Attitude Dynamics and Control of Solar Sails with Articulated Vanes

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Abstract

In this paper we develop a robust nonlinear algorithm for the attitude control of a solar sailcraft with M single degree-of-freedom articulated control vanes. A general attitude controller that tracks an admissible trajectory while rejecting disturbances such as torques due to center-of-mass to center-of-pressure offsets is applied to this problem. We then describe a methodology based on nonlinear programming to allocate the required control torques among the control vanes. A simplified allocation strategy is then applied to a solar sail with four articulated control vanes, and simulation results are given. The performance of the control algorithm and possible limitations of vane-only control are then discussed.

1 Introduction

The search for alternative methods of spacecraft propulsion has led to an increased interest in solar sail technology [3, 1, 7]. As a result, a number of various mechanizations have been proposed to perform three-axis attitude control of solar sails. For example, center-of-mass to center-of-pressure (CM-CP) offset using a gimbaled sail-mounted boom (e.g., bi-state gimbal mechanization [2]), control vanes [4], sail panel translation/warping [5], and free-moving ballast masses [6] are all mechanizations of current interest. In this paper, we focus on attitude control of solar sails using only control vanes. Here the idea is to utilize small (compared to the area of the sail) reflective control vanes located at the spar

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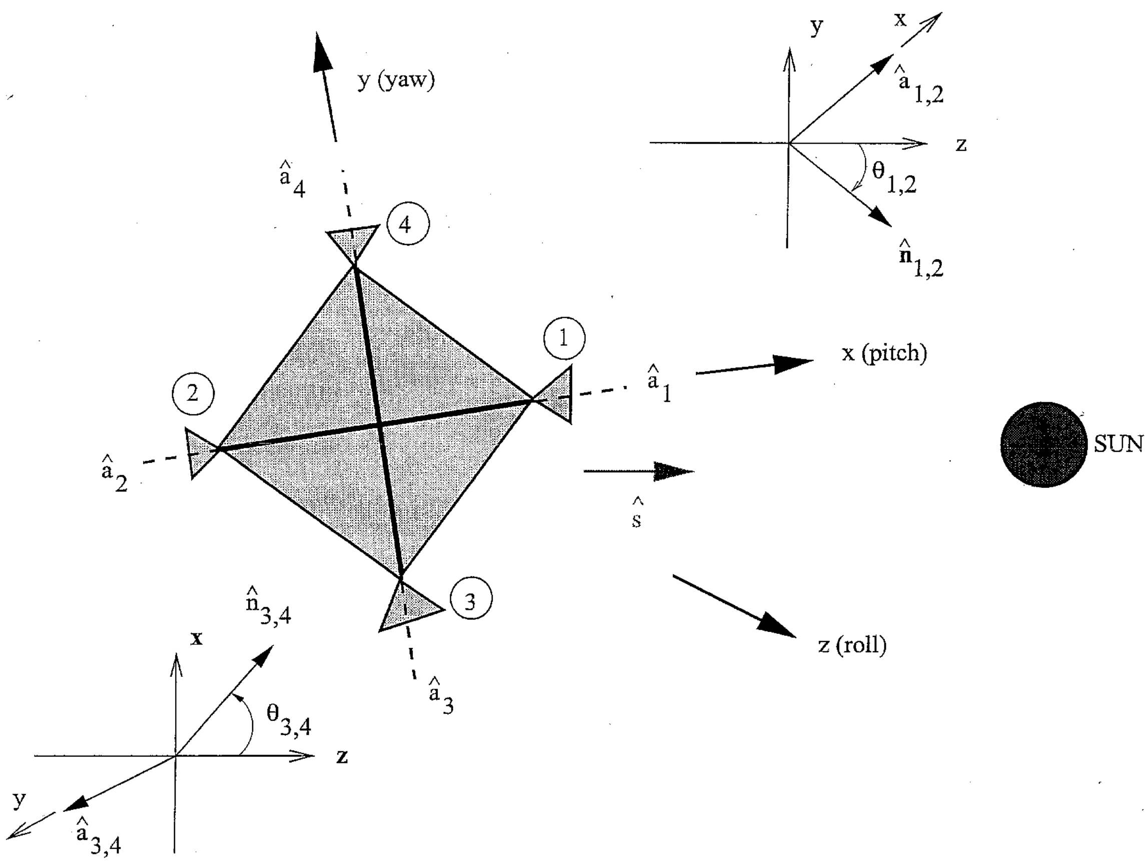

Figure 1: Solar Sail with Four Vanes

tips of the sail. A preliminary analysis of vane control has been presented in [4]. We extend the insight to this problem, and develop a robust nonlinear control algorithm for solar sails with an arbitrary number of single axis vanes. We also describe a methodology based on nonlinear programming to allocate the required control torques among the control vanes. The resulting algorithm is applied to a model of a square sail with four spar-tip mounted vanes. See Figure 1. In order to assess control authority, and control performance under vane-only control, the control/torque allocation algorithms are tested in simulation. Finally, benefits/limitations of vane-only control are discussed and some important areas for future study are suggested.

2 Results and Conclusions

The attitude control strategy developed here is based on utilizing an adaptive attitude controller that tracks a given trajectory while rejecting disturbances such as torques due to center-of-mass to center-of-pressure offsets. The controller has a standard PD (proportional-derivative) part, a feed-forward part, as well as a dynamic component which acts like a generalized integrator. The adaptive attitude controller globally tracks reference signals when there is no actuator constraints such at saturation and delay. As a result, the performance of the controller under vane saturation and delay is an important aspect of this research. An algorithm to allocate the control torque between the four vanes is also developed. The conclusions of this research are summarized as:

- A robust nonlinear control algorithm is implemented with a practical and onboard implementable control allocation algorithm. The simulation results show that the controller have good stability and performance characteristics.

- There is intentional bounded limit-cycling around the roll axis when the proposed control allocation algorithm is used. This occurs because we assume that the vane commanding is not instantaneous but done every Δt seconds. This cyclic motion can be reduced via selection of the vane areas and reducing the vane angle commanding interval Δt.

- The vane angle commanding at every Δt seconds puts limitations on the closed loop performance. Further performance improvements require smaller Δt that may not be realizable in flight hardware. Also, vane surface flatness can be an issue for areas that approach 20% of the sail dimensions.

- CM-CP offset impacts vane control dynamic range, and must be constrained to minimum achievable values. Our simulations show that the vanes must be capable of providing torques that are at least twice of the disturbance torque caused by CM-CP offset, in order to have good control performance. For a sailcraft, where the vane area is one hundredth of the sail area, this corresponds to an upper bound of 0.5% on the ratio of CM-CP offset to sail length. The simulations also show that acceptable turn rates can be achieved when this condition is satisfied.

- As a future research objective, it will be very useful to establish explicit nonconservative bounds on the region of attraction for the closed loop error dynamics.

- We assume perfect state knowledge in the simulations presented in this paper. The effects of measurement noise on the control performance will be investigated as a part of future research.

- Profiling the angle and angular rate commands can improve the control performance, and this is a future research objective.

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