CUBESATS: PAVING THE WAY TOWARDS AN EFFECTIVE RELIABILITY – ORIENTED APPROACH

G. Fois and G. Mura *

DIEE, University of Cagliari, 09123 Piazza D'Armi Cagliari, Italy – (g.fois20@studenti, giovanna.mura)@unica.it

KEY WORDS: CubeSats, COTS, Reliability, Design for Reliability, Debris, LEO

ABSTRACT:

CubeSats enable the development of a new Space economy towards a Space that is now open and accessible to all kinds of activities, industries and even end-users. However, the failure rate of these satellites is high enough to significantly contribute to the Low-Earth Orbit congestion. This issue can be addressed with a gradual decrease of the formation rate of new debris, while removing the existing one, to prevent future collisions. To ensure a long-term sustainability in Space, a Design for Reliability approach on the new generation of CubeSats could enable a safe and effective maintenance in LEO. Reliability procedures applied from the beginning of the design process can significantly improve the mission success rates.

1. INTRODUCTION

1.1 Introduction

Earth Observation and Remote Sensing is considered the most significant and fastest-growing segment in the small satellite market. Earth observation services primarily cover the monitoring of agricultural fields, detection of climatic changes, disaster mitigation, meteorology, and several other resources. Micro and nanosatellites offer the opportunity to assess and address climate changes and their sustainability on a global scale. CubeSats are widely used in this context, enabling the development of a new Space economy, with its renovated market accessible to all kinds of activities, industries and universities. Nowadays, the percentage of failure for University-built CubeSats within the first six months of operation is estimated to be slightly below 50% (Langer, 2016). Moreover, failed CubeSats are a liability for other satellites, increasing orbital debris due to collision or system failure. As Space becomes more congested, the threat of collision of new satellites and rocket launches with "Space junk" has grown. For these reasons, debris in Space challenge the usefulness of building spacecraft in LEO.

Reliability should represent a vital characteristic of a Space system and must be properly evaluated to assure the mission objectives. Designing a reliable product today is genuinely a concurrent engineering process. A Space-qualified component has undergone rigorous, and therefore costly, testing and validation. On the other hand, Space-qualified components are expensive and limited in specific abilities.

Speaking about CubeSats, the utilization of commercial-off-the-shelf components (COTS) for Space applications is a must as they limit the cost and time associated with the mission's development.

Nevertheless, to stay attractive and affordable, traditional Space testing cannot be implemented in CubeSat projects. A *buy-and-flying* approach poses a threat to the Space environment because not all COTS are suitable for Space.

Properly analysis and design/testing methods should ensure that the dependability targets are met, maintaining the reduced costs and timing. In this paper, a preliminary built-in reliability approach based on Design for Reliability (DfR) procedures aims at reducing failures to ensure the mission profile expectation. The study starts from a small-scale project funded by Fondazione di Sardegna under the project ARGOSAT-Microsatellite cluster to observe optical transients in Astronomy. It aims to acquire global requirements, their translation into DfR-oriented requirements and the subsequent high-level design of the system elements for the microsatellite constellation. These evaluations can easily be extended to other missions.

2. CUBESATS: CRITICALITIES AND RELIABILITY

2.1 CubeSats philosophy

In the past, the satellite design philosophy was dominated by highly reliable components and conservative designs built for durability under extreme environmental conditions of Space, featuring redundancies and extensive qualification and performance testing at part, sub-system and integrated system levels. (Perdu, 2018)

The arrival of CubeSats changed the traditional philosophy favouring utilizing state-of-the-art COTS components able to offer increased low-cost performance.

A CubeSat is a small satellite whose basic unit form is a 10cm edge cube, namely 1U. They can be 1U, 2U, 3U, or 6U in size and typically weighs less than 1.33 kg per U.

NASA defines COTS as "any grade [part] that is not Space qualified and radiation hardened".

The design approach for CubeSats usually consists in building and launching fast, using COTS electronics. Due to budgetary and time constraints, the number of tests performed is reduced up to zero compared to the ones Space agencies are using for their high-reliability, expensive and large spacecraft.

The reliability of electron devices depends on their capability to withstand stresses. The most prominent environmental aspects that affect electronics in Space are noise, vibration and shocks, outgassing, electrostatic discharges, atomic oxygen, vacuum, Space radiations, temperature fluctuations.

Intrinsically weak devices may react extremely fast to the applied stress, causing early failures. The reduced or annulled testing phase induces a critically high number of early failures (above 50% from 1994 to 2017). It is sensibly contributing to

---

* Corresponding author

the risk of congesting the Low-Earth Orbit (LEO) and the Geosynchronous-Equatorial Orbit (GEO) with debris. Relying on natural decay is unsustainable because this process lasts from decades to centuries, depending on the orbital altitude. Otherwise, the solution proposed of moving the satellites by propulsive means to an orbit closer to earth before retirement, where earth's drag eventually brings objects back into the earth's atmosphere, appears at the moment, not resolutive.

2.2 Debris

The term orbital or Space debris includes old spacecraft and satellites no longer in use, fragments of various sizes, and multiple launchers stages. Collisions with other spacecraft can generate debris clouds that could ignite a collision avalanche known as Kessler syndrome.

Moreover, debris could represent a serious safety issue for terrestrial. A recent example is provided by the uncontrolled re-entry of a portion of the CZ-5B rocket in May 2021.

A detailed overview of the concerns related to debris has been recently proposed in (Murtaza, 2020).

The debris issue can be faced by reducing the probability of new debris, by removing the existing debris and by preventing future collisions. Actions can be related to mitigation (to limit the creation of more debris), remediation (to remove debris from orbit), and Space situational awareness (to prevent operational satellite collision). On several occasions, the International Space Station changed its trajectory to avoid Space debris, which is one solution to prevent collisions.

More sustainable solutions include using lasers to vaporize Space debris or remotely controlled vehicles to remove Space junk from orbit. A reliability-oriented approach during the design phase of the satellite can lead to a systematic reduction of the failures extending the mission success and duration. In addition, even though the removal of a satellite from its orbit presents large amount of challenges, the concept of Design for Removal is paving the way to ease the removal of future satellites.

2.3 CubeSats: Reliability concerns

From a reliability standpoint, a Cubesat is a complex system, containing many components, on which six significant subsystems can be identified: structure, communication, power, attitude determination and control, command and data handling, and the payload.

The evaluation proposed in (Langer, 2016) showed that the overall reliability of CubeSats is strongly dominated by high rates of dead-on-arrival (DOA) cases, where the satellite is ejected from the deployer but never achieved a detectable functional state. The 2-year reliability estimation ranges from 65.49% on the upper end of the confidence interval to 48.49% on the lower one after two years in orbit. The authors suggested that a significant percentage of those DOA and infant mortality early failure cases could have been avoided by more careful and adequate system-level functional testing on the ground.

The three main subsystems that cause the most CubeSat failures within the 90 days are the electrical power system, on-board computer and communication system, and, in addition, there is the "unknown" category.

It is fundamental to avoid or reduce the large number of infant mortality cases, to evolve the CubeSats into more reliable platforms.

Finally, even (Swartwout, 2013) pointed out that many early failures are due to inadequate system-level functional testing, i.e. the spacecraft was not operated (or not long enough operated) in a flight-equivalent state before launch.

2.4 Design for Reliability (DfR)

Reliability is defined as "the probability that an item can perform its intended function for a specified interval under stated conditions" (MIL-STD-721C).

The Design for Reliability (DfR) ensures that a system performs the specified function within the customer's use environment over the expected lifetime. It refers to the process of designing reliability into a product since the design phase.

The DfR includes an entire set of procedures and practices that support product design from early in the concept stage through to obsolescence, and where the reliability engineering is built into the total development cycle. It relies on reliability engineering tools and a proper understanding of when and how to use them throughout the design cycle.

In the Space context, the DfR can be beneficial to achieve the expected reliability of the system for the predicted mission duration.

By following reliability- oriented approach, it is fundamental to point out the significant criticalities, the mandatory requirements, and what aspects of mission assurance can significantly improve the mission success rates. From this evaluation, a reduced set of tests can be defined able to screen early failures and enhancing the probability of success.

2.5 CubeSats: Reliability improvements

A DfR approach at the system level can significantly reduce the satellite failure rate. In addition, the application of this technique at the component level could lead the assessments in terms of obsolescence, de-rating, redundancy where possible. Finally, component/ system-level tests can ensure a high level of confidence and the success of the mission.

Targeted screening and reduced qualification procedures on the components should be individuated based on the specific mission profile.

The inputs to identify the mission are its orbit, the duration and device shielding. It is crucial to determine the level of reliability needed, to address budget and time constraints concerning the components being selected. In this context, (Langer, 2017) proposed a reliability estimation tool able to estimate their required functional testing time on subsystem and system level at an early project stage to function the targeted reliability goal for the designed CubeSat. Anyway, it is not intended to replace the environmental tests needed for verifying Space hardware (e.g. thermal-vacuum tests, mechanical stress tests, radiation tests).

Since the design phase, in synergy, Failure Modes, Effects Analysis (FMEA) and Fault Tree Analysis (FTA) can support a reliability-oriented approach.

FMEA (MIL-STD-1629A) and FTA (MIL-STD-882) are complementary techniques.

FMEA is an inductive method that identifies all the possible failure modes of a single component in the system and their possible failure mechanisms. It lists the resulting consequences associating with a risk priority number. The FMEA can be extended to Failure Modes, Effects and Criticality Analysis (FMECA) by adding a criticality analysis.

FTA is a deductive method that takes an undesirable state in the system. Using a logic tree illustrates how specific faults, or combinations thereof, will lead to the undesired state. The individuation of the "cut set," which is a collection of events that, when combined, will result in the failure of the selected top event is a key aspect of this procedure.

FMEA can manage CubeSat reliability data and prioritize criticalities early in the design phase to prevent failures

(Menchinelli, 2018). Fault Tree Analysis (FTA) can be used not only for investigating the anomalies to help recover the mission as proposed in (Stevina, 2020) but even for a preliminary evaluation of the possible events able to cause failures (Vesely, 2002) (Bidner, 2010).

The combination of FMEA and FTA can be beneficial in detecting the undesired events that have the highest chance of happening. The analysis of the system from two different points of view enables corrective actions that include the selection of components with higher reliability, the derating for critical elements, and redundancy or additional detection methods.

The overall Cubesat reliability cannot be achieved with the same processes and procedures used for Space-grade components. The use of COTS components in Space is increasing more and more, and there is still not a clear and homogeneous policy to follow when using these components. Nevertheless, as not all COTS are suitable for Space (Crocker, 2005) (Lu, 2012) (Mura, 2009) (Mura, 2018) (Sinclair, 2013), a buy and flying approach is risky, and an appropriate selection of COTS electronics is mandatory.

An intelligent evaluation should identify COTS components that are already intrinsically robust, highly reliable, and that natively show good robustness to the radiative environment. Moreover, burn-in (MIL-STD-883F) and screening are DfR tools that prevent infant mortality failures, typically caused by manufacturing-related problems, from happening on-orbit.

After an FMEA/FTA analysis, a reduced set of critical components can be pointed out, and proper testing addressed.

It could furthermore allow selecting a reduced set of up-screening and qualification testing that guarantees the fulfilment of the mission requirements. Consequently, a significant containing of the costs and development times of the project can be reached. In addition, for less critical devices, even existing qualification results of similar products can guide the selection and reliability assessments by structural similarity.

Automotive components have significant potential for mainly being adequate and robust in a Space application.

The Automotive business model, thanks to its ppm-level quality and reliability targets, offers the opportunity to consider Automotive components eligible for Space application. It can be beneficial due to this high-production, high reliability, well-screened market.

Qualification extension and subsequent accelerated ageing test plan based on the device family (ASIC, RF, Optoelectronic, etc.) and the specific mission profile can fill the gap. An extension of the emerging “robust qualification” Automotive policy by applying additional series of reliability tests selected through a failure mechanism driven approach is proposed in (Enrici Vaion, 2017) (Enrici Vaion, 2018).

Automotive COTS can offer reliable performance in extreme conditions with a set of reduced tests able to close discrepancies.

Thermal/vacuum and radiative tests are mandatory.

In (Stevenson, 2017) (Fernandes, 2016), comprehensive specifications on thermal tests are proposed.

(Sinclair, 2013) proposes the “Careful COTS” considered between Space-grade requirements and the buy-and-fly approach. It involves proving radiation tolerance of specific commercial parts required for the mission and implementing screening and process control to improve reliability. Moreover, radiation requirements in LEO can be assured by a reduced set of proton testing that allows exploration of total dose, displacement damage, and some single-event effects, together with controlled lot buys.

Moreover, in (Hatch, 2020), several single event tests were carried out on several automotive-grade parts for use in Spaceflight. None of the components tested suffered from catastrophic failure during testing showing intrinsically good robustness to Space.

These evaluations are the starting point of a small-scale project funded by Fondazione di Sardegna under the project "ARGOSAT- Microsatellite cluster to observe optical transients in Astronomy".

It aims to acquire global requirements, their translation into DfR-oriented requirements and the subsequent high-level design of the system elements of the microsatellite constellation.

With the ambition of providing general guidance, the idea involves the expertise necessary for any subsystem and evaluating the more reliable choice resulting from a good balance between costs and time.

The definition of a set of procedures for a thermal qualification of a CubeSat is in progress. For each procedure we will provide a justification, along with details, from a known space standard. The solution that will be proposed does not involve only the testing phase but also includes specific analyses and additions that may help the overall system reliability.

An overestimated effort may force unnecessary inflations in terms of costs and testing time, whereas an underestimated one may hide faults to compromise the mission.

The expected results will be easily extended to other missions.

CONCLUSIONS

CubeSats are changing the new Space economy and will probably play a more critical role in the Space context soon. Despite these advantages, there are concerns that CubeSats may increase the number of Space debris. About 50% of launched CubeSats did not complete their intended mission. Around 20% of all failures occurred either during launch or during the deployment phase (Villela, 2019).

Reduced development time, size and weight constraints and the use of COTS components contribute to early failures.

COTS are not designed to work in the Space environment.

Undoubtedly, Cubesats design and development cannot operate, applying the reliability standards. It is necessary to translate them in a suitable shape for the new Space domain finding a proper balance between traditional procedures and specific requests, between reliability and costs. A reliable and sustainable new Space economy is the ultimate goal, and acting responsibly to reduce junk production is the first achievement.

ACKNOWLEDGEMENTS

This work has been founded by “Fondazione di Sardegna” under project “ARGOSAT – Microsatellite cluster for the observation of optical transients in Astronomy”, CUP: F74I19001070007.

REFERENCES

Bidner, F., 2010. Fault Tree Analysis of the HERMES CubeSat University of Colorado at Boulder.

Cassanellli, G., 2006. Failure Analysis-assisted FMEA *Microel. Reliab*. vol 46, 9–11, pp. 1795-1799.

Crocker, D., 2005. Commercial Electronic Components (COTS) and Reliability In: *56th International Astronautical Congress*, 9, pp. 5842 – 5847.

Enrici Vaion, R., 2017. Qualification extension of automotive smart power and digital ICs to harsh Aerospace mission profiles: Gaps and opportunities. *Microelect. Reliab*. 76–77, pp. 438-443.

Enrici Vaion, R., 2018. From Automotive to Space qualification: Overlaps, gaps and possible convergence. In: *IEEE International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA).*

Fernandes, G., 2016. Thermal Tests for CubeSat in Brazil: lessons learned and the challenges for the future. In: *67th International Astronautical Congress (IAC).*

Gohardani A.S., 2018. Small satellites: Observations and considerations. In: *AIAA Aerospace Sciences Meeting.*

Hatch, J., 2020. Recent Single Event Transients, Upsets, and Latchup Test Results for TPS3307-18, TL1431, INA129, AM26LV31 & 32 Electronic Parts. In: *IEEE Radiation Effects Data Workshop.*

Lu, J., 2012. MIM capacitor-related early-stage field failures. *Microelec. Reliab*., 52, 9–10, pp. 2073-2076.

Langer, M., 2016. Reliability of CubeSats – Statistical Data, Developers’ Beliefs and the Way Forward. In: *30th Annual AIAA/USU Conference on Small Satellites,* pp. 1-12.

Langer, M., 2017. A reliability estimation tool for reducing infant mortality in Cubesat missions. In: *2017 IEEE AeroSpace Conference.*

Menchinelli, A., 2018. A Reliability Engineering Approach for Managing Risks in CubeSats. *AeroSpace 2018*, 5, 121.

Mura, G., 2009. Lot reliability issues in commercial off the shelf (COTS) microelectronic devices. *Microelec. Reliab*., 49, 9–11, pp. 1196-1199.

Mura, G., 2018. Reliability concerns from the gray market”, Microelectron. Reliab., 88-90.

Murtaza, A., 2020. Orbital Debris Threat for Space Sustainability and Way Forward (Review Article). *IEEE Access,* pp. 61000-18.

Perdu, P., 2018. Failure Analysis on Space Electronics: Best Practices, Challenges and Trends. In: *2018 IEEE International Symposium on the Physical and Failure Analysis of Integrated Circuits.*

Sinclair, D., 2013. Radiation effects and COTS parts in SmallSats. In: *27th Annual AIAA/USU Conference on Small Satellites.*

Stesina, F., 2020. Investigation of a CubeSat in Orbit Anomaly through Verification on Ground. *AeroSpace*, 7, 38.

Stevenson, R., 2017. Method for CubeSat Thermal-Vacuum Cycling Test Specification. In: *47th International Conference on Environmental Systems.*

Swartwout, M., 2013. The first one hundred cubesats: A statistical look. Journal of Small Satellites, 2(2), pp. 213-233.

Vesely, W., 2002. Fault tree handbook with aerospace applications. In: *NASA office of safety and mission assurance.*

Villela, T., 2019. Towards the Thousandth CubeSat: A Statistical Overview. Int. Journal of AeroSpace Engineering 3, pp.1-13.

This work is licensed under a Creative Commons Attribution-No Derivatives 4.0 International License.