Deorbit Sail for PW-Sat2 satellite mission – low energy consumption and high efficiency system

POLAND
Inna Uwarowa[1], Ewelina Ryszawa[1], Mateusz Sobiecki[1]
[1]*Students Space Association,*
The Faculty of Power and Aeronautical Engineering
Warsaw University of Technology, Poland
iouvarova@gmail.com

Keyword: Deorbit sail, CubeSat, Low energy, Flat springs

INTRODUCTION

PW-Sat2 is a CubeSat project developed by the 30 members of Students' Space Association (SKA) at Warsaw University of Technology (WUT), Poland. The project started in 2013 after the successful development and launch of the previous CubeSat – PW-Sat. PW-Sat2 is a 2-unit CubeSat that is going to be sent into orbit in 2017 and carries several experiments aboard: a 4 m^2 deorbit sail, a compact Sun sensor, and deployable solar panels. All of these are designed by project members, and more than 60 students have already worked on them. At the beginning of 2016 the project received financial support from Polish Ministry of Science and Higher Education to launch PW-Sat2 into orbit.

The main experiment – a large square-shaped deorbit sail – will dramatically decrease the life-time of the satellite's orbit. It will be made from durable foil stretched across four flat springs attached to a custom designed pin. The sail will be coiled and placed in a cylinder with a diameter of about 80 mm and the height of the whole system not exceeding 70 mm. After burning through a Dyneema string, the sail will be unlocked and deployed a safe distance away from the satellite. During the procedure the sail flat springs will expand and assume their original shape that will stiffen the entire structure. As a result, the area and aerodynamic drag of the satellite will be significantly increased, accelerating the satellite's deorbitation. The moment of deployment will be recorded by two on-board cameras.

There will be also a Sun sensor aboard PW-Sat2, consisting of four specifically aligned walls with ambient light sensors. It will allow us to determine the orientation of the satellite relative to the Sun. Its accuracy will be compared to a commercial, reference Sun sensor. Hinges for the deployable solar arrays is another experiment of the project.

SAIL PERFORMANCE ANALYSIS

The performance of the PW-Sat2 deorbit sail has been simulated and analyzed using STELA (Semi-Analytic Tool for End of Life Analysis) software, designed and freely distributed for the academia by The French Space Agency (CNES). The tool has been designed to support the implementation of the French Space Act which guidelines concerning the debris removal are based on the IADCs Space Debris Mitigation Guidelines. STELA is based on semi-analytic extrapolator method, meaning that short term components that do not have impact on long term simulations are omitted for computational speed. The perturbations included in the dynamic model are listed in Table 1.

Table 1 Orbital perturbations included in the STELA software

Earth's gravity field	Complete 15x15 Model including J2
Air drag	Oblate Earth, Rotating Atmosphere
Gravitational force of Sun and Moon	Yes
Solar radiation pressure	Yes, including Earth's shadow

STELA allows to perform the Monte Carlo analyses while varying different simulation parameters. The PW-Sat2 sail performance analyses were conducted with varying launch date, semi major axis, RAAN, mean anomaly, inclination, coefficient of drag, reflectivity coefficient, solar activity F10.7 index and geomagnetic activity AP index. As the exact attitude of the spacecraft with the opened deorbit sail is not known, the conservative worst case scenario has been considered in which the plane of the sail is very close to being aligned with the velocity vector (oscillating 0-5° from velocity vector). This resulted in the effective drag area of 0.2266 m^2 used for simulation. For comparison to compare, the total area of the sail is 4 m^2 and the effective drag area for random tumbling is 2.0150 m^2. There were 7 different cases analyzed for different orbits. These orbits included 5 circular SSO orbits of altitudes between 400 and 780 km, as well as 2 other circular orbits with different inclinations. All of the orbits taken into account in the analysis were the possible orbits for the PW-Sat2 which came from the actual offers received from different launch providers. Results of the conducted analyses show that for all considered orbits, excluding the 780 km SSO orbit, the deorbit sail performance will be sufficient enough to deorbit PW-Sat2 in less than 25 years, which makes it compliant with the IADC guidelines. It is worth noting that the considered effective area may have been greatly underestimated in this conservative approach and that if more data on the satellite attitude behavior during reentry could be obtained, the simulation results may potentially improve. The next step in the sail performance analysis would be to analyze the performance of the sail for the bigger satellites from the micro and small segments, as the potential users of the PW-Sat2 sail design.

Table 2 Summary of multiparameter analyses, worst case; table presents the probability of the lifetime of the satellite to be shorter than a value given in the first column. Columns represent 7 different orbit cases.

x [years]	**Worst case** (effective drag area = 0.2266 m^2)						
	Probability of lifetime shorter than x						
	SSO780 km	SSO700 km	SSO600 km	SSO500 km	SSO400 km	600km 52deg	575km 65deg
< 1	0 %	0 %	23 %	63 %	100 %	24 %	32 %
< 2	0 %	6 %	43 %	92 %	100 %	44 %	51 %
< 3	0 %	17 %	56 %	99 %	100 %	57 %	64 %
< 4	1 %	27 %	65 %	100 %	100 %	67 %	78 %
< 6	5 %	42 %	93 %	100 %	100 %	93 %	99 %
< 10	17 %	86 %	100 %	100 %	100 %	100 %	100 %
< 15	52 %	98 %	100 %	100 %	100 %	100 %	100 %
< 25	96 %	100 %	100 %	100 %	100 %	100 %	100 %
min; max; max/min lifetime [years]							
max	31.60	17.43	7.81	3.57	0.50	7.90	6.65
min	2.94	0.90	0.24	0.08	0.02	0.21	0.16

MAIN DESIGN

The PW-Sat2 sail is a 2 x 2 m square made from 6 or 12 μm (to be defined in further tests) thick aluminized Mylar as its main material. The deployment from the system container is based on a 300 mm long conical spring, while the unwinding of the structure is provided by the deployment of flat springs. In the stowed position, the sail is wrapped around the cylindrical aluminum reel and held between two limiting plates. It is then placed in an aluminum container with dimensions of 80 mm diameter and 51 mm height, which enables us to mount the sail inside the satellite. On orbit, after the deployment command, the Sail Release Mechanism releases a conical spring which is mounted to both the container and the reel. Release is provided by the melting of a Dyneema link which keeps the system in the closed position. The link is burned by heating a resistor to a high temperature (above 150 °C). Similar solutions were repeatedly tested in space missions and allow us to maintain the system in a folded state for a prolonged time. The tension of the Dyneema link is ensured by tension springs selected specifically for the task, additional kick-off the springs are used to support the deployment during its initial phase.

A conical spring, together with a specially designed net system for spring oscillations dumping, pushes the reel 200 mm above the satellite. As soon as the reel slides out of the container, the arms start to unwrap the sail material. Each arm is made from two flat steel springs, which together form the shape of an X-beam.

This kind of system requires no engines and uses only the energy accumulated in the wrapped flat springs. The total power used for deployment is below 2 W in time t < 1 min. This increases the reliability and allows for the opening of the sail even in the case when the energy available on board the satellite is very low. The flat springs are held in sleeves made of Mylar and is attached to the main material along the

diagonals of a square. Such attachment ensures that even in the case of damage to the material near the sail arms, the effective area will not change significantly. If the material was to be mounted to the arms only at certain points, then the damage to one connection could result in the loss of as much as 25 % of the sail area.
Arms are mounted to the reel on two different heights in order to decrease the diameter of the wrapped sail, which again minimizes the volume of the whole deorbit system. The mass of the entire system does not exceed 0.65 kg with volume of maximum 0.7U (1U: 1 unit, CubeSat Standard). The designed deorbit sail is intended for use on micro and small satellites (minimum 2U CubeSat). Interfaces are currently designed to fit CubeSat Standard, but can easily be redesigned for use on different CubeSat structures or non-CubeSat satellites. Moreover, the whole system can be scaled, although it assumes a change in the sail area.
Particular emphasis has been put on the right choice of materials to ensure adequate reliability and system operation in space environment, e.g. to avoid cold welding of elements.

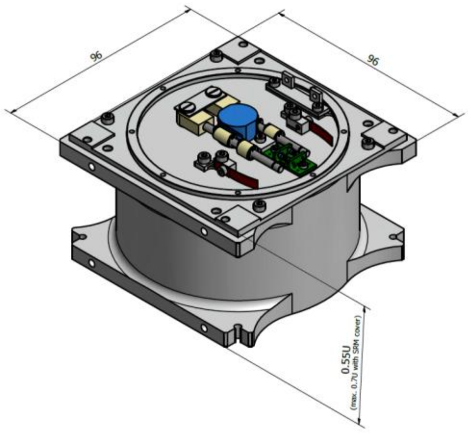

Figure 1 Integrated deorbit system, view on Sail Release Mechanism; main system dimensions

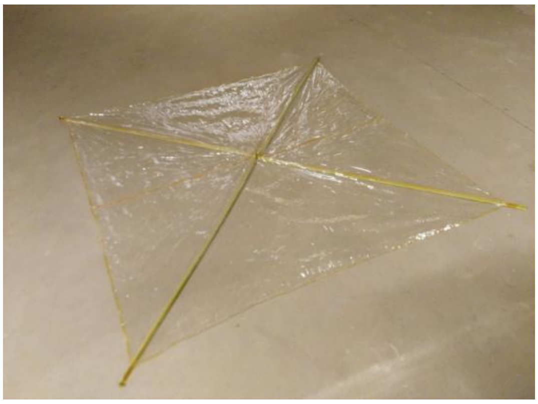

Figure 2 Unfolded, full-scale prototype of the sail

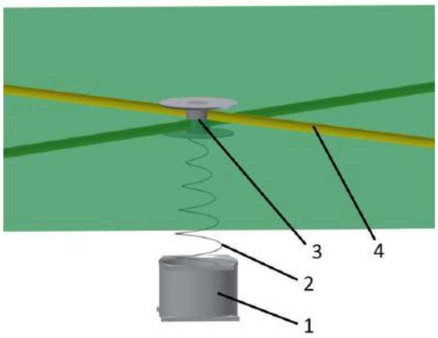

Figure 3 Design of deorbit sail; deployment mechanism close-up, (1) sail container, (2) - conical spring, (3) - sail reel, (4) - flat springs (sail arms)

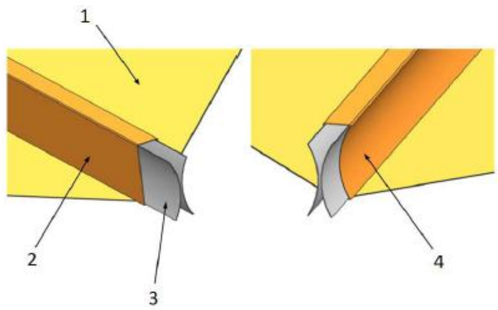

Figure 4 Flat springs in pocket; (1) - sail surface, (2) - spring "pocket" (unstuck side), (3) - flat metal springs (sail arms), (4) springs "pocket" (side stuck to one of the flat springs)

SYSTEM VERSATILITY

PW-Sat2 project's main goal is to design as universal, low-cost and easy-to-produce as possible, while still being able to use a deorbit sail. Although, the sail as the key payload was always destined to be mounted on a 2U CubeSat satellite, it can be easily scaled in order to be used on larger satellites or even the smaller ones (1U).

Initially, the sail was designed to have 4 m^2 of Mylar membrane mounted on the sail's arms, packed into the container (around 0.6 U volume). PW-Sat2's 2U design guarantees that the sail system can successfully fit into every structure of a satellite following CubeSat standard. This construction can be adapted to any larger units (3U and non-CubeSat) as well as can be enlarged without any changes to the concept. However, the sail's area will always be determined by the container's capacity, so any enlargement of the sail will cause enlargement of the container's diameter as well. The same goes with reducing the area. PW-Sat2's sail system can be adapted to 1 U satellite, but its 0.6 U volume significantly reduces the space left for other components. Lowering the container's height can be considered but it will also result in the reduction of the effective area of the sail.

Moving on to the subject of power demand, the PW-Sat2 sail system is as energy-efficient as it could be designed to fulfill its tasks. After integration of the system with the container, the only element which prevents the sail from its deployment is a Dyneema wire which will be burned by resistors. The simplicity of the SRM (Sail Release Mechanism) results in the requirement of really small amounts of electric voltage (used as standard) and a properly designed EPS. There is no need for a dedicated controller for the system. All of the commands activating the deployment process are implemented in the EPS, which also should provide an option to deploy the sail (based on on-board timer) if every other command should fail to do so.

Following the Dyneema burning, the sail system does not need any electric energy to finish its deployment. All the energy needed to move the sail outside the satellite is accumulated in the conical spring and flat springs which act as the sail's arms, stretching out the material.

All in all, adaptation of the system to another satellite is possible and requires only a properly designed EPS. The whole process of releasing the sail does not act negatively on any other subsystem nor any other satellites from an electromagnetic interference point of view. However, it must be said, that it does have its drawbacks. A fully deployed sail may cause problems with communication for smaller satellites using omnidirectional antennas, and would require specific analyses for a satellite to ensure it will avoid the problem. There should not be any disturbances for directional antennas. The only other problem concerns difficulties with satellite control. After deployment of the sail, the satellite is rotating randomly as a result of releasing the flat springs of the sail. All subsystems should reduce its activity during this phase and wait until the satellite regains stability.

Apart from mechanical and power integrity, the most important aspect of designing this sail system was cost. Our goal was to reduce it as much as possible such that each of the components and the system as a whole should be easily affordable for satellite projects similar to PW-Sat2. Most of the parts of the sail system are made of aluminum (which is known to be easily workable) – container, sail's reel, parts of SRM. Sail's arms are made from commercial flat springs which showed almost the same effectiveness as much more advanced ones. Sail's membrane's material is Mylar – another easily accessible element. All in all, the purchasing and manufacturing process of these parts is the reason for the affordable and competitive price of PW-Sat2's sail system in comparison to other deorbit sails.

Considering maintainability, PW-Sat2's sail system does not need any attention after full integration of the satellite. The sail system is highly reliable, which has been proven by tests in rougher, Earth environment (including all friction). All of the materials have been analyzed for aging and does not show any regress. Components are resistant to the influence of UV radiation, atomic oxygen, vibrations and mechanical shocks. The system does not contain any flammable materials or under pressure tanks so the satellite do not need any special treatment. In addition, after integration the satellite does not have to be kept in any special conditions, which greatly reduces the cost of its maintenance.

After releasing the sail, the satellite still does not need any special treatment. In fact, it does not even have to be active after deployment. The sail should turn the satellite perpendicularly to the velocity vector on its own, which will significantly reduce its orbit over a longer period of time.

PROTOTYPING AND TESTING

The sail's design had come through many steps of the evolution until it was ready to produce first prototypes feasible for mechanism's effectiveness tests.

Prototypes included sail structure design and release mechanism design. Many sail structure prototypes were made enabling the gradual optimization of the sail structure unfolding process and improvement of the mounting of the structure to the rest of the system. Additionally a sail folding stand was specifically designed for the PW-Sat2 sail design together with a detailed folding and preparation procedure. Careful design of the folding stand and the maturation of the procedures by numerous tests allowed to achieve a high repeatability of the folding process. As a result, an improvement of the reliability of the sail deployment and minimization of the folded sail volume has been gained.

Many prototypes of the sail were prepared and tested. Initially only the sail structure – flat springs and reel, without the sail material – was tested and the idea of the tape springs as an unfolding mechanism was validated. Further on, the tests of a miniaturized sail, including the sail material, were made, with an examination of the material folding process and rate of sail's compression. Sail materials used in the initial test were thick and a problem with the air left between the folded material layers occurred. In the later tests the use of the thinner sail material – a Mylar foil – eliminated the problem.

Because of the specificity of the low gravity and vacuum environment for the mechanism, it is hard to prepare proper tests, revealing the entire truth about mechanism's effectiveness. We do not have any vacuum chamber big enough, nor any zero friction surface, and it is harder for the sail to deploy in an Earth environment. Therefore different tests are being made for the different phases of the sail deployment:

- the deployment initiation and closed sail ejection from the container;
- the sail unfolding.

The tests of sail ejection from the container are easier to carry out and give more information about ejection dynamic, how the sail moves out of the container and how the conical spring works. The main problems for the tests of sail unfolding are gravity and air. There is a problem with the surface friction, which is getting worse with increasing sail area, and it is hard to simulate this situation in the Earth's environment. The only solution is to cover the surface with a low friction coefficient material, which can give lower losses of the unfolding dynamic. In the test the sail is unfolding on a ball bearing, with additional mass, in the same way as it will be on a satellite. It is considered as a worst case. If the sail opens on the table, it will be easier to deploy it in space.

The idea for the final sail subsystem integration with a satellite is to prepare 5 identical flight models of the sail structure, choose the best one and do the unfolding tests with the other four sails. If all four will unfold in the proper way, the fifth one will be integrated with the container. We made a decision not to open the flight model which is supposed to be folded the best. The sail is a one-time opened structure and there is a risk associated with repeatedly folding and unfolding the structure and material. The sail's folding is highly repeatable and gives us the certainty, that every sail folded the same way will deploy the same way.

SUMMARY

The deorbit sail has been designed to ensure passive deorbitation on its test flight with PW-Sat2, which will let us test the efficiency of the sail when deployed in low Earth orbit. The system is developed with reliability and low energy consumption in mind, while keeping focus on using easily available and affordable materials and components for the construction. Over the course of the development phase, more than a dozen working sail prototypes was produced during the design iterations to ensure maximum reliability. We are now preparing prototypes of all the mechanisms involved in the complete system, and are approaching the final performance tests. Over the coming months we wish to perform system integration of the satellite and prepare for overall testing, and make sure we're ready for the final satellite launch and on-orbit technology testing.

(End)