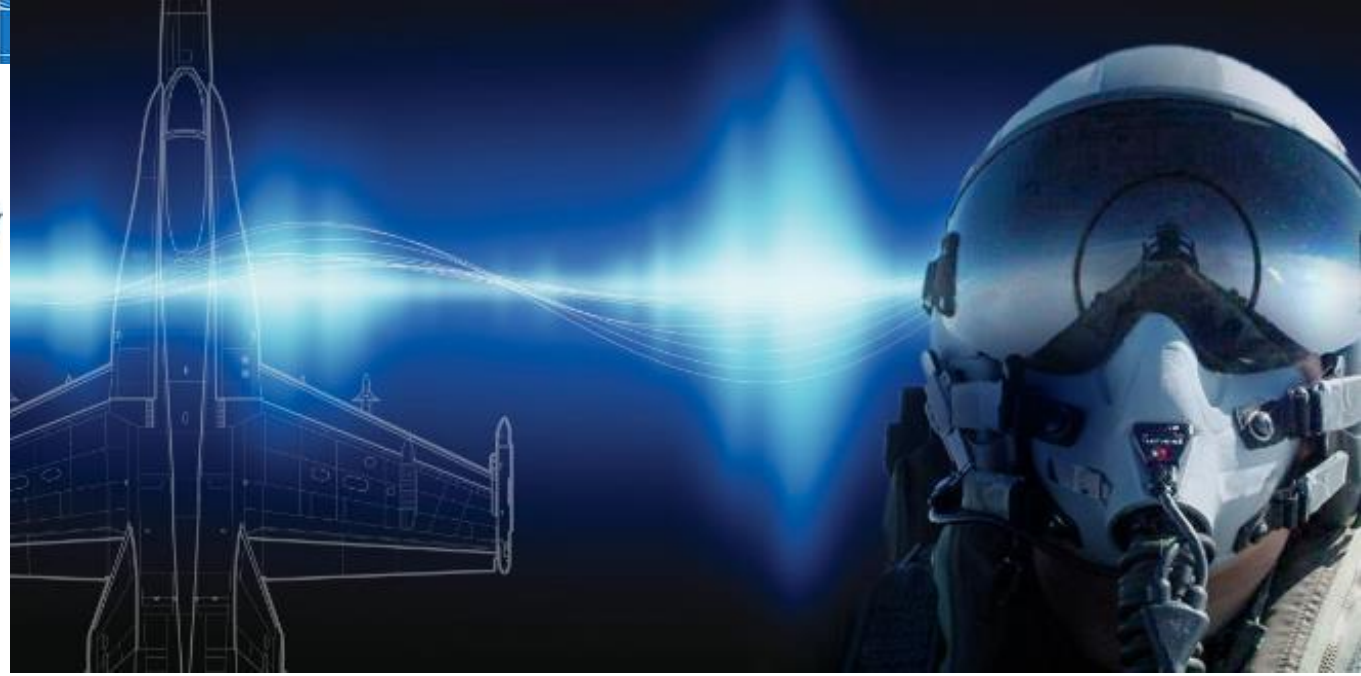

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Trajectory Planning for Autonomous Parafoils in Complex Terrain

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DRAPER

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Outline

- Introduction to Guided Airdrop
- Overview of Parafoil Guidance
- The Rewire-RRT Algorithm
- Results and Conclusions

Figure 1: An airdrop mission begins. How will it end?

Introduction to Guided Airdrop

What is Airdrop?

Figure 2: Unguided airdrop

Figure 3: Guided airdrop with autonomous parafoils

Advantage of Guided Airdrop

- Accuracy – lands closer to target!

Guided Airdrop System

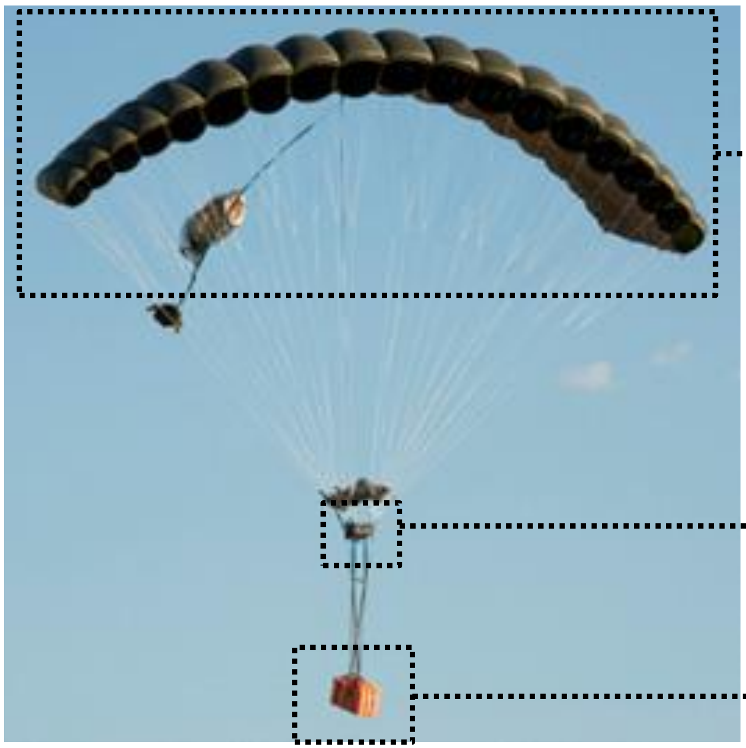

Figure 4: Autonomous parafoil with attached payload

Guided Airdrop GNC

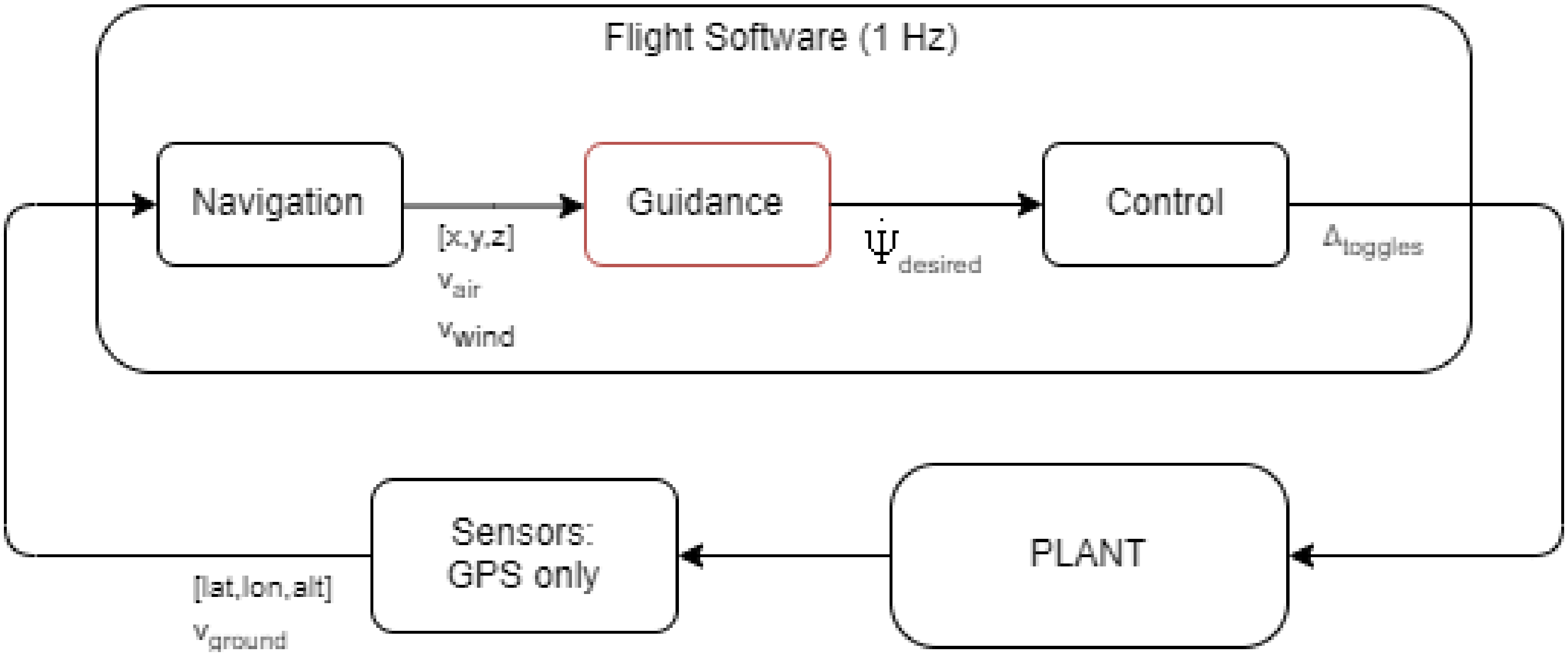

Figure 5: System diagram

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Parafoil Guidance Overview

Guidance Strategy

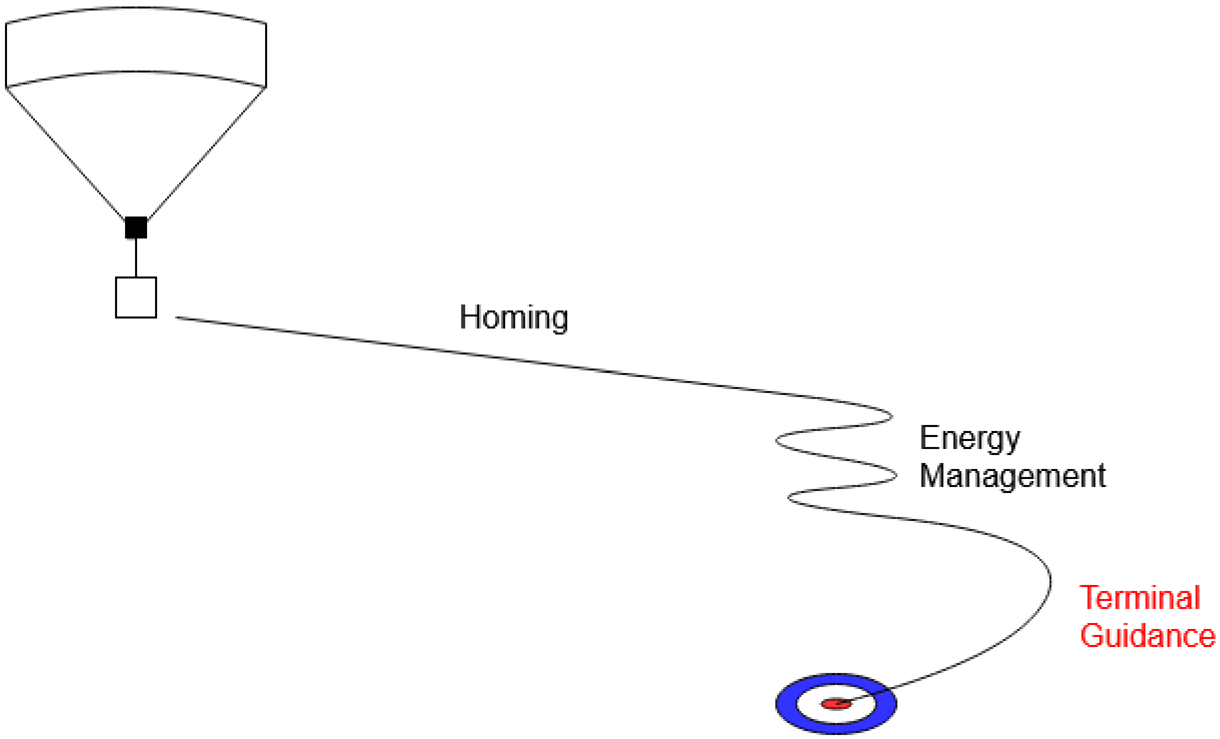

Figure 6: Parafoil Guidance Phases

Terminal Guidance Problem Statement

- Assume simplified parafoil dynamics:

$$\dot{p}_x = v(p_z)\cos\psi + w_x,$$
$$\dot{p}_y = v(p_z)\sin\psi + w_y,$$
$$\dot{p}_z = \frac{-v(p_z)}{L_D} + w_z,$$
$$\dot{\psi} = sat(C\mathbf{s} + Du, -\omega_{max}, \omega_{max}),$$
$$\dot{\mathbf{s}} = A\mathbf{s} + Bu$$

- Input $u = \dot{\psi}_{desired}(t), t_0 \leq t \leq t_{land}$
- Miss distance $d_{miss} = \left\| p(t_{land}) - p_{target} \right\|$

Find $\dot{\psi}_{desired}(t)$, that minimizes miss distance from target!

Existing Terminal Guidance Approach

- Band-Limited Guidance (BLG) is a direct optimization approach
- Trajectory parameterized by three equally spaced heading rates $\dot{\psi}_{desired}(t) = f(\dot{\psi}_1, \dot{\psi}_2, \dot{\psi}_3\ )$:
  - Band-Limited interpolation determines intermediate heading rates
- Optimization performed by Nelder-Mead algorithm

Limitations of BLG

- Constrained trajectory shape
- Slow convergence in presence of obstacles

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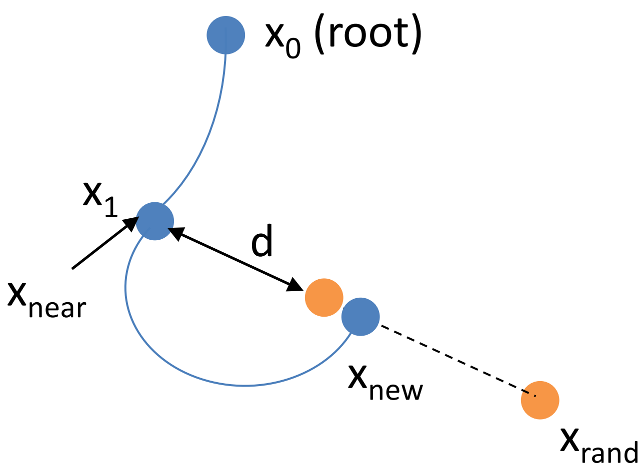
The Rewire-RRT Algorithm

Rapidly-Exploring Random Trees

- Introduced in 1998 [LaValle]
- Incremental construction of a tree of trajectories



Advantages

- No preconceived notion of trajectory shape
- Rapidly explore large state-space
- Alternative trajectories available

Parafoil-RRT

- RRT was adapted to parafoil guidance problem

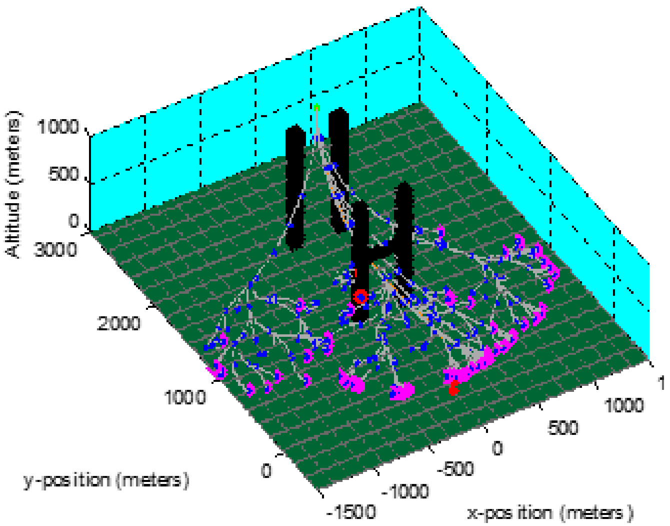


Figure 7: Tree of trajectories formed by Parafoil-RRT

Disadvantages

- Consistent but poor miss distance; RRT is guaranteed suboptimal [Karaman et al]
- Unsafe proximity of trajectory to terrain/obstacles

Solution 1 of 2 (Safety)

- Use Analytic Chance Constraints [Luders et al] to estimate probability of collision
  - Uncertain winds yield distribution of possible future states
- Total cost is weighted sum of safety and miss-distance costs

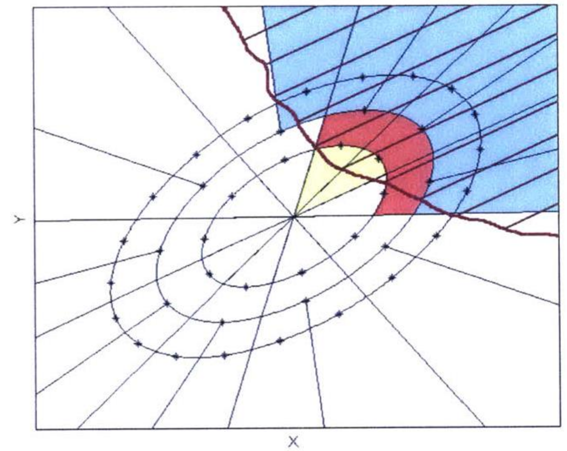


Figure 8: Collision probability region [Luders]

Two-part cost considers safety and miss-distance

Solution 2 of 2 (Performance)

- Adapt two methods from RRT* [Karaman et al]
  1. Choose-Parent
  2. Rewire

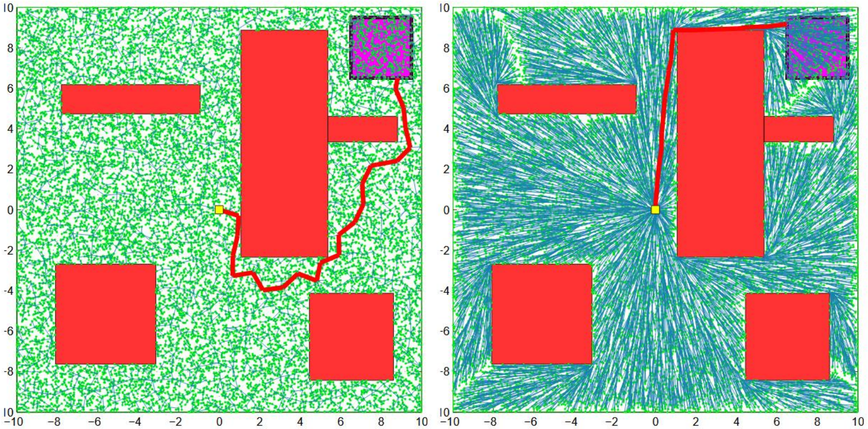
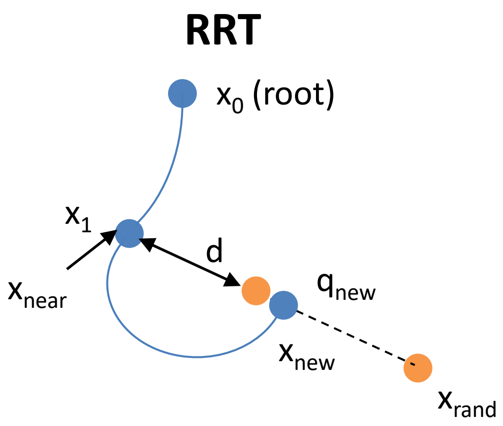
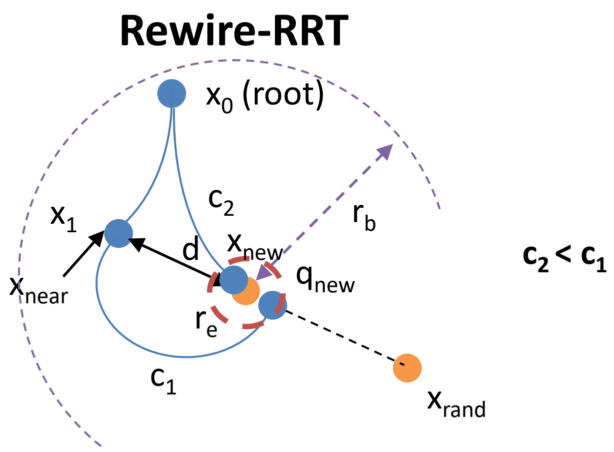


Figure 9: RRT (left) vs. RRT* (right) [Karaman]

RRT* is asymptotically optimal, but can be hard to implement for underactuated systems

Solution 2 of 2 (Performance) Choose-Parent Procedure

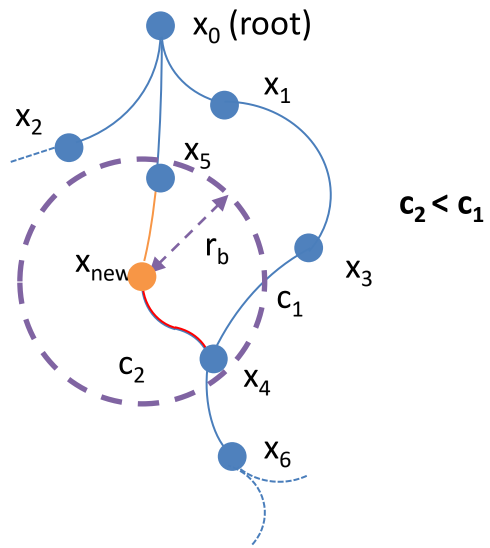




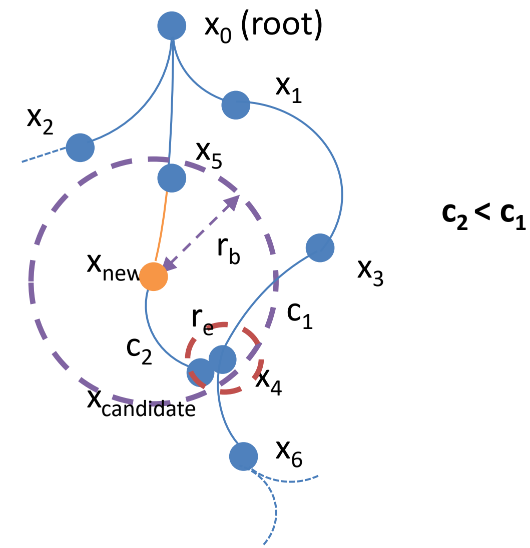
Choose-Parent improves trajectory quality when new nodes are added to the tree

Solution 2 of 2 (Performance) Rewire Procedure

RRT*



Rewire-RRT



Rewire improves trajectory quality within the existing tree

Results and Conclusions

Static Planning Setup

- 50 trials per algorithm
- Three seconds of tree growth
- Evaluate lowest-cost path in tree

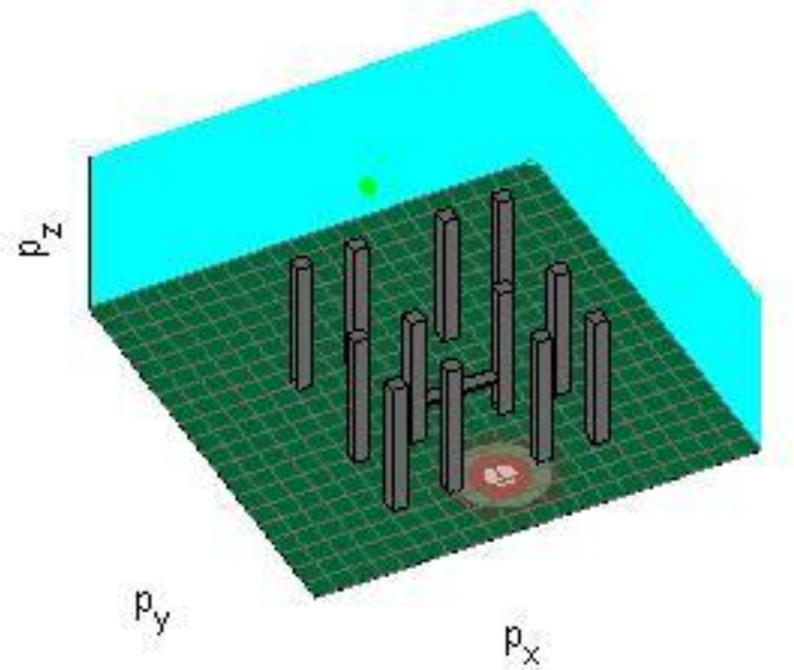


Figure 10: Simplified urban drop-zone with buildings and bridge

Static Planning Results

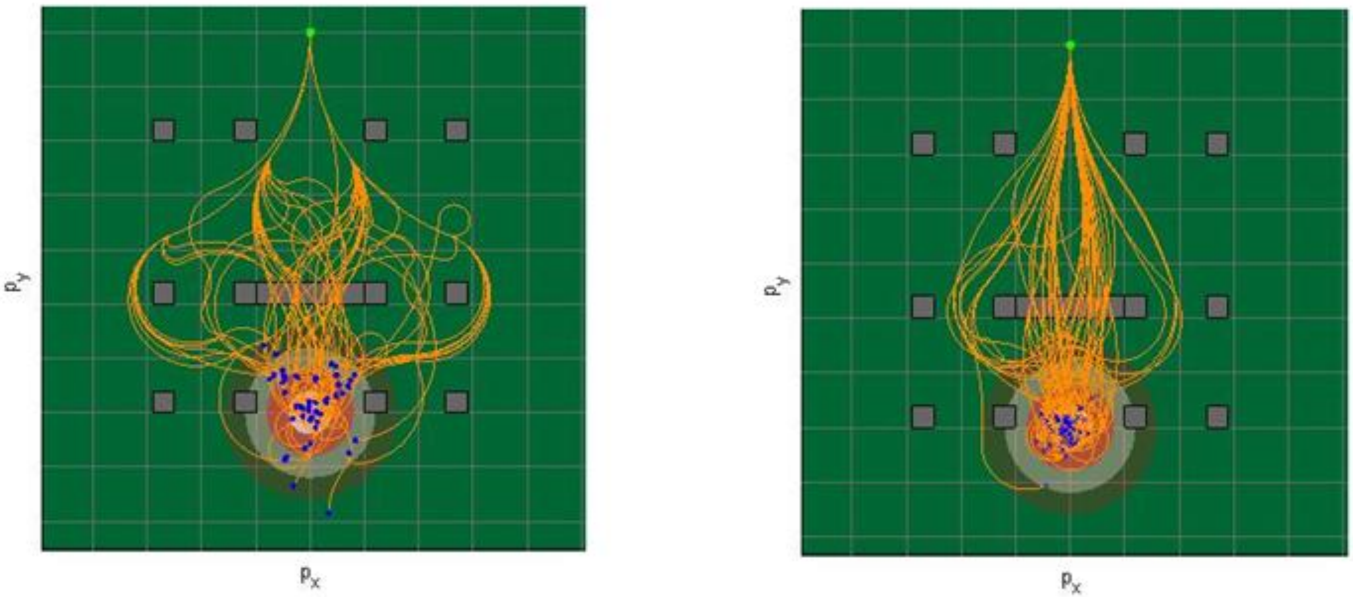


Figure 11: RRT (left) vs Rewire-RRT (right)

Mean miss distance for Rewire-RRT is reduced 29%

Simulation Setup

- Monte-Carlo simulations of entire flight profile
- Utilizes Draper's extensively verified parafoil simulator
- 50 trials per algorithm

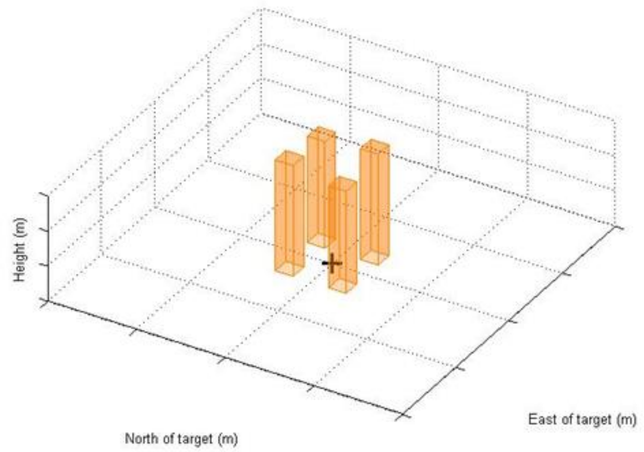


Figure 11: Simplified urban drop-zone for simulation experiments

Simulation Results

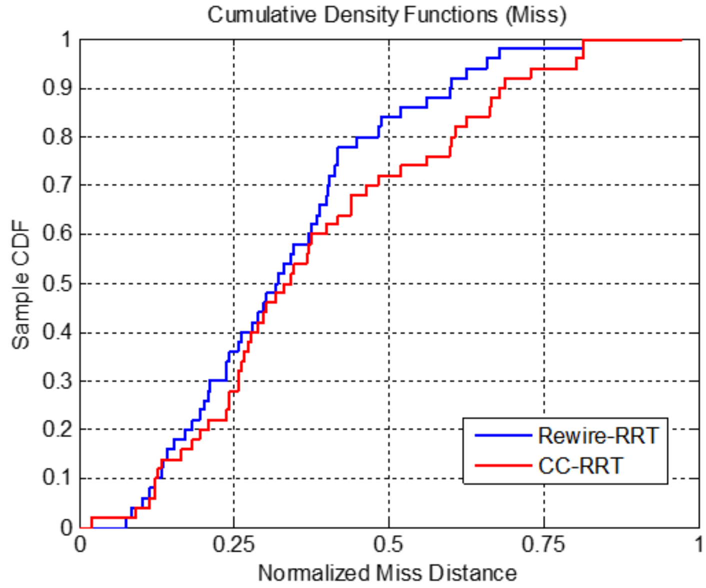


Figure 11: Cumulative density function of normalized miss distance

Demonstrated improvements with Rewire-RRT:

- Mean miss distance reduced 9%
- Miss distance at 80^{th} percentile improved 22.9%

Conclusions

- Rewire-RRT is a sampling-based parafoil path-planner that explicitly minimizes the risk of collision with obstacles along each path and minimizes the expected final miss distance from the target.

- Contributions:
  - Novel cost function considering the airdrop objectives
  - A fast, analytic method to rewire the tree for the under actuated parafoil system
  - Simulation results that demonstrate the ability of Rewire-RRT to find better paths through the environment than RRT and CC-RRT.

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Thank you!
Questions/Comments?

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