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Mission design and analysis of a PocketQube swarm mission for distributed beamforming

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Abstract

A tendency towards miniaturisation of electronics, along with a reduction in launch costs, have enabled the growth of miniaturised spacecraft missions. Satellites such as CubeSats have widened access to space, with several missions already operating in orbit and many more being planned. Still, even smaller sub-CubeSat-sized spacecraft such as PocketQubes and ChipSats could enable unprecedented missions that are not possible with traditional-sized satellites. One of these applications is distributed beamforming where, instead of deploying a spacecraft with a single large antenna, a swarm of satellites is used as a distributed antenna array to obtain an electronically steerable beam. This paper introduces for the first time the mission design and analysis of a distributed beamforming mission adopting PocketQube satellites. First, it details the low Earth orbit dynamics of a PocketQube swarm formed by a chief node and a cloud of deputy nodes, including the analysis of the orbital perturbations. The swarm dynamics is coupled to the beamforming principles and characteristics to assess the performance of the PocketQube swarm to achieve beamforming.

Keywords: PocketQube, Satellite Swarm, Orbital Dynamics, Distributed Beamforming

1. Introduction

Since the early 2000s, a tendency towards miniaturisation of electronics enabled the growth of miniaturised space missions [1]. The CubeSat standard, published in 1999 [2], defines the CubeSat as a modular satellite composed of 10x10x10 cm cubes, with each cube or unit (1U) weighing less than 1.3 kg. Since then, more than 2300 CubeSats have been launched to space [3].

After CubeSats, further reduction in mass and size led to spacecraft which are smaller than a 1U CubeSat, such as PocketQubes, cube shaped satellites with a 5 cm edge and maximum weight of 250 g [4], and ChipSats, planar satellites made up of a printed circuit board of down to 3.5x3.5 cm and a weight as low as 5 g [5]. Since the first PocketQubes were deployed into space in 2013, over 80 PocketQubes have been launched [3].

While satellites such as CubeSats have widened access to space, with several missions already operating in orbit and many more being planned (e.g. Milani [6], LUMIO [7], Firefly [8]), even smaller sub-CubeSat-sized spacecraft such as PocketQubes and ChipSats could enable unprecedented missions that are not possible with traditional-sized satellites [9].

One important advantage of miniaturised platforms is the capability of flying in swarm configuration, allowing distributed scientific and technological operations [10].

One of these applications is distributed beamforming where, instead of deploying a spacecraft with a single large antenna, a swarm of satellites is used as a distributed antenna array to obtain an electronically steerable beam [11]. Adopting sub-CubeSat platforms for distributed beamforming presents the opportunity for applications in which the relative displacement between antenna elements needs to be larger than the one allowed by a monolithic satellite.

This work introduces the mission design and analysis of a distributed beamforming mission adopting PocketQube satellites. First, it details the low Earth orbit (LEO) dynamics of a PocketQube swarm formed by a chief node and a cloud of deputy nodes, including the analysis of the orbital perturbations. The swarm dynamics is coupled to the beamforming principles to assess the performance of the PocketQube swarm to achieve beamforming.

2. PocketQube orbit dynamics

The Keplerian motion of a satellite orbiting Earth, assuming Earth is perfectly spherical, is given by the two-body equation

$$\frac{d\bar{v}}{dt} = -\frac{\mu}{\|\bar{r}\|^3}\bar{r} \tag{1}$$

where μ is the standard gravitational parameter of Earth, and is the product of its gravitational constant and its mass, GM.

When dealing with the environment in LEO, the existence of various perturbing forces means that equation (1) can be used only as an approximation. Among these perturbations, the most influential ones in

LEO are solar radiation pressure (SRP), atmospheric drag, third body influence from the Moon, and Earth oblateness (J2).

The general form of the equation of motion, including perturbations, is then expressed as

$$\frac{d\bar{v}}{dt} = -\frac{\mu}{\|\bar{r}\|^3}\bar{r} + \bar{a}_P$$

where $\bar{a}_P$ is the sum of all the perturbing accelerations

$$\bar{a}_P = \bar{a}_m + \bar{a}_{drag} + \bar{a}_{J2} + \bar{a}_{SRP}$$

2.1 Solar radiation pressure

The acceleration due to solar radiation pressure is given by the expression

$$\bar{a}_{SRP} = c_{SRP}\frac{\bar{r}_{b-s}}{\|\bar{r}_{b-s}\|^3}$$

where $\bar{r}_{b-s}$ is the satellite position vector with respect to the sun, c_{SRP} is the solar radiation pressure coefficient and is given by

$$c_{SRP} = \frac{Ac_rP_0}{mc}{D_{AU}}^2$$

where A is the surface area of the satellite normal to the incident radiation, c_r is the reflectivity coefficient of the satellite, P_0 is the solar flux at 1 astronomical unit, m is the mass of the satellite, c is the speed of light and D_{AU} is one astronomical unit.

2.2 Atmospheric drag

The acceleration due to atmospheric drag is calculated with the expression

$$\bar{a}_{drag} = -\frac{1}{2}\frac{Ac_d\rho}{m}\|\bar{v}_r\|^2\hat{v}_r$$

where A is the surface area of the satellite normal to the velocity vector of the satellite, c_d is the drag coefficient of the satellite and ρ is the atmospheric density.

As a first approximation, an exponential density model where density varies exponentially with altitude is considered,

$$\rho = \rho_0\, exp\left(-\frac{h-h_0}{H}\right)$$

where h is the altitude of the satellite, ρ_0 is the reference density at the reference altitude h_0 and H is the scale height.

Later, the NRLMSISE-00 model is used. This model is based on earlier models that use mass spectrometer and incoherent radar scatter data obtained from ground and satellite measurements and improves on them by incorporating updated drag data.

2.3 Third-body influence from the Moon

The third body influence due to the moon is calculated as

$$\bar{a}_m = \mu_m\left(\frac{\bar{r}_{e-m}}{\|\bar{r}_{e-m}\|^3} - \frac{\bar{r}_{b-m}}{\|\bar{r}_{b-m}\|^3}\right)$$

where μ_m is the standard gravitational parameter of the Moon, $\bar{r}_{e-m}$ is the Earth position vector with respect to the Moon, and $\bar{r}_{b-m}$ is the satellite position vector with respect to the Moon.

2.4 Earth oblateness

The perturbation due to Earth's oblateness considering the first non-spherical term J_2 is

$$\bar{a}_{J2} = -\frac{\mu}{\|\bar{r}\|^3}{T_I}^P\begin{bmatrix} x\frac{3}{2}J_2\left(\frac{R}{\|\bar{r}_n\|}\right)^2\left(1-5\frac{z^2}{\|\bar{r}_n\|^2}\right) \\ y\frac{3}{2}J_2\left(\frac{R}{\|\bar{r}_n\|}\right)^2\left(1-5\frac{z^2}{\|\bar{r}_n\|^2}\right) \\ z\frac{3}{2}J_2\left(\frac{R}{\|\bar{r}_n\|}\right)^2\left(3-5\frac{z^2}{\|\bar{r}_n\|^2}\right) \end{bmatrix}$$

where $\bar{r}_n = (x, y, z)$ is in the ECEF rotating frame, T_I^P is the rotation matrix to go from the rotating frame back to the inertial frame, J_2 is the second-degree zonal harmonic coefficient of Earth, and R is the radius of Earth.

3. Phased array beamforming

The electric field in the far field of one antenna element is given by the expression

$$\bar{E}(\bar{r}) = \frac{E_0}{r}e^{-jkr}\hat{e}$$

where E_0 is the electric radiation pattern of the element, $\hat{e}$ is its direction, r is the distance from the antenna element to the far field point, and k is the wave vector.

For an array of N antenna elements, the electric field in the far field is given by

$$\bar{E}_t = \frac{E_0}{r}\,e^{-jkr}\cdot AF$$

where AF is the array factor, which represents the response of an array of isotropic elements, and is defined as

$$AF = \sum_{n=1}^{N} e^{j(kd_n cos\vartheta + \beta_n)}$$

where d_n is the relative distance between antenna elements, ϑ is the angle of the desired beam pointing, and β_n is the phase difference between the array elements.

4. Results

The coupling between the orbital dynamics of the swarm and the beamforming was performed with MATLAB. Some results will be presented.

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