University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects – ASEN 4018

FeatherCraft
Conceptual Design Document

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1.0 Information

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2.0 Project Description

The FeatherCraft project presented by Surrey Satellite Technology-US (SST-US) involves the design, assembly and testing of a lightweight satellite structure to serve as a platform for payloads deploying from the International Space Station (ISS) into low-Earth orbit. The FeatherCraft team will build a structural test model (STM) of a design, create and implement an instrumentation system for vibration tests along with developing a software package that will record and analyze data from the instrumentation system.

Satellites to be launched from the ISS will be transported to the Station onboard commercial cargo transportation vehicles and experience far lower launch loadings than traditional launch vehicles. Upon delivery to the ISS, satellites will be positioned into orbit by the planned NanoRacks Kaber satellite deployment system, onboard the Japanese Experiment Module (JEM). The FeatherCraft structure is a new small satellite that takes advantage of the unique launch and deployment environment of the ISS. The reduction of structural mass provides greater payload capability at a lower cost to the customer[5]. No other satellite structure currently on the market uses this environment to their advantage.

The FeatherCraft design shall provide a 5 kg structural platform for a 100 kg satellite. The structure shall be rectangular and fit within a 19"x 30"x 30" volume (sized to the internal bay of the Kaber deployment system). The interior of the structure shall be divided into two bays of equal size: a payload bay and an avionics bay.

Of the six sides of a rectangular satellite, three exterior faces shall interface with the customer-defined solar panels. One face shall be an open aperture to accommodate payload instruments, and another face shall act as a radiator to deep space. The design and the STM must be able to interface with a 3rd party specified propulsion plate (not included in the 5kg structural mass) and shall provide mounting locations for payload and avionics components such that their layout can be modified to meet multiple mission criteria. The STM shall be designed to survive the combined launch loads experienced by a soft-stowed payload during launch in an ISS cargo vehicle – and shall be tested with a 9.47 vibration table setting in a 3-axis random vibration test. During this test, the STM shall support 95 kg of analog weights that simulate non-structural components of the satellite.

The benefits of a FeatherCraft design that meets the requirements listed below will be its ease of construction and low mass, which will improve the small-satellite market and advance the industry of station-launched satellites.

2.1 Acronym Definition

ADC - Analog to Digital Converter
GEVS - General Environmental Verification Specifications
GUI - Graphical User Interface
JEM - Japanese Experiment Module
PDR - Preliminary Design Review
SPDM - Special Purpose Dexterous Manipulator
SPI - Serial Peripheral Interface
SSP - Synchronous Serial Port
SST-US - Surrey Satellite Technologies – United States
STK - Systems Tool Kit
STM - Structural Test Model

2.2 Nomenclature

A - Area
CTE - Coefficient of Linear Thermal Expansion
δ - Deflection of a beam
ϵ - Emissivity
E - Modulus of Elasticity
F - Force
I_{zz} - Moment of Inertia
ρ - Density
σ - Stephan Boltzman Constant
σ_{Max} - Maximum Stress
σ_u -Ultimate Stress
σ_y - Yield stress
y_{Max} - Maximum Strain
Q - Heat Radiated
q - Equal pressure distribution
T - Temperature
t - Thickness

2.3 Definition of Sides

Throughout the document sides of the spacecraft will be referenced. Figure 2.1 shows these sides and how they relate to one another.

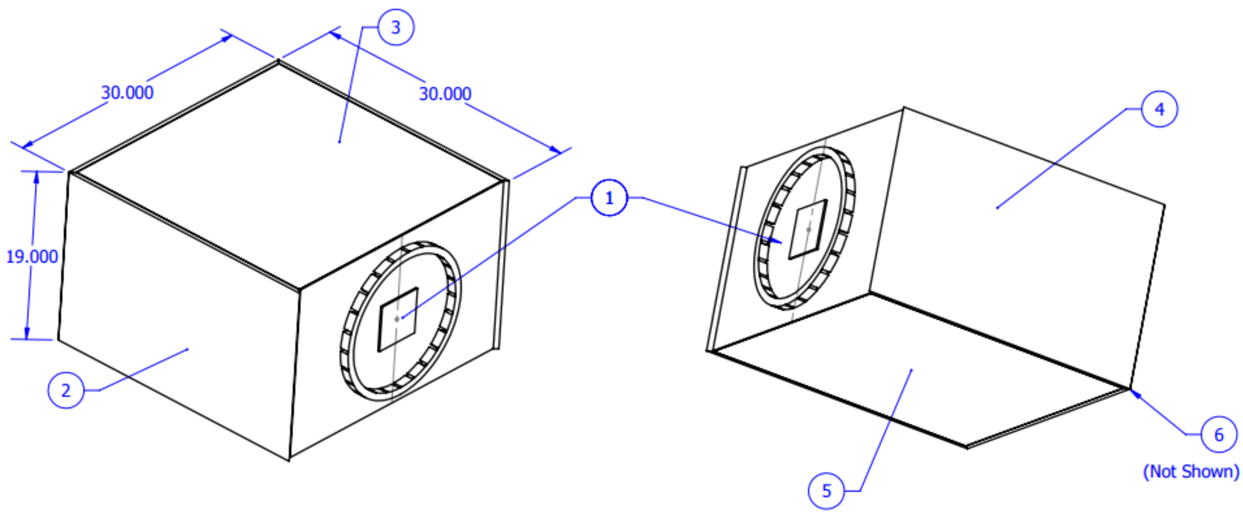


Figure 2.1: Definitions of Sides

Table 2.1: Side Number and Function

Side # :	Function :
1	Propulsion Plate (19''x29'')
2	Solar Panel (19''x30'') or Radiator (19''x30'' maximum)
3	Solar Panel (30''x30'')
4	Solar Panel (19''x30'') or Radiator (19''x30'')
5	Payload Aperture
6	Radiator Plate (19''x30'' maximum) or Solar Panel (19''x30'')

2.4 Concept of Operations

To meet the criteria set forth in the requirements, a design must be created and this design model will be simulated under random vibrations and expected loadings. Once the design has been verified with simulation, a STM will be fabricated with equivalent material properties. The STM will undergo testing on a vibration table with data collected by a designed data acquisition system. This will fulfill FR 6 and subsequently demonstrate feasibility of the design. After the design is delivered to SST-US, it shall be further tested and eventually integrated with the avionics and provide a bus for small payloads. The structure will be launch on ISS resupply missions and placed inside the JEM airlock, part of the Nanoracks Kaber Deployment System. Finally, the SPDM grapple the Kaber System and translate it to face retrograde from the ISS. Here, the satellite will be released and free to maneuver, likely to a higher altitude orbit, and complete its mission for five years[16]. Because of the timeline of the course, the design team will be involved in the design and prototyping of the structure, but steps 6-12 will not be accomplished for many years, after the Kaber System is operational. The design work will take place in the fall semester, with fabrication of the STM, creation of the data acquisition system, and vibration testing occurring in the spring. The overall concept of operations is shown in Figure 2.2.

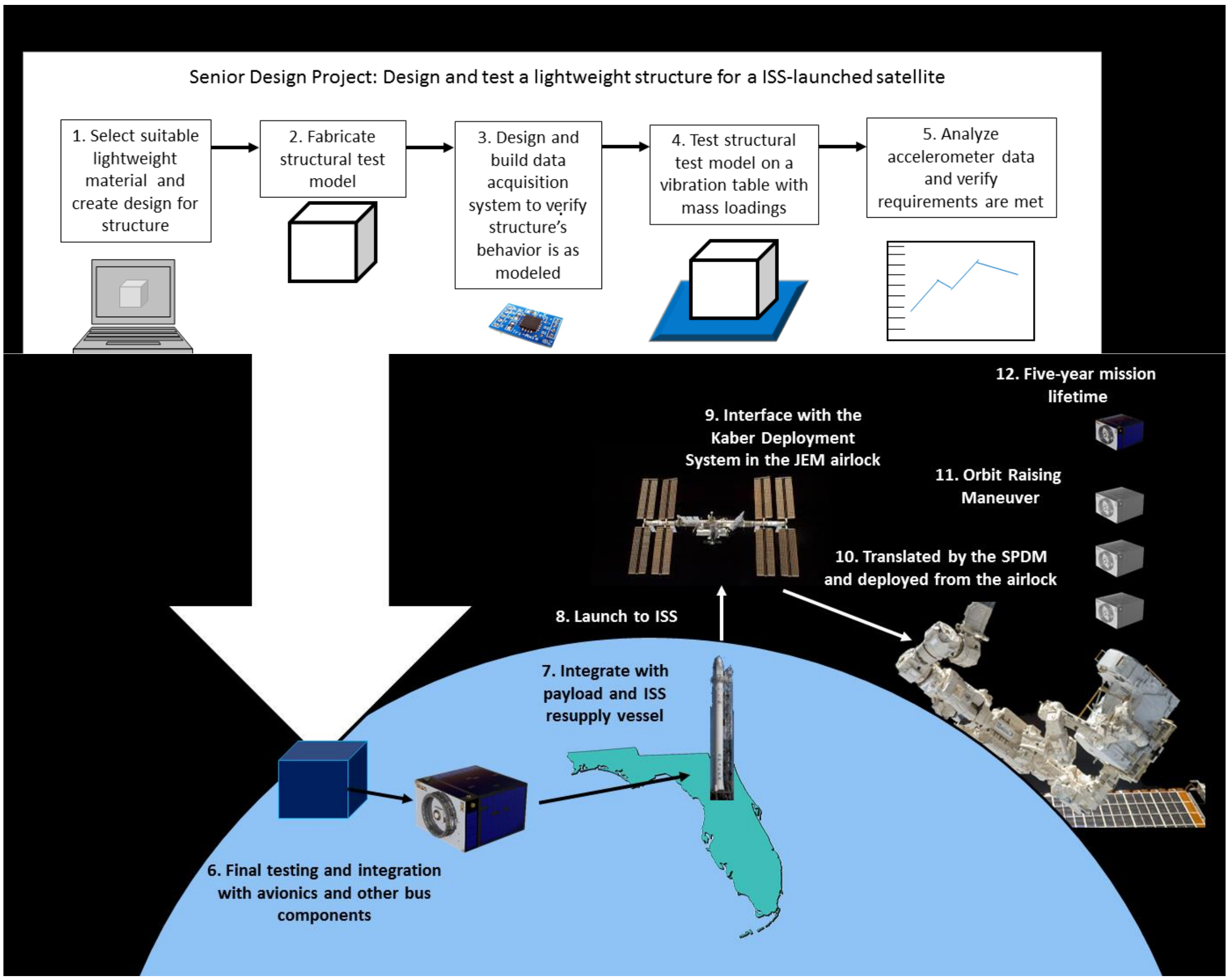


Figure 2.2: CONOPS Diagram

2.5 Functional Block Diagram

The first step of the project will be to design a structure that meets all requirements and incorporate a radiative plate in the design to dissipate heat. The design flows into the fabricated model, which will have similar properties as verified by SST-US. The STM will mount SST-US-provided mass dummies and this structure will be tested on a vibration table. Accelerometers will be mounted to the structure within bubble wrap (the number of accelerometers needed and where they will be located will be determined by the shape of the final structure) and this data will be transmitted into the data acquisition system. The data acquisition system will convert data to saved files as well as display frequency data in real time. Finally, these files will be post-processed with a data analysis program suite to identify properties of the structure and test anomalies. Both raw files and post-processed files will be saved in an Excel-compatible format. The entire process is shown in Figure 2.3.

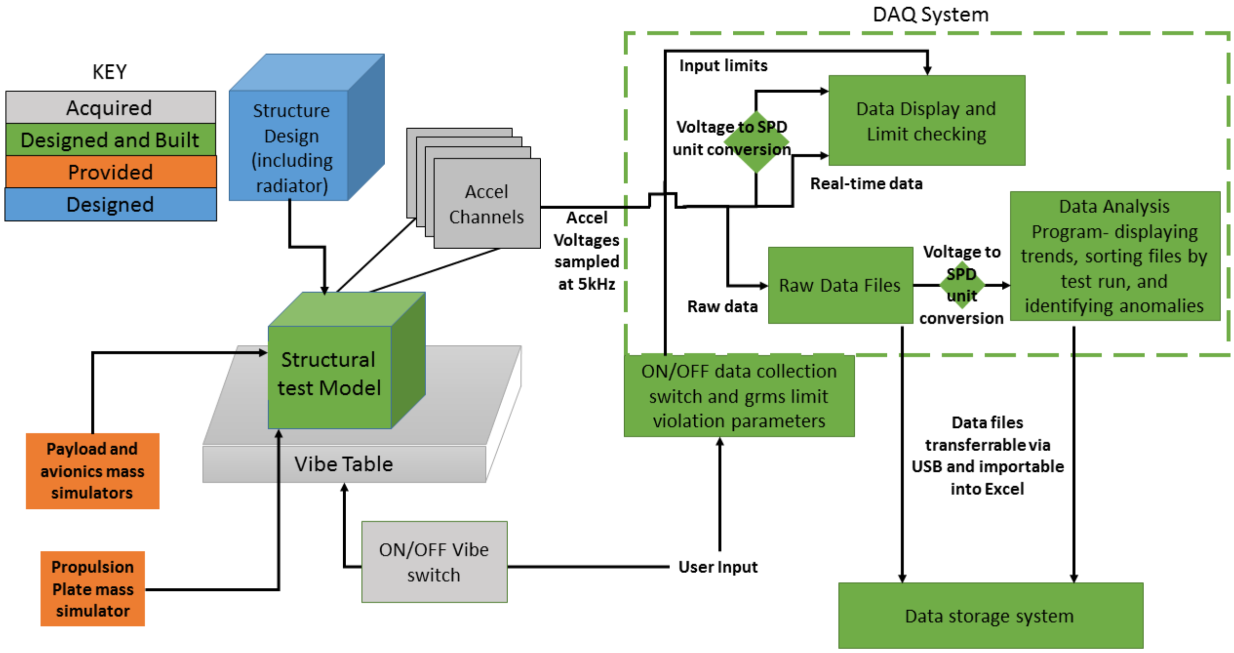


Figure 2.3: Functional Block Diagram

2.6 Functional Requirements

Table 2.2: Functional Requirements

1	The Feathercraft structure design shall be lightweight.
2	The Feathercraft structure design shall reduce manufacturing time and material cost from SST-US's typical spacecraft estimates.
3	FeatherCraft Structure shall be designed to withstand a vibration table setting of 9.47 grms in soft-stowed configuration.
4	FeatherCraft Structure shall be designed to deploy from the Kaber Deployment Service.
5	FeatherCraft structure design shall interface with STS-US-provided spacecraft components and mission design.
6	An equivalent manufactured STM of the FeatherCraft structure design shall be used to demonstrate the feasibility of the FeatherCraft structure through a random vibration test to the requirements of SSP 50835.

3.0 Design Requirements

Goal Statement: The 5 kg FeatherCraft structure shall provide support for a 100 kg total mass commercial spacecraft with reduced structural manufacturing time and materials cost, and enable the spacecraft to survive launch to and deployment from the ISS for a nadir facing mission.

FR 1: The FeatherCraft structure design shall be lightweight.

- ❖ DR 1.1: Structural design mass shall be less than 5 kg.

  Source: Customer requirement. Increasing the structural mass beyond 5 kg would prevent SST-US from providing a profitable weight class of payloads

  Verification: Modeling and analysis, comparison with measurement of STM

FR 2: The Feathercraft structure design shall reduce manufacturing time and material cost from SST-US's typical spacecraft estimates.

- ❖ DR 2.1: Structure design material cost shall be less than $20,000.

  Source: Customer requirement, SST-US typically expends $40,000 on a spacecraft material and this design shall reduce that metric by 50%.

  Verification: Budget analysis

- ❖ DR 2.2: Structure design manufacturing and assembling shall take less than 9 months.

  Source: Customer requirement, SST-US typically spends 18 months on spacecraft manufacturing and assembling and this design shall reduce that metric by 50%.

  Verification: Manufacturing estimates and analysis

- ❖ DR 2.3: Structure design manufacturing and building labor shall cost less than $80,000.

  Source: Customer requirement. This is a 50% reduction of SST-US's typical manufacturing and building cost of $160,000 and will help the company meet the goal total price of $6 million.

  Verification: Budget estimates and analysis

FR 3: FeatherCraft Structure shall be designed to withstand a vibration table setting of 9.47 grms in a soft-stowed configuration.

- ❖ DR 3.1: FeatherCraft structure in launch configuration shall be designed to not be damaged by simulated launch environment, up to a 9.47 grms random vibration environment with safety factors as outlined in the GEVS ISS Pressured Volume Hardware Common Interface Requirements Document Rev C.

  Source : Customer requirement. To remain profitable, the FeatherCraft package needs to be reliable and provide a robust platform for their customers, as well as meet all NASA requirements for launch to the ISS.

  Verification: Vibration test executed on STM in FR 5 and measurement of STM before and after vibration test

FR 4: FeatherCraft Structure shall be designed to deploy from the Kaber Deployment Service.

- ❖ DR 4.1 FeatherCraft structure design including mounted components shall fit within the volume of 30”x30”x19”.

  Source: The spacecraft as a whole must be placed within the Kaber volume to be deployed and begin its mission. This volume ensures at least 2’’ of space between the spacecraft volume and the edge of the JEM airlock. Soft stowed as defined by GEVS ISS Pressured Volume Hardware Common Interface Requirements Document Rev C.

  Verification: Inspection of drawings, demonstration with measurement

FR 5: FeatherCraft structure design shall interface with SST-US-provided spacecraft components and mission design.

- DR 5.1: FeatherCraft structure design shall provide mounting positions on the three sides of the structure that will maximize the sun exposure for one 30''x30''x0.125'' solar panels of mass 2 kg and two 30''x18.976''x0.125'' solar panel of mass 1.5 kg.

    Source: Customer requirement, knowing that this is a nadir-facing mission; the three sides that spend the most time facing the sun should have solar panels mounted on them. These sides will be determined through STK analysis, with the assumption that the propulsion plate will always face the negative velocity direction. Three are required by the customer to provide adequate power for interfacing components.

    <u>Verification:</u> Modeling and analysis in STK, STM demonstration in FR 5.
- DR 5.2: FeatherCraft structure design shall provide a mounting position for a 29.094''x18.976''x0.125'' propulsion plate of mass 12 kg on Side 1.

    Source: Customer requirement. The propulsion plate design has been finalized, and its dimensions necessitate its mounting location.

    <u>Verification:</u> modeling and inspection of drawings, STM demonstration in FR 5
- DR 5.3 FeatherCraft structure design shall have an internal structural component equally bisecting the 19'' height dimension to provide mounting capabilities to the avionics components and payload components.

    Source: Customer requirement. The mounting capabilities are necessary for the customer to assemble the spacecraft easily and safely. This bisecting structural component defines a payload bay and avionics bay so that a payload volume is defined for potential customers.

    <u>Verification:</u> Inspection of drawings, Test (measure STM)
- DR 5.4 FeatherCraft structure design shall dissipate up to 100 W of heat generated equally by avionics and payload bays at an operating temperature of -20 to 50 degrees C.

    Source: Customer requirement. The maximum power output is estimated by the customer to remain below 100W. The specifics of this analysis are presented in Section 4.1.4.

    <u>Verification:</u> Analysis

    - DR 5.4.1: FeatherCraft structure design shall have a radiative material on the side facing deep space most often to dissipate heat.

        Source: Customer requirement, derived from DR 5.4. This shall be determined in the same STK analysis that determines which sides of the spacecraft experience the most direct sunlight over a year.

        <u>Verification:</u> Inspection of model, STK analysis
- DR 5.5 FeatherCraft structure design shall keep side 5 open.

    Source: Customer requirement, payload use and space for antenna(s) facing nadir.

    <u>Verification:</u> modeling, demonstration in STM
- DR 5.6 FeatherCraft structure design shall remain operational for five years in a space environment.

    Source: Customer requirement, the spacecraft bus will be advertised as a five-year mission.

    <u>Verification:</u> Analysis of structure material and assembly method for similarity to previous missions' material heritage

FR 6: A manufactured STM of the FeatherCraft structure design shall be used to validate the design through a modal vibration sweep and a random vibration test to the requirements of SSP 50835.

- DR 6.1 STM shall be manufactured with sufficient similarity to the structural design such that it can be used for validation of the designed structure. It shall fulfill all of the requirements of the designed structure with the exception of the 5kg structural mass requirement, which may be exceeded.

    Source: Customer requirement. A physical test must be performed to provide a baseline of feasibility; this can only be proved if the STM is similar to the design. However, the materials of the STM are constrained to the FeatherCraft team budget.

    <u>Verification:</u> Analysis of materials
- DR 6.2 STM shall be tested on a vibration table for a vibration profile of 20-2000 Hz and up to a vibration table setting of 9.47 grms with each test lasting 60 seconds.

    Source: GEVS table 3.1.1.2.1.2.3.2-1 (Page 3-17 of ISS Pressured Volume Hardware Common Interface Requirements Document Rev C.) It is estimated by this document that with a vibration table setting of 9.47 grms, the bubble-wrapped structure should experience 1.29 grms.

    <u>Verification:</u> Inspection of test plan, test

- DR 6.3 STM shall support loads through vibration testing that are equivalent to the required loading of the designed structure.

  Source: Validation of FR 6

  Verification: Demonstration

  - DR 6.3.1 STM shall have a provided mass analog propulsion plate of mass and size specified in 5.2 mounted to side 1

    Source: Validation of DR 5.2 and FR 5.

    Verification: Inspection
  - DR 6.3.2 STM shall have provided solar panel mass analog plates mounted on sides determined from DR 5.1 with mass and size specified in DR 5.1

    Source: Validation of DR 5.1 and FR 6.

    Verification: Inspection
  - DR 6.3.3 STM shall have an internal loading of 35 kg mounted inside the structure in the avionics bay to represent the avionics mass.

    Source: Validation of DR 5.3 and FR 6. This is the total mass of all spacecraft components SST-US intends to place inside the avionics bay.

    Verification: Measure mass, Inspection of drawings of vibration test configuration
  - DR 6.3.4 STM shall have an internal loading of 47.5 kg mounted inside the structure in the payload bay to represent the payload mass.

    Source: Validation of DR 5.3 and FR 6. This is the SST-US provided estimate it will allow for payload mass.

    Verification: Measure mass, inspection of drawings of vibration test configuration
- DR 6.4: STM shall be wrapped in three layers of SECO 88 bubble wrap prior to testing.

  Source: Customer Requirement stemming from ISS Pressured Volume Hardware Common Interface Requirements Document Rev C. The test shall be performed with the STM in the flight configuration.

  Verification: Demonstration, inspection
- DR 6.5 FEM model shall be verified using structural accelerometer information.

  Source: Provides evidence for completion of FR 6 and allows data collection for later correlation to designed structure. The number of accelerometers necessary and their positons will be determined after the structural design is determined.

  Verification: Analysis of FEM model, inspection of drawings of vibration test configuration
- DR 6.6 A data acquisition and analysis system shall be designed and created for this test and further tests of structural STMs to validate structural properties.

  Source: Customer requirement, it will save the project money to own a data acquisition system, and this can be used for custom data collection and future tests

  Verification: Demonstration

  - DR 6.6.1 Accelerometers determined by FR 6.5 shall be acquired for the testing of the STM, with one tri-axial accelerometer and one single-axis accelerometer retained by the design team.

    Source: Customer requirement. The number of accelerometers needed to validate the FEM model will be determined by the structure shape, and SST-US would like one accelerometer to base an expanded data acquisition system on if they could acquire it at the end of the project.

    Verification: Analysis of FEM model, demonstration
  - DR 6.6.2 DAQ shall contain 60 channels for the possibility of 20 tri-axial accelerometer inputs.

    Source: Customer requirement, although the budget of the project limits the number of accelerometers to be used for the test in spring, future tests with 20 tri-axial accelerometers may be performed and data would be taken from all 20 at the same time.

    Verification: Analysis of circuitry and inspection of design drawings

- DR 6.6.3: Accelerometer data shall display in the form of power spectral density plots during each test
  Source: Customer requirement, safety for structure during test, real-time performance analysis
  Verification: Demonstration
- DR 6.6.4 Accelerometer data shall be saved during each test in an Excel-compatible format
  Source: Customer requirement, post-test analysis
  Verification: Demonstration
- DR 6.6.5 Accelerometer data shall be transferable via USB from the microprocessor collecting data to any personal computer running Microsoft Windows operating systems.
  Source: Customer Requirement. To prevent errors and wasted time, data should be easy to transfer to any of SST-US' computers.
  Verification: Demonstration

4.0 Key Design Options Considered

4.1 Structure Options

4.1.1 *Material Selection*

To meet DR 1.1, one of the most significant design parameters to vary is the structure's material. Because many structural designs can be considered with multiple materials, the properties of each material are presented here first.

4.1.1.1 Metal Alloys

4.1.1.1.1 Aluminum

In aerospace structures, metal alloys such as titanium and aluminum are a common choice. Aluminum is desirable because it is relatively lightweight and strong. It can be welded, is easily fastened, and is readily available, which makes it an attractive choice for an overall structure. Titanium and stainless steel also have desirable strength properties, but the densities of Grade 5 Titanium and Stainless Steel type 304 are much higher than aluminum. Aluminum alloys are also easy to manufacture, are readily available, and their material properties are well characterized. In addition, aluminum alloys provide a less expensive alternative to rarer alloys like magnesium, titanium, or beryllium. Because of this, aluminum could prove to be an easy method of prototyping even if an entire aluminum structure may not be feasible to meet DR 1.1

Table 4.1: Mechanical Properties of Aluminum (T60-61).

$\boldsymbol{\rho}$	2.7 g/cc
$\boldsymbol{E}$	67 GPa
$\boldsymbol{\sigma_y}$	276 MPa
$\boldsymbol{\sigma_u}$	310 MPa
CTE	23.6 ppm/K

Table 4.2: Pros and Cons of Aluminum

Pros:	Cons:
Low cost and may already be available at CU	Heavier than many composites
Easy to manufacture and weld, variety of shapes possible	
Material properties are well known	

4.1.1.1.2 Titanium

Titanium is used in spacecraft when its mechanical properties are required and justify the higher cost and more difficult manufacturing techniques. It is generally used for high pressure tanks and struts.

Table 4.3: Pros and Cons of Titanium (Grade 5)

$\boldsymbol{\rho}$	4.43 g/cc
$\boldsymbol{E}$	113.8 GPa
$\boldsymbol{\sigma_y}$	880 MPa
$\boldsymbol{\sigma_u}$	950 MPa
CTE	8.61 ppm/K

Table 4.4: Pros and Cons of Titanium

Pros:	Cons:
High strength to weight ratio	More expensive than aluminum
Low thermal expansion	More difficult to machine

4.1.1.1.3 Magnesium

Another alternative to aluminum is magnesium. It is much lighter (by roughly two thirds) than aluminum and has good specific mechanical properties. However, it has poor corrosion resistance and is much more expensive than aluminum. Magnesium can be used successfully in aerospace structures, as was demonstrated by the Mariner 5 spacecraft, which used an octagonal magnesium frame. The structural mass of Mariner 5 was about 13% of the total mass.

Table 4.5: Mechanical Properties of Magnesium (AZ-80A)

$\boldsymbol{\rho}$	1.8 g/cc
$\boldsymbol{E}$	45 GPa
$\boldsymbol{\sigma_y}$	250 MPa
$\boldsymbol{\sigma_u}$	340 MPa
CTE	26 ppm/K

Table 4.6: Pros and Cons of Magnesium

Pros:	Cons:
High strength to weight ratio	More expensive than aluminum
	Harder to acquire

4.1.1.1.4 Beryllium

Another option is to use metals and alloys like beryllium, Al-Be, and Al-Li alloys. Beryllium has the highest specific stiffness of any pure metal, yet is more expensive than traditional alloys and requires stringent safety standards during fabrication. Aluminum alloys with rare materials such as beryllium, while prohibitively expensive, provide even higher specific stiffness and strengths and could prove to be a design alternative.

Table 4.7: Mechanical Properties of Beryllium

$\boldsymbol{\rho}$	1.85 g/cc
$\boldsymbol{E}$	303.4 GPa
$\boldsymbol{\sigma_y}$	241 MPa
$\boldsymbol{\sigma_u}$	324 MPa
CTE	11.4 ppm/K

Table 4.8: Pros and Cons of Beryllium

Pros:	Cons:
High strength to weight ratio	Expensive
	Toxic
	Brittle

4.1.1.1.5 Aluminum Alloys with Rare Alloys

Table 4.9: Mechanical Properties of an Aluminum-Beryllium Alloy

$\boldsymbol{\rho}$	2.1 g/cc
$\boldsymbol{E}$	193 GPa
$\boldsymbol{\sigma_y}$	328 MPa
$\boldsymbol{\sigma_u}$	139 MPa
CTE	13.9 ppm/K

Table 4.10: Pros and Cons of AlBeMet and Aluminum-Beryllium Alloy

Pros:	Cons:
Incredibly high strength to weight ratio	Expensive
Low thermal expansion	Not available from standard sources
Very high specific stiffness	
Can be fabricated with usual methods	

4.1.1.2 Composites

4.1.1.2.1 Carbon Fiber

Carbon Fiber is becoming a popular choice in aerospace structures for its high strength, low weight, and desirable thermal properties. Carbon fiber sheets coupled with a honeycomb material produce a lightweight but strong material, and the aircraft industry has already implemented this technology successfully. The main difficulties that may arise with this type of material are the mounting possibilities for heavier components, as well as the cost and time required to manufacture such pieces. One possible provider of a carbon fiber composite is ACP Composites, which sells a 24’’ x 48’’ sheet of Carbon Fiber Weave Honeycomb for $419.75[17]. This carbon fiber composite in 1/8’’ thickness has a weight of 3.0 oz/ft^2, translating to 0.2883 g/cc. While this may be an option for one side of the final structure, it is expensive and more difficult to fasten than traditional materials. However, the possibility of meeting the low mass requirement for the structure with carbon fiber is promising.

Table 4.11: Pros and Cons of Carbon Fiber

Pros:	Cons:
Lightweight	Expensive
Many possibilities of core material, variation of structural properties	Difficult to manufacture, especially in more precise shapes
	Requires coating

4.1.1.2.2 Glass Fiber

Fiberglass is another composite material that is often used to supplement or replace traditional structural materials. Its tensile strength properties are similar to carbon fiber, although glass fiber materials typically have lower stiffness than a carbon-based product. The main advantage that glass fiber has over carbon fiber in terms of this project is cost. ACP Composites sells a comparable 24” x 48” fiberglass honeycomb panel for $270.75, a 35% cost reduction from the carbon fiber panel listed above. The main disadvantage of glass fiber products is weight. While glass fiber materials provide similar mechanical properties to carbon fiber, they are denser and require a greater mass to achieve the same structural properties.

Table 4.12: Mechanical Properties of Glass Fiber

$\boldsymbol{\rho}$	2.60 g/cc
$\boldsymbol{E}$	40 GPa
$\boldsymbol{\sigma_y}$	2000 Mpa
$\boldsymbol{\alpha_1}$	5.0 E-6 /K

Table 4.13: Pros and Cons of Glass Fiber

Pros:	Cons:
Inexpensive, with similar tensile strength of carbon fiber	High density
Variability in core materials and properties	Difficult to manufacture
	Low stiffness

4.1.1.2.3 Aramid Fiber

Aramid fibers are synthetic composites, often referred to as "Kevlar". The properties of aramid materials typically fall within the ranges of glass fiber and carbon fiber. Aramid fibers provide a higher stiffness than glass fibers but still do not equal that of carbon fiber. Aramid fiber tends to be less brittle than carbon fiber, making it better suited to handle impact loads. Aramid fiber has similar density and strength properties to carbon that exceed the capabilities of glass fiber and are better suited to a lightweight structure. But, like carbon fiber, aramid and Kevlar products are expensive.

Table 4.14: Mechanical Properties of Aramid Fiber

$\boldsymbol{\rho}$	1.44 g/cc
$\boldsymbol{E}$	90 GPa
$\boldsymbol{\sigma_y}$	570 Mpa

Table 4.15: Pros and Cons of Aramid Fiber

Pros:	Cons:
Lightweight	Expensive
Fracture toughness	Low Stiffness
	Difficult to Manufacture

4.1.1.2.4 Honeycomb

Honeycomb materials are hugely popular in the aerospace industry. They are typically a sandwich structure, using a strong sheet of facing material on either side with a honeycomb material in between. Honeycomb composites provide excellent bending stiffness through the face sheets, while the internal material gives the composite its high stiffness. The result is a strong but exceedingly lightweight material that is reasonably affordable. The two ACP products priced above are honeycomb composites, as these types of panels are easily purchased in a variety of thicknesses and with varying sheet and core material types.

Table 4.16: Pros and Cons of Honeycomb

Pros:	Cons:
Lightweight	Expensive
High stiffness and strength	Difficult to Manufacture

4.1.1.3 Plastics

The growing popularity of 3D printing makes the use of thermoplastics a more promising option for spacecraft structures. Recently, JPL utilized Stratasys's Fused Deposition Modeling machine to print large antennas out of ULTEM 9085 and these antennas still maintained the structural properties needed to survive launch. This enabled JPL to build the complicated antenna structures quickly, and also manufacture them all in one piece and avoid additional manufacturing costs. Although ULTEM 9085 has never been used in spaceflight, this thermoplastic demonstrated a CVCM index of 0% outgassing (0.1% maximum), and Stratsys claims it passes tests for launch vibration loads[18]. In this case, S13G high emissivity protective paint is used to reflect solar radiation, but use of this paint increases the costs associated with this process. Although the density of ULTEM 9085 is a low 1.34 g/cc and this may meet FR 1, FR 2 demands a low cost material and manufacturing method which may not be accomplished with 3D printing technology today[19].

Table 4.17: Pros and Cons of Thermoplastic

Pros:	Cons:
Potentially easy to manufacture if 3D printing machine is acquired	Expensive
Variety of possible shapes	Relatively new technology, limited test data and manufacturing options

4.1.2 *Structural Design*

4.1.2.1 Traditional Approach

This design, shown in Figure 4.1, takes a traditional approach to meet anticipated launch loads. The structure is made of 0.375" thick, drawn and tempered aluminum AL T6061-T6, which is a proven material for spacecraft applications. The volume is constructed as shown in the drawing below. Panels are optimized and mass is reduced in many places using a 0.375" diameter for all cutouts; this sizing of cutouts also helps to minimize stress concentration. Currently the mass of this structure is estimated to be 18 kg. Assuming additional weight reductions can be made to the structure, the minimum anticipated mass is approximately 14 kg. Using material science, the design can be analytically quantified in aluminum but then a more lightweight material with similar strength indices can be used to improve performance and preserve the overall dimensions. The preliminary analysis shows that using a different material, an additional mass reduction may be expected with a factor of 2.14, translating to a new mass of 7 kg. This fails the 5kg requirement, but more analysis would be required to determine if this mass estimate is accurate.

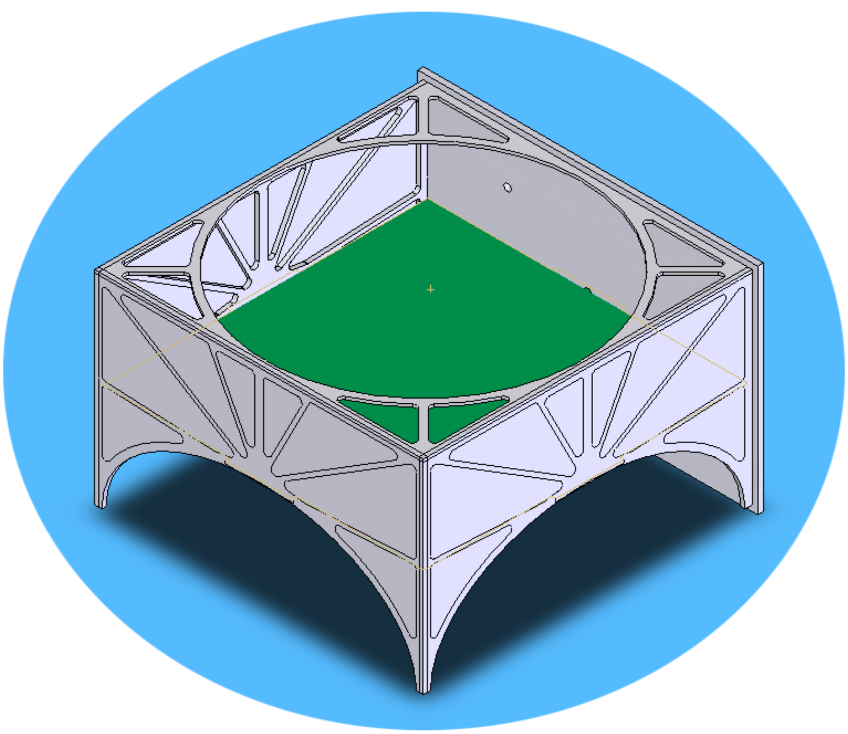


Figure 4.1: Traditional Design

Table 4.18: Pros and Cons of Traditional Approach

Pros:	Cons:
Traditional approach to structure design	Exceeds required mass limit
Allows for easy mounting of components	

4.1.2.2 Mass-reduced panel box

4.1.2.2.1 Design Description

Another possibility to minimize weight of a plated structure is a cut-out design. The design below (Figure 4.2) cuts out four rounded triangular shapes from a standard plate to maintain rigidity and mounting positions while reducing mass. This cutout design is applied to the surfaces on which the solar panels and radiative plate will be mounted. The cutout plates may be easily manufacturing in aluminum or another metal alloy, and a welding technique may still be used to merge all corners of the structure. However, to meet stricter loading requirements, a complete launch loading analysis must be conducted to ensure stress does not build up on the tightly curved corners. This is also dependent on the type of material used for these plates, and the cutout designs may be difficult to manufacture with a composite material.

The mass of just the structural components (removing the extra base plate and propulsion plate from the left image in Figure 4.3) totals to 11 kg in Aluminum 6061 and ~9 kg in carbon fiber Hexcel AS4C. (Hexcel AS4C has a significantly higher density than the previously analyzed carbon fiber honeycomb core sheets). This model assumes a 0.125'' thickness for all components, so these masses may be increased if the thickness is found to be inadequate.

Table 4.19: Pros and Cons of Mass-reduced panel box

Pros:	Cons:
Easy to modify cutout shapes to fit loading needs	Heavy
Possibly simple connections between plates	
Could be manufactured with different materials	

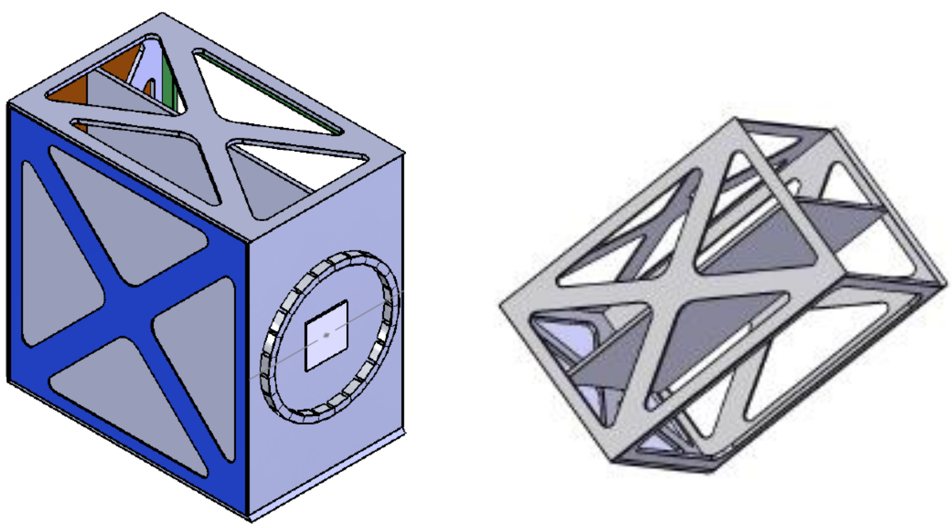


Figure 4.2: Mass Reduced Paneled Box Structure
(With components on left, only structure and radiator on right)

4.1.2.2.2 Feasibility Analysis

Back of the envelope analysis can be used to determine an initial panel thickness as well as weight and strength estimates. This is done assuming that the greatest loads experienced by the structure will be at the middle panel. This panel supports the combined mass of the payload and avionics (90kg), and has to transmit the loads from these masses through the structure and into the corners of the structure where it will be fastened (where the straps will support the structure in its padding). If this is the case, and assuming that the structure will fail in bending, not buckling, the worst loading will be the vibration load along the axis perpendicular to this flat plate.

The driving load is a 9.47 grms random vibration load, and from this the maximum probable acceleration seen by the structure can be extracted. According to GEVS ISS Pressured Volume Hardware Common Interface Requirements Document Rev C, a structure in a soft stowed condition will to experience a load of 1.29 grms. A 4σ acceleration of this 1.29 grms (5.16 g), should capture 99.99% percent of the loads experienced by the structure in soft stowed condition (assuming a normal distribution), and so this static acceleration is used as the basis for this back of the envelope calculation. Because there is not an excess of volume in the payload and avionics bays (initial analysis shows that the avionics components will cover roughly 70% of the middle panel), the calculations assume that the payload and avionics masses are spread across the entire panel, creating an even pressure distribution (q), as shown below in Figure 4.3.

$$q = \frac{F}{A} = \frac{(90\ kg)\left(5.16 \cdot 9.81 \frac{m}{s^2}\right)}{0.5798\ m^2} = 7.86\ kPa$$

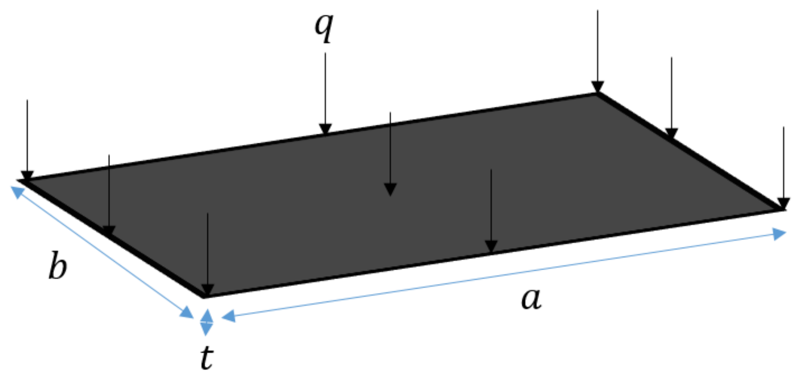


Figure 4.3: Flat plate showing uniform pressure distribution (q) and plate dimensions

For the purpose of this analysis, it is assumed that the side plates of the structure provide enough stiffness to keep the edges of the plate from deforming, but are not stiff enough to totally take out rotation along the edges. This results in simply supported boundary conditions, which are more conservative than assuming the four sides are fixed. From Roark9, it is seen that the maximum stress and maximum deflection of the plate under this loading condition (see Table 11.4 of Roark) are functions of the ratio of the side lengths, the magnitude of the pressure, q, as well as the stiffness and thickness of the material:

$$\sigma_{Max} = \frac{\beta q b^2}{t^2} \tag{4.1}$$

$$y_{Max} = \frac{-\alpha W b^2}{E t^3} \tag{4.2}$$

Where β and α are coefficients determined by the ratio of a to b. In this case, both a and b are 30 inches, so their ratio is 1. From Roark[9], this results in:

$$\beta = 0.2874$$

$$\alpha = 0.0444$$

Which results in:

$$\sigma_{Max} = \frac{1300}{t^2} Pa$$

Using a yield stress of 270 MPa (roughly that of 6061-T6 Aluminum), and applying a factor of 2 reduction to that (as a back of the envelope safety factor), the necessary thickness found is:

$$t = \sqrt{\frac{1300}{\frac{\sigma_y}{2}}} = \sqrt{\frac{1300}{135000000}} = 0.0031m = 0.1221in$$

This reveals that assuming 1/8" panels, visually weight-reduced to the best of the design team's engineering intuition, this mass estimate will be in the realm of feasibility.

4.1.2.3 Folded Composites Sandwich Structure

4.1.2.3.1 Design Description

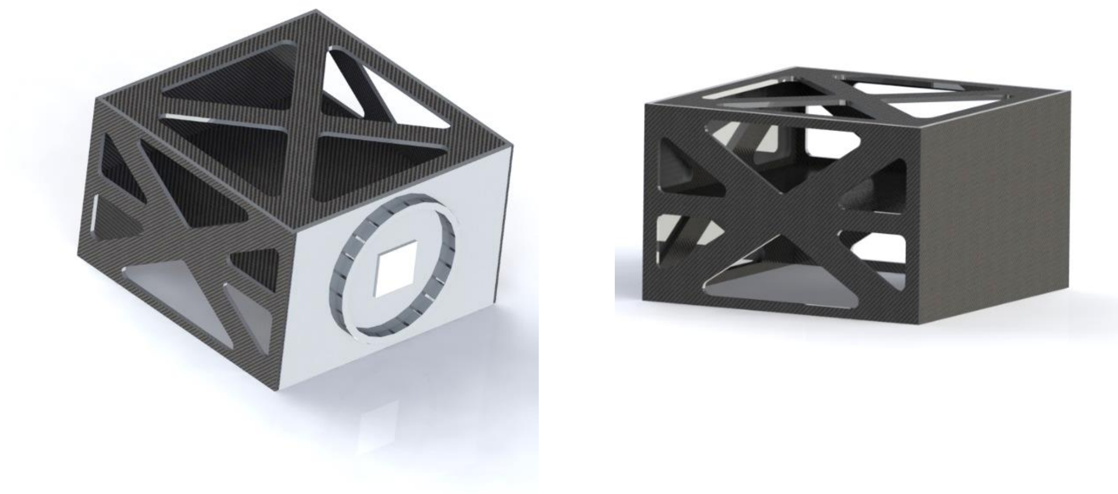


Figure 4.4: Rendering of proposed sandwich structure with weight-relieving cutouts

In addition to the weight-relieved solid panels, the structure could be fabricated from composite-honeycomb sandwich panels made up of a core (usually aluminum) and two face sheets (carbon fiber, glass fiber, aluminum, etc). This presents an opportunity in providing stiffness while keeping weight to a minimum. These panels also present an opportunity for lowering fastener count and increasing ease of assembly in that they can be cut and folded into shape and can take advantage of a tongue-and-groove construction system, as illustrated in Figure 4.5.

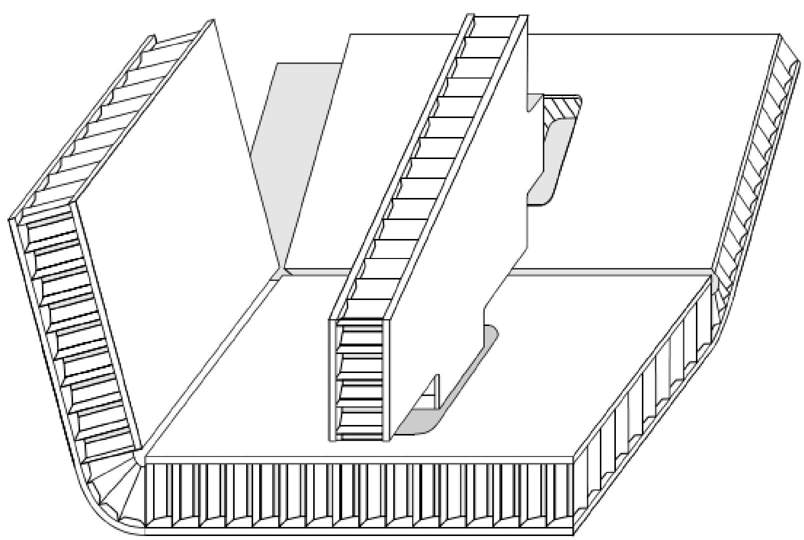


Figure 4.5: Concept drawing of folded-panel construction[1]

In a brief analysis using data and analysis methods from the Hexcel design guide, "Honeycomb Sandwich Design Technology"[8], the panels were assumed to be made from a honeycomb core (.375 in) of 5052

Aluminum with ¼" cells and a density of 127 kg/m^3. The face sheets were assumed to be one ply (~11 mils) of Carbon/Epoxy fabric (G793-5HS 60% volume). Using the layout pictured in Figure 4.4, the bare panels come out to a weight of 4.03kg, which leaves a margin for adhesives, fasteners, potting material, and manufacturing defects.

Table 4.20: Pros and Cons of Sandwich panel box

Pros	Cons
Very light weight – initial analysis demonstrates feasibility	Composite construction makes manufacturing difficult
Possibility of very low fastener count	Very expensive materials.

4.1.2.3.2 Feasibility Analysis

Numerical models for a composite structure must take into account the anisotropy of the material, and honeycomb panels become even more complex when material properties are smeared across a bending honeycomb structure. Composite structures are also very different throughout the manufacturing process – they cannot be welded, they are much harder to machine, and the installation of fasteners becomes more involved.
The same calculation as presented in Section 4.1.2.2.1 can be done for a honeycomb panel structure, with some modifications to account for the hybrid nature of the panels In order to achieve a mass goal of 4kg (and leave a mass budget for fasteners and stiffeners), a 0.375" panel with materials and properties was chosen. From Hexcel[8], the maximum stress and deflection of the same simply supported square plate are given by:

$$\sigma_{Max} = \frac{K_2 q b^4 \lambda}{E_f t_f h^2} \tag{4.3}$$

$$y_{Max} = \frac{-2K_2 q b^2}{h t_f} \tag{4.4}$$

Where t_f, and h are defined as shown below[8]:

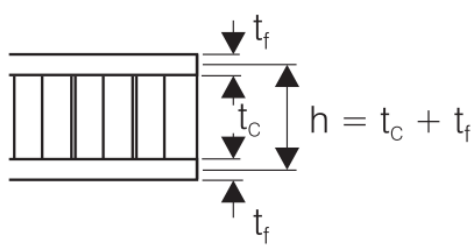


Figure 4.6: Definitions of honeycomb geometry terms

The coefficients K_1 and K_2 are found by comparing the material properties of the face sheets and core material with charts given in the design guide[8]. The materials used are 1-ply face sheets of a woven carbon epoxy (G793-5HS, .3mm thick) and 5052 Aluminum honeycomb with ¼" cells and a density of 127kg/m^3. Assuming that 0.375" panels are used (h), this results in:

$$\sigma_{Max} = \frac{\left(.048\frac{N}{m^3}\right)(7860Pa)(.7614m)^4(\sim 1)}{(70GPa)(.0003m)(.0101m)^2} = 62.4MPa$$

This value is almost an order of magnitude less than the strength of the carbon fiber sheets. Because this is not the driving factor, other values were also calculated including the deflection, compressive shear on the honeycomb, and local compression. The local compression was multiple orders of magnitude above the crush strength of the honeycomb, but deflection and shear came out to:

$$y_{Max} = .0085mm$$

$$\tau_{Max} = .174\ MPa$$

The shear is several orders of magnitude below the strength of the material, and the deflection was determined to be a non-issue. From this, it is concluded that a thickness of 0.375" would achieve the mass requirements and is within the realm of viability.

4.1.2.4 Stiff Columns box

4.1.2.4.1 Design Description

Figure 4.7: Stiff Columns Design

An alternative design is to use the propulsion plate as a base for four stiff columns, shown in Figure 4.7. These columns would interface with the propulsion plate and then run the remainder of the 30'' length of the spacecraft. To maximize the versatility of the structure, the column shape would to allow panels to slide the 30'' length. These panels would provide interface locations for avionics, payload and solar panels along with providing structural stability for the columns. The radiator would interface with the top of the columns, opposite the propulsion plate, sandwiching the columns and preventing torsion of the craft. When preliminarily modeled in Solidworks, the total mass of structure (disregarding the propulsion plate and using a 1/8 inch thick Thornel VCB Carbon Cloth radiator) using 6061 Aluminum Alloy is 5.694 kg. This mass could be further reduced if the sliding panels were made of composite materials. The columns have the potential to be manufactured as either a custom composite by wrapping sheets of pre-impregnated carbon fiber material around a form, or purchasing square tube carbon fiber. This model assumes a 0.125" thickness for all components.

Table 4.21: Pros and Cons of Stiff Columns Design

Pros:	Cons:
Lightweight	Possible problem with twisting
Highly adjustable to accommodate various payloads, avionics and solar panels	
Can be manufactured in a combination of materials	
Easy use of "snap together" design	

4.1.2.4.2 Feasibility Analysis

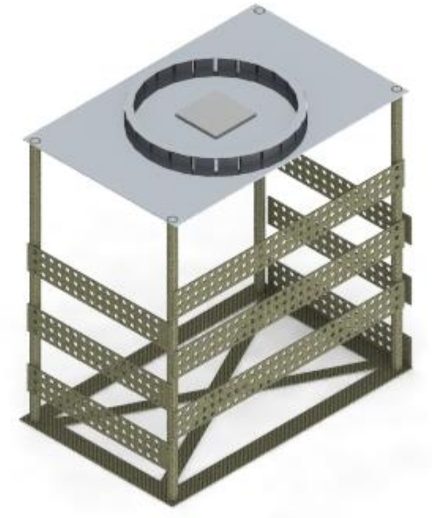
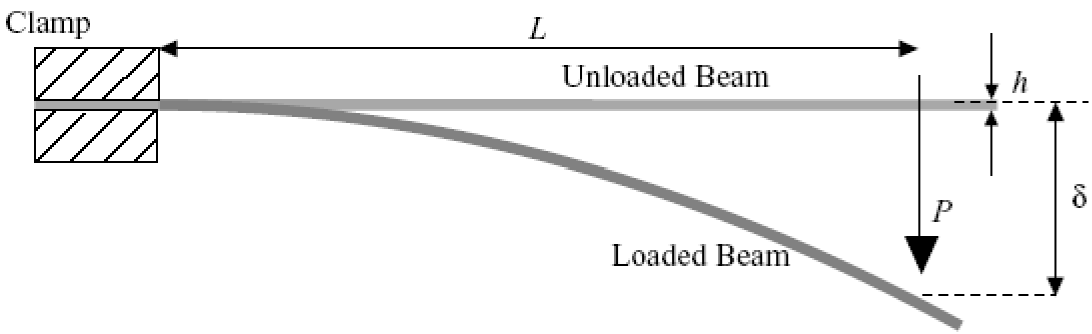


Figure 4.8: Column Box after Feasibility Analysis

In order to determine the shape and necessary wall thickness for the columns, a single beam was modeled as a cantilever beam.



To find the maximum deflection of the beam:

$$\delta = \frac{-PL^3}{3EI_{zz}} \tag{4.5}$$

Where L is the length of the beams, P is the force, E is the modulus of elasticity and I_{zz} is the moment of interia. The force was determined using the same 4σ value mentioned in Section 4.1.1 and assuming one quarter of the previously stated 90 kg is loaded on the beam. When using a square cross section, a maximum deflection of 9.86 cm resulted. This is a very large deflection and definitely removes square columns from the realm of possibility. In an effort to determine what could be used, a circular cross section was substituted into the equation. This resulted in a maximum deflection of only 0.82 cm. While this is still a large deflection, it is acceptable under these exaggerated loading conditions and can definitely be decreased with reinforcement later in the design.

Changing the material from the perspective design in section 4.1.2.4.1 of T6061 Aluminum to carbon fiber, the mass of the structure decreased from over 5 kg to about 4.01 kg. As shown here, this design utilizes off-the-shelf composite tubes and panels which decrease cost and manufacturing time.

4.1.3 Assembly Options

Once the structure is manufactured it must be assembled, and to do this the various components of the structure must be bonded in some way. Although the method of assembly depends hugely on the material(s) used to make the components of the structure, various methods of assembly were compared to determine which, if any, could be eliminated or which stood out as the best possible option. The four options considered are traditional fasteners, snap together components, adhesives and welding. Criteria such as cost, availability, ease of use, ease of analysis, life expectancy, strength, easy of disassembly, and additional mass were considered when determining the pros and cons of each assembly method

4.1.3.1 Traditional Fasteners

Traditional fasteners such as machine screws, bolts, washers and nuts are typically used in the aerospace industry to assemble space craft. However, rather than stainless steel fasteners, which could be purchased in a hardware store, A286 Fasteners are typically used; a precipitation hardened alloy with the properties listed in Table 4.22. While the cost is significantly higher than that of typical fasteners, the performance is much higher.

Table 4.22: Mechanical Properties of A286 Fasteners[14]

Rockwell Hardness	1.44 g/cc
$\boldsymbol{\sigma_y}$ **(min)**	724 MPa

Table 4.23: Pros and Cons of Traditional Fasteners

Pros	Cons
Available	Heavy
Strong	Expensive
Easy to analyze	
Easy to design for	

4.1.3.2 Snap Together Design

Another option is to design the structure to snap together on its own. This would be simpler for assembly, but could make using off the shelf components very challenging.

Table 4.24: Pros and Cons of a Snap Together Design

Pros	Cons
Low additional cost	Difficult to model
Available	Difficult to design
Low additional mass	Difficult to achieve sufficient strength
Ease of assembly	

4.1.3.3 Adhesives

Although not traditionally used in space applications because of outgassing and brittleness concerns, some adhesives have been developed which can withstand the challenging conditions of space. These are usually used for attaching components and not for structural components[15]. So, while this may be a viable option for attaching payload, avionics and solar arrays, there may be an additional method required to hold the structure together.

Table 4.25: Pros and Cons of Adhesives

Pros	Cons
Low additional mass	Expensive
Ease of assembly	Difficult to analyze
	Little heritage knowledge

4.1.3.4 Welding/Co-bonding

If an aluminum design is chosen, welding components is a low mass, high strength option to permanently attach components. If a composite design is chosen components can be co-bonded with very little additional mass. Both options require additional skill to execute well.

Table 4.26: Pros and Cons of Welding/Co-Bonding

Pros	Cons
Low additional mass	Permanently Attached
Low additional cost	Requires high skill
Easy to Analyze	
Strong	

4.1.4 Radiator Selection

As per DR 5.4, the FeatherCraft structure design shall dissipate 100W of heat generated by the avionics and payload bays. Per DR 5.4.1, the structure design shall accomplish the100 W dissipation by including an emissive material on Side 6 to face deep space and radiate thermal energy. There is no requirement to analyze thermal pathways through the structure, only to include in the design a radiator capable of dissipating 100 W of heat produced by the remainder of the satellite. The maximum area allocated for thermal radiation is one 19" x 30" side of the spacecraft structure. Spacecraft radiators are available in a variety of forms and configurations, but ultimately involve a surface that emits heat from its surface at a rate dependent on the emissive properties of the material, the area available to radiate from, and the temperature of the surface. Design options for the FeatherCraft radiator are analyzed in
Table 4.27, Table 4.28, and Table 4.29. Given the relatively low 100 W dissipation requirement and the project's emphasis on reducing costs, mass, and complexity, only passive thermal radiator solutions are considered. The complexity and extra mass required of active thermal control does not make it a feasible option[20].

4.1.4.1 Body Mounted Panel

A body-mounted radiator is a simple passive solution for a spacecraft that requires small amounts of thermal radiation. Mounting an additional radiator to a spacecraft requires additional mass from the radiator and its fastening. It would typically be used for a structure that has a very specific design necessary to supporting the rest of the spacecraft. If this design requires a specific material or configuration that makes the structure itself not suitable for thermal radiation, a radiator can be mounted to the spacecraft and provide thermal pathways to the spacecraft interior. Despite the drawbacks of additional mass, advantages of a mounted radiator include the ability to operate the radiator at a different temperature than the spacecraft, and to choose a different material for the radiator itself, both of which increase its effectiveness.

Table 4.27: Pros and Cons of Body Mounted Panel Radiator

Pros:	Cons:
Radiator can operate and a different temperature than the spacecraft	Additional mass of the radiator panel and any fastening method
Material selection is independent of the structure	Impact to structural volume
	Increased technical difficulty of conducting heat into the radiator

4.1.4.2 Structural Panel

Another popular form of passive thermal control is the use of a part of the spacecraft structure as the radiator. This provides the obvious advantage of not needing the additional mass of a mounted radiator by simply using the mass and surface area already allocated to a structural panel. The main difficulty of using a structural radiator is that the radiator cannot be designed independent of the structure. Its material selection must take into account the need to physically support the spacecraft. Passive radiators rely on sufficient surface area to reject enough heat, which also impacts the structural design by limiting the amount of mass reduction that can be performed on the radiator panel.

Table 4.28: Pros and Cons of a Structural Panel Radiator

Pros:	Cons:
No additional radiator weight	Requires panel surface area, impacting the ability to reduce the mass of side 6
Radiator contributes to structural support and rigidity	
Simplistic thermal design	
Flexible material selection	

4.1.4.3 Deployable

Deployable radiators are a thermal solution for cases where structural or mounted radiators are incapable of providing enough heat rejection. Deployable radiators can utilize more surface area, and radiate more heat, and a panel. However, this requires a far more complex design to deploy the radiator and provide thermal pathways to it. Ultimately if sufficient thermal radiation can be achieved with one of the other options, they are far more feasible for use on the FeatherCraft structure.

Table 4.29: Pros and Cons of a Deployable Radiator

Pros:	Cons:
Flexibility in material selection and available surface area	Technical complexity
	Additional mass

Based on the pros and cons of the three passive thermal radiator design options, the most feasible and attainable design option is a structural panel radiator. This design will use one 19” x 30” of the FeatherCraft structure as the thermal radiator. This design allows the structure to meet the thermal dissipation requirement without adding unnecessary mass for a separate radiator panel. The main drawback of a structural radiator is the need for surface area to radiate from, which may limit the ability to reduce the mass of the panel. Radiation from a structural panel facing deep space is characterized using Eq. (4.6), where q is heat radiated, σ is the Stefan Boltzmann constant, ϵ is the emissivity of the material, and T is the temperature of the panel.

$$Q = \sigma \epsilon A T^4 \tag{4.6}$$

The ability to radiate heat from a panel radiator is dependent on the expected temperature of the panel, the emissivity of the outside of the radiator, and the surface area of the radiator. It is preferable to minimize the necessary surface area for emission. This allows more flexibility for mass reduction of the Side 6 panel. Reducing A is done by increasing thermal emissivity, which is dependent on the material of the radiator. Since material selection is being studied for the overall FeatherCraft structure, two options are being considered for the radiator. If the panel is made of a type of metal or similarly low emissivity material, a highly emissive coating must be used on the outside of the radiator. If the panel is made of carbon fiber or a similarly high emissivity material, no coating is necessary, and the structural panel itself will provide enough thermal emission to meet requirements. Typical thermal emissivity values of carbon based materials, as well as thermally emissive coatings, exceed 0.8. A sample calculation of the surface area needed to emit 100 W is shown using an emissivity of 0.7 (design margin), and an operating temperature of -20 to 50 degrees Celsius as specified by the customer.

$$A = \frac{Q}{\sigma \epsilon T^4} = \frac{100\ W}{\left(5.67 * 10^{-8} \frac{W}{m^2 K^4}\right)(0.7)(303\ K)^4} = 0.299\ m^2 = 463.30\ in^2$$

The available surface area the panel on Side 6 is 19” x 30” or 570 in^2. This demonstrates that even with design margins considered, Side 6 of the FeatherCraft structure can be used as a thermal radiator and still allow mass reduction of around 30% of the total panel area, provided that either the material of the panel or a thermally emissive coating has a thermal emissivity over 0.7.

4.2 Data Acquisition Options

4.2.2 Accelerometers

Because many accelerometers are desired for ease of testing but not many are required in terms of retaining them for the system, three options are considered for obtaining accelerometers. The pros and cons of each option are described in Table 4.30 and Table 4.32.

4.2.1.1 Build Digital Output Accelerometers

This design option considers building a breakout board and communication protocol around an accelerometer IC chip. Several IC chips – including the STM LIS3DH and STM IIS2DH– feature an accelerometer, ADC, and I2C or SPI digital data outputs all integrated into a single chip. The SPI protocol supports clock speeds up to 10 Mbps.

The devices have load ranges of $\pm 4g$ or $\pm 8g$, selected by setting bit registers as desired. The devices have output data rates up to 5 kHz, and -3 dB bandwidths of 2.5 kHzx[12].

A miniature breakout board will be built around the accelerometers. The breakout boards will require power capabilities – typically 3.3V at a few μA – including decoupling capacitors. The breakout board will also require a data output location in the form of a pin in which to solder a wire.

The IC's cost around $3 per unit, decoupling capacitors and other peripherals cost a few dollars in bulk, and the printed circuit board costs around $40 for a 20 sq. inch design. Each breakout board should be about 1 sq. inch large, if that. The total monetary cost per unit for this design option will be around $6[12].

Table 4.30: Pros and Cons of Building Digital Output Accelerometers

Pros:	Cons:
Inexpensive	Debugging Intensive
Reduces need for multiple channel inputs	Production time
No external ADC's required	Lower reliability than more expensive devices
Digital output means robust data transfer	Software intensive to set up and executed communication protocol
	Performance of MEMS accelerometers degrades at high frequencies

The accelerometer selection drives the hardware configuration for the data acquisition system, which is presented next. Assuming the 'Build Digital Output Accelerometers' design option is selected for accelerometers, the data acquisition hardware configuration would be as shown in Figure 4.9. Several IC's can be connected to the same micro-controller – limited only by the number of digital pins available on the micro-controller – using the SPI or I2C communication protocols. The micro-controller provides power to each of the IC's, and the IC's provide 3-axis acceleration data. The micro-controller is connected to a PC via a USB connection.

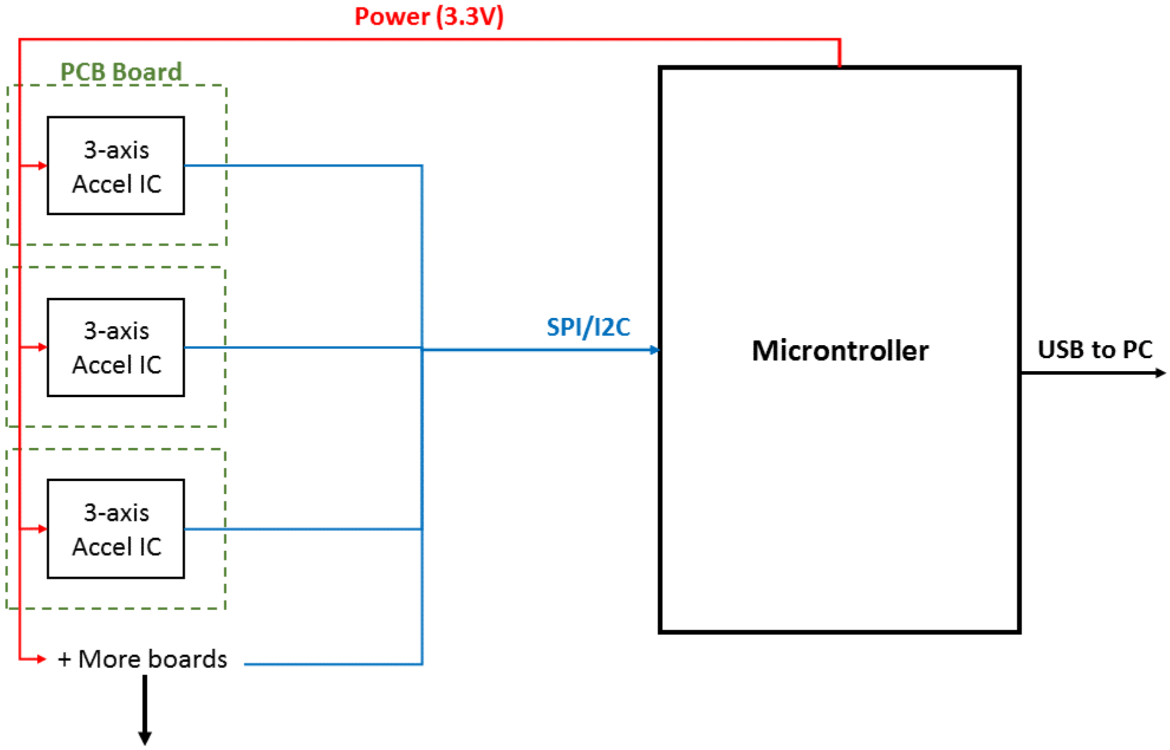


Figure 4.9: Digital Output Accelerometers Design Option Configuration

Each of breakout boards is flat on the back and can be mounted to the structure using a simple adhesive.

4.2.1.2 Buy Piezoelectric Accelerometers

This design option focuses on the purchase of existing off-the-shelf accelerometers. The primary supplier of these accelerometers is PCB Piezotronics Inc. who specializes in piezoelectric sensors and their required signal conditioning units. Two accelerometers were selected that meet the required vibrations testing for this project, the single axis model #333B30 and the triaxial model 356A16[11]. Specifications for each are listed below in Table 4.31.

Table 4.31: Accelerometer Specifications[11]

Spec:	333B30:	356A16:
Sensitivity ($\pm$ 10%)	100 mV/g	100 mV/g
Measurement Range	$\pm$ 50 g pk	$\pm$ 50 g pk
Frequency Range ($\pm$ 5%)	0.5 – 3000 Hz	0.5 – 3000 Hz
Resonant Frequency	$\geq$ 40 kHz	$\geq$ 25 kHz
Broadband Resolution	0.00015 grms	0.0001 grms

These piezoelectric sensors have internal circuitry that amplify and convert the piezoelectric capacitance signals to a readable voltage output. This voltage output requires a charge amplifying circuit before it is sent to the data acquisition system. This circuit, given below in Figure 4.10, can be purchased from PCB or built by the team as part of the data acquisition system.

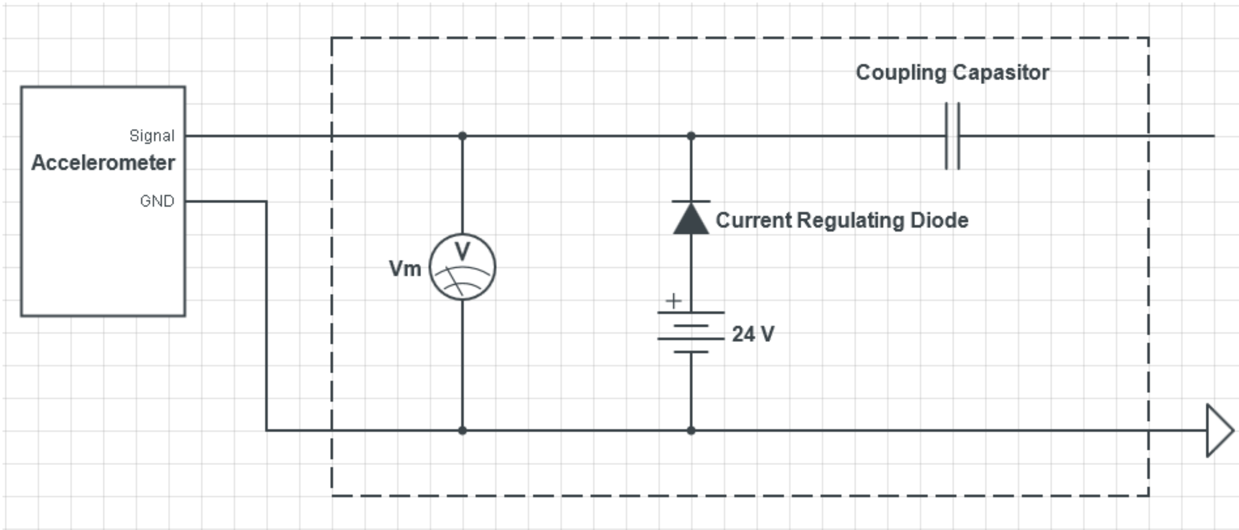


Figure 4.10: Charge Amplifying Circuit

The primary concern for this design option is cost. A current quote from PCB lists the single axis accelerometers at $297.00 per unit, the triaxial accelerometers at $931.50 per unit, and a four-channel charge amplifying signal conditioning unit at $472.50 per unit[13]. Table 4.32 summarizes the pros and cons of this design option.

Table 4.32: Pros and Cons of Buying Accelerometers

Pro:	Con:
Very Accurate and repeatable	Expensive
Easy to use	Requires additional signal conditioning
Prebuilt resulting in saving time	

4.2.1.3 Rent Piezoelectric Accelerometers

This design option focuses on the use of rented accelerometers from The Modal Shop Inc. The Modal Shop Inc. is a member of the PCB Group and has PCB brand accelerometers and signal conditioning hardware available for rent. This design option is similar to the Buy option listed above; the only difference is the accelerometers are rented instead of purchased in an effort to save money. The current Modal Shop domestic pricing is listed below in Table 4.33.

Table 4.33: Accelerometer Rental Prices

Hardware:	Price:
333B30 Single Axis Accelerometer	$60.00 per 30 days
356A16 Triaxial Accelerometer	$200 per 30 days
482C05 4-channel Charge Amplifying Signal Conditioning Deck	$140 per 30 days

4.2.3 Data Analysis Software

4.2.2.1 Python

Python is an open-source, high-level, object-oriented scripting language that contains libraries with GUI support, mathematical operations, and plotting features. A Python script is written using an open-source IDE and can be loaded and executed by a laptop computer. All libraries used in the executed file must be present and in a known location.

The age and open-source nature of Python entails support via different avenues, including, but not limited to: peers, professors, online forums, and pre-built libraries for certain sensors and GUIs.

Table 4.34: Pros and Cons of Python

Pro:	Con:
Scripting language easier to use	Libraries need to be installed
Lots of prebuilt libraries i.e. FFT	Not very portable
Works well with file I/O	Python debugging is time consuming

4.2.2.2 Perl

Perl is also an open-source scripting language. Perl is a medium-high-level wrapping language based on C that contains modules of user generated functions for GUI creation, data plotting, mathematical operations, etc. Perl is written in a runnable source code format that requires an OS to compile at every use. All libraries and executable files must be present in a known location for operation. As with Python, the age and open-source availability of Perl allows for extensive support and modular pre-built functions and libraries.

Table 4.35: Pros and Cons of Perl

Pro:	Con:
Lots of prebuilt modules ie. Excel, FFT, GUI, plotting	Libraries need to be installed
ShareWare with plenty of online support	Low level coding (wrapper for C)
Not very resource intensive (Processes, RAM, memory)	Must be compiled every execution

4.2.2.3 LabVIEW

LabVIEW is a National Instruments product used in testing data acquisition systems. LabVIEW uses a graphical programing system as opposed to most scripting languages. LabVIEW has the capabilities of working through an embedded system with other National Instruments data collecting units. Another draw is that LabVIEW excels at real time display during a test. Almost all of the experimental labs in the Aerospace curriculum used real time display during the test to show graphs and all data was exported into an Excel file for ease of use. The major problem with this option is the licensing information, whether the program can exist solely on a USB external drive or if it will have a problem being used on different laptops.

Table 4.36: Pros and Cons of LabVIEW

Pro:	Con:
Has a lot of complex math tools	Lacking group knowledge
Is designed to work with data acquisition	Have to pay for licensing
Can display real time display easily	Portability is little to none
Export to Excel simply	

4.3 Data Acquisition System Designs

4.3.2 Design 1 – Digital Accelerometers System

This design option incorporates the building of accelerometer breakout boards that will provide data via a digital communication protocol. This configuration involves one serial line connecting all the accelerometers to the micro-controller. Figure 4.9 shows a functional block diagram of this design option.

4.3.3 Design 2 – Build Data Acquisition System with One Micro-Controller

This design option would use accelerometers purchased. The accelerometers would be hooked up to the designed data acquisition system as seen in Figure 4.11.

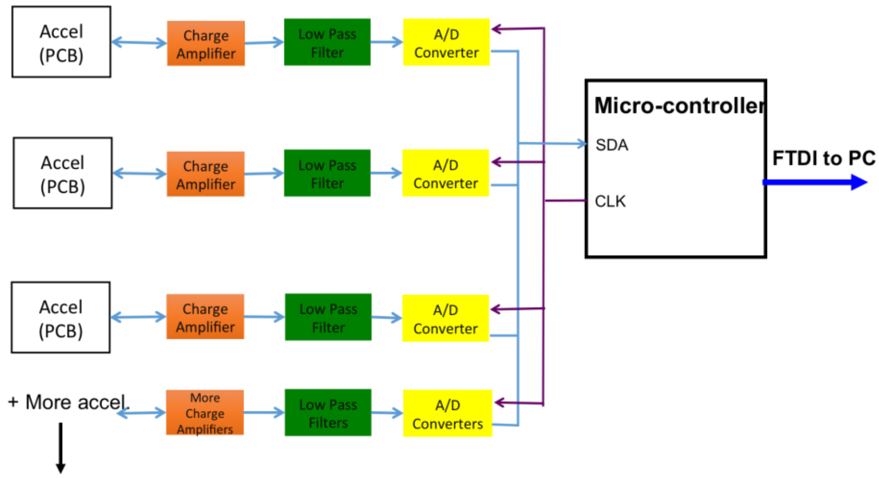


Figure 4.11: Build Data Acquisition System with One Micro-Controller

The system would include a charge amplifier to power the accelerometers. There will also be a low pass filter to remove any higher harmonic frequencies that could be experienced during testing. Both of these will have to be built for each accelerometer. These will then connect to an analog to digital converter, which converts the signal into a digital output that can be translated into the I2C or SPI communication protocol. Through this method the amount of inputs on the micro-controller can be cut down since there only needs to be a clock signal and a digital input for the I2C/SPI communication protocol to function correctly. The software used to control the micro-controller and configure the settings on the micro-controller will be C. The micro-controller will be hooked up using an FTDI cord through a serial port to a computer for real time display and also displayed using a third party software uploaded via USB stick. Raw data then can be exported off the controller after the completion of the test. Graphic User Interfaces (GUIs) will be developed to display the data on the user's computer. The circuit diagram below demonstrates how the signal will flow for this specific configuration.

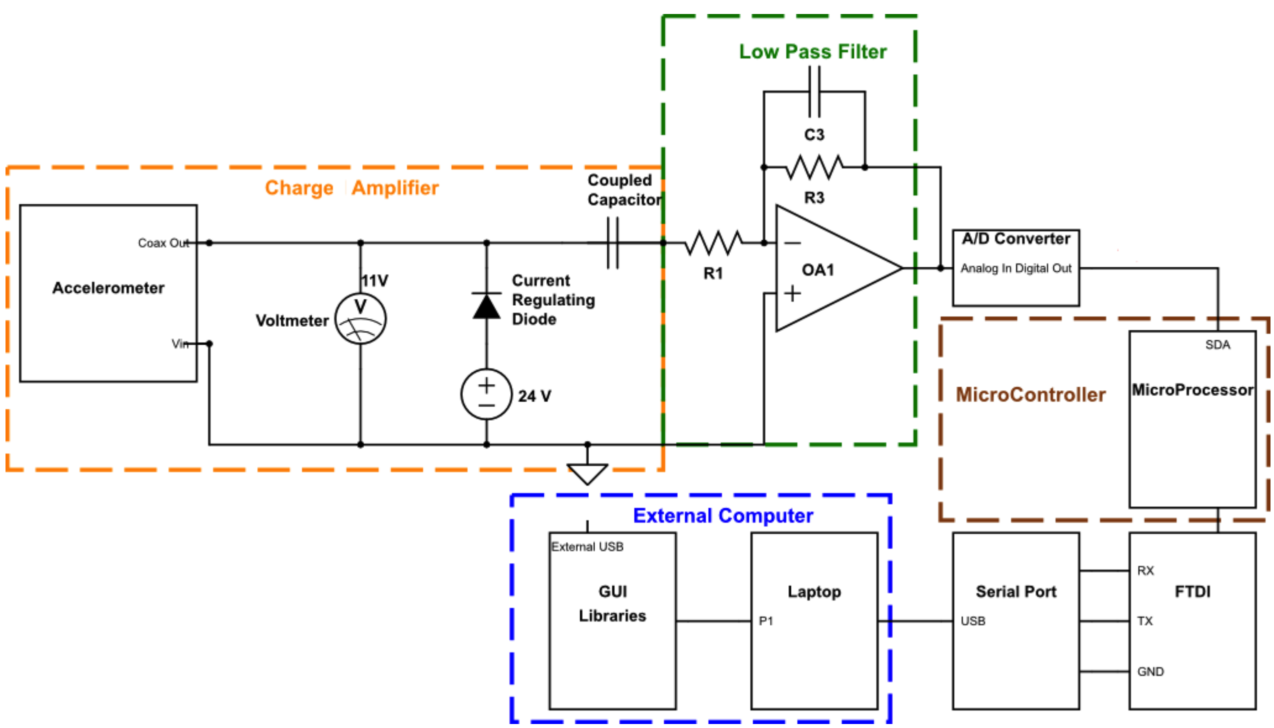


Figure 4.12: Circuit Diagram for Single Microcontroller Sesign

4.3.4 Design 3 – Build Data Acquisition System with Multiple Micro-Controllers

This design is similar to that of the previous. The baseline electronics are all the same except for multiple micro-controllers will be used. The design can be seen in Figure 4.13.

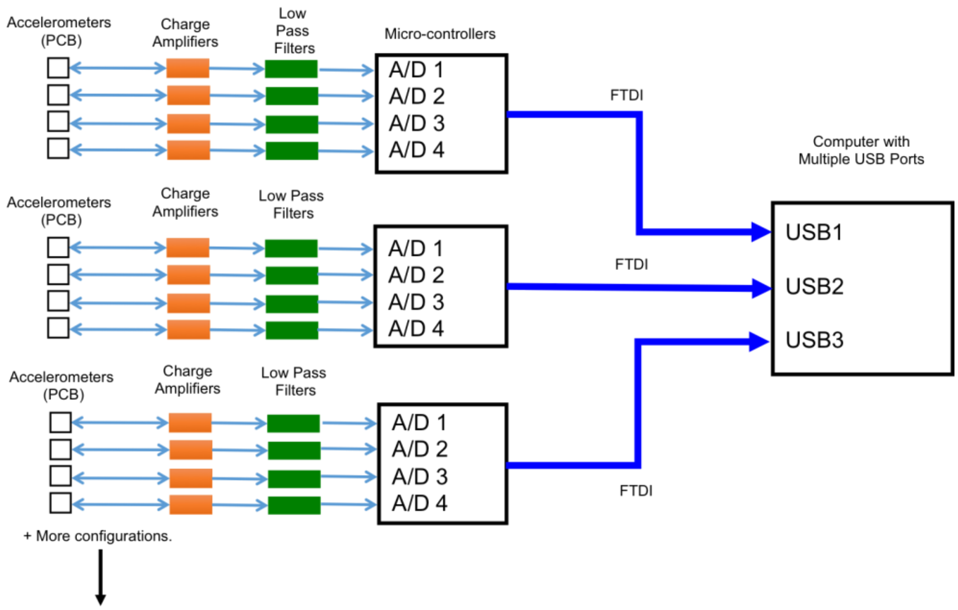


Figure 4.13: Design with Multiple Micro-Controllers

For this design there will be multiple micro-controllers that connect to a set of accelerometers, charge amplifiers, and low pass filters in order to provide enough channels for A/D conversion. The micro-controllers will each utilize an FTDI cord and a serial bus to transfer the digital data to the computer. There will be a slight timing issue when the data reaches the computer because the micro-controller's timing will not be synced up and instead will rely on the fact that the data acquisition starts at the same time on each micro-controller. Each configuration will be on its own board. The circuit diagram seen in Figure 4.14 is almost identical to the one for the single micro-controller the only real difference being that the A/D conversion occurs within the micro-controller.

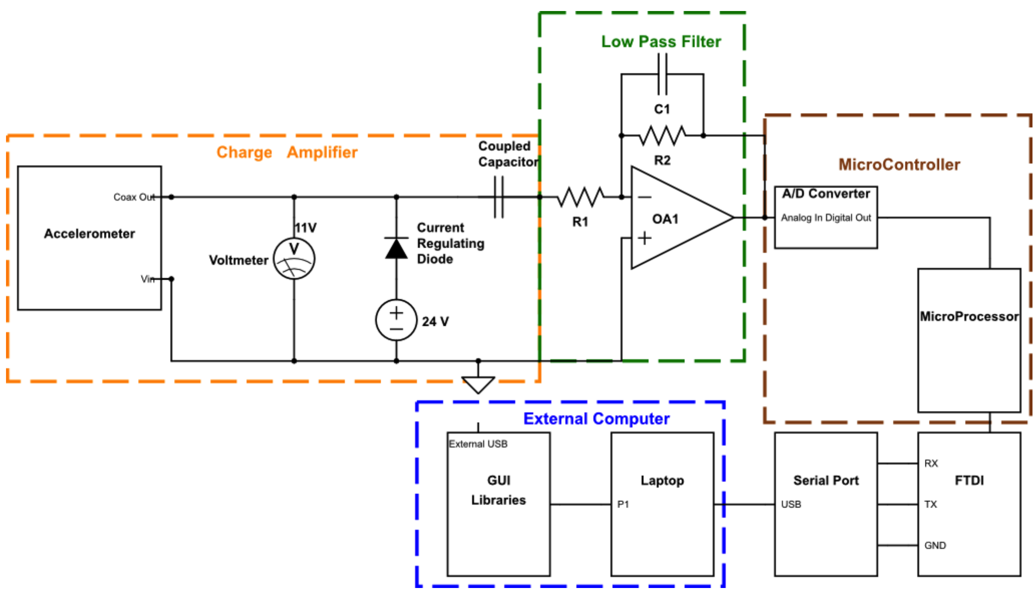


Figure 4.14: Circuit Diagram for Multiple Micro-Controller Configuration

5.0 Trade Study Process and Results

5.1 Structural Design Trades

5.1.1 *Trade Study Criteria*

The three key designs presented in section 4.3 all demonstrate some feasibility in simple stress and mass calculations, but many differences set them apart in actual implementation. A trade study is performed to differentiate many factors flowing into the design. The criteria considered are as follows, ordered from most important to least important.

Mass of the overall design is the dominating factor in this trade study. All materials and shapes have shown a possibility to meet DR 1.1, but the overall designs must be compared to determine the most likely candidate to meet the requirement after fabrication. Designs with masses in the 4-5 kg mass range are most desirable because this allows flexibility for assembly and mounting methods. Because of the high level requirement placed on mass, this criterion has the heaviest weighting.

Ease of manufacturing is critical to the project both for the customer and the design team. DR 2.2 and DR 2.3 state the necessity of the assembly to be manufactured quickly and at a lower cost than previous designs. This is difficult to quantify in numbers, but best estimates are given from manufacturing knowledge and research. The design team must fabricate a similar structure for FR 5, so this prototype must maintain structural properties of the design but be manufactured in one semester.

The *ease of analysis* of a particular design is a consideration required because of the extensive modelling needed to design an expensive structure. Thorough analyses must be performed before fabricating any component and complicated structures and materials increase the time and cost involved.

Material cost is relevant to the project because the funds for prototype fabrication are limited. However, DR 2.1 presents a significantly higher budget, and the materials researched thus far are not approaching the limit of this budget. Therefore, there is some budget consideration for the trade study, but it is the lowest level of consideration because it is not a challenge for DR 2.1 and an alternative, cheaper material will be chosen if prototype fabrication costs exceed the allotted $5000 team budget.

5.1.2 *Trade Study Metric Definitions*

Table 5.1: Metrics for Design Trade

	10	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
Material Cost (kg)	1	2	3	5	7.5	10	12.5	15	17.5	20
Mass (kg)	4	5	5.5	6	6.5	7	7.5	8	9	>10
Ease of Manufacturing (hrs)	10	20	30	40	50	60	70	80	90	100
Ease of Analysis	A monkey could do it	Plug and play	Very little effort required	Little effort required	Some effort required	Neutral	Effort required	Much effort required	Too much effort required	I quit

5.1.3 *Trade Study*

Table 5.2: Mechanical Design Trade Study

		Metallic Weight-relieved Panels	**Honeycomb Weight-relieved Panels**	**Columns**	**BatBox**
Criteria:	**Weight:**	**Score:**	**Score:**	**Score:**	**Score:**
Material Cost	16%	10	6	8	9
Mass	35%	2	10	9	2
Ease of Manufacturing	26%	7	6	7	5
Ease of Analysis	23%	8	8	6	8
Weighted Total:		5.95	7.86	7.63	5.26

The designs clearly fall within two categories: the feasible lightweight options and the heavier options. All options do not require significant analysis effort and also similar manufacturing time, which is well below the maximum manufacturing time allowed by customer requirements. Because of the closeness of the Honeycomb weight-relieved panels and the Columns method, these will be further discussed in Section 6.

5.2 Data Acquisition System Design Trades

5.2.1 *Accelerometers*

5.2.1.1 Accelerometers Study Criteria

The following criteria were used to conduct trades studies on the accelerator options; also presented is the rational for each criteria selection.

Unit cost was included due to the inflexible budget constraint for the project. This makes unit cost the top priority for the accelerometers, especially since their price was a primary and immediate concern after learning the customer requirement DR 6.6.1.

Ease of Design, meaning the facility with which the final product is designed and implemented – to include time invested and debugging efforts when dealing with the accelerometers – is important due to the structured nature and hard deadlines of Senior Projects. This means the accelerometers must be simple enough to be able to have a plan for them whether it is buying, building, or renting at the readiness level required for each stage of the class (PDR, CDR, etc.).

The accelerometers must be *easy to interface* with the structure, given that they are required to be mounted to the structure – and remain on it – during vibration testing. This warrants considerations in the interface methodology.

For the purposes of repeating tests, the accelerometer's *reliability* must be considered. Not only is a test failure undesirable, but also system degradation – especially if it occurs at a rate that prevents repeatable results during the same set of tests.

Finally, system *mass is* considered and should be maintained as low as possible. It is important that the accelerometers be small and light enough to be considered negligible with respect to the mass of the rest of the structure, thereby guaranteeing no interference with measurements during the vibration test.

5.2.1.2 Accelerometers Trade Study Metric Definitions

The trade study criteria are assigned a normalizing factor in Table 5.3. The factors are distributed form 1 to 10 with metrics linearly distributed. The range of the metrics is determined based on preliminary research findings: for example, the most expensive accelerometers found cost just under $900, therefore the largest value for cost included in Table 5.3 is $1000. Note that qualitative metrics are distributed to the extrema.

Table 5.3: Normalizing Factors for Trade Study Criteria

	10	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
Unit Cost	< $1	$1-$5	$5-$10	$10-$50	$50-$100	$100-$250	$250-$500	$500-$750	$750-$1000	>$1000
Reliability	90-100%	80-90%	70-80%	60-70%	50-60%	40-50%	30-40%	20-30%	10-20%	0-10%
Ease of interface to the structure	A baby can do it	Plug and play	Very little effort required	Little effort required	Some effort required	Neutral	Effort required	Much effort required	Too much effort required	I quit
Ease of design (including time invested)	Done!	Very easy	Easy	Somewhat easy	Neutral	Somewhat hard	Hard	Very hard	Uber hard	Impossible
Size/mass	0 - 0.5g	0.5 - 1g	1 - 1.5g	1.5 - 2g	2 - 2.5g	2.5 - 3g	3 - 3.5g	3.5 - 4g	4 - 4.5g	>4.5g

5.2.1.3 Accelerometers Trade Study

Table 5.4: Accelerometers Trade Study

		Digital Accelerometers	Buy Piezoelectric Accelerometers	Rent Piezoelectric Accelerometers
Criteria:	**Weight:**	**Score:**	**Score:**	**Score:**
Unit Cost	37.5%	8	2	5
Reliability	37.5%	1	10	9
Ease of Interface to the Structure	5%	6	9	9
Ease of Design (including time invested)	15%	4	10	10
Size/mass	5%	8	2	2
Weighted Total:		4.625	6.55	7.3

From this trade study, the obvious choice is to rent piezoelectric accelerometers. This option has all the benefits of buying piezoelectric accelerometers but with less cost, and the requirement set forth by the customer only describes a need to purchase one tri-axial and one single-axis accelerometer. Digital accelerometers drastically lose appeal with their low reliability.

5.2.2 *Data Analysis Software*

5.2.2.1 Data Analysis Software Study Criteria

Cost was included in the trade study because the low budget margin makes the impact of even a student license to software important. Scripting languages such as Perl or Python are Shareware and free to use and implement, but higher level software such as LabVIEW and MATLAB require expensive licenses to use.

Ease of implementation refers to the amount of time and effort required to script the software for the desired purpose. Higher level languages that have ready to use functions will be easier to implement than lower level scripting languages that require more original coding by the team.

Resources Available refers to the amount and accessibility of supporting documentation and debugging help that a specific scripting language has. This includes things like online documentation, forums, reference books, local resident experts in the university that can be called upon, etc.

5.2.2.2 Data Analysis Software Trade Study Metric Definition

Table 5.5: Software Metric Definitions

	10	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
Cost	Free	$50-$100	$100-$150	$150-$200	$200-$250	$250-$300	$300-$350	$350-$450	$400-$450	>$450
Ease of implementation	A baby can do it	Plug and play	Very little effort required	Little effort required	Some effort required	Neutral	Effort required	Much effort required	Too much effort required	I quit
Resources Available	You can ask your mom for help	Courses taught on this, easy tutorials	Resident experts along with lower level resources	Profs., peers, online material	Peers, abundant online material	Peers, some online resources	Manuals, few online resources	Few online resources	Select books offer resources	No help from any resource

5.2.2.3 Data Analysis Software Trade Study

Table 5.6: Software Trade Study

		Python	**Perl**	**LabVIEW**
Criteria:	**Weight:**	**Score:**	**Score:**	**Score:**
Cost	20%	10	10	5
Ease of implementation	60%	6	4	7
Resources Available	20%	9	9	8
Weighted Total		7.4	6.2	6.8

This trade study results in a very close weighted total, due to the equal resources available for all software types and the cost vs ease of implementation for LabVIEW against Python and Perl. However, Python does stand slightly above the other two options and is rated highly in all categories.

5.2.3 *Data Acquisition Hardware Configurations*

5.2.3.1 Data Acquisition Hardware Configuration Trade Study Criteria

Manufacturing Difficulty is considered due to the fact that the team is investigating team manufactured data acquisition boards where electrical component selection, circuit design, and manufacturing will be done in-house. Difficulties such as soldering requirements, board verification and testing, and required manufacturing precision make up this criterion.

Total Cost is considered once again because of the fixed budget of the project.

Complexity of Design refers to the amount of detailed components are required for proper operation of the design. The more complex a design is the more points of failure that exist and probability of failures can increase especially when a complex design is manufactured in-house.

Reliability refers to how reliable a design is expected to be. Factors such as documented reliability from part manufacturers and the amount of confidence held in the team's manufacturing reliability are considered.

5.2.3.2 Data Acquisition Hardware Configuration Trade Study Metric Definition

Table 5.7: Hardware Metric Definition

	10	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
Manufacturing Difficulty	A baby can do it	Plug and play	Very little effort required	Little effort required	Some effort require d	Neutral	Effort required	Much effort required	Too much effort required	I quit
Total Cost	<$20	$20-$75	$75-$150	$150-$250	$250-$375	$375-$525	$525-$700	$500-$700	$700-$1000	>$1000
Complexity of Design	No work involved	Extremel y Simple	Very Simple	Simple	Somew hat simple	Neutral	Somewh at Complex	Complex	Extremel y Complex	Impossible
Reliability	90-100%	80-90%	70-80%	60-70%	50-60%	40-50%	30-40%	20-30%	10-20%	0-10%

5.2.3.3 Trade Study

Table 5.8: Hardware Trade Study

		Digital DAQ	**Single μC**	**Multiple μC**
Criteria:	**Weight:**	**Score:**	**Score:**	**Score:**
Manufacturing Difficulty	10%	7	4	3
Total Cost	40%	8	4	5
Complexity of Design	10%	5	4	3
Reliability	40%	1	9	8
Weighted Total		4.8	6.0	5.8

Again, all designs are rated similarly in the weighted total, and each design demonstrates its own strength. However, a significant portion of the budget is allotted to a reliable data acquisition system, so the single micro-controller leads in feasibility.

5.3 Vibration Testing Location

Selection of a suitable vibration table is crucial to the verification of FR 6 and DR 6.2. Given the size and mass of the final STM and payload mass analogs used in vibration testing, the FeatherCraft team is pursuing the use of several professional testing facilities with vibration tables large enough to accommodate the size of the structure and perform random vibration test profile provided by the customer. All possible vibration tables are capable of supporting the final structure and executing the vibration test profile. An original trade study included availability as a factor. This factor has been removed as all candidates can be similarly accessed by appointment and testing is far enough in advance for the FeatherCraft to secure a testing day at any facility. Specifications for the two target facilities are shown in Table 5.9.

Table 5.9: Vibration Table Facility Specifications

	Cascade Tek:	**Rocky Mountain Testing Services:**
Cost ($/8 hour day):	$1800	$2700
Proximity (travel hours):	1	8
Connection:	Customer	None

One of the largest challenges facing the FeatherCraft project is staying under budget, and for any facility, vibration testing will have a large monetary impact. For this reason, the vibration test is weighted 0.5 in the trade study's importance. A weight of 0.3 is given to proximity of the test facility. Given the rigidity of the student team's schedules, it will be much easier for the team to accomplish the vibration test if the facility can be accessed within a few hours of CU during the spring semester. A weight of 0.2 is given to the nature of the FeatherCraft team's connection to each facility. This has an impact on facility considerations due to the increased reliability it provides, as well as the potential for the team to obtain any academic discounts to lower the budgetary impact of vibration testing.

Table 5.10: Vibration Table Trade Study and Normalization and Scoring

	3	**2**	**1**	**Weight**
Cost ($/8 hour day)	0-1000	1000-2000	2000-3000	0.5
Proximity (travel hours)	0-3	3-6	6-9	0.3
Connection	University	Professional	None	0.2

Using the specifications, weights, and normalization outlined above, the final trade study is used to characterize the three different vibration test facilities, shown in Table 5.11.

Table 5.11: Vibration Table Facility Trade Study

		Cascade Tek	**RMTS:**
Criteria:	**Weight:**	**Score:**	**Score:**
Cost	50%	2	1
Proximity	30%	3	1
Connection	20%	2	1
Weighted Total:		**2.3**	**1**

Although use of Cascade Tek's vibration table is expensive, it is nearby and the most viable option at this time.

6.0 Selection of Baseline Design

6.1 Structure

The structural trade study demonstrated that designs using conventional materials and layouts (aerospace metal alloys) can be taken out of the design space. The two metallic designs (weight-relieved panels and the traditional approach) both scored much lower than either the honeycomb panel or the column structure. Despite their advantages in cost and ease of analysis, their disadvantage in mass makes them less desirable. A sensitivity study was done to test for biases in the trade by removing the effects of each of the criteria (sequentially setting one criteria weight to zero), and by assigning equal weights to each of the criteria. In every case (apart from removing the effects of mass), the honeycomb panel beat the others. However, it was always quite close to the score of the column structure, so both structures will be analyzed further as the team moves towards PDR.

6.2 Data Acquisition System

Accelerometers: The three design choices for the accelerometers were digital accelerometers, buying piezoelectric accelerometers, and renting piezoelectric accelerometers. The final decision was to buy accelerometers in order to satisfy the derived requirement, DR 6.6.1 and rent the rest needed to validate the STM. As seen in the trade study (5.2.1.3) renting accelerometers had a large reliability and a somewhat reasonable price. Reliability included the test results that were obtained from the chosen accelerometers. Even though the digital accelerometers were cheap, they are not as reliable at the frequencies that the vibration test will be conducted at. Ideally buying the piezoelectric accelerometers would produce the most reliable results; however the cost is far higher than renting. A combination of renting and buying accelerometers will both satisfy the requirements mentioned above as well as keep cost low.

Software: The final design option for software decision impacts the language that the GUI and real-time streaming capability will be written in; hence it will exist on the computer that is connected to the data acquisition system. Python is listed as the best option, because there is a larger base of knowledge for Python that exists on the team as opposed to that for Perl and LabVIEW. This allows the team to easily build from that base of knowledge with the ample amount of resources available including online forums, peers and professors, and lots of downloadable libraries. Since Python is free and has no licensing issues it becomes the ideal choice for interfacing between a computer GUI setup and the data acquisition board.

Data Acquisition Configuration: The configuration for the entire data acquisition system involves the single micro-controller approach. This means there will have to be a set of ADCs that interface with the low-pass filters, the charge amplifiers, and the accelerometers. The ADCs then transmit the digital signal to the micro-controller. Even though this setup potentially involves multiple ADCs – although using only one is possible – it is cheaper than buying several micro-controllers. Further, this configuration reduces the complexity of the system in that it does not require synchronization among all the micro-controllers. Fewer micro-controllers also means there will be less places for the system to fail, resulting in a higher reliability. Given that several types of ADCs with varying number of inputs exist, this design also allows for flexibility without changing the hardware complexity; that is, changing out a single piece of hardware is easier than changing out several micro-controllers and their software.

Totaling the outcomes of all the trades, the optimal software was determined to be Python, based on previous experience, cost, and capabilities. The final design also includes the option to rent the accelerometers. This option would allow for a reduced cost of test for the time period of which they are needed. The best option for the data acquisition system was determined to be the configuration involving a single micro-controller. The primary reason for this design is the reduced complexity, increased reliability, and reduced cost.

7.0 References

[1] "Aluminum 6061-T6." ASM Material Data Sheet. Aerospace Specification Metals Inc., n.d. Web. 27 Sept. 2015. <http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6>.

[2] "Titanium Ti-6Al-4V (Grade 5), Annealed." ASM Material Data Sheet. Aerospace Specification Metals, Inc., n.d. Web. 27 Sept. 2015. <http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MTP641>.

[3] David Fraser, Hank Kleespies, and Cliff Vasicek. Spacecraft Structures. Ed. Cyril Annarella. N.p.: n.p., 1991. Print.

[4] "Beryllium S200-F, Vacuum Hot Pressed." MatWeb - The Online Materials Information Resource. Matweb Material Property Data, n.d. Web. 27 Sept. 2015. <http://www.matweb.com/search/datasheet.aspx?matguid=92475f881cd3410388a35959474f17b2>.

[5] "Magnesium AZ80A-T5, Forged." MatWeb - The Online Materials Information Resource. Matweb Material Property Data, n.d. Web. 27 Sept. 2015. <http://www.matweb.com/search/datasheet.aspx?matguid=be17820e155a4fd4a30cbd28edd14f10&ckck=1>.

[6] Materion Coroporation. AlBeMet Property Datasheet. Elmore, OH: Beryllium & Composites, n.d. Print.

[7] Sandwich Panel Fabrication Technology. N.p.: Hexcel Composites, 2001. Print.

[8] Honeycomb Sandwich Design Technology. N.p.: Hexcel Composites, 2000. Print.

[9] Roark, Raymond J., and Warren C. Young. Formulas for Stress and Strain. New York: McGraw-Hill, 1975. Print.

[10] Microchip. PIC32MZ Embedded Connectivity with Floating Point Unit (EF) Family. Phoenix AZ: Microchip, n.d. PDF.

[11] PCB Piezotronics. Aerospace Ground Test. Depew, NY: PCB Piezotronics, n.d. PDF.

[12] ST Microelectronics. MEMS digital output motion sensor ultra low-power high performance 3-axes "nano" accelerometer. n.p.: ST Microelectronics, 2010. PDF.

[13] PCB Piezotronics. Quote: SGL11887. Depew, NY: PCB Piezotronics, 2015. PDF.

[14] " Alloy A286" Delta Fastner Corp. Web. 27 Sept. 2015.. <http://www.deltafastener.com/a286.html>

[15] "The Use of Silicone Adhesives in Space Applications" Adhesives and Sealant Industry. Web. 27 Sept 2015. <http://www.adhesivesmag.com/articles/85082-the-use-of-silicone-adhesives-in-space-applications>

[16] "Kaber Small Satellite Deployment System" NanoRacks. Web. 26 Sept 2015. http://nanoracks.com/wp-content/uploads/Kaber-Small-Satellite-Deployment-System-Presentation.pdf

[17] "Sandwich Panels". ACP Composites. Web. 22 Sept 2015. < http://www.acpsales.com/Carbon-Fiber-Sandwich-Panels.html>

[18] "Stratasys Direct Manufacturing Builds the First 3D Printed Parts to Function on the Exterior of a Satellite". *Stratasys Direct Manufacturing.* N.p., 2015. Web. Sep 19 2015.

[19] "ULTEM 9085" *Stratasys Direct Manufacturing.* N.p., 2015. Web. Sep 19 2015.

[20] "Spacecraft Thermal Control – Chapter 6" 2011. Print.