De-Orbiting of Satellites using Solar Sails

Reporting

Project Information

DEORBIT SAIL

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Project website ↗

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Closed project

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Final Report Summary - DEORBIT SAIL (De-Orbiting of Satellites using Solar Sails)

Executive Summary:
The uncontrolled growth of the space debris population has to be avoided in order to ensure safe operations in space for the future. Space system operators need to take measures to conserve a space debris environment with tolerable risk levels, particularly in Low Earth Orbit (LEO) altitude regions. The European Code of Conduct for Space Debris Mitigation requires that satellites in the LEO protected region (<2000km) are disposed of by destructive re-entry in the atmosphere within 25 years from their end of life.

The DeOrbitSail project aims to demonstrate that deorbiting can be achieved with a deployable sail, and to provide a proven design for the deployment system that can be used as a deorbiting device on future spacecraft. The DeOrbitSail mission will be the first to demonstrate a practical attitude control system to 3-axis stabilize a sail and demonstrate drag sailing in low earth orbit. The sail will deploy from a 3U CubeSat to demonstrate the benefit of low-mass-to-sail-area missions on a CubeSat platform avoiding the cost and technical challenges of developing a large spacecraft.

This project's approach is to modify solar sail deployment technology for use as a satellite and/or rocket upper stage deorbiting system. The effectiveness of such deorbiting device is predicted to be high at altitudes lower than 1000 km for minisatellites (20 to 500 kg) if deorbiting time constraints of 25 years are being considered. The same design will also be capable of using solar radiation pressure as a deorbiting force above the 1000 km mark. In contrast with JAXA's spin-deployed deep space solar sail, IKAROS , DeOrbitSail will deploy and maintain its shape through relatively stiff structural booms.

The deorbiting capability of the DeOrbitSail satellite is due to increased aerodynamic drag from the large surface area. Aerodynamic drag is the force that acts opposite the relative velocity vector of a satellite in low Earth orbit (LEO). It is a result of air molecules interacting with the satellite surface and the general result is a decrease in orbit eccentricity and semi-major axis over time. Eventually a satellite that is influenced by drag will return to the Earth and either burn up in the atmosphere or, for big satellites or part of space stations, impact the surface (or have fragments that impact the Earth surface).

The magnitude of the drag force is proportional to the cross-sectional surface area exposed to the incoming air molecules. By increasing the area the drag force is increased and the time from the initial orbit to orbital decay is shortened. The relatively large area of the sail will result in a rapid deorbiting.

DeOrbitSail satellite will have a deployable sail consisting of a 4 by 4 m square membrane and four

slender booms. A motor deploys the booms from a compartment at one end of the satellite. As the booms extend, they will unfold the membrane and draw it taut. With the deployed sail and a complete ADCS, DeOrbitSail will have a frontal area of 16 m2 and deorbit to demise in Earth's atmosphere within months after launch. The complete satellite will fit in a standard 3U CubeSat deployer, the ISIPOD, and it will weigh less than 6 kg.

The 3U CubeSat goal is a critical design driver for DeOrbitSail. A 3U CubeSat has dimensions of approximately 10 by 10 by 34 cm, with some loss for the thickness of solar panels and other considerations.

The longest axis is divided into three sections: approximately 14 cm of length for the satellite bus, 10 cm for the stowage of the sail membrane, and the remains for the sail deployment system. This system consists of four deployable booms, which are stowed, like carpenters' tapes, via elastic deformation. DLR (Deutsches Zentrum für Luft- und Raumfahrt e.V.) has modified existing booms from their Gossamer project and longstanding deployable boom program for use on DeOrbitSail. The DeOrbitSail booms will be slender in comparison to DLR booms used in other projects, and the deployment system will be much smaller and lighter.

As well as the boom deployment system, also a member of the consortium, namely the Stellenbosch University, has designed the attitude determination and control system (ADCS) ad hoc for the DeOrbitSail mission.

This subsystem is a demanding constraint; the mission requires, indeed, pointing which is optimised for drag. That means that the ADCS will force the satellite to face the atmospheric drag always with its maximum area side.

The hardware to realise that will be a customized configuration of Stellenbosch's CubeSense and CubeComputer systems, with control from a set of three magnetorquers and a y-axis reaction wheel. Detumbling after separation from the launch vehicle will be accomplished using the magnetorquers and the reaction wheel. The attitude determination system will be based on CubeSense, combining data from a small magnetometer, six coarse sun-sensing photodiodes, and sun and nadir cameras.

Direct imaging will be acquired through at least one camera, the CubeSense horizon camera. It provides a 180° view in grey-scale and at a relatively low resolution of approximately 460 pixels in diameter. The camera is further limited by its dual use; in order to have a good view of Earth's horizon, the camera cannot be entirely obstructed by the sail membrane. It will nonetheless be able to capture an image confirming the deployment of half the sail.

Initially a solution to provide an additional stabilization through offsetting the centre of pressure was studied. This could be accomplished with a translation stage between the satellite bus and the sail. Unfortunately the results of the vibration test showed problems with the translation stage's capability to survive the launch solicitations. Thus, the subsystem has been removed. This change will not affect the capability of DeOrbitSail to accomplish its mission.

Althought DeOrbitSail is equipped with an attitude control system, it is limited to detumbling, stabilization, and pitch manouvers. Since the purpose of the sail system is to deorbit the spacecraft, it always faces the direction of travel to present the maximum cross-sectional area. The orientation of the spacecraft is thus entirely determined by the deorbiting objective and the pointing requirements of the attitude determination

system. As it is the case with many CubeSats, the solar panels do not have any sun-tracking capability;

the mechanical system would occupy too much volume and present an engineering challenge that is beyond the scope of DeOrbitSail. The design for the panels must therefore provide adequate power both during tumbling and drag deorbiting, with only a single change in configuration.

After ejection from the CubeSat deployer, the antennas are deployed to enable communications. After initial detumbling into a Y-Thompson spin, and before the solar panel deployment, the solar cells are on the four long sides of the spacecraft. This arrangement is acceptable for the power budget unless the satellite is perfectly pointed away from the sun. After the four solar panels are released to expose the sail and boom deployment system, the panels must meet a number of requirements at once:
• they must deploy via a simple mechanism;
• their final arrangement must not interfere with the sail deployment;
• they must not entirely occlude the field of view of the attitude determination cameras;
• none of the solar cells can occupy the inner walls of the panels adjacent to the sail storage area or the boom deployer, which do not have any volume margin.
This last requirement is due to the fact that, prior to their deployment, the four deployable carbon fibre (each equipped with 6 solar cells) serve a further purpose as a hold-down mechanism for the primary mission payloads. This dual use of the solar panels is an unusual design element of the DeOrbitSail satellite, and allows a single actuation to fulfill multiple structural control purposes.

Project Context and Objectives:
The project objectives are to provide research in the field of deorbiting, demonstrate and verify design for deorbiting of satellites or debris, and show effective and efficient propulsion technologies, based on sails. The initial objectives of this project would have been fulfilled with the production, launch and operation of a satellite that will deploy a large sail membrane, but, due to the re-scoping of the M36, those objectives have changed in terms of production and delivery of a tested, ready-to-flight spacecraft that will deploy a large sail membrane. As proposed, the satellite form factor will be that of a 3U CubeSat, and the sail will be a square shape formed of 4 triangles, supported by 4 deployable booms.
The top-level requirements are therefore:
• DeOrbitSail shall demonstrate drag deorbiting of a nano-satellite.
• Deorbiting shall be accomplished by drag on a deployable sail of approximate area 16 m2
• The DeOrbitSail satellite shall be able to stabilize the attitude of the satellite so that the sail is perpendicular to the velocity direction.
• The satellite shall have a communications link to a ground station from where commands can be sent and telemetry can be requested.
• DeOrbitSail shall be able to record and transmit attitude angles and rates.
• The deployed state of the sail shall be verifiable.
• DeOrbitSail shall demonstrate drag deorbiting from an initial circular orbit at 650 km to demise in Earth's atmosphere within 120 days.
• The DeOrbitSail satellite shall be compatible with an existing launcher from ISIS.
Verification of the sail deployment will be achieved by transmitting pictures of the sail itself taken with an on-board camera, and additional information will be gained using on-board attitude data as well as ground observations of the orbital decay.

Even if the re-scoping of the month 36 removes the launch requirements, the consortium found a launch opportunity and intends to perform the last acceptance test in December 2014 with the aim to accomplish the launch and operational tasks, even if those are outside the duration of the contract.

Project Results:
a) Deployment system
DLR has improved an existing boom design for the use on DeOrbitSail. The DeOrbitSail booms will be slender in comparison to DLR booms used in other projects, and the deployment system will be much smaller and lighter.

The state-of-the-art booms are made of carbon-fibre-reinforced polymer. Each boom consists of two 3.5-meter-long half-shells, joint along their flanges. This omega-shaped half-shell design can be flattened and coiled, which will allow the booms and their deployer to fit into approximately 1U of the satellite's volume, a section less than 10 cm high and only slightly wider. To deploy these booms, the new deployer shown in Figure 5 was designed.

This innovative solution is based on an electric motor that pulls the booms out of their compartment by reeling up the cords on a separate spool. This design was chosen instead of one based on the boom self-deployment due to the spring effect (caused by the elastically stored strain energy inside their shells), because it is more robust against high off-nominal loads acting on the booms or arising inside the boom deployer.

Furthermore, this system suppresses two failure modes relevant to the self-deployment concept: pushing the boom package open from the inside blossoming and formation of buckles in the outer windings of the booms.

Another engineering challenge was the problem of the transition zone between the fully deployed boom's tip and the part that is still connected to the spool. In between, indeed, the cross section turns from completely flattened at the spool to fully open in some distance to the spool (see Figure 6). Therefore, also the in-plane cross-sectional moment of inertia changes from almost zero to its full value. As the load carrying capability corresponds to the moment of inertia, the booms possess in this state almost no bending stiffness in the in-plane direction while the out-of-plane direction is very much endangered to flexural torsional buckling near the spool where the boom is flattened. To increase in-plane stiffness as well as out-of-plane strength a deployable arm that supports the boom in some distance to the spool is used (see Figure 7). At the end of the arm a foldable bracket surrounds the boom and prevents it from torsional as well as out-of-plane deformations. The arm is thereby integrated into the doors of the boom container.

Another challenge in the design is the boom damping control: long and flexible booms, indeed, if not properly damped may cause attitude control problems and affect the performance of the satellite. Normally, the space environment does not have large disturbing torques to start the vibration of the booms. However, the following are possible sources of boom vibration:
• Attitude manoeuvres
• Boom deployment
• Thermal shock going from shadow to sunlight or the opposite
DeOrbitSail will operate as an aerodynamic drag sail, in locked rotation mode. Thus, the sailplane will be always perpendicular to the orbital plane. A solar sail would have required the change of the sail attitude

continuously in the every orbit, resulting in large inertia loads on the booms. In the current operation, once

proper orientation is achieved, the attitude control will be carried out against small disturbances. Consequently, large slew manoeuvres are not needed, and are not considered in this report.

The boom borne vibrations due to thermal shock as well as during deployment are investigated. Both vibrations should be damped by proper means. An active vibration control does not seem feasible. For this reason, passive damping mechanisms are investigated. Among them SMA damping is found to be not very effective since it requires large strains to display pseudo-elastic effect. On the other hand viscoelastic materials are much more effective. Viscous and coulomb friction mechanisms are also investigated, and found to be quite effective in damping boom vibrations. . Points where high friction is induced to the booms and its composition can be observed in Figure 8. In this part the friction in joints of telescopic doors also contribute to the overall friction within the mechanism as well. It is assumed that there is a constant friction torque in the telescopic door hinges and a constant force in between boom and bracket. This force is assumed to be transformed to friction torque about central of the boom.

The simulation results for the first node and tip node deflections given in Figure 9. From these results, it is clear that, friction in the deployment system may damp out the vibrations.

b) Sail Manufacture and Folding
The four triangles that constitute the sail are made from a transparent yellow film of Kapton HN in 12.5-micron thickness.(Figure 10) The primary fold lines are parallel to the long edge and spaced at 88 mm intervals; the secondary fold lines are spaced at 49 mm intervals. This makes it possible to fold the sail into a box of 93 x 50 x 37 mm. Two sets of four sail quadrants (QM/FM) were manufactured, as well as one further flight spare quadrant. A narrow strip (6 mm) of Kapton tape was applied to all outer edges of the sail, to reduce the risk of ripping the sail during handling and as rip stops in space.

The main challenge in this subsystem is the folding. For the double z-folding two sets of folds need to be made into the membrane. The primary z-folds folds are applied, aligning the fold markings and flattening the folds with a rubber brayer. The spacing between these folds is 88 mm, with the total height of the folded strip less than 93 mm in all places. Despite very accurate fold placement, up to within 0.5 mm, during creasing, in the stacked configuration the folds generally do not align with the precision of an individual crease. Positioning the sails is complicated due to the static generated by the handling; anti-static brushes were used to selectively free membrane sections during folding. To entirely avoid static problems during manufacture and deployment the flight sail has an aluminium coating. Creasing the primary z-folds is the most time and labour-intensive part of the entire sail manufacturing process. The secondary z-folds are spaced at 49 mm intervals. (Figure 11, Figure 12 and Figure 13)

The sail is stored in a dedicated lightweight, non-structural container as shown in Figure 14. Its purpose is to slightly restrain the sail so that it will not spring open upon release of the doors. This is necessary to prevent the sail membrane from entangling itself in the booms during the early stages of deployment. The sail segments are intended to be stored in an area of 50 x 37 x 95 mm.

c) Attitude determination and control
Approximately 1U of space is available for all electronic systems on DeOrbitSail. This is a demanding

constraint; the mission requires deployment confirmation, pointing optimized for drag, and

communications.

Stellenbosch University is developing an attitude determination and control system ad hoc for DeOrbitSail. The hardware will be a customized configuration of Stellenbosch's CubeSense and CubeComputer systems, with control from a set of three magnetorquers and a y-axis reaction wheel. Detumbling after separation from the launch vehicle will be accomplished using the magnetorquers and reaction wheel. The attitude determination system will be based on CubeSense, combining data from a small magnetometer, six coarse sun-sensing photodiodes, and sun and nadir cameras.

There are three different attitude control modes for different phases of the mission. The first control mode (Mode 1) will be used to de-tumble the satellite initially, when the sail and solar panels are still stowed. The only sensor measurements required during Mode 1 will be the magnetometer B-field vector and a MEMS rate sensor for the body YB spin.

In the Control Mode 2, the Y-momentum wheel will ensure gyroscopic stiffness to the roll and yaw axes through the YB direction angular momentum vector. The pitch rotation around the YB axis can also be controlled. When the attitude has been stabilised at zero pitch, roll and yaw angles the sail will be deployed.

It is important to realise that the sail deployment configuration must be with the Centre of Pressure (sail) behind the Centre of Mass (main satellite body) along the flight direction (body XB axis) to ensure a passively stable attitude.

Simulation studies showed that post-deployment control mode (Mode 2) could actively maintain all 3-axis attitude angles within 5 degrees of the reference configuration. In this way, Control Mode 2 will be able to keep the sail deployed normal to the velocity vector to ensure the mission success (i.e. to maximise aerodynamic drag).

After the sail deployment, 3-axis attitude stabilisation of the satellite is achieved using the cross product of magnetic and Y-momentum wheel controllers in Mode 2 (Control Mode 3).

On the hardware point of view, many new attitude control sensors and actuators were specifically designed for this mission. Their main characteristics are listed in the Table 1.

All attitude sensors and control actuators are accessed at 10 Hz by the CubeSat's ADCS OBC (Cube-Computer an on-board processor executing the ADCS code, see Figure 15) via an ADCS Interface Module (CubeAIM). The AIM hardware is implemented on a single PC104 board with a standard CubeSat connector weighing approximately 70g at an average power of 180 mW. The heart of the AIM consists of two low power micro-controllers with several I/O ports, Analogue to Digital inputs and a dual I2C communication bus. The first I2C bus is connected to the CubeSat's main OBC (the CubeComputer module) and the second to the CubeSense module. The latter is a dual camera system with wide FOV lenses (190^0 fisheye field of view) to measure the sun and nadir vectors accurately.

All the controllers and estimators have been flown successfully in orbit on other small satellites before but this implementation will be the first for a CubeSat mission.

d) Electronics Chassis

The innovative hybrid design for the CubeSat chassis uses both aluminium Alloy 7075 and carbon-fibre composite components.

The main structural frame is made of four aluminium rails and two aluminium square brackets bolted

together (see Figure 16). The rails have a thickness of 1.5mm and the two brackets are 6mm thick. The cut-out in the top aluminium bracket accommodates the ADCS momentum wheel mounted on the CFRP – Y side. Finally, an extension of 3.5mm thickness was added to each rail. This modification helps with the appropriate placement of the chassis inside the ISIPOD as well the mounting of the Release Mechanism. The rails are hard-anodized to reduce friction contact with the ISIPOD guide rails.

The side panels have cut-outs to provide access for the sun and horizon cameras, and for wiring from the solar cells to the EPS and coarse sun sensors to CubeSense board. The bottom CFRP panel cut-out provides wiring access to the magnetometer and coarse sun sensor.
The chassis is 133mm long (total length of the rails) and covers the bottom 1U of the overall 3U structure. All the external dimensions of the chassis are in line with the ISIPOD specifications.
During assembly of the prototype chassis some alignment issues occurred (compare also delivery D3.5) so for the flight model chassis a simple alignment rig will be used to check the chassis dimensions, and ensure that the rails are parallel. This rig will be useful to check the CFRP panels as well.

e) Deployable Solar Panels
The DeOrbitSail satellite design includes four deployable CFRP solar panels, which are hinged at the base of the electronics chassis and are held down during launch using a hold down release mechanism (HDRM) system. In the deployed configuration the four solar panels lie in a plane parallel to the sail; the power generation in this configuration was found to be compatible with the current launch opportunity for DeOrbitSail.
Even if many CubeSats carries deployable solar panels, a COTS solution is not available yet and the panel has been designed ad hoc for this mission.
Along the central section of the solar panels, aligned with the sail storage section, are two hard-anodized aluminium brackets. These engage with the guide rails of the ISIPOD, and bridge the gap between the guide rails along the chassis and the boom deployer.
The aluminium brackets on adjacent solar panels interlock: two opposing panels engage with the ISIPOD rails ('outer' panels) and further constrain the 'inner' panels. The brackets further provide bending stiffness to the solar panels. (Figure 17) Due to tight clearances between the guide rails and the boom deployer, the tops of the rails are chamfered by 15° to avoid contact as the solar panels open.

Potential Impact:
The potential impact

Controlling the amount of space debris is widely recognised as an important task to maintaining a

sustainable space access for the decades to come. This is mainly due to the high risk of collisions that can easily invalidate both human and robotic mission. Currently, many leading space companies are developing space debris removal systems. These systems can conditionally be divided into two types: passive and active ones.

Passive systems are mounted onto objects that have to be deorbited in advance, and are activated after their mission is complete. These systems can use different physics for deorbiting.

The DeOrbitSail project aims to demonstrate that deorbiting can be achieved with a deployable sail, and to provide a proven design for the deployment system that can be re-used as a deorbiting device on future spacecraft. DeOrbitSail itself will deorbit very quickly, within a matter of months, but a larger satellite with an identical system would aim to meet the 25-year IADC (Inter-Agency Space Debris Coordinating Committee) Guidelines requirement.

Dissemination activities

a) Presentations and publications
Material from DeOrbitSail has been presented at the following venues:
• January 5-9, 2015, 56th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Gaylord Palms and Convention Center, Kissimmee FL.
o Hillebrandt M, "Deployment testing of the DeOrbitSail flight hardware",
• April 1-4, 2014, European Conference on Spacecraft Structures, Materials and Environmental Testing, Braunschweig, Germany
o Hillebrandt M, "The boom design of the DeOrbitSail satellite"
o Meyer S, "Design of the DeOrbitSail boom deployment unit"
• January 13 - 17, 2014, 55th AIAA/ASMe/ASCE/AHS/SC Structures, Structural Dynamics, and Materials Conference
o Stohlman O, Schenk M and Lappas V, "Development of the DeOrbitSail flight model"
• July 21-26, 2013, In Geoscience and Remote Sensing Symposium (IGARSS), Melbourne, VIC.
o Steyn W.H.and van Zyl R, Inggs M and Cilliers P, "Current and future small satellite projects in South Africa"
• June 11-13, 2013, 3rd International Symposium on Solar Sailing, Glasgow, Scotland
o Lappas V, Fernandez J, Visagie L, Stohlman O, Viquerat A, Prassinos G, Theodorou T and Schenk M, "Demonstrator Flight Missions at the Surrey Space Centre involving Gossamer Sails"
• April 8-11, 2013 54th AIAA/ASMe/ASCE/AHS/SC Structures, Structural Dynamics, and Materials Conference, (Boston, MA, USA),
o Stohlman, O. R. and Lappas, V. J. DeOrbitSail: a deployable sail for de-orbiting
o Stohlman, O. R.; Fernandez, J. M.; Lappas, V. J.; Hillebrandt, M.; Straubel, M.; Hühne, C. Testing of the DeOrbitSail drag sail subsystem
• November 15-16, 2012, 2nd FP7 Space Conference (Larnaca, Cyprus),
• October 22, 2012, ESA Space Debris Conference (Brussels),
• February 28, 2012, EU Space Meeting (Brussels, Belgium),
• September 15-17, 2011, 2nd International Conference on Space Technology (Athens, Greece),:
o Lappas, V.; Pellegrino, S.; Guenat, H.; Straubel, M.; Steyn, H.; Kostopoulos, V.; Sarris, E.; Tekinalp, O.; Wokes, S.; Bonnema, A. DEORBITSAIL: De-orbiting of satellites using solar sails

o EU Space Event, DeOrbitSail poster

List of Websites:

www.deorbitsail.com

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