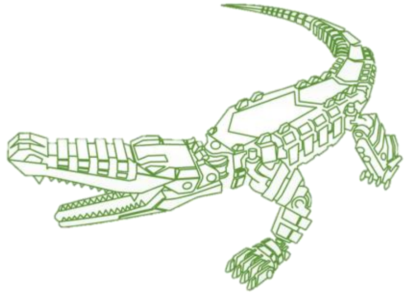

Pathways Intern Report

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General Overview

During my time at NASA, I worked with the Granular Mechanics and Regolith Organization (GMRO), better known as Swamp Works. The goal of the lab is to find ways to utilize resources found after the astronaut or robot has landed on another planet or asteroid. This concept is known as in-situ resource utilization and it is critical to long term missions such as those to Mars. During my time here I worked on the Asteroid and Lava Tube Free Flyer project (ALTFF). A lava tube, such as the one shown in figure 1, is a long tear drop shaped cavern that is produced when molten lava tunnels through the surrounding rock creating large unground pathways.

Figure 1: Lava tube on Earth, similar lava tubes have been found on Mars

Before mining for resources on Mars or on asteroids, a sampling mission must be done to scout out useful resource deposits. ALTFF's goal is to provide a low cost, autonomous scout robot that can sample the surface and return to the mother ship or lander for further processing of the samples. The vehicle will be looking for water ice in the regolith that can be processed into either potable water, hydrogen and oxygen fuel, or a binder material for 3D printing. By using a low cost craft to sample, there is much less risk to the more expensive mother ship or lander. While my main task was the construction of a simulation environment to test control code in and the construction of the asteroid free flyer prototype, there were other tasks that I performed relating to the ALTFF project.

Thruster Test Stand

The first thing I worked on was the thruster test stand. When designing a software control architecture for a quad copter, it is important to know the characteristics of your motors, propellers, and motor controllers and how they respond to a given PWM signal. To analyze these characteristics (force, torque, rpm, voltage, amperage) a test fixture was designed and constructed. When I arrived, it was complete but several different systems needed testing. A laser and photo sensor measure the number rotations per second of the blades by registering when the photo sensor is shadowed by a fan blade. The force data is taken in by a strain gauge attached to a lever. The fulcrum of the level is a set distance from the gauge as well as the center of the prop, which is on the opposing side of the fulcrum. Finally, voltage and amperage are measured by the data acquisition computer and recorded. The data acquisition computer takes in all these values at a rate set in the user interface, but the rate can vary between 50 Hz to 10,000 Hz depending on the desired granularity of the test as well as the limit on file size.

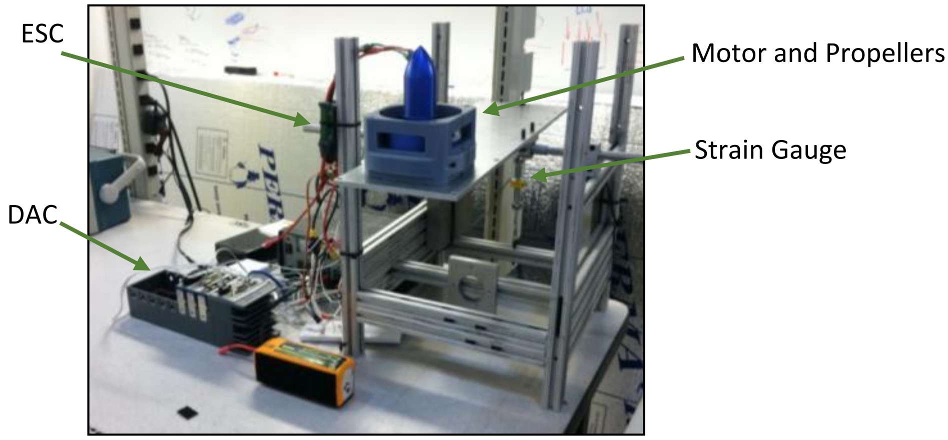

Figure 2: Original test stand set up

Embry-Riddle has a 3DR quad copter that is used for experimental testing of their non-linear dynamic inversion controls system (NLDI). The NLDI uses characteristic equations for non-linear systems to control them. To get these characteristic equations, testing needed done using the motors, props, and motor controllers called ESC's. The test stand produces a PWM signal that is taken in by the ESC. The test stand then reads in sensor data to determine all the characteristics the user is interested in. My task was to run this motor at a myriad of PWM values ranging from 1200 to 2000 and record the data.

Figure 3: 3DR quad copter getting ready for testing

The second major motor to be tested during my stay at Swamp Works was the Hacker A60. This motor can produce over 30 lbs. of thrust at full power and required a specialized mounting setup that allowed such a large motor to attach to the test stand as well as withstand the thrust of the motor without deflecting. If the motor were to deflect, the strain gauge measurements would be invalid. I used the existing mounting hardware that came with the motor to attach it to a piece of 80/20 aluminum extrusion. That was then bolted to the test stand and to reduce deflection, I 3D printed support pieces that were placed in compression.

Figure 4: Hacker A60 motor

Mini Free Flyer

Before the ALTFF project there was Extreme Access. With a similar goal as ALTFF, Extreme Access was an attempt at making an excavation and scout flyer for investigating permanently-shadowed regions at the Moon's South Pole. A full scale version of the Extreme Access Free Flyer was constructed with ducted fans as substitutes for the cold gas thrusters. Along with the full scale version, there was a Mini Free Flyer that was built. The Mini Free Flyer is used to test different control architectures while minimizing risk by putting them on a small, four pound, craft that can be flown indoors.

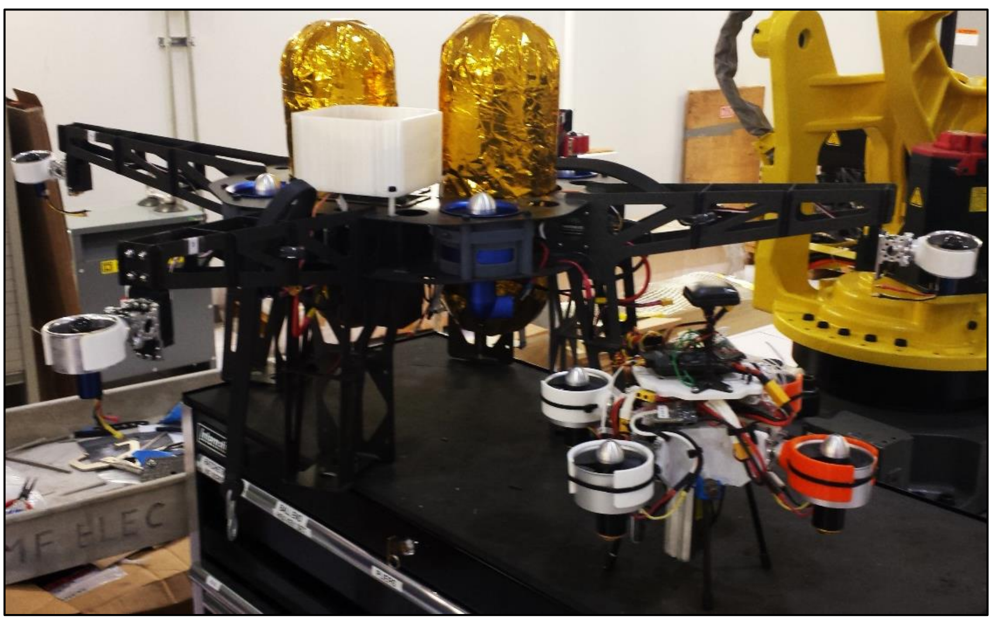

Figure 5: Mini Free Flyer next to the larger Extreme Access Free Flyer

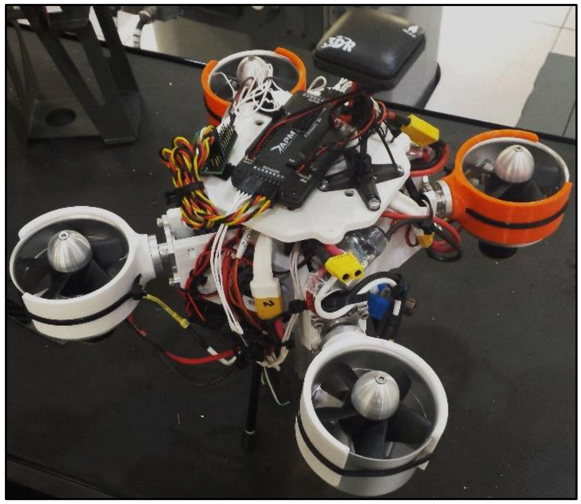

Figure 6: Mini Free Flyer

While at Swamp Works, I connected the ESCs on the Mini Free Flyer to the digital output pins on the APM processor. I also bound and connected the receiver to transmitter and APM respectively, and performed maintenance tasks such as repairing broken Molex connections and charging and replacing the battery. While the Mini Free Flyer had been mostly built by the time I had arrived at Swamp Works, the software had not been developed, nor had the servos been characterized. My next task was to find the PWM values for each motor that corresponded to the thruster pointing strait down, -45 degrees, and 45 degrees so that the data could be used to calculate desired PWM outputs in a future control architecture. To accurately measure the angle of the thruster, I used a Microstrain IMU that was mounted using a 3D printed plate that kept the IMU's Z axis parallel to the rotational axis of the propeller, shown in figure 6.

Figure 7: Microstrain IMU measuring thrust angle on Mini Free Flyer

As a learning experience for the Swamp Works team, my mentor and I began the development of a PID control system for the Mini Free Flyer in Simulink Real Time. The Mini Free Flyer was suspended from the ceiling of the safety cage using four 400 lb. spectra line. For yaw control, a normal quad copter would have counter rotating pairs of blades to make the net torque on the vehicle zero. In the case of the Mini Free Flyer, all the ducted fan thrusters rotate in the same direction. To combat the torque produced by the fans, the servos rotate the fans. Thus, to control the yaw, the system angles the thrust vector. The pitch and roll are coupled due to the "X" configuration of the Mini Free Flyer. In this configuration all four fans affect both pitch and roll. To tune one axis at a time, I developed a way to suspend the vehicle along either the X or Y axis. The spectra line is tied off to two shoulder bolts that are affixed to the vehicle along its rotational axis. This method proved to work well at allowing the vehicle to rotate around either X or Y.

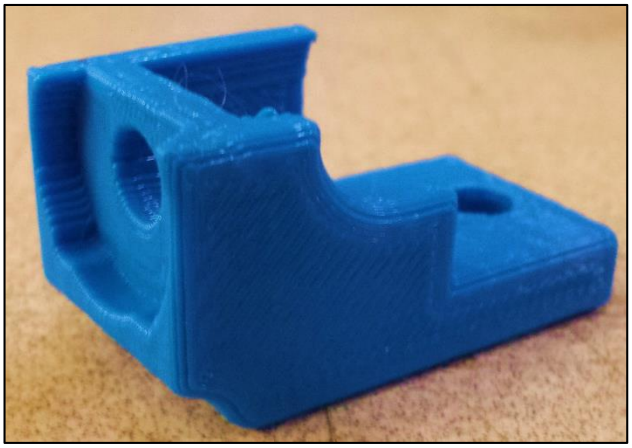

Figure 8: 3D printed part. Attaches the shoulder bolt to the free flyer

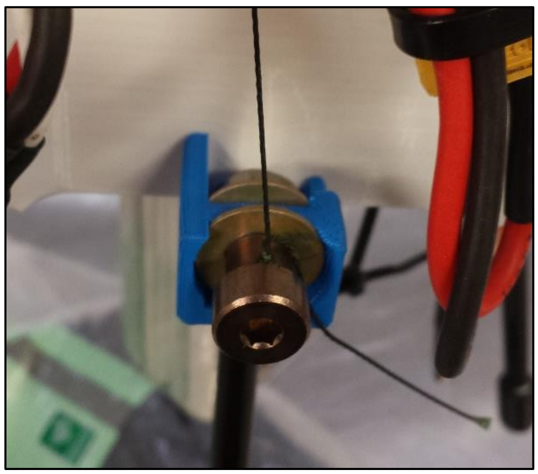

Figure 9: Roll/Pitch Axis rotation system on Mini Free Flyer

Asteroid Free Flyer Design and Construction

For the asteroid case of the ATLFF project, a physical prototype was constructed. The Asteroid Free Flyer uses twelve cold gas thrusters. The thrusters are in six opposing pairs. This allows the Free Flyer to roll, pitch, yaw, and move in any principle direction. The nozzles are screwed into solenoids that are actuated via relays that are switched on and off using the digital outputs of the on board Athena computer. The computer is programmed using Simulink Real Time and uses a NLDI control architecture. The fluid system is monitored by pressure and temperature sensors that are output on scopes on Simulink. I was tasked with putting together the electrical system and selecting parts for the fluid system such as the ball valves, filer, accumulator, regulator, relief valves, and tanks that were all rated for the required pressure as well as being low mass. The temperature sensors required amplification circuitry to be read in as the thermo couple outputs in the millivolt range and the Athena cannot read analog inputs that low. Using IC amplifiers, I assembled the temperature sensors and attached them to the analog inputs of the Athena using Molex connectors. The Pressure sensors output .5v to 5v so the analog pins on the Athena can read that without amplification. The system's power can be shut off using an emergency stop relay. The e-stop uses a radio transmitter to send either on or off to a receiver that switches on power to the relay's coil. All of this uses its own power supply so that it can shut down main power to rest of the system. If the e-stop's battery malfunctions or is disconnected, the relay will not be energized and thus the entire Free Flyer will be cut off from power.

Many of the parts were 3D printed. Shown in figure 9 was the original CAD for the system. All blue items were 3D printed parts. In the finally design that was constructed, the blue electronics bins on the top of the Free Flyer were omitted in exchange for individual 3D printed cases for some electronics to DIM rail systems for the relays. I chose to change to this to allow better modularity, easier wire management, and to guarantee that there were no loose components that could come free if the vehicle inverts inside the three axis gimbal system.

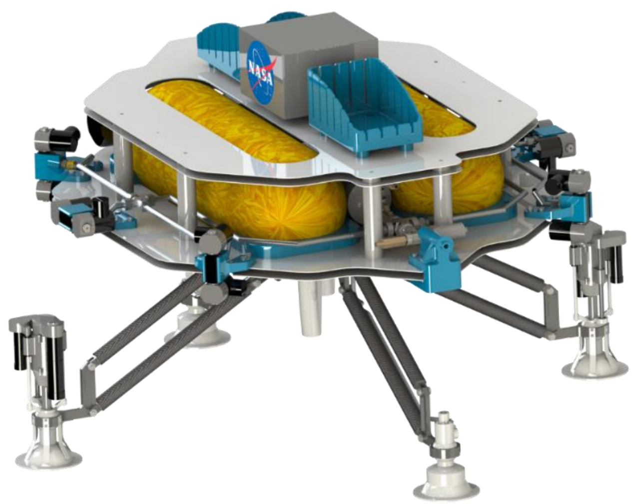

Figure 10: Asteroid Free Flyer CAD model

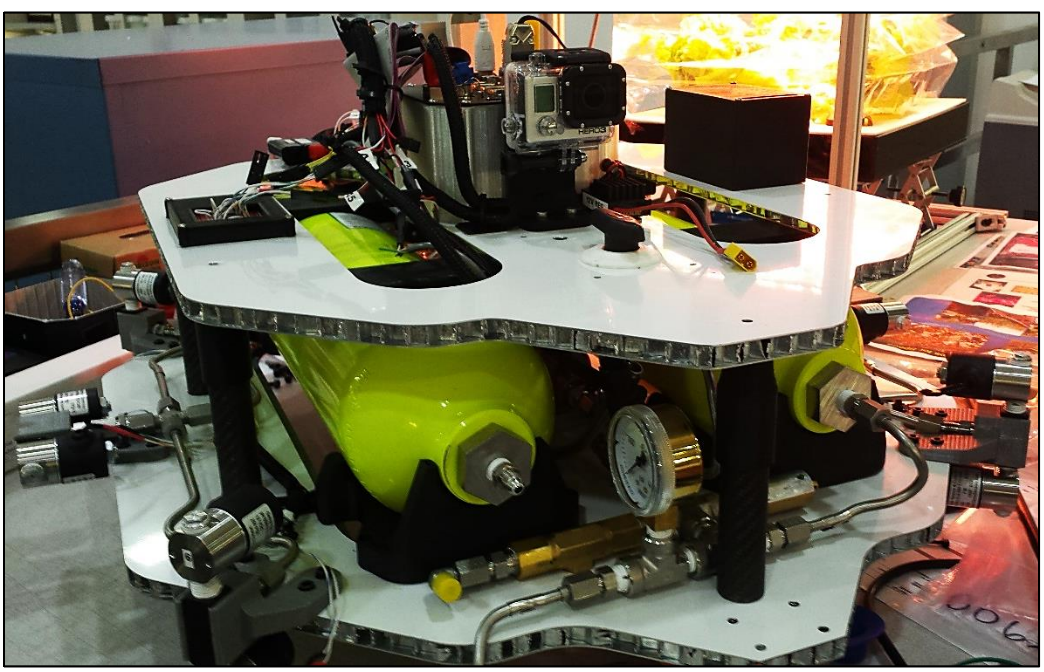

Figure 11: Asteroid Free Flyer getting ready for fittings to be tightened down

Before tuning the NLDI controller, test data was taken of the force output of a thruster. The thruster pod, consisting of the solenoid and nozzle was mounted to the thruster test stand using a 3D printed bracket; a flex hose was used to span between the thruster pod, to the vehicle, to the port where the solenoid would normal be attached. This was done to get the most representative test data possible. After checking for leaks in the system, the tanks on the Free Flyer were filled via a K bottle and the system was used to actuate the solenoid on the test stand.

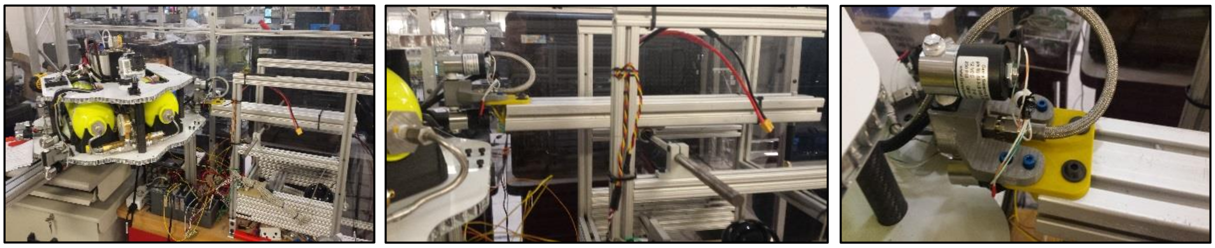

Figure 12: Asteroid Free Flyer attached to the test stand for thruster testing

Gimbal System

To allow the Asteroid Free Flyer to rotate freely. We constructed a gimbal system. The original design used fiber rods but because they were too flexible, the rings of the gimbal would collide under load. After this issue was uncovered, a new gimbal design was conceived that when complete would be three rotating rings made out of plates of carbon fiber. The plates would create a hollow square cross section with foam as an inner core. The side walls were cut into quarter circle pieces and the top and bottom walls of each ring were uni-directional carbon fiber bent to match the profile of the side walls. While the gimbal passed load testing and is approved to be used to support the Asteroid Free Flyer, there are some issues with the roller bearings. They are press fit into the gimbal rings but because they only have a depth of 1/8 inches, they tend to come loose and could cause wear on the gimbal rings. The shafts of each ring were threaded and a nut was used to keep the shafts in place, instead of the collar that was used originally. A good future upgrade would be wider roller bearings and figuring out a way to improve the alignment of the shafts and bearings.

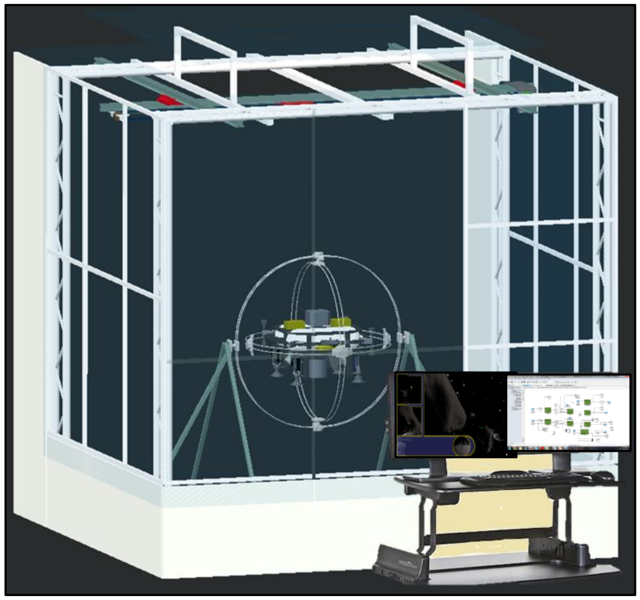

Figure 13: Original gimbal concept

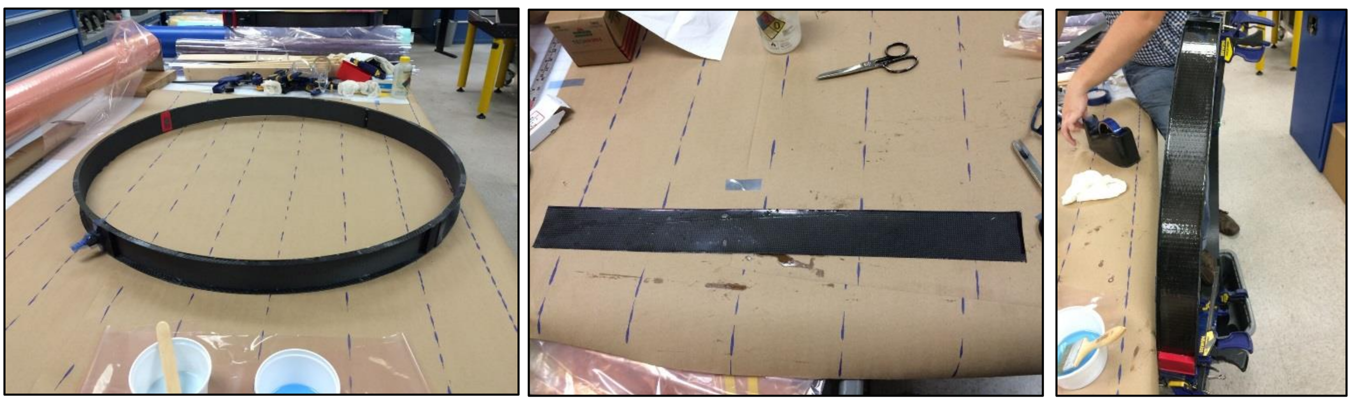

Figure 14: Making largest gimbal ring

Figure 15: After messing up some pants, I put on overalls.

JME3 Simulations

While the asteroid case has a physical prototype that can be run and demonstrated, the Martian lava tube case is in simulation. More specifically, it is in hardware in the loop (HIL) simulation. In HIL the Simulink Real-Time code is run on embedded hardware. The Free Flyer control code is run on one processor while an environment and sensors are simulated on another. To graphically represent the environment and free flyer, I created a visual simulation using a java coding program called "JMonkey Engine 3" (JME3). Environments were made to represent both the lava tube and asteroid cases. Several different software packages were considered: Xplane, Flight Gear, JME3, and even the 3D Animation block set with in Simulink. Each software package had its pros and cons. Flight Gear and Xplane both are very well designed flight simulation environments that Simulink has blocks that can directly send state and attitude data to. The issue with both is a lack customizability. They are designed to work with flat maps of terrain on Earth. This means that simulating a lava tube underground or an orbitable asteroid are impossible. While Simulink 3D Animation can easily talk with other Simulink code, and is fully customizable, the graphics are outdated, limited to only simple shapes and no advanced shaders such as shadows, depth of field, fog, and metallic materials. JME3, unlike the other choices is highly customizable and its graphical fidelity is limited only by the computer hardware and the skill and of the programmer. The down side is that a simulation in JME3 must be built from the ground up. This means that I had to make models and write code for how they are shown on screen, as well as setting up lighting, shaders, heads up display text, and the networking code to communicate with Simulink.

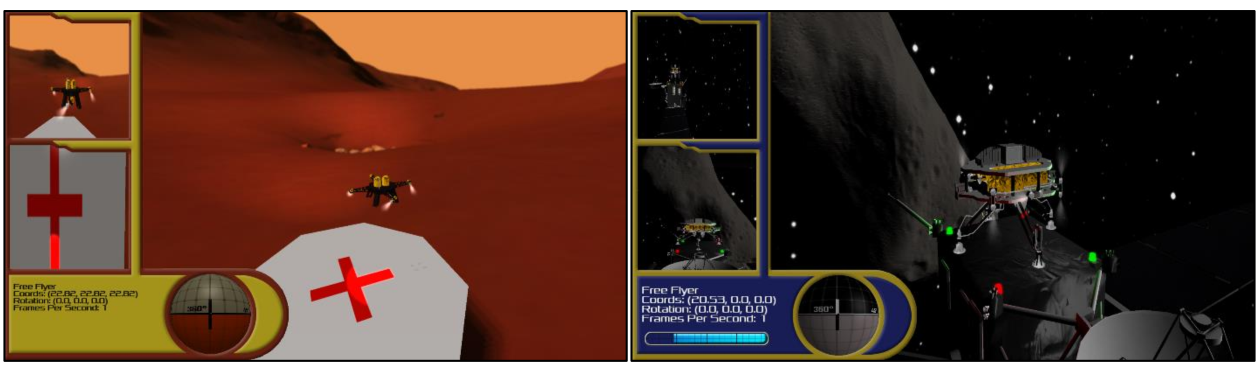

Figure 16: Mars and Asteroid Case JME3 Visual Simulations

Both simulation environments are very graphically intensive. On my assigned work computer both simulations ran at around 14 frames per second. This produces a very choppy movement of the Free Flyers. To run the simulations at a higher frame rate, preferably above 50 fps, I selected parts for a simulation computer that could run the JME3 simulations as well as future simulations and advanced computational tasks for Swamp Works. A large screen monitor was also acquired for the demo of the Asteroid Free Flyer and Mars HIL systems.

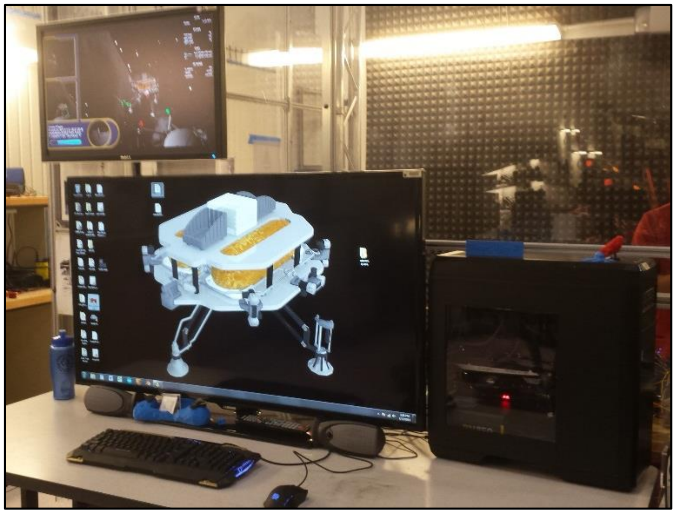

Figure 17: Simulation computer

3D Printing, General

During my time working on the Asteroid and Lava Tube Free Flyer project, Swamp Works acquired a Lulzbot Taz 5 printer. I spent some of my time setting up the printer to use a dedicated desktop computer so that anyone in the lab would be able to use the Taz without needing to download and set up software on their workstations. One of the tasks I performed as creating a series of calibration prints and sample prints that could be used to help design parts to be printed. One of these was the hole plate shown in figure 18. This part has holes from .1mm to 8.1mm in .1mm increments. Due to shrinkage of parts after being printed, it is hard to accurately size a hole in CAD. With the plate, the user would select a hole on the plate based on its fit against for example a bolt or rod. They would then use the hole size on the plate for the hole size in their actual part. Another print was the overhang sample prints. These blocks have overhangs at different angles from 15 to 60 degrees. If the overhang is able to print properly, then it is safe to print at that inclination on a functional part. An interesting issue that came up with the Taz was printing tall parts in ABS. There was noticeable delamination of the layers of the parts. Our first hypothesis was that it was the air temperature in GMRO being too low causing the ABS layers to deform. After encasing the Taz in a box and warming it up inside the box, there was a reduced amount of delamination but it was still present. The final hypothesis was that the delamination was a combination of the cold air and the z axis having a small bit of error. Since PLA prints well and does not warp thanks to the heated bed, it was decided that the lab would only use PLA.

Figure 18: Lulzbot Taz5

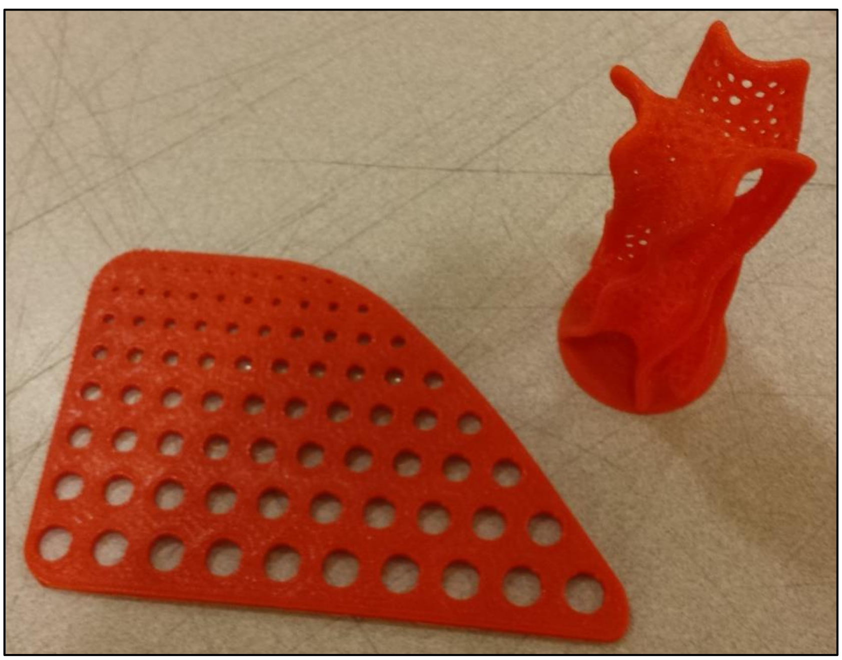

Figure 19: Calibration Prints on the Taz 5 Printer

Future Work & Lessons Learned

As of writing this report, the Asteroid and Mar Free Flyer demos have not been performed. They will be completed at the end of July while I remain at Swamp Works. After those demos, the project will continue with the goal of creating both a new miniature and full scale Mars Free Flyer that can be tested at the Morpheus test site. A miniature version of the gimbal will be made for the smaller prototypes and quad copters. The Asteroid Free Flyer will be converted from using GN2 to Air as its propellant and the gimbal will be upgraded with larger roller bearings and encoders on the shafts to calculate attitude.

Before coming to Swamp Works, I had never worked with carbon fiber, nor had I ever actually made it. It was fun using it to make the gimbal and I am now more knowledgeable about how to design carbon fiber parts that can be manufactured. Due to the high pressure system on the Asteroid Free Flyer, all of the components had to have detailed pedigree with adequate rated pressure before they could be used. I learned a lot about how to select parts and how system safety verification works here at Kennedy Space Center. I had never used Java until I worked with JME3 so I had to learn Java coding from scratch without formal training. I am more confident in my ability now to pick up a new coding language. I also have a deeper understanding of "Object oriented" coding languages since before using JME3 I had not even understood the concept or how one would write code in such language. I also learned advanced mesh manipulation techniques for Blender for making models for the simulations and editing STL files used in 3D printing. I also feel that I am more capable of working on a professional project independently without the direct guidance of a superior. On many tasks I was shown the basics of how to perform it and was handed the reins to complete the task. Other times I would be assigned a task and given the ability to pursue my own solution and explain as to why I chose to go that route. I enjoyed my time at Swamp Works and hope that after graduation there will be room for me to continue working with my mentor on both the ALTFF project and other projects as a full time employee.