Development of an efficient Mono-frame CubeSat platform for fast and demanding missions

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CubeSats for advanced mass production missions are now possible. However, this requires high-throughput and fast delivery due to the imposed time and budget constraints. Therefore, it is crucial to evaluate the entire development cycle and streamline the process for enhancing efficiency.

The frequent assembly and disassembly of the satellite during the design and testing of the development have to be efficient hence it affects the overall productivity and prevents any delay in the delivery of the satellites. From an integration point of view, conventional CubeSat designs are prone to inefficiency as they utilize several structural parts and require longer assembly time. This is due to the inherent mechanical and electrical interface method used to mount the internal subsystems onto the main structural frame.

The envisioned structural design intends to reduce part count and complexity significantly using an additively manufactured mono-frame CubeSat made out of AlSi12. The new and previous designs were evaluated to assess their suitability for high-efficiency demanding mass-production applications. The initial phase of this research intends to investigate the feasibility AM method for the production of a slot-based structure.

Key Words: Mono-frame CubeSat Structure, Slot, Efficient, Mass production

1. Background

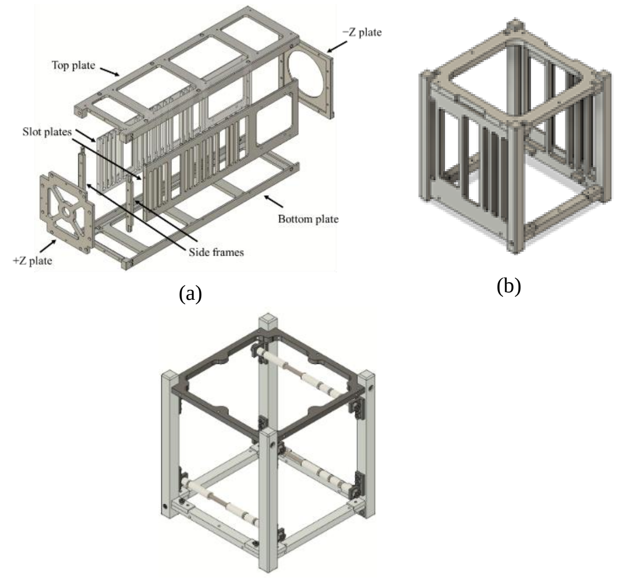
A CubeSat is a standardized satellite platform with a size of about a cubic decimeter. It has been widely used for technological demonstration missions mostly in an academic environment to teach students how to build a real satellite. In recent years CubeSat's mission capability has increased from these simple demonstrative missions to more complex and highly demanding applications. CubeSat mass production applications for constellation missions can be taken as a good example. Therefore, the design requirements to achieve a high level of mission capability have increased.

As the commercial viability of CubeSats grows, the need for the fast delivery of the satellite in time using the low-cost option becomes vital. Narrowing down to a satellite integration and assembly point of view, the critical factors that determine the efficiency of the development are the integration simplicity, length of assembly steps, and production cost. Therefore, considering these factors in the initial phase of the development will have an impact on the project.

1.1. Slot-based CubeSat structural platform

Prior to this research work, a similar study[1)] has been conducted at the Kyushu Institute of Technology (Kyutech) to investigate the issue associated with conventional type structural designs and develop a flexible 3U CubeSat structural concept named Flexible CubeSat platform (FCP) for highly demanding applications like mass production as shown in Fig. 1(a) and (b). Part count and integration simplicity evaluation have been conducted. The design concept of this flexible structure is based on a slot interface that is tested as an STM model. It is composed of only 8 structural parts. The scalability of the concept was also evaluated using a 1U size CubeSat. The evaluation was done by comparing this 1U FCP design with a conventional CubeSat structural design which utilizes several structural rails, rods, and frames to mount internal subsystem assembly in stacked form as shown in Fig. 1(c). The evaluation result shows significant improvement and its potential for the abovementioned demanding applications by reducing the structural part count and complexity [1)]. Currently, this 3U design model is at the stage of a flight model.

After this initial FCP version, different other versions have been developed based on the basic slot interface concept. For the 3U model, some improvements have been made to the EM and FM models by further lowering the structural count to 5. Similarly, for the 1U, after the production of the prototype using only five structural parts, different other options were explored to further reduce the part count down to a minimum by making use of design modifications and alternative manufacturing methods. This research seeks to explore the possibility of using an additive manufacturing method to produce an improved mono-frame structure called FMCF.



(a) (b)

(c)

Fig. 1. (a) 3U FCP model. (b) 1U FCP model. (c) 1U conventional type design

2.2. Additive manufacturing (3D Printing)

Additive manufacturing (AM), or 3D printing, is a process in which a structure is built layer by layer from a computer-aided design (CAD) model. This method of manufacturing is transforming the way of design and manufacturing by lowering the part count of assemblies, reducing production time and cost, as well as material waste. Complex parts that would be much more difficult and costly to develop with traditional machining processes can be constructed. These processes have the potential to fulfill demands for reducing the design-to-manufacture time by replacing a series of production processes with a single-step process 2). Besides the widely used resin material for 3D printing, recently metal 3D printing technologies are also growing. As research is progressing rapidly, promising results are opening up a range of possible applications across both scientific and industrial sectors 2).

AM printing technology has been introduced in the space industry for the manufacturing of satellite parts. A project called ReDSHIFT investigated the potential benefits of 3D printing to reduce space debris using an 8U CubeSat. A complete redesign is performed to the primary structure taking conventionally manufacture 8U CubeSat designed as a baseline to take full advantage of the benefits of AM 3). It was demonstrated that clear mass reductions and performance improvements were achieved, which highlights the future potential of this technology in the satellite design process and the space sector.

Another research work done at the University of Texas at El Paso (UTEP) aimed to maximize CubeSat volume by embedding electronic parts into the structure. To evaluate the feasibility, several 3D printing materials were assessed for their electrical properties, radiation shielding, thermal properties, and general structural performance in a printed mode 4).

Generally, metal AM systems can be classed as (a) powder bed fusion (PBD), (b) direct energy deposition (DED), and (c) droplet-on-demand systems. The most common PBD printing technique is selective laser melting (SLM) in which the powders are fully melted and fused after laser scanning 5, 8).

The proposed Mono-frame slot structural concept is produced using an SLM 3D printing technique to further reduce the structural part count to a unit or two. All internal slot design follows the previously developed standard platforms (FCP) which use a subtractive manufacturing method. In addition, the method of mounting the satellite subsystems into the slots using special spacers is also unchanged.

Special attention is required during the production phase to maintain the tolerance and accuracy of the slot rails as small misalignment could result in difficulty during the insertion of the internal subsystems. It is also important to achieve a good surface finish to the external rails to achieve the minimum requirement set by the CubeSat interface document from JAXA 6). Due to the sliding mechanism used to assemble the internal subsystems into the slots, close tolerance to the thickness of the spacers and the width of the slots is required. Though this parameter can be easily controlled in the traditional CNC milling method, for AM cases usually post-processing is required. The post-processing is however limited to the locations on the structure to where the machining tool can have access. Thus, this should be taken into account during the design and production phases.

In this initial phase of the research, the possibility of producing a Mono-frame structure using the PBD method is assessed to understand the potential advantage and challenges.

This research paper is organized into five sections. The introduction section provides a brief background about CubeSat mass production and the concept of a slot-based flexible CubeSat platform using subtractive manufacturing. Furthermore, the current Mono-frame CubeSat platform is also introduced. Section two describes the design and manufacturing of the proposed design concept. The next section evaluates the design and manufactured frame. The result and discussion are described in section four. The last section provides a conclusion and future work.

2. Design and Manufacturing

As discussed in the previous section, the structural design of the FMCP follows the previous Slot-based FCP design concept. The design is done according to the interface control document from JAXA, JEM payload accommodation handbook, which is used as a design reference for dimensional, strength, and material requirements 6).

The internal width of slots is defined according to the FCP model. The slot width is standardized to 6 mm. Some slots can be adaptable to mount oversize components like the Battery and communication board. The special type of spacers is designed to be attached to each subsystem as shown in Fig. 2. They are similar to the spacers used for the FCP model. They are used as an interface between the structure's slots and the subsystems to protect the PCBs from wearing during the sliding action.

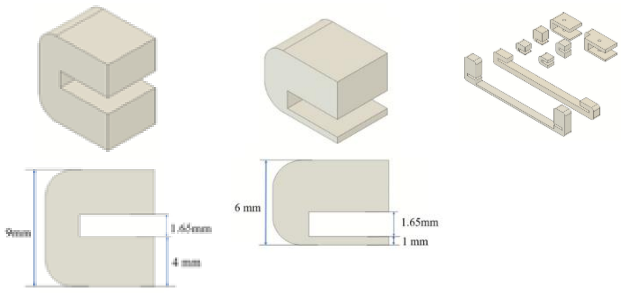


Fig. 2. Unique type of spacer design.

A resin material like PEEK is used for the spacers that can even be manufactured easily using a 3D printer with a close tolerance with that of the corresponding width of the slot. They are assembled easily at the four corners of the PCBs with press-fit as shown in Fig. 3. Subsystems are then inserted into the standardized slots.

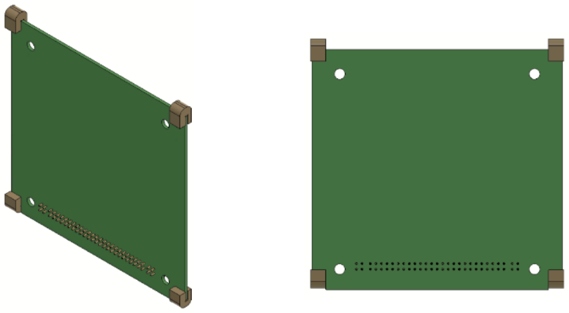
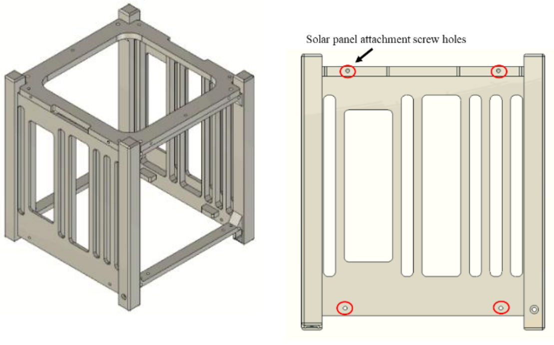


Fig. 3. Spacer attachment to the internal PCBs.

2.1. Design of Mono-Cubic frame

The structure is modeled using Fusion 360 CAD software taking into account the Design for Additive Manufacturing (DfMP) approach. The Mono-frame has two internal mirrored faces where the slot rails are positioned as shown in Fig. 4 (a). An additional structural plate is used to enclose the entire internal subsystems within the CubeSat frame and fully constrain any movement. All the screw holes which are necessary to mount the solar panels, the spring plunger and the backplane board are already integrated into the structure as unthreaded holes. The threads are then made later during the postprocessing phase as shown in Fig 4 (b). In addition, some recessed features are integrated into the main structural rails to mount the deployment switches.



(a) (b)

Fig. 4. (a) 3D model of the Mono-Slot frame structure. (b) Side view of the model with four holes for the solar panel mount.

2.2. *3D printing of FMCP prototype*

After the completion of the design and modeling, an external 3D printing manufacturing company was selected based on printing technique, material type, and printing cost. During the manufacturing phase, some changes were suggested for modification. The sharp 90-degree edges on the structure were changed to help the 3D printing process. Those edges are replaced with triangular wedges to increase the strength of the support material during printing as shown in Fig. 5.

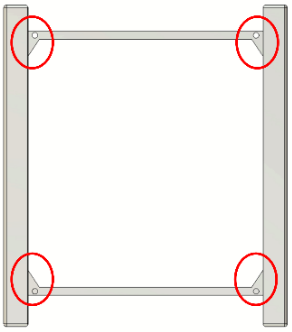


Fig. 5. Modified edges of the frame

The printing was done using the SLM or direct metal printing (DMP) technique which is based on PBD. A Prox300 3D printing machine is used to manufacture the structure. The quality, surface finish, and strength of the final print depend on the printing parameters such as print layer thickness, and heat treatment. During the manufacturing process of this Mono-frame, special attention was given to parameters such as the precision of the main rail, and alignment of the slots. After blasting, about Ra10~12 roughness level can be achieved with ProX300. In addition, a layer resolution of about 40~50 microns can be attained. The lower the printing layer thickness, the better surface of the finishing and the longer the time it takes to finish the printing.

There are obvious limitations in the selection of 3D printing material for CubeSats. Materials that meet basic requirements such as strength, weight, stress corrosion and quality of surface finish are limited in number. Besides, metal 3D print-based materials are not often included in the list of approved materials for space use. For instance, for CubeSats launched via JEM Small Satellite Orbital Deployer (J-SSOD), the acceptable list of satellite materials is specified considering their out-gassing property 6). Utilization of materials different from this list requires lengthy negotiation with JAXA.

Several alloy materials were available in powder form. Aluminum alloys such as AlSi12 and AlSi10Mg are mostly used as structural metal 3D printing materials. AlSi12 has been chosen for printing due to its higher yield strength and lightweight. Heat treatment was not possible, because it reduces the hardness of the printed structure. As a result, the stress could not be relieved. The build direction was along the Z axis to minimize the support material as much as possible as shown in Fig. 6. The build orientation determines the surface finish. This may affect factors, such as the production time, the support structure requirements, residual stresses, surface roughness, microstructure, and the effects of build anisotropy 2).

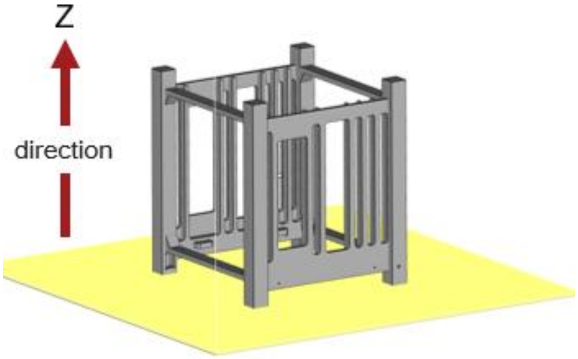


Fig. 6. Build direction during printing.

After the completion of the print, post-processing has been done for the surface of the external rails to meet the minimum surface finish and GD&T requirements. The final printed 1U Mono-frame platform is shown in Fig. 7.

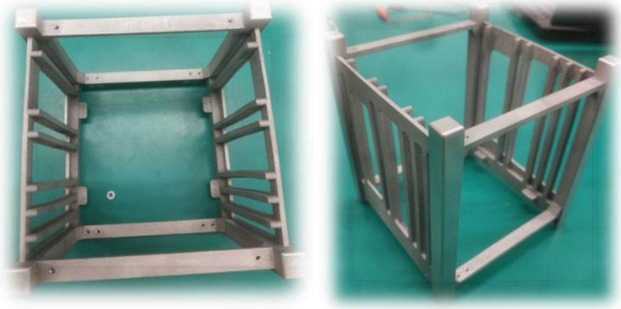
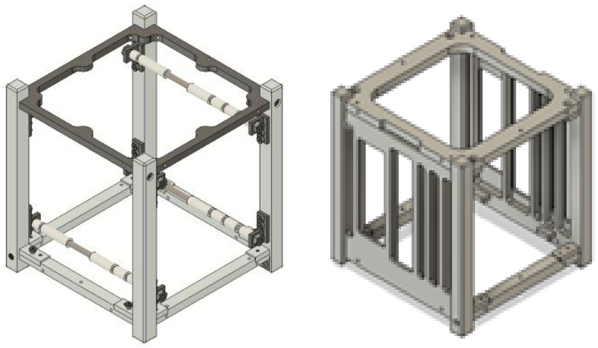


Fig. 7. 3D Printed Mono-frame structural platform

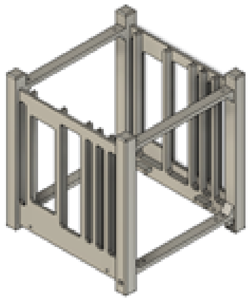
3. Evaluation of Design Concepts

3.1. Part Count and complexity evaluation

Part count analysis is done as it is an important parameter that affects the time required to finish assembly and integration. The assembly step is also a function of structural parts count. As the part count increase, the cost of production also increases. The evaluation is made by comparing the proposed Mono-frame structure with the conventional CubeSat design and slot-based FCP as shown in Fig. 8.



(a) (b)



(c)

Fig. 8. (a) Conventional-based BIRDS-3 1U structural frame. (b) Slot-based FCP frame. (c) Mono-CubeSat frame.

BIRDS-3 structural frame is used as a conventional design method where long rods are used to mount the internal Bus and payload stackings and main structural frames which support the entire satellite assembly. Table 1 shows the count of main structural frames and screws separately to provide an overview of the improvement between the design concepts.

Table 1. Form of the paper.

Structure Type	No. of structural parts without Spacers	No. of Structural screws	Structural assembly steps
Conventional: BIRDS-3	27	26	16
Slot-based FCP	5	8	5
Slot-based FMCP	2	4	2

A similar complexity evaluation metric is used as the FCP model to calculate the difficulty of the design concept during the assembly and integration phases. The result of the analysis is shown in Fig. 9. To evaluate the total complexity of the three structures' design concepts, different complexity parameters were computed [1,7]. For details information about the method used to compute the complexity, a reader may refer to the following research papers [1,9].

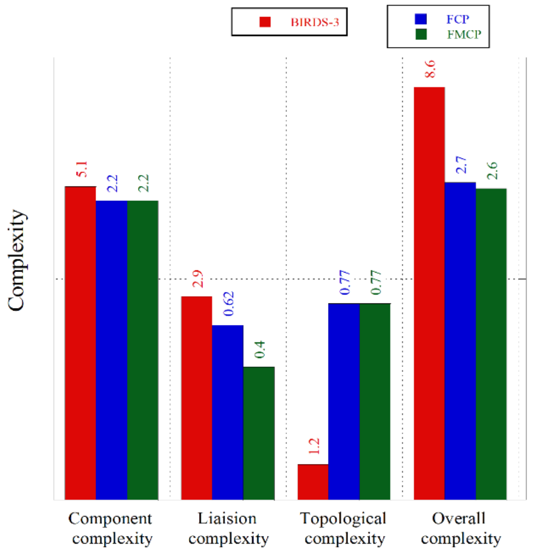


Fig. 9. Complexity value of the three structural design concepts.

4. Result and Discussion

The part count evaluation shows significant improvement in the number of structural parts and screws compare to both conventional type and slot-based FCP structures. Compared to a total of five structural parts for FCP, only two structural parts are used for the Mono-frame structure having a similar interface design. This is attributed to AM method used. A similar reduction of about 50% is achieved for the screw count.

As shown in Fig. 9 the complexity of the FMCP design is slightly improved from 2.7 to 2.6. This shows a small improvement in simplification during the integration and assembly phase.

To Feasibility of 3D printed structure

Visual inspection of the printed structure shows that the internal slot rails were slightly deformed as shown in Fig. 10. Thus, the rails are not parallel. The deformation is caused by the accumulated stress which was not removed using heat treatment. Therefore, a correction was needed to correct the alignment and surface finish issues. However, post-processing is not possible to do due to the inaccessibility of those features for machining tools. This is, however, very important for the assembly of the internal subsystems as a sliding mechanism is used for insertion with low friction between the mating parts.

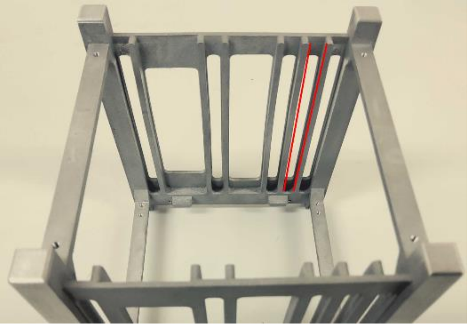


Fig. 10. Slight deformation of the FMCP rails.

5. Conclusion and Future Work

In general, it can be concluded that the phase-I of additively manufactured Mono-frame CubeSat structure has future potential for improvement as the technology is growing fast. The evaluation shows this FMCP design enhanced the efficiency of the CubeSat development from that of a similar design using the subtractive manufacturing method. This has special importance for demanding applications like CubeSat mass production where easy and flexible CubeSat integration with minimal assembly steps is required. However, the limitation in the quality of the print requires further extensive experiments on the right printing technique, material type, and printing parameters to obtain the desired quality.

Design improvement to reduce the total weight of the structure is also part of future work. This issue is common for both FCP and FMCP designs as the slot rails cause extra weight to the total structure assembly. This issue can be addressed by shortening the rail only to the top and bottom parts of the frame which will be incorporated in the next phase of this project.

Acknowledgments

The authors would like to acknowledge the support of the Japanese Ministry of Economy, Trade, and Industry (METI) through the Promotion of Energy Saving and Related International Standards.

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