Acta Astronautica 128 (2016) 313–321

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

An active attitude control system for a drag sail satellite

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ARTICLE INFO

Article history:
Received 26 January 2016
Accepted 7 July 2016
Available online 29 July 2016

Keywords:
Attitude control
Drag sail
Orbit decay
Atmospheric drag
Magnetic detumbling
Momentum stabilisation

ABSTRACT

The paper describes the development and simulation results of a full ADCS subsystem for the *deOrbitSail* drag sail mission. The *deOrbitSail* satellite was developed as part of an European FP7 collaboration research project. The satellite was launched and commissioning started on 10th July 2015. Various new actuators and sensors designed for this mission will be presented. The *deOrbitSail* satellite is a 3U CubeSat to deploy a 4 by 4 m drag sail from an initial 650 km circular polar low earth orbit. With an active attitude control system it will be shown that by maximising the drag force, the expected de-orbiting period from the initial altitude will be less than 50 days. A future application of this technology will be the use of small drag sails as low-cost devices to de-orbit LEO satellites, when they have reached their end of life, without having to use expensive propulsion systems. Simulation and Hardware-in-Loop experiments proved the feasibility of the proposed attitude control system. A magnetic-only control approach using a Y-Thomson spin, is used to detumble the 3U Cubesat with stowed sail and subsequently to 3-axis stabilise the satellite to be ready for the final deployment phase. Minituarised torquer rods, a nano-sized momentum wheel, attitude sensor hardware (magnetometer, sun, earth) developed for this phase will be presented. The final phase will be to deploy and 3-axis stabilise the drag sail normal to the satellite's velocity vector, using a combined Y-momentum wheel and magnetic controller. The design and performance improvements when using a 2-axis translation stage to adjust the sail centre-of-pressure to satellite centre-of-mass offset, will also be discussed, although for launch risk reasons this stage was not included in the final flight configuration. To accurately determine the drag sail's attitude during the sunlit part of the orbit, an accurate wide field of view dual sensor to measure both the sun and nadir vector direction was developed for this mission. The calibration results for this new Cubesat sensor (*CubeSense*), will also be presented.

1. Introduction

Recently the first solar/drag sails have been launched and successfully deployed in space, i.e. 1) the JAXA Ikaros mission [1,2] deployed a 200 square metre solar sail in June 2010 on its way towards Venus, 2) NASA's Nanosail-D2 3 U Cubesat [1,3] deployed a 10 square metre drag sail in January 2011, while orbiting at 650 km in a low earth orbit and The Planetary Society's LightSail-1 3U CubeSat [4] deployed a 32 square metre sail in June 2015 from a 356 by 705 km orbit. Ikaros is stabilised as a 2 rpm spinning sail with embedded blocks of LCD panels to control the spin attitude by adjusting the LCD reflectance. Nanosail-D2 was only passively stabilised by the atmospheric drag force on the sail, until it finally deorbit 9 months later in September 2011. LightSail-1 was also only passively stabilised by aerodynamic torques and de-orbit 7 days later as a result of its initial low perigee and a high satellite area/mass ratio of 6.5 m^2/kg. A few other papers [5,6,7] presented drag sail designs to deorbit, but none of these have flown. The 10 square metre drag sail proposed for Knightsat II [5] a 50 kg microsatellite, is the only sail envisaged to stabilise by active magnetic damping control. The paper on drag sails for space debris mitigation [6] demonstrates a reduction in collision risk after sail deployment by comparing the simpler Area-Time-Product with a more precise collission risk analysis.

The *deOrbitSail* FP7 mission as coordinated by the Surrey Space Centre at the University of Surrey aims to be the first satellite to demonstrate a practical attitude control system [5] to 3-axis stabilise a deployed sail and demonstrate maximum drag sailing in low-earth orbit. The 16 square metre sail will deploy from a 3U CubeSat of 3.4 kg (area/mass ratio of 4.7). To avoid the cost and technical challenges of a larger spacecraft, it is possible to demonstrate the benefit of high area/mass de-orbiting missions on a CubeSat platform in LEO as successfully demonstrated by Nano-Sail-D2 and LightSail-1. The aim will be to actively control the sail normal to the velocity vector for maximum drag, see Fig. 1.

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http://dx.doi.org/10.1016/j.actaastro.2016.07.039
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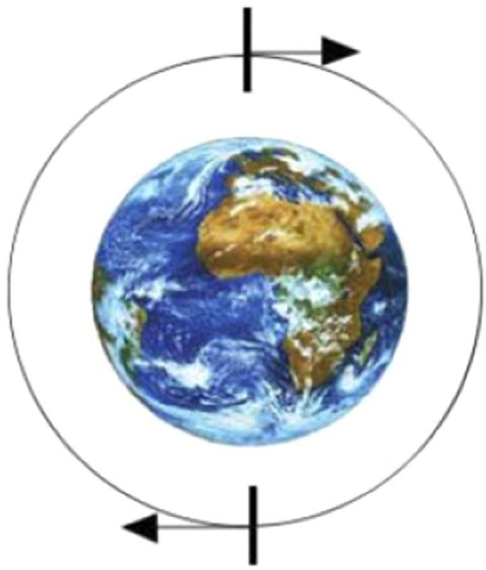

Fig. 1. Orbit Configuration of *deOrbitSail*.

A passively stabilised sail with the centre-of-pressure (CoP) behind the spacecraft centre-of-mass (CoM) may still induce large sail oscillations, especially due to variations in the aerodynamic and solar torque disturbances. For example, an initial 45° sail surface angle relative to the maximum drag force vector, results in oscillations that will reduce the effective drag force by about 25%. For the case of a tumbling flat sail, simulation studies showed a sustained reduction of the effective drag force as much as 67%, depending on the initial conditions. To maximise the drag force in the passively stable attitude, will therefore require damping of the sail's tumbling attitude or oscillations. This can easily be achieved either through passive or active magnetic damping. For the *deOrbitSail* project it was decided to implement an actively controlled sail attitude control system to compensate for the external torque disturbances and to 3-axis stabilise the drag sail towards the maximum drag force direction. The same active control system can then also be utilised to change the sail's pitch angle, i.e. when using the solar pressure force [8] to deorbit from higher initial altitudes. For example, in a combined solar/drag sail deorbiting application, above 650 km the sail will use the dominant solar pressure force to deorbit and below 650 km the dominant aerodynamic drag force will be used.

Simulation orbit decay studies predict re-entry between 30 and 50 days after sail deployment, as shown in Fig. 2. Without the drag sail a 3U CubeSat will stay in low earth orbit for more than 25 years from it's initial 650 km orbit.

The ADCS body coordinate frame is shown in Fig. 3 with partially deployed solar panels. The *X*-body axis will be pointed

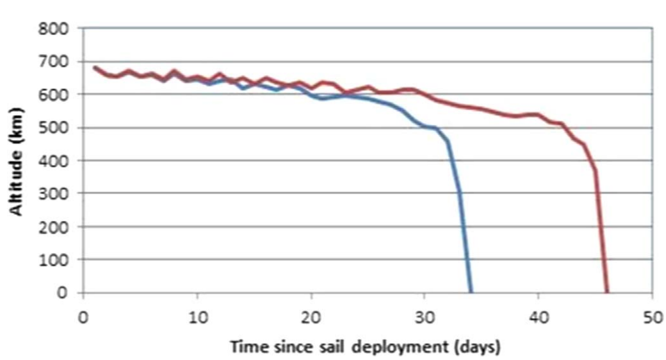

Fig. 2. Orbit decay analysis for *deOrbitSail*.

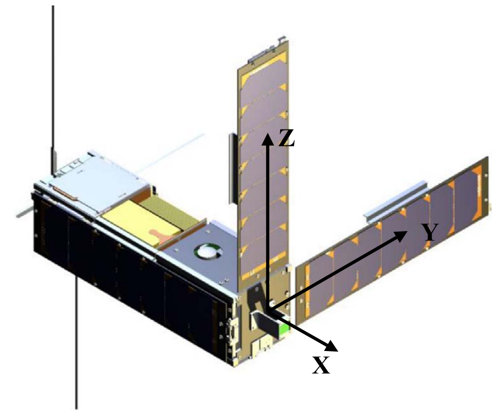

Fig. 3. ADCS body coordinates for *deOrbitSail*.

towards the nominal velocity vector and the *Z*-body axis towards nadir when the satellite is 3-axis stabilised before sail deployment.

As already explained the ADCS of *deOrbitSail* was designed to fly with the sail aligned to the velocity vector to maximise the aerodynamic drag force and to fly with the centre-of-pressure (CoP for sail) behind the centre-of-mass (CoM of satellite) for passive aerodynamic stability. Maintaining this attitude will therefore ensures rapid deorbiting. Fig. 4 shows the satellite with the sail deployed.

When the project started in late 2011, no CubeSat ADCS existed to stabilise a large sail or any active 3-axis sail control has ever been demonstrated. As part of the research effort during the *deOrbitSail* FP7 project a novel ADCS bundle (shown in Fig. 5) was developed for a 3U CubeSat. It consists of the following modules (from bottom to top), *CubeComputer* [9] a 32-bit radiation tolerant CubeSat OBC for satellite house-keeping and executing the ADCS software, *CubeCoil* a magnetorquer coil for the *X*-body axis, *CubeSense* [9] a sun and nadir camera sensor with 180° field of view, *CubeAim* [9] with the *Y*- and *Z*-axis magnetorquers mounted on the PCB and acting as a sensor interface to 10 coarse sun sensors, a 3-axis magnetometer and a MEMS Y-rate sensor. *CubeAim* also contains the drive electronics for the magnetorquers, Y-wheel, stepper motors of the *Y*/*Z* sail translation stage and the sail deployment motor. The *CubeWheel* [9] momentum wheel is the final component shown to the right front with its spin axis aligned to the *Y*-body axis to give inertial stiffness to the body roll (*X*) and yaw (*Z*) axes.

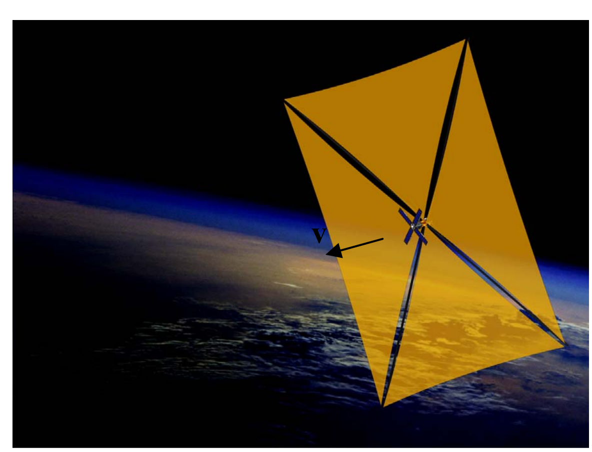

Fig. 4. *deOrbitSail* in final flight configuration.