Additive Manufacturing Applied to the Design of Small Satellite Structure for Space Debris Reduction

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Abstract

Space debris has become a major aspect in the last few years. The vast amount of artificial objects orbiting the Earth is increasing. These objects are a threat for active and future missions. Besides, the possibility of uncontrolled re-entry of some of them reaching the surface of the Earth exists. The aim of this work is to provide a view on how to use additive manufacturing technology to design the next generation of satellites in order to reduce the space debris. The components that can be manufactured with additive manufacturing are identified, together with the technologies that are enabled by additive manufacturing to reduce space debris. Finally, the results of these studies and analysis are incorporated into the design of the structure of a small satellite. This study is being part of the H2020 European Project ReDSHIFT (Project ID 687500).

Keywords: additive manufacturing, space debris, satellite structural design, ReDSHIFT H2020 project; CubeSat, impacts mitigation

1. Introduction

Additive manufacturing (AM) is changing the way of designing and manufacturing in multiple sectors. The possibilities that this fabrication method offers compared with the classical ones give it applicability in the space sector. Some advantages of using additive manufacturing technology are the following:

- Possibility of building lots of pieces in short time.
- Weight reduction can be easily achievable with new designs while ensuring structural properties.

- Less environmental impact because of the decrease in time of fabrication and required material. Also, these factors reduce power consumption in fabrication.
- Process speed optimization.
- Part complexity has little impact on manufacturing time and cost plus fewer manufacturing constrains on part design allowing AM to manufacture complex parts. This enables "design for need" instead of "design for manufacturing".
- Creation of composites using printers with double extruder: one for the fiber and one for the matrix. This allows reinforcing selected parts of the components or including specific designs for embedding a bolt or other harness.
- Possibility of embedding wiring or sensors to generate multifunctional structures.
- Applicability to many materials such as metals, composites, polymers or ceramics.
- Some indicate the possibility of in-orbit or on-planet manufacturing [1].

These advantages over classical manufacturing methods indicate that they can be applied in space for new applications or to improve the existing ones. Since the manufacture process with additive manufacturing offers new design possibilities, and also new geometries that are difficult to be obtained with classical methods, it is *a priori* expected that those characteristics can be used to improve the mechanical behavior of a system by establishing new requirements and boundary conditions.

In this work, the use of additive manufacturing is analyzed along with other technologies that this manufacturing method enables. The objective is to implement space debris reduction measures in the design of small spacecraft.

To achieve this objective, additive manufacturing in the space sector is reviewed and analyzed to find which components of spacecraft are susceptible of being manufactured with this methodology. Besides, the technologies enabled by additive manufacturing and applicable to the design of spacecraft are studied. Finally, a design of an 8 U CubeSat structure is proposed, and its impact in space debris reduction is analyzed.

2. Additive manufacturing in space

Considering the advantages of additive manufacturing defined in the introduction, the first objective is to identify which are the applications for additive manufacturing in space. In this section, the main applications of additive manufacturing in satellites are reviewed in order to identify which components of a satellite can be 3D printed and which of them can contribute to space debris reduction.

2.1. Identification of components that can be printed with additive manufacturing

Additive manufacturing has been applied to different components of spacecraft. Some of them are found to have potential to reduce space debris.

2.1.1. Harness

A major challenge in a satellite is the distribution of harness since it is not always easy to place. The design of the spacecraft is based on the payload and tries to minimize the volume of the structure. For that purpose, the components are strategically placed to reduce the internal volume, and harnessing a satellite becomes a major aspect. As a manner to reduce the harness into a satellite, additive manufacturing allows embedding wiring and even sensors into the panels of the structure. At least two options exist to embed electronics into the walls of satellite structures: (1) interrupting the 3D printer in the appropriate layer to place the component or (2) making use of a printer with dual extruder to print a circuit with a conductive material in just one process (see [2, 3]). In these works, the authors contemplate the possibility of embedding an antenna that can be directly printed into the walls of a spacecraft for space-to-ground links. The use of a wall as a backplane for addition of equipment provides multifunctionality to the structure. These applications, although they present some advantages, as for example the use of embedded wiring and sensors can contribute to reduce the debris generated in a catastrophic impact: in principle, the lower the number of components affected by a catastrophic impact, the lower the number of fragments generated. However, they also present major drawbacks such as difficulties to be repaired during the testing or qualification stages of a satellite if needed. This is analyzed in detail in Section 3.2.

2.1.2. Electronics shielding

Protecting sensitive circuitry from the damage caused by the exposure to space radiation is a current problem, which is overcome with the housing of sensitive components inside metal boxes. This, known as shielding, increases the volume and weight of the spacecraft, which are key parameters. The use of additive manufacturing offers an intriguing alternative because the protective metal could be selectively printed to enclose the part, minimizing volume and maximizing protection [4]. Shielding can highly contribute to the reduction of space debris if the satellite is shielded in order to resist impacts of debris particles. Most of these fragments are of size under 1 mm. By designing a shielding capable to resist in orbit the impact of projectiles of this size, the number of generated fragments would be highly reduced and, for instance, the number of space debris particles.

2.1.3. Active thermal management solutions

Additive manufacturing can provide new advances in thermal management; for example, in the fabrication of surface topologies into radiating panels. This solution increases the surface area of the panel and heat pipes embedded into the structure of the spacecraft [3].

2.1.4. Structure

The application of additive manufacturing to the functional structure of the spacecraft can potentially reduce its weight and manufacturing time with respect to classical approaches, such as computer numerical control (CNC) milling. The use of this technology provides more freedom to the designers, who can make use of more complex geometries to improve the structural efficiency without bearing in mind the complexity of manufacturing a part. Small satellites can be benefited with the use of this technology. In The CubeSat Challenge [5], several designs that could be manufactured with additive manufacturing technology were presented. In this case, when designing the structure, the designer shall bear in mind that the structure and all the components of the spacecraft shall be integrated: the reduction of joints can be a major advantage, for example, but it will also make more difficult the integration tasks of the spacecraft components inside the volume of the structure.

However, for large satellites, the use of 3D printing to be part of the functional structure has limitations, mainly because of the reduced 3D printing volume of the metal 3D printers. Then, the use of additive manufacturing for the functional structure of large satellites is nowadays limited to the manufacture of specific components or parts. Otherwise, the advantages of using this technology would be reduced.

2.1.5. Metal brackets

A potential use of additive manufacturing in the functional structure of a spacecraft is the manufacture of metal brackets. The current generation of satellites includes specific brackets used as mechanical interface between the main frame of the satellite and some components such as star trackers, GPS receivers, reflectors and reaction wheels, among others. The main benefits are the weight reduction and the design for need. These advantages have motivated the introduction of additive manufacturing in the manufacture of brackets for satellites, for example the swiss company RUAG optimized the antenna bracket of Sentinel-1A by using this technology [6].

2.1.6. Propulsion

In the space propulsion area, the improvements that come from the application of additive manufacturing are not only focused on mass reduction through new designs of propellant tanks but also on the improvement of the performance. In this case, the possibility of building rocket injectors serves as example of a complex component easily built with a 3D printer with same or even better performances and tolerances than manufactured with classical approaches. One example is the injector for RL-10 upper-stage rocket engine by Aerojet Rocketdyne [7]. This company also used additive manufacturing in the fabrication of a titanium piston, the propellant tank and the pressurant tank of a propulsion system for CubeSat [8].

2.1.7. Space telescopes

NASA's Goddard Space Flight Center analyzed the possibility of assembling a space imaging telescope made almost exclusively from 3D printed components [9].

2.1.8. Shaped antenna reflector

Some antenna reflectors have complex geometries. This makes their manufacture a complex issue. Additive manufacturing can facilitate the manufacture of antenna reflectors for space applications and satellites, making possible the manufacture of the whole antenna in a single piece, independently of the complexity that its geometry can have. The European Space Agency (ESA) developed a 3D printed antenna for satellites in a single piece to be tested in [10]. NASA and Stratasys also developed antennas by using additive manufacturing in [11]. In this last study, in which they validated the technology for space, they claimed that the use of additive manufacturing saved time and money. However, it shall be considered that plastic materials are highly reactive to oxygen atoms present at the operating height of the satellite. This can produce degradation in the component. They solved this problem by painting the components with a high emissivity protective paint to form a glass-like layer on the plastic structure. With this solution, the component can reflect a high percentage of solar radiation and optimize thermal control of the antenna operating conditions.

2.1.9. Fuel tanks

Lockheed Martin used additive manufacturing in the prototyping of fuel tanks, commonly made of titanium, which along with reaction wheels are also a major problem for space debris and which also have a high casualty risk since titanium is very resistant to the effect of the atmosphere in the reentry. They analyzed the design and the manufacture process to develop this component [12]. In that publication, they claimed that additive manufacturing reduced mass, cycle time and material waste.

3. Other technologies for space debris reduction

As described in the previous section, additive manufacturing can be applied itself in several components of a satellite. However, the characteristics of this technology apart from the generally claimed mass reduction, waste reduction, manufacturing time and prototyping, what seems to be really interesting is the (i) design for need, which changes the whole design paradigm previously established in the design for manufacturability and (ii) independence of the complexity of the geometry to manufacture. These two factors facilitate the appearance of new technologies which before additive manufacturing were very difficult to apply, or even impossible, at least in the way they can be applied with additive manufacturing. Two technologies that can highly contribute to the design of satellites to reduce the space debris were identified.

3.1. Lattice/microlattice structures

Additive manufacturing independence of geometry complexity facilitates the manufacturing of metallic lattices, which without this technology were very difficult to manufacture, they being reduced to the creation of foams and other irregular similar structures. However, the capability to generate a lattice with complex although with regular geometry guarantees that the mechanical behavior of such a structure is the same across the whole section. Besides, the lattice can be designed for a specific need to improve or maximize the performance of specific mechanical behaviors. In addition, lattice structures can also reach negative Poisson rates, which increase the resistance of the structure, fracture thoroughness and shear resistance [13].

Boeing created the microlattice variant to lattice, which is the lightest material ever made (microlattice variant is about 99% air) [14].

As reviewed in [15], the most commonly used debris shields for spacecraft rely on several layers with a large standoff distance between them to dissipate the impact energy. However, proven effective, this type of solution is difficult to suit in small satellites in which volume is even more important than mass.

Current solutions are based on structures such as the honeycomb panels. They have poor impact mitigation and may be difficult to integrate in small satellites satisfying, for example, the envelope limits of the CubeSat standard deployment pods. However, lattices can be used to replace the core of the panels and be manufactured integrated with the structure requiring little extra space and at the same time increasing the impact mitigation. For this concept, the energy of the impact is dissipated through plastic deformation and generation of break surfaces; thus, the design can be easily miniaturized. This performance increase was analyzed by NASA through testing [16] by comparing honeycomb panels with open cell foam core sandwich panels (open cell foam has similar mechanical behavior than lattice) concluding that for equivalent panels the impact mitigation was always better for foam core panels.

3.2. Embedded technologies into 3D printed structure

The other set of technologies enabled by additive manufacturing are those linked to embedded wiring and sensors into the 3D printed structure. Some of them can be directly printed or perfectly placed in strategic locations of the structure. Besides, as indicated before, this can reduce the number of fragments if a catastrophic impact occurs in orbit. These technologies were divided into three main groups: embedded devices (such as sensors, electronics and antennas), embedded batteries and embedded wiring. The main limitation of this set of technologies is that it can only be used over not electrically conductive or very well isolated materials. They are reviewed in the following section.

3.2.1. Embedded devices

There are three different approaches to embedded sensors:

- An off-the-shelf device made by traditional methods introduced in the structure during the printing process. In this case, the provided device must be prepared to survive to the printing environment with no damage. In [17], three accelerometers and other electronic devices were embedded in a polymeric matrix with a combination of Fused Deposition Modeling (FDM) and Stereolithography (SLA) additive manufacturing methods.
- An offline 3D printed device introduced in a 3D printed structure. This is similar to the previous case, but instead of embedding an off-the-shelf device, a 3D printed one is embedded instead. An example is the 3D Hall Effect displacement sensor introduced in [18].
- A device printed in the structure. This can be done with the same process or intercalating two or more manufacturing methods. In this case, if a single process is used, the process needs to provide at least two different materials in the same print. Examples of sensors printed in the structure are the 3D printed strain sensors. These consist of injecting a conductive resin in an elastomeric uncured matrix. The final result is a part with an

embedded flexible strain sensor [19]. Other application that was included in this classification is that of the antennas that can be printed in a structure or surface: in [20], the authors used Inkjet technology to print a metallic ink (silver based) on convex and concave surfaces. They used conductive meander lines with connected feed lines (printed separately) obtaining performance levels comparable to theoretical results. These 3D printed and miniaturized antennas have multiple applications in addition to classical communication uses.

A review of 3D printing methods in the sensor industry can be found in [21]. It is remarkable that none of the examples described there uses a metallic substrate (structure material) and most of them use printing methods based on polymerization not melting.

3.2.2. 3DP batteries

Considering the advantage of additive manufacturing referred to the independence of geometry stated above, this technology can be applied to print batteries of any shape. This can be an advantage in satellites because empty spaces in the structure or in the volume of the spacecraft can be used to create a battery that perfectly fits in.

Several Li-Ion battery designs were developed by using additive manufacturing. For example, the authors in [22] used graphene oxide-based ink to print miniaturized batteries, which could be potentially embedded within a spacecraft structure. The capacity of these cells (called 3D-IMA) was 1.2 $\mathrm{mAh{\cdot}cm^{-2}}$ normalized with the area of the current collector.

3.2.3. Embedded wiring

Embedded wiring for space applications mostly relies on recent conductive inks developed for Inkjet technologies. As stated by Kief et al. in [3], these materials were successfully proven to produce conductive inks for electronics in complex geometries. But low limits in curing temperature led to poor performance in terms of conductivity and carrying capacity which are required for high-power high-frequency applications.

Additionally embedding metallic meshes into polymeric structures were tested, this meshes can act as back planes for electronic components like antennas or as ground planes. Even more meshes can work as support points to weld metallic parts and plastic ones together.

3.2.4. Analysis of embedded technology

This analysis shows that although all these 3DP embedded technologies seemed to be promising, they have relevant technical implementation drawbacks. The advantages of using 3D printed embedded technologies, in general terms are associated to the perfect positioning of sensors, elimination of wiring, optimization of space, and reduction of debris fragments but their integrability in a critical system, such as a satellite is still risky: first, any 3D printed conductive element shall be printed on isolated surfaces such as polymers. This obliges satellite manufacturers to come up with new fabrication methods, materials, or additional surface treatment. Second, these technologies present difficulties in any repairing process that can appear during testing or qualification stages. It would be critical that a main sensor or circuit, embedded in a structural element, fails at any stage of the manufacturing or testing processes, obliging manufacturers to create additional parts. The installation of individual sensors that can be repaired or changed with accessibility seems more applicable. Third, the use of multiple extruders should be used in most of cases, with the exception of printing surfaces with conductive inks, as the cases with strain sensors and printed antennas, which could be printed after the metallic part is complete. The printing with different materials is complex and not viable when the thermal properties of the materials being printed substantially differ, as it is the case of many polymers and metals that can be used in space.

However, some of the previous technologies can provide benefits for specific applications:

- 3D printed embedded strain sensors. This solution would provide a perfect positioning of the strain in the surface to be monitored. Furthermore, the surface can be covered, for example with thermal isolation or shielding without affecting the functionality since it is a measure of an intrinsic parameter of the surface in which the strain is placed. Nevertheless, additional analysis and testing should be done in the process of isolation of metallic surfaces and adhesion of the sensor because there are different materials under critical mechanical and thermal loads. This technology would reduce harness and electromechanical components that can be fragmented in case of collision, potentially reducing the space debris of future systems.
- 3D printed embedded antennas. This technology, as described in the analysis, requires an unused area to be printed on. Furthermore, that area cannot be covered with thermal isolation, radiators or shielding. This is difficult to provide in a satellite. However, in some cases, it would be beneficial to manufacture an antenna through an additive manufacturing process that optimizes its shape and performance and then it is installed in the spacecraft as a component afterwards.
- 3D printed batteries. They present the same drawbacks of embedded devices into the satellite structure (if they are embedded in the structure); however, they can be separately printed and integrated in the satellite afterwards. This presents many advantages because they can be printed with any shape, which would be beneficial to make use of any available volume available in the spacecraft or in the structure.

Thus, this analysis indicates that more research and development is needed for 3D printed embedded technologies to reduce the risk of implementation in operative missions.

4. Small satellite structure to reduce space debris

Considering the analysis carried out in the previous sections, an 8 U CubeSat satellite structure was designed to reduce space debris. Notice that there is no mission defined as the design was done to demonstrate the use of different technologies that contribute to space debris reduction, which is the objective of this work. The reasons of selecting an 8 U CubeSat instead of other type were the following:

- To apply additive manufacturing to the whole functional structure of the satellite for demonstration purposes was intended. The 8 U CubeSat is small enough to be fully printed in a typical SLM metal printer such the ConceptLaser M2. This metal printer has a printing volume of 238 × 238 × 230 mm (length × width × height). The 8 U CubeSat has a volume of 200 × 200 × 200 mm, which fits in the 3D printer.
- The 8 U CubeSat follows the CubeSat standard so the analysis carried out in this work can be applied to a large number of satellites (smaller than 1, 1, 1.5, 2, 3 and 6 U), not only to a specific satellite with a specific design.
- The 8 U will facilitate further work on additional analysis of casualty risk of propulsion titanium tanks and reaction wheels.

The technologies implemented in the design of the 8 U CubeSat were additive manufacturing and lattice structures, applied in the structure to improve the shielding. Embedded devices technologies were not considered in this work because of the high risk of implementation in operative mission. Future improvements on those technologies would lead to additional solutions with the benefits already described. Furthermore, the research was focused in the design of the structure, so the implementation of additive manufacturing to other components of the satellite was not addressed, such as metal brackets, harness, propulsion subsystems including propellant tanks, telescopes and antennas. The AlSi10Mg aluminum alloy was selected as the reference material for the structure. The mechanical properties of the material can be funded in [23].

This work does not enter into details of the structural design of the 8 U CubeSat by following the CubeSat standard. This can be found in [24]. It is focused on the design of the lattice core panels.

4.1. Lattice panel concept

Following the work carried out by NASA in [25], the geometry of the lattice core panel was defined to provide the best impact efficiency possible. The panel was designed as a sandwich panel concept. It was divided into three parts: (1) an inner panel, (2) lattice core and (3) shear panel. Because of the benefits of using additive manufacturing, the inner panel and the lattice core can be printed together. The shear panel can be assembled afterwards with bolted unions. The three parts were not printed together because the SLM printer used metal powder. If the volume to be printed was closed, the residual powder could not be extracted from the part, remaining inside and changing the mechanical properties of the part. **Figure 1** shows the concept of the panel with lattice core. For instance, the structure was constituted by six independent faces with lattice core panel.

A common CubeSat usually has the maximum thickness of 7.7 mm and with 1 mm to assemble shear panels. Thus, the total margin to increase the shielding and width of the structure was 8.7 mm. Increasing this margin would limit the incorporation of standard COTS components in the satellite and would also difficult the integration of the spacecraft in a POD, which is the common interface with the launcher for CubeSats. So excluding the shear panel, the lattice thickness plus the inner wall added could not be wider than 7.7 mm.

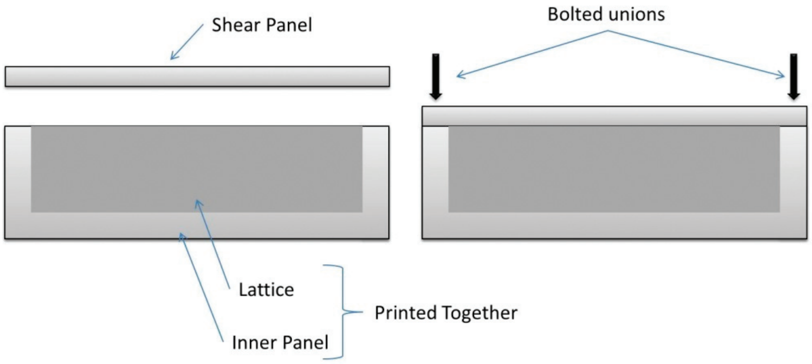

Figure 1. Lattice core panel concept.

4.2. Lattice core panel design

To design the panel, a three-dimensional cost function is generated by relating (1) the impact area efficiency when a projectile of aluminum alloy impacts the surface with an angle of 0° (i.e., perpendicular to the impact surface and a velocity of 8 km/s magnitude) with (2) lattice relative density and with (3) lattice thickness. Eq. (1) was adapted from [25]:

$$d_c = 1,915\frac{(t_w + 0,5AD_{latt}/\rho_w)^{2/3}{t_{latt}}^{0,45}(\sigma/70)^{1/3}}{{\rho_p}^{1/3}{\rho_f}^{1/9}(V)^{2/3}\ cos\ (\theta)^{4/5}} \tag{1}$$

where d_c is the critical projectile diameter at shield failure in cm, t_w is the rear wall thickness in cm, AD_{latt} is the area density of the lattice core in g/cm^2, ρ_w is the density of the rear wall in g/cm^3, t_{latt} is the thickness of the lattice in cm, σ is the rear wall at 0.2% offset tensile yield stress in ksi (kilopound per square inch), ρ_p is the density of the projectile in g/cm^3, ρ_f is the density of the shear panel in g/cm^3, V is the impact velocity in km/s and θ is the impact angle from the target normal vector.

$$AD_{latt} = \rho_{LRel}\rho_{AlSi10Mg}t_{latt} \tag{2}$$

where $\rho_{AlSi10Mg}$ is the AlSi10Mg aluminum alloy density in g/cm^3, and ρ_{LRel} is the relative density of the lattice from 0 to 1.

$$\rho_A = \left(\rho_{AlSi10Mg}(t_w + t_s) + AD_{latt}\right) \tag{3}$$

ρ_A stands for the area density of the lattice core panel in g/cm^2 and t_s is the shear panel thickness in centimetre.

$$\mu_I = \frac{d_c}{\rho_A} \tag{4}$$

where μ_I is the impact area efficiency in cm^3/g.

Figure 2 depicts the results of the optimization region. From this region it was concluded that the optimal solution was a lattice of 10% relative density. Ideally, a higher reduction of the

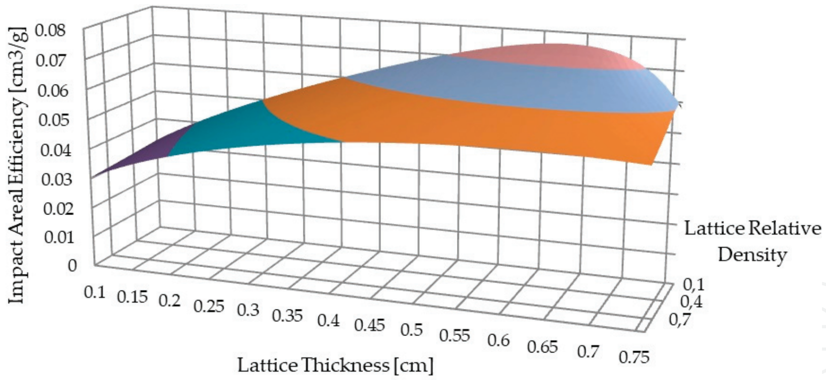

Figure 2. Lattice core sandwich impact areal efficiency [cm^3/g].

lattice relative density would increase the efficiency, but there is a physical limit as the printer has limited resolution and the model used to calculate the critical projectile diameter is not valid since the mechanic behavior changes for lower relative densities.

Figures 3 and **4** depict the lattice thickness in function of the impact aerial efficiency defined in Eq. (4) and the critical projectile diameter defined in Eq. (1) with a lattice relative density of 10%. The design point was chosen to have a lattice thickness of 0.35 mm, a relative lattice density of 10%, and an inner panel with 0.42 mm thickness. This point is not the maximum of the curve but by having moved the design point slightly to the left, although there is lower impact aerial efficiency, there is higher resistance to impacts of projectiles of larger size. The decision of maximizing the impact resistance instead of the efficiency was taken due to the fact that the majority of the space debris has a size lower than 1 mm. In addition, these fragments cannot be tracked so impact avoidance maneuvers cannot be done [26, 27]. Consequently, the Impact Areal Efficiency for the design point was $5.97 \times 10^{-2} cm^3/g$, the Critical Projectile Diameter was 8.9×10^{-2} cm and the designed panel mass is 0.60 kg.

4.3. Lattice core panel analysis

In this section, the shielding performance of the lattice core panel designed is compared with three cases:

- A classical shear panel of 1 mm thickness. This solution weights 0.11 kg.
- An IsoMass panel: it keeps the same mass than the lattice core panel. It has larger thickness than the 1 mm shear panel and generates an equivalent solid plate to that of the lattice core panel. This solution measures the benefit of making a more complex geometry which cannot be made with traditional methods. For a 20 × 20 cm plate, this solution weights 0.60 kg.
- IsoVolume panel: CubeSats are restricted in volume to take advantage of COTS pods so a second variant is presented, instead of keeping the same mass now a solid plate with the same volume as the panel with lattice is defined. This approach evaluates how volume efficient the lattice core solution is compared to a heavier solution with its same volume. For a 20 × 20 cm plate, this solution weights 0.94 kg.

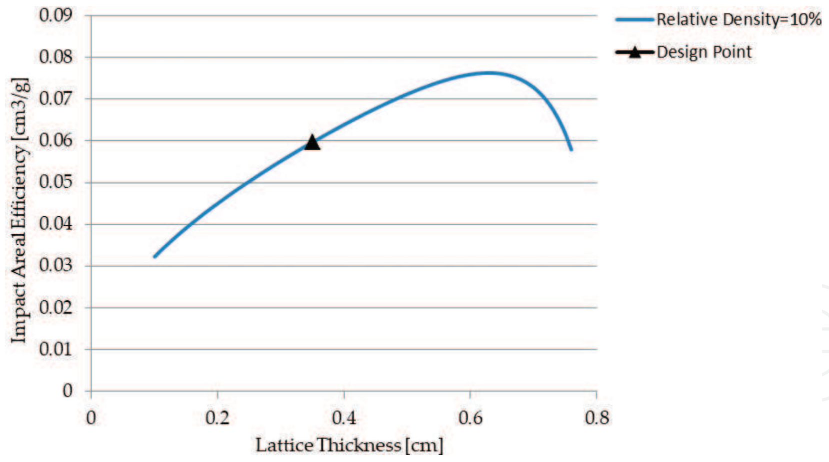

Figure 3. Impact areal efficiency vs. lattice thickness for a relative density of 10%.

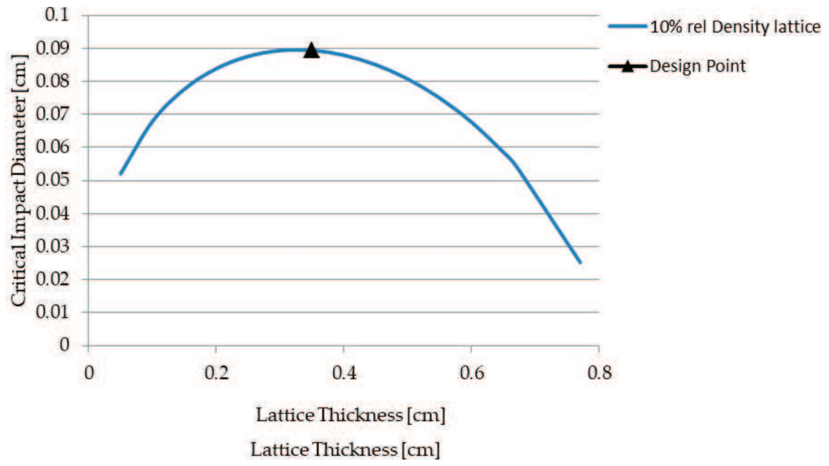

Figure 4. Critical projectile diameter vs. lattice thickness for a relative density of 10%.

The different plates and the lattice core critical projectile diameters, d_c, for a span of impact velocities can be obtained by implementing the equations introduced in [16] for the single plates and in [25] for the lattice core panel. The relative impact mitigation (RIM) of the plates compared with the lattice can be obtained with the following equation:

$$RIM = \frac{d_{c_{plate}} - d_{c_{lattice}}}{d_{c_{lattice}}} \times 100 \tag{5}$$

where $d_{c_{plate}}$ is the critical projectile diameter at shield failure for the solid plate and $d_{c_{lattice}}$ the same parameter for the lattice core panel.

Figure 5 shows the critical projectile diameter at shield failure for all the four panels. For velocities of the projectile lower than 4.6 km/s both the IsoMass and the IsoVolume panels resist to projectiles with higher diameters than the lattice core panel. At this speed both the IsoMass and the lattice core panels can resist impacts of projectiles with 0.13 cm size, while the IsoVolume panel can resist impacts with projectiles of 0.20 cm size. However, from 4.5 km/s, the lattice core panel resists to larger size impacts than the IsoMass panel, and from velocities

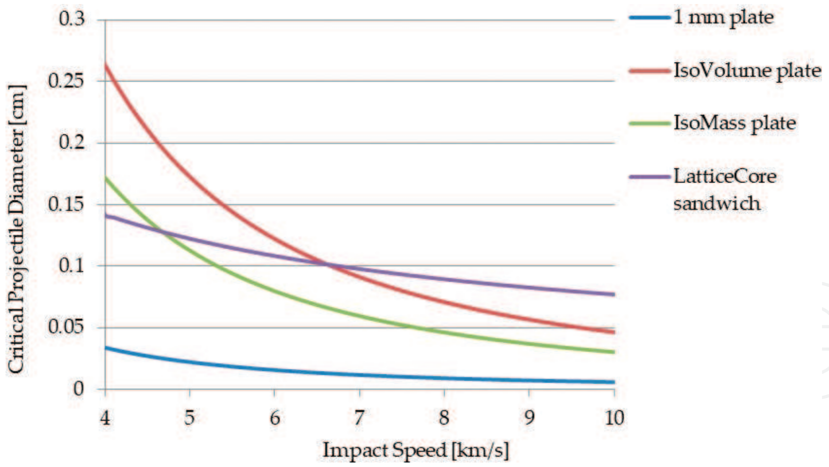

Figure 5. Plates vs. lattice core critical projectile.

higher than 6.4 km/s (at which both lattice and IsoVolume panels resist impacts of projectiles with 0.1 cm size), the lattice panel has more resistance than the IsoVolume panel to impacts of projectiles with larger size. This result is notorious since the IsoVolume panel having more mass than lattice has lower resistance to impacts. In addition, the classical panel with 1 mm width has lower resistance than the lattice core panels in all conditions, as could be expected.

Figure 6 shows the relative impact mitigation in percentage of the plates with regard to the lattice core panel. Even though an optimized lattice impact mitigation of only 0.089 cm at 8 km/s may seem too low, when compared to solid plates results are remarkable. A simple shear panel shields an 80% less than the lattice core panel for the hypersonic regime while the mass is only a 55% higher; compared then with the solution with the same mass the lattice core panel performs better for high speed impacts which are the impacts potentially more dangerous: 7 km/h or higher. The lattice core for these impacts outperforms the IsoVolume plate, which is an 80% heavier solution.

Finally, the designed 8 U CubeSat structure can be seen in **Figure 7**.

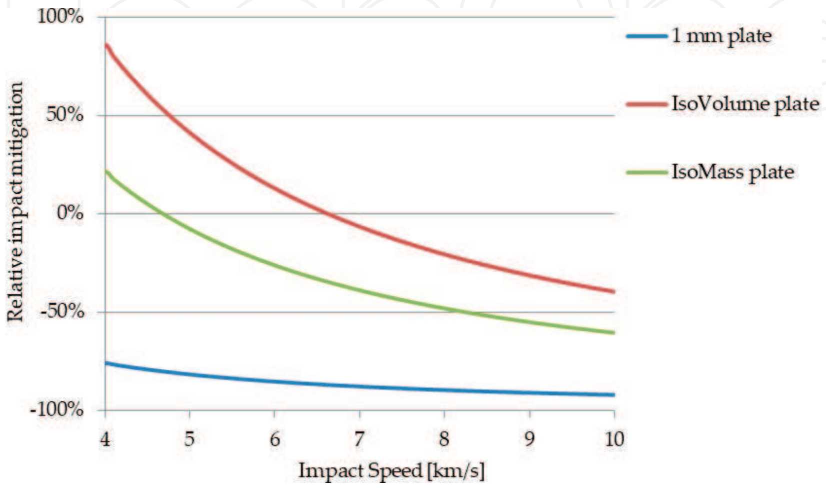

Figure 6. Relative impact mitigation.

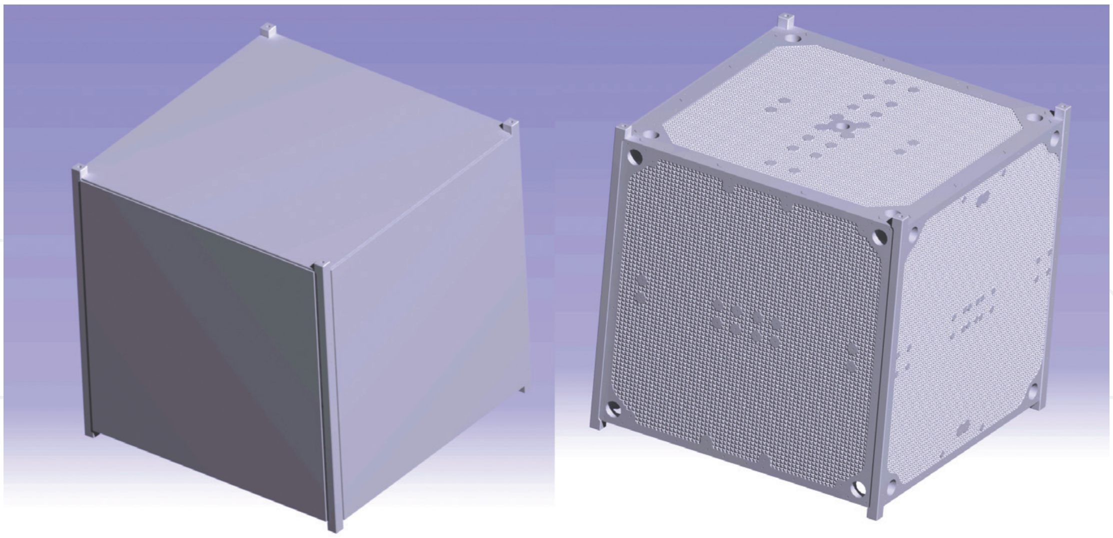

Figure 7. Isometric view of the small satellite structure with and without shear panels (left and right views).

5. Conclusions

In this chapter, a review of the additive manufacturing technology applied to satellites was done. Besides, the applicability of other technologies that can be enabled by this manufacturing method was also analyzed. As a consequence of the study, it was found that the application of additive manufacturing and lattice structures could be applied to improve the behavior of a satellite to reduce space debris when these technologies were incorporated in the functional structure of small satellites and in the impacts shielding of the system. Then the structure of an 8 U CubeSat was proposed and designed incorporating a sandwich panel with lattice core. The design was analyzed and compared with classical CubeSat panels of 1 mm thickness, with an IsoMass panel (i.e., same mass than the lattice core panel) and with an IsoVolume panel (i.e., an aluminum panel with the same volume than the lattice core panel but with 56.7% more mass). It was found that the lattice core panel in impacts with particles at velocities higher than 4.6 km/s provides more shielding than the IsoMass panel and in impacts with higher velocity than 6.4 km/s provides more shielding than with the IsoVolume panel.

For instance, the improvement in the impact shielding of a spacecraft can dramatically reduce the space debris by designing the future satellites accordingly. If they resist to a larger number of impacts, new fragments of space debris will not be generated. According to National Research Council [26], the highest population of space debris within 1600 km of the Earth surface is constituted of small size fragments lower than 1 mm diameter. The authors estimate that hundreds of trillions of fragments under this size are orbiting and impact at velocities with magnitudes between 6 and 8 km/s. They can be potentially destructive since objects of this size cannot be tracked. On the other hand, they estimate that approximately the order of magnitude of larger fragments is 10 millions. However, objects with size between 1 and 5 cm and higher can be tracked, so collision avoidance maneuvers could be done to avoid impacts [27]. This indicates that the proposed design can resist impacts of hundreds of trillions of debris fragments, in the order of magnitude of 10,000 fragments can be tracked so collision avoidance manoeuvers could be executed (most destructive ones) and that the design would be exposed to approximately 1–10 million fragments of size between 1 mm and 1 cm sizes.

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Conflict of interest

This publication reflects only the author’s views and the European Commission is not liable for any use that may be made of the information contained therein.

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