Solid Freeform Fabrication 2024: Proceedings of the 35th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference

Application of Solid Freeform Fabrication for Manufacturing and Prototyping of a Reconfigurable CubeSat for Ease of Assembly, Testing and Experimentation

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Abstract

Within the educational community, CubeSats have democratized access to space by providing a cost-effective platform to conduct space based missions and experiments. Hands-on activities help students contextualize classroom learning with an actual physical system. We are using a reconfigurable architecture of 1U (100mm X 100mmX100mm) CubeSats to perform multiple experiments in satellite technology. Our experiments range from vision, communication, IMU, solar power storage and distribution, and dynamic loads. We are using Solid Freeform Fabrication to manufacture structural elements that allow for (1) ease of assembly and disassembly (2) ease of debugging and (3) mounting various modules for experiments. Structural elements allow the student to reduce total assembly time, reconfigure the satellite, attach different modules, route connecting cables, and access the internal volume for debugging and maintenance.

1. Introduction

CubeSats are standardized small form factor satellites. They are widely used for scientific research missions, research and technology demonstration, commercial and government applications where a cost-effective rapid deployment is needed. Cubesats have recently become popular in education and DIY communities as a hands-on learning tool. Students are using them to experiment and get practical experience in design, testing and operating satellite systems.

The form factor of a CubeSat is standardized and expressed in CubeSat Design Specification (CDS). The basic unit of a CubeSat is a 10 cm cubic unit, referred to as 1U. Multiple 1U cubesats can be combined to create larger Cubesat configurations. For example, a 2U CubeSat would be 10 cm × 10 cm × 20 cm, and a 3U CubeSat would be 10 cm × 10 cm × 30 cm, and so on. The standardized mass for each 1U unit is approximately 1.33kg; however, the actual mass may vary on the application, components and specific design.

In 1999, Jordi Puig-Suari of California Polytechnic State University and Professor Bob Twiggs of Stanford University Cal Poly students introduced CubeSats (as picosatellite), space development projects for educational institutions[1,2]. CubeSat Design Specification (CDS), defining dimensions and mass limits was formalized in 2003 [3].

MIT's Beaver Works Summer Institute offers the Build a CubeSat Challenge for high school students. The challenge focuses on school teams to work together and develop a satellite subsystem that can power and support a vision-based payload and analyze data and wireless transmitting to a ground station [4]. Students are given an opportunity to learn the fundamentals of satellite systems. Then they develop a new CubeSat design, prototype it and perform a mock mission. The authors participated in the year 2024 challenge and created a satellite for natural disaster monitoring and resource planning. Motivated by the learning opportunities, we designed and developed a set of modules that can be reconfigured and re-assembled to develop a range of 1U cubesat and experiments can be performed. 3D printing was applied in a novel way to fabricate a range of parts. The parts were used for the installation of solar panels, power storage, IMU unit, sensors, vision system, microcontrollers and microcomputers. 3D printed parts were designed to enable ease of reconfiguration as well as withstand static and dynamic loads.

Designs, considerations for 3D printing, reduction in geometrical errors, 3D printing based support feature manufacturing, simulation of static and dynamic loads and measurements are reported in the following sections. Inherent to the design are features that will enable efficient space utilization. The designs are available on an open source site [6] for anyone to download, manufacture and experiment with their own satellites. Lessons learnt during the 3D printing of the parts are shared.

2. General architecture of CubeSat and learning opportunities

The subsystems of a CubeSat include Structure, Power System, Communication System, Onboard Computer, Payload, Thermal Control System, Data Handling and Storage and Deployment Mechanisms.

The structure is a standardized cubic structure, usually in sizes known as 1U, 2U, 3U and must be sturdy enough to withstand launch forces and the space environment. Similarly, the Power System uses solar panels to harness electricity from the sun. Power storage unit is required to store the power, a power distribution circuitry is required to distribute power to different subsystems. The solar panel may be connected to a solar power management module.

The CubeSat also has a communication system to transmit data back to Earth and receive commands from ground stations. The Onboard Computer controls the satellite operations and manages data processing. The Attitude Determination and Control System is used for orienting the CubeSat in space. It includes sensors such as gyroscopes, magnetometers, and sun sensors to determine orientation (attitude). Actuators such as reaction wheels, magnetic torquers, or thrusters are used to adjust or maintain the CubeSat's orientation.

The onboard payload on the satellite is driven by the primary purpose of the CubeSat mission. Other accessories on the CubeSat include a data handling and onboard data storage unit. One of the critical systems is the deployment mechanism for CubeSats. The deployment mechanisms ensure that CubeSats are safely released into their intended orbit. As an additional opportunity to learn and explore, authors created additional modules for experimentation and additional applications.

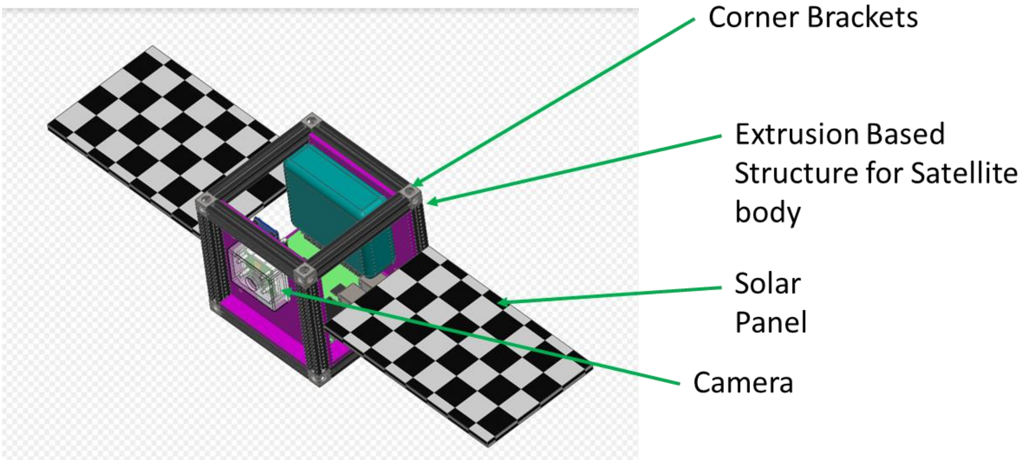


Figure 1: Schematics for a basic Cubesat

1. Modules to reconfigure and expand total solar power collection
2. Modules for creating mounting arrangements for power supply, IMU, vision system, power storage computer.
3. Camera installations for different Field of View and Optics

3. Developing a reconfigurable platform and using 3D printing to customize cubesats

3.1 Solar panel design configuration and testing

Solar panels are used for converting the solar energy into electrical energy. By increasing the total area exposed to sun rays and orienting the solar panel we can maximize the total electrical energy. A payload such as a camera may require access to the external surface of the satellite and therefore limit the mounting positions for the solar panel structure. We therefore designed and tested a set of brackets for combining, mounting and orienting the solar panels. The brackets allow a user to configure a solar panel in a number of ways. As a cost effective alternative, we designed these parts to be reusable so that one part allows you to connect a solar panel in multiple different orientations. For example, one part allows for the solar panel to connect to other solar panels, and creates an interface where other smaller parts can connect the frame of the cubesat to the solar panel. The system is designed to use small footprint m3 screws. Using this system, a user can connect multiple panels to the satellite. Additionally, the panels can be arranged in different configurations. Different configurations are more amenable to varied applications and dependencies such as - the payload distribution, sensor placement, camera placement, dynamic loads etc. (orthogonal or 45 degree orientation). During the prototyping phase we manufactured parts using a 3D printer. The features account for minimum material dispense resolutions and the layer thickness for functionality as well as interchangeability. Figure 2 describes different configurations for the solar panel.

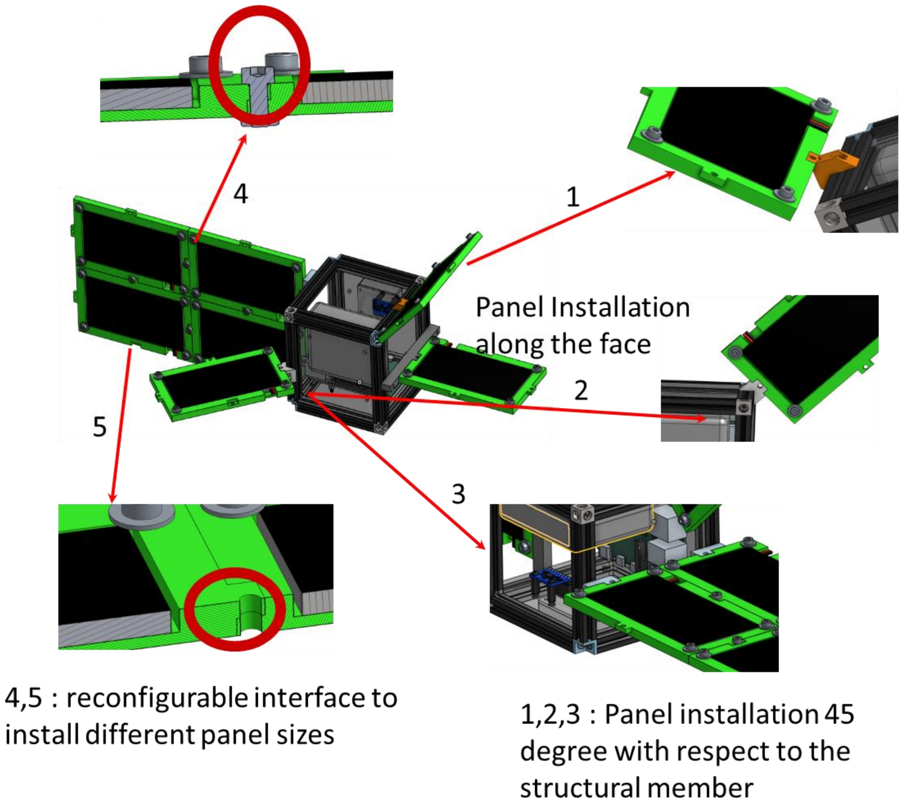
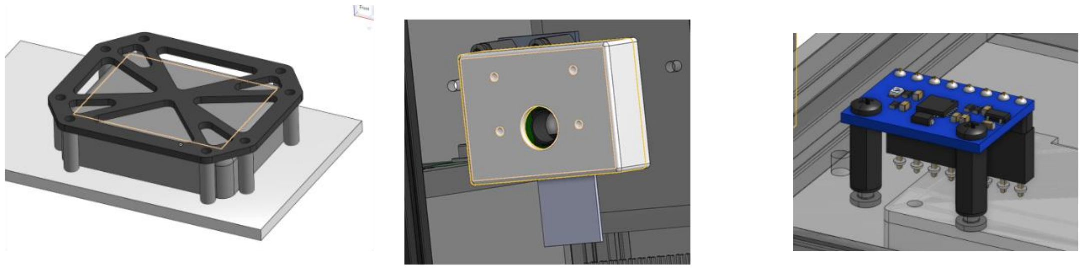


Figure 2: Design features to enable different configuration for solar panel installation

3.2 Brackets for mounting modules inside the satellite

Sensors, microcomputers and sensors are mounted using standard M3 standoffs. Overall weight of the PCBs ranges from 23g to 42g. The PCBs have mounting holes to attach standoffs. The PCBs are flat with maximum width, including the components, not exceeding 7mm. However, other modules such as the power storage battery weigh almost 250g with a width of 20mm. The off-the-shelf power supply modules do not have mounting holes. The power supply is stored in a special enclosure that maintains a positive load on the storage unit. The inner walls of the enclosure are manufactured to be convex and maintain a positive stress on the package. The enclosure has mounting features that allow power supply to be assembled along different orientations.



a. Power storage unit mount

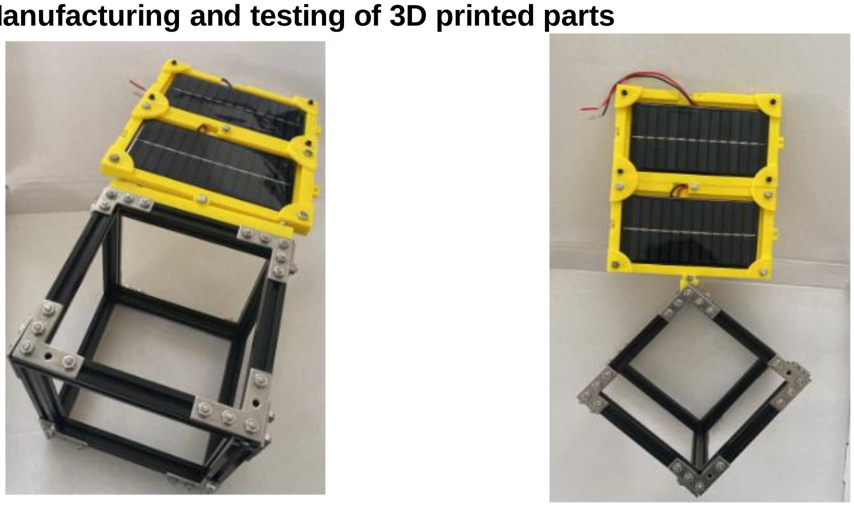
b. Camera enclosure mount

c. Other PCB mounts

Figure 3: Mount for different payload modules

In order to mount the camera, we designed a mount that splits into two parts for printing. One part connects the camera to the main body of the frame, while another part fully encloses the camera, which protects it from hitting other components of the satellite or the body of the rocket, which could potentially damage it. Fixture for the camera mount is designed to ensure that the camera along with its optical unit reside inside the satellite volume. The lens used for the camera may have different lengths to accommodate field of view. The height of the camera is adjusted such that the camera resides inside the volume.

4. Manufacturing and testing of 3D printed parts



a. Solar Panels mounted in-line

b. Solar Panels mounted 45 degree with respect to the member

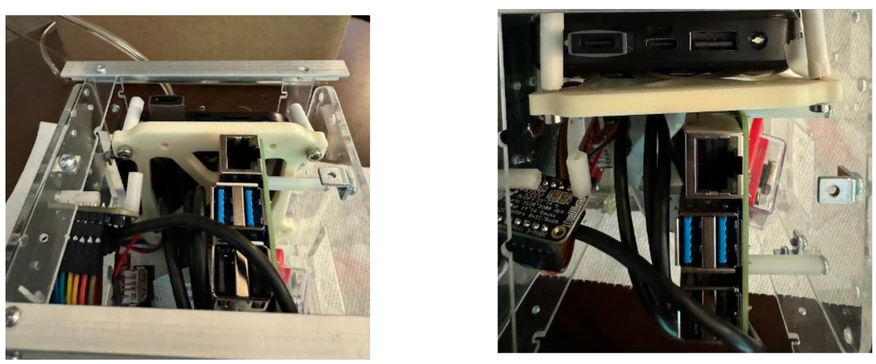
Figure 4: 3D printed attachment for the solar panels

We used two different printers to manufacture and test the parts. We used a Bambu Lab X1 Carbon to 3D print the brackets and mounting modules for the solar panels and the corner brackets. The parts were printed with a 0.4mm nozzle, 15% infill, and 2 wall loops. The attachment for the power supply and camera were manufactured using Stratasys Fortus 450mc and the material used for printing is ASA with tip thickness ofT40=thick tip and T16.

a. Camera Mounted Flush

b. Camera is recessed inside the body to adjust for optics and protection

Figure 5: 3D printed attachments for the camera



a. Isometric - view

b. Top - view

Figure 6 : Attachment for the power storage unit

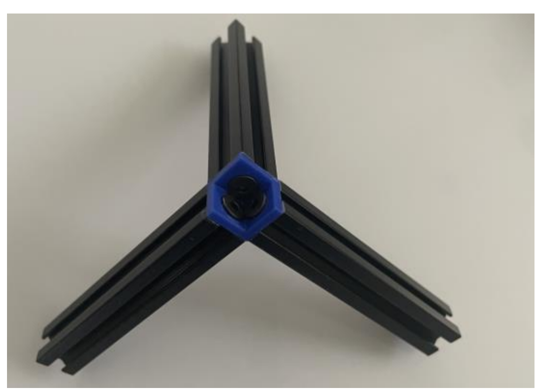


Figure 7 : Corner bracket for the structural members

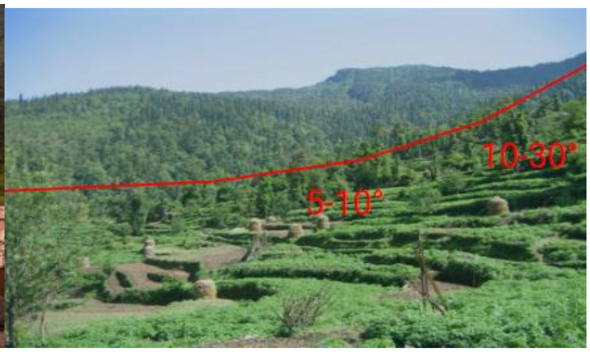
As a basic test for reconfiguration, we assembled and disassembled the parts 15 times. The parts sustain the structural integrity. As described in the previous section, the attachment for the power supply is convex and applies a positive load. The holes are adjusted to accommodate the minor deformation. The structure maintains positive load after the 15 cycles of assembly and disassembly.

5. CubeSat based projects and experiments

The MIT-based CubeSat challenge for 2024 was themed around natural disasters. The team used CubeSat for a project, finding ways to both identify and propose solutions for large scale issues arising from flooding. We used the cubesat to estimate the loss of arable top-soil and impact on losses to the crop as well as the impact on jobs. An estimate of the total impacted area will help pertinent authorities to prepare for short term and long term support to local communities.

Our first step to simulate flooding was to determine a well-suited area. We looked into common agriculture practices, and found a ratio of ground angles typically found in hills and mountains surrounding farmlands (10-30°, 5-10°, 0-5°) [5]. We prepared our experiment ground to mimic the general slope.

Sacred Valley (Peru)



Himalayan Foothills (Nepal)

Ground prepared for the required slope

Figure 8: Preparing the ground for required slope

To represent farmland, different materials are placed in layers to represent [6] bedrock, subsoil, surface soil and vegetation. To simulate we placed a tarp over the ground to isolate the experimental layers from the existing soil. For bedrock we used gravel, for subsoil we used sand, for surface soil we used traditional topsoil, and we used local vegetation to cover our model, representing crops.

Figure 9: Layers for simulating typical soil horizons

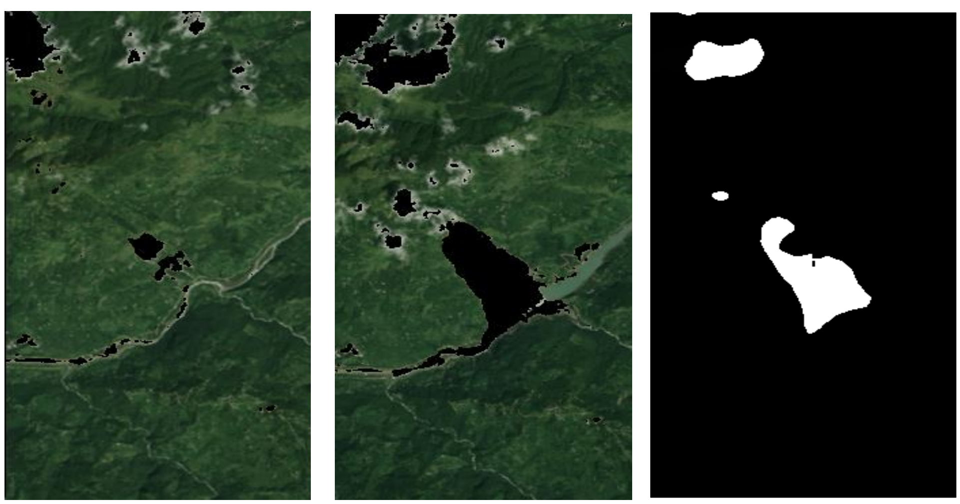
Our CubeSat mounted on a tripod *CubeSat from an upward-facing angle*

Figure 10 : Cubesat suspended from a tripod monitors the terrain

The CubeSat is suspended from a tripod. A down looking camera captures the picture. We used a hose to spray from uphill, representing rain and flooding. This caused a downward stream, or ‘flood,’ to wash away a lot of soil and vegetation. The camera is connected to Raspberry Pi . We use a laptop as the base station. PuTTY (a terminal emulator) is used to establish SSH (Secure Shell) serial communications with a Raspberry Pi. Through SSH, PuTTY allows remote access to the Raspberry Pi's command line interface over a network. Images are captured at 3 second intervals. We used image processing modules implemented in Python to identify the impacted land area. We employed color thresholding techniques to identify potential landslides in satellite imagery. Initially, during the first satellite pass, all green regions are delineated. In subsequent passes, if the color in these regions changes, it indicates a probable landslide occurrence. Given that our primary focus is on farmland where green is the predominant color, we set the thresholds to HSV(40, 20, 20) for the lower bound and HSV(80, 255, 255) for the upper bound to capture the green hues.

The process starts by loading and converting images to the HSV color space. Color thresholding is then applied to segment green pixels, creating bitmasks for each image. By subtracting the bitmask of the initial image from that of subsequent images, we generate a difference matrix. This matrix is then subjected to median filtering to mitigate noise. Contour detection is used to highlight significant changes in the image regions. If these changes meet a predefined threshold, the area is identified as a potential landslide.

During testing, the CubeSat captured images of the vegetation below. We encountered challenges with not having immediate access to the images, which led to issues such as capturing vegetation outside the model boundaries. These extraneous elements required cropping during post-processing to focus on relevant data.



Original *After flooding* *Vegetation loss*

Figure 11: Captured images and processing to estimate the loss to top soil

Conclusion

A reconfigurable CubeSat was built using extrusions and 3D printed parts. The CubeSat payload included solar panels, camera, microcomputer, power supply and an IMU. A basic experiment was performed to estimate loss to agricultural land. The CubeSat model is reconfigurable to enable a wide range of experiments. The models are provided for learners and educators to build a CubeSat and perform a range of experiments.

References

1. J. Puig-Suari, C. Turner and W. Ahlgren, "Development of the standard CubeSat deployer and a CubeSat class PicoSatellite," *2001 IEEE Aerospace Conference Proceedings (Cat. No.01TH8542)*, Big Sky, MT, USA, 2001, pp. 1/347-1/353 vol.1, doi: 10.1109/AERO.2001.931726.

2. Heidt, Hank, Jordi Puig-Suari, Augustus Moore, Shinichi Nakasuka, and Robert Twiggs. "CubeSat: A new generation of picosatellite for education and industry low-cost space experimentation." Proceedings of the 14th Annual AIAA/USU Conference on Small Satellites, 1999.

3. CubeSat. "www.cubesat.org".

4. "Research and Innovation through Project-Based Learning | Beaver Works." *Beaverworks.ll.mit.edu*, beaverworks.ll.mit.edu. Accessed 5 July 2024.

5. "Why Is Topography Important in Agriculture?." *GeoPard Agriculture*, 10 June 2022, geopard.tech/blog/topography-and-nutrition-content-in-soil-and-yield/.

6. "A Soil Profile | Natural Resources Conservation Service." *Www.nrcs.usda.gov*, www.nrcs.usda.gov/resources/education-and-teaching-materials/a-soil-profile.