End-to-end process of hollow spacecraft structures with high frequency and low mass obtained with in-house structural optimization tool and additive manufacturing

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***Abstract:** In the space sector the most decisive elements are: mass reduction, cost saving and minimum lead time; here, structural optimization and additive layer manufacturing (ALM) fit best. The design must be driven by stiffness, because an important requirement for spacecraft (S/C) structures is to reduce the dynamic coupling between the S/C and the launch vehicle. The objective is to create an end-to-end process, from the input given by the customer to the manufacturing of an aluminum part as light as possible but at the same time considerably stiffer while taking the full advantage of the design flexibility given by ALM. To design and optimize the parts, a specialized in-house tool was used, guaranteeing a load-sufficient material distribution. Using topological optimization, the iterations between the design and the stress departments were diminished, thus greatly reducing the lead time. In order to improve and lighten the obtained structure a design with internal cavities and hollow beams was considered. This implied developing of a procedure for powder evacuation through iterations with the manufacturer while optimizing the design for ALM. The resulted part can be then manufactured via ALM with no need of further design adjustments. To achieve a high-quality part with maximum efficiency, it is essential to have a loop between the design team and the manufacturer. Topological optimization and ALM work hand in hand if used properly. The team achieved a more efficient structure using topology optimization and ALM, than using conventional design and manufacturing methods.*

***Key Words:** end-to-end, in-house tool, structural optimization, topology optimization, 3D Printing, additive manufacturing, ALM, hollow, powder removal, metal powders, high frequency, low mass, space applications, mass reduction, cost saving, minimum lead time*

1. INTRODUCTION

Nowadays, one of the most important aspects in space structures development is reducing the overall cost. It is well known that developing space components is extremely expensive, but less known is that most of the cost is the investment of time and knowledge of designing, analyzing, testing, documenting, inspecting, monitoring and controlling the entire process.

Topology optimization is a technique that enables development of efficient designs with minimal prior decisions [7]. Because of the complexity of the solutions obtained, topology optimization was often constrained to research and theoretical studies. Additive layer manufacturing (ALM), a rapidly evolving field, fills the gap between topology optimization and application thanks to its minimal limitations on the shape and complexity of the design [1]. The impact of metal 3D printing on the manufacturing landscape has become significantly more measurable within the last decade. Material developments and concentrated research into producing fully dense additive metal parts has led to recent widespread adoption of the technology for end-use production. Metal 3D printing materials are familiar and widely used in the aerospace sector. The key to realizing metal parts using ALM is in understanding that 3D printed metal parts differ in properties from machined ones just like aluminum cast parts differ from aluminum machined parts [2]. ALM is a method commonly used for structures with complex geometries, thin walls or internal cavities. This paper aims to present an end-to-end process of a support bracket for space use.

2. INPUT DATA

Figure 1 presents the geometrical constraints given by the customer regarding the envelope, attachment points and components to be supported by the structure. An important requirement for spacecraft (S/C) structures is to reduce the dynamic coupling between the S/C and the launch vehicle [5]; another important aspect provided by the customer was that the structure must be as light as possible but its first frequency determined by a modal analysis must be over 100 Hz. A static analysis must be made to ensure that the provided structure can sustain 30g loads in all directions.

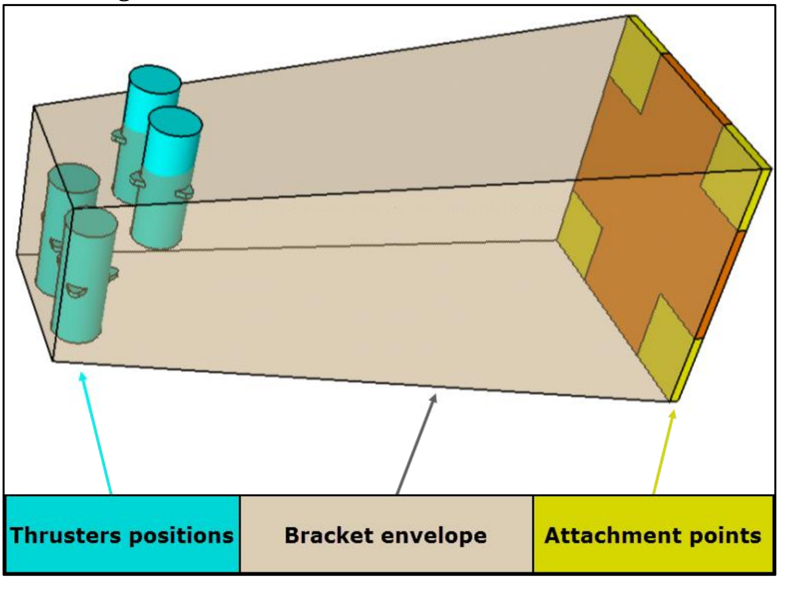

Figure 1. Input data

Table 1. Structure’s analysis requirements

	Modal analysis	**Static analysis**
Requirements	>100 Hz	± 30g in all directions

The aim is to obtain a structure by minimizing the mass while maximizing the frequency with respect of the constraints.

3. DESIGN APPROACH

Taking into consideration the number and position of the attachment points, the overall dimensions of the envelope and the scope of the part, a truss beam structure was considered. In order to determine the optimum material distribution of the material an in-house tool of optimization developed by INCAS [3] was used.

The input design space is presented in Figure 2. The optimization was made considering a static load of 30g on each direction (X, Y, Z) and the structure resulted is presented in Figure 3.

The diameter of the output truss beams varies from 3.9 mm at the base to 2 mm at the tip of the structure.

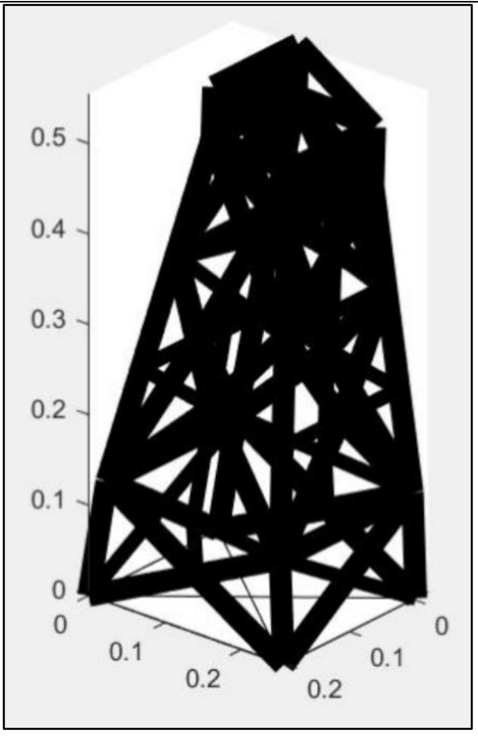

Figure 2. Optimization analysis input

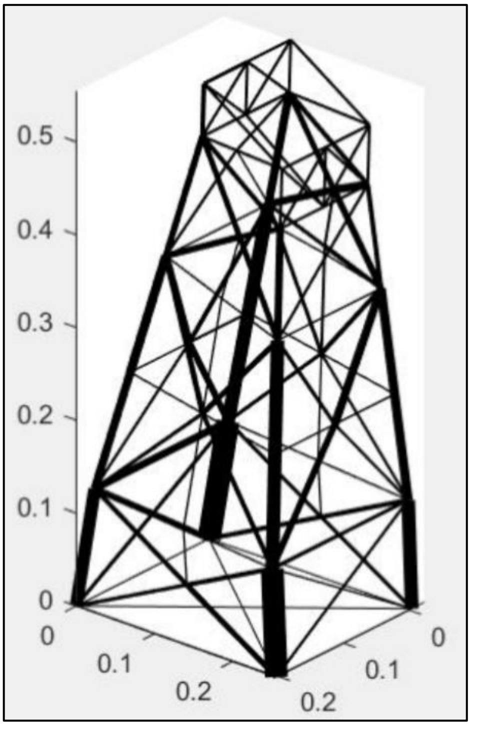

Figure 3. Optimization output

Taking into account the advantages offered by the ALM, in order to reduce the mass furthermore, while still increasing the stiffness, a hollow structure with internal cavities was considered.

This enabled a mass reduction of approximately 70%. The obtained structure is presented in Figure 4 where the internal cavities are highlighted with green for better understanding.

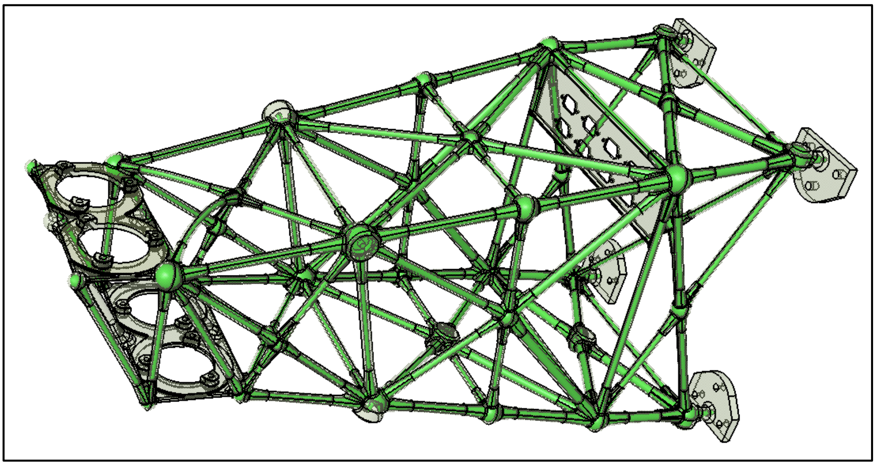

Figure 4. Internal cavities highlighted with green

After having a complete design the next step was to discuss with the manufacturer about the constraints of the machine and the possibilities to improve the present design. Part orientation plays a crucial role on where support material is located.

By reorienting a part, the amount of supports (and therefore the cost of the print) can be drastically reduced, also the parts positioning can play an important role in the overall quality of the parts. The most suited minimum thickness recommended by the manufacturer is to be at least 1 mm.

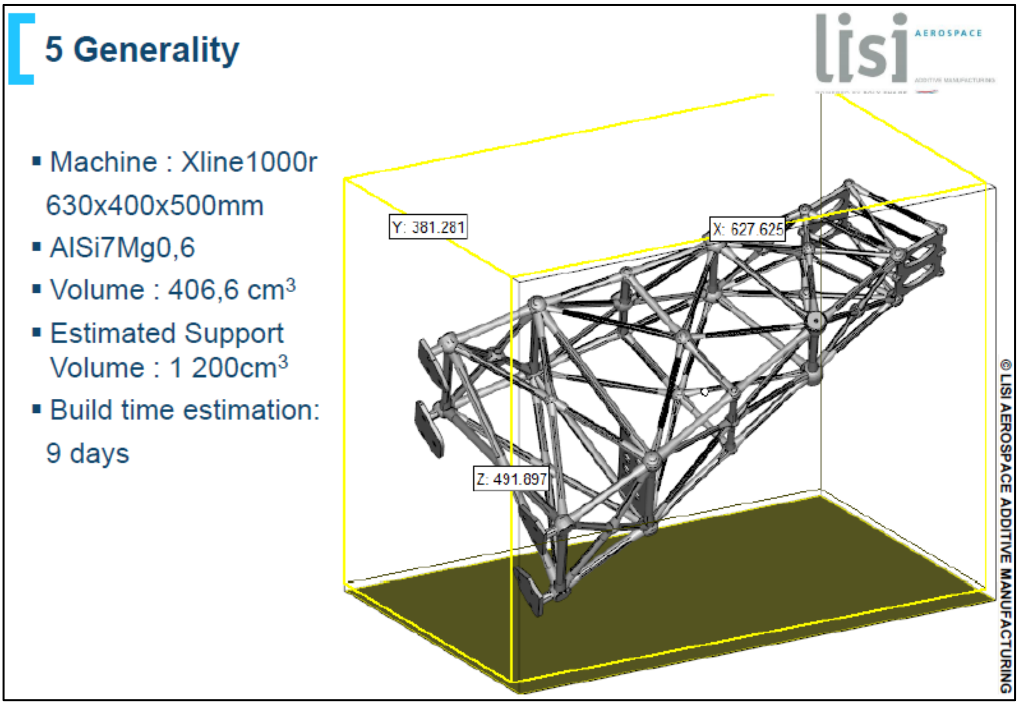

Figure 5. Parts orientation

Another important suggestion refers to the shape of the bars, because a circular cross section needs significantly more supports than a square or water drop cross section. Support structures have an impact on surface finish as they require post-processing work to remove, resulting in blemishes or surface roughness. Although the estimated volume of the support was 3 times bigger than the one necessary for the actual part, the circular cross section was kept thanks to the high stiffness properties of the structure.

Most structures produced using ALM require post-processing. Effective utilization of ALM processes requires not only a knowledge of AM process benefits and limitations, but also of the requisite post-processing operations necessary to finalize the part for use. Whether using automated secondary machining, choosing and properly implementing the best ALM process, material and post-processing combination for intended application is critical for success [4].

4. POWDER REMOVAL PROCEDURE

As stated before, all major design directions and decisions must take into account the manufacturing. The design decision to make the part hollow rises some problems because, beyond the minimum thickness constraint that needs to be taken into account, there is also a powder removal procedure that needs to be developed. This procedure implies additional design constraints from which we can mention a minimum internal diameter for all internal cavities, in order to efficiently remove the powder. Once the internal diameter is discussed and accepted with the manufacturer, the next step is to modify the design in such a manner that all the internal cavities are interconnected. All the cavities then must have a significant amount of evacuation holes to safely remove all the powder. The created evacuation holes are circled in Figure 7.

Collaborating with LAAM, the team learned that evacuation holes positioning is also an important factor that must be taken into account. They must be positioned in such a manner that after printing, the powder can be efficiently eliminated before removing the supports. A thermal treatment is needed to remove the internal stresses induced by the printing process, otherwise the structure can deform. If the thermal treatment is made before removing the powder, it will weld to the structure. An information loop between the manufacturer and the design team resolves all the presented problems. The manufacturing process of LAAM in case of hollow structures is presented in Figure 6.

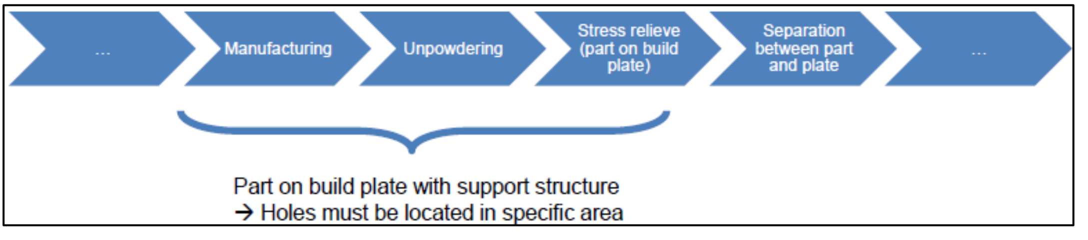

Figure 6. Manufacturing process of LAAM in case of hollow structures

Although ALM gives a huge freedom to a designer, there are also some constraints that are needed to be taken into account to have an efficient design. The first constraint regarding the minimum thickness has been addressed in the previous chapter, but there are many others. Even though the support material is common, when working with ALM, the main interest is to limit their appearance. Generally, the support material is needed when the geometry has “angles less than 45^{O} in respect of the horizontal plane” [6]. In case of hollow structures, the internal support material shall be avoided because of the impossibility to remove it. Internal supports were eliminated by locally modifying the solid in the vicinity as shown in Figure 7.

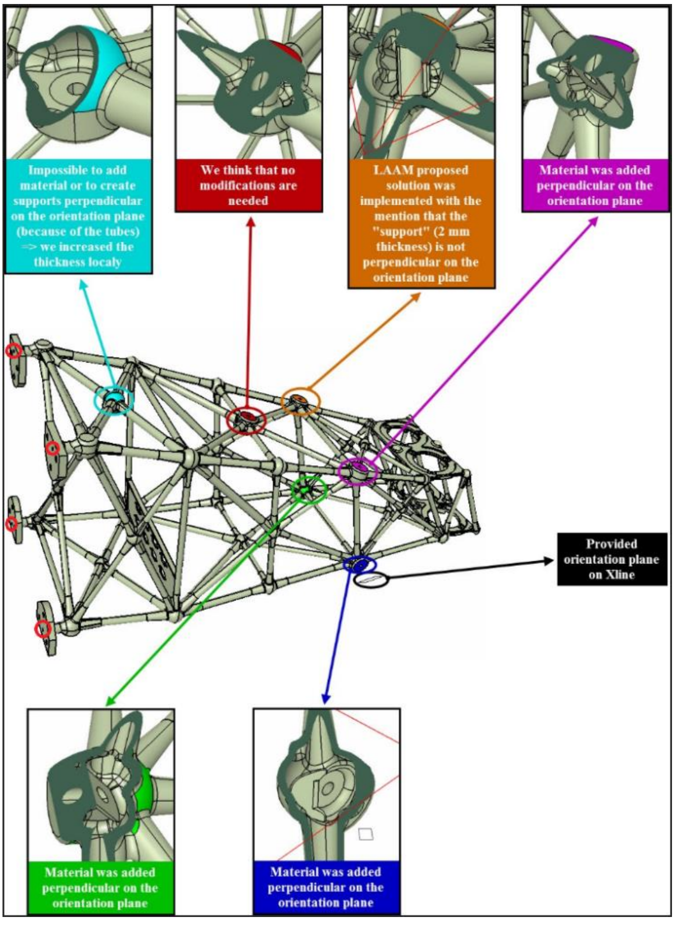

Figure 7. INCAS proposal in eliminating internal supports which was accepted by LAAM

5. QUALIFICATION

Although the additive manufacturing technology is not a new manufacturing process, a qualification procedure is needed in order to have an approval for a spacecraft component to be made in this manner. The qualification procedure implies mainly a lot of test specimens printed once with the structure of interest, and need to follow all the finishing procedures as the part. All the test specimens need to be disposed through the whole build volume in such a manner that the properties of the resulted part will be the same (not depending on the height or positioning in plate plane).

The main test for which test specimens where placed in the build volume are:

- Bar along the height of the part (for CT scan),
- Chemical composition analysis,
- Tensile test 3 directions,
- Macro/micrographic examination,
- Fatigue test,
- Density,
- Hardness,
- Roughness check.

In spacecraft related structures like the one in discussion, remaining powder in the part is a high-risk problem because the possibility of contaminating nearby components. Although for the powder evacuation a great number of holes where made, a checking procedure is also needed. Through discussions with the manufacturer, CT scan was proposed accepted and used for two reasons, firstly to thoroughly check if there is remaining powder in the internal cavities and secondly to check if the created structures have defects that would jeopardize the spacecraft. The second objective was also needed for qualification reasons.

The manufacturer, LAAM, has made a CT scan in order to verify the raised problems. The CT scan main objectives where:

- Material filling;
- Porosities and cracks;
- Lack of fusion;
- Powder residues;
- Unmolten powder.

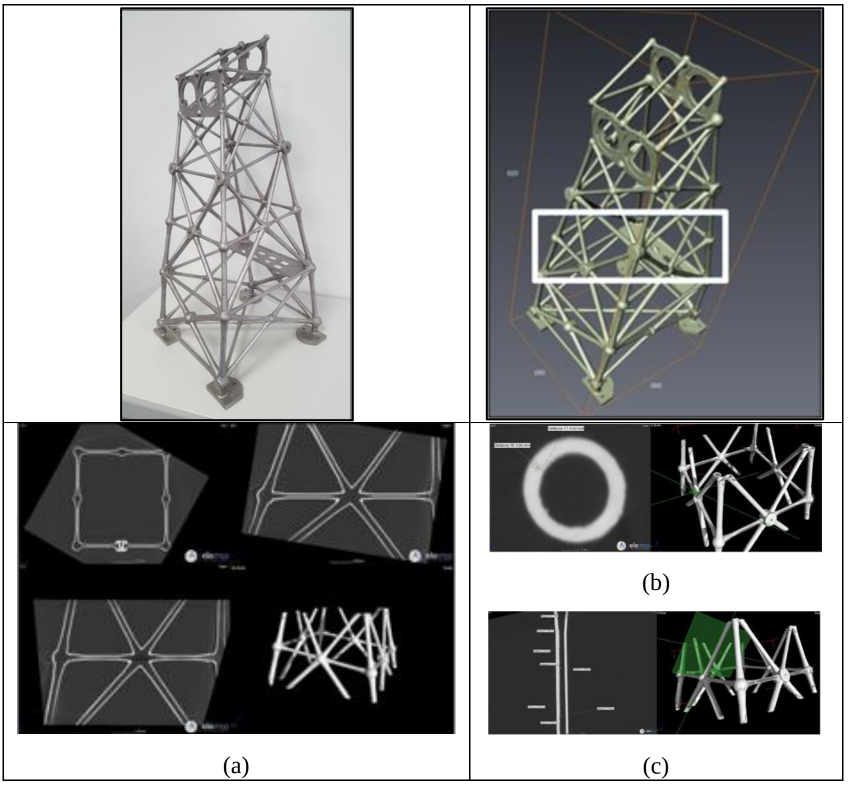

Figure 8. LAAM CT Scan

The conclusions resulted from the CT scan are:

- There are no problem about material filling and molten powder;
- Very few porosities, no cracks. See Figure 8 (b);
- No lack of fusion has been identified;
- No residue of powder has been identified;
- No area of unmolten powder has been identified;
- Internal roughness depends of orientation of pipes during manufacturing (see Figure 8 (c));

- Moreover, all the pipes opening will be closed after cleaning to ensure absence of outgoing particles.

6. CONCLUSIONS

An end-to-end process for a spacecraft structure using in-house optimization tools and ALM manufacturing was successfully presented in this paper.

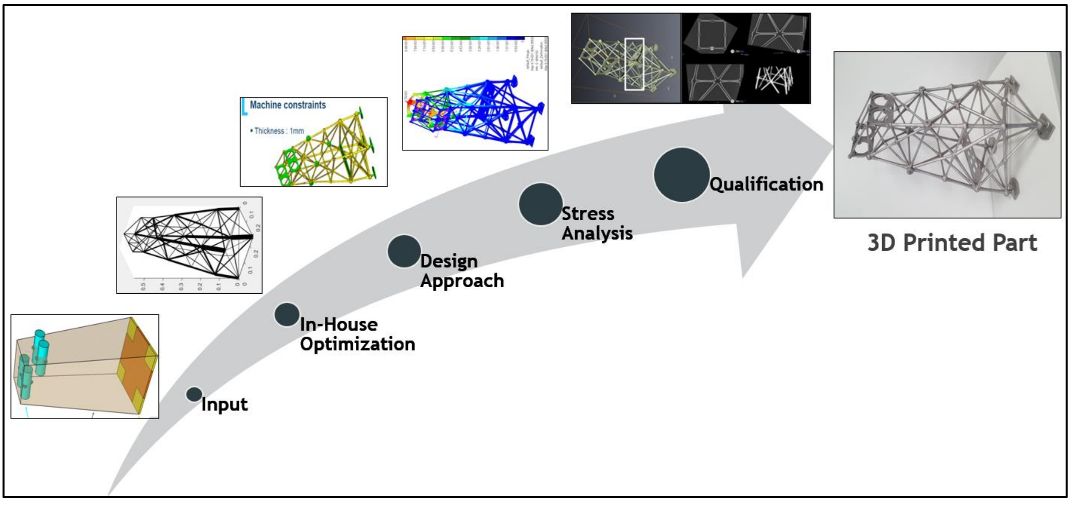

Figure 9. End-to-end process made with in-house optimization

Evacuation holes must me created taking into account the evacuation procedure.

In case of hollow structures, internal supports must be avoided in order to make the powder evacuation process as efficient as possible.

CT scan is the best way to verify if there is any trapped powder.

Internal roughness is dependent on the part orientation.

The manufacturer needs to be in the design loop from the beginning in order to have an efficient design for the additive manufacturing structures.

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