Controlling Nanosatellite Formations Using Drag Panels

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Mechanical & Aerospace Engineering 207 - Advanced Astrodynamics
15 December 2023

I. Abstract

This study investigates (1) the significance of drag perturbations on nanosatellites in formation flying and (2) using drag panels to control and maintain the orbits of satellites in formation. The drag panels change the cross-sectional area of the nanosatellites, which increase or decrease the drag force on the satellite. From simulating a simple two-satellite formation with a chief and deputy, a change in area of 10% can lead to significant drift between the satellites. Another simulation implemented a simple law that controlled the drag sail's area over time. The satellites with controlled areas were bounded within a distance between each other, while the satellites with constant areas were unbounded and began to drift further and further from one another. This showed that adjusting the drag panel on a satellite can help in maintaining a spacecraft formation.

II. Introduction

Spacecraft formation flying is a method of using more than one satellite to accomplish the goal of a single satellite. Examples of these goals include communication or imaging. Formations can be much more efficient and less expensive than one satellite with the same objectives [1].

Nanosatellites are a classification of satellites that are low in mass and size. The Dove satellite is a cluster of nanosatellites that fly in formation within the Earth's atmosphere to continuously image the planet's surface. Nanosatellites, like all satellites, are subject to different kinds of perturbations. They are particularly subject to drag perturbations, due to their high surface-area-to-mass ratio. These perturbations can cause satellites in formation to drift apart from one another. However, the differential drag between satellites can be used to control the satellite's drag perturbations and thus their orbits and formation. As shown in Figure 1, this can be done by designing satellites with drag panels that change their cross-sectional area and thus their drag perturbations.

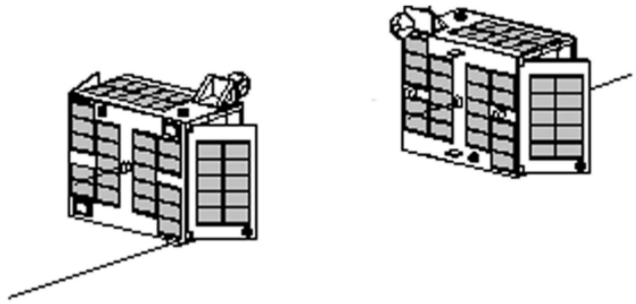

Figure 1: Example of formation keeping with drag panels [2].

Control of satellites in formation can be done with a propulsion system, but due to the size limitations of nanosatellites, this may not always be possible. Thus, controlling the orbits of nanosatellites using drag panels can save mass on the spacecraft. [2]

III. Technical Statement of Problem

The satellites' orbits can be described using Newton's Equations in an inertial frame. With N satellites in the formation, acceleration can be calculated using

$$\vec{a}_N = \frac{-\mu}{r_N^3}\vec{r}_N + \vec{a}_{D,N},$$

where the acceleration due to drag is

$$\vec{a}_{D,N} = -\frac{C_d A \rho v_N^2}{2m_N}\frac{\vec{v}_N}{|\vec{v}_N|},$$

r_N is the radius vector, v_N is the velocity vector, m is the satellite mass, $\mu = 3.986\times10^5 \frac{km^3}{s^2}$ is the standard gravitational parameter of Earth, C_d is the satellite drag coefficient, A is the satellite cross-sectional area, and ρ is the atmospheric density. [2]

The radius and velocity vectors can be used to compute the classical orbital elements, namely the semi-major axis, eccentricity, inclination, argument of periapsis, longitude of the ascending node, and mean anomaly.

IV. Specific Problem Analyzed

To simplify the problem of spacecraft formation flying, only two satellites are studied, a chief satellite and a deputy satellite. The orbits are assumed to be approximately circular (i.e. the eccentricity is close to zero). The satellites' orbits are studied by simulating the drift between the two satellites due to drag perturbations. Only drag perturbations are studied; other types of perturbations, such as J2 or solar radiation pressure, are considered negligible.

The satellites begin at an altitude of 400 km above the Earth's surface, with a mass of 5.8 kg (modeled after the Dove satellites) [3]. They are assumed to have an effective cross-sectional area of 0.09 m^2, though they have drag panels that can increase their cross-sectional area by up to 10%. The drag coefficients are assumed to have a constant value of 2.0 [2].

Mean Orbit Elements	a (km)	e	i (°)	□ (°)	ω (°)	M (°)
Chief	6778	0.05	64.9	0	30	0
Deputy	6778	0.0501	64.901035	0.005	30.01	-0.01
Difference	-3.519e-4	0.0001	0.001035	0.005	0.01	-0.01

Table 1: Classical orbital elements used for chief and deputy satellite simulations, as well as their difference.

As time goes on and the satellites travel their orbits, the satellites begin to drift apart from each other due to their differential drag. These orbits are examined to see if the drift between the satellites is significant. The drag panels can change the effective cross-sectional area of the satellites to study the effects of drag perturbations on the spacecraft formation.

V. Solution Techniques and Validation

A. Relative Orbit Comparison with Identical and Differing Areas

First, a simulation of relative orbit comparisons is done with a chief and deputy satellite, where both satellites have a constant cross-sectional area of 0.09 m^2. As time goes on, the displacement vector between the two satellites is plotted to see the changes in displacement for each orbit.

To contrast with equal cross-sectional areas, a simulation shows the relative orbit comparison for satellites with differing cross-sectional areas, namely $A_{c,chief}$ = 0.09 m^2, $A_{c,deputy}$ = 0.099 m^2. Due to the deputy satellite's higher cross-sectional area, it is subject to more drag perturbations. Thus, for each successive orbit, the drift between the chief and deputy satellites increases.

Each simulation is run for a length of 45 periods, which corresponds to a total of 2.895 days. This allows for sufficient time for the orbits of the chief and deputy satellites to have significant drift. These simulations are compared to study the effects of cross-sectional area on drift.

B. Distance Between Satellites for Constant and Changing Areas

With significant drift between spacecrafts in formation, the control of the satellites' orbits using differential drag is investigated. The chief and deputy are simulated to compare satellites with constant area and satellites with changing area over a length of 90 periods, which corresponds to a total of 5.971 days. In the first simulation, both the chief and the deputy have constant cross-sectional areas of $A_{c,chief}$ = $A_{c,deputy}$ = 0.0945 m^2.

In the second simulation, the chief has a constant cross-sectional area of $A_{c,chief}$ = 0.0945 m^2, while the deputy begins with an area of $A_{c,deputy}$ = 0.0945 m^2 but changes throughout the simulation. The deputy's area changes every 0.9 periods, or 1.390 hours. For t = 0 to t = 2.316 days, the area decreases by 0.0001 m^2, until it has an area of $A_{c,deputy}$ = 0.0905 m^2. For t = 2.316 days to t = 4.053 days, the area increases by 0.0002 m^2, until it has an area of $A_{c,deputy}$ = 0.0965 m^2. For t = 4.053 days to t = 5.791 days, the area decreases by 0.0001 m^2, until it has an area of $A_{c,deputy}$ = 0.0935 m^2.

In both simulations, the distances between the chief and the deputy are calculated by taking the magnitude of the difference of their radius vectors. The two simulations are compared over time.

VI. Discussion

A. Relative Orbit Comparison with Identical and Differing Areas

The simulations show that the satellites have more drift when the cross-sectional areas are different compared to when they are the same. This can be seen in Figures 2 and 3, where the orbits in Figure 3 drift significantly further than in Figure 2.

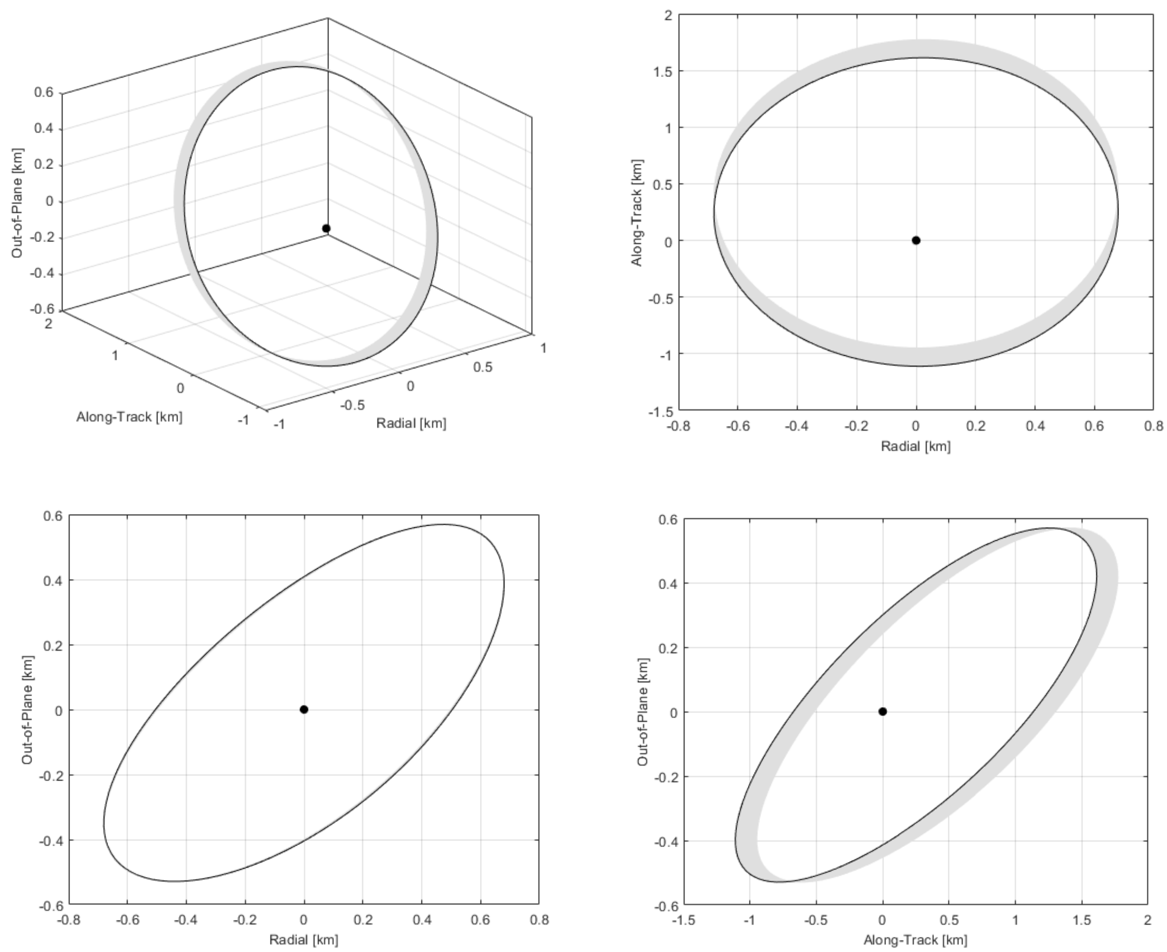

Figure 2: Relative orbit comparison for satellites with identical cross-sectional areas (A_c = 0.09 m^2)

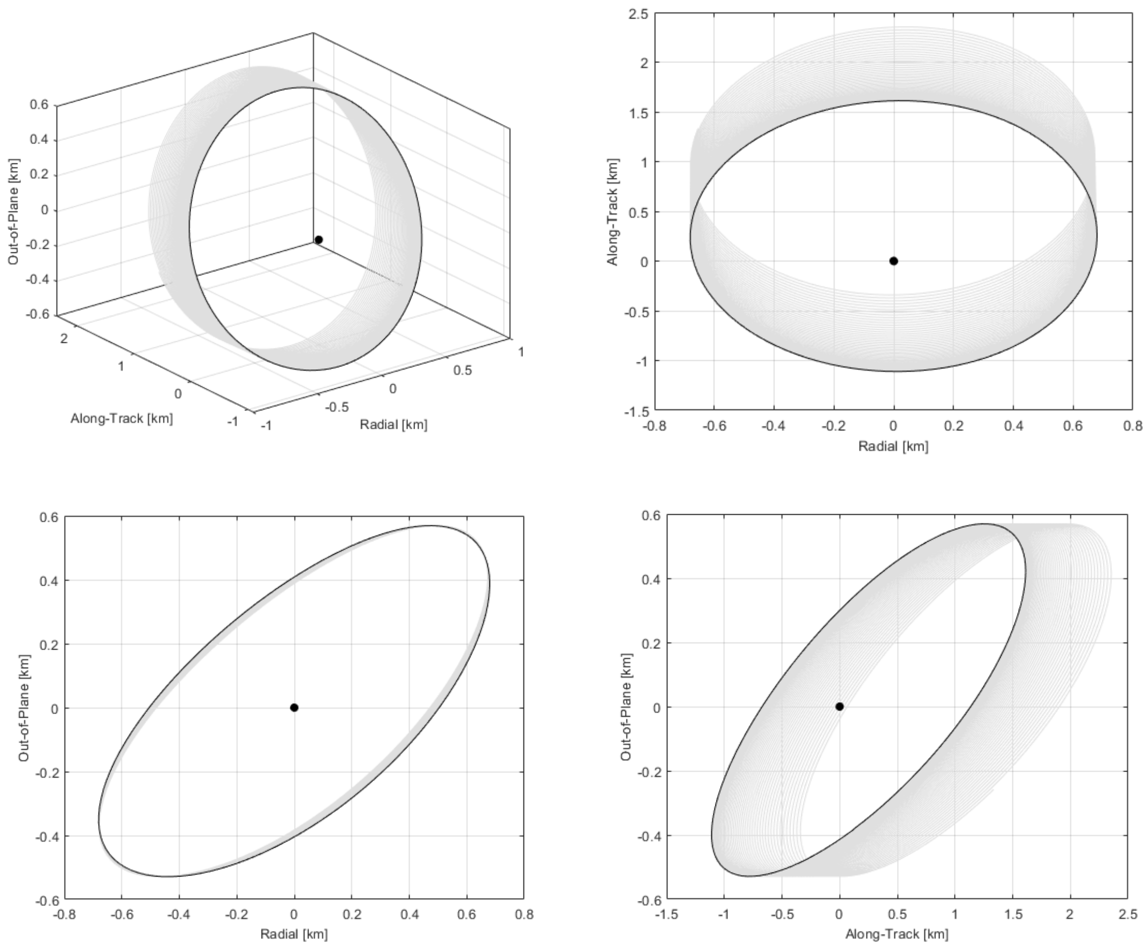

Figure 3: Relative orbit comparison for satellites with cross-sectional areas differing by 10% ($A_{c,chief}$ = 0.09 m^2, $A_{c,deputy}$ = 0.099 m^2)

The maximum distance between the satellites with identical areas is 1.825 km, while the maximum distance between the two satellites with differing areas is 2.393 km. By increasing the cross-sectional area of the deputy satellite by 10%, the maximum distance between the satellites increased by 23.7% over a period of 2.985 days. In other words, the satellites with differing areas drifted an average distance of 0.190 $\frac{km}{day}$ further than the satellites with identical areas.

B. Distance Between Satellites for Constant and Changing Areas

After 90 periods, the satellites with constant area drift further apart than the satellites with changing area, as seen in Figure 4.

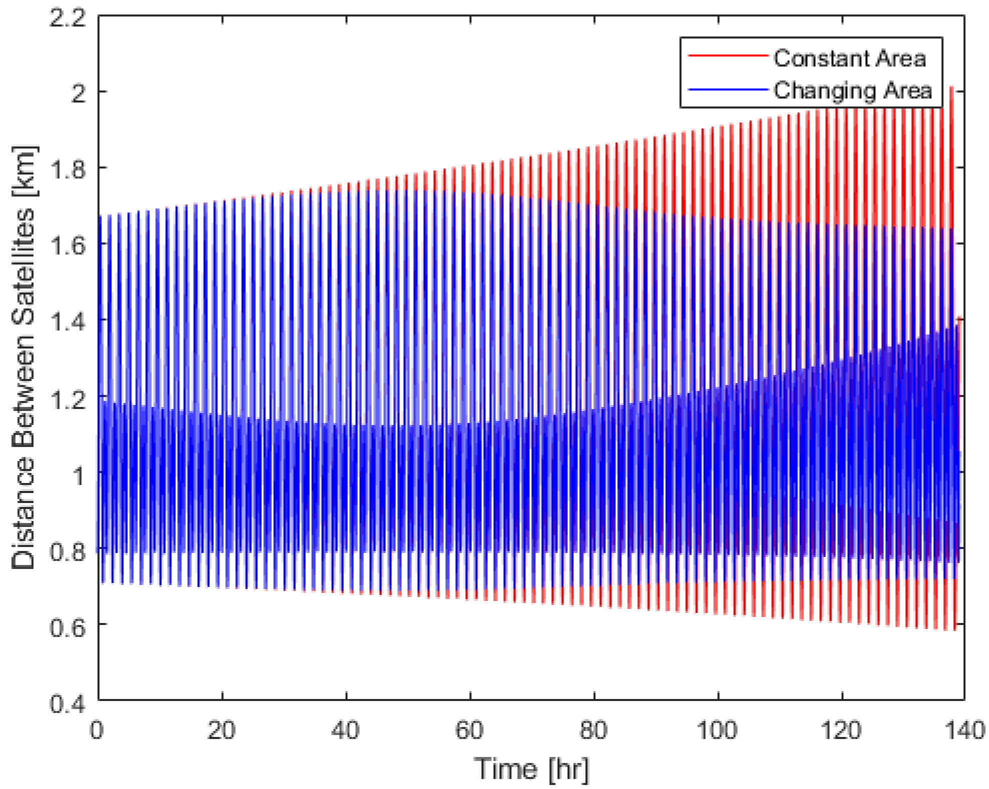

Figure 4: Distance between satellites over time. Shown in red is the distance between the satellites when both the chief and deputy satellites have constant cross-sectional area (A_c = 0.0945 m^2). Shown in blue is the distance between the satellites when the deputy satellite has a changing cross-sectional area.

Over the course of the simulation, the maximum distance between the satellites with constant areas is 2.013 km, while the maximum distance between the satellites with one changing area is 1.740 km. The amplitude of the oscillation increases over time for the constant area satellites, while the amplitude of the oscillation for the changing area satellites appears to be bounded. This means that the constant area satellites will continue to drift further and further apart, while the changing area satellites are able to stay within a certain distance from each other.

Thus, the spacecraft formation is able to be controlled with drag panels changing the satellites cross-sectional area. This simulation was done with a very rudimentary law for the drag sail's area in time, so there is potential for better results with a more sophisticated control system.

VII. Conclusion

In conclusion, spacecraft formation flying can be controlled by taking advantage of drag perturbations from a satellite's drag panels. A change in cross-sectional area of a satellite by just 10% can drastically change its orbit and increase the drift between it and the other satellites in its formation. By controlling a satellite's drag panels, the drift between satellites can be decreased to the point where there is potentially no significant net drag perturbation.

Future considerations in this topic could include implementing a more effective control system rather than simply increasing and decreasing the satellite area based on time. An example of this would be tuning a PID controller for the system. These simulations only changed the area of one satellite, so controlling all of the satellites in a formation would be more effective. This study also assumed that change in area was instantaneous, which is unrealistic as the drag panels would change the area at a continuous rate of change. So, a more accurate model could consider the area as changing in continuous time instead of discrete time.

VIII. Bibliography

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