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Design and Analysis of an Innovative Modular Cubesat Structure for ITU-pSAT II

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Abstract— **In this paper, we present the design and analysis of an innovative modular cubesat structure for ITU pSAT II mission. The design hinges on innovative modular structural columns which support rack-like operation for our ITU pSAT II nanosatellite. ITU pSAT II aims to demonstrate on-orbit a standardized bus architecture and an indigenous in-house developed ADCS. The envisioned structure provides the much needed flexibility to the satellite designers during the design, development and test cycle. Specifically, the structure allows the designers to change the location of subsytems or perform design modifications to the subystems without the need and the necessity to re-design the main structure. This new modular structure is also in accordance with standards that are determined by Cal Poly State University for the cubesats and thus carries one-to-one compatibility with launch pods. In this paper, we explain in detail the design and the analysis (FEM, quasi-static and modal) phase while step-by-step addressing deficiencies on the already developed and commercially available cubesat structures.**

Keywords- ***nano-satellite; cubesat; structure design; ITUpSAT-II.***

I. Introduction

Cubesats are nano and pico size satellites that are standardized in cubic sizes. The main goal of cubesats has been to make hard-earned space science and technology [1-5] readily accessible for students, engineers and even for some governments at a fraction of design/build/launch costs in comparison to standard satellite projects.

The most distinct properties of cubesats are weight and size. A standard cube shaped satellites must be less than 1 kg and its size must be approximately 10 cm per size that is called one unit -1U- cubesat. Correspondingly 2U cubesats have 20*10*10 cm size and 3U's have 30*10*10 cm size, and also their weights increase respectively. This standardization makes easy compatibility between developers. Towards this end, in this paper we present the design and analysis of a modular 3U structure that gives provides the much needed flexibility to the satellite designers during the system integration phase. This modular structure is first tailored towards ITU pSAT II nanosatellite. ITU-PSAT II is the second student satellite project of ITU Controls and Avionics Laboratory, and the project aims to demonstrate on-orbit an advanced ADCS for nano-satellites (1-10 kg) with high precision three axis control needs.

In Section II, we first review the ITU pSAT II project and the design drivers. In Section III, we present the design process (and requirements) for the structure delineating the need for such a modular approach. Section IV covers the modeling and the analysis of the modular cubesat structure.

II. ITU pSAT-II Project

ITU PSAT II is a nano satellite of 10x10x30 cm dimension in 3U form with a maximum of 4 kg weight. The satellite is designed to perform missions on a 640-840 km altitude sun synchronous orbit. The spacecraft carries three axis active attitude control. As the primary payload, the nanosatellite includes a camera in addition to experimental attitude determination and control hardware. The nanosatellite's main mission is to take high resolution images (100-200 meters per pixel in nano satellite standards) and transmit them to the ITU ground stations. In addition, ITU pSAT II carries a payload compartment which allows other universities or research institute's to carry experiments on board of the satellite

Weight and power budget of the prototype model (Figure 3) is presented in Table 1. The power budget represents the maximum value and the operational value is around 5 Watts and the major elements are duty-cycled during operations.

TABLE I. Weight-Power Budget

COMPONENETS	Weight (gr)	Power (mW)
Structure (incl. mechanisms)	560	0
Solar Panels	660	0
EPS	315	250
OBC	70	250
Communication	160	10000
ADCS	550	14000
Camera	400	600
Payload	1000	5000
	3715	30100

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The scope of our project can be summed in three headings. These are a) indigenous design and development of high performance nano satellite ADCS and b) indigenous design and development of innovative nanosatellite structures and mechanisms and c) design and development of a reliable nanosatellite bus that can be used of the shelf for future missions. Naturally, from the structures perspective, we aim for a structural shape that not only provides the lightest configuration that can withstand the loads, but also provide convenient reconfigurable structure for future missions. In the next section, we step-by-step characterize the design philosophy and the design requirements.

III. Design Philosophy and Requirements

The envisioned structure is needed to provide the flexibility to the satellite designers during the design, development and test cycle. Specifically, the structure should allow the designers to change the location of subsytems or perform design modifications to the subystems without the need and the necessity to re-design the main structure. This new modular structure should also be in accordance with standards that are determined by Cal Poly State University for the cubesats and thus carry one-to-one compatibility with launch pods. Under this process we first present the design process and then item-by-item review the requirements coming from a) the launch vehicle and deployment system and b) cubesat standardization and c) space/launch compatible material selection.

A. Design Process

Satellite structure has gone through several phases starting with concept design and reaching to the final model. After every phase, the requirements and the constraints are checked whether they are fulfilled or not. The design flowchart which shows all the phases is given in Figure1. For example, if the structural design cannot fulfill the launch requirements after Finite Element Analysis, we return back to design phase. While for some designs only modeling was sufficient, for some special designs prototyping were done to visual design concepts. In addition, computer programs were used to simulate space and launch environment [6-7].

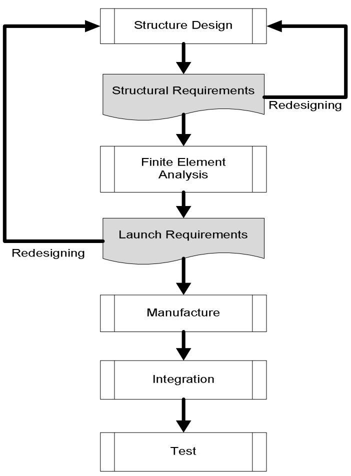

Figure 1. Design Flowchart

B. Launch Vehicle and Deployment System

The selection of launch vehicle is one of the important steps to determine the launch scenario. Quasi-static launch loads and natural frequencies of rocket will determine the cubesat launch requirements. In Figure 2 the launch scenario and launch loads are demonstrated from launch to orbit for Dnepr Rocket as an example [8]. ITU pSAT II is planned to be launched via the most readily available Polar Satellite Launch Vehicle (PSLV) from India [9].

Predicting of loads that comes from the launch vehicle is one of the hardest steps of designing a spacecraft. Because of the complexity and high variety of mission environments little inaccuracies in the finite element models are capable of causing large errors [10]. During its launch, a satellite is subject to various external loads resulting from steady-state booster acceleration, vibro-acoustic noise, air turbulence, gusts, propulsion system engine vibrations, booster ignition and burn-out, stage separations, vehicle maneuvers, propellant slosh, payload fairing separation and ejection. These sources' characteristic feature is being random and independent [11].

Every event generates structural loads in the life of a spacecraft from launch to put on orbit. Even though launch causes the highest value loads for most spacecraft structures; any other event can be critical and significant for some parts of the structure, such as manufacturing, ground handling- testing, pre-launch preparations, payload separation, on-orbit operations, landing [12].

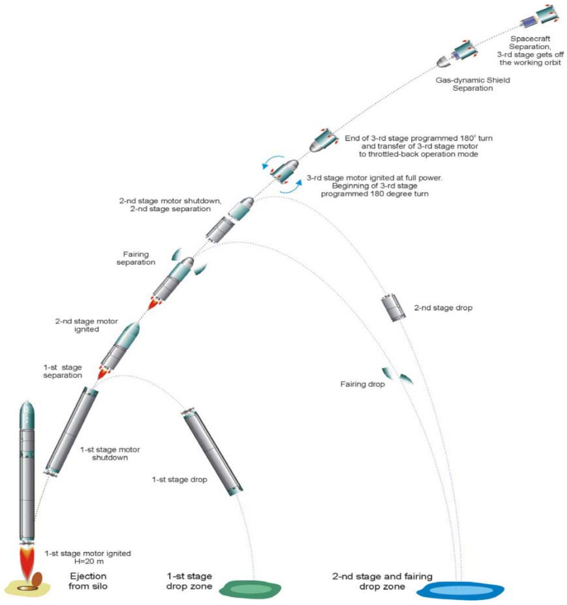

Figure 2. Dnepr Rocket Launch Loads

Deployment System is an important step to provide reliable and cost-effective launch. The adaptor is the interface structure between the satellite and launch vehicle. Cubesats should be well suited with the deployment mechanism to ensure safety and success of the mission. Generally, there are a rectangular aluminum box, a door and a spring mechanism inside the system. Furthermore, various adaptors that are single or multiple, are used to launch cubesats from launch vehicle to orbit. Poly-Picosatellite Orbital Deployer (PPOD) or Single Picosatellite Launcher (SPL) can be indicated as two of them [13-14].

One of the important notes is the orientation of the deployment system in the launch vehicle. Direction of deployment system is determined before launching and design of the cubesat should be complete according to this requirements. In the case of indefiniteness, modeling and analyzing should be performed by considering the worst case scenario. PPOD will be used for ITU pSAT II as a deployment system.

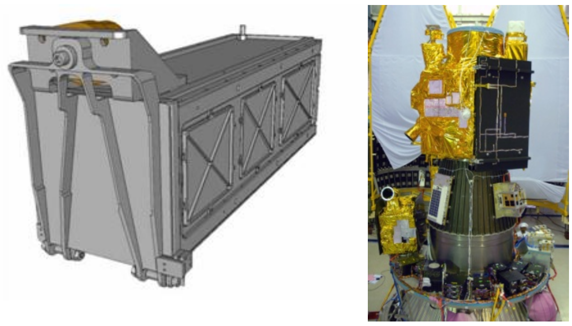

Figure 3. PPOD and Its Allocation in Launch Vehicle

C. Cubesat Standardization

Within the scope of the Cubesat Program, the Cal Poly is the driving institute at regulating (in reality harmonizing and bringing commonality) "Cubesat Design Specifications" (CDS). These specifications drive a significant number of constraints and requirements of the design [15]. Some rules about the structure design must be implemented to provide compatibility with interface adaptor. For example, all parts of satellite shall remain attached during launch, ejection, and operation. Risky materials shall not use on cubesat. Materials of cubesat must have low out-gassing property. Features and physical dimensions of design are shown in the Cubesat Specification Drawing in the Specification. Nevertheless, just mechanical requirements will be mentioned in this part:

- Each triple cubesat mass should be low in 4 kg.
- Center of gravity of the cubesat should be allocated wthin a sphere of 2 cm from its center of geometry.
- For cubesat main structure, AL 6061 or 7075 should be used. Since, the material of satellite should be similar properties with the material of adaptor.
- The cubesat's contact areas with the adaptor should be hard anodized.
- The coordinate system of the cubesat should be the same with the CDS Drawing for compatibility with the adaptor.
- The cubesat's wide should be 100+- 0.1 mm for X and Y directions. In addition, a triple cubesat's tall should be 340.5+-0.3 mm for Z direction.
- No components should exceed 6.5 mm normal to the surface of the 100 mm cube.
- Exterior surface of the cubesat should not contact with the interior surface of adaptor such as deployable panels and antennas.
- Rails should have a minimum width of 8.5 mm and at least %75 of rails should contact with the adaptor rails.

D. Material Selection

The selection of material is one of the significant steps on design of satellite structure. Since weightiness is an important factor for on-orbit object. Specially, for a 3U and 4 kg cubesat, small changes on the structure can result in valuable space for other subsystems and components. Not only weight factor, but also strength, stiffness, thermal conductivity, thermal expansion, manufacturability, and cost factor are considered during the satellite design [16]. Material requirements, in line with the space environment, are given below:

- All materials that will use in satellite should be selected from list that NASA determined.
- Thermal expansion coefficient of the selected material should be similar with the material of deployment mechanism.
- Yield strength of the selected material should be bigger than max Von Mises stress.
- The material should be easy manufacturability.
- To minimize the mass the material that has low density should be selected.
- The material that has low out-gassing property should be selected.

CDS provides AL 6061 and AL 7075 as the mainstream two alternatives for cubesat structure materials. By considering weight, strength, coefficient of thermal expansion, manufacturability, and the cost criteria, AL-7075 is selected for the material selection of the ITU pSAT II structure. Even though AL 6061 T6 is lighter than AL 7075, we selected AL 7075 because of the fact that it has easier manufacturability. This is in compliance since the major material of the launch PODs is usually AL-7073-T73.

IV. MODELLING AND ANALYSING

The aim of this work is to develop a highly modular 3U main structure for cubesat satellites. Towards this goal, we have designed an innovative modular cubesat structure around structural columns, which support rack-like operation for our ITU pSAT II nanosatellite. The envisioned structure provides the much-needed flexibility to the satellite designers during the design, development and test cycle. Specifically, the structure allows the designers to change the location of subsystems or perform design modifications to the subsystems without the need and the necessity to re-design the main structure. This new modular structure is also in accordance with standards that are determined by Cal Poly State University for the cubesats and thus carries one-to-one compatibility with launch pods.

The sizing of the satellite in the main three dimensions, the design of rails in corners and solar panels, and protrusions for the six sides of the satellite are decided according to the "Cubesat Design Specifications" constraints. Also, by considering material criteria, the material selection of AL-7075 is made for the structure of the cubesat. CATIA V5R18 is used for modeling of ITU pSAT II structure and components as a CAD programming.

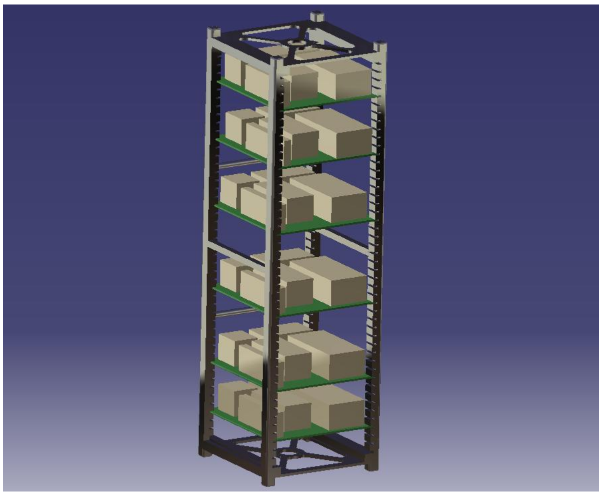

Figure 4. ITUSAT2 Main Structure Conceptual Design

In addition to structural requirements that are given in the "Cubesat Design Specifications", the following requirements are underlined for our design:

- The weight of satellite main structure (bearing frame) should be less than 450gr,
- The number of fasteners (such as screw, nut, spacers, and metal bar) that are used for connecting subsystems, solar panels and main structure should be minimized for operational ease,
- When the satellite change mission to mission, the cubesat structure should be fulfilled the new mission. A unique structure design should be respond for all payload changes,
- Internal volume of cubesat should be maximized, and external volume should be modular to add deployable solar panel when required. Besides ease of access to satellite internal volume should be provided during integration,
- Satellite main structure should be multi-functional. The structure should allow design modifications (such as subsystem size and position change) to be made without any changing the main structure of the satellite during the design, manufacture, and test,
- All carrier boards of satellite subsystems should be put into main structure as horizontally or vertically when it is required.

In light of the above requirements, the designed structure (which is merely 400 grams) is made up of a frame structure in which the columns in the corners are designed to carry main loads. The structural columns are planned as a rack system and subsystem boards are placed into the rack that is shown in Figure 4 (Dummy payloads are seen in the figure). In addition, the number of fasteners used in the design is almost %60 less in comparison to commercially available structures.

The rack system provides a very modular structure in the way that it allows flexible placement of the subsystems. For example, as seen in Figure 5, boards that cannot be fixed onto the satellite horizontally can be located vertically. For example, boards, which are off from standard PC-104 dimensions, can be easily located in the vertical plane. In such a case, 1U bus system can be put into upper side of the structure as a unit block, and the rest of the satellite can be used for bigger payloads such as camera, antenna deployable mechanism and magnetometer booms. Moreover, side panel solar panels are embedded into the main structure in order to make additional room for deployable solar panels in case of the need for extra energy.

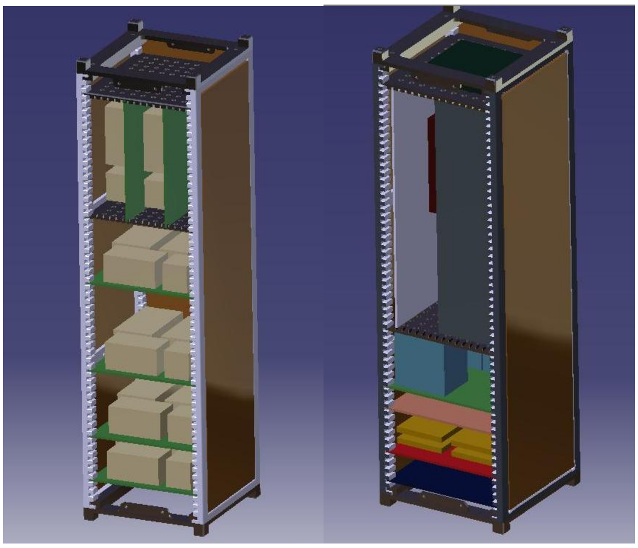

Figure 5. ITUSAT2 Main Structure Conceptual Design II and III

In order to analyze the strains on the main structure, various structural analyses of the satellite structure are performed. First, satellite main structure and representatives of the subsystems are built in 3D through the CAD program. Later static and modal analyses are completed using the loads that are projected to come from the launch vehicle. As it is scheduled, we are expecting that the satellite will be launched with Polar Satellite Launch Vehicle (PSLV) from India. By considering the worst-case scenario on PSLV (using static acceleration and vibration data from previous flights), static loads and natural frequencies and boundary conditions of the P-POD, total deformation across the structure and Von Mises stresses are evaluated [17-18]. ANSYS Workbench 11 is used for analyzing ITU pSAT II as a FEA programming.

Quasi-static launch loads are 11 g in the longitudinal direction and 6 g in the lateral direction for auxiliary satellites inside the PSLV rocket. Because the ultimate load factor is 1.25, the maximum quasi-static acceleration is 13.2 g. Therefore, we used 13.2 g for all three directions to apply worst case scenario [9].

Boundary conditions, which are basically feet support of the cubesat, are determined according to the allocation inside the P-POD.

V. Results

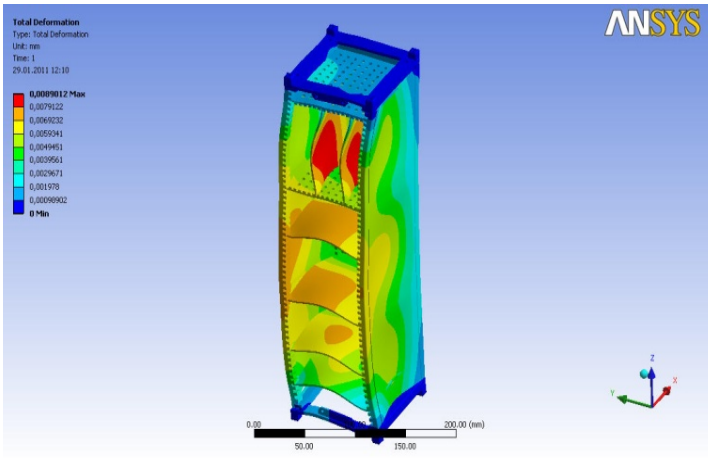

Figure 6. Total deformation of ITUSAT2 Structure

Figure 7.

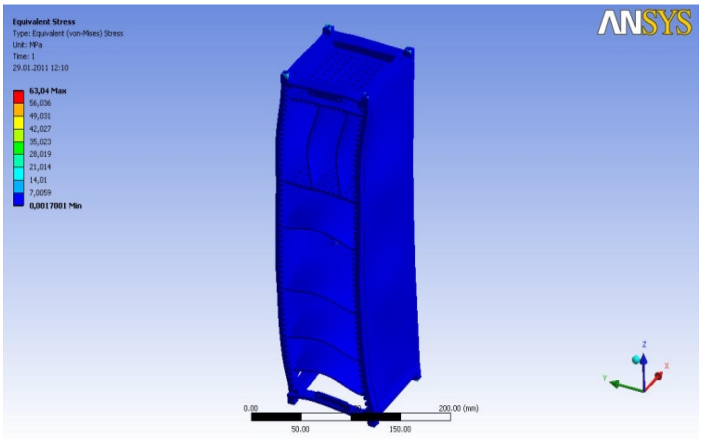

Figure 8. Von Mises Stress of ITUSAT2 Structure

Total deformation and the stresses on the satellite are shown in Figure 6 and 7, respectively. The analysis indicates that the total deformation is 0.009 mm and it is very small in comparison to the satellite dimensions. In addition, the analysis indicates that Von Mises stress is observed as 63 MPa, and this value is within the specifications since AL-7075 yield strength is 300 MPa.

Natural Frequencies of the cubesat structure in the range of 0 to 2000 Hz has analyzed in accordance with the user's guide of Polar Satellite Launch Vehicle. Under launch vehicle regulations, the payload of the launch vehicle has to be designed with a structural stiffness which guarantees that the values of fundamental frequencies of the satellite at the launch vehicle interface are not less than 35 Hz in the longitudinal axis and 20 Hz in the lateral axis. In order to prevent a resonance, the natural frequencies calculated by the analysis must be above these constraint values. The first mode of the structure is 216 Hz. All modes are shown in Table II.

TABLE II. NATURAL FREQUENCIES OF ITUPSAT-II

Modes	Natural Frequencies (Hz)	Modes	Natural Frequencies (Hz)
1	216,25	17	1317,7
2	730,57	18	1331,9
3	769,53	19	1338,1
4	775,01	20	1338,8
5	788,06	21	1359,1
6	802,12	22	1379,8
7	843,02	23	1386,9
8	1086,6	24	1439,4
9	1193,2	25	1538,9
10	1221	26	1596,3
11	1226,3	27	1610,7
12	1239,2	28	1630,7
13	1244,1	29	1807,9
14	1272,7	30	1820,6
15	1276	31	1917,6
16	1293,1		

VI. Conclusion

In this work, we presented the design philosophy and the design process of a modular 3U cubesat structure to be used in the ITU pSAT II mission. The standardized bus of the ITU pSAT II is envisioned to be used for future missions. Towards this end, the designed structure provides the much needed flexibility to support placements both on the vertical and the horizontal planes. In addition, the rack like structure allows the system engineers to experiment with the design during the prototyping phase.

Using FEM, quasi-static and modal analysis, the design is shown to be in compliance with the major launch loads and design requirements.

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