Structural Design, Analysis, and Test of the Prox-1 Spacecraft

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The Prox-1 Structure was created to contain and secure all subsystem components of the Prox-1 satellite, the Georgia Institute of Technology's entry in the 7th University Nanosatellite Program (UNP) Competition. In order to meet system requirements as well as those requirements set forth by the UNP the Prox-1 Structure underwent a two year design, analysis, and test procedure. The structural design was created with modularity and simplicity in mind, which was of great advantage in later stages of the design cycle. Analysis and testing verified that the structure met all of the requirements set forth by the Prox-1 team and the UNP.

Nomenclature

AFRL	=	Air Force Research Lab
CubeSat	=	A 10X10X30 cm standardized satellite bus
FDR	=	final design review
PDR	=	preliminary design review
Ppod	=	the deployment box from which the CubeSat is launched
Lightband	=	Interface ring between the satellite and a cylindrical mount within the rocket
Lightsail	=	Planetary Society CubeSat mission, housed within the Prox-1 satellite
LVI	=	Launch Vehicle Interface, where the Lightband is attached to the satellite structure
UNP-7	=	University Nanosatellite Program, 7th competition cycle

I.   Introduction

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HE Prox-1 spacecraft is Georgia Institute of Technology's entry into the 7th University Nanosatellite Program Competition, a two year cycle competition for the AFRL where university teams consisting of both graduate and undergraduate students design, build, and test a 50 kg nanosatellite for a team-specified mission. Judging is based on various presentations to the AFRL review teams, importance of the mission to AFRL objectives, and development of a sound nanosatellite system among other criteria [5].

Prox-1 is a nanosatellite which will demonstrate the use of low-thrust propulsion for automated safe trajectory control during proximity operations. Passive, image based observations will be used for the navigation and closed-loop attitude control of Prox-1 relative to a deployed CubeSat. Prox-1's objectives include: Rendezvous and proximity operations with a target CubeSat, automated relative navigation and trajectory control, closed-loop attitude control based upon automated image processing, and relative orbit determination using image-based angle and range estimates, validated by the Mission Operations System [4]. The student's particular research involved design, build, and test of the structural components of the Prox-1 satellite. This paper will describe what design information was based on previous Prox-1 structure iterations, what design modifications were made to improve the structure's capabilities and meet requirements, what analysis and testing was performed to validate those requirements, and what was needed to integrate with the subsystem components.

When referring to different plate orientations in this document, the Prox-1 body coordinate frame is used. This is centered at the middle of the Lightband interface ring on the bottom plate, and in the same plane as the Launch Vehicle Interface. In the final structure configuration, the X-axis is pointing toward the Ppod deployment direction and cameras, the positive Y-axis is in the direction opposite of the thruster, and the Z-axis is pointing from the LVI plate toward the top plate [2]. All figures depicting the spacecraft will have this body coordinate frame pictured.

II. Previous Work

A. Previous Structural Arrangement

The Prox-1 structure initial design was done by a previous graduate student during the first year of the UNP-7 project. The structure was a rectangular prism composed of four rectangular sides with crosspieces for structural stability, a square base which interfaced with the Lightband separation unit, and a top plate which was a hollow rim. Each exterior edge consisted of an interlocking pattern to decrease the amount of shear on the bolts holding the plates together and cut down on vibrations [4]. The structure also had a central plate across the XY plane for subsystem mounting. This configuration can be seen in Figure 1.
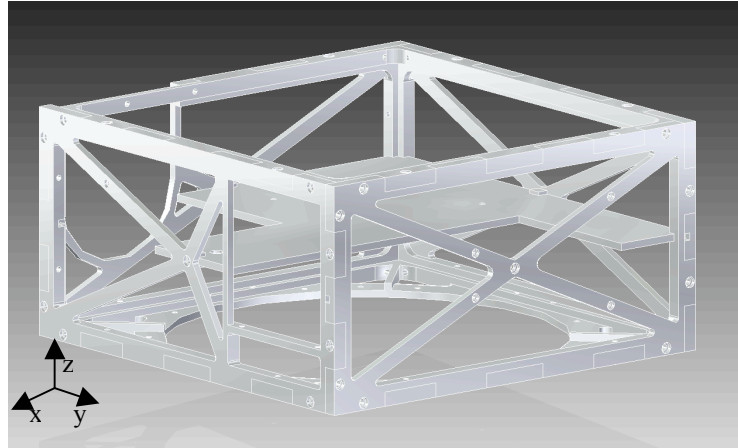
Figure 1: First Iteration of the Prox-1 Structure

The subsystems in this first version of Prox-1 included two reaction wheels, a star tracker, and two hydrazine thrusters. For the initial configuration, all subsystems were assumed to be mounted to the central plate. After the first version both the subsystem components' geometry and their mounting scheme changed significantly. The structure had to change to reflect these new mounting configurations and parts.

B. Previous Structural Analysis and Testing

All structural analysis of Prox-1 was performed using Abaqus software. Structural analysis of the initial structure did not include the central XY-plane plate. This meant that the natural modes found in the analysis did not reflect the actual modes of the complete structure, as a large central plate would probably have had a very low frequency mode, but attaching it to the centerpoints of the exterior plates might have increased the frequency of their lowest vibrational modes. Doing FEA analysis on only the external structure, however, still produced a lowest natural frequency mode of 281 Hz.

Testing of the initial structure had inconclusive results. Testing was done with a laser vibrometer, which used Doppler imaging to detect out-of-plane vibration on one of the side plates and the top plate of the initial structure. The side plate graphs indicate a minor peak at 104 Hz, and another at 183 Hz, with stronger peaks at 229 and 268 Hz. The top plate graphs indicate a possible minor peak at 105 and 126 Hz, with major peaks at 225 and 268 Hz. However, the graphs depicted in the initial test document do not display positive dB amplitude [4]. It is structurally impossible for all amplitudes to be negative, thus it is debatable whether or not these results are valid.

The student's research encompassed design, analysis and test of a new Prox-1 structure. A new approach to design was implemented, the Abaqus FEA re-run, and a new test procedure used to find the natural modes of the flight structure. The advancements are described in the following sections of this paper.

III.   Design Work

The student's design of the Prox-1 structure has been an ongoing process, with some parts continuing into the preparation for FDR. The primary structure, characterized by six large external plates and seven smaller interior plates, was designed while subsystem geometries were still in a state of flux, and so had to encompass several possibilities of what was to fit within the structure. Interface structures, those which are dictated by the subsystems' detailed size and shape, were designed once the subsystems' geometry was finalized. Thus, a modular primary structure was necessary, along with definitive solutions to interfacing the structure with individual subsystem components. This section will discuss the design of the structural components, while section V will discuss the integration of subsystem components with the finalized structure.

C. Modification of Primary Structure

The primary change made to the structure upon redesign was to create a more modular structure. Figure 2 depicts the new arrangement of several interior plates within the Prox-1 satellite structure. These plates serve to increase the area over which subsystems can be bolted and also increases the lowest natural frequency of the structure. Area of available mounting surface increased from 230,006.9 mm2 for the initial single plate to over twice that amount for the flight structure, with an available mounting surface area of 520,120.5 mm2 before interior plate cutouts.
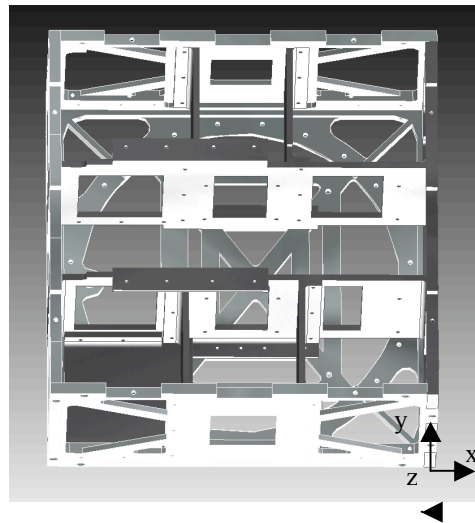

Figure 2: Interior arrangement of structural plates

Modularity, as defined for this structure, is "designed with standardized units or dimensions, as for easy assembly and repair or flexible arrangement and use"[3]. The four small interior plates can be arranged in several patterns- with mounting tabs (where the plate is bolted to the other plates) facing in or out, the plate slid left or right, or with cutouts machined in the plate for wiring or placement of additional subsystems. This modification was used for the TNC placement elaborated on in section V. The modular structure also makes it easier to mount subsystems during integration as an interior plate can be removed from the larger structure, a subsystem mounted to it, and then the plate returned to the larger structure. In this way subsystems can be easily accessed for repair or replacement during assembly and testing.

The interior plates of the structure act as reinforcing members for the exterior plates present in the initial version of the structure. They increase the frequency of the lowest structural mode by anchoring larger plates near their most flexible points (as defined by the initial structure's FEA analysis) [4]. The two long interior plates are affixed near the center of the large top and LVI plates, and the short interior plates are affixed near the center of the long interior and exterior side plates. In section IV it is shown that the analyzed modular structure has a lowest frequency mode much greater than seen in the open structure without interior plates.

Table 1 shows the masses of the primary structure plates, not including screws. The masses of the interior plates are for before mass-saving holes are milled in them. These are the masses of the plates as they are in the testing structure. The interior plate masses will decrease once holes for wire-pass and mass savings have been milled out of them. Exterior plate masses will remain constant.

Table 1: Primary Structure Plate Masses

Plate	Mass of Plate
Exterior Ppod Side Plate	1.028 kg
Exterior Back Side Plate	1.325 kg
Exterior Thruster Side Plate	1.110 kg
Exterior Non-Thruster Side Plate	1.276 kg
Exterior Top Plate	1.290 kg
Exterior LVI Plate	2.086 kg
Interior Long Plate 1	1.691 kg
Interior Long Plate 2	1.692 kg
Interior Short Plate 1	0.582 kg
Interior Short Plate 2	0.580 kg
Interior Short Plate 3	0.582 kg
Interior Short Plate 4	0.585 kg
Interior Z-axis Plate	0.439 kg

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[3] Dictionary.com definition of "modularity."

D. Interface Design Considerations

Subsystem integration into the primary structure required a variety of mounting holes, interface brackets, and interface blocks. For some subsystems the structures team was responsible for the box containing the subsystem components, in order to better interface them with the primary structure. Table 2 lists each subsystem component and the interface mounting required to attach it securely to the primary structure. Note that electrical boxes are required to be mounted with at least size #8-32 screws.

Table 2: Subsystem Interfaces

Part	Subsystem	Mounting Holes	Interface
P-pod	Payload	12 #6-32 holes	Screws
Thruster	Propulsion	8 2-mm holes	Screws and brackets
Visible Camera	Instruments	4 #8-32 holes	Screws and block
Microbolometer	Instruments	6 #6-32 holes	Screws
UHF Receiver	Communications	4 #8-32 holes	Screws and brackets
UHF Antenna	Communications	4 2mm holes	Screws
S-band Transmitter	Communications	4 #6-32 holes	Screws
S-band Antenna (2)	Communications	#8-32 hole each	N/A- screw-in mount
TNC	Communications	4 #8-32 holes	Screws and brackets
GPS Receiver Board	ADCS	4 #4-40 holes	Screws
Magnetometer	ADCS	2 #8-32 holes	Bolts and nuts
Torque Rods (3)	ADCS	4 #8-32 holes each	Screws and brackets
Sun Sensors (4)	ADCS	4 #6-32 holes each	Screws and blocks
Reaction Wheels	ADCS	4 #8-32 holes	Screws
GPS Antenna	ADCS	4 #4-40 holes	Screws
Solar Panels (6)	Power	4 #8-32 holes each	Screws
Power Boards	Power	5 #8-32 holes	Screws and box
Batteries	Power	6 #8-32 holes	Bolts, nuts, and box
C&DH Boards	C&DH	8 #10-32 holes	Screws and boxes (2)

The subsystems in Table 2 with boxes are also those which emit electromagnetic radiation. The boxes were designed with overlapping edges to shield this electromagnetic radiation and reflect it inside of the box. All boxes and screw holes are vented according to UNP specifications [5].
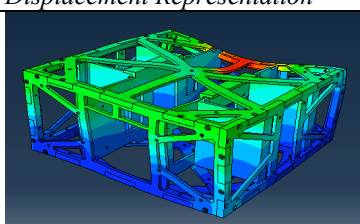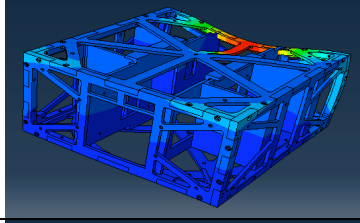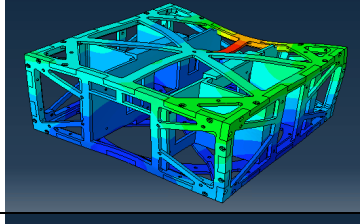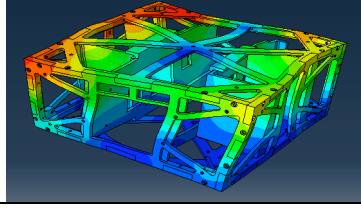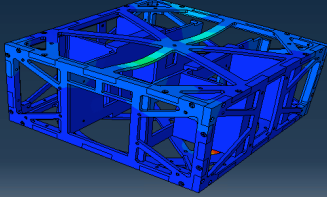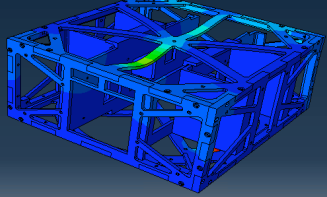
IV.   Analysis and Testing

The students at Georgia Tech were responsible for analysis and testing of random vibrations such as those seen during launch of the satellite. The analysis was performed using Abaqus FEA software and the testing was performed on a single axis vibe table located on campus.

E. Analysis

Analysis of the flight structure included all exterior and interior plates, but not the subsystem interface structures or the subsystems themselves. This analysis was then verified with random vibration testing of the actual flight structure. It is evident in Table 3 that the UNP requirement for a lower frequency mode limit of 100 Hz was well met. The lowest frequency mode seen in analysis was 500 Hz, a factor of safety 5x that of the lower threshold.

Table 3: Lowest 6 Modes of Structural Vibration, FEA Analysis

| Displacement Representation	Frequency	Mode
	500	Vertical vibration of top edge, corresponding horizontal vibration of back side.
	511	Vertical vibration of top edge, corresponding horizontal vibration of back side.
	622	Horizontal and vertical vibration of top edge, corresponding horizontal vibration of back side.
	735	Twisting vibration of left and right halves.

	841	Horizontal vibration of front and back halves, corresponding vertical vibration of top plate.
	853	Rocking mode along the diagonal, corresponding vertical vibration of top plate.

Structural analysis of individual components was used to verify their structural integrity under 20 g loading. The analysis was performed using Solid Edge's built-in "Simulation Express" FEA software and automatically generated meshes. All structural interface components were stress analyzed with one screw failed in order to verify that the failure of a single screw (in a critical position) would not cause failure of the entire structural interface. The results of these tests indicated that all structural components have a factor of safety of at least 2 with one failed screw under 20 g loading. Results are listed in the Prox-1 Structural Analysis document [3].

F. Testing

Testing for the Prox-1 structure was performed on a shake table located on the Georgia Institute of Technology campus. It performed 20-2000 Hz random vibrations along one axis at a time, and the structure was tested along both the x and y axis to determine the overall vibrational modes of the structure. Z-axis plane vibrations were not tested, however, the FEA analysis showed that the modes in the z plane were not among the lowest frequency vibrational modes. The Prox-1 structure was fitted with two single-axis accelerometers per side. These accelerometers were then referenced against an identical accelerometer located along the axis of vibration on the shake table itself. The results can be seen in Figure 3.
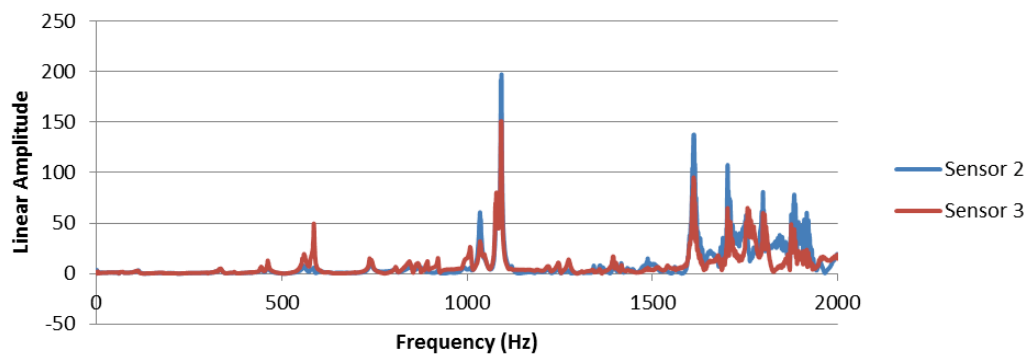
Linear Frequency Response of Ppod Side Plate
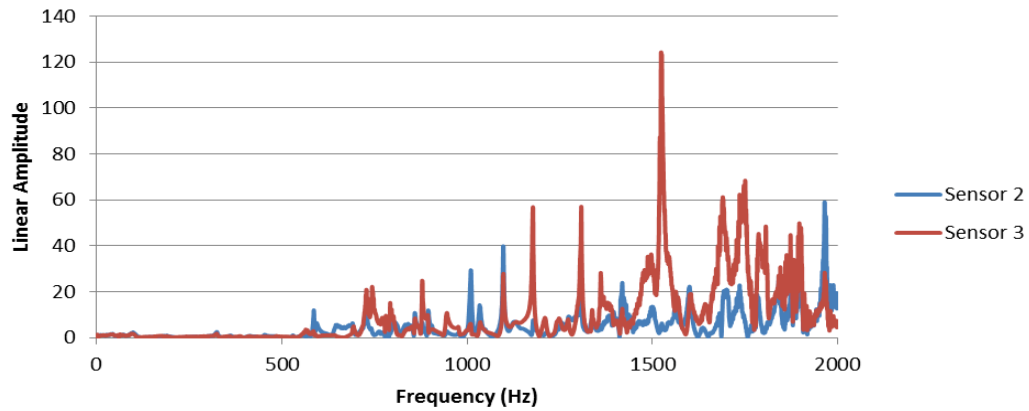
Linear Frequency Response of Back Side Plate
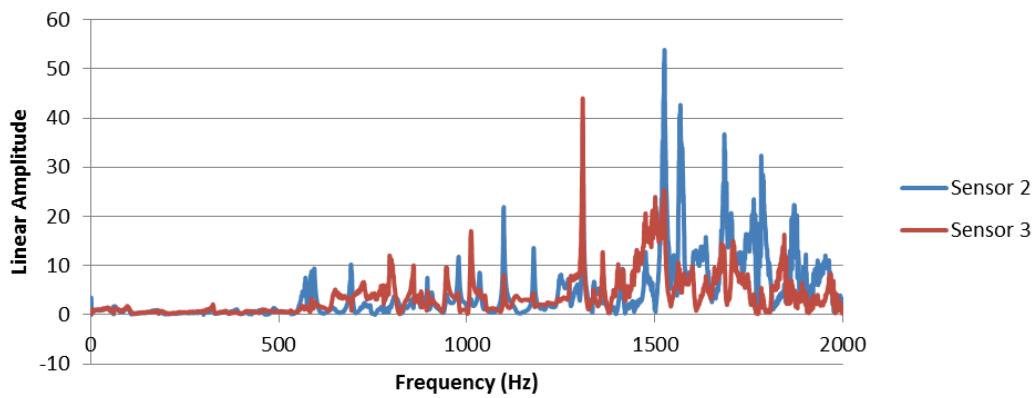
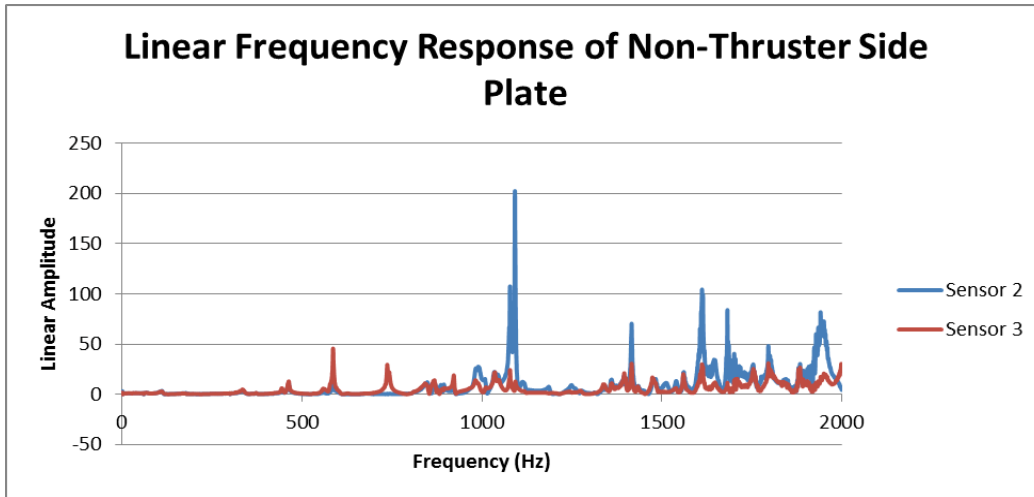**Linear Frequency Response of Thruster Side Plate**

Figure 3: Linear Frequency Responses of Side Plates

The vibration test showed the following frequency peaks above 5 on a linear amplitude scale relative to the reference accelerometer (>14 dB), indicating a possible structural mode at that frequency:

Ppod Side Peaks (Lowest 3):
- 586.25 Hz at 11.94 (Sensor 2)
- 593.75 Hz at 6.33 (Sensor 2)
- 645.63 Hz at 5.54 (Sensor 2)

Back Side Peaks (Lowest 3):
- 568.75 Hz at 6.33 (Sensor 2)
- 570.63 Hz at 7.53 (Sensor 2)
- 586.25 Hz at 8.73 (Sensor 2)

Thruster Side Peaks (Lowest 3):
- 335.00 Hz at 5.10 (Sensor 3)
- 444.38 Hz at 6.88 (Sensor 3)
- 461.88 Hz at 13.02 (Sensor 3)

Non-Thruster Side Peaks (Lowest 3):
- 443.13 Hz at 6.11 (Sensor 3)
- 463.13 Hz at 12.92 (Sensor 3)
- 561.25 Hz at 5.61 (Sensor 3)

These frequency values were all above the minimum required 100 Hz limit for lowest structural vibrational mode. Therefore, the Prox-1 structure meets the UNP-7 requirements for vibrational testing with a factor of safety >2. Amplitude peaks less than 2 mV/g (<13.86 dB) were not counted as vibrational modes.

G. Analysis vs. Testing Comparison

The results of the vibrational testing did not completely agree with the analytical results obtained via FEA analysis. The thruster side and non-thruster side (which are geometrically identical) both had small peaks around 443 Hz, and the peak at 335.0 Hz had just enough amplitude to be considered significant. These are lower peaks than predicted by FEA. However, one hypothesis is that the structure's screws and manufacturing imperfections contributed to additional vibrations at lower frequencies. The FEA analysis did not use screws as points of contact, but instead used tie relationships. There were, however, peaks around 560 Hz, and modes in the range of ~500-600 Hz were predicted as some of the lowest modes by the FEA analysis. Still, the analysis is an imperfect gauge of testing results and it is recommended that they be used only as a guide for what range of frequency values the structure should have as natural modes.

V. Integration

Several subsystems did not have mounting holes which would integrate directly with the Prox-1 structure. Therefore, the structure team also designed several electronics boxes and interface mounts for subsystems. These interfaces were water jet machined when possible, but many had to be hand milled due to their 3-dimensional details. All were made of Aluminum 6061-T6. The masses of the integration pieces (with screws included) are included in Table 4 with a 10% margin for inclusion in the structural mass budget. This margin was chosen in case of changes in screws or small machining design changes.

Table 4: Subsystem Interface Structures Listing

Subsystem to Interface	Interface Structure	Mass of Interface Structure w/Screws + 10% Margin
UHF Receiver	Receiver Brackets (2)	0.029 kg each
TNC	TNC Brackets (1 large, 2 small)	Large: 0.058 kg Small: 0.012 kg each
Power Board	Power Board Box	0.574 kg
C&DH Boards	C&DH Box 1	1.069 kg
C&DH Board Overflow	C&DH Box Add-On	0.953 kg
Torque Rods (3)	Torque Rod Brackets (6) *	0.014 kg each
Sun Sensors (4)	Sun Sensor Mounts (4)	0.154 kg each
Batteries (8)	Battery Box	3.216 kg

*Torque rod brackets are approximate, as their design is for only one of the torque rods.

Assembly of the subsystem components within the structure took careful consideration for mounting. In some cases subsystems could not be mounted on both sides of a plate because there would be no way to access screw heads for torqueing the screws with a tool. This is the reasoning behind placing the Power Board Box on an exterior plate instead of the interior plate, which also has the thruster mounted on the opposite side. The Power Board Box mounting screws would not be accessible if mounted on the interior plate. In other cases one component needed to mount to a plate before the plate was put in place in the overall structure, in order to be positioned properly. This is the case with the visible camera, since it will need to be carefully aligned for AutoNavigation purposes. The structure itself needed to be assembled in a certain order in order to have correct placement of all plates, external and internal. The assembly order is detailed in the Prox-1 Assembly Document [1].

VI. Conclusion

The Prox-1 structure's adaptability has been of great benefit in the design phase of the satellite. Plates needed to be modified several times in order to accommodate shifting subsystem geometries, and in some cases entirely new subsystem components late in the design cycle. Having a modular structure with fairly similar sized "cells" to mount components to allowed the subsystem components to shift without having to re-design the structure.

In future work, the interface boxes will need to have wiring connector holes milled out in order to wire the electronic components to each other. Also, the center of gravity (CG) will need to shift in the -X and Y directions. The current CG is located at X: 1.048 cm, Y: -1.21 cm, and Z: 10.81 cm with respect to the center of the Lightband interface. UNP requirements state that it must be within 0.5 of the center of the Lightband interface in the X and Y directions. Therefore, balance weight blocks, probably made of stainless steel 18-8 or aluminum 6061-T6, will be attached to the structure after finalizing wiring and bolting other subsystems in place to bring the CG into alignment.

In addition, the interior plates will have wire-pass and mass-reduction holes milled out after all subsystem component placement is finalized (screw holes drilled in structure is considered finalized). Thus, the internal plates' mass will be decreased while still having provided maximum mounting location flexibility throughout the design. If holes were milled in the plates before the finalization of component locations, it could potentially limit component placement. This was encountered with mounting components to exterior plates. Because the exterior plates had

milled-out crossbeams, as seen in Figure 4, the mounting locations were limited, leading to less optimal mounting of exterior plate mounted subsystem components. The student recommends not milling out material unnecessarily early on primary structural panels until late in the design process, if possible. This provides the maximum amount of optimization for subsystem component placement.
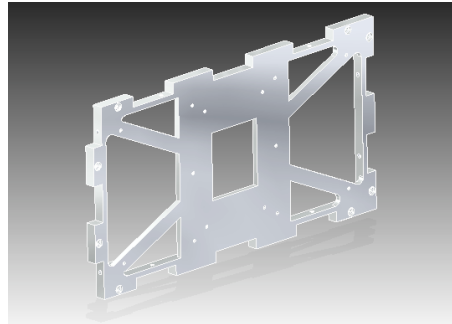

Figure 4: Thruster Side Plate with Milled-Out Crossbeams Evident

In conclusion, the Prox-1 structure is fully capable of supporting the other Prox-1 subsystems, though additional work must be done to aid integration of the components. Structures have been analyzed and tested to within UNP-7 required tolerances [5], although additional testing, such as sine burst test and 20 g loading test, will be performed by the AFRL if Prox-1 is selected for launch. Additional information about the Prox-1 structure can be found in the Structure Detail Design Document or by contacting the Prox-1 structures team.

Appendix

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Acknowledgments

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[4] Willingham, A., Pappas, T., and Keir, C. "Structure Detail Design Document", Prox-1 Documentation, Georgia Institute of Technology, Atlanta, GA, 2012.

[5] "UNP-7 Handbook", Air Force Research Lab, Albuquerque, NM, 2010.