Small Satellite Development at UTEP

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SMALL SATELLITE DEVELOPMENT AT UTEP

EMILY HERZOG
Master’s Program in Mechanical Engineering

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SMALL SATELLITE DEVELOPMENT AT UTEP

by

EMILY HERZOG, BSME, MBA

THESIS

Presented to the Faculty of the Graduate School of
The University of Texas at El Paso
in Partial Fulfillment
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Department of Mechanical Engineering
THE UNIVERSITY OF TEXAS AT EL PASO

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Abstract

The small satellite industry has seen tremendous growth in recent years. A CubeSat is a particular type of standardized small satellite that follows the CubeSat specifications. These specifications define the structural, testing, and operational requirements of the satellite. This standard facilitates cheaper design, integration, and launch of satellites, allowing smaller organizations to participate in the normally costly area of space exploration.

The University of Texas at El Paso has recognized the opportunity and has begun developing several CubeSats. The two that are the topic of this thesis are called Orbital Factory II (OFII) and Orbital Factory X (OFX). An on-orbit thermal analysis of OFII was completed in order to assure that the off-the-shelf modules would survive the mission. OFX will have on-orbit propulsion provided by four 1 N monopropellant thrusters. A custom propellant tank was designed to maximize the volume of propellant. Finite element analysis of the tank was completed in order to ensure that the tank will be able to handle the loads from the pressurized propellant.
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Chapter 1: Introduction

**BACKGROUND ON CUBESATS**

Small satellites, defined as satellites that weigh less than 600 kg, have become increasingly popular in recent years. Between 2012 and 2018, more than 1,300 small satellites were launched into space [1]. A CubeSat is a particular type of small satellite that follows the standard developed by Cal Poly and Stanford in 1999. There are specifications that dictate the structural, electrical, testing, and operational requirements of a CubeSat [2]. Due to the standardization of CubeSats, many components can be purchased and do not have to be designed or fabricated in-house. It also allows for a standardized, and therefore cheaper, launch process. The relative low cost of designing, building, and launching a CubeSat leads to more organizations participating in space exploration. The standard dimensions of CubeSats are 10 cm x 10 cm x 10 cm, which is called 1U (unit). They can also be 2U, 3U, or 6U in size. The standard weight is about 1.3 kg or 3 lbs per each “U”.

**UTEP’S CUBESATS**

Since the launch of the first CubeSat in 2003, CubeSats have greatly increased in popularity. Between 2012 and 2018, more than 950 CubeSats were launched, compared to the approximately 100 that were launched before 2012 [1] [2]. Currently, the University of Texas at El Paso (UTEP) Center for Space Exploration and Technology Research (cSETR) is developing two CubeSats. The first is Orbital Factory II (OFII), which will demonstrate an in-house built 3D printer. The second is named Orbital Factory X (OFX) and will use a monopropellant with catalytic decomposition in order to produce thrust. This thesis discusses some of the work conducted in order to advance the design of these two CubeSats.
Chapter 2: Orbital Factory II

BACKGROUND ON OFII

Orbital Factory II is a 1U CubeSat that’s primary payload is to demonstrate an on-orbit 3D printer. This 3D printer is a proof of concept for printing an electrically conductive ink in space. The future plan is for this 3D printer to be used as an on-orbit repair unit for solar panels. In addition to the primary payload, OFII is intended to demonstrate a 3D printed patch antenna as well as an electron emitting film surface charge monitor (ELF/SCM) which will manage the charge of the satellite.

Most CubeSats are sent into low earth orbit (LEO), however OFII will be one of the first CubeSats to go into a geostationary transfer orbit (GTO). Putting a CubeSat into GTO presents new challenges that aren’t present with LEO missions, such as communication limitations and radiation from the Van Allen belts.

The Van Allen belts are zones of charged particles that are trapped by Earth’s magnetic field. Solar panels and other electronic equipment can be damaged by these charged particles, so it is important to limit their exposure. Since CubeSats are generally not sent into GTO, the charged particles of the Van Allen belts are not taken into consideration. Therefore, a typical off-the-shelf chassis does not have solid walls. In order to conserve mass, the typical chassis will have cut-outs like shown in Figure 1.

However, since OFII will be passing through the Van Allen belts, it will need to have a chassis that is completely enclosed to prevent charged particles from entering. Figure 2 shows the design for the chassis of OFII with the modules inside. It will be completely enclosed except for a few ports necessary for the charging and communication cables of the modules. The top and bottom sections of the chassis will also overlap in order to provide an extra barrier to the entry of charged particles.
Figure 1 – Typical Chassis of 1U CubeSat [3]

Figure 2 – OFII Chassis and Modules
THERMAL ANALYSIS

Because of the limited space within a CubeSat, it is often hard to include a way to regulate temperature. There may not be space for a heater or for a cooling system. Since OFII utilizes off-the-shelf parts, it is important to know what temperatures the modules will be exposed to and if these temperatures will be outside of the operating range of the parts. In order to analyze the heat transfer to the satellite during orbit, a thermal model of OFII was made using Thermal Desktop. Thermal Desktop is a program that “allows users to quickly build, analyze, and post-process sophisticated thermal models” [4]. It is of particular interest to the aerospace field because it can calculate orbital heating rates and radiation exchange factors.

Figure 3 shows the definition of the orbit inclination, which is defined as the angle between the orbital plane and the reference plane. In this case, because OFII will be in a GTO, the reference plane would be Earth’s equatorial plane. The ascending node is the point where the orbit plane intersects the plane of reference. The Right Ascension of Ascending Node (R. A. of Ascending Node) is the angle between the reference direction and the ascending node. It is sometimes referred to as the longitude of the ascending node, as it is in Figure 3. The argument of periapsis is the angle between the satellite’s periapsis (in this case, perigee), the point at which the satellite is closest to Earth, and the ascending node.
Figure 3 - Parameters of an Orbit [5]
Figure 4 – Visual of OFII Orbit

Figure 5 – OFII Orbit Parameters
In order to protect the modules from damage from radiation during the duration of the mission, the operations team of OFII determined 3 mm of shielding was needed. Therefore, the wall thickness of the chassis is modelled as 3 mm of titanium. In the Thermal Desktop model, there are nodes on both the inside and outside surface of each face. Using the parameters shown in Figure 5, the expected temperatures during orbit were simulated and the result are summarized in Figures 6 and 7.

Figure 6 – Temperatures of Outside Faces of OFII During Orbit
Since the chassis is very thin, the temperatures of the inside and outside faces are very similar. The temperatures vary between approximately 270 and 307 K (-3 and 34 °C).

Table 1 – OFII Module Operating Temperatures

<table>
<thead>
<tr>
<th>Module Name</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Min. Operating Temp. (°C)</th>
<th>Max. Operating Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>GOM Space</td>
<td>NanoPower P31u Battery</td>
<td>-40</td>
<td>85</td>
</tr>
<tr>
<td>OBC</td>
<td>Pumpkin</td>
<td>Motherboard P/N 710-00484</td>
<td>-40</td>
<td>85</td>
</tr>
<tr>
<td>Transceiver</td>
<td>GOM Space</td>
<td>NanoCom AX100</td>
<td>-30</td>
<td>85</td>
</tr>
<tr>
<td>Antenna</td>
<td>EnduroSat</td>
<td>CubeSat UHF Antenna</td>
<td>15</td>
<td>27</td>
</tr>
</tbody>
</table>
The on-orbit temperatures only exceed the operating temperatures for the antenna. However, on the data sheet of the antenna, these temperatures are listed as the “ideal” operating temperatures. The OFII team is operating under the assumption that the antenna will still operate outside of this temperature range, just less efficiently. Further investigation into the effect of the temperature on the performance of the antenna needs to be conducted. The mission can also be planned to avoid sending signals during the periods that the satellite temperatures would be outside of the antenna’s operating range.
Chapter 3: Orbital Factory X

INTRODUCTION

Orbital Factory X (OFX) is a planned CubeSat currently in development by the cSETR. It is a 2U module that is meant to serve as a propulsion unit. It has four 1 N monopropellant thrusters that utilize catalytic decomposition in order to produce thrust for maneuvers. For attitude control, it will include Micro-cathode arc thrusters (µ-CAT) developed by George Washington University.

Figure 8 – Preliminary Configuration of OFX
**Propellant Tank Design**

Since OFX is still in the conceptual phase, two different tank designs were investigated. In the first design, the thrusters and tank are oriented vertically. In the second design, the tank is oriented horizontal with respect to the thrusters. In both designs, there are two cavities inside the tank. One cavity is for the pressurizing gas, and the other is for the propellant. The expected operating pressure of the tank is 1,000 kPa (145 psi). Using a factor of safety of 2.5, the pressure that the FEA simulations are subjected to is 2,500 kPa (363 psi). The material under consideration for both tank designs is a titanium alloy Ti-6Al-4V.

![Figure 9 – Vertical Tank](image)
Vertical Tank Design

FEA Simulations

In the design for the vertical propellant tank, the wall thickness is 4 mm. The constraints are fixed in the areas shown in Figure 11. The 2,500 kPa load is applied to all inner faces of the tank.
Figure 11 – Constraints of Vertical Tank
Figure 12 – von Mises Stress of Vertical Tank
The factor of safety for the propellant tank is greater than 2.5 in all locations, meaning the design is safe.
Since CubeSats are subjected to strict requirements regarding weight, it is important to investigate different ways of minimizing the weight of the tank. In order to optimize the strength and weight of the vertical tank, the use of generative design and lattice structures was investigated. Using Autodesk Netfabb, the effects of several different types of lattice structures
were investigated. In order to implement lattice structures, several parameters have to be defined. The regions that will be the front and back “skin” and their thickness has to be defined. The skin is the region of the model that will remain solid, while the area that is to be replaced with a lattice structure will be defined as “hollow”.

Figure 15 – “3D Spider” Lattice Structure
Figure 16 – “Column” Lattice Structure

Figure 17 – “Cross Pattee” Lattice Structure
Figure 18 – “Crush” Lattice Structure

Figure 19 – “Dark Horse” Lattice Structure
Figure 20 – “Endoskeleton” Lattice Structure

Figure 21 – “Hexagrid” Lattice Structure
Figure 22 – “Icosahedron” Lattice Structure

Figure 23 – “Rhombic Dodecahedron” Lattice Structure
Figure 24 – “Snowflake” Lattice Structure

Figure 25 – “Soft Box” Lattice Structure
Figure 26 – “Star” Lattice Structure

Figure 27 – “Tetra” Lattice Structure
Figure 28 – “Vin Tiles” Lattice Structure

Figure 29 – “W” Lattice Structure
Figure 30 – “X” Lattice Structure

Table 2 summarizes the parameters of the lattice structure investigated as well as the maximum stress.

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit Size (mm)</th>
<th>Lattice Thickness (mm)</th>
<th>Front Skin Thickness (mm)</th>
<th>Back Skin Thickness (mm)</th>
<th>Max. Stress (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column</td>
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<td>0.5</td>
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<td>1</td>
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<td>Crush</td>
<td>3</td>
<td>0.5</td>
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<td>1</td>
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<td>Units</td>
<td>Lattice Thickness</td>
<td>Front Skin Thickness</td>
<td>Back Skin Thickness</td>
<td>Maximum Stress (MPa)</td>
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<td>Icosahedron</td>
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<td>Pyritohedron</td>
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<td>1</td>
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<td>Rhombic Dodecahedron</td>
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<td>0.5</td>
<td>1</td>
<td>1</td>
<td>2.67</td>
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<td>Snowflake</td>
<td>3</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>2.22</td>
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<tr>
<td>Soft Box</td>
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<td>1</td>
<td>1</td>
<td>1.98</td>
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<td>Star</td>
<td>3</td>
<td>0.5</td>
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<td>1</td>
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<td>0.5</td>
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<td>1</td>
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<td>W</td>
<td>3</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>1.98</td>
</tr>
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<td>X</td>
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<td>1.89</td>
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<td>X Z:3</td>
<td>0.8</td>
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<td>0.6</td>
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<td>0.5</td>
<td>1</td>
<td>1</td>
<td>2.65</td>
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</table>

Using a unit size of 3 mm, lattice thickness of 0.5 mm, and a front and back skin thickness of 1 mm, the “X” lattice structure showed the lowest maximum stress and therefore was chosen as the best type of lattice for the tank. After establishing that the X lattice would be used, the parameters were optimized in order to lower the maximum stress even further. Using a unit size of 3 mm in the Z-direction, 2.5 in the X and Y-direction, a front skin thickness of 1.2 mm and a back skin thickness of 2.25 mm, a maximum stress of 601 MPa was obtained. The maximum stress on the tank without the lattice structure was 397 MPa. The factor of safety decreases from 2.6 without the lattice structure to 1.7 with the lattice structure, which is still in the acceptable range of greater than 1.5. The volume of the tank without lattice structure was 103,776 mm³ and with the lattice structures was 85,276 mm³. This is a reduction in volume of
around 18%. Given that the density of Ti-6Al-4V is 4.43 g/cm³, the reduction in volume corresponds to a reduction in mass of about 82 g.

**Additive Manufacturing Simulations**

Due to the complex shape of the lattice structures, it is not possible to manufacture the lattice structures using traditional manufacturing methods. Therefore, the option of using additive manufacturing (AM) was investigated.

Autodesk Netfabb has a feature called Simulation Utility that allows the user to simulate the AM process and predict where the part is likely to warp during printing. The material simulated was Ti-6Al-4V with the SLM 125 HL as the printer. The power of the laser was 250 W, the speed of the printer was 1000 mm/s, and the layer thickness was 40 µm.

![Simulation of Additive Manufacturing of Vertical Propellant Tank](image)

*Figure 31 – Simulation of Additive Manufacturing of Vertical Propellant Tank*
As Figure 31 shows, the areas of maximum displacement or warping are on the sharp, overhanging corners of the tank. In order to compensate for this warping, the sharp edges were rounded.

![Simulation of Additive Manufacturing of Compensated Vertical Propellant Tank](image)

Figure 32 – Simulation of Additive Manufacturing of Compensated Vertical Propellant Tank

The warping on the compensated design is very similar to the warping on the previous design. This could mean that the compensated design does not actually help to prevent warping at all. However, due to computational constraints, a very low-resolution mesh was used. In order to verify that the results are accurate, the simulations need to be run again with a higher resolution mesh.
**Horizontal Tank Design**

Ultimately, the horizontal tank design was chosen because the arrangement of the thrusters would allow them to provide more torque. In the vertical design, the thrusters are about 3 cm from the center of the tank, providing 0.03 Nm of torque. In the horizontal design, the thrusters are about 7 cm away from the center, which would provide the CubeSat with 0.07 Nm of torque.

**FEA Simulations**

The 3D model of the horizontal tank was subject to Finite Element Analysis (FEA) to ensure that it would be able to withstand applicable loads from the propellant within, as well as the high temperatures from the thruster. Using information about the thruster from OFX’s propulsion team, the estimated heat power that the thruster generates is 70 watts. There are 4 thrusters, so the total heat power applied to the model of the tank was 280 W. The maximum pressure expected within the tank is 1,000 kPa (145 psi). With a factor of safety of 2.5, the simulation load is 2,500 kPa (363 psi). The areas of the tank that were held fixed are shown in blue in Figure 33.
Figure 33 – Constraints of FEA of Horizontal Tank Design

Figure 34 – von Mises Stress on Horizontal Tank
Figure 35 – Deformation of Horizontal Tank (Scale 39.84)

Figure 36 – Factory of Safety of Horizontal Tank
**Machining the Horizontal Tank**

In order to test the design before 3D printing it, a prototype of the horizontal tank was made using traditional machining. In order to avoid any over-complicated parts and facilitate machining, the tank was divided into four separate parts that will be welded together.

![Figure 37 – Part One of Horizontal Machined Tank (Top)](image)
Figure 38 – Part Two of Horizontal Machined Tank

Figure 39 – Part Three of Horizontal Machined Tank
Figure 40 – Part Four of Horizontal Machined Tank (Bottom)
Figure 41 – Machined Horizontal Tank Parts
Figure 42 – Machined Horizontal Tank Parts Assembled

Figure 43 – Machined Horizontal Tank Parts Assembled
Hydrostatic Testing

Since the propellant tank for OFX is an irregular shape, it can be difficult to determine the necessary wall thickness using pressure vessel equations. As discussed in the previous sections, the propellant tank was subjected to FEA using SolidWorks. In order to verify the results from the FEA, hydro-static testing needs to be conducted. A hydrostatic pump system that was purchased from AirHydro will be used to pressurize the propellant tank to the desired pressure, which in this case is 1.5 x the maximum expected operating pressure (MEOP) of 1,000 kPa. In order to measure the deformation of the tank, strain gauges will be placed on the surface of the tank and the results will be compared to the FEA.

Figure 44 – Hydrostatic Pump System
The low pressure side will be connected to an air compressor or gas cylinder that will supply the pump with 100 psi.
The high pressure side of the pump system delivers water to the tank and can pressurize it up to 2,600 psi.

Figure 46 – Hydrostatic Pump System (High Pressure Side)

Figure 47 – Schematic for Hydrostatic Test Setup
In order to start the hydrostatic testing of the propellant tank, the setup needs to be assembled according to the schematic in Figure 47. Since these tests will involve very high pressures, the hydrostatic testing will take place in the cSETR Fabens facility in Fabens, Texas.

**Future Work**

There are still several tasks that need to be complete in order to finalize the design of OFX’s propellant tank. The hydrostatic testing of the traditionally machined tank needs to be completed to provide a preliminary look at any weak points in the tank design. After the testing of the machined tank is completed, further investigation into additively manufacturing the tank needs to take place. Because the material properties of AM parts and traditionally manufactured parts can vary, the 3D printed tank needs to be hydrostatically tested as well.

Once the structural design of the tank is finalized, OFX’s tank team and thruster team will collaborate to develop the delivery system of the propellant to the thruster. Figures 48 and 49 show a preliminary design for the integration of the valves, thrusters, and delivery system.

![Figure 48 – Propellant Delivery System](image)
Figure 49 – Propellant Delivery System
Bibliography


Vita

In 2015, Emily Herzog completed her Bachelor of Science in Mechanical Engineering at Midwestern State University in Wichita Falls, Texas. During her time at Midwestern State, she interned at Alcoa Howmet (now known as Arconic) and conducted research on the concept of a dual-rotor wind turbine. In 2016, she completed her Master of Business Administration, also at Midwestern State University.

She began attending the University of Texas at El Paso and conducting research for the Center for Space Exploration and Technology Research (cSETR) in the fall of 2016. In her time as a graduate student at UTEP, she internships at NASA Glenn Research Center in Cleveland, Ohio and the Air Force Research Lab in Albuquerque, New Mexico.