Propellant-free Spacecraft Relative Maneuvering via Atmospheric Differential Drag -- Research Activities and Accomplishments

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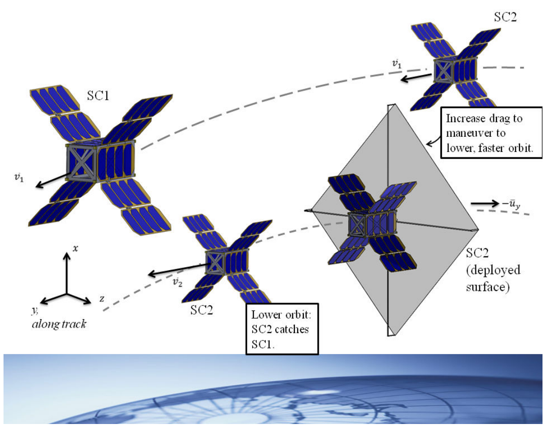
1. Guidance and Control

Guidance and Control algorithms are being designed and tested for autonomous propellant-less maneuvering of Low Earth Orbit (LEO) spacecraft (S/C) using atmospheric Differential Drag. These Guidance and Control algorithms and the results of the high fidelity numerical simulations are summarized in this section.

a) Lyapunov control



A Lyapunov controller was designed and tested inspired on [1]. Lyapunov principles were used to develop a criterion for the activation of the actuators of the surfaces (see image on the side) which generate the Differential Drag. More specifically, the controller signal is chosen such that the Lyapunov function of the tracking error is positive, and the derivative of the Lyapunov function is negative, thus ensuring that the tracking error converges to zero. The Lyapunov controller can be used to force the nonlinear model (that is the dynamics of the Target and Chaser S/C) to directly track a desired constant final state, a desired guidance trajectory, or the dynamics of a linear reference model. The model from [2] was chosen as reference since it is able to represent the effects of J2 .

b) Critical Value

An analytical expression for the Differential Drag acceleration critical value that ensures stability in the sense of Lyapunov for the system was found. This expression can be calculated in real time, and provides a lower bound for the drag acceleration necessary to ensure that the Lyapunov controller is able to force the system toward the desired states.

c) Adaptive Lyapunov Controller

The control strategy was further refined. A new Adaptive Lyapunov Controller, which uses adaptation to choose in real time an appropriate positive definite matrix $\underline{\boldsymbol{P}}$ in a quadratic Lyapunov function, was designed and tested. Analytical expressions for the partial derivatives of the critical value with respect to the independent variable matrices required by the Lyapunov controller were derived. These partial derivatives were used for the development of the adaptation strategy for the Lyapunov function. The adaptation consist on modifying the quadratic Lyapunov function in real time, during flight, minimizing the value of the Differential Drag critical acceleration, thus maximizing the control authority margin.

d) Rendezvous

A guidance methodology for rendezvous maneuvers using Differential Drag has been selected. This methodology was presented in [3] and [4] . Simulations were performed for the following cases:

1) The Lyapunov controller is used to force the nonlinear system to directly track the analytically generated guidance trajectory
2) The Lyapunov controller forces the nonlinear system to track the trajectory of the reference model which is regulated, thus driving both models to the origin
3) The Lyapunov controller forces the nonlinear system to track the trajectory of the reference model which is tracking the analytically generated guidance trajectory.
4) The Lyapunov Controller is used directly to regulate the nonlinear dynamics without the intervention of the reference model

Simulations indicate that for rendezvous the cases in which the controller acts as a regulator give better results in terms of maneuver duration and control effort (see [5]). When regulating, the controller drives the sates to zero, that is both target and chaser S/C have the same positions and velocity and therefore have rendezvoused. Furthermore, simulations of two S/C using both the Lyapunov and Adaptive Lyapunov Controller for the fourth case were performed. These simulations (see Fig. 1) show that the Adaptive Lyapunov controller outperforms the Lyapunov Controller in terms of maneuver duration (29 hr vs. 38 hr) and control effort (55 vs. 113 rotations of the panels) (see [6]).

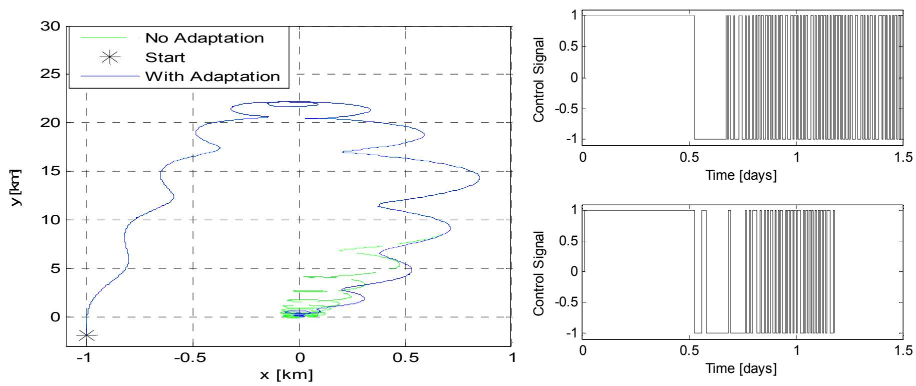


Fig. 1 Rendezvous Regulation simulation results: Trajectory (Left). Control signals for no adaptation (Right Top) and adaptive controllers (Right Bottom)

For all the simulations, the guidance and control algorithms have been programmed in MATLAB. These algorithms interact with STK via STK Connect. STK's High-Precision Orbit Propagator (HPOP) has been used for modeling the mechanics of the maneuver, including J2 perturbations, solar pressure radiation and atmospheric drag using the empirical NRLMSISE-00 model.

e) Re-Phase

Both the Lyapunov and Adaptive Lyapunov Controller have been used in simulations for the Re-Phase maneuver. The Controllers are used to regulate (fourth case) the error between the simulated relative positions and velocities and the desired final relative positions and velocities (those of the orbits with the desired phase difference). The Adaptive Lyapunov controller again offers better performance in terms of maneuver duration (11 hr vs. 13 hr) and control effort (45 vs. 62 rotations of the panels) (see Fig. 2).

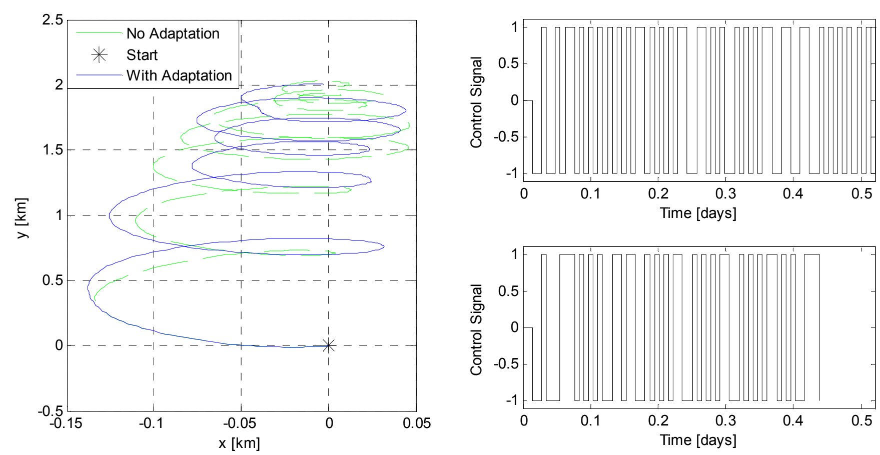


Fig. 2 Re-Phase Regulation simulation results: Trajectory (Left). Control signals for no adaptation (Right Top) and adaptive controllers (Right Bottom)

f) Fly-Around

The guidance methodology developed in [7] has been selected for the Fly-Around maneuver. Both the Lyapunov and Adaptive Lyapunov Controller have been used in simulations for the Fly-Around maneuver. For this maneuver, regulation is no longer used since the desire final state is not a constant final relative positions and velocities, but stable relative orbits of the chaser about the target. Hence, the controllers force the nonlinear dynamics to follow the desired Fly-Around guidance and not just to converge to a final state (First case). The simulations show that the implementation of the adaptive controller results in a final orbit with some drift but much closer to the desired final stable orbit (See Fig. 3 Left).

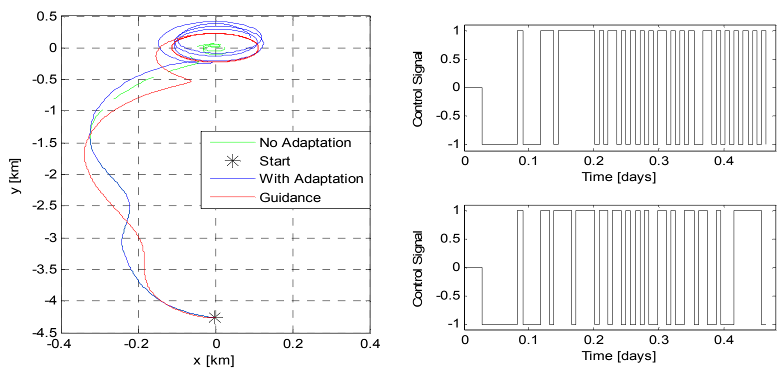


Fig. 3 Re-Phase Guidance tracking simulation results: Trajectory (Left). Control signals for no adaptation (Right Top) and adaptive controllers (Right Bottom)

2. Origami-Based Drag Sail

Differential Drag Sail for CubeSat is an ongoing project in the ADAMUS Lab at RPI that is an effort to create a drag sail that is attached to a CubeSat and can be opened and closed as desired. This sail is being designed to be a modular 0.5U block that can be attached to the back of any CubeSat and will allow satellites to perform relative maneuvers using accelerations provided by the atmospheric drag present in LEO. The project began as part of a class in the spring 2012 semester and has continued over the summer to its current state. Current state sees the sail based on a origami folding pattern, minimizing the contracted volume, and maximizing the deployed surface.

3. Achievements

Perez, D., Bevilacqua, R., "Differential Drag Spacecraft Rendezvous using an Adaptive Lyapunov Control Strategy", accepted for publication on Acta Astronautica, to appear.

BEST STUDENT PAPER AWARD FOR THE CATEGORY: SPACECRAFT GUIDANCE, NAVIGATION, AND CONTROL. 1st International Academy of Astronautics Conference on Dynamics and Control of Space Systems – DyCoSS'2012, Porto, Portugal, 19-21 March 2012.

BEST ORAL PRESENTATION in the Theoretical Category:Undergraduate research by Skyler Kleinschmidt at the Rensselaer's Third Annual Undergraduate Research Symposium: "Origami-Based Drag Sail for Differential Drag Controlled Satellites", Wednesday, April 4, 2012.

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