Comparative Analysis of Sliding Mode and Proportional-Derivative Controllers on a Flexible Quadrotor

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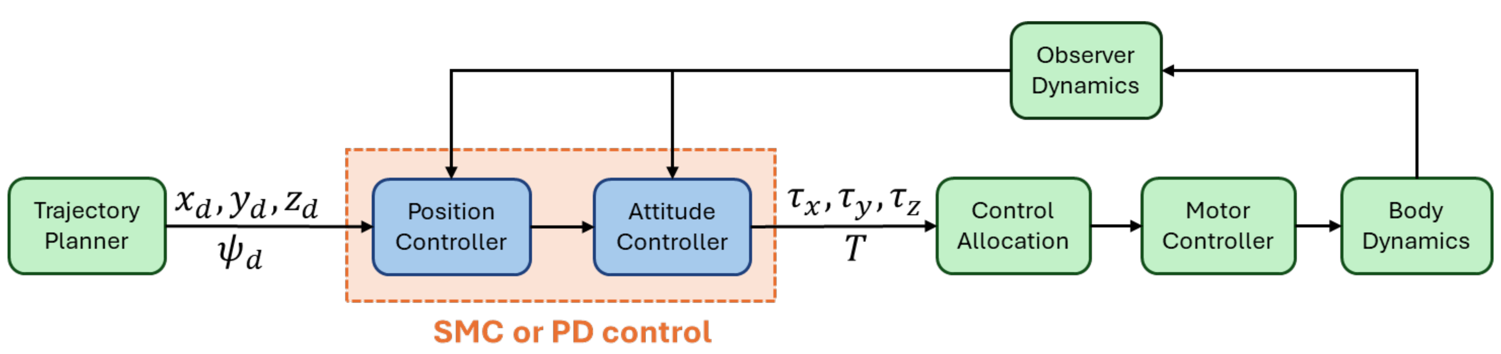
Introduction

The U.S. Navy prioritizes safety and efficiency in all its operations. Similarly, ship-board tasks adhere to these principles, but safety and time efficiency can be further enhanced by deploying quadrotors to replace personnel in hazardous and repetitive maintenance roles. This technology can help keep crew members healthier and more available for other duties, ensuring the continued dominance of the world's strongest naval force.

Quadrotors are extensively used in industrial and recreational applications and typically employ Proportional-Derivative (PD) or Proportional-Integral-Derivative (PID) controllers. These controllers handle well for small quadrotors in calm environments, but lack the robustness needed to control larger quadrotors where many disturbances are present.

Sliding Mode Control (SMC) has been demonstrated to be a robust control scheme. Implementation of SMC on a quadrotor can provide the necessary robustness to make quadrotors a viable platform for getting people out of harms way.



A controller using PD or SMC share the same input and outputs handled by the quadrotor's processor. Treating the vehicle as flexible, rather than rigid, does not change this but does create a nonlinear system. To be flexible means to account for the torques and moments that the propellers and motors force onto the arms of the quadrotor [1]. The nonlinear dynamics defining the quadrotor's movement can be hard for the PD controller to work through. However, SMC can handle these nonlinear dynamics and accurately maneuver the tight, swaying confines of a naval ship.

SMC accounts for the nonlinearities of the flexible quadrotor primarily due to its use of a sliding hyperplane concept. Once this hyperplane mathematically achieves its designed position, the system can then be treated as linear. If any disturbances occur, the hyperplane will force the system back to linearity [2].

Objectives

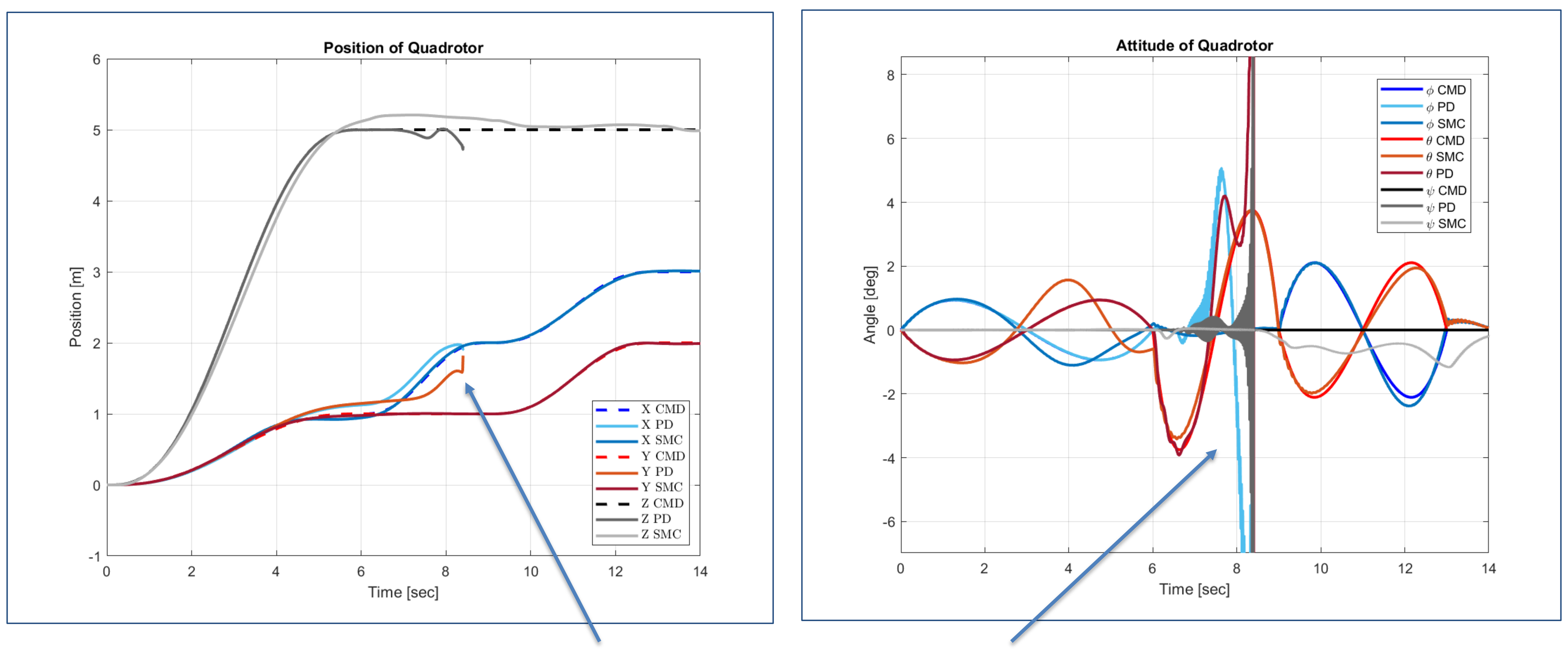
- Investigate the robust controller design for an autonomous quadrotor under structural flexibility and external wind disturbances.
- Compare the quadrotor's tracking performance using SMC and PD control.

Methodology

- Combine SMC and PD controllers into a flexible quadrotor 6DOF flight simulation.
    - PD controller developed by myself
    - Sliding mode controller developed by Dr. Smith
- Execute both controllers individually, then concurrently.
- Use flight path of (0,0,0), (1,1,5), (1,2,5), and (2,3,5) at times of 0, 6, 9, and 13 seconds respectively.
- Add wind disturbance by forcing an increase in rotor RPM.
- Compare tracking performance of both algorithms.
    - Position
    - Attitude
- Analyze the different hyperplane behaviors.

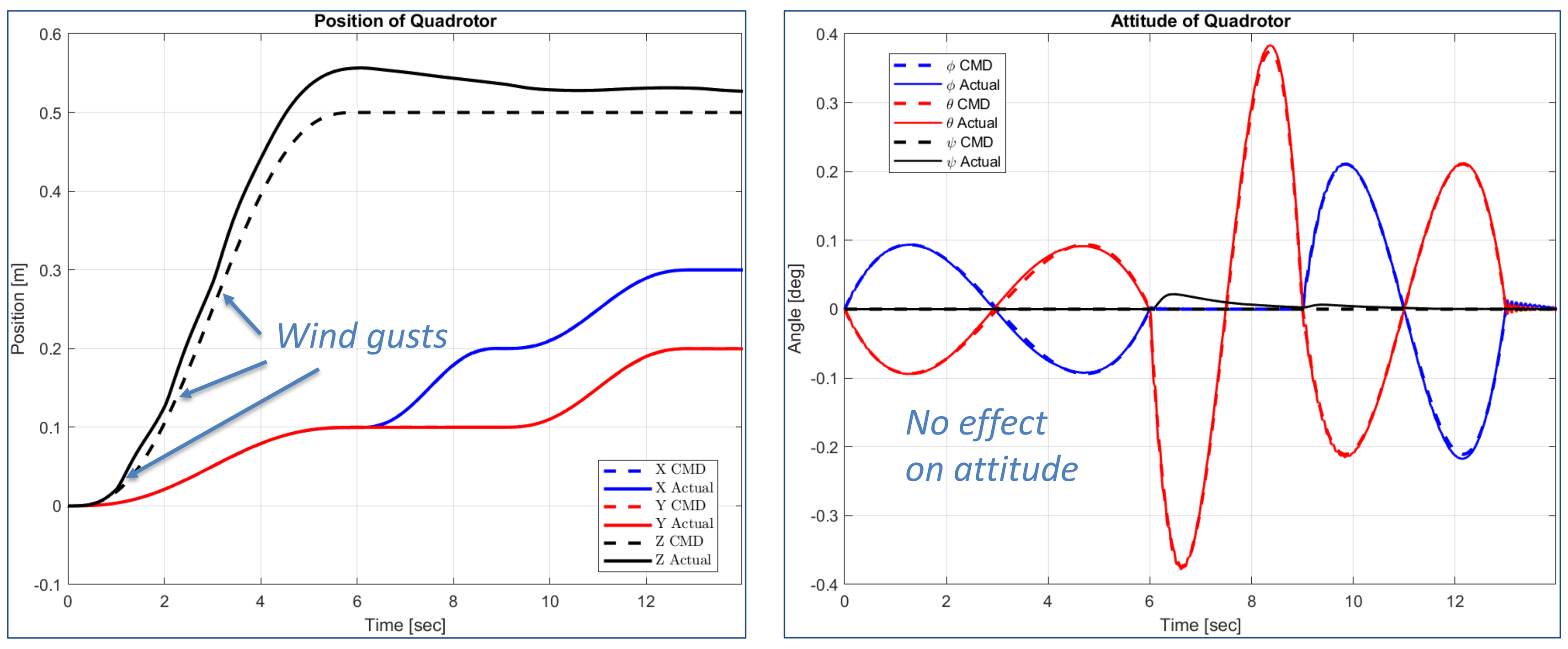
Results / Analysis

- SMC outperforms the PD controller by handling the structural disturbances of the flexible quadrotor

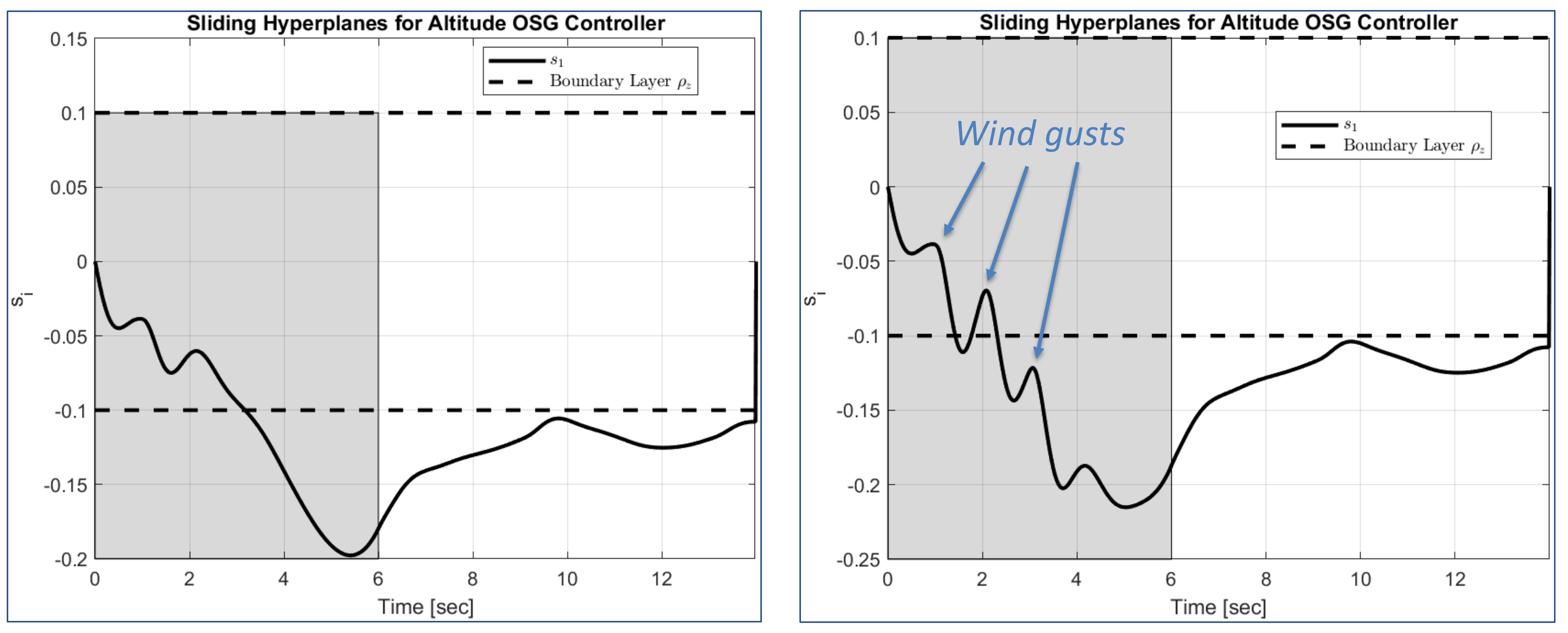


PD controller fails at ~8.5s, just before the second waypoint

- Wind gust disturbance is added to the SMC to test robustness
    - An instant 5% increase in rotor RPM at 1s, 2s, and 3s



- Analyzing the hyperplane responsible for altitude with and without wind gust disturbance



SMC forces the quadrotor control system to linearity and recovers from the disturbances

Future Objectives

- Adapt the written MATLAB scripts to Python or C++ and optimize for efficiency to decrease runtime.
- Implement the Sliding Mode controller into a real quadrotor to test in real life.

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References

[1] C. S. Smith, "Dynamics and Control of Flexible Quadrotor Aircraft." Order No. 30720571, The Pennsylvania State University, United States -- Pennsylvania, 2023.
[2] J.-J. E. Slotine and W. Li, Applied Nonlinear Control. Englewood Cliffs, NJ, USA: Prentice-Hall, 1991.