Topology optimization and additive manufacturing applied to a camera bracket for a 3U CubeSat

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Abstract: This work is aimed to perform the optimization of the design of a camera bracket for a 3U CubeSat. The weight of the initial design is 1.15 kg which needs to be reduced below 150 g, maintaining enough stiffness to withstand the launch loads. Topology Optimization is applied with Altair’s OptiStruct Inspire software to fulfil the mass reduction requirement, with promising result. Lastly, a PLA prototype is manufactured via Additive Manufacturing.

Keywords: Additive Manufacturing, 3D printing, Topology Optimization, CubeSat.

1. Introduction

Recent commercialization together with the growing success of the CubeSat standard have unleashed opportunities for benefiting from newcomer technologies. Space components are characterized by the uniqueness of each developed part, adapted to a specific mission. Considering the high impact of the design process in the global development costs [1], the integration of optimization in the early phases of a project has great importance. Therefore, the use of numerical simulation to optimize space components is essential in order to test geometry, materials and to better understand the involved physical phenomena [2]. One of the main category of shape optimization is the Topology Optimization (TO), a mathematical technique applied to structural problems defined to “obtain without any explicit or implicit restriction, the best shape possible even if topology changes” [3]. This is an adequate method for a new part design, since it explores new concepts and solutions.

Additive Manufacturing (AM) offers superior freedom of design, allowing complex designs with virtually no cost increase. Thus, the synergy of AM, able to build almost any shape, and TO seems promising, since it involves competitive solutions for the design and manufacturing of space components [4]. In fact, the TO will provide innovative forms but requires adaptation process from traditional manufacturing.

Sugimura [5] pioneered the use of AM to reduce the weight of panels keeping their strength. Other researches develop specific structures [6 – 9]. However, these studies did not use the opportunity to integrate notion of mechanical strength. The TO can solve this problem.

In this context, the present work describes the design and optimization of the structural support of a lightweight CubeSat camera, using TO and AM.

2. Initial design

In the design of the optical bench support structure —the camera bracket—, one of the main concerns is that CubeSat cameras include a very fragile optical assembly that must stay precisely aligned during
all launch and ascension stages and during the on-orbit operation of the satellite. To ensure the survival of this optical assembly and its correct alignment, the camera bracket must be stiff enough to be securely fastened to the CubeSat structure. For this reason, the initial design will start as an indisputable rigid structure: a solid block of EN AW 6061-T6 aluminum, illustrated in Figure 1. The 6 M4 threaded holes must be noted: the 4 in the Z axis will interface with the CubeSat plate, and the 2 on the Y axis with the camera.

![Figure 1. CAD model of the initial design for the camera bracket.](image)

This block represents the design space for the TO problem. One may be tempted to manually contribute to the optimization by starting off with a more refined structure, including pockets, grooves, or other strategies to help reduce the initial mass. Nevertheless, when applying TO to a structure, it is desirable to define the design space as the most primitive geometry to avoid biasing the solution.

### 2.1. Mass budget

With the selected aluminum, the initial design for the camera bracket has a mass of 1.15 kg. Considering the available information in the technical sheets of Commercial Off-The-Shelf (COTS) 3U CubeSat components (references [10, 11]), a preliminary mass budget is presented in Table 1.

The maximum allowable weight of the satellite is determined by the CubeSat standard, which limits the mass of a 3U CubeSat to 3 kg. In order to comply with this standard, the weight of the camera bracket needs to be reduced from 1.15 kg to 0.15 kg, a whole 87%.

| Subsystem         | Mass (kg) |
|-------------------|-----------|
| Structure         | 0.30      |
| Battery           | 0.30      |
| Solar panels      | 0.35      |
| Communications    | 0.30      |
| C&DH              | 0.25      |
| ADCS              | 0.25      |
| Experiment        | 1.00      |
| Camera            | 0.10      |
| Camera bracket    | 1.15      |
| **Total**         | **4.00**  |
| **Maximum allowable** | **3.00**  |
| **Difference**    | **−1.00** |
3. Optimized design requirements definition

Mass reduction always involves some level of deterioration in the structural behavior of the element, such as the reduction of its stiffness. Thus, several considerations must be observed to proceed with the optimization of the design. The following design requirements, presented in Table 2, will serve as guidelines to determine which solutions are valid for the optimized design.

| ID # | Design requirement |
|------|--------------------|
| DR-01 | The mass of the optimized design shall not exceed 0.15 kg. |
| DR-02 | The optimized design shall be made of EN AW 6061-T6. |
| DR-03 | The optimized design shall maintain both interfaces with the CubeSat structure and camera as defined in Figure 1. |
| DR-04 | The optimized design shall be contained in the volume defined by the initial design shown in Figure 1. |
| DR-05 | The optimized design shall be manufacturable through additive manufacturing. |
| DR-06 | The optimized design shall withstand all lateral and longitudinal loads of the launcher during all ascension stages. |

3.1. Launcher requirements

To meet design requirement DR-06, it is necessary to characterize the acceleration profile that the CubeSat will experience during launch. The selected launcher for the mission is the Falcon 9. Most of the launch data can be extracted from its User’s Guide [12], available online to the public. Two categories of loads are experienced by the payload: Static and Dynamic.

3.1.1. Static loads: constant acceleration. Falcon 9 User’s Guide provides the acceleration map shown in figure 2 (a). Since the orientation in which the CubeSat will be installed in the launcher is unknown, so is the direction of axial and lateral loads for the camera bracket. To ensure its survival in any possible orientation, the most restrictive acceleration value will be considered in all directions during its analyses and optimization. According to in figure 2 (a) acceleration map, the worst-case static load is the axial acceleration with maximum value of 8.5 g.

![Figure 2. (a) Design load factors for low-mass payloads onboard the Falcon 9. In red the acceleration envelope for payload masses below 1.81 kg. (b) PSD plot of the random vibrations onboard Falcon 9 at a statistical level of P95/50. Note that the most energetic frequency range is the 800-1000 Hz. [12]](image)
3.1.2. Dynamic loads: random acceleration. Falcon 9 User’s Guide also provides the PSD plot shown in Figure 2 (b). This plot describes the energy level that the CubeSat must withstand at a certain frequency range. These accelerations have a random nature. In order to completely determine the structural response, an exhaustive random vibration FE analysis must be performed. This analysis is beyond the scope of this preliminary study. Instead, Modal Analysis will be used to predict the resonant frequencies of the structure, so that the first mode frequency of the optimized design is kept above 1500 Hz. This will ensure that the camera bracket does not resonate during the launch.

To summarize, considering the static and dynamic loads’ restrictions, the design requirement DR-06 can be further extended to:

- The optimized design shall be analyzed under a constant load of 8.5 g applied in all directions.
- The first resonant frequency of the optimized design shall be kept above 1500 Hz.

4. Structural analysis of the initial design

4.1. Boundary conditions

Boundary conditions of the camera bracket are determined by the interfaces with both the CubeSat structure and the camera. These conditions are simulated as simple supports, and the camera is modelled as a point mass of 0.1 kg joined through rigid elements (see figure 3).

![Figure 3. Boundary conditions applied to the initial design.](image)

4.2. Load conditions

The applied load conditions are the ones described in subsection 3.1: constant accelerations of 8.5 g in each axis.

4.3. FEM analysis

The structure is analyzed using Altair’s OptiStruct Inspire software. The four first resonant frequencies are obtained through modal analysis. The results of the analysis are presented in Table 3.

It must be highlighted that the first resonant frequency is well above the minimum allowed value of 1500 Hz for the optimized design. This implies that mass can be reduced while keeping the required structural stiffness.

| Frequency # | Value (Hz) |
|-------------|------------|
| $f_1$       | 3797       |
| $f_2$       | 8021       |
| $f_3$       | 13520      |
| $f_4$       | 15498      |

Table 3. First four resonant frequencies of the initial design.
5. **Topology optimization of the initial design**

5.1. **Definition of the design space**

According to DR-03, all 6 interface joints shall be kept unmodified. For this purpose, these holes are partitioned inside cylinders to be left out of the design space, as shown in Figure 4.

![Figure 4](https://via.placeholder.com/150)

**Figure 4.** Design space definition. Grey cylinders are left out of the design space to ensure fulfilment of DR-03.

5.2. **Optimization parameters**

The following optimization parameters can be tuned to control the achieved results:

- **Objective**: Available options are to minimize mass or maximize stiffness of the structure.
- **Mass Targets**: This option is only available if the optimization objective is not to minimize mass. In that case, a mass target can be specified with a corresponding percentage value.
- **Percentage**: Only when mass target is checked. The desired mass shall not surpass 13% of the initial mass. To allow a certain margin, this parameter will be set as 10% when applicable.
- **Frequency Constraints**: This option allows maximizing resonant frequencies or establishing a minimum value for the first resonant frequency, in this case 1500 Hz.

The combination of these parameters allows the definition of three compatible configurations for the TO, summarized in table 4.

In all cases, a symmetry restriction in YZ plane is applied to the optimization process.

| Parameter               | Value (Hz)                  | Optimization 1                | Optimization 2                | Optimization 3                |
|-------------------------|------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Optimization #          | Minimize Mass                | Maximize Stiffness            | Maximize Stiffness            |                               |
| Objective               |                              |                               |                               |                               |
| Mass Targets            | -                            | % of Design Space Volume      | % of Design Space Volume      |                               |
| Percentage              | -                            | 10%                           | 10%                           |                               |
| Frequency Constraints   | Minimum: 1500 Hz             | Minimum: 1500 Hz              | Maximize frequencies         |                               |

5.3. **Topology optimization of the design space**

The parameters presented in Subsection 5.2 entails the success criteria of the optimization process. Additionally, further configuration of the optimization algorithm *per se* is allowed. Particularly, the optimization process is deeply influenced by the value of the minimum thickness allowed in the generated geometries:
Reducing the minimum allowed thickness is very computationally expensive. The algorithm may take a very long time to converge or not converge at all. Even if it does converge, the solution may contain thicknesses too small to manufacture.

Increasing the minimum allowed thickness facilitates convergence of the algorithm, but if the value is too large the solution may contain not fully connected geometries (refer to Figure 5.a).

It is important to bear in mind this trade-off between convergence and refinement of the solution when setting the minimum thickness value. Nevertheless, there are some cases where this trade-off cannot be achieved with a certain set of optimization parameters, and the process is not successful. This is the case with Optimization 1, as shown in Table 5. Conversely, Optimizations 2 and 3 successfully converged.

| Parameter          | Optimization # | Optimization 1 | Optimization 2 | Optimization 3 |
|--------------------|----------------|----------------|----------------|----------------|
| Minimum thickness  | 1-5 mm         | > 5 mm         | 7 mm           | 7 mm           |
| Convergence status | Failed         | Not connected  | Converged      | Converged      |
| Resulting mass     | -              | -              | 92.3 g         | 105.1 g        |

**Figure 5.** Resulting geometries from (a) Optimization 1. Note that the resulting optimized geometry is not connected. (b) Optimization 2. Mass: 92.3 g (c) Optimization 3. Mass: 105.1 g.

### 5.4. FEM analysis

The structure generated in Optimization 1 is discarded. Structures generated in Optimizations 2 and 3 are analyzed to check that the first resonant frequency is above 1500 Hz, as required. Boundary and load conditions are applied as described in subsections 4.1 and 4.2, respectively. The first four resonant frequencies resulting from the FEM analysis are presented for both Optimization 2 and 3 in Table 6.

It must be noted that both optimizations have $f_1 > 1500$ Hz, complying with the requirement imposed by the launcher.

| Frequency # | Value (Hz) |
|-------------|------------|
| $f_1$       | 1572       |
| $f_2$       | 1753       |
| $f_3$       | 1782       |
| $f_4$       | 2672       |

**Table 6.** First four resonant frequencies of the structures resulting from topology optimizations 2 and 3.
6. Selection of the final design and post-processing

Considering the results presented in Table 5 and Table 6, it is clear that both Optimization 2 and 3 fulfill the requirements, but Optimization 2 is slightly lighter. Since weight reduction is essential for space systems, this optimization will be selected as the final camera bracket design.

6.1. Finishing of the selected geometry with the PolyNURBS tool

The geometry resulting from the TO must be post-processed before it is feasible to manufacture it. Inspire software offers a tool especially designed with this purpose. The PolyNURBS tool allows the user to wrap the geometry in smooth surfaces that can be manually adjusted.

This operation is applied to the selected geometry (Optimization 2), as shown in Figure 6. Note that, since the process slightly increases the design’s volume, the mass also grows. In this case, from 92.3 g to 126.3 g.

![Figure 6](image)

**Figure 6.** (a) Resulting geometry from TO (Optimization 2). (b) Geometry generated with the PolyNURBS tool. Note the slight increase in volume.

6.2. Validation of the final design

Compliance of the final design with all requirements is verified as summarized in Table 7.

| Design requirement ID # | Result             | Compliance |
|-------------------------|--------------------|------------|
| DR-01                   | $M_{opt} = 0.126$ kg | Yes        |
| DR-02                   | -                  | Yes        |
| DR-03                   | -                  | Yes        |
| DR-04                   | -                  | Yes        |
| DR-05                   | -                  | Yes        |
| DR-06                   | $f_1 = 1572$ Hz    | Yes        |

7. Additive manufacturing of a prototype of the final design

A prototype of the camera bracket is printed in PLA material using an Artillery Genius machine. The result is shown in Figure 7.

8. Conclusions

An analysis and optimization of a 3U CubeSat camera bracket is presented in this work. Through the application of TO with Altair’s OptiStruct Inspire software, a mass reduction of over 85% is achieved, fulfilling all design requirements. A prototype of the camera bracket is manufactured in PLA using an Artillery Genius 3D printer. This work shows the promising opportunities for design that AM together with TO enable, and their advantages for the space industry.
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