MPC for Spacecraft RVD - A Problem Statement

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1 Problem Statement

Spacecraft Rendezvous and Docking (RVD) is a critical operation in modern space missions, requiring a chaser spacecraft to approach and dock with a target in orbit with extremely high precision. The maneuver involves controlling the spacecraft in six degrees of freedom—three translational and three rotational—while satisfying strict safety and performance constraints. Precise trajectory tracking, alignment, and orientation are essential to prevent collisions, misalignments, or mission failure, particularly during the close-proximity final-phase docking.

Achieving such precision is challenging due to the inherently nonlinear and coupled dynamics of spacecraft, the influence of orbital perturbations, and limitations in actuation. Traditional linear controllers, while effective in simple scenarios, may struggle to handle complex trajectory optimization and constraint management over extended horizons.

This project investigates the application of Model Predictive Control (MPC) as a robust and flexible framework for autonomous spacecraft RVD across all operational phases, including far-field approach, mid-field rendezvous, and final-phase docking. MPC enables the chaser spacecraft to anticipate future states, optimize control inputs over a prediction horizon, and satisfy constraints on actuator capabilities, collision avoidance, and alignment requirements. By explicitly accounting for the full six-degree-of-freedom dynamics and operational constraints, the proposed control strategy aims to ensure precise, safe, and reliable docking in a fully autonomous setting, demonstrating the potential for high-fidelity guidance and control in complex space operations.

1.0.1 Proposed Control Architecture

This project proposes a control system for autonomous spacecraft Rendezvous and Docking (RVD) that leverages the strengths of Model Predictive Control (MPC) for precise trajectory tracking and constraint satisfaction. MPC is applied across all operational phases—far-field, mid-field, and final-phase docking—allowing the controller to anticipate future states and optimize control inputs over a prediction horizon while satisfying constraints on actuator capabilities, alignment, and collision avoidance.

Linear Quadratic Regulation (LQR) is used as a benchmark for comparison. While LQR provides fast and stable control for simple scenarios, it lacks the ability to explicitly handle constraints, non-linearities, and trajectory optimization over a horizon. MPC, on the other hand, captures these aspects, providing a more flexible and high-performance framework suitable for fully autonomous RVD operations.

1.0.2 Plant Model and Simulation Setup

- The plant is modeled using linearized 6-DOF dynamics, assuming rigid body behavior.
- Translational dynamics are derived from the Clohessy-Wiltshire-Hill (CWH) equations for relative orbital motion, while rotational dynamics are represented using a simplified linear attitude model.
- Full-state observability is assumed; sensor faults and partial observability are reserved for future work..

1.0.3 Benchmarking and Evaluation

The following controllers will be compared under identical mission profiles across far-field, mid-field, and final-phase docking:

1. **LQR (baseline)** – standard linear controller for unconstrained systems.
2. **Standard MPC** – optimized for trajectory tracking and constraint satisfaction across all phases, capturing nonlinearities, actuator limits, and collision avoidance.

The evaluation focuses on precision in trajectory tracking, alignment accuracy, actuator effort, and overall ability to satisfy constraints. MPC is expected to outperform LQR by explicitly optimizing over a horizon and handling constraints that LQR cannot.