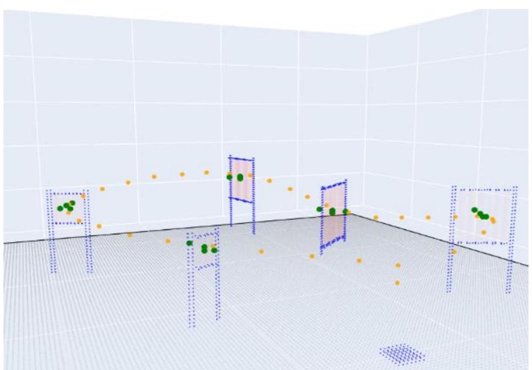
Optimizing Quadrotor Trajectories with Spline Geometry

Andrew Brown (370751)

Professor : Alcherio Martinoli
Assistant(s) : Alexander Wallén Kiessling

The rapid growth of drone racing has underscored the need for advanced trajectory planning methods that strike a balance between speed, safety, and dynamic feasibility. While consumer drones now enable accessible racing, the underlying mathematics of optimal path planning remains challenging, particularly when navigating complex environments with obstacles. This research examines the geometric intricacies of how spline interpolation can generate optimal racing trajectories that possess three key characteristics: geometric flexibility, dynamic feasibility, and implementation simplicity.

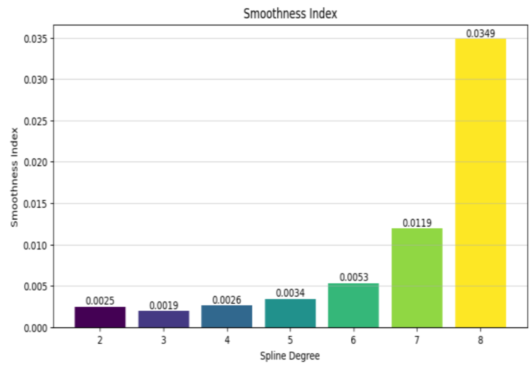
Through extensive quantitative and simulation testing, we demonstrate that cubic (degree 3) and quartic (degree 4) B-splines provide the optimal balance between smoothness and local control. While higher-degree polynomials theoretically offer greater continuity, they reduce local control and introduce unpredictable behavior, as evidenced by increased jerk and snap metrics. Our quantitative analysis reveals nearly identical performance between degree 3 and 4 splines in both obstacle-free and obstacle-rich environments, with average lap times differing by less than 0.2 seconds across all test cases.



Discretized drone racing environment with B-spline Path

The research uncovered two key findings:

1. B-splines, particularly those of degree 3 and 4 polynomials, provide the most suitable basis for drone racing applications, both with and without obstacles.
2. In both obstacle-free and obstacle-rich environments, degree 3 splines achieve the lowest smoothness index, while degree 4 splines minimize the maximum jerk and snap.



Comparison of the Smoothness Index of B-spline-interpolated paths of various polynomial degrees

The proposed pipeline combines B-spline interpolation with simple safety constraints, such as obstacle margins and elastic band repulsion fields, creating a straightforward solution for racing applications, including student drone racing teams. The method's effectiveness stems from the inherent properties of B-splines: local control for obstacle avoidance and guaranteed continuity for smooth motion. While current simulation controls limited our ability to demonstrate more pronounced performance differences between polynomial degrees, the framework provides a foundation for future work in trajectory optimization.

This work demonstrates that cubic and quartic B-splines offer the most practical solution for generating trajectories for racing drones. Future improvements could focus on incorporating drone dynamic constraints through quadratic programming, utilizing clothoids to smooth gate transitions, and enhancing the simulation environment to enable more aggressive flight.