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DEVELOPMENT AND ANALYSIS OF A BRAZILIAN CUBESAT STRUCTURE

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Abstract. *This paper presents the processes of developing a physical solution to the structural subsystem of the Brazilian Technological Institute of Aeronautics – ITA CubeSat, the AESP-14 Project. This work also shows static and modal structural analysis through computational methods, in order to predict the structural response to launch environment. The INPE's capacities for manufacturing CubeSat main structures, are also discussed and proved through Reverse Engineering applied to a Commercial Off The Shelf - COTS structure. Results of analysis showed that in average launch environment levels, the structure developed reaches maximum stresses quite below used material's limits. Natural frequencies found are also eligible to major piggy-back launch requirements.*

Keywords: *CubeSat structure, AESP-14 CubeSat, Reverse engineering, structure analysis.*

1. INTRODUCTION

Projects related to miniaturized satellites are increasing as important educational tools, showing that academic satellite projects are a great opportunity for students to practice their knowledge learnt in class, providing hands-on experience. Another reason to miniaturize satellites is to reduce the costs. Although launch prices have risen quite substantially across the board of launch providers, a CubeSat still forms the most cost-effective independent means of getting a payload into orbit (David, L., 2004). The activities in miniaturized satellites development are constantly increasing along with progress in areas like electronics, mechanical and thermal by searching new and advanced technologies, as they need to be tested and small satellites are ideal for achieving these aims.

Since 2000, a new generation of nanosatellite called CubeSat has being developed by several organizations and universities in many developed and developing countries as low cost space access opportunities to experiment platforms. Many start-ups have arisen in groups with little or no experience in satellite design and flight experience, but this is what the CubeSat concept is all about. Universities, NASA centers, military units and private enterprises are active in CubeSat building. (Hansen, F., 2001)

The Brazilian AESP-14 CubeSat project has the involvement of ITA's Aerospace Engineering undergraduate course students and professors, ITA and INPE graduate students and INPE specialists. The project main task is to develop a CubeSat that meets a specific scientific mission to be defined based on INPE's research scientists' needs. The technological mission consists on the multi-mission national CubeSat platform validation.

The launch of any satellite is one of the major and costly steps in the way to the orbit or to outer space. When a launch vehicle lifts-off, strong vibrations are transmitted through the joining sections to the satellite on-board. CubeSats are ejected from a launch interface named Picosatllite Orbital Deployer - POD, specifically designed and built for

CubeSats which use piggy-back launch opportunity. During its launch, a satellite is subject to various external loads, thus a satellite must meet the requirements given by the launcher based on the launch vehicle specifications. CubeSat projects often have difficulties finding a suitable launch vehicle, so it is traditional to analyze them with worst-case launch loads, qualifying the projects to a wide variety of launchers (Cihan *et al*, 2008).

In this paper, AESP-14 structural analysis is discussed based on computational methods to predict the response of its structure to the launch loads. Firstly the printed circuit board – PCB attachment solution is analyzed. The static analysis of the whole structure and the five first natural frequency modes are shown and discussed. In order to evaluate the local manufacturing capabilities, a reverse engineering CubeSat structure is shown.

2. CUBESATS

The CubeSat class, Fig. 1, was developed in 1999 through a partnership between Prof. Jordi Puig-Suari from California Polytechnic State University (Cal Poly), San Luis Obispo, and Prof. Robert Twiggs from Stanford University's Space Systems Development Laboratory (SSDL). The project's initial objective was the standardized platform creation in order to reduce development costs, time, increase space access and maintain frequent launch opportunities to small payloads. (CubeSat Design Specification, Rev. 12).

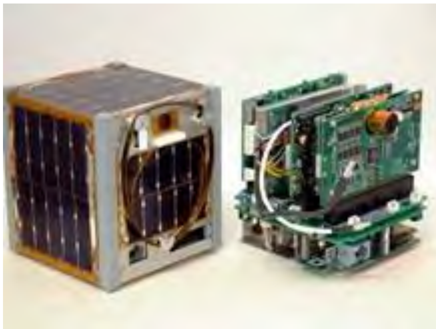

Figure 1. University of Tokyo Cubesat. From: http://www.space.t.u-tokyo.ac.jp/cubesat/mission/V/index-e.html

The public document *CubeSat Design Specification* – CDS shows mandatory requirements and specifications that shall be met in order to have the satellites classified as CubeSats. The standard has approximately 10[cm³] of volume and weighs up to 1,33[Kg]. The nanosatellites are launched trough the standardized interface known as POD – Picosatellite Orbital Deployer, Fig. 2, which due to its space qualification and the interface absence between satellite and launcher, allows the use of COTS components in CubeSats.

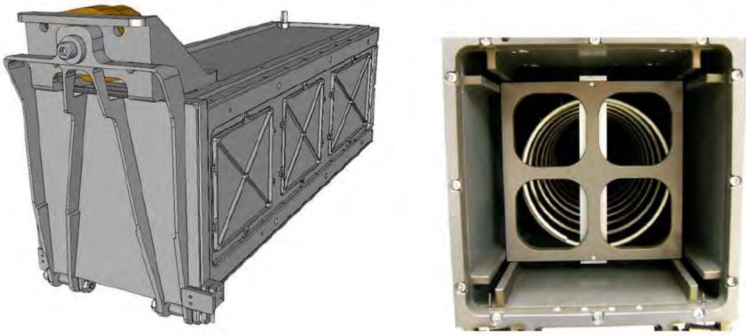

Figure 2. P-POD CAD model (left) and inside of a P-POD (right). From: CubeSat Design Specification, Rev. 12.

The launch of such satellites are usually made as a tertiary payload (piggy-back), thus the POD interface is attached at the launcher's mounting base, Fig. 3. The major kinds of POD carry up to 3 CubeSats, the system consists on a metallic box with an opening lid and a spring mechanism to ejection. A cable actuator opens the lid at the desired orbit, pushing the satellites outside the POD through a spring-plate mechanism guided with rails. The CubeSats are ejected with a linear velocity about 0.3 [m/s]. Due to such only mechanical interfaces between satellite and POD there is a great launch flexibility.

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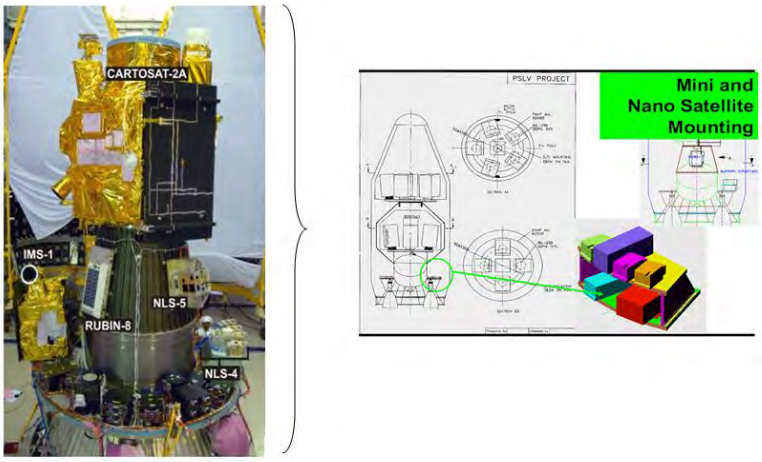

Figure 3. PODs attached to the Indian PSLV launcher mounting base. From: Raghava Murthy, D. V. A (2009).

Due to the successful launch and operation of the first CubeSat missions, low costs, low risks (due to low impact) and short development time, this technology is now also being used as a *in situ* (space environment) platform to test new technologies by international space agencies (NASA and ESA, for example), military agencies, commercial and private organizations and it is a widespread practice in universities as a hands-on way of teaching aerospace disciplines. CubeSats have also become a very high cost-effective mean to realize space science experiments, as well as fostering the creation of several aerospace branch companies through university projects spin-offs.

CubeSats operate on radio-amateur frequencies which are controlled by International Amateur Radio Union – IARU, and they basically consist on the following subsystems: thermal, structural, on-board computer (OBC), attitude control system (ACS), communication (COM), power and payload.

According Twiggs *et al* (2005), this miniaturized system was developed in order to reduce space missions schedule up to two years. Such a fast schedule allows students to get involved in the whole mission life-cycle, specifically through the phases:

- Mission planning and requirements;
- Design, analysis and tests;
- Manufacturing, assembly and quality control;
- Integration and system tests;
- Satellite operation.

3. AESP-14 PROJECT

AESP-14 project was conceived in early 2012, being included in the "Início da indústria brasileira de pico-satélites universitários (PICO-SA)" proposal related to the AEB / MCT / CNPq No. 033/2010 notice, approved in november 2011 under Dr. Geilson Loureiro (INPE Senior Technologist III and ITA Professor) coordination. The project motivation is the group technological capability development, which involves ITA's Aerospace Engineering course undergraduate students and professors, ITA and INPE graduate students and INPE specialists.

The AESP-14 project encompasses all space product life-cycle stages, starting with mission definition, architecture development and construction, hardware, software, assembly, integration and tests, launch and operations. Project members should conceive, design, implement and operate the CubeSat over three years (the duration of undergraduate course at ITA).

The project main task is to develop a CubeSat that meets a specific scientific mission to be defined based on INPE's research scientists' needs. The technological mission consists on the multi-mission national CubeSat platform validation. The scientific mission is to obtain scientific parameters from the ionized atmosphere in a low orbit, with emphasis on the plasma bubbles study. AESP-14 nanosatellite will be launched as a secondary payload in low orbit and the data acquired by ground stations will be processed and provided to geophysics and astrophysics INPE researchers from CEA (Atmospheric Space Sciences). (Zambrano, 2012).

4. STRUCTURE DESIGN

According to the European Space Agency Standard (ECSS, 2009), structure is the set of mechanical components or assemblies designed to support loads or pressures, providing stiffness or stability, or providing support or containment.

The main function of a satellite structural subsystem is the satellite subsystems' mechanical support as a whole, with adequate resistance and structural stiffness margins during the natural or induced environments which the system will be exposed, as follows: handling, tests, transport, launch and space environment. This makes the engineering of space structures relatively unique, because there is a direct dependence of all other subsystems, mainly thermal control subsystem and attitude control. The structural design requirements main sources in a space project are (Fortescue, *et al.,* 2003):

- Launch vehicle interface;
- Load paths;
- Equipment positions;
- Launch loads;
- Test loads;
- Safety factors;
- Stiffness requirements;
- Environmental care;
- Alignments;
- Thermal and electrical paths;
- Accessibility;
- Mass;
- Fracture control.

A satellite structural design shall meet the requirements listed above respecting mass constraints with the highest possible reliability. The project should also consider managerial aspects, fulfilling a regular schedule and cost limit. The diversity of requirements sources ratifies that a structural design does not only covers the selecting material and configuration steps, it is also necessary to include analysis and verification as part of the development process. It is noted that with the project evolution and staff experience, the analysis reliability can waive some verification steps, which by the way reduces time and costs. (Fortescue, *et al.,* 2003)

CubeSat structures are much simpler than bigger satellites structures. This is mainly because the size and parts number. The AESP-14 CubeSat structure design was based on concurrent engineering methods, which is an approach that encompasses all products' life-cycle elements, since conception to disposal, anticipating requirements to early phases that without this approach could be lately noted in the project, resulting in increased costs. The concurrent engineering technics applied to this structural design are (Huang, 1996):

- Design for Assembly (DFA): method that simplifies the product structure, resulting on easy to implement products and more efficient assembly;
- Design for Manufacturing (DFM): This technic linked to DFA as a procedure that focuses on manufacturing process to minimize part number;
- Design for Inspectability (DFI): this approach guides the product design development to ease the inspection procedures. It is necessary when stakeholders require high quality. Such ease on inspection in the manufactured products gives a quick and precise response to process control activities.

The AESP-14 structure gathers high modularity, low mass and easy manufacturing. The design was also based on other nanosatellites, such as the Brazilian NANOSATC-BR1, purchased from ISIS Company. The final AESP-14 structure in shown in Fig. 4.

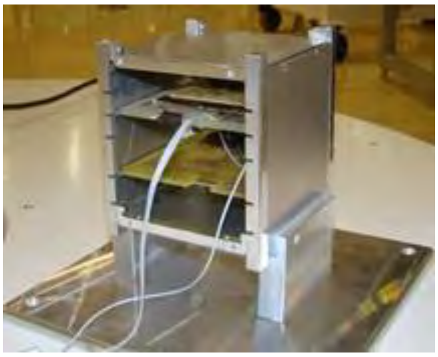

Figure 4. AESP-14 structure.

ISSN 2176-5480

5. STRUCTURAL ANALYSES

5.1 Printed Circuit Board Analysis

The PCBs attachment method used on AESP-14 raises some uncertainties related to the boards' structural integrity due to the small areas that support the board, and the high induced loads from launch vehicle. A static analysis was performed in the heaviest PCB in order to evaluate the boards' integrity during launch, with FEMAP with NX NASTRAN software.

The board is supported at the four corners, each one with about 22,5 [mm²]. Therefore the respective 42 corners' nodes are restricted at 6 degrees of freedom in X, Y and Z axes to translation and rotation.

Plate parabolic elements (CQUAD8) were used, Fig. 5. According to the FR10G4 material properties, the board has 28 [g]. Over this board a 200 [g] centered mass was added, through non-structural concept, in order to analyze a worst case of overweight.

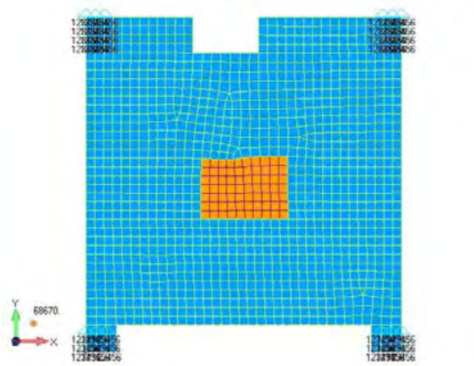

Figure 5. PCB board mesh, showing the supporting configuration and non-structural mass (orange).

The board characteristics, analysis input configurations and ultimate tensile strength allowable to the FR4G-10 material are shown in Tab. 1. As the transversal load is the most severe in all launches, a 7 [g] load (value usually applied to CubeSats analyses) in –Z axis was uniformly applied to the PCB.

Table 1. Analysis input configurations.

ITEM	VALUE
Board mass	28 [g]
Added mass (orange)	200 [g]
Element type	Plate parabolic CQUAD8
Applied load	7 [g] eixo -Z
Degrees of freedom restriction	42 restricted nodes – rotation and translation to X, Y and Z
PCB material	Glass fiber FR4 G-10
Density	2.3E-6 [Kg/mm³]
Tensile strength(σ)	205 [MPa]
Non-metal safety factor (FSNM)	2
Qualification factor (FSQ)	2
Ultimate tensile strength ($\sigma_{máx}$)	**51.25 [MPa]**

Analysis results show that the response generated by static load on the PCB reaches the maximum of 15.7 [MPa], Fig. 6, in the lower corners (in red), where there is stress concentration. To minimize such effect, the boards will be manufactured with the inside corners with roundings.

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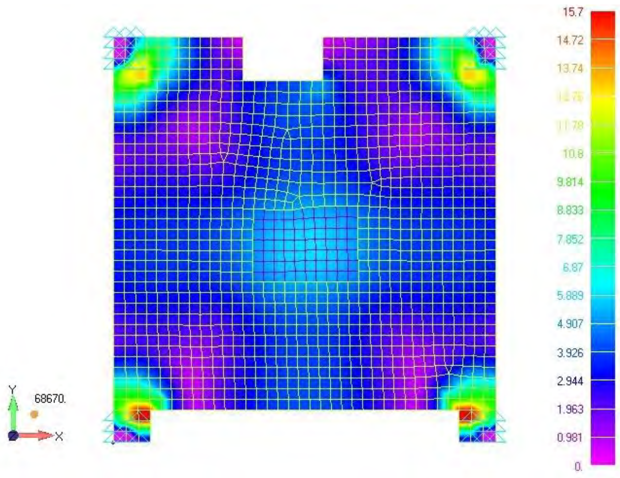

Figure 6. Von Misses stresses, values in [MPa].

Figure 7 right below shows the analysis resultant displacement, indicating the maximum of 0.264 [mm] at the center of the board due to the 200 [g] added on that spot.

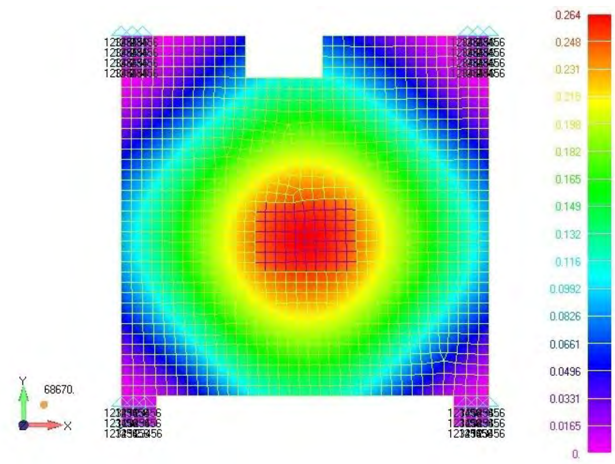

Figure 7. Analysis resultant displacement, values in [mm].

The results observation confirms that the board attachment method resists to predicted static loads because the obtained values are quite below PCB material limits. The calculation shows the margin of safety (MS) obtained, in other words, the number of times the Von Misses Stress found could still be applied until reaching the Ultimate Tensile Strength ($\sigma_{máx}$).

$$MS = (\sigma_{máx} / \sigma_{von\ Misses}) - 1 = (51.25/15.7) - 1 = 2.26 \quad (1)$$

5.2 Structure static load analysis

In order to evaluate the structural integrity of the whole AESP-14 structural subsystem (STR), a static analysis was conducted with FEMAP with NX NASTRAN software. Should be noted that this analysis is preliminary, as the final analysis shall be performed with the communication subsystem and antennas, which are under development. Figure 8 shows the mesh applied to the structure.

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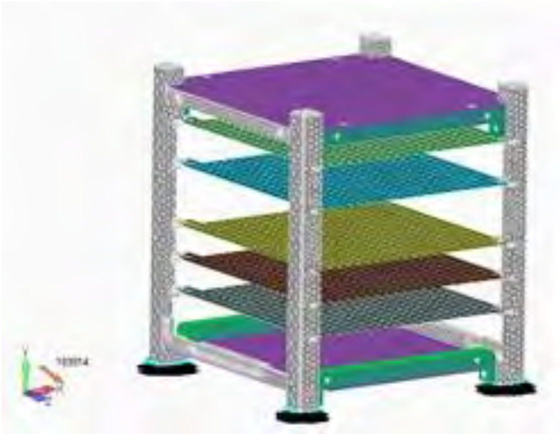

Figure 8. Mesh used in the analysis via FEMAP *with* NX NASTRAN.

The material properties, analysis input configuration and ultimate tensile strength (σmáx) are exposed in Tab. 2 below. Even though the majority of launch vehicles most dominant loads are 7[g] in vertical direction and 1.5 [g] in horizontal direction, the analysis was overloaded to give more confidence in the structural design and also to encompass more launch vehicles.

Table 2. Analysis input configuration.

ITEM	VALUE
Total mass	STR: 193.4[g] PCBs: 340 [g]
Element type	STR: solid parabolic (CTETRA) PCBs: CQUAD8 SCREWS: rigid (RBE2)
Applied loads	axis Y: 10 [g] and axis X and Z: 5[g]
Degrees of freedom restriction	4 feet restricted – rotation and translation to X Y and Z
Structure material	Al 6061-T6
Density	3.69E-06 [Kg/mm³]
Tensile Strength (σ)	282.7 [MPa]
Factor of safety (FS)	1.35
Qualification factor (FSQ)	2
Ultimate tensile Strenght ($\sigma_{máx}$)	**104.70 [MPa]**

Analysis results show that the response generated by static load on the structure reaches the maximum of 17.87[MPa], Fig. 9, at the heaviest PCB (228[g]) attachment area (red circle).

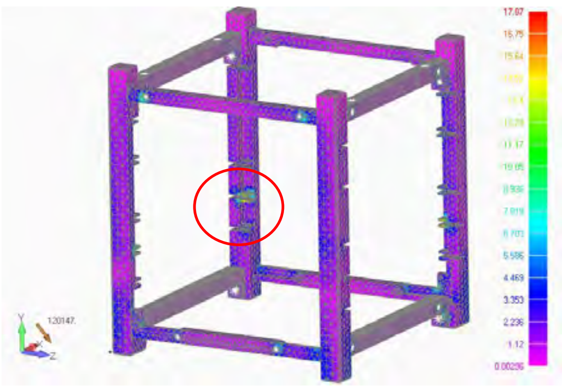

Figure 9. Von Misses stresses, values in [MPa].

Figure 10 below shows the displacement analysis, indicating the maximum of 0.196[mm] at the heaviest PCB. It is noted that the following figure has exaggerated deformations for observation purposes.

ISSN 2176-5480

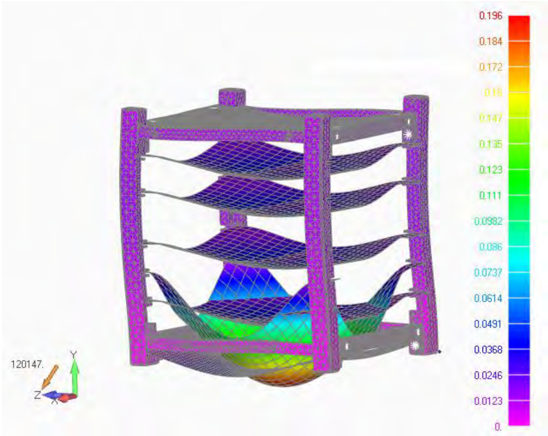

Figure 10. Displacement analysis, values in [mm].

The calculation below shows the analysis safety margin (MS).

$$MS = (\sigma_{máx}/\ \sigma_{von\ Misses})-1 = (104.7/17.86)\ -1 = 4.86 \qquad (2)$$

The structural static load analysis results showed that the AESP-14 design is feasible, and even with subsystem overweight the structure will resist launch loads of major launch vehicles with a high safety margin.

5.3 Modal analysis

The five first natural frequencies of the AESP-14 structure are found as a result of modal analysis with SolidWorks software, and are shown in Tab. 3, and the first mode of AESP-14 structure is shown in Fig. 11. It shall be noticed that in a modal analysis the displacement results do not have any true physical meaning, rather they are representative of the relative amplitudes of motion for each node on the structure.

Table 3. First natural frequencies of AESP-14 structure.

MODE	NATURAL FREQUENCY [Hz]
1	415.87
2	448.382
3	555.757
4	714.171
5	1579.86

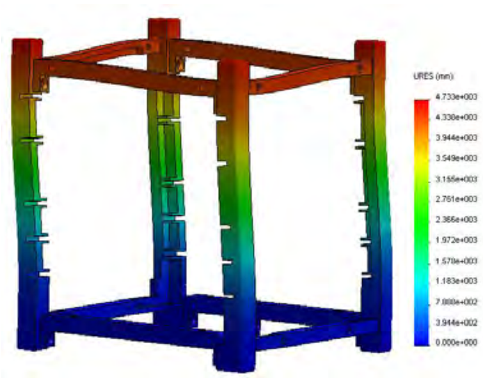

Figure 11. First mode of AESP-14 structure.

According to major launch vehicles (PSLV for example), secondary satellites shall be designed with a structural stiffness which guarantees that the fundamental frequencies are not less than 90 [Hz] in longitudinal axis and 45 [Hz] in lateral axis. In order to prevent resonance, the natural frequencies calculated by analysis must be above these values. The first natural frequency of AESP-14 structure is 415.87 [Hz], which is well beyond the minimum limits.

6. REVERSE ENGINEERING AND MANUFACTURING

In order to evaluate the local manufacturing capability, a reverse engineering at the NANOSATC-BR1 Brazilian CubeSat structure, which was purchased from ISIS company, showed that INPE facilities, staff and equipment are able to manufacture such a small and low tolerance range aluminum alloy CubeSat structure. Thus, the AESP-14 structure will be designed and manufactured in-house, being the first Brazilian CubeSat structure. The reverse engineering CubeSat is shown in Fig. 12.

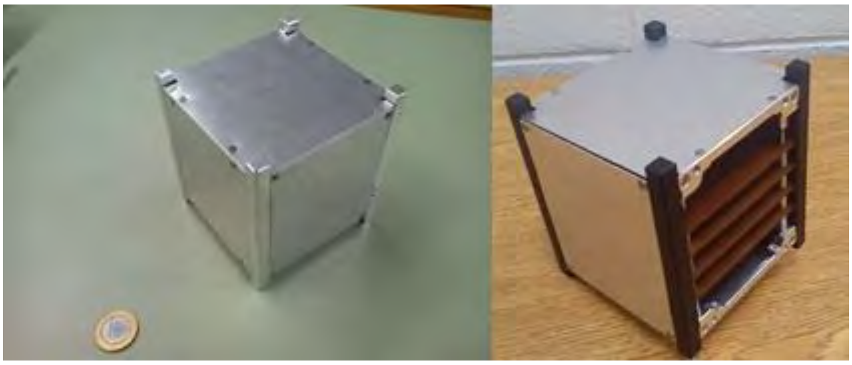

Figure 12. Reverse Engineering CubeSat.

7. RESULTS AND DISCUSSION

Preliminary results from finite element analyses showed that the AESP-14 CubeSat structure is able to resist the major launch vehicles loads. The PCB attachment method will not affect the boards' integrity, despite this some changes in the PCB shape will decrease the concentration stress points. The first natural frequency of AESP-14 structure is well beyond the lower limit, this will avoid resonance in most launch vehicles. Even though the launch vehicle of the AESP-14 CubeSat is not defined yet, these analyses prove that the CubeSat may be launched on a wide variety of launchers. The local manufacturing capability was evaluated, and conclusions are that AESP-14 structure will be designed and manufactured at INPE facilities.

8. ACKNOWLEDGEMENTS

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