Executive Summary

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Prepared by:	Campbell Pegg	Date: 14.01.2016
Checked by:	Egbert Van der Veen	Date: 14.01.2016

1 Introduction

Additive manufacturing (AM) is a manufacturing technology that allows significant flexibility in the complexity of a design. The implementation of this technology has a large variety of capabilities for components/ subsystems including;

- Reduction of mass
- Customisation of components
- Increased functional benefits
- Possibility to introduce internal channels
- Integrated subassemblies
- Optimised designs
- Reduced cost
- Reduced raw material consumption
- Reduced development time

For spacecraft, these AM capabilities are able to have a positive influence on a system level, hence the key aim of this study is to find and assess the areas of a spacecraft that have the highest system level impact if additive manufacturing was to be exploited. To achieve this, a four step process was implemented to find the high impact areas quickly and thus ultimately identifying key areas for future work. These steps are presented in the in Figure 1.

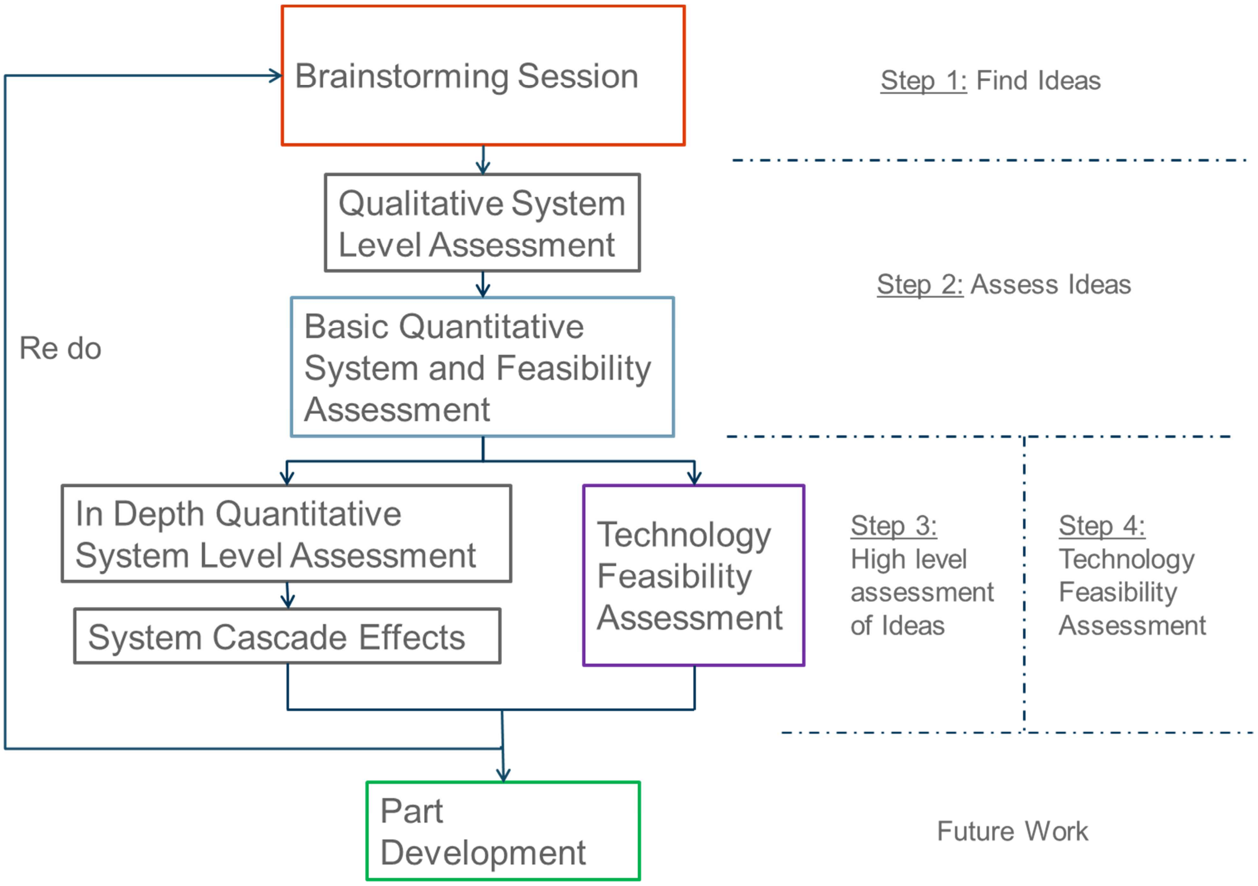


Figure 1: Systematic approach of finding as assessing the key areas that are influenced by AM on a spacecraft.

2 Find Ideas

A wide variety of methods were used to find the areas of the spacecraft that could potentially have high system level impact if AM was implemented. These were conducted via a wide range of brainstorming sessions, heritage mission reviews, RFI campaigns and call for ideas. A result of this collection is found in Figure 2 with the highest potential highlighted in red.

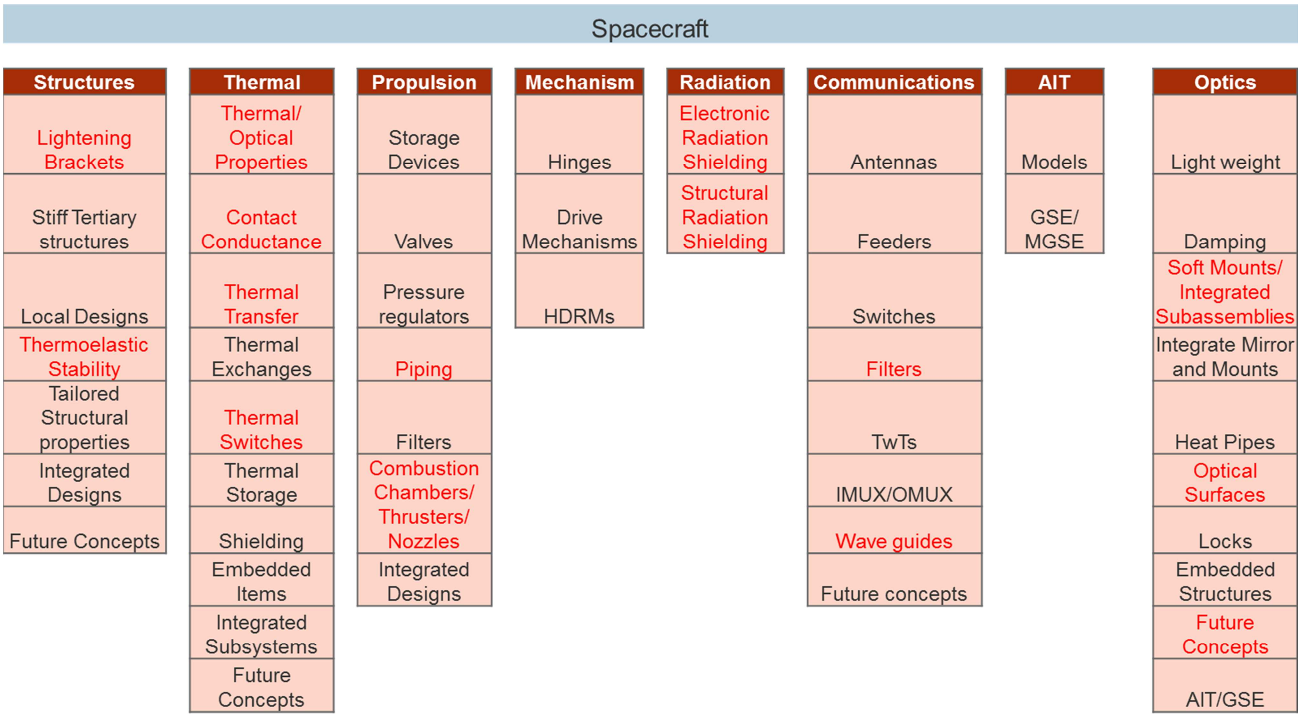


Figure 2: Summary of components/areas of interested with a potential high system level impact if AM was implemented.

3 Key Areas of Interest

3.1 Overview

After following the step process, the number of components that have a potentially high system level impact, have been identified for further examination. These applications include:

- High pointing performance brackets
- Anisotropic cleats/ Lattice Structures
- Flat heat panels
- Optical Baffles
- RF filters
- Waveguides

A system level and technology manufacturing assessment was conducted on all of these items.

3.1.1 HIGH POINTING PERFORMANCE BRACKETS

The ability for AM to produce highly complex configurations allows a user to produce structures that are not only mass efficient but could also potentially provide a stable platform under a range of thermal environments. Areas on a spacecraft that require high stability under different thermal environments include optical payloads and star tracker brackets. For system relevance, in an OHB heritage mission the star tracker has been allocated approximately 25% of the pointing allocation for a payload, thus an improvement in this component can have a relatively large impact on the pointing of the system.

Figure 3: Ultra stable bracket is designed to compensate the varying thermal environment while providing a stable platform for the unit.

Apart of this project a general concept has been found that is able to provide a highly stable platform for a varying thermal environment (Figure 3). Some of the key areas of interested for the development of such a part include:

- Overall Design
- Support structures location
- Thermal optimisation methodology
- Proof of concept

High pointing performance brackets have generally been assessed as feasible with a high potential to positively impact the system pointing budget.

3.1.2 LATTICE STRUCTURES

The ability for additive manufacturing to produce very complex structures allows the user to create lattice structures with mechanical properties, which were previously only theorised (Figure 4). The potential for these structure are immense and thus to focus the study, a static example was taken along with the capability of having a different young modulus in different geometrical directions.

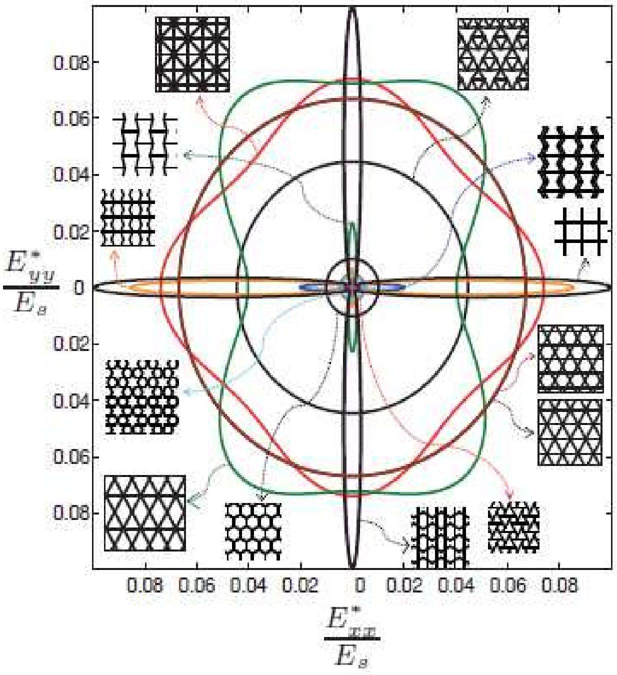


Figure 4: Two dimensional lattice structures with anisotropic properties [Chopra, 2011]

To give system relevance, the study aim was to use these lattices to design a cleat that was able to reduce the influence of an aluminum panel (connected to a CFRP panel) on the pointing of the spacecraft. For the reference mission used, nearly 80% of the spacecraft pointing allocation was given to the platform due to these contracting aluminum radiator panels.

Various cleat designs were investigated with the use of these lattice structures (example is shown in Figure 5).

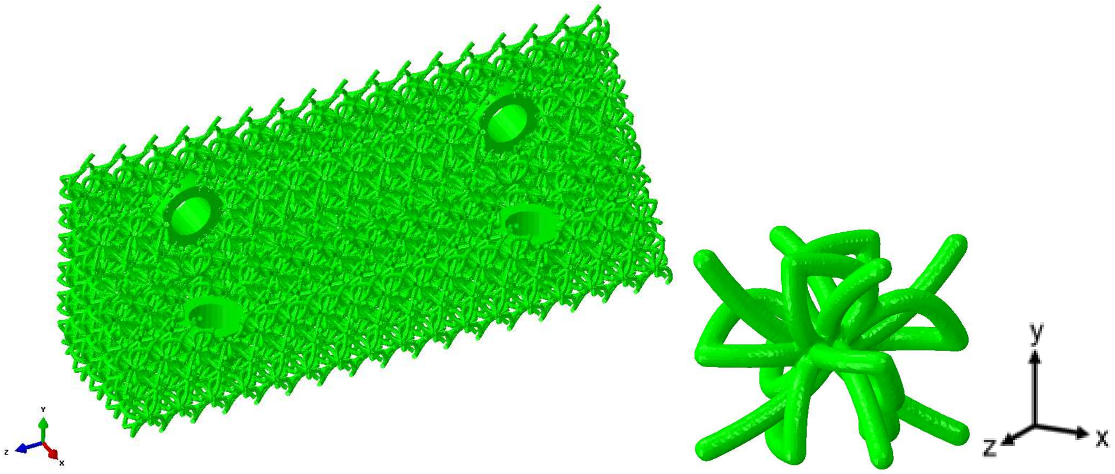


Figure 5: Left: Lightweight design of the cleat with Shamrock unit cells; Right: Shamrock unit cell geometry with bended beams, (almost) isotropic stiffness

One of the major issues with the use of these lattice structures is lack of technical information available on the mechanical properties of different designs. Once these were fully explored the maximum stiffness ratio that was considered feasible between two material directions was deemed a value of E2/E1 = 10. Once the system level analysis was updated the relative performance improvement was considered minimal.

In light of this conclusion, the use of AM lattice structures has a significantly huge potential and thus further investigations in to the types of designs and applications is required to be conducted.

3.1.3 FLAT HEAT PANELS

In a predominate number of satellites, the use of the heat pipe networks inside the radiators has been used to spread heat in 2 directions along a panel to ensure maximum efficiency of the radiator has occurred without a large mass penalty. Due to the freedom of complexity that has occurred with additive manufacturing, a heat pipe is not confined to only one direction and hence the generation of a heat panel is now possible.

The use of a flat heat panel has a potential to allow for better spreading of the heat in 2 directions along a panel and thus increase the efficiency of the radiator. This efficiency increase would be in the order or 5-10% thus allowing for more thermally dissipating units to be attached to the radiator panels and hence improving the payload capability on the spacecraft.

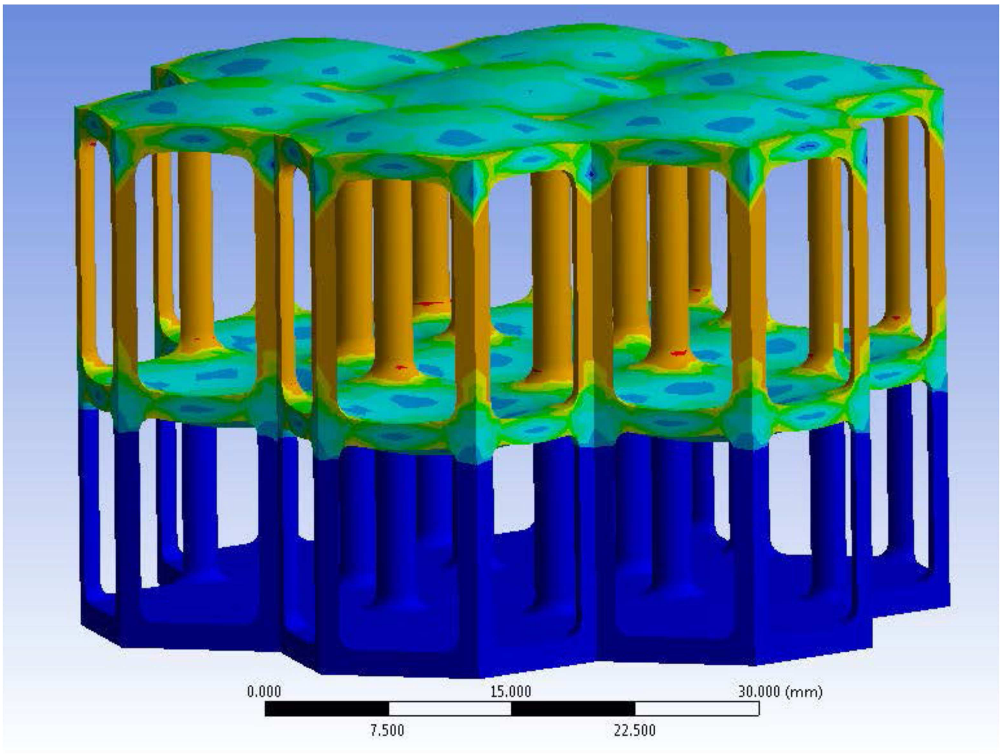


Figure 6: Flat Heat Panel concept design

Apart of the project. a feasibility assessment was conducted to overcome the main challenges which include

- Structural integrity due to Internal pressure
- Cleanliness
- Redundant
- I/F Units
- Size Limitation
- Mass

Each of these areas have been addressed and deemed feasible for small (30ccm x 30cm) radiators but further development of the concept is required to be conducted. This innovative solution to 2D heat flow does have the potential to change the spacecraft significantly and thus continuation of this project is recommended.

3.1.4 OPTICAL BAFFLES

For majority of optical payloads today, an optical baffle is used to ensure that the stray light does not enter the optical instrument. Unfortunately the internal geometry makes the manufacturing of this part very difficult to achieve in a short time frame. For the reference mission chosen for this project the complete development of the optical baffle including STM, EM and PFM is up to 1.5 years. With the use of AM, the baffle development time could be reduced by a third which is directly linked to the critical path of the satellite.

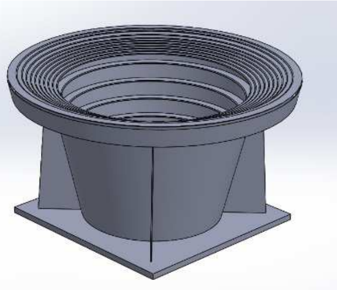


Figure 7: Folded Optical baffle for fast manufacturing time

A feasibility assessment on the manufacturing of such an item was conducted in which a range of open questions/challenges were answered. These challenges include

- Surface roughness
- Build angle constraints
- Geometric tolerances
- Coating of surfaces

After the assessment, some of these challenges are proven difficult (but not a show stopper) when the nominal manufacturing requirements are account for. If the baffle requirements were altered to design of AM, then the possibilities become broader. Thus the potential to AM an optical baffle is highly feasible, but during the design phase of this part, optical and manufacturing experts are required to be present.

3.1.5 RF FILTERS AND WAVEGUIDES

The majority of communications systems within a spacecraft use numerous components to manipulate the RF signal to ensure it is within the system requirements. Some of the major components that conduct this manipulation include RF filters. One of the key areas within these components that form many of the key signal characteristics are the resonator cavities within the filters. Normally the geometry of these cavities are limited to the manufacturing technique available to date but with AM the geometric freedom is now unlimited thus the ability to customize the signal for specific requirements is now possible. (Figure 8)

If the cavity design is allowed to have complete geometric freedom, there are potentially two system level properties that can be affected positively:

- Reduction of guard-band
- Reduction of insertion loss

Both of these benefits can lead to an increase of the data rate of the communication system. This can have a significant impact on the whole spacecraft thus allowing for possible new communication concepts.

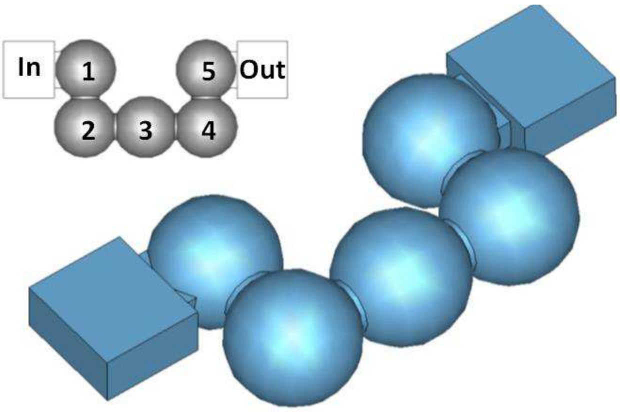


Figure 8: AM RF Filter [DOI: 10.1109/LMWC.2015.2427653]

There are a significant number of challenges relating to AM and the design of RF filters including

- Cavity Shape
- Geometric Tolerance
- Surface Roughness
- Surface conductivity

All of these challenges have been addressed, yet the high geometric tolerance seems very difficult to achieve. This is not a show stopper, but the filter designs would have to be re-designed from first principles to better adapt to the new manufacturing technique.

4 Cascade Effect

To fully explore the impacts of these technologies on the system a complete flow down assessment is required to understand the inter linking of the key attribute of a satellite and how the new technology influences them. To focus the assessment, only the most promising impacts have been flown down through the satellite to understand their influence. These technologies and their first order impacts are as follows:

- Reduction of component structure mass with AM tertiary structures
- Reduction of RF losses with RF waveguides
- Increased efficiency of radiators with flat heat panels
- Combination of all AM technologies in one spacecraft

The results of this assessment are shown in Table 1.

Table 1: The flow down benefits of the implementation of new AM parts in a heritage mission

Technology induced 1st order benefits	flow down benefits for the individual assessments	Combined aspects
30% Waveguide, 50% tertiary structure mass reduction	Reduction of CT mass 6.7%	Reduction of propellent mass
10% Reduction in Waveguide losses	CT mass reduction 8% Panel mass reduction 6% SA mass reduction 4% MLI mass reduction 6.9% Harness mass reduction 8% Spacecraft height reduction 8.5% Spacecraft power reduction ~10%	
10% increase efficiency of radiator	Radiator size reduction 10% CT mass reduction 8% Panel mass reduction 6% MLI mass reduction 6.9% Harness mass reduction 8% Spacecraft height reduction 8.5%	

When a combination of all of these benefits are implemented on one heritage spacecraft the ultimate system level attributes can change significantly as shown Table 2.

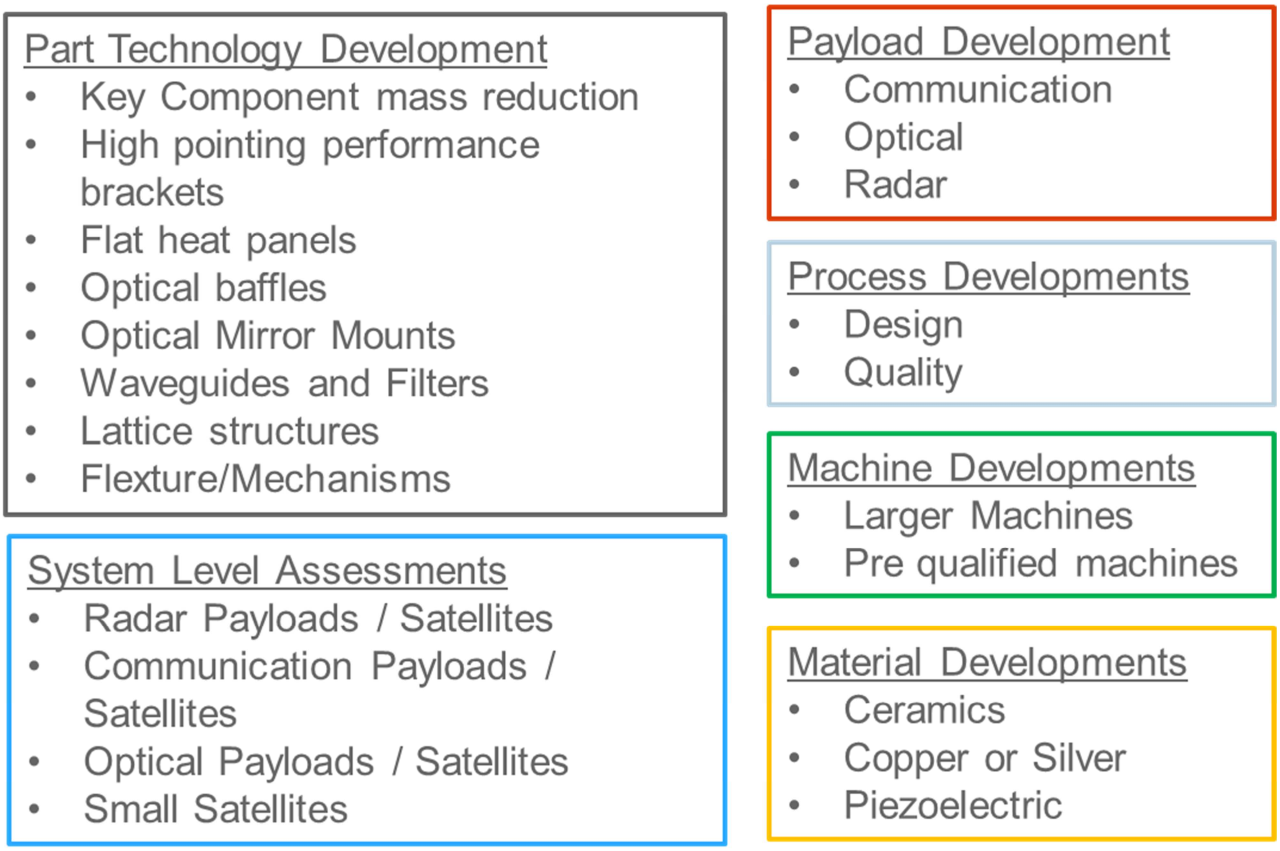
Table 2: Overall System benefits when AM attributes are implemented into the a heritage mission

System level benefits	Potential system level benefits when AM technologies are included in spacecraft
Spacecraft mass	-11%
Spacecraft size	-16%
Spacecraft power	-10%

These types of changes in the system level attributes have the potential of creating new missions as well making missions that were previously infeasible now possible. Thus in summary, AM can have a very large positive system level impact on a spacecraft.

5 Conclusion and Future Work

After the conduction of the study a various number of future projects were identified for further work. These projects have been sub divided in six categories, to help navigate the areas that require key focus (Figure 9).



Part Technology Development
- Key Component mass reduction
- High pointing performance brackets
- Flat heat panels
- Optical baffles
- Optical Mirror Mounts
- Waveguides and Filters
- Lattice structures
- Flexture/Mechanisms

System Level Assessments
- Radar Payloads / Satellites
- Communication Payloads / Satellites
- Optical Payloads / Satellites
- Small Satellites

Payload Development
- Communication
- Optical
- Radar

Process Developments
- Design
- Quality

Machine Developments
- Larger Machines
- Pre qualified machines

Material Developments
- Ceramics
- Copper or Silver
- Piezoelectric

Figure 9: Potential future projects if implemented would exploit the potential of AM for spacecraft

In summary, there is a significant amount of potential for AM to impact the space sector greatly and hence further investment, development and research would be highly recommended to utilize the full potential this manufacturing technology brings.