

Design of a multifunctional composite structure for modular CubeSat applications

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Abstract. CubeSats primary structures are usually made with aluminium alloys, with few examples of CFRP primary structures under study. Power system battery arrays usually occupy spacecraft internal volume and mass that should be available to the payload. A CFRP structural/battery array configuration has been designed, allowing to integrate the electrical power system in the bus primary structure. Its configuration has been developed with the modular design philosophy of the AraMiS CubeSat. It is sized as a tile, mounted on an external face of the 1U CubeSat. It accommodates two solar cells, while the opposite face accommodates power system circuitry. Following a cellular structure concept, a set of commercial LiPo batteries has been placed between two CFRP panels and spaced out with CFRP ribs. Compliance with launch mechanical loads has been evaluated with a finite element analysis. A preliminary thermal analysis has been performed to simulate a LEO orbit environment. The results indicate that even with a low degree of structural integration, more volume and mass can be allocated to the payload, with respect to traditional, functionally separated designs in aluminium alloy. The low degree of integration allows to employ relatively cheap, commercial off-the-shelf components.

1 Introduction

Space missions in recent years have experienced an outburst of CubeSats, either in support of larger spacecrafts or as the very own space segment. The CubeSat was first defined in 1999 as a cubic spacecraft with 100 mm sides (corresponding today to 1 unit, 1U) and a maximum mass of 1 kg (today 1.33 kg) [1, 2].

Since then, an increasing number of CubeSat missions has gone beyond the original educational objectives of the program and is aiming at cutting edge technological and scientific objectives [3]. Currently, there are just a few missions beyond Low Earth Orbit (LEO) and the prevailing form factor is 3U (100 x 100 x 300 mm, maximum mass 4 kg [2]) [4].

Active missions adopt aluminium alloy primary structures, at times with composite materials secondary structures. Apart from limited and obvious multifunctional integration (e.g. solar cells mounted on external panels), functionalization of the spacecraft primary structure by inclusion of bus functions is usually not considered [4]. However, the

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increasing complexity of the mission objectives and architectures has already led in some cases to overcrowded CubeSats [5]. Moreover, the structural mass ratio, i.e. the ratio of structural mass and spacecraft total mass, is not always satisfying. In the case of the STRaND-1 CubeSat, a structural mass ratio of 30% has been considered unsatisfying [6].

Although structural integration has already been considered in some nanosatellites design [7], composite primary structures were not considered and integration can be pushed forward, aspiring to a higher volume and mass available for the spacecraft payload. Indeed, composite materials offer a wide range of tailoring and embedding possibilities, encouraging the design of lightweight and highly functionalized structures. Moreover, it has been shown that properly designed composite primary structures for CubeSats produce lower stresses and displacements, and higher fundamental frequencies with respect to traditional aluminium alloy structures [8].

The present study deals with the design of a Carbon Fiber Reinforced Plastic (CFRP) integrated primary structure component, that is part of a 1U satellite bus. It houses an embedded Electrical Power System (EPS) to show the above-mentioned advantages of functionalized composite primary structures for CubeSats, pico- and nanosatellites. The EPS includes solar cells, batteries and the related circuitry. Its integration within the CFRP primary structure allows to save the mass of non-energy-storing components, such as the case and the electrodes, and the CFRP laminates provide containment and protection for the batteries. The carbon fibre structure is designed to be mounted on a 1U commercial, aluminium alloy, cubic frame and occupies one face of the cube.

The present work is part of the AraMiS project [9] and shares its design philosophy. The objective is to design, produce and test a set of smart tiles (Table 1), to be mounted on the faces of a 1U CubeSat (Figure 1). The tiles are modular and each one houses the components of mainly one spacecraft bus subsystem (Figure 2). Tiles modularity is necessary to reduce design, assembly and testing costs and time. Cost is further reduced by employing Commercial Off The Shelf (COTS) components, with the adequate level of redundancy. Examples of smart tiles are the telecommunication tile, with Tracking, Telemetry and Command (TT&C) subsystem components, the reaction wheel tile, with Attitude and Orbit Control System (AOCS) components and the power management tile. In particular, the present design aims at improving the previous 1B8 power management tile, that employed Printed Circuit Boards (PCBs) as a primary structure and did not have power storing functions.

Besides space applications, energy storing composite structural components are studied in the automotive, aeronautical and marine sector [10, 11, 12]. Vehicle mass saving in this case is more useful than internal volume saving. It has been shown that energy storing

composites can significantly increase the range of aircrafts [13]. This can contribute importantly to the development of low-emissions aircrafts, powered by fuel cells and solar cells [14, 15].

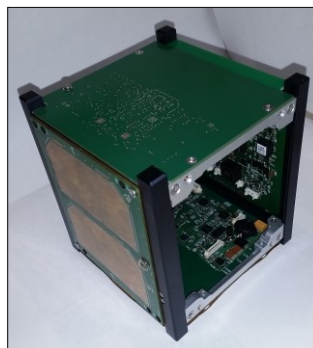


Fig. 1. AraMiS CubeSat prototype.

Tab. 1. Existing smart tiles.

Name	Code	Main subsystem/components
Power management tile	1B8	- OBC (On Board Computer, simple microprocessor) - EPS (solar cells, primary converter) -AOCS (gyroscopes, magnetometers, magnetorquers)
CFRP power management tile version 1	1B68_V1	- EPS (solar cells, secondary batteries)
CFRP power management tile version 2	1B68_V2	- EPS (solar cells, secondary batteries) - AOCS (magnetorquers)
Telecommunication tile	1B9	- TT&C components (frequency bands: 437 MHz and 2.4 GHz)
Reaction wheel tile	1B213A	- AOCS (reaction wheel, gyroscopes, magnetometers) - EPS (solar cells)

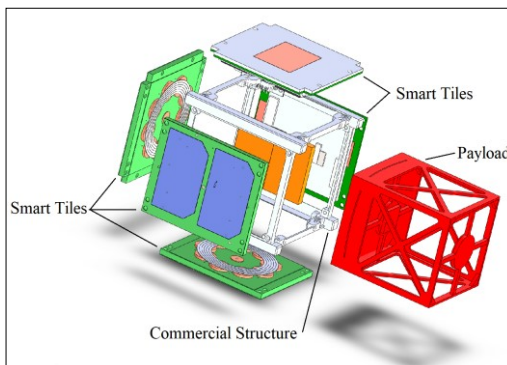


Fig. 2. AraMiS CubeSat architecture.

2 Methodology

The functionalization of the smart tiles must take into account a strong constraint, imposed by CubeSat deployment procedure. CubeSats are usually accommodated inside the launch vehicle in standard deployers, for example the Poly Picosatellite Orbital Deployer (P-POD) for 1U-3U form factors [16]. The P-POD is an anodized aluminium rectangular box. A spring in the deployer pushes into space the CubeSats, that are guided by their rails (the vertical rods shown in Figure 1), in contact with rails on the deployer. For this reason, no component is allowed to protrude more than 6.5 mm normal to the plane of the rails (CubeSat mechanical requirement 3.2.3 and 3.2.3.1 [2]).

The functionalization of the primary structure has begun with the design of the reaction wheel tile prototype. It consisted in merging the reaction wheel and the relative mechanisms and electronic components, the solar cells with related circuitry and the primary structure. The structure was still made with PCBs, and thus in FR4, an epoxy resin with glass fibers thought for electronic circuits.

The next step is represented by the design of an energy storing smart tile prototype, with the employment of composite materials. This will free internal volume, available to the payload, and will allow spacecraft bus mass saving.

2.1 Power storage composite structures

There is a wide variety of integrated energy storage systems, that can be conveniently described in terms of their degree of integration [17]. Traditional energy storing subsystems with no structural integration have a null degree of integration. A low degree of integration can be represented by the embedded battery, where existing energy storing components are included in structural elements. Although the assembly has both functions, there is functional separation at the components level. On the contrary, the high degree of integration extreme includes genuine structural batteries, whose components have the structural and the electrical function at the same time. One example of structural battery has been recently developed [10]. It consists of a unidirectional carbon fiber lamina where the fibers act as battery electrodes and the matrix acts as the battery electrolyte. As a result, the lamina can store electrical energy.

Embedded battery systems come in a variety of configurations, the most usual ones are the laminate structure [18], the sandwich structure [19] and the stiffener structure [19]. The laminate structure consists of a classical composite material laminate with a set of batteries accommodated in the inner layers. The batteries are mechanically connected with the laminae thanks to a resin rich region, that usually has an irregular shape. The sandwich structure houses the batteries in cavities of the core material, which usually has inferior mechanical properties with respect to the skins material. Finally, batteries can be placed in the inner regions of stiffeners.

Although high degree of integration batteries are promising and allow for greater mass and volume savings, to comply with AraMiS project design philosophy, a low degree of integration has been chosen, with COTS components that can be easily assembled and tested.

3 Power management tile architecture

For the present design, an innovative configuration was chosen [20]. It is a cellular configuration previously conceived for sailplanes wing boxes, in particular for the upper and lower skins. A section showing half of the smart tile is shown in Figure 3.

3.1 Tile mechanical and electrical configuration

The upper and lower structural panels are composite laminates and hold the PCBs for the solar cells (upper panel in Figure 3) and the electrical subsystem circuitry (lower panel in Figure 3). The batteries are placed between the two panels, with four CFRP stiffeners among them.

Mechanical connection between the batteries and the CFRP laminates is obtained with a silicone resin, to provide thermal protection and vibration reduction for the batteries. Electrical connection between the batteries and the inner PCB (lower PCB in Figure 3) is obtained with holes in the CFRP lower panel to allow the passage of batteries connectors.

This configuration has some advantages with respect to the classical configurations. It is more rigid of the laminate structure, thanks to the distance from the neutral axis of the CFRP panels. Moreover, the laminate structure had holes to house the batteries, that are missing in the cellular structure. It is more rigid than the sandwich structure also, thanks to the stiffeners. In addition, CFRP cells obtained with upper and lower panels and the stiffeners provide protection and containment for the batteries. Finally, there is enough area on the PCBs to contain two solar cells, the set of electronic components and their electrical connections to allow the proper operation of the electrical power subsystem.

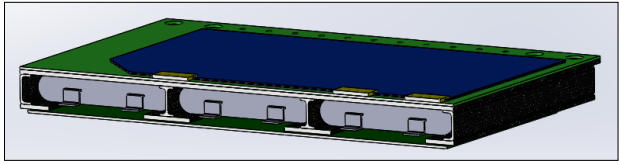


Fig. 3. Power management tile, section.

3.2 Commercial batteries selection

Once the Lithium Polymer (LiPo) battery was chosen as the battery type, a preliminary investigation was performed to find the maximum energy storage capacity. The maximum battery thickness was set to 4.5 mm. Various prismatic batteries have been considered, and the potential tile energy storage capacity was estimated. The chosen array of six commercial batteries allows to store approximately 11 Wh in one power management tile. The total capacity is in line with actual commercial 1U-2U EPS systems [21]. In addition, the smart tiles modular approach can be exploited to obtain higher energy capacities. With two or three power management tiles mounted on the same 1U CubeSat it is possible to reach 22 or 33 Wh, respectively. Moreover, in multiples of 1U, the area of some smart tiles is increased and thus more commercial batteries can be stored in the same power management tile. For example, a 2U tile has twice the area of a 1U tile, and this allows to store up to 22 Wh with the present design.

4 Analyses

A set of analyses has been made to assess the compatibility of the design with the launch mechanical environment, objective of the structural analysis, and the compatibility with the thermal environment once in the designed orbit, objective of the thermal analysis.

4.1 Structural analysis

A structural Finite Element (FE) analysis has been conducted to assess the mechanical response of the proposed design to the launch. The Vega launch vehicle has been chosen for the analysis. The applicable launch condition [22] imposes a Limit Load (LL) of 7 g. The chosen Safety Factor (SF) is 1.8 and thus the Ultimate Load (UL) is 13 g:

$$UL = SF \cdot LL = 1.8 \cdot 7 \text{ g} = 12.6 \text{ g} \approx 13 \text{ g} \quad (1)$$

The power management tile is mounted on the aluminium alloy frame with screws passing through four cylindrical holes in the tile (Figure 1). Depending on which face of the frame is involved, screws must pass through the four external holes or through the four internal holes. Thus, for the FE analysis, the nodes belonging to the inner or outer holes have been considered blocked. A static analysis has been conducted to evaluate strains, stresses and nodes displacements. In addition, the resonance frequencies have been evaluated.

4.2 Thermal analysis

Finally, a preliminary thermal analysis has been performed with a lumped-element model. The model considers a 1U CubeSat with power management tiles on all of the six faces and a possible payload, for the typical duration of a LEO orbit of 90 minutes. The model

considers the solar irradiation at 1 AU from the Sun for 70% of the orbit (reasonable for LEO orbits). The incoming power P_{in} is then:

$$P_{in} = P_{sun} \cdot a \cdot b \cdot \alpha = \quad (2)$$
$$= 1.361 \text{ kW/m}^2 \cdot 97.8 \text{ mm} \cdot 82.4 \text{ mm} \cdot 0.9 = 9.87 \text{ W}$$

Where P_{sun} is the solar constant, a and b are the tile dimensions, and α is the mean tile absorbance.

The incoming power is exerted on the same smart tile for the entire orbit. In addition, an incoming thermal power of 1 W, due to the payload dissipation, is considered.

Methodologies to dissipate tile internal heat generation are under evaluation. In particular, heat due to batteries dissipation can be conducted outside of the smart tile, towards the commercial aluminium alloy structure, with simple heat-transfer devices as metal strips.

5 Results

The total tile mass is 137 g, with a CFRP mass of 15 g. A comparison of total and partial masses can be done with a commercial embedded EPS [21] and a commercial aluminium alloy structure [23] (Table 2). For the latter structure, one face of the 1U cube has been considered.

The PCBs weight of the proposed design is inferior with respect to the commercial embedded EPS (respectively 7,6 g and 25,6 g). Clearly, in the proposed design there is no structural function of the PCBs, and thus their thickness can be reduced, while for the commercial EPS, the PCB panel is the only component able to withstand loads, and thus it has a major thickness. The structural mass for the present design (15 g) is given by the mass of CFRP elements. It is clearly inferior with respect to the structural mass of the commercial aluminium alloy panel (28 g), due to the use of composite materials. However, the overall mass of the proposed design is greater than the mass of the commercial EPS. This is mainly due to the resin employed for mechanical and thermal insulation of the batteries, whose mass can be reduced with lighter materials like foams. In addition, the present design has advantages with respect to its commercial counterpart. Batteries are protected from vibrations, excessive temperatures and thermal shocks, and the CFRP cells provide containment and protection from the batteries for the rest of the spacecraft. Furthermore with two, lighter PCBs, more area can be devoted to EPS electronic components and circuits. Finally, no internal volume is subtracted to the payload.

The ratio between the tile mass and the CubeSat maximum mass is 10%. Although it is a partial result and does not involve the whole CubeSat with its payload, it is inferior to the structural mass ratio of 30%, identified as unsatisfactory in the STRaND-1 project [6]. There is still margin to place the remaining subsystems components.

The FE static analysis (Figure 4) has revealed that the smart tile can easily survive the launch, with a maximum displacement of 4.8 μm in the worst case, i.e. with external holes blocked. All the stresses and the strains are within materials allowable limits in both cases. The modal analysis has provided a minimum fundamental frequency of 963 Hz, with the external holes blocked. Vega User's Manual [24] prescribes that the lateral axis fundamental frequency, f_{lat} , must be equal or greater than 15 Hz:

$$f_{lat} \geq 15 \text{ Hz} \quad (3)$$

And the longitudinal axis fundamental frequency, f_{long} , must be in the range:

$$20 \text{ Hz} < f_{long} < 45 \text{ Hz} \text{ or } f_{long} > 60 \text{ Hz} \quad (4)$$

Although this is a partial result about power management tile local resonance, the above requirements are satisfied.

The preliminary thermal analysis has shown that maximum temperatures are within components allowable limits.

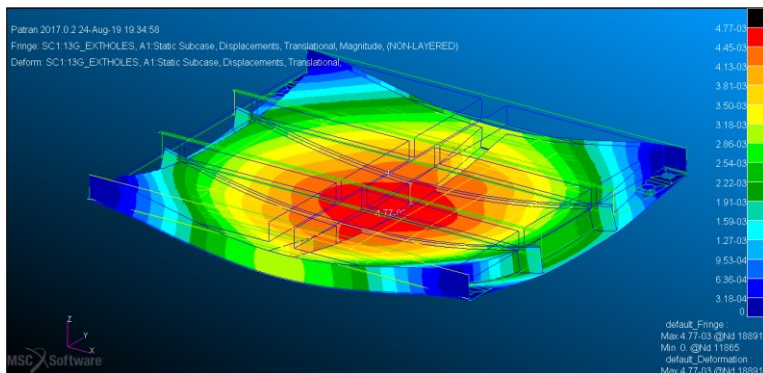


Fig. 4. Static deformation with external holes blocked.

Tab.2. Masses comparison.

	Proposed design	Commercial embedded battery	Commercial structure panel
Total mass [g]	137	80	28
PCB mass [g]	7,6	25,6 (estimated)	-
Structural mass [g]	15	-	28

6 Conclusions

The results seem to suggest that the present design method can give positive results. The designed embedded battery can withstand the mechanical launch environment and the thermal environment once in a LEO orbit, with advantages on the structural mass and the volume for the payload. Moreover, the FE static analysis suggests that the proposed design can be pushed forward, introducing cut-outs in the CFRP laminates. This would allow a lower structural mass while maintaining an adequate structural response.

Finally, the results presented in the previous section seem to show that functionalization of a 1U CubeSat primary structure can successfully be implemented with composite materials, leading to a lighter spacecraft bus, with more volume available for the payload. With the increasing complexity of future space missions, these advantages will be pivotal in defining new space technologies.

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