorithms are a key enabler for a vast array of future spacecraft missions.

**Satellite Rendezvous**
- Approach and docking impose difficult-to-handle constraints:
  - Waypoints/approach corridors
  - Thruster plume impingement
  - Field-of-view requirements
  - Demands safety guarantees for collision avoidance with debris, non-convex geometries, etc.

**On-Orbit Servicing**
- Satellite repair/harvesting operates in close-proximity of potentially uncooperative targets
  - Requires:
    - High-precision maneuvering
    - Real-time decision making

**Agile, Opportunistic Science**
- Enables novel exploration missions to dynamic, cluttered scientific targets of interest
- Allows a science-driven mission approach
- Permits deep-space missions unable to rely on ground support

## Challenges Unique to Spacecraft Applications

Spacecraft present a number of unique challenges compared to traditional robotic motion planning applications. Though studies have addressed many such aspects in isolation, a practical unifying framework that solves the general problem has yet to be demonstrated.

- **Limited computational capability**
- **Mixed state/control constraints**
  - Solar sail propulsion
  - Thruster plume impingement
  - Non-convex spacecraft geometry
  - Booms/antennae
  - Solar arrays
- **Coupled attitude/trajectory dynamics**
- **Dynamic drift/under-actuation**
- **Risk constraints**
- **Control limitations**
  - Limited fuel supply
  - Minimum thruster on/off times
  - Momentum wheel saturation

## Proposed Solution: Sampling-Based Algorithms

**Sampling-Based Motion Planning**

Sampling-based motion planning leverages a robot from an initial state to a set of goal states subject to obstacles and a cost functional by breaking the problem into smaller geometric subproblems. The free configuration space is sampled, and samples are connected to form a tree and iteratively improve the global solution.

**FMT* (Fast-Marching Tree) Algorithm**

FMT* samples $n$ points in the configuration space, and then expands outwards in cost-to-come space from the initial state, forming a minimum cost spanning tree. It maintains dual sets W, the set of nodes not in the tree, and H, the set of nodes in the tree yet close enough to the leaves to be able to connect to some node in W.

The Algorithm
1. Sample $n$ points in the configuration space
2. Select $z$, the lowest cost node in H
3. Find all of the nodes in W reachable within cost $r$ of $z$
4. For each node, find its optimal cost-to-come parent in H. If the path between them is collision free, create an edge between them.
5. Add the newly-connected nodes to H and remove them from W
6. Remove $z$ from H
7. Repeat 2-6 until $z$ is in the goal region

**Features**
- No explicit representation required for $C_{\text{obs}}$
- Asymptotic convergence to the globally optimal path
- Tree structure can incorporate dynamic constraints more efficiently than a graph-based structure

## Numerical Simulations

**FMT*: Improving the State of the Art of Sampling-Based Motion Planning**

Simulations compare FMT* with RRT* (a tree-based planner) and PRM* (a graph-based planner), two of the main asymptotically optimal sampling-based motion planning algorithms. In all cases, FMT* is able to achieve a lower path cost per execution time. The improvement is most marked in higher dimensions with more obstacles; precisely the regime necessary for spacecraft applications.

**Extension to Kinodynamic Systems**

Spacecraft controls do not accommodate paths between arbitrary states; feasible paths are subject to kinodynamic constraints. In order to extend FMT* to these scenarios, we shall begin by considering control-affine systems of the form:

$$\dot{x} = f(x) + \sum_{i} g_i(x)u_i$$

The $u_i$ are input control functions, the $g_i$ are their actions, and $f$, if nonzero, is the drift term. For driftless systems with small time local controllability (STLC), the extension to FMT* is well understood. For the class of dynamic systems with drift, however, it is in general harder to guarantee STLC, and optimal steering is known only for special cases. Devising an efficient and accurate local planner for these cases will be the key challenge in extending the FMT* algorithm.

## Experimental Testbed

The Free-flying Space Robotics Facility of the Autonomous Systems Lab consists of three 3-DOF free-floating spacecraft testbeds and a 6 camera motion capture system for autonomous control algorithm testing. The spacecraft are each equipped with:
- One 8 kg momentum wheel
- Four compressed air thrusters
- Air-bearings for simulated microgravity in the horizontal plane

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