Orbit Control Using Aerodynamic Forces

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Introduction/Purpose

• Research regarding use of solely aerodynamic forces for orbit control.
  – Drag characteristics of the satellites varied by changing attitudes

• Control relative position of multiple satellites in orbit.
  – Satellites could maintain constant separation without thrusters

• Allows for resolution over time and space

• Ability for observation with multiple satellites makes small satellites great!
Circular Orbit Analysis

• $\omega = \text{orbital angular velocity} = \frac{2\pi}{T} = \sqrt{\frac{\mu}{R^3}}$

• $\Delta \theta (\text{radians}) = (\omega_1 - \omega_2)\Delta t = \Delta t\sqrt{\mu}(\frac{3}{2}R_1^3 - \frac{3}{2}R_2^3)$

• $\Delta \theta (\text{radians}) = \frac{3}{2}\mu^2\Delta t \left(\frac{\delta}{R^{5/2}}\right)$ (by binomial expansion)

• The change in angular separation ($\Delta \theta$) with respect to time between two satellites in circular orbits at different altitudes is:
  - Governed solely by altitude difference ($\delta$) and orbital radius ($R$).
    - The altitude difference will be the significant variable.

• $\Delta X = R \Delta \theta$ (distance between satellites)

• If we can manipulate $\delta$, we can manipulate $\Delta X$. 

T = Orbital Period
$\mu$ = Gravitational Parameter
R = Average Orbital Radius
$\delta$ = height difference
$\theta$ = Angular Separation
1 degree = about 122km at alt = 600 km (R = 6978km)
Aerodynamic Forces

- Aerodynamic drag used to vary satellite altitudes, thereby varying $\delta$ (altitude difference)
  - $F_d = \frac{1}{2} \rho v^2 S c_d = ma$
  - $F = \text{force}$, $\rho = \text{density}$, $v = \text{velocity}$, $S = \text{surface area orthogonal to velocity}$, $c_d = \text{drag coefficient}$, $m = \text{mass}$, $a = \text{acceleration}$
  - Essentially an ongoing in-plane orbit transfer
    - Aero drag vector always parallel to velocity vector (will reduce orbit energy)
  - Satellite will spiral toward Earth’s center.
  - Altitude loss per spiral very small
    - Can be approximated as series of circular orbits with progressively lower altitudes

Traditional Hohmann orbit transfer with impulsive burns
Finding Density

- Density is dependent on:
  - Altitude
  - Geomagnetic and Solar activity
    - Can cause drastic density changes (2 orders of magnitude)
- Advanced atmospheric models for obtaining density
  - NRLMSISE-00
  - JB2008
- 1976 US Standard atmosphere tables used for initial calculations
- Orbits between 500 and 600 km popular for CubeSats
  - 5 < lifespan < 25 years

Note: Polar orbits have longer lifespans
Software Modeling

• Numerical integrator software written in java
  – Can account for external forces
  – Does not make simplifying assumptions (circular orbits, constant density)
• Forces that affect both satellites equally or cancel out over time ignored (J2 (Earth oblateness), Sun/Moon gravity, Solar pressure) .
Force Model Verification With STK

• STK and Java Simulator models of two 1.5U CubeSats initially in identical 600km circular orbits.
  
• One satellite in max drag configuration, other in min drag configuration.
  
  – 1976 Standard atmosphere model used in both sims

• Angular separation over time results from both simulators compared.
  
  – Less than 1% difference in sim values with same density models
  
  – Shows that forces that effect both satellites equally can be safely ignored when calculating separation over time

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Solar Pressure

Sat1’s orbit loses more energy from solar pressure than Sat2’s.

Sat1’s orbit gains more energy from solar pressure than Sat2’s.

Energy Gains and Losses from already weak solar pressure forces roughly cancel out, so orbits are not significantly perturbed.

Video: No drag, max SP sat 1, no SP sat 2
Solar Pressure Verification With STK

• Two identical satellites in identical initial orbits
  – Solar pressure simulation turned on for sat1 (4.5U panel array facing sun at all times) and turned off for sat2.

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Solar pressure makes little difference in terms of satellite separation over time and can be safely ignored!
Separation Control Simulation

- Two satellites in identical circular orbits with a given distance between them
- User wants to change satellite separation by a desired amount
- Satellite Orientations controlled autonomously by software to produce desired changes
Simulation Procedures

• Drag coefficient for CubeSat with 2 single deployed long edge solar panels \( \approx 2.2 \)

• Density function to fit 1976 US standard atmosphere values.
  - \( 1.137 \times 10^{-13} \text{ kg/m}^3 \) at 600 km altitude

• Max drag configuration:
  - \( \frac{A}{m} = \frac{.045 \text{ m}^2}{1.5 \text{ kg}} = .0300 \frac{\text{m}^2}{\text{kg}} \)

• Min drag configuration:
  - \( \frac{A}{m} = \frac{.01 \text{ m}^2}{1.5 \text{ kg}} = .0067 \frac{\text{m}^2}{\text{kg}} \)
Control Algorithm Step 1

Chasing satellite set to max drag configuration while leading satellite set to min drag configuration

- Allows chasing sat to drop to a lower altitude and catch up to leading sat (similar to phasing maneuver).
Control Algorithm Step 2

When half desired distance closed, swap satellite configurations (leader has max drag while chaser has min drag).

– Allows satellites to return to same altitudes
– Descent and ascent paths will be roughly symmetric

This satellite drops more quickly

Drag Force
Control Algorithm Step 3

• When satellites have reached the same altitude, set satellites to same minimum drag configurations.
Orbit Simulator Demo
Graphs of Results

Altitude Difference Over Time

Altitude Over Time

Separation Over Time
Simulation Conclusions

\[ \Delta \theta = \frac{3}{2} \mu^2 \Delta t \left( \frac{\delta}{R^{5/2}} \right) \]

<table>
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<th>Desired Distance Closed (km)</th>
<th>Time required (days)</th>
<th>Total Altitude loss (meters)</th>
<th>Max Altitude Difference (δ) (meters)</th>
<th>Estimated Closure (km) Based on average δ and Δϕ Eq.</th>
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- It is more efficient to wait as long as possible before initiating control algorithm
  - average altitude difference will be greater.
- If it takes time \( t_1 \) to change satellite separation by a distance \( x_1 \), then the time \( t_2 \) it will take to change separation by a distance \( x_2 \) can be calculated by
  \[ t_2 = \sqrt{\frac{x_2}{x_1}} t_1 \]
  (about 10.4 days to close 100 km. \[ \sqrt{\frac{1000}{100}} (10.4) \approx 32.9 \text{ days to close 1000km} \])
- Times calculated above would be ideal for simple CubeSat missions
- NORAD radar could be used to track satellites, and all orbit control commands could be issued from the ground
  - Satellites would not need to communicate with each other or know their positions.
Future Goals

• Improve software user interface
• Improve density estimation
  – Effects of solar and geomagnetic activity
  – Effects of night and day
  – Use existing simulation software/algorithms
• Improve drag coefficient estimation
• Possible simulation of out of plane transfers using aerodynamic lift
Questions?

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