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An Overview of the Application of 3D Printed Spacecraft Structures within the ReDSHIFT Project

S.J.I. Walker[a]*, F. Romei[a], J. Becedas Rodríguez[b], F. Dalla Vedova[c], J. Beck[d], I. Holbrough[d], A. Francesconi[e], L. Olivieri[e], Andrés Caparrós[b], Gerardo Rodríguez Flores[b], Pablo Morillo[b], H. Stokes[f], A. Rossi[g], C. Colombo[h]

[a] *Department of Aeronautics and Astronautics, University of Southampton, Boldrewood Campus, Burgess Road, Southampton, SO16 7QF, United Kingdom, sjiw@soton.ac.uk*
[b] *Elecnor Deimos Satellite Systems, Spain*
[c] *LUXSpace, Luxembourg*
[d] *Belstead Ltd., UK*
[e] *Universita di Padova, Padova, Italy*
[f] *PHS Space Ltd., UK*
[g] *IFAC-CNR, Florence, Italy*
[h] *Politecnico di Milano, Milano, Italy*
* Corresponding Author

Abstract

The investigation of additive manufacturing technology started in the 1980’s and over the previous four decades has developed dramatically. The advantages of this technology, such as increased geometrical design freedom, faster production times, the possibility of increased functional integration, the reduction of material waste and reduced costs have driven the development of this technology in many market sectors. However, the benefits of additive manufacturing is only starting to be realised within the spacecraft industry. Within the last five years there has been a growing momentum of research and development into the application of additive manufacturing for spacecraft and in many cases, this has been constrained to the optimisation and production of small secondary structural components.

The European Union funded research project entitled ‘ReDSHIFT’ (Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies) began in 2016 and focused on passive means of reducing the impact of space debris by prevention, mitigation and protection. The main innovative aspects of the project were focused around a synergy between various theoretical and experimental studies. These included: long term astrodynamics simulations, de-orbiting devices, hypervelocity impact testing, design for demise, legal and normative issues and the application of 3D printing for future satellite design.

This paper presents an overview of the work performed on the application of 3D printing to future satellite design as part of the ReDSHIFT project, which finished in March 2019, along with the key results. This work was led by the University of Southampton in the UK with the coordination and support of the project partners and involved the design, simulation and test of many functional components as well as a complete 3D printed small satellite 8U cubesat structure. The work performed within ReDSHIFT has enabled the potential of this technology for multiple applications to be quantifiably identified.

Keywords: ReDSHIFT, 3D printing, satellite structures, sandwich panels

Acronyms/Abbreviations

AM – Additive Manufacturing
CFRP – Carbon Fibre Reinforced Polymer
CNC – Computer Numerical Control
EDSS – Elecnor Deimos Satellite Systems
FDM – Fused Deposition Modelling
LPF – Laser Powder Forming
ReDSHIFT – Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies
SLA – Stereolithography
SLS – Selective Laser Sintering

1. Introduction

1.1 The ReDSHIFT Project

The design process of satellites in the future will have many more imposed constraints and requirements than those that exist today, due to our increasing understanding in the sustainable use of the space environment. Operational satellites in low Earth orbit need to survive in an increasingly harsh debris environment and in an effort to stabilise this environment the manufacturers are being urged to ensure their own satellites do not add to the long term debris population. Satellite manufactures and operators are being asked to comply with specific requirements for the de-orbiting and disposal of their satellites. In order to achieve this, these requirements must be considered at the initial design stages.

The European Union funded research project called 'ReDSHIFT' (http://redshift-h2020.eu/) aimed to tackle this problem by looking at new disruptive technologies with a consortium of 13 European institutions and companies. The main innovative aspects of the project were focused around a synergy between various theoretical and experimental studies. These included: long term astrodynamics simulations, de-orbiting devices, hypervelocity impact testing, design for demise, legal and normative issues and the application of 3D printing for future satellite design. 6 out of the 13 consortium members were involved in the work on 3D printing, which was led and coordinated by the University of Southampton in the U.K.

1.2 3D Printing

The investigation of additive manufacturing (AM) technology started in the 1980s [1, 2] with the practical application of stereolithography [3] (SLA). Since then, an array of other additive manufacturing technologies have been developed and are in use today. For metal and polymer manufacturing, the list can roughly be categorised into Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM) and Laser Powder Forming (LPF) [4, 5, 6, 7]. Each of these technologies exhibits strength and weaknesses, and might be more suitable for polymers or metal.

Additive manufacturing exhibits unique benefits for manufacturing as well as maintenance and repair but still faces critical challenges inhibiting its disruptive potential. Common advantages of AM include: on demand manufacturing in remote locations such as space; an increase in design freedom for 3D parts and assemblies enabling geometries that are impossible to realize with other manufacturing techniques; the possibility for functional integration of an assembly into one part; a faster production time from design to manufacture compared to other manufacturing technologies; economic manufacturing for small series due to low upfront and parts cost; and a significant reduction in waste products compared to milling. However, some of the future challenges include: sensitivity to environmental factors including temperature and cleanliness of the build environment as well as machine-to-machine differences, which affect component manufacture repeatability; SLS, FDM, and LPF apply heat locally and layer by layer to the build article resulting in localized temperature cycling, which in turn induces anisotropies in the microstructure and in the mechanical properties and therefore, potential weak points [8]; the AM process is prone to produce impurities such as internal porosity; AM research has only focused on a few select materials and as a result most materials do not have significant heritage to ensure high quality production; the surface roughness of additive manufactured parts is typically limited by the built resolution of the additive manufacturing process in the tens of micro meter range; built resolution also limits the tolerances to which AM articles can be built. Despite these challenges, the use of AM continues to grow and has already found applications in the current commercial aerospace industry. AM is especially suitable for application in this sector as it typically features low part numbers and highly optimised low mass components.

Due to the conservative nature of the space industry, AM parts have been used in specific applications over the last five years to gain experience with the technology, to understand the potential benefits and to manage the challenges. One common application area is for secondary structural components. These components are not part of the primary load path, require low numbers to be manufactured and can involve complex three dimensional geometries. As such they are well suited to being 3D printed. Examples of this include brackets and fittings for Boeing spacecraft, antennae structures, a bracket for the Atlantic Bird 7 satellite and antennae brackets for use on the Sentinel satellites [9, 10, 11]. Another recent application area is for propulsion system components. Here, the geometrical freedom offered by 3D printing can directly result in a functional improvement of the subsystem. Examples of this include oxidiser valves for Space X's Merlin engine [12] and the injector for Aerojet Rocketdyne's AR1 engine [13].

These applications represent the first steps into the wider use of AM for spacecraft which will expand dramatically over the next decade as the challenges are addressed and standardisation becomes more common.

2. 3D Printing Strategies within ReDSHIFT

Within the context of the ReDSHIFT project 3D printing investigations were performed to study the future disruptive potential of this technology by exploring how 3D printing could be applied to the design of future satellites if/when current technological barriers are addressed (such as limited print volumes).

A key future development of AM technology is the advancement of multi-material printing, most significantly between metallic and non-metallic components. This will enable greater material freedom within the complex geometries, which will inevitably lead to truly embedded components, sensors and electrical systems. However, this development is likely to be driven by other industrial sectors.

When considering the future application of AM to spacecraft, i.e. moving from small components to larger subsystem or system level structures, this implies the replacement of existing primary and second structural components. It is therefore important to be aware of the driving structural requirements of these components (such as stiffness, strength, natural frequency etc). To achieve these requirements modern satellites commonly utilise composite structures either as individual components or in honeycomb panels. As a result of their laminate construction and fibre orientation, composites are already highly optimised structures, which provide very high values of specific strength and stiffness, easily surpassing metallic components. Therefore using current AM technology for larger primary structural components would not result in a more efficient structure. As a result, the future application areas and integration of AM technologies for spacecraft need to be carefully identified to ensure that there is a net benefit to the overall system.

Three general application areas of AM technology for spacecraft can be identified.

1. Improvements in the component design or manufacturing process
2. Improvements in the functional performance
3. Improvements in the efficiency of the whole satellite system (through systems integration/multi-functionality).

These application areas are defined and discussed in more detail in the following subsections.

2.1 Improvements in the Component Design/Manufacturing Process

This application area is the first step in incorporating AM into the spacecraft design process and has already been highlighted from the literature. Small specialised components can be structurally optimised, or produced with improved functionality at a reduced manufacturing cost and development time. Efficiencies in the development process can also be realised by rapid prototyping. This application area has seen increased interest and development over recent years but will continue to expand to larger, more complex components as the possible print volumes grow. Within the ReDSHIFT project this application area has been explored in two fields: monolithic core structures and mechanical components.

As previously identified, the primary structures for most satellites utilise composites and honeycomb panels which are already highly optimised structures. The honeycomb panels generally consist of carbon fibre reinforced polymer (CFRP) facesheets and an aluminium core. Attaching components to these panels requires inserts to be added to the core geometry which can either be ‘hot’ or ‘cold’ bonded (i.e. inserts embedded while the panel is being manufactured or afterwards). This process requires the careful and time consuming integration of the insert with the core using adhesive. If the core was manufactured using AM then the inserts could not only be designed into the core and built as a monolithic structure but other features of the geometry could also be improved, such as the material bonding area with the facesheets. This area of research was explored at the University of Southampton.

Mechanical components are specific area of interest where the advantages of AM could be applied to reduce the mass and increase the functionality of components. This application of AM has been explored with the ReDSHIFT partner LuxSpace. The support structure and mechanical components of a solar sail device was chosen as it features various complex geometries which are well suited for AM. The individual component sizes were also compatible with current 3D printing build volumes.

Both of these fields within this application area have been explored at component level and are outlined in section 3.

2.2 Improvements in the Functional Performance

In the long term, with developments in AM technology, it could be envisioned that this technology would enable the in-orbit manufacturing of not only components but inevitably whole satellites. This would also be revolutionary for deployable structures. No longer would structures need to be folded for launch, as they could just be manufactured on orbit with a geometry that has been optimised solely for that environment, improving the functional performance and efficiency of that subsystem. However, many AM technology developments need to be realised before this becomes a reality.

In the more near term it is important to assess how AM can be applied to improve the functional performance of specific subsystems. Within the ReDSHIFT project, this area has the additional focus of technology areas that can facilitate clean space strategies. As a result the application of AM for satellite demise and shielding has been investigated. These investigations were performed with the ReDSHIFT partner Belstead Research Limited for the demise activity and the University of Padova and PHS Space Ltd. for the shielding investigations.

Both of these fields within this application area have again been explored at component level and are outlined in section 3.

2.3 Improvements in the Efficiency of the Whole Satellite System

Small spacecraft structures (within the size range of cubesats, i.e. 1-10 kg) are well suited to potential performance benefits that can be realised through AM as these structures typically are not made using composites. They tend to currently be manufactured out of standard aluminium alloys to reduce cost and increase simplicity. Therefore the utilisation of AM for these structures is an inevitable first step in assessing the system level benefits of this technology at low cost and with low risk. This application is also compatible with the current AM constraint of limited build volumes. This application of AM has been explored with the ReDSHIFT partner Elecnor Deimos Satellite Systems (EDSS) and is outlined in section 4.

3. Component Level Investigations

3.1 Structural Testing

Structural testing was performed at the University of Southampton to investigate the application of 3D printing to medium/large satellite primary structures, along with testing to support all the collaborative research areas performed with the ReDSHIFT partners. Samples have been design and tested to gather data in four main areas:

- the experimental assessment of material properties
- the investigation into the structural performance of various 3D printed honeycomb cores and inserts
- the investigation into the structural performance of various 3D printed lattice cores
- the investigation into the structural performance of a sample of 3D printed shield geometries.

Whilst the number of possible test variables is large in each area, specific variables have been targeted with enough repeats to gather a good 'first pass' experimental assessment of these structures. As part of this test campaign, quantities of space grade structural material was purchased from INVENT. This consisted of 5 m^2 of CFRP facesheet and two 30 x 30 cm honeycomb sandwich panels with the same CFRP facesheets. The core of these sandwich panels was 19.4 mm high with a cell size of 3/16 of an inch. These honeycomb sandwich panels represented the baseline 'standard' panel utilised for primary structure applications in the space industry and as such represented the performance benchmark for comparative purposes.

Initial testing was first performed to confirm the material properties of both the 3D printed material, Al-Si-10Mg, as well as the purchased CFRP facesheets. Different print orientations and angles were studied with five repeat specimens for each test type. A range of the test coupons is shown in Fig. 1, where the samples are still attached to the print plate. Overall 125 material test samples (including both AM and CFRP samples) were loaded to failure in an Instron test machine to establish the baseline material properties for the subsequent investigations.

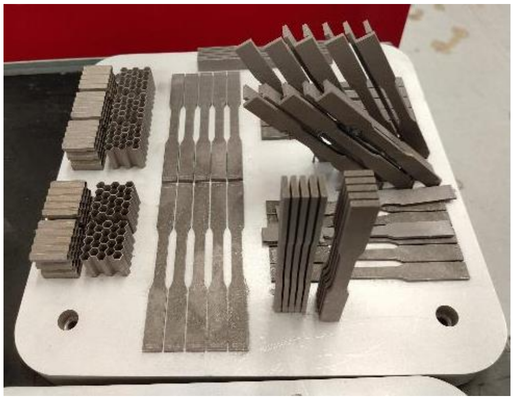

Fig. 1. Tensile test coupons along with honeycomb test print samples

To investigate the structural performance of the 3D printed honeycomb sandwich panels, 29 samples were subjected to 3 point bending tests, out of plane compression tests and insert pull out tests. A test sample of a sandwich panel with CFRP facesheets and a 3D printed honeycomb core is shown in Fig. 2. The range of tests were selected to investigate:

- the structural performance of the panel with a 3D printed core compared to the baseline panel
- the variation in the structural bending performance when the material contact area between the core and the facesheets was increased
- a method of reducing the mass of the 3D printed core
- the change in pull out strength between a baseline and redesigned insert.

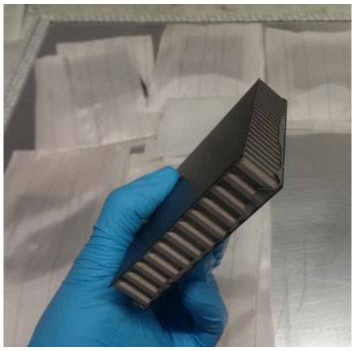

Fig. 2. Honeycomb sandwich panel with CFRP facesheets and a 3D printed core during manufacture

Mass increases for each of the AM samples was expected due to the increased minimum thickness of the honeycomb walls. However, significant structural improvements were also identified. From an initial assessment of the data the following key results could be identified.

From the 3 point bending tests:

- the structural efficiency increased for samples with a 3D printed core (a 1.9x mass increase resulted in a 3.6x increase in the failure load)
- by increasing the contact area the failure load is increased (2.8x mass increase resulted in 6.1x increase in the failure load).

From the compression tests:

- an increase in the structural efficiency was seen for the 3D printed cores which resulted in a 13x increase in the strength to mass ratio.

From the insert pull out tests:

- the optimised insert, enabled with the use of AM, improved the pull out strength (a 1.2x mass increase resulted in a 6.7x increase in the failure load).

Lattice geometries were also structurally investigated which involved 36 samples being subjected to 3 point bending tests, out of plane compression tests, insert pull out tests and in plane tension tests. The range of tests were selected to investigate:

- the general bending performance of the lattice in supporting both CFRP and integral Aluminium facesheets
- the tensile and compressive strength of a similar lattice geometry with varying infill
- the pull out strength of inserts embedded into the lattice.

Three repeat tests were performed for each geometry tested. The three lattice samples with Aluminium facesheets subjected to the 3 point bending tests can be seen in Fig. 3.

The structural tensile tests performed identified that the highest structural efficiency was achieved for the lowest infill that was tested (which was 25 %).

Further structural testing was also performed on shield geometries that were selected by the University of Padova and PHS Space Ltd. In this set of tests, 18 samples were subjected to 3 point bend tests and out of plane compression tests.

Fig. 3. Lattice samples with integrated Aluminium facesheets

Overall 208 samples were loaded to failure throughout these structural test campaigns.

3.2 Mechanical Components

The investigation into the application of 3D printing for spacecraft mechanical components was performed with the ReDSHIFT partner LuxSpace. The support structure and mechanical components of a deployable solar sail device for deorbit applications was utilised. The initial designs were based around geometries that could be manufactured using standard existing processes. Nine separate component geometries were investigated that included solid block geometries, interface components and a component of the sail container. Each geometry went through a redesign process with the aim of minimising the mass whilst ensuring the printability of the component. The general philosophy was to utilise lattice structures in the internal volumes with a 0.8 mm exterior surface layer. Solid internal sections were incorporated to support fastener locations and load points. The most geometrically complex component was part of the sail container. This incorporated a sandwich panel, with exterior supports and structures. The redesign of this component also included the topological optimisation of the outer structure to minimise mass whilst achieving the resonant frequency requirements.

From the nine geometries a total of twenty individual components were manufactured, as repeats of some of the geometries were required to create the deployable device. As a result of the component redesigns, the new masses ranged from a 68 % reduction in mass to a 23 % increase in mass. The mass increases were due to aspects of the redesign process where it was more advantageous to move some design features from one part to another. The overall mass reduction across all the components was 28.5 %. All of the components were subjected to environmental tests (including both thermal vacuum and vibration tests) along with subsequent functional tests. All the components passed these test campaigns.

3.3 Satellite Demise Tests

Due to the limited current knowledge of the demisability of spacecraft materials and components, the main objective of the design for demise test campaign was to provide some basic phenomenological data for Aluminium panels, CFRP and honeycomb sandwich panels as well as representative spacecraft components (such as reaction wheels). The tests were conducted in the DLR L2K facility. As part of this test campaign, some 3D printed samples were manufactured to produce some comparative data.

The samples consisted of 9 individual components:

- four sandwich panels with CFRP facesheets and a 3D printed Aluminium honeycomb core to identify if the demisability was consistent with the baseline sandwich panel samples

- two sandwich panels with CFRP facesheets and a 3D printed Aluminium honeycomb core with an integrated insert to compare with the baseline panels with an insert
- three top hat geometries to investigate the failure physics of the 3D printed Aluminium.

The results of the tests are described in more detail in Beck (2018) [14] and some key outcomes are discussed in Rossi et al. (2019) [16].

3.4 Satellite Shield Tests

The aim of the shielding activity within the ReDSHIFT project was to investigate the level of impact shielding that could be achieved by using AM, hence potentially improving the functional performance of this subsystem. The testing was performed in two phases:

- the first phase focused on determining the baseline shielding performance of the material using a range of simple geometries
- the second phase investigated more advanced and promising geometries identified from the first test campaign.

A total of 91 components were manufactured to support this testing activity, a selection of which can be seen in Fig. 4. More details on the test results and the overall body of work performed as part of the shielding work packages can be found in Olivieri et al. (2018) [15] and Rossi et al. (2019) [16]. A key result from this investigation was that the advanced shield panel concepts provided a substantial level of impact protection when compared to an equivalent standard honeycomb sandwich panel due to the geometrical freedom offered by AM.

Fig. 4. A selection of the 3D printed test samples

4. 3D Printed Spacecraft

4.1 Baseline Design and Design Process

The selected spacecraft, provided by EDSS, was an 8U CubeSat (200 x 200 x 200 mm) designed for an Earth Observation multi-spectral mission. As identified previously in section 2, small spacecraft structures are well suited to explore the potential performance benefits that can be realised through AM. These structures are typically not made using composites and are normally manufactured from standard aluminium alloys to reduce cost and increase simplicity. This is demonstrated by the selected spacecraft configuration shown in Fig. 5. The structural subsystem is comprised of:

- the main body structure (six side panels identified as +X, -X, +Y, -Y, +Z and –Z)
- one avionics tray
- one mounting bracket.

The main body structure and the centre avionics tray supporting the subsystems can be seen in the figure. The mounting bracket is located on the underside of the tray.

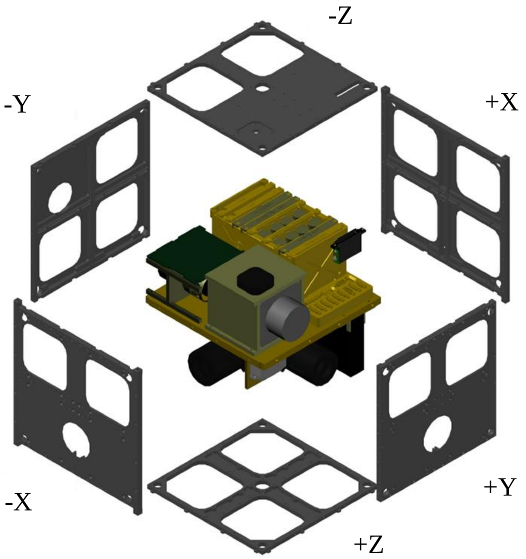

Fig. 5. Baseline 8U cubesat structural configuration

The general procedure followed within the ReDSHIFT project was to use the structure manufactured using subtractive manufacturing with Computer Numerical Control (CNC) as the baseline configuration. Three different 3D printed variants were then progressively design, manufactured and tested. The first variant was a 3D printed Aluminium structure similar to the configuration shown in Fig. 5 to identify the effect of the manufacturing method on the structural properties at system level. The second variant was a 3D printed structure similar to the baseline configuration, but manufactured using a plastic material called ULTEM™ [17]. Finally the third variant involved a complete redesign of the primary structure to take full advantage of the benefits of AM. This paper will focus on the design and test of the third variant.

4.2 Redesign of the Main Body Structure

In order to maximise the specific stiffness of the main body structure the first thing that was considered was the division of the body structure into separate components. When the structure is to be manufactured using subtractive methods (such as CNC machines) it is sensible to manufacture each face of the main body separately to minimise material waste. However, this creates multiple joints in the structure focusing the load paths through the fasteners and unavoidably reducing the overall stiffness of the structure. The inherent geometrical freedom created by AM allows the location and number of the joints in the main body structure to be reassessed and optimised. This was also conducted with a view to maintaining the practical ease of the integration of the subsystems. The existing baseline design was well suited for joint minimisation, due to its deck mounted configuration. All the internal subsystems are mounted to the central avionics tray, which in turn connects to the main body structure around the perimeter of the tray. It was therefore identified that the minimum number of joints can be achieved by dividing the main body structure into two half cubes that join together around the tray perimeter. A single joint line can therefore be utilised to connect the two components of the main body structure and the tray, which also reduces the total number of fasteners required (hence the total mass of the fasteners required). This design logic implied that the main body structure would be printed in two components. These would consist of the +Z face with half the wall height of panels +X, -X, +Y and –Y, and the –Z face with half the wall height of panels +X, -X, +Y and –Y. However, in printing these two components, the material waste (i.e. the support structure required) also needed to be minimised. Only one print direction was feasible to achieve this. Each half needed to be printed with the Z faces against the print plate with the X and Y faces being printed perpendicular to the print plate.

Following the design decision of the main body structural division, it was necessary to select the wall section properties. This directly impacts the bending rigidity of each face as the structural material has been pre-selected. It could be argued that CFRP facesheets could be used in the main body structure. However, this would dramatically increase cost and complexity which is avoided in the small satellite market.

Each panel of the baseline structure utilises sections that can be manufactured using CNC machines, i.e. a thin panel supported by structural stiffeners, which has been cut from a solid block of Aluminium. With complete geometrical freedom offered by AM, a more efficient section could be chosen based around a thicker overall panel, comprised of an inner and outer wall. The corner rails still needed to be present to comply to the cubesat standard. By separating the Aluminium between the two walls the material is more efficiently used around the neutral axis of the section. The greater the separation between the walls the greater the stiffness. However, for small satellites like this 8U cubesat, the limitation for how thick the wall can be is well defined between the inner components and the outer margin for the deployer. Using basic sectional calculations within these constraints it can be found that a comparable value (with respect to the baseline panel) of the second moment of area can be achieved with about 90% of the material area. In this example the bending stiffness of the panel is more evenly distributed between the corner rails and the wall in-between the rails, each providing about 50% of the stiffness.

Further performance and improvements can be achieved using more advanced 3D geometries in the gap between the walls rather than conventional stiffeners. These geometries can also be used within the corner rail sections to further reduce the mass. Various types of geometries could be used in these volumes such as honeycomb or lattice structures. There are also a wide range of variables to choose from for each of these geometries. An important driver in the selection of the core geometry is the minimisation of overhanging geometries that require support structures for the printing process. An example of this would be the horizontal elements in a regular cube lattice. Other than the structural performance, this was a key driver in the selection of the core geometry, which was chosen to be a diamond lattice structure.

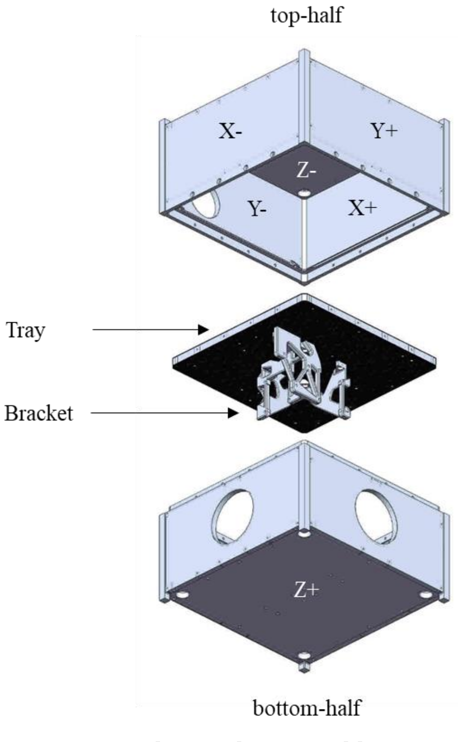

Fig. 6. Redesigned structural layout

Having defined the general form of the main body structural components, position of the joints and the basic section properties, practical integration and operational constraints were considered. For example, some cut outs were required in the main body structure for functional purposes, such as the operation of the star trackers, and the mounting locations for external solar panels also needed to be incorporated. Features to aid the integration of the central subsystems into the main body structure were also included. With uncertainty in the dimensional accuracy of the joint line due to potential AM errors, generous tolerances and adjustability was included into the design to ensure the successful integration of all the components. The basic form of the redesigned main body structure is shown in Fig. 6.

4.3 Redesign of the Avionics Tray

The baseline avionics tray structure was manufactured using one solid piece of Aluminium. As a result, there was a significant opportunity to reduce the mass of this component for the AM design. Due to the basic panel geometry of the tray, the selected structure to be employed for this application was a honeycomb sandwich panel. Such structures are widely used for this application in larger satellites. However, they are not generally used for small satellites due to the high cost and manufacturing complexity, especially when all the mounting fastener locations are factored in to the design choice. This tray is the main structural load path between the inertial loads of the components and the main body structure. As such the subsystem components need to be mounted with fasteners normal to the plane of the panel, whereas the connection points from the main body structure are mounted into the edges of the tray, in-plane with the panel. The use of traditional honeycomb sandwich panels in this application would be avoided due to the number of inserts required, in different orientations, throughout the relatively small volume of the panel. However, this avionics tray is an excellent example of how 3D printed cores can reduce mass and manufacturing complexity for spacecraft.

In this redesign the tray was manufactured using space grade CFRP facesheets and a 3D printed Aluminium honeycomb core. Various geometries could have been used in the core as for the main body structure. However, in this application where the panel is flat and the subsystem masses are mounted on either side of the panel the optimum out of plane compression strength is achieved with a honeycomb structure. The insert locations for all the required fasteners were designed into the panel (using standard insert geometries) and printed as one monolithic structure before the facesheets were bonded to the core. This resulted in a structure that was not only more mass efficient but also much easier to manufacture than a traditional honeycomb sandwich panel. The core geometry, incorporating all the inserts is shown in Fig. 7.

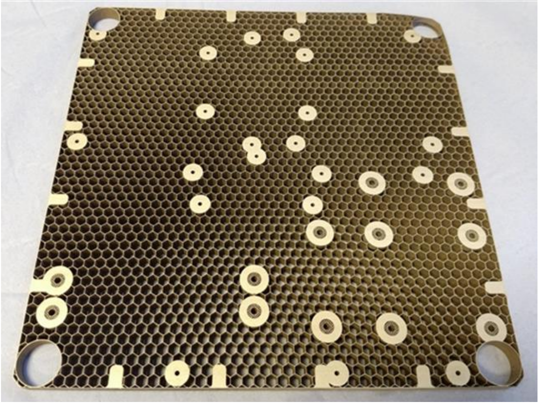

Fig. 7. 3D printed core used in the avionics tray

4.4 Redesign of the Mounting Bracket

The mounting bracket in the baseline satellite design, which connects three subsystem components to the avionics tray was a relatively straightforward geometrical design made from solid Aluminium and was designed with standard manufacturing methods in mind. This is typical of a secondary structural component that given the geometrical freedom that AM offers, can be structurally improved using topological optimisation methods resulting in mass reductions. This is a common current application of AM when applied to spacecraft structures as discussed previously.

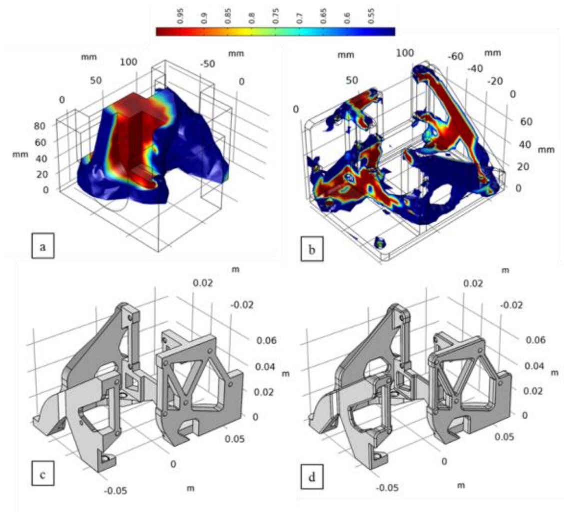

Fig. 8. Topological optimisation process

As the mounting bracket is connected to the avionics tray using fasteners, these items could be printed as one component. However, this would have affected the coverage of the CFRP facesheet over the tray, reducing the area of one of the facesheets, and as a result affected its overall bending strength. Therefore, as there was no structural advantage of printing these structures together, it was decided to keep them separate. The general process of the topological optimisation is shown in Fig.

8. New fastener locations were explored as part of this process and this resulted in the use of a new fastener position and a general change in the bracket design. The new bracket design is displayed in Fig. 9. This redesign reduced the mass of the bracket by 45% whilst maintaining the stiffness requirements.

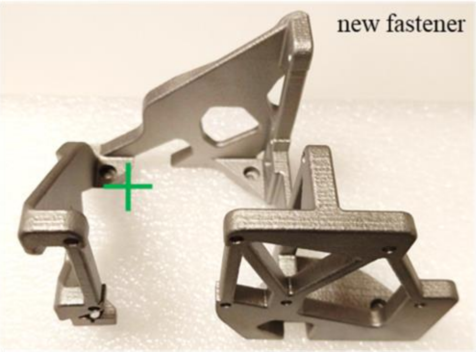

Fig. 9. Optimised bracket design

Throughout the satellite redesign process the design changes were assessed using finite element analysis simulations. The final AM manufactured and assembled satellite is shown in Fig. 10. The mass of the structural components for the baseline configuration was 2951 g, whereas the redesigned structural mass was 2067 g. The use of AM methods therefore resulted in a 30 % reduction in the structural mass of the spacecraft.

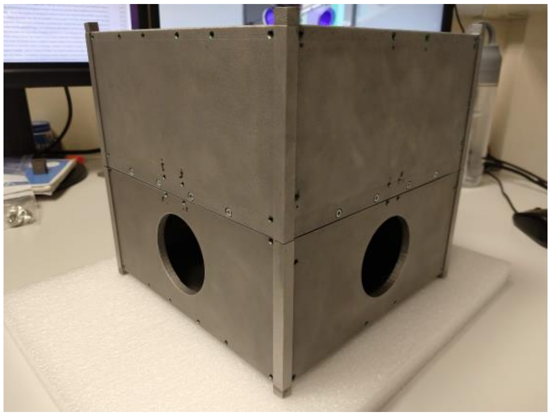

Fig. 10. The redesigned spacecraft structure, with integrated tray and bracket

4.5 Test Results

To assess the comparative performance of the 3D printed spacecraft with respect to the baseline design, all design variants were subjected to environmental test campaigns that included both structural and thermo-vacuum tests. The structural testing consisted of quasi-static loading, high level sine sweeps, random vibration and robustness tests. The baseline structural satellite configuration achieved the load levels shown in Table 1 without failure. The equivalent load levels achieved by the redesigned satellite structure using AM is shown in Table 2.

QSL	Sine	Random	Robustness
✓	✓	✓	✓
8.5 G	2.5 G (10-100 Hz)	6.08 G_{RMS}	21.72 G_{RMS}

Table 1. Achieved load levels for the baseline structural design

QSL	Sine	Random	Robustness
✓	✓	✓	✓
10.8 G	3.75 G (10-100Hz)	15.28 G_{RMS}	25.8 G_{RMS}

Table 2. Achieved load levels for the baseline structural design

It can be seen that the structural performance of the AM design surpassed that of the baseline design for every structural test performed. The improvement in the structural performance was most clearly apparent when comparing the first fundamental bending modes. For the baseline design this was found to occur at 190.77 Hz, whereas the redesigned structure's fundamental bending frequency occurred at 378.75 Hz.

5. Conclusions

This paper has provided a high level overview of the 3D printing activities that were performed as part of the ReDSHIFT project, which was concluded at the end of March 2019. Over 340 samples were successfully produced and tested to assess the capabilities of 3D printing for spacecraft structural applications (applied to all satellite mass ranges), mechanical components, satellite demiseability and shielding. The investigations at component level have produced a large body of experimental data which will be used to develop the application of this technology further. 3D printing approaches have also been applied to a small satellite baseline design to investigate the potential benefits of this technology. Clear mass reductions and performance improvements have been demonstrated, highlighting the future potential of this technology within the satellite design process and the space sector.

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References

[1] D.L. Bourell, M.C. Leu, D.W. Rosen, Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing, Austin, Texas, 2009.

[2] D.L.D. Bourell, J.J. Beaman, M.C. Leu, D.W. Rosen, A brief history of additive manufacturing and the 2009 roadmap for additive manufacturing: looking back and looking ahead, in: US – TURKEY Work. Rapid Technol., 2009: pp. 5–11.

[3] C.W. Hull, Apparatus for production of three-dimensional objects by stereolithography, US 4575330 A, 1984. doi:10.1145/634067.634234.

[4] K. V. Wong, A. Hernandez, A Review of Additive Manufacturing, ISRN Mech. Eng. 2012 (2012) 1–10. doi:10.5402/2012/208760.

[5] E.C. Santos, M. Shiomi, K. Osakada, T. Laoui, Rapid manufacturing of metal components by laser forming, Int. J. Mach. Tools Manuf. 46 (2006) 1459–1468. doi:10.1016/j.ijmachtools.2005.09.005.

[6] L.E. Murr, S.M. Gaytan, D.A. Ramirez, E. Martinez, J. Hernandez, K.N. Amato, P.W. Shindo, F.R. Medina, R.B. Wicker, Metal Fabrication by Additive Manufacturing Using Laser and Electron Beam Melting Technologies, J. Mater. Sci. Technol. 28 (2012) 1–14. doi:10.1016/S1005-0302(12)60016-4.

[7] D.D. Gu, W. Meiners, K. Wissenbach, R. Poprawe, Laser additive manufacturing of metallic components: materials, processes and mechanisms, Int. Mater. Rev. 57 (2012) 133–164. doi:10.1179/1743280411Y.0000000014.

[8] S.M. Kelly, S.L. Kampe, Microstructural evolution in laser-deposited multilayer Ti-6Al-4V builds: Part II. Thermal modeling, Metall. Mater. Trans. A. 35 (2004) 1861–1867. doi:10.1007/s11661-004-0094-8.

[9] D. Werner, 3D printing saving satellite builders time and money, SpaceNews.com (2016).

[10] Space System Loral, SSL demonstrates innovative use of advanced technologies, Www.sslmda.com. (2017).

[11] M. Bromberger, From the 3D Printer into Space, http://innovationintelligence.com (2015).

[12] SpaceX, SpaceX Launches 3D-Printed Part to Space, Creates Printed Engine Chamber, http://www.spacex.com (2014).

[13] Aerojet Rocketdyne, Aerojet Rocketdyne Hot-Fire Tests Additive Manufactured Components for the AR1 Engine to Maintain 2019 Delivery, www.rocket.com. (2015).

[14] Beck J., Improved representation of destructive spacecraft re-entry from analysis of high enthalpy wind tunnel tests of spacecraft structures and equipment, Paper IAC-18,A6,2,5,x43971, 69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018.

[15] Olivieri L., C. Giacomuzzo, A. Francesconi, S. Geradin, M. Bagatin, A. Paccagnella, A. Finozzi, H. Stokes, F. Romei, S. Walker, A. Rossi, Experimental characterization of multi-layer 3D-printed shields for microsatellites, Paper IAC-18,A6,3,7, 69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018.

[16] Rossi, A., E.M. Alessi, G. Schettino, J. Beck, I. Holbrough, T. Schleutker, F. Letterio, Gonzalo Vicario de Miguel, J. Becedas Rodríguez, F. Dalla Vedova, H. Stokes, C. Colombo, I. Gkolias, F. Bernelli Zazzera, N. Miguel, S. Walker, F. Romei, K. Tsiganis, D. Skoulidou K.l, E. Stoll, V. Schaus, R. Popova, Y. Kim, A. Francesconi, L. Olivieri, S. Gerardin, The H2020 ReDSHIFT Project: A Successful European Effort Towards Space Debris Mitigation, IAC-19,A6,6,4,x53705, 70th International Astronautical Congress (IAC), Washington D.C., USA, 21-25 October 2019.

[17] Becedas J. and Caparrós A., Additive Manufacturing Applied to the Design of Small Satellite Structure for Space Debris Reduction, in Applications of Design for Manufacturing and Assembly, http://dx.doi.org/10.5772/intechopen.78762, IntechOpen, 2018.