Developments in ISISPACE Small Satellite architectures due to Space Debris Mitigation requirements

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ABSTRACT

With an increasing number of CubeSats in LEO, the need for sustainable practices becomes more critical with the day. This paper outlines the results of a study towards a CubeSat architecture compliant to a wide range of space debris mitigation requirements, covering the currently enforced along with foreseen additional restrictions. All aspects of debris mitigation are addressed, ranging from space traffic management to passivation and disposal operations.

1 INTRODUCTION

With the exponential increase of the population in high demand orbits, the risk of Kessler syndrome prevails. This drives the need for stricter regulations related to space debris mitigation. ISISPACE has a wide variety of customers spread all over the world, and for each customer, a slightly different set of debris mitigation requirements is applicable, depending on the desires of the customer itself, the country of satellite registration and the launch authority. To navigate this landscape, a study is being executed to find several suitable satellite architectures that would comply with an overarching set of debris mitigation requirements.

The mission under study is an IOD/IOV CubeSat mission focusing on design gaps that can provide compliancy to these requirements. While the baselined concept consists of a 12U CubeSat operating in LEO at ~600 km altitude, sensitivity analyses are being performed to assess whether the architecture requires modifications when extending to a smaller (6-8U) or larger (16U) form factor and to a different orbital range in LEO. While most CubeSats currently rely on passive compliancy to the requirements (i.e. passive re-entry within the required time), the mission under study will rather demonstrate reliable deorbiting with a de-orbit device. Additionally, the mission will include measures such as collision avoidance capabilities, reliable passivation and more. Several technological challenges from the Zero Debris Charter [1] and the Zero Debris Technical Booklet [2] are addressed during the study.

One of the main objectives of the study is to assess improvements related to space traffic management. Multiple trade-offs are being performed to find a solid system baseline that ensures compliancy to the requirements. As main highlight, firstly, different methods for collision avoidance are being assessed based on their reliability and effectivity. The methods under study are chemical propulsion, electrical propulsion and use of differential drag. Secondly, a trade-off is be performed towards improving spacecraft identification shortly after a rideshare launch. Methods that are under study are the use of a commercial off-the-shelf (COTS) retroflector, GNSS beacons, Doppler measurements through a satellite communications link and others.

Another important aspect is an assessment on how to quantify and improve reliability figures on the relevant debris mitigation technologies. The current ESA requirements [1] only request a certain reliability for end-of-life disposal and passivation, but it could be anticipated that in the future this is also required for collision avoidance. It is currently a challenge for CubeSats to associate functionalities with reliability figures due to the use of COTS components. Therefore, several methods are addressed on how to quantify the reliability.

This work is largely funded through the ESA pre-phase A CleanCube study. As the study is still ongoing, not all trade-offs have been concluded, so the paper is mostly focussed on the identification of the trade space.

This paper starts with a lay-out of the requirements that are used as input to the study. Next, in Section 3, the topic of reliability is discussed, since this serves as input to most of the topics outlined thereafter. In the next sections, the following items are addressed: end-of-life disposal, collision avoidance, space traffic management

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

and passivation. In Section 9 a conclusion as well as recommendations for future work can be found.

2 REQUIREMENTS

The strictest requirements currently present are the ESA Space Debris Mitigation Requirements [3], tightening the restrictions imposed already by the ISO Standard [4]. Several driving requirements for CubeSats are stated below:

- The reduction of the LEO disposal phase to 5 years with a probability of success above 90%.
- Unambiguous identification within 1 day after launch
- Collision avoidance capability available 2 days after launch.
- Need for quick responsiveness to Conjunction Data Messages (CDM)
- Probability of successful passivation of at least 90%
- Need of failure prognostics, wear out data and Failure In Time (FIT) data

Besides ESA, two other main sources of requirements are accounted for: FCC [8] and the French law [5]. Especially the French law contains several requirements that are stricter than ESA. For example, if the mission lifetime is only one year, the satellite shall de-orbit within three years.

Lastly, a set of forward-looking requirements has been added. As an example, the current ESA requirements do not ask for a probability of success on Collision Avoidance Manoeuvre (CAM) capability, but it can be anticipated that in the future this may be needed.

3 RELIABILITY

Reliability computations have been shown to be a key issue when using commercial COTS electronic, electrical, electromechanical (EEE) components which is typically done for CubeSats. The use of COTS components provides great advantages of short lead times, low Size, Weight and Power (SWaP) and extensive functionality at a competitive price point. But a widely acknowledged disadvantage of the COTS approach is lower reliability. Broadly speaking, there are two reasons for this. Firstly, the random failure rate may be higher due to lower design margins and reduced quality control for commercial-grade components. Secondly the in-orbit environment is more challenging compared to the terrestrial environment that COTS EEE components are typically exposed to. These COTS components most often do not come with any reliability figures from the manufacturers, which is the source for the difficulty of performing a reliability analysis. Other methods exist, such as using FIDES analysis, but since this is a time-consuming exercise, it is often not compatible with CubeSat timelines and costs. Nevertheless, the applicable requirements still request the provision of a quantified reliability. Therefore, as part of the study, an assessment will be performed on the use of FIDES or alternative methods for critical items.

Additionally, within ISISPACE exercises are being performed to increase reliability without quantifying it. A high-level assessment of reliability figures (e.g. through parts count) can be made with the goal of comparing certain spacecraft architectures with each other, which can feed into conclusions on how to increase the reliability. This activity, together with Failure Mode Effect & Criticality Analysis (FMECA) studies, shows that the most efficient method to increase reliability is to implement a one fault tolerant architecture through redundancy, which is typically not implemented in CubeSats. Therefore, it is anticipated that this mission will be one-fault tolerant for space debris mitigation technologies requiring a reliability assessment.

Another consideration related to this topic is the need for improved methods to assess the health status of critical functions related to debris mitigation. From literature review there are common denominators in this regard. First, a review is needed regarding what additional telemetry of the subsystems could be meaningful as an indication of the health status, using the internal sensors on the boards. To handle this information, more detailed on-board data analysis can be implemented, providing early detection of off-nominal behaviour. This increased autonomy will enhance the reaction time, in contrast to the traditional implementation based on threshold values triggering a change in satellite modes, subsystem resets and on ground data analysis. Additionally, the inclusion of additional sensors is widely recommended (temperature, acceleration and angular velocity). These can be used to validate the integrity of the readings from the main sensors or as a back-up when the ADCS is not operational. These fall under the best practices leading towards what is known as predictive maintenance. The use of COTS in the CubeSat niche limits the available data for the implementation of predictive models, hence the available solutions will be analysed to identify adequate candidates (if any).

4 END-OF-LIFE DISPOSAL

The requirement related to end-of-life disposal is to de-orbit after the end-of-life within 5 years with a probability of success higher than 90%, and it can be anticipated that the required probability of success may increase even more in the future. Using propulsion for a de-orbit maneuver is often considered the solution to this, but, it is seen that propulsion is particularly difficult for CubeSats, due to the following reasons:

- CubeSat propulsion systems are a challenging technology, so the reliability of the unit itself is likely not compatible with the requirement.

- Nearly the entire platform needs to be operational at the end-of-life to perform a deorbit maneuver. Working ADCS is required, as well as high power for the propulsion unit and communications to plan and schedule a maneuver. Ensuring this scenario at the end-of-life with a 90% probability of success is currently deemed unrealistic.

Therefore, the probability of success points us in the direction of a passive deorbit device, meaning that it is stand-alone from the platform. In order to reach a sufficiently high reliability, the deorbit functionality will be one-fault tolerant to increase the reliability. This leads us to the inclusion of two stand-alone de-orbit devices, where both systems are able to work upon command as well as autonomously, i.e. if a ping has not been received by the on-board computer within a to be defined amount of time, it will be automatically deployed. This trigger would also work in the case of a dead-on-arrival.

The proposed system is a drag device from GAMA, named the AstroBrake. In order to ensure a high reliability, the electronics of the device are carefully selected, tested, and placed in a redundant configuration, designed both against the risk of early-deployment and deployment failure. The behavior is completely hardware-defined, removing any software risk from the equation. Power is ensured autonomously through $LiSoCl_2$ primary cells that allow up to 6 years of power independence, which actuate a single HDRM at end-of-life. The structural members (booms) are stored coiled, storing the mechanical energy they need for deployment through elastic deformation, and hold against the system's external door. When deployment is triggered, the actuation mechanism allows the door to open and the booms deploy by releasing their stored energy, pulling the 1.5m² polyimide sail open. The deployment trigger can be either timer-only (up to 4 years) or through health-sensing via redundant heartbeat signals from the spacecraft systems as a timer reset mechanism. This whole system, designed by GAMA under the name Astrobrake-S, is packaged in a half-unit configuration (two can fit in a 10cm side cube) and is being further developed to target being compliant with today's dominant CubeSat structures on the market, thus making it a great option for CubeSats with sizes 3U and up.

Having a de-orbit device with a high reliability comes at a higher cost, but the main advantage is that it allows to by-pass high reliability needs on the platform, allowing faster mission development timelines.

5 SPACE SITUATIONAL AWARENESS

One of the main goals of space debris mitigation is to better understand the space environment, and a solution needs to be provided to enhance information on the whereabouts of the spacecraft. For this purpose, the mission needs to include a space surveillance segment, for which Neuraspace has been selected as service provider [6].

The current ESA requirements ask for unambiguous identification 1 day after orbit injection, which is particularly difficult for spacecraft on rideshare launches (referred to as the so-called 'CubeSat confusion' [7]). Currently it may take several weeks until all CubeSats on a rideshare launch have been matched with a Two Line Element (TLE). Even when powering on the on-board GNSS receiver within 1 day after launch, it stays difficult to match a TLE with the GNSS data. Therefore, it is expected that the orbit will be determined by combining several different sources of data:

- The satellite could include a laser retroflector to enhance its tracking. This solution would be of low impact to the satellite design while providing very high accuracy orbit determination.
- The Neuraspace optical telescopes can be used to provide orbit determination of the objects on the rideshare launch.
- GNSS data can be downlinked during the first pass in LEOP. This data would need to be matched with an on-ground observation to enable full identification of the object.
- A Doppler shift assessment can be performed during the first ground station pass, this data can be used to match the satellite to existing TLEs.
- LEDs on the satellite could be used to enhance on-ground visibility.
- A relay satellite constellation could be used to improve coverage.

Each of the above options comes with its pro's and con's, so a careful assessment is required to define a solid baseline. For example, powering on the GNSS receiver in LEOP impacts the satellite power budget in a risky mission phase, telescopes cannot provide guaranteed visibility due to weather effects and coverage constraints, and the use of LEDs may impact the mission compliancy to dark and quiet skies requirements. While it seems that sufficient possibilities are available, further work is needed to solve this issue.

Once a solution has been selected for the LEOP identification, it is anticipated that the same solution can be used throughout the entire mission to improve satellite surveillance.

6 COLLISION AVOIDANCE

Related to collision avoidance capability, a fault tolerant system will be included to ensure an appropriate reliability. The first solution to be included is a propulsion system to perform collision avoidance manoeuvres. However, since it is seen that propulsion may have a relatively low reliability on CubeSats, the differential drag method will also be implemented. This requires the spacecraft to be able to change its drag area. With a 12U spacecraft this is possible and deployable solar panels may be added to increase the effectivity of this solution. One concern is that differential drag and/or electrical propulsion may not allow to manoeuvre fast enough to ensure compliancy to the ESA requirements. Therefore, the study will include an assessment on the efficiency of each of these methods. It needs to be noted that the current ESA expectation is that differential drag is not good enough to meet the requirements. However, if the mission propulsion system fails or if it is unavailable, using differential drag is still better than not doing anything. Therefore, it is essential to understand how effective this option would be.

Additionally, the mission will implement the use of an external service that will be on call 24/7, and reach out to ISISPACE in case urgent action is needed. The urgent action may be to implement a manoeuvre, therefore a high availability is also required on the operator side. It needs to be noted that for many low-cost missions is it difficult to be on call during weekends and/or nighttime (e.g. for university projects), so methods will be assessed to simplify this process. To meet this objective, a statistical assessment will be performed to assess the risk of being unavailable during the weekend and in the nights. Secondly, possible options for automation will be addressed. Ultimately this comes down to a trade-off where the main criterium is costs; operation costs vs. automation costs.

A last stringent requirement is to be able to perform collision avoidance manoeuvres 2 days after orbit injection. On first thoughts, it is considered a high risk activity to manoeuvre so shortly after a rideshare launch, when most of the objects have not been properly identified yet (see Chapter 5). This is in accordance with launch authority requirements, e.g. on Transporter missions it is not allowed to manoeuvre within 7 days after the launch [9]. If such requirements are present, this takes precedence over the ESA requirements. But even if the requirement is to be able to manoeuvre 7 days after launch, this remains a key challenge as it requires the full AOCS including propulsion system to be commissioned. For this purpose also, it is beneficial to show the efficiency of the differential drag method, which is significantly easier to be executed shortly after launch.

7 PASSIVATION

To minimize the internal break-up risk, the platform will implement passivation of its onboard energy sources. The following systems will be passivated: the propulsion system (especially if it is with pressurized gas), AOCS (desaturation of the reaction wheels) and the electrical subsystem (battery pack depletion and Solar panel disconnection). The aim is to provide a reliability figure, but due to the use of COTS this may be challenging (see Section 3). Fault tolerance is currently under study on the passivation of the EPS (designed in-house) to increase the reliability of passivation. The propulsion system and reaction wheels are third party products on ISISPACE satellites, so the passivation implementation will be discussed with the providers.

8 OTHER CONSIDERATIONS

Several less critical but nonetheless important items are preparation for removal, dark and quiet skies, mitigation of effects of collisions with untraceable objects and on-ground casualty risk. None of them are addressed in detail in this paper as they are not driving for CubeSat designs. Nevertheless, it is noted that our satellite designs do account for these items.

9 CONCLUSION AND FURTHER WORK

It can be concluded that space debris mitigation for CubeSats is becoming increasingly important and touches a wide amount of subjects in mission and satellite design. It is clear that certain items that are required for debris mitigation purposes will also result in a performance increase for the mission itself, e.g. reliability assessments and health monitoring. A variety of mitigation technologies has been proposed, including drag sails and space traffic management solutions, each offering unique benefits and challenges. While progress has been made in identifying these options, significant trade-offs remain to be addressed. Factors such as cost and operational complexity must be carefully balanced to ensure that mitigation strategies are both effective and feasible for CubeSat missions. Moving forward, the proposed trade-offs will be concluded to identify suitable CubeSat architectures compliant with the Zero Debris objectives.

10 ACKNOWLEDGEMENTS

The work described in this paper has been largely funded by the European Space Agency as part of the CleanCube Pre-Phase A study under the SYSNOVA initiative.

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