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THESIS

ASSEMBLY AND DESIGN MINIATURIZATION OF FLOATING SPACECRAFT SIMULATOR AND ITS MAGNETIC DOCKING INTERFACE

by

Jonathan Park

September 2016

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Second Reader: Josep Virgili-Llop

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13. ABSTRACT (maximum 200 words)

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ASSEMBLY AND DESIGN MINIATURIZATION OF FLOATING SPACECRAFT SIMULATOR AND ITS MAGNETIC DOCKING INTERFACE

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Submitted in partial fulfillment of the
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A detailed description of the assembly procedure of the Floating Spacecraft Simulator (FSS) has been produced for the Naval Postgraduate School's Spacecraft Robotics Laboratory. This procedure has been used to assemble an additional FSS, resulting in a total of three operational units. The second part of the research effort was devoted to the design of a miniaturized version of the FSS. Due to the finite size of the testbed, it was desirable to reduce the footprint of the FSS to increase the available space. The preliminary, yet detailed, design of the miniaturized FSS reduced its footprint by nearly 70%, from 729cm^2 to 225cm^2. The components for the design were selected from commercial-off-the-shelf sources to standardize hardware and reduce cost. A new magnetic docking interface for the miniaturized FSS has also been designed. The main features of the docking interface include an electromagnet for docking and undocking, a spring-loaded connector, and an air connection used to transfer air. Future research will build a prototype of the miniaturized simulator and its docking interface, test its capabilities, and apply upgrades as new and improved components become available.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
A	ampere
AC	alternating current
ARM	Advanced RISC Machines
CAD	computer-aided drafting
ci	cubic inches
cm	centimeter
COTS	commercial off the shelf
cpi	counts per inch
CPU	computer processing unit
CUDA	Compute Unified Device Architecture
DC	direct current
eMMC	embedded MultiMedia Card
FOG	fiber optic gyro
fps	frames per second
FS	full scale
FSS	floating spacecraft simulator
g	grams
GigE	Gigabit Ethernet
GPU	graphics processing unit
HDMI	High Definition Multimedia Interface
IMU	inertial measurement unit
Hz	hertz
K	kelvin
kPa	kilopascals
LAN	Local Area Network
lbs	pounds
LCD	liquid crystal display
Li-ion	lithium ion
Li-Po	lithium polymer

mA	milliampere
mAh	milliampere hour
MIT	Massachusetts Institute of Technology
MFSS	miniaturized floating spacecraft simulator
mm	millimeter
MMC	MultiMediaCard
Ms	milliseconds
N	newtons
NLPM	normalized liters per minute
NPS	Naval Postgraduate School
PCIE	Peripheral Component Interconnect Express
POSEIDYN	Proximity Operation of Spacecraft: Experimental hardware-in-the-loop Dynamic Simulator
psi	pounds per square inch
RISC	Reduced Instruction Set Computer
SD	Secure Digital
SLC	spring loaded connector
SOC	system on chip
SRL	Spacecraft Robotics Laboratory
SSD	solid state drive
SSDL	Stanford University’s Development Laboratory
STL	stereolithography
USB	Universal Serial Bus
UUV	unmanned underwater vehicle
V	volts
VDC	volts direct current
W	watts

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I. INTRODUCTION

A. RESEARCH MOTIVATION

Interest in robotics is growing, whether as a field of study or as a consumer of its technologies. From medical instruments to unmanned underwater vehicles to toy drones, the application of robotics is becoming a part of our everyday lives. But what is more fascinating is the miniaturization of these technologies.

The term miniaturization was coined by Richard P. Feynman, a Nobel Laureate, in 1960. Making things smaller, better, cheaper, and faster is the goal, and it began with electronics [1]. Mobile phones are a great example of this process, and even creators of personal drones have begun producing miniature versions. In fact, miniaturization in the area of larger scale robotics, such as spacecraft and satellites, shows great promise. Reducing size can reduce weight, as well as cost to manufacture and launch. The best paradigmatic example of this in space is CubeSat.

CubeSat developed in 1999 as a collaboration between California Polytechnic State University (Cal Poly) and Stanford University's Space Systems Development Laboratory (SSDL). It was started to provide a standard design to "reduce cost and development time, increase accessibility to space, and sustain frequent launches" [2]. Due to the satellites' small size, a large number of them can be put into space with a single launch. Space is an inherently unsafe place for humans and advancements in robotics allow for a cost-effective method for space exploration.

With advancements in components and reductions in size, it is inevitable that robotics will continue to progress to a smaller scale. Miniaturization is only the beginning. Just as computer chips have been reduced to micro and nano sizes, robotics will continue in the same manner.

B. STATE OF THE ART

Air bearing systems are typically used to simulate space, because they provide a near frictionless and weightless environment. Universities such as Stanford, Massachusetts Institute of Technology (MIT), and the Naval Postgraduate School (NPS) use such testbeds for experiments in spacecraft proximity operations. Although there are testbeds that have the air bearing system built into the flat surface, the system is commonly on the robotic vehicle itself. All three universities have mentioned using granite tables for their space simulation purposes. A testbed is required because it "provides an analogous kinematic and dynamic environment for which to test close proximity operations" [3].

MIT uses a granite table that is approximately 4m x 7m (see Figure 1), while Stanford University reports using one that is 2m x 4m (see Figure 2). NPS uses a 4m x 4m table (see Figure 3). These precision-grade granite tables provide the robots the ability to move on a two-dimensional plane with three degrees of freedom (two translational and one rotational) [4]. These granite tables are expensive and difficult to move around due to their weight and size, which is limited to what can be transported on the road.

Figure 1. Granite Table at the Controls and Automation Laboratory at MIT (2014). Source [5].

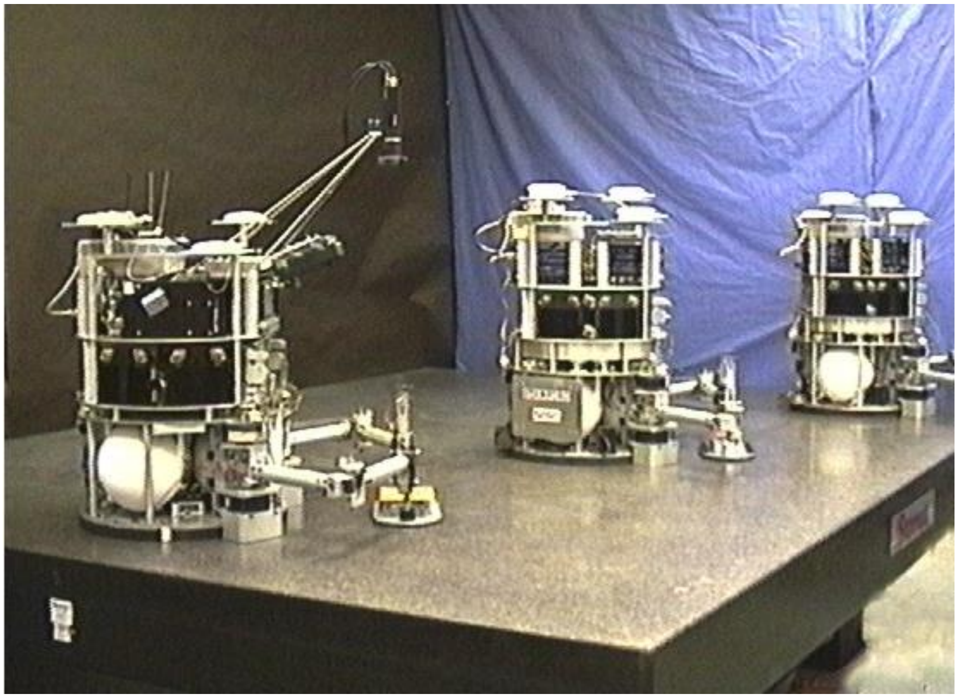
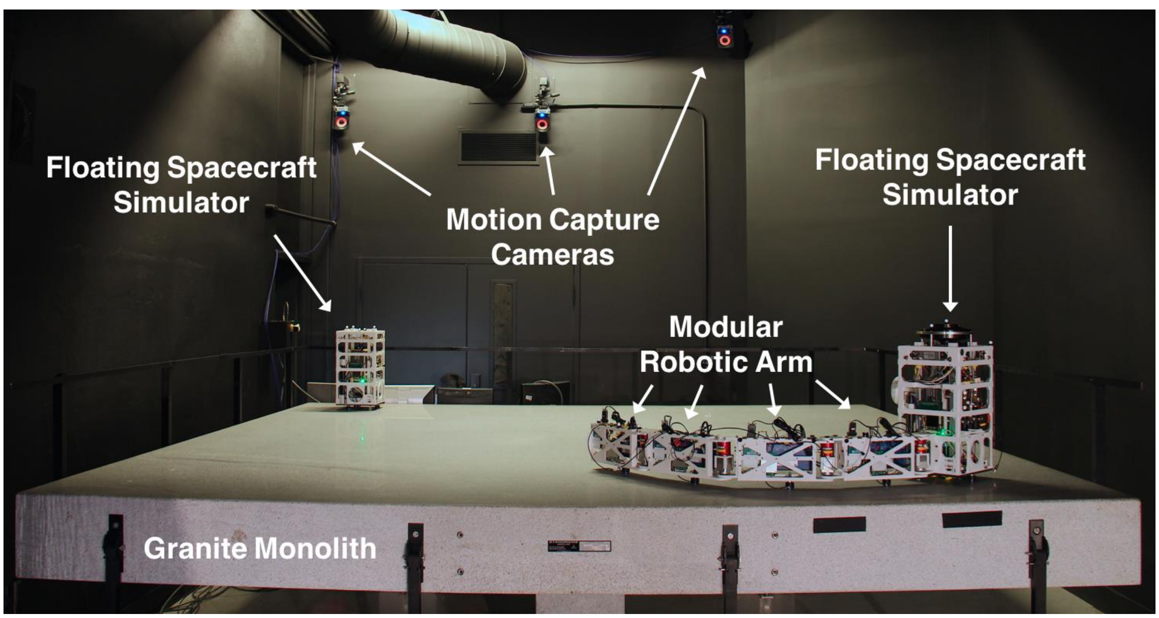


Figure 2. Granite Table at Stanford Aerospace Robotics Laboratory (2010). Source [6].



This system is also known as POSEIDYN (Proximity Operation of Spacecraft: Experimental hardware-in-the-loop Dynamic Simulator).

Figure 3. Granite Flat-Floor at Spacecraft Robotics Laboratory at NPS

Generally, free-floating spacecraft simulators built by universities are considered large; limiting the number of spacecraft simulators that can be operated on a given testbed. For example, NPS's Floating Spacecraft Simulator (FSS) currently has a base of 27cm x 27cm with a height of 53cm. Although an individual spacecraft simulator does not need much space to maneuver, three spacecraft simulators—in an environment with obstacles and manipulators—need significantly more. In order to increase the available space, the spacecraft simulators must be reduced in size. Miniaturization is a key step for the NPS Spacecraft Research Laboratory (SRL) to pursue multi-robot coordinated control.

C. RESEARCH OBJECTIVES

This research has four primary objectives, which will contribute to the development of autonomous rendezvous and docking of spacecraft.

1. Assemble a Floating Spacecraft Simulator

The assembly of a FSS will provide the NPS SRL with a total of three spacecraft simulators. The additional FSS will allow the SRL team to work more complex situations with respect to obstacle avoidance, formation movements, docking maneuvers, and scenarios involving one or more manipulators. The addition of a third spacecraft simulator will also provide the option to experiment with two while the third is on standby or undergoing repairs. More importantly to this research, it will give a better understanding of the hardware, electronics, and pneumatics required for the FSS.

2. Create an Assembly Guide for the Floating Spacecraft Simulator

There is no documentation on how to assemble the FSS. The assembly guide will develop in unison with the assembly itself. The difficulty in this process is reverse engineering—looking at the current production of the spacecraft simulator when not in use and identifying which components need to be installed before another. Furthermore, the assembly guide needs to be clear which wires connect to which components and how to easily trace the wire from source to component for troubleshooting issues. The assembly guide will also provide snapshots of the current design at each step.

3. Design Miniaturization of the Floating Spacecraft Simulator

The assembly of the FSS will provide insight into the components required for the miniaturization: electronics, pneumatics, and hardware. The goal is to reduce the current footprint of the FSS from 27cm x 27cm to 10cm x 10cm. It will be designed using computer-aided design (CAD) software, and in the process, it will provide insight into the problems, issues and benefits of miniaturization.

4. Design a Docking Interface for the Miniature Floating Spacecraft Simulator (MFSS)

The current docking mechanism on the FSS is cone-shaped and has a magnet at the tip to assist in the docking maneuver. The issue with this design is that due to the magnet, the FSS is unable to remove itself from the dock without human assistance. The goal is to design a docking mechanism that can accomplish three specific tasks: dock and remove from dock without assistance, transfer data once docked, and transfer air to the air bearings of another MFSS when docked.

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II. ASSEMBLY DOCUMENTATION

A. FLOATING SPACECRAFT SIMULATOR OVERVIEW

The FSS support structure is made of carbon fiber for the base, aluminum rods for the internal support structure, and 3D printed material for the external and internal framework. Figure 4 is a picture of the current design.

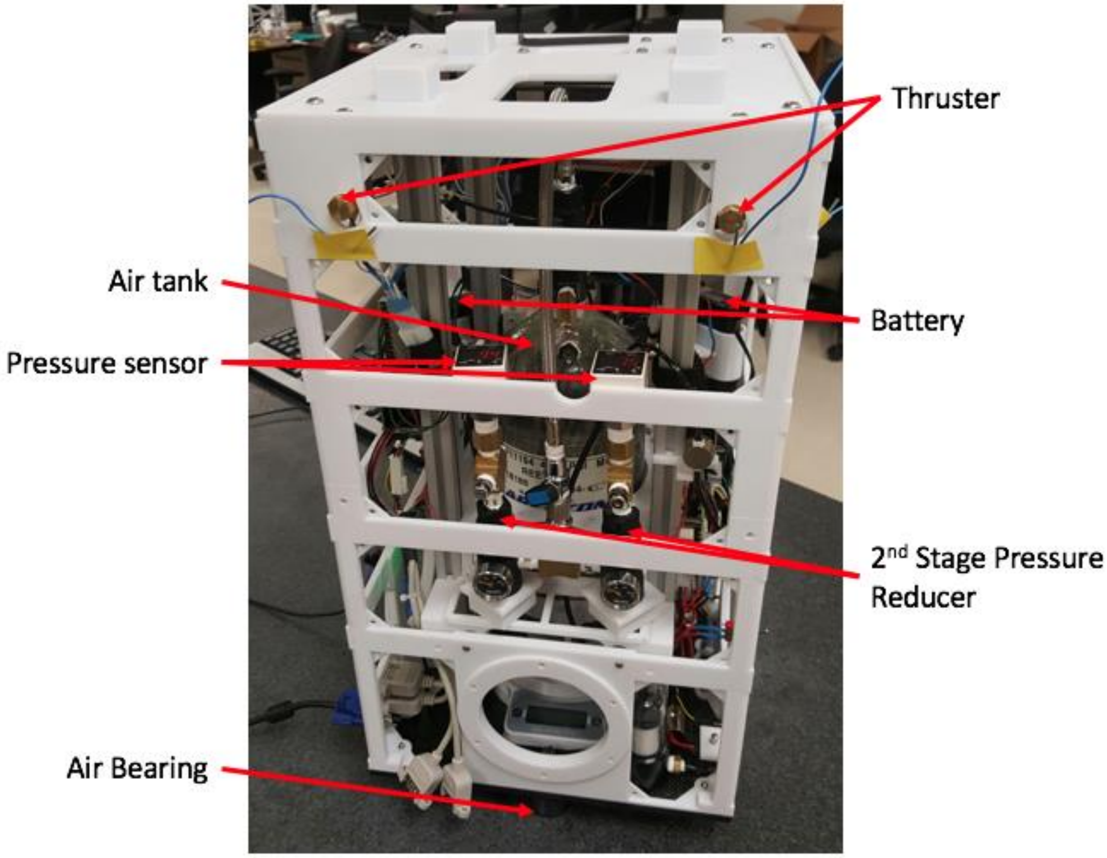


Figure 4. Current FSS Design

Figure 5 illustrates the pneumatic schematic of the FSS. Beginning with the 1868cm^3 (114ci) Air Tank rated at 31026kPa (4500psi), the air passes through a first stage reducer bringing the pressure down to 5516kPa (800psi). The on/off ball valve allows the air to be cut off when not in use. From the ball valve, the air is directed to two separate second stage reducers that bring the pressure down to the operating pressure of

414kPa (60psi). One set of second-stage reducers supplies air to eight solenoid valves, which are the thrusters for the FSS. The other is directed through a micro-solenoid valve, to the air filter, and finally to the three air bearings. The micro-solenoid valve acts as a switch, which can be turned on and off wirelessly to allow air to the air bearings. The air filter is used as a precaution to ensure that micro-particles do not block the flow to the air bearings. Lastly, the air bearings allow the FSS to float five microns from the surface of the testbed, reducing friction.

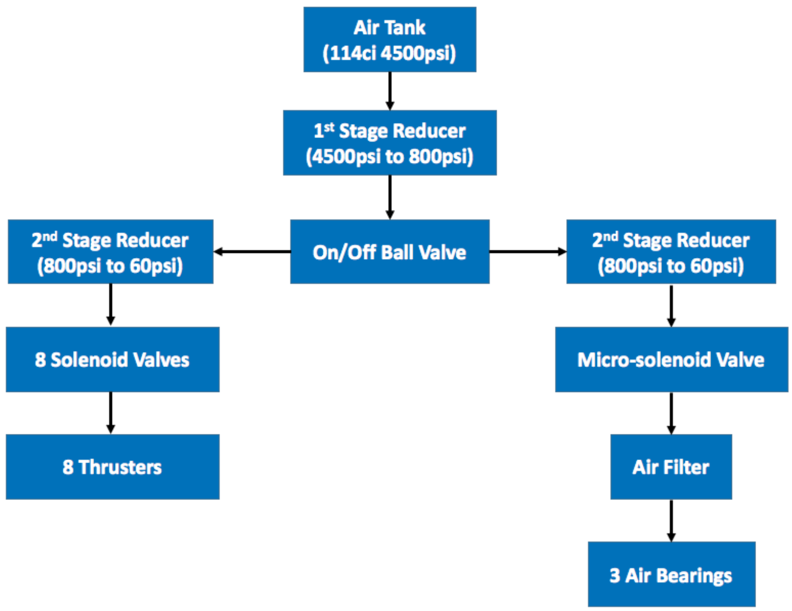


Figure 5. FSS Pneumatic Schematic

Figure 6 illustrates the electrical schematic of the FSS. Two lithium-ion batteries provide power for FSS. The 14.4V from the batteries are stepped up through the mini battery management module to 18V, which is then connected to a DC-DC converter that steps down the voltage to 5V and 12V, required for some of the electrical components such as the micro-solenoid valve, fiber optic gyro (FOG), central processing unit (CPU), wireless router, and another DC-DC converter. The second DC-DC converter steps up the voltage to 24V, which supplies power to the pressure sensors and the eight solenoid valves. The CPU has a data connection to the FOG, wireless router, and relay board. The relay board is also connected to the micro-solenoid valve and the eight solenoid valves, acting as a switch for opening and closing of air flow to the thrusters and air bearings.

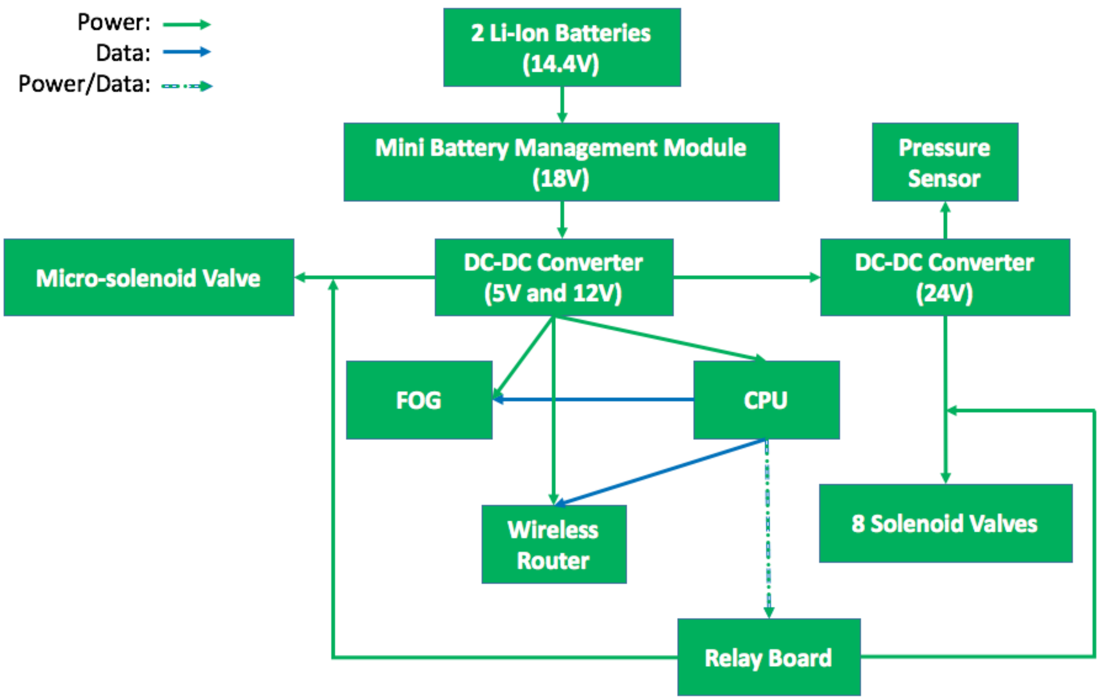


Figure 6. FSS Electrical Schematic

B. INTENT OF DOCUMENTATION

The intent of this section is to document the major components required to assemble the FSS. It will describe each individual component, its specifications as well as its purpose in the FSS. There is no previous documentation on assembling the FSS and therefore this is the first. Appendix A contains the full list of electrical and pneumatic parts required to build the FSS. Appendix B is the complete assembly guide with a step by step process on building the FSS for future productions.

C. MAJOR COMPONENTS FOR PNEUMATIC SYSTEM

1. 1868cm^3 (114ci) Air Tank

The air tank in the FSS is 1868cm^3 (114ci) rated at 31026kPa (4500psi) (see Figure 7). This tank will provide air to the air bearings and supersonic thrusters and is the limiting factor for the endurance of the FSS. Air supplied to the three air bearings underneath the FSS, allow it to float, and the supersonic thrusters allow the FSS to maneuver. A smaller tank can be used for this specific build of the FSS as long as the diameter of the tank is the same or smaller.

Figure 7. 1868cm^3 (114ci) Air Tank with Filler Attachment

2. First Stage Pressure Reduction

The 1868cm^3 (114ci) air tank used is rated at 31026kPa (4500psi) and although it is not necessary to pressurize the tank to its specified rating, the FSS uses a two-step reduction process to safely bring the pressure down to 414kPa (60psi) for operational use. Assuming, the tank has been pressurized to 31026kPa (4500psi), the first reduction is completed by using a Ninja Ultralite Regulator (see Figure 8). The Ninja Ultralite Regulator, attaches directly to the air tank, is designed to accept up to 31026kPa (4500psi) and output an adjustable pressure of 3447kPa (500psi), 4482kPa (650psi), or 5516kPa (800psi) [7]. It comes shipped preset at 5516kPa (800psi) and that was the setting used for the FSS. Adjusting the output pressure to the other two options is acceptable, as well.

Figure 8. Ninja Ultralite Regulator

3. Second Stage Pressure Reduction

The second reduction takes the 5516kPa (800psi) output of the Ninja regulator to 414kPa (60psi) using Palmers Pursuit Shop's Fatty Stabilizer Regulator (see Figure 9). This stabilizer regulator is adjustable from 0 to 2758kPa (400psi) [8]. Although this regulator has a 4137kPa (600psi) gauge, it is difficult to fine tune to 414kPa (60psi), thus the digital pressure sensor is required. Once the pressure sensor is attached to the stabilizer regulator and then to the Ninja regulator, a hex key can be used to manually adjust the pressure on the stabilizer regulator down to 414kPa (60psi) while observing the digital readout of the pressure. The FSS requires two of these regulators, one to supply the air bearings and the other for the solenoid valves.

Figure 9. Two Palmers Pursuit Shop's Fatty Stabilizer Regulator

4. Solenoid Valves

Solenoid valves are required to act as thrusters for the FSS. Gems Sensors and Controls have an EH series designed for use with applications that require fast response times with high pressure and high flow [9]. Specifically, the EH2012 model (see Figure 10) is used for the FSS and a total of eight are required. The EH2012 is a 2-way sub-miniature solenoid valve rated at 2W and 24VDC [9]. Miniature brass pipe fittings are attached to the inlet of the solenoid valves to direct 414kPa (60psi) air into it and a customized micro-orifice is attached to the outlet to focus the air for thrust use (see Figure 11).

Figure 10. Gems Sensors and Controls EH2012 Solenoid Valve

Figure 11. EH2012 Solenoid Valve with Miniature Brass Pipe Fitting and Customized Micro-orifice Attached

5. 25mm Flat Round Air Bearings

There are various sizes of air bearings ranging from 25mm to 300mm in diameter from New Way Air Bearings and the FSS uses the smallest, the 25mm air bearings (see Figure 12). The underside of the bearings is porous allowing it to have a fly height of 5 microns and the FSS has three air bearings installed to maintain stability when floating (see Figure 13). Each individual 25mm air bearing has an ideal load of 80N (18lbs) with an ideal input pressure of 414kPa (60psi) [10]. Although a single larger bearing can be used, using the three smaller air bearings allow for a longer floating time as they consume less air.

Figure 12. 25mm New Way Air Bearing

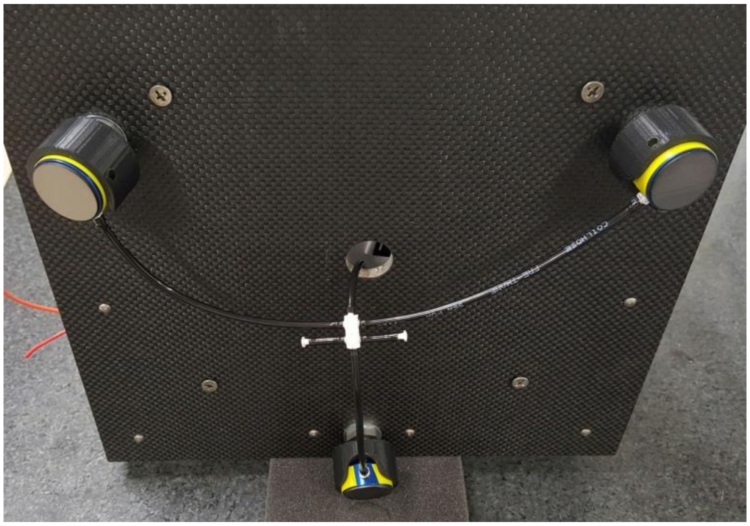


Figure 13. Underside of the FSS with Three 25mm Air Bearings Installed

6. Digital Pressure Sensor

Two pressure sensors are installed, one to read the pressure going to the solenoid valves that provide thrust and the other for the three flat round air bearings. The Ashcroft GC31 Ultra-Compact Pressure Sensors (see Figure 14) were used on the FSS. The face of the digital reader is measured at 30mm x 30mm with a total height of 49mm. It requires a supply voltage of 11–27VDC and the gauges can read up to 10342kPa (1500psi) with an accuracy of plus or minus 1.0% full scale (FS) [11]. 414kPa (60psi) is required for the solenoid valves and air bearings and the pressure sensor allows the user to easily make adjustments before applying pressure. Excessive pressure can damage components and blow out of the air tubing can occur.

Figure 14. Ashcroft GC31 Pressure Sensor

The pressure sensors have five cable wires color coded for installation (see Figure 15). The only two required for the FSS is the brown and blue cable wires. As indicated in Figure 15, the blue is ground and the brown is the input power, in this case 24VDC. The remaining three cable wires, orange, black, and white are for the switch and transducer features that are not required in the FSS.

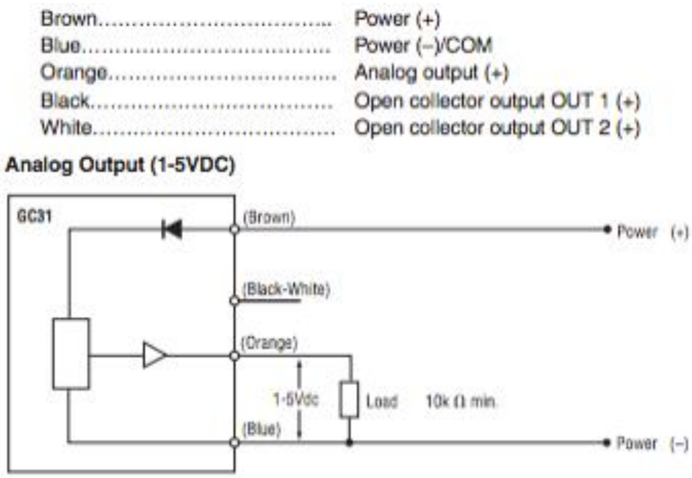


Figure 15. Ashcroft GC31 Wiring Diagram. Source: [12].

D. MAJOR COMPONENTS FOR ELECTRICAL SYSTEM

1. Portable Battery

Two rechargeable smart lithium ion battery packs (see Figure 16) are used to power all of the electrical components on the FSS. The batteries are portable and are made by Inspired Energy. The battery contains twelve rechargeable cells, “assembled in a 4 series / 3 parallel” configuration and each battery provides a nominal voltage of 14.4V [13]. It has a liquid crystal display (LCD) panel that remains on indicating the amount of charge the battery has and uses molex connectors to attach to the component it is powering.

Figure 16. Two Inspired Energy Rechargeable Smart Lithium Ion Battery Pack. Source: [13].

2. Mini Battery Management Module

The mini battery management module by Ocean Server Technology is ideal for the FSS in that in can accept up to four smart battery packs such as the previously mentioned portable battery by Inspired Energy. Currently, the FSS uses only two batteries, but can expand up to an additional two if more power is needed when additional components or sensors are added. The module model used is the BB-04SR (see Figure 17), the smallest that Ocean Server Technology has, which “provides unregulated DC power (RAW battery voltage) output at 11–18VDC to the DC-DC Converter” [14].

Figure 17. BB-04SR Mini Battery Management Module. Source: [14].

3. DC-DC Converters

In order to provide the correct voltages to the electrical components from the batteries via the mini battery management module, DC-DC converters are necessary. Ocean Server has several types of DC-DC converters specifically designed to be used with their battery management module and the two types used on the FSS are the DC1U-1VR DC-DC Converter (see Figure 18) and the DC123SR Ultra High Efficiency ATX DC-DC Converter Module (see Figure 19). The added benefit of using products from the same company is that they are stackable, which allows to save space on the FSS.

The DC1U-1VR is 96% efficient, provides regulated DC output, and is factory configured for 19V, 20V, 24V, or 28V [15]. The one used for the FSS was configured for 24V to power the two digital pressure sensors and this specific converter accepts input voltages ranging from 12V to 23V.

Figure 18. Ocean Server Technology DC1U-1VR DC-DC Converter

The DC123SR Ultra High Efficiency ATX DC-DC Converter is 97% efficient and also “provides regulated power 3.3V at 10A, 5V at 10A and 12V at 12A” [16]. The 3.3V output is not required for the FSS, but the 5V and 12V outputs are used to power the various electrical components such as the solenoid valves, lights, and gyroscope.

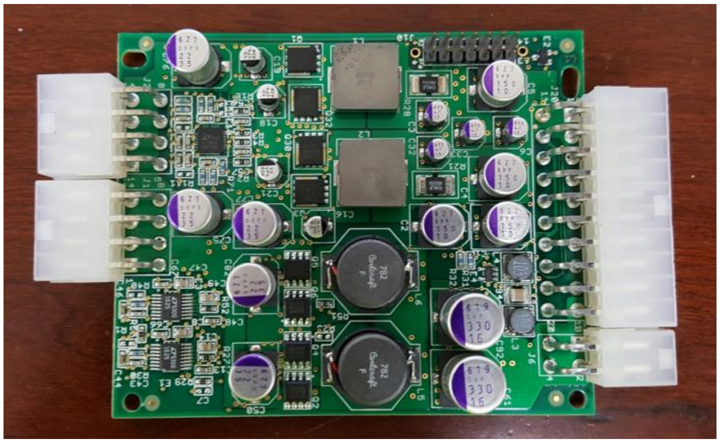


Figure 19. Ocean Server Technology DC123SR Ultra High Efficiency ATX DC-DC Converter

4. Central Processing Unit (CPU)

The CPU mounted on the FSS is an Intel Atom, single core processor, with an added low profile heatsink (see Figure 20). It is 90mm x 96mm, which is a relatively small form factor, and contains the basic necessities required for programming the FSS, such as an onboard solid state drive (SSD), keyboard and mouse inputs, and windows operating system [17]. A wide variety of CPUs can be used for the FSS and there is no particular reason for using the Intel Atom CPU. The main benefit of this specific board is that it is a PC104 form factor allowing it to be attached to the relay board easily.

Figure 20. Intel Atom CPU. Source: [17].

5. Fiber Optic Gyroscope

Although a much cheaper inertial navigation unit would suffice for the FSS, the one used on this model is the $4,000 DSP-3000 Fiber Optic Gyro (FOG) by KVH Industries (see Figure 21). The DSP-3000 is a commercial-off-the-shelf (COTS) product and is a single axis FOG with a modular design for that can have up to a 3-axis configuration [18]. This gyroscope was readily available in the SRL; thus this was used as a cost-saving measure. The gyro is "connected via the onboard computer serial ports [and] provides angular rate readings at a 100Hz" [19].

Figure 21. KVH Industries DSP-3000 Fiber Optic Gyro

6. Relay Board

A relay board is essential in controlling the air going to the solenoid valves. Using the software designed by the SRL, the relay board allows individual solenoid valves to turn on and off, allowing pressurized air to pass to be used as thrust. Since the FSS has a cuboid shape, each face has two solenoid valves allowing it to essentially be holonomic on the two dimensional plane. The relay board used on the FSS is built by Tri-M Engineering (see Figure 22) and has a total of twenty channels, which accepts inputs ranging from 3–24V (DC or AC) with a max current of 5A (AC or DC) [20]. Also, the relay board uses a PC104 form factor for easy connection to other electrical components used in the FSS. While the FSS only requires nine of the twenty channels, the additional channels can be used for expansion of the FSS capabilities and future upgrades.

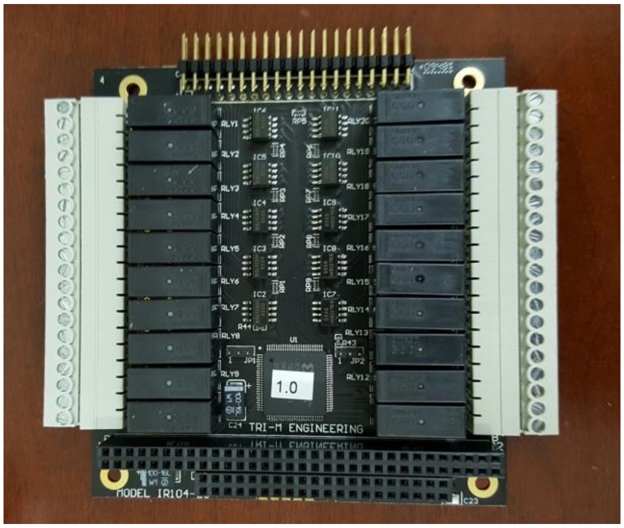


Figure 22. Tri-M Engineering IR104-PBF Relay Board

III. MINIATURIZATION

A. REASON FOR MINIATURIZATION

The testbed used at the SRL is 4m x 4m and due to the set size, miniaturization is a key step in increasing the available maneuver space. A miniaturized FSS will allow for more work space and an increased number of MFSS units that can operate at a given time. With more units on the testbed, more complex multi-robot coordinated control scenarios can be conducted.

B. REQUIREMENTS AND GOALS

The design requirements and goals for the MFSS are as follows:

- Reduce footprint of FSS, ideally to 10cm x 10cm
- Use COTS components to minimize time waiting for parts and increase the speed of production
- Float at least twenty minutes
- Accept two types of computing platforms: Raspberry Pi 3 Model B and NVIDIA Jetson TK1
- Use a single air bearing if possible
- Have the ability to navigate without Vicon's motion capture system
- Minimize cost

C. COMPONENT SELECTION

Using Appendix B, which contains all the pneumatic and electrical components required to build the FSS, the search began to find components that were smaller and had equivalent specifications. Components were selected by first identifying if the manufacturer of a component on the FSS had a smaller version. If not, an Internet search was conducted to find the product. After selecting a component, in order to reduce costs, a search was conducted on Internet-based sites to see if the same component was available at a reduced price.

1. Air Bearing and Air Tank

Currently, the FSS uses three 25mm New Way Air Bearings with a 1868cm^3 (114ci) air tank as its supply giving it an estimated float time of 3.7 hours. Two primary companies were compared for air bearings, New Way Air Bearings and OAV Air Bearings. Both company's specifications and pricing on their air bearings were very similar, but New Way Air Bearings were selected because they have already been used on the FSS. There is a wide variety of sizes, but the range that was researched was 25mm, 40mm, 50mm and 60mm.

Before selecting an air bearing, air tank sizes had to be compared to each air bearing size to calculate estimated float time. The air tank sizes that were used in this calculation were 213cm^3 (13ci), 426cm^3 (26ci), 574cm^3 (35ci), and 623cm^3 (38ci). New Way Air Bearings specifications contain normal liters per minute (NLPM) numbers and it was converted to liters per minute (LPM) using an equation shown in Figure 23. Using each air bearing size and air tank size, calculations were made for estimated float time for a single air bearing (see Table 1).

Conversion from LPM to NLPM(Europe):

$$F[NLPM] = F[LPM] \times (273.15 / T_{gas}) \times (P_{gas} / 14.696)$$

P_{gas} – Absolute gas pressure in Psia
T_{gas} – Gas Temperature in K

T_{gas} used for calculation was room temperature at 294.3K and P_{gas} was 3014.696psi.

Figure 23. NLPM to LPM Conversion Equation. Source [21].

Table 1. Float Time Calculation

Air Bearing Size	NLPM	Input Pressure kPa (psi)	LPM	Time w/ 623cm^3 (38ci) Tank (hours)	Time w/ 574cm^3 (35ci) Tank (hours)	Time w/ 426cm^3 (26ci) Tank (hours)	Time w/ 213cm^3 (13ci) Tank (hours)
25mm	0.53	414 (60)	0.0028	3.7106	3.4177	2.5389	1.2694
40mm	0.74	414 (60)	0.0039	2.6576	2.4478	1.8183	0.9092
50mm	1.1	414 (60)	0.0058	1.7879	1.6467	1.2232	0.6116
60mm	1.4	414 (60)	0.0074	1.4047	1.2938	0.9611	0.4806

Initial decision was to use either the 50mm (see Figure 24) or 60mm (see Figure 25) air bearing with a 213cm^3 (13ci) tank (see Figure 26). This accomplished the goal of using a single air bearing, minimizing the size of the air tank component and having a float time of at least 20 minutes. Although there were some concerns in regards to stability using one air bearing, assuming the final base would be 10cm x 10cm with minimal height, using a static mount instead of a ball mounting screw end would mitigate this concern.

Figure 24. New Way Air Bearing 50mm. Source [22].

Figure 25. New Way Air bearing 60mm. Source [22].

Figure 26. Guerilla Air 213cm^3 (13ci) 20684kPa (3000psi) Aluminum HPA Tank. Source [23].

2. Regulators

All of the air tanks that were researched were rated at 20684kPa (3000psi) and Ninja's Ultralite Regulator was already compact in size and could accept tanks rated at up to 31026kPa (4500psi). No change was needed for the first pressure reduction component from 20684kPa (3000psi) to 5516kPa (800psi). Additionally, no change was needed for the second stage reduction component, Palmers Pursuit Shop's Fatty Stabilizer Regulator. Although the company had smaller stabilizer regulators, none were able to reduce to a desired 414kPa (60psi) from 5516kPa (800psi). Other companies had regulators that had the desired specifications, but component size was larger than the currently used regulator.

The FSS used two stabilizer regulators, one for the air pads and the other for the thrusters (solenoid valves). To minimize the number of components, hardware and to maximize space availability on the miniaturized version, it was decided that only one stabilizer regulator would be used for all air requiring components. To further save space, the digital pressure sensor that attached to the stabilizer regulator was removed.

3. Solenoid Valves

The solenoid valve component for the thrusters remains the same. The only change with these valves will be their placement. The FSS had all solenoids on the same level, which essentially required more space. With the miniaturized version, the valves will be stacked in sets of two to minimize the amount of space the components will use.

4. Battery

To keep the overall design small, rather than looking into lithium ion (Li-ion) batteries, lithium polymer (Li-Po) batteries were researched. Compared to Li-ion, Li-Po batteries can provide more power in a smaller form factor. The Li-Po selected was the Tiger Li-Po 2200mAh (see Figure 27) which has a max continuous discharge of 25C and a max burst discharge of 60C, fully capable of powering all the necessary electrical components on the miniaturized version. With future upgrades and enhancements, an additional Li-Po battery can easily be added.

Figure 27. Tiger Li-Po 2200mAh Battery

5. Step-up Voltage Converter

All of the electrical components require at least 24V or less and since the Li-Po battery only provides 11.1V, a step-up voltage regulator is required. The Geeetech 150W Boost Converter (see Figure 28) accomplishes this by taking 10–32V input and outputting 12–35V adjustable. It costs $7 on Amazon and its size is only 7.4cm x 5.8cm x 3.81cm.

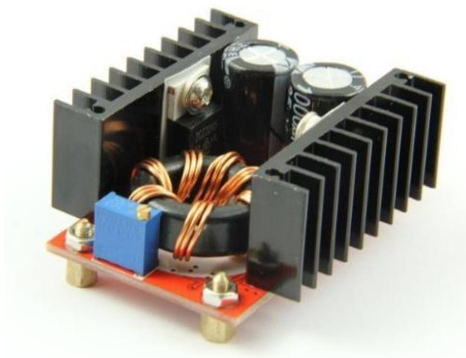


Figure 28. Geeetech 150W Boost Converter. Source [24].

6. Raspberry Pi 3 Model B

The Raspberry Pi 3 Model B is one of two primary onboard computers that will be used (see Figure 29). This particular model is the third iteration of the Raspberry Pi series, improving upon the Raspberry Pi 2 Model B. Compared to the NVIDIA Jetson TK1, the Raspberry Pi's form factor is significantly smaller, approximately 8.7cm x 5.7cm x 2cm. In addition, it is considerably cheaper with an average price of $35. Listed below are the specifications of the Raspberry Pi 3 Model B [25].

- 1.2GHz 64-bit quad-core ARMv8 CPU
- 802.11n Wireless LAN
- Bluetooth 4.1
- Bluetooth Low Energy (BLE)
- 1GB RAM
- 4USB ports
- 40 GPIO pins
- Full HDMI port
- Ethernet port
- Combined 3.5mm audio jack and composite video
- Camera interface (CSI)
- Display interface (DSI)

- Micro SD card slot
- VideoCore IV 3D graphics core

Figure 29. Raspberry Pi 3 Model B

7. NVIDIA Jetson TK1

While the Raspberry Pi 3 Model B can be used as a starting point for onboard computers, the NVIDIA Jetson TK1 is much more capable (see Figure 30). If the MFSS were to be upgraded to have additional sensors and other electrical components, the Jetson TK1 is better fitted for enhancements. Specifically, because the Jetson TK1 has a graphics processing unit (GPU) and the Raspberry Pi does not, the Jetson TK1 is ideal for vision capabilities.

An issue with using this computer board is that it will not fit in the ideal 10cm x 10cm footprint, due to its dimensions being approximately 127cm x 127cm x 12cm. The initial design segment will discuss further in addressing this issue. Listed below are the specifications of the NVIDIA Jetson TK1 [26].

- Tegra K1 SOC (NVIDIA Kepler GPU with 192 CUDA Cores and NVIDIA 4-Plus-1 Quad-Core ARM Cortex-A15 CPU)
- 2 GB x16 Memory with 64-bit Width

- 16 GB 4.51 eMMC Memory
- 1 Half Mini-PCIE Slot
- 1 Full-Size SD/MMC Connector
- 1 Full-Size HDMI Port
- 1 USB 2.0 Port
- 1 USB 3.0 Port
- 1 RS232 Serial Port
- 1 ALC5639 Realtek Audio Codec with Mic In and Line Out
- 1 RTL8111GS Realtek GigE LAN
- SPI 4 Mbyte Boot Flash

Figure 30. NVIDIA Jetson TK1

8. Laser Motion Sensor

One of the goals was to move away from the Vicon Motion Capture System and have the MFSS have its own navigation system that can track its movements. In a step toward achieving this goal, laser motion sensors were explored, essentially what a typical computer mouse uses. The ADNS-9800 Laser Motion Sensor (see Figure 31 and Figure

32) was ideal for robotic applications where distance traveled needed to be tracked. Although a single sensor can provide distance traveled (X and Y plane), the MFSS needs to be able to track rotational movement as well. To address this, two laser motion sensors will be placed underneath the base of the MFSS to track X, Y and rotation along the plane.

Some of the features of the ADNS-9800 are listed below [27].

- Small form factor chip-on-board package
- Dual power supply selections, 3V or 5V
- No laser power calibration needed
- Self-adjusting frame rate for optimum performance
- Motion detect pin output
- Frame rate up to 12,000fps
- Resolution up to 8200cpi
- X and Y axes independent resolution setting

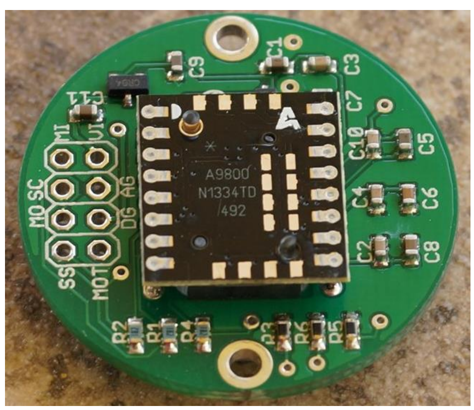


Figure 31. ADNS-9800 Laser Motion Sensor (Top View). Source [27].

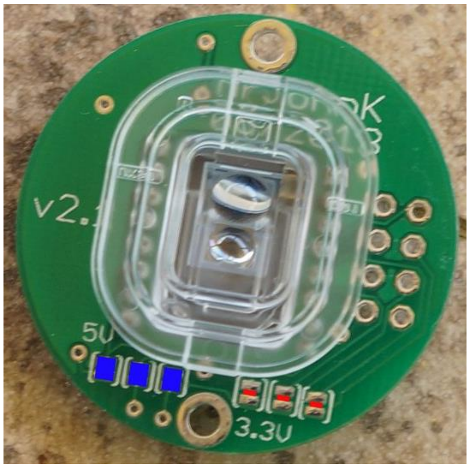


Figure 32. ADNS-9800 Laser Motion Sensor (Bottom View). Source [27].

9. Relay Board

The FSS presently uses a relay board that has twenty channels in which only nine of them are used, eight for the solenoid valves used as thrusters and one for the micro-solenoid valve which allows the operator to wirelessly allow air to pass to the air bearings. With this in mind, the Denkovi 10 Channel Relay Board (see Figure 33) was selected. An input voltage of 3V-30V with a 1.5mA max is required to turn each individual switch on. Its dimensions are 85mm x 198mm x 20mm, making it longer than the original Tri-M Engineering 20 Channel Relay Board, but much narrower, which will allow it to fit vertically within the 10cm x 10cm idea footprint of the MFSS.

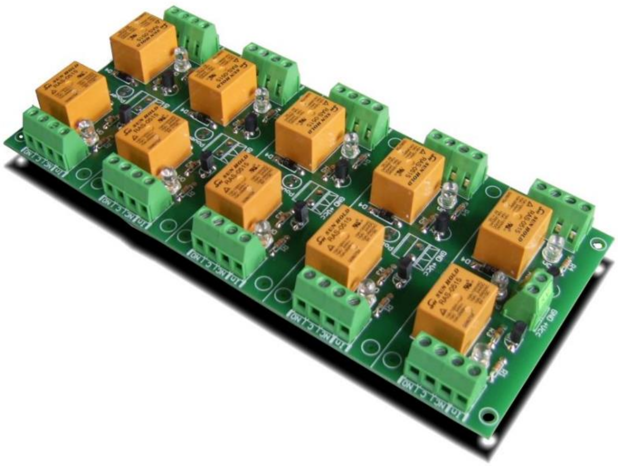


Figure 33. Denkovi 10 Channel Relay Board. Source [28].

10. Inertial Measurement Unit (IMU)

The gyroscope used in the FSS was much too expensive and for a tenth of the price, Analog Devices' ADIS16362 IMU (see Figure 34) is ideal for miniaturization. The dimensions are 23mm x 23mm x 23mm, costs $469, and has features that are sufficient for the miniaturized version as listed below [29].

- Triaxis digital gyroscope with digital range scaling ±75°/sec, ±150°/sec, ±300°/sec settings. Tight orthogonal alignment: <0.05°
- Triaxis digital accelerometer: ±1.7*g*
- Wide sensor bandwidth: 330 Hz
- Autonomous operation and data collection. No external configuration commands required. Start-uptime:180ms. Sleep mode recovery time: 4ms
- Factory-calibrated sensitivity, bias, and axial alignment. Calibration temperature range: −20°C to +70°C
- SPI-compatible serial interface
- Embedded temperature sensor
- Programmable operation and control - See data sheet
- Single-supply operation: 4.75 V to 5.25 V
- 2000 *g* shock survivability
- Operating temperature range: −40°C to +105°C

Figure 34. Analog Device ADIS16362 IMU. Source: [30].

Additionally, this company also has a breakout board (see Figure 35) that was designed specifically for their IMUs. The ADIS16362 IMU can attach directly on top of the ADIS16IMU1/PCBZ Breakout Board (see Figure 36), and it has a “16-pin, dual row, 2mm pitch connecter that support 1mm ribbon cable systems” [31].

Figure 35. ADIS16IMU1/PCBZ Breakout Board. Source [31].

Figure 36. ADIS16362 IMU Attached to ADIS16IMU1/PCBZ Breakout Board. Source: [31].

D. INITIAL DESIGN

The proposed pneumatic and electrical schematics for the MFSS are shown in Figure 37 and Figure 38, respectively. For the electrical schematic, low-dropout regulators will need to be selected appropriately to bring the stepped-up voltage of 24V down to the required voltages for some of the electrical components.

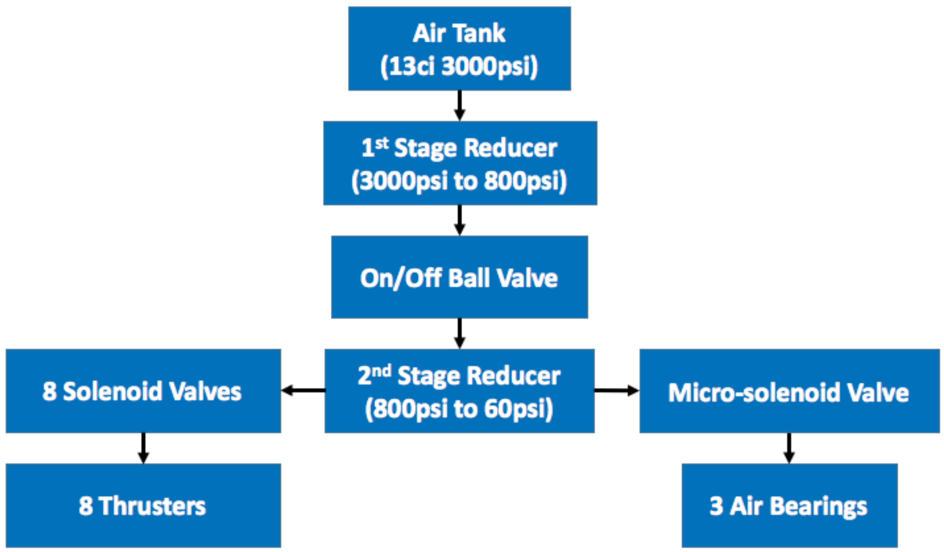


Figure 37. Proposed Pneumatic Schematic for MFSS

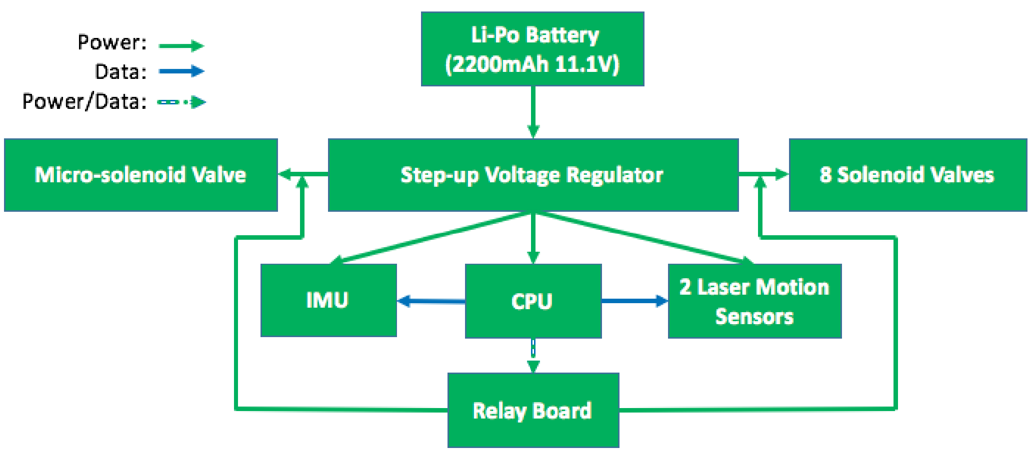


Figure 38. Proposed Electrical Schematic for MFSS

The program used to make the 3D designs of the MFSS was TINKERCAD, which is a website that allows users to make their personal creations for free. The initial process began with creating a 3D model of every major component and saving each as a stereolithography (STL) file. For components that were readily available in the lab, measurements were taken to accurately replicate its dimensions such as Palmer Pursuit Shop's Fatty Stabilizer Regulator, Raspberry Pi 3 Model B, and NVIDIA Jetson TK1. For other components, information about dimensions was found browsing websites, chatting on instant messaging with companies and occasional phone calls. The following are the list of components that were modeled in TINKERCAD with several 3D-modeled snapshots.

- 50mm and 60mm New Way Air Bearing
- Guerrilla 213cm^3 (13ci) 20684kPa (3000psi) Air Tank (see Figure 39)

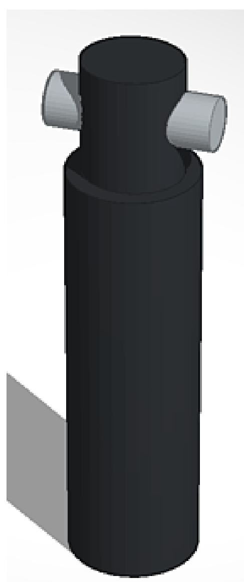


Figure 39. 3D Model of Guerrilla 213cm^3 (13ci) 20684kPa (3000psi) Air Tank

- ADNS9800 Laser Motion Sensor
- Tiger 2200mAh Li-Po Battery
- Denkovi 10 Channel Relay Board (see Figure 40)

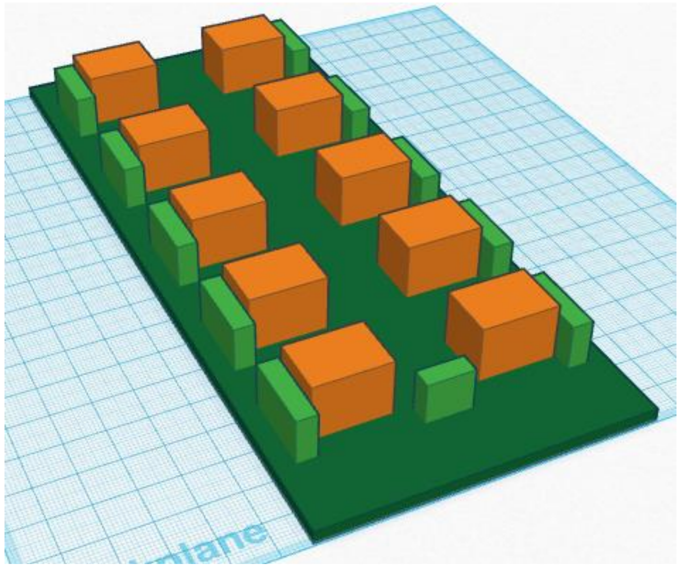


Figure 40. 3D Model of Denkovi 10 Channel Relay Board

- Palmer Pursuit Shop Fatty Stabilizer Regulator (see Figure 41)

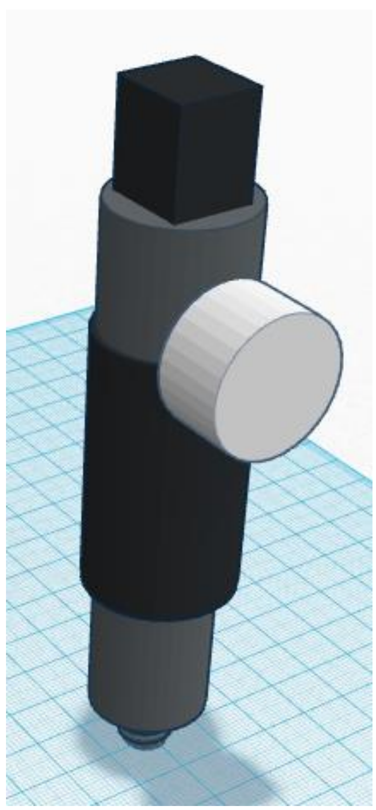


Figure 41. 3D Model of Palmers Pursuit Shop Fatty Stabilizer Regulator

- NVIDIA Jetson TK1 (see Figure 42)

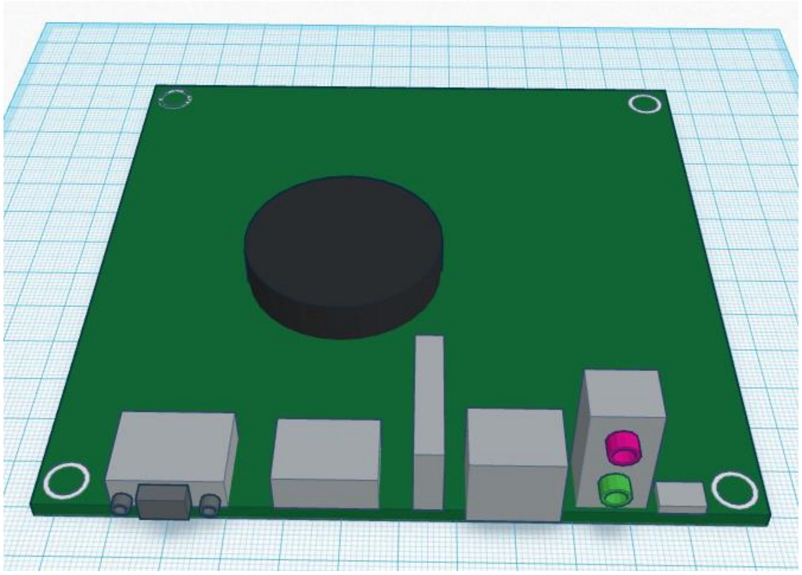


Figure 42. 3D Model of NVIDIA Jetson TK1

- Raspberry Pi 3 Model B (see Figure 43)

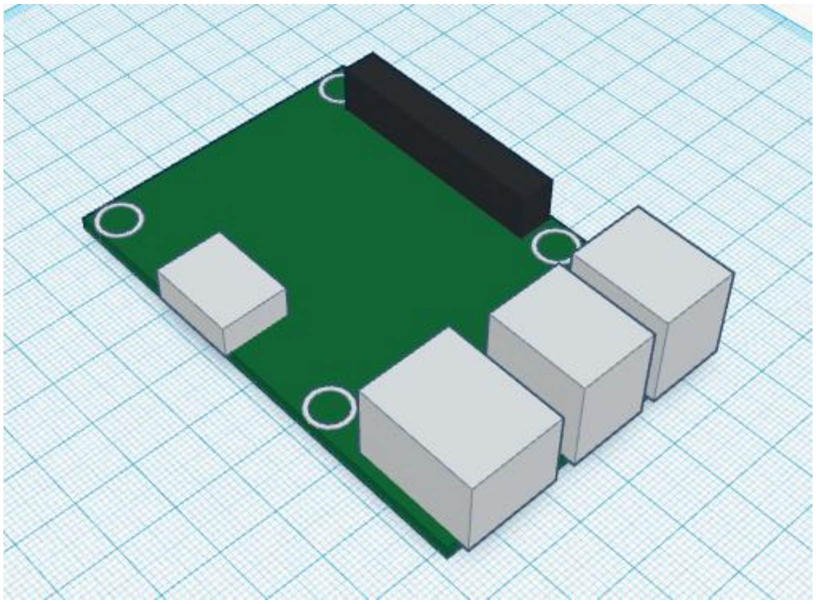


Figure 43. 3D Model of Raspberry Pi 3 Model B

- Geeetech 150W Step-up Voltage Regulator

- Air Filter (for air bearings, but not required) (see Figure 44)

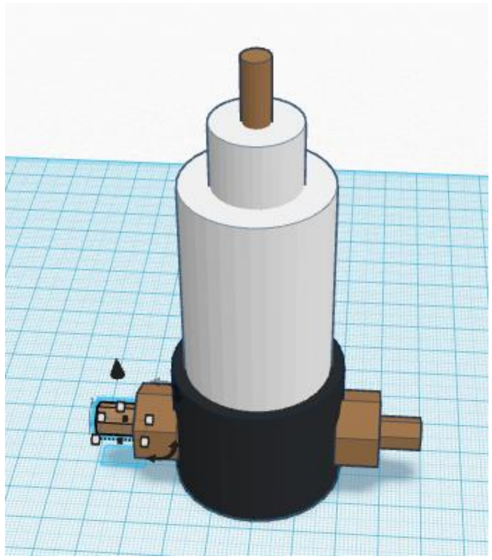


Figure 44. Air Filter

- On/Off Ball Valve Connection from Air Tank to Stabilizer Regulator
- Pressure Release Attachment
- Solenoid Valves
- Analog Device ADIS16362 IMU with ADIS16IMU1/PCBZ Breakout Board

Once each component was modeled, a base plate of 10cm x 10cm with 3mm thickness was modeled. This gave a visual on how small the area was and how to orient the components to properly fit and operate within that constraint. Furthermore, every attempt was made to minimize the height for better stability.

Since the NVIDIA Jetson TK1 was physically too large to fit in the 10cm x 10cm footprint, an attempt was made with the Raspberry Pi 3 Model B. After several attempts at situating each component, a few issues were realized. The stabilizer regulator with the pressure release attachment would make the MFSS too tall or would exceed outside of the 10cm footprint (see Figure 45). Moreover, although most of the components would fit within the area constraint, there would be no room for support structure. The ideal footprint mark could not be met with the components selected, and so the footprint constraint was enlarged to 15cm x 15cm.

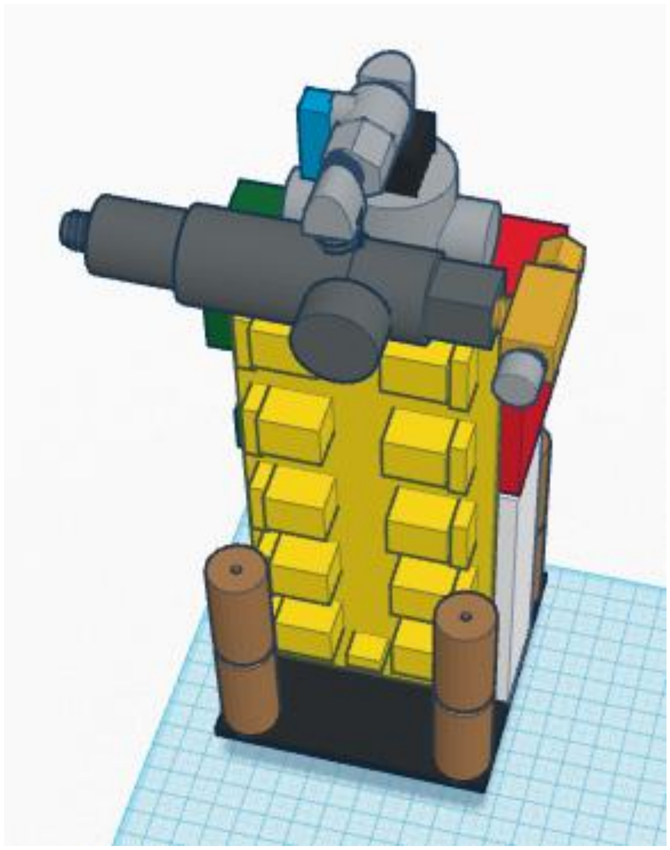


Figure 45. MFSS with 10cm x 10cm Base and Total Height of 27.2cm

E. MODIFICATIONS

With the adjustment of the base to 15cm x 15cm, which allowed all components to fit within the area with support structure, a few components were changed to enhance the modification. With the increased area, a single 50mm or 60mm air bearing would not be sufficient to keep the MFSS stable. A minimum of three air bearings would be required in a triangle formation, same as the original FSS, to maintain stability. Using a 213cm^3 (13ci) air tank and having three 50mm or 60mm air bearings would reduce the float time from 36.7min to 12.2min or 28.8min to 9.6min, respectively. Neither would satisfy the minimum 20min float time requirement. To maximize float time using three air bearings, the 25mm (smallest of the air bearings) size was selected, which would allow an estimated 25.4min of float time.

In the process of orienting and situating the components, it was realized that a larger tank could be accommodated. The Guerrilla 213cm^3 (13ci) Air Tank has a diameter of 51mm and it was replaced with the Tippmann 426cm^3 (26ci) 20684kPa (3000psi) Air Tank (see Figure 46), which has a diameter of 64mm. Doubling the size of the air tank and using the three 25mm air bearings increased the float time from 25.4min to 50.8min.

Figure 46. Tippmann 426cm^3 (26ci) 20684kPa (3000psi) Air Tank. Source: [32].

The final modification was the addition of the air filter by Parker Hannifin Corp (see Figure 47). Although it is not required if the air being used to fill the tank is from a compressor designed for scuba tanks, as is the case in the SRL, it may be prudent to use it for the air bearings. The original FSS does have the air filter installed.

Figure 47. Parker Hannifin Corp Air Filter

F. FINAL DESIGN

The final design incorporated the three modifications successfully with some room for potential upgrades. The 3D model of the base was increased to 15cm x 15cm and all components were arranged to fit within the area and maintain functionality. It was also designed with the thought of wire routing for the electrical components as well as the air tubing for the air bearings and solenoid valves. Once all components were placed in their positions, the support structure was designed around their placements. For example, the solenoid valves were stacked in two on each corner and the outer support frame was structured by including the valves into the frame itself. Also, since the design required it to accept both the Raspberry Pi 3 Model B and NVIDIA Jetson TK1, a large back plate was designed into the support structure. This allows either of the computer processors to be installed in the same location and can be swapped out easily as desired. The final design had a total height, from the bottom of the air bearings to the top of the frame, of 35cm. Figure 48 and Figure 49 shows the front corner and rear corner view, respectively, of the final design of the MFSS with the NVIDIA Jetson TK1 installed. Figure 50 is the bottom view of the MFSS to show the three air bearings and two laser motion sensors installed. Figure 51 is the front corner view with the Raspberry Pi 3 Model B for comparison to Figure 48.

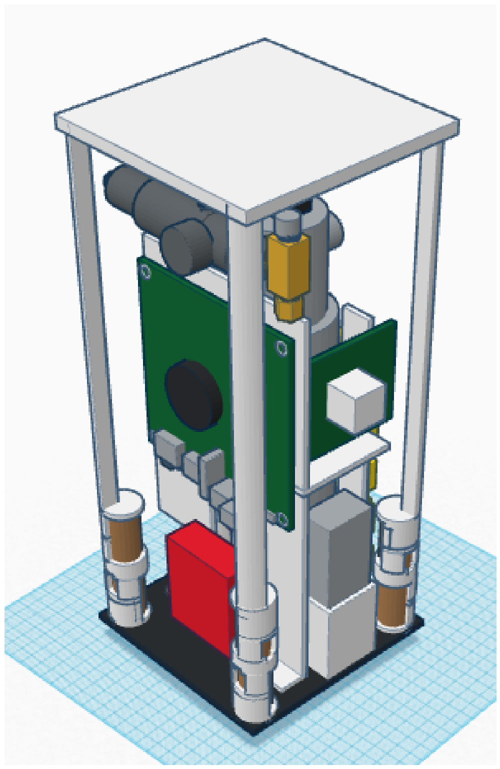


Figure 48. Front, Corner View of Final Design of MFSS with NVIDIA Jetson TK1

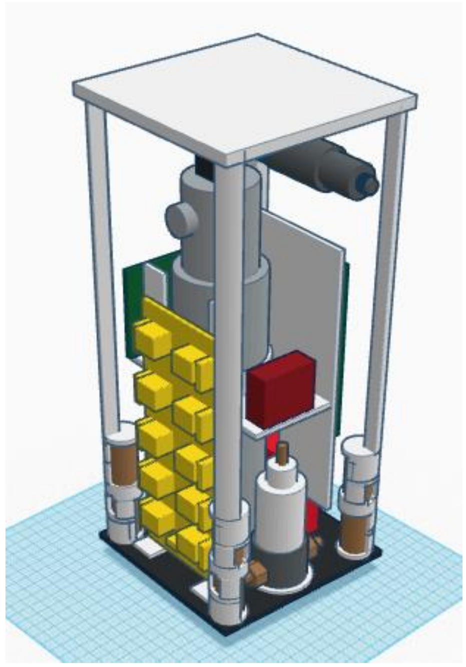
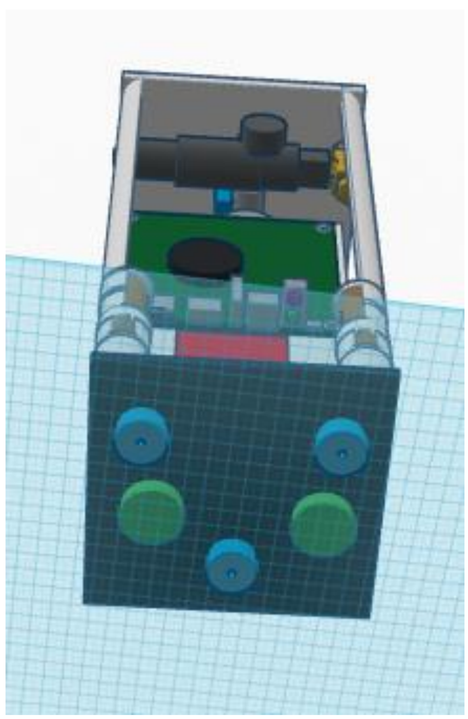


Figure 49. Rear, Corner View of Final Design of MFSS with NVIDIA Jetson TK1



The green cylindrical components are the laser motion sensors and the blue cylindrical components are the 25mm air bearings.

Figure 50. Bottom View of Final Design of MFSS with NVIDIA Jetson TK1

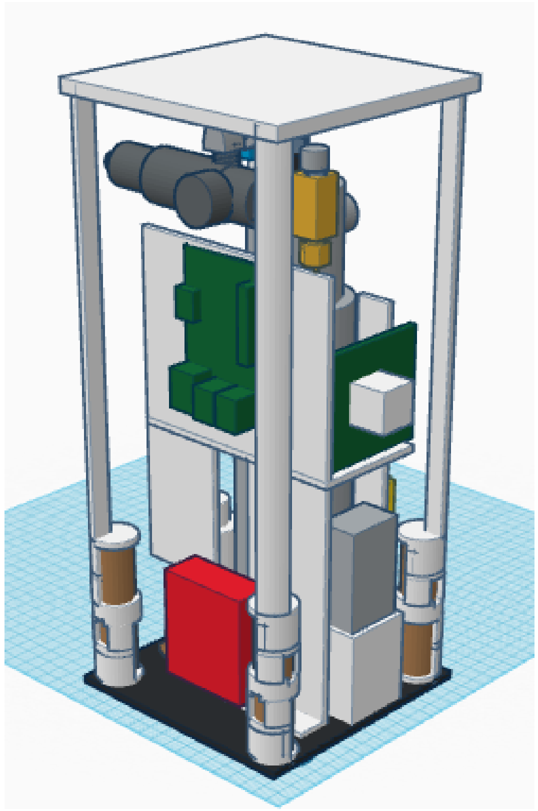


Figure 51. Front, Corner View of Final Design of MFSS with Raspberry Pi 3 Model B

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IV. DOCKING MECHANISM FOR MINIATURIZED FLOATING SPACECRAFT SIMULATOR

A. REQUIREMENTS

The FSS currently has a basic cone-shaped docking mechanism (see Figure 52). The docking mechanism is simple and does not include any additional functionality other than that it guides the FSS in the final moments of the docking maneuver. The tip of the cone has a 1cm diameter magnet that acts as a latch once docked. One issue with the magnetic latching interface is that the FSS is not able to undock itself. The thrust from the solenoid valves are not strong enough to repel the magnetic force therefore human assistance is required to undock the FSS. Significant improvements can be made on the docking mechanism.

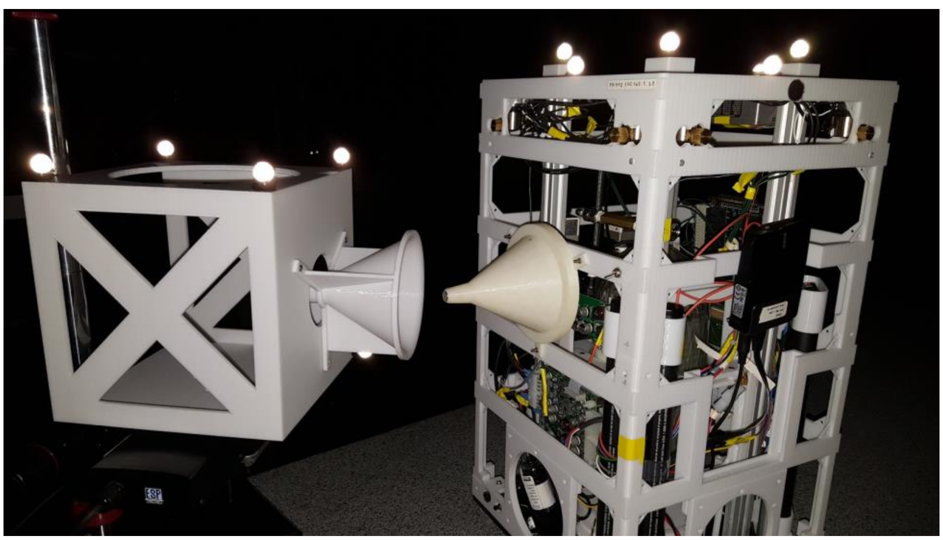


Figure 52. Docking Station (left) and FSS with Docking Mechanism (right)

The evolved docking mechanism for the MFSS had three requirements that needed to be met.

1. The docking mechanism must have the ability to allow the MFSS to dock and remove itself from the docking station autonomously. This ability would allow the MFSS to conduct multiple docking maneuvers in a given scenario.

2. The docking mechanism must have the ability to transfer data to the docking station or to another MFSS. A data connection can have a variety of uses such as, the transfer commands to acting as a switch to potentially recharging the batteries.

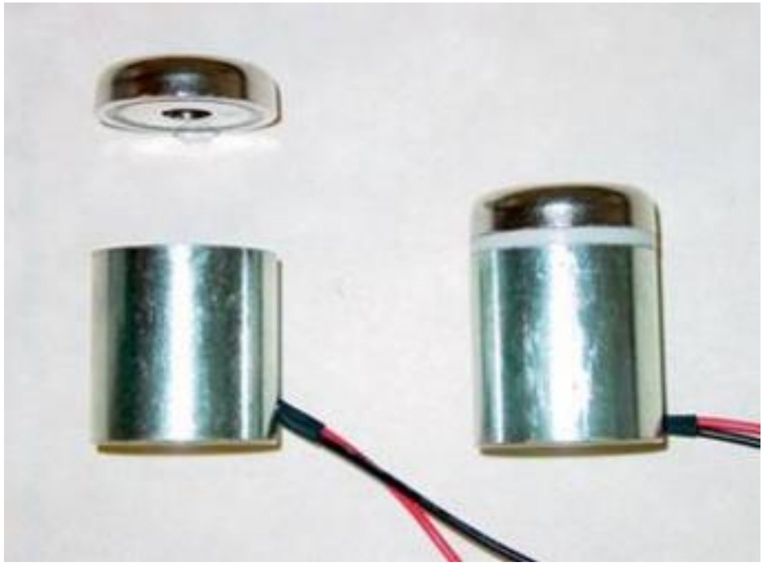
3. The docking mechanism must have the ability to transfer air to the air bearings of another MFSS when docked together. In a situation where a MFSS is out of its air supply, another MFSS can supply air or it can simply extend the float time of an MFSS.

B. COMPONENT SELECTION

1. Electromagnet

Electromagnets are ideal to accomplish the first requirement of being able to dock and remove itself from dock autonomously. Electromagnets work by creating magnetic field when an electric current is applied to it and when the current is removed, they act as regular magnets. An electromagnet attached to a docking mechanism, which would then be attached to the MFSS, would draw its power directly from the spacecraft simulator. Additionally, a simple solenoid switch would allow the current to be applied and removed as required.

Magnetech Corporation has a push-pull electromagnet (see Figure 53) design that holds without electricity and repels when current is applied. Their design has two parts: an electromagnet and a matching cap. “The cap pulls (attracts) the electromagnet when DC power is off [and] the electromagnet pushes (repels) the cap when DC power” is applied [33]. This is ideal, as power is only required during the brief period of undocking. The specifications are shown in Table 2.



The cap detached from the electromagnet (left) and the cap attached to the electromagnet (right).

Figure 53. Magnetech Corporation’s Push-Pull Electromagnet. Source: [33].

Table 2. Specifications of Magnetech Corporation’s Push-Pull Electromagnet and Cap (Part #PP-1007-12). Source [33].

Push Value		**Pull Value**		**Electromagnet**		**Cap**		**Net Weight**
1/16” gap	1/8” gap	1/16” gap	1/8” gap	Diameter	Height	Diameter	Thickness	
8.9N	4.4N	6.7N	2.2N	2.5cm	1.9cm	2.5cm	0.6cm	28.3g

2. Data Transfer Component

Mill-Max manufactures interconnect components that can transfer data through contact, in which there is a receiver and transmitting component. Specifically, the 430 Interconnect Target Connecter series (see Figure 54), the receiver, and 826 Interconnect Spring Loaded Connecter (SLC) Header series (see Figure 55), the transmitter, was desirable. They can be ordered as a single or a double row of connectors with the number of pins ranging from 4 to 72. There are also four types of ends that can be selected for the

430 Interconnect Target Connector which are standard solder tails, long solder tails, elevated with solder tails, and solder cups [34].

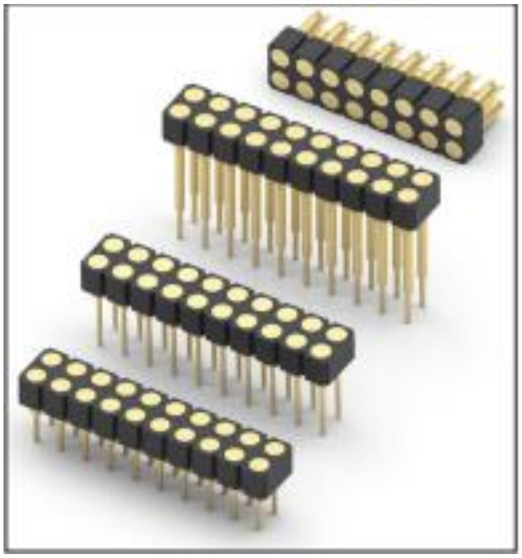


Figure 54. Mill-Max 430 Interconnect Target Connector Series. Source: [34].

Figure 55. Mill-Max 826 Interconnect SLC Header Series. Source: [35].

The configuration selected for the MFSS was double row with a total of 8 pins with the standard solder tail. With this design, the 430 Interconnect Target Connector's dimensions would be 5.08mm x 10.16mm x 7.37mm, an extremely small form factor. The connectors are gold-plated and have a flat face specifically designed for contact with their SLC headers.

The 826 Interconnect SLC Header's dimensions would be 5.08mm x 10.16mm x 11.2mm. Like the 430 series connectors, the 826 SLC headers are gold plated as well, indicated by Mill-Max, assuring that their connectors are good for 1,000,000 cycles. The pistons on the SLC are measured at 0.7mm for mid stroke and 1.4mm for max stroke [35]. This is important to know, because it will affect the placement and position of the connector. The electromagnet will hold the MFSS in place when docked and if the pistons are pushed passed their max stroke point it has the potential of damaging the connectors and if it is not close enough, data will not be transferred. The main use for this connection will be to transfer commands from one MFSS to another. Additional uses include the recharging of batteries and acting as a contact switch.

3. Air Transfer Component

The original FSS uses a twist lock quick disconnect coupling (see Figure 56) as one of the components for disconnecting the air provided from the stabilizer regulator to the solenoid valves. The same part is to be used to fulfill requirement three, of being able to dock to another MFSS and supply air to its air bearings. The two-piece coupling has a valved socket and a non-valved plug (see Figure 57). The valved socket acts as a shut-off valve when disconnected, therefore it will need to be connected to the MFSS that will supply the air. The non-valved plug will be attached to the receiving MFSS.

Figure 56. Twist Lock Quick Disconnect Coupling (Connected)

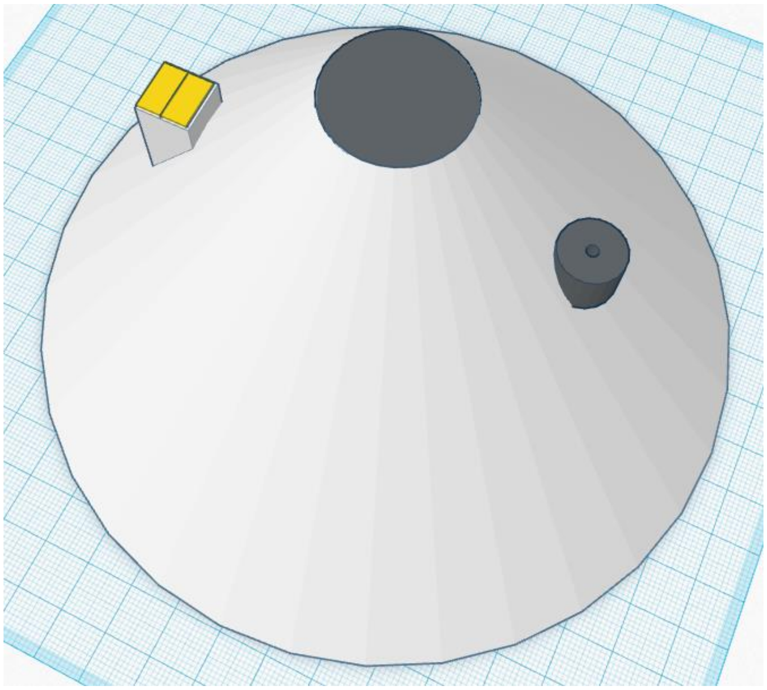
The left component is the valved socket and the right component is the non-valved plug.

Figure 57. Twist Lock Quick Disconnect Coupling (Disconnected)

The coupling currently requires a person to physically twist the couplings together to lock it in place. Since the transfer of air needs to happen automatically, the idea is to physically cut off the locking mechanism from one or both of the pieces. The electromagnet will latch the air connection together and the removal of the locking mechanism will eliminate the possibility of the coupling locking itself in place when the docking is complete.

C. INITIAL DESIGN

Individual components and the cone-shaped docking mechanism were 3D-modeled in TINKERCAD. The original cone shape measurements were approximately 12cm in diameter with a height of 11cm. The initial design of the cone shape for the miniature version had a 15cm diameter with an 8.3cm height. The thought was the have the diameter be 15cm so that it can be attached directly to the external support structure of the MFSS. The electromagnet was positioned at the center of the cone, acting as the tip. Two sets of data transfer components were combined together and placed to the left of the electromagnet and the air transfer component was placed to the right of the electromagnet. Both components on either side of the electromagnet were positioned protruding from the cone to allow better connection when docked. Overall it was a very simplistic design as shown in Figure 58.



The two yellow colored components are the two sets of 826 Interconnect SLC Headers, the larger grey circular component is the electromagnet without the cap, and the smaller gray circular component is the quick disconnect coupling.

Figure 58. Initial Design of the Docking Mechanism for the MFSS

D. MODIFICATIONS

After the initial design, it was thought that the protruding components might cause an issue with the docking maneuver. Either components could scrape against the docking port as it guided itself in, potentially being damaged in the process. Furthermore, it was recommended that the diameter of the cone be reduced and be able to attach to the MFSS using tabs. Going along with tabs, an additional tab was created at the top of the cone for the placement of the two sets of 826 Interconnect SLC Headers and the quick disconnect coupling. This would alleviate the concern with damaging the components during the docking process.

E. FINAL DESIGN

The final design constituted a cone with a diameter of 12cm, height of 8.2cm, and two tabs, approximately 1.5cm wide, on either side of the cone for attachment to the external structure of the MFSS. Additionally, another tab was attached to the cone at the top for the placement of the data and air transfer components. Figure 59 shows the finalized design concept of the docking mechanism for the MFSS.

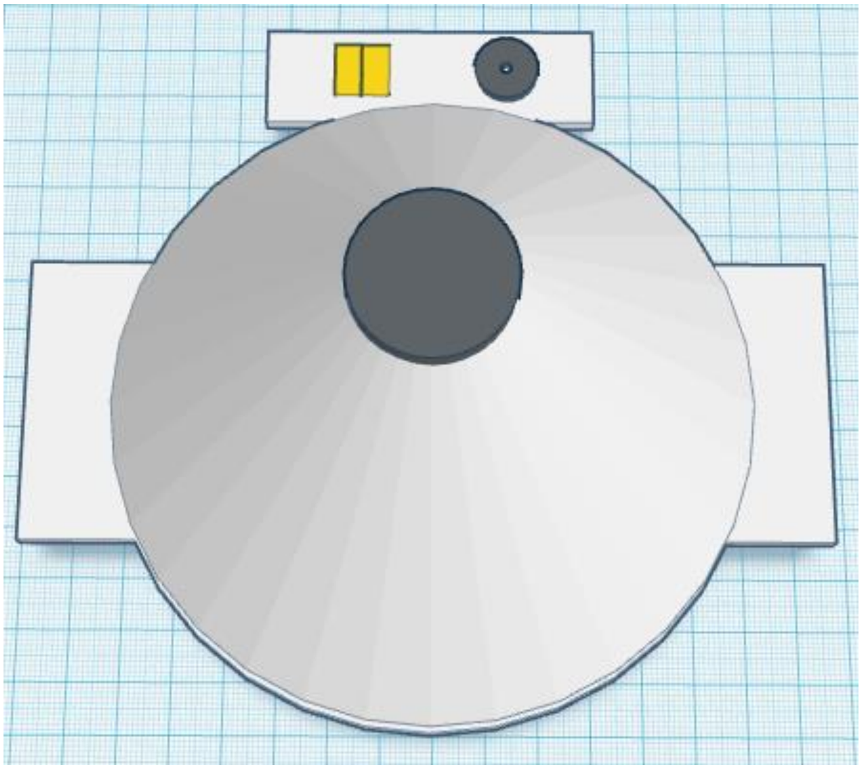


Figure 59. Final Design of the Docking Mechanism for the MFSS

V. CONCLUSION

A. SUMMARY OF WORK

The reverse engineering and assembly of the FSS was critical in understanding the pneumatic, electrical, and hardware components required. Throughout the process of assembly, the two FSS were regularly being used for testing by other students and professors in the SRL, which halted progress on the assembly and the assembly guide. Furthermore, although much thought went into which component should be installed first and in what order, there were many instances when components had to be disassembled or removed in order for another component to be mounted. This process was at times tedious, but it promoted the development of better instructions for the assembly guide. Pictures were taken in every step with additional instructions and illustrations, down to the routing of wires, in the assembly guide so that future productions by the SRL can be built with ease.

With the understanding of the FSS components and the assembly guide complete, the MFSS design was started with the knowledge attained. The main struggle with the development of the design was learning how to use TINKERCAD. Although it was easier to learn than other 3D programs, having never used it before, it took time and patience going through the tutorials. Every major component was modeled in 3D individually and later imported into a single file for the design development. Components were constantly rotated, inverted, stacked in every which way in TINKERCAD for the best possible construction.

After using TINKERCAD for the MFSS, the designing of the docking mechanism went much more smoothly. Having only a few parts for the docking mechanism, modeling of the components were simple and modifications were easily made within the program. Both the MFSS and the docking mechanism will be the first of its kind.

B. FUTURE WORK

1. Assembly of the MFSS

Since the design of the MFSS is complete with all major components and support structure, parts can be ordered and the structure can be 3D printed. Like the FSS, during the assembly of the MFSS, an assembly guide will need to be created. The process will take time and require the builder to figure out what order to install the parts. Furthermore, several MFSS will need to be constructed to allow the SRL to conduct tests. The tests will give insight into potential issues and if necessary, modifications that are required to correct the problem.

2. Component Upgrades

Over time, components are discontinued and upgraded. Smaller, faster, and more efficient electronics are created. It is possible that, by the time the MFSS is ready to be assembled, more compact and upgraded parts will be available. Future work will require someone to research these parts and see if they can replace or modify a component on the MFSS to make the overall size smaller. It is also possible that better components for the MFSS are currently available, as they were not found during this research process.

3. Assembly of the Docking Mechanism and Attachment to MFSS

The parts will need to be ordered and the cone shaped dock will need to be 3D printed. After assembly, the docking mechanism will need to be tested against a dock to see if the connections are made properly between the data, air transfer components as well as the electromagnet. Once testing is complete, the docking mechanism can be attached to the MFSS for additional testing.

4. Manipulator for the MFSS

The FSS currently has a four link manipulator, therefore it is likely that a manipulator will need to be designed for the MFSS. The size of each link of the manipulator must be significantly reduced, therefore smaller parts will be required. Additional information about the development of the "modular, multi-link, spacecraft-based robotic manipulator" can be found in [36].

C. RESEARCH SIGNIFICANCE

The significance of this research is mainly towards the miniaturization of the FSS and its docking interface. Although the MFSS is designed with a similar structure as the FSS with several new components, it is the first of its kind and a step towards miniaturization. The ideal footprint goal of 10cm x 10cm was not met, but it gave meaningful insight into the miniaturization process. When the MFSS is eventually built, it will provide the SRL with more space on the test bed to conduct their experiments, potentially making the current FSS obsolete.

The docking mechanism provides an upgrade to the original, in that it now has the ability to transfer data and air. This will allow further research into the type of data that should be transferred and experiment on transferring and supplying air from one MFSS to another. Because this research was only the first framework for miniaturization, the development and design concepts will continue to mature over the years as future students of NPS join the SRL research program.

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APPENDIX A. FLOATING SPACECRAFT SIMULATOR PARTS LIST

Type	Part	Part Number	Brand	# required
Pneumatics	114ci Tank	6190	AirTanksForSale	1
	Round End Ball Mounting Screw	S8013B06	New Way Air Bearings	3
	Air Bearings	S102501	New Way Air Bearings	3
	Nozzles	012-056-M5		8
	Solenoid Valves	EH2012	Gems Sensors and Controls	8
	Micro-Solenoid Valve	10-32 FB301V044A	Farmington Engineering	1
	Pressure Sensor	GC31	Ashcroft	2
	Plastic tubing	1A-157-01	Freelin-wade	500ft
	Finite Filter	AQ5S 6HM06-013	Parker	1
	Ninja 4.5k Ultralite Regulator	NINJAREG45KUL	Ninja	1
	Pipe	SS-2-HLN-2.50 or (3.00)	Swagelok	1
	Coupling	SS-2-HCG	Swagelok	1
	Stainless Mesh Hose	HOSE0*	Palmers Pursuit Shop	1
	Male to Female Reducer	FITT045	Palmers Pursuit Shop	4
	Female to Male Reducer	FITT044	Palmers Pursuit Shop	2
	On/Off Ball Valve	FITT016	Palmers Pursuit Shop	1
	Female TEE	FITT017	Palmers Pursuit Shop	1
	Stabilizer Regulator	PPSP015	Palmers Pursuit Shop	2
	Bleeder Valve	FITT066	Palmers Pursuit Shop	2
	Hose Barb	PNEUM316	Palmers Pursuit Shop	3
	Hose Barb	PNEU013 or FITT024N	Palmers Pursuit Shop	15
	Air Supply Adapter	PPSP983	Palmers Pursuit Shop	3

Electronics	Relay Board	Diamond IR-104-PBF	Tri-M Engineering or Diamond Systems	1
	PC104 Extender	6B-DE-104/16	Douglas Electronics	1
	COM1 Ribbon Cable	100-9665	ADL Embedded Solutions	1
	Passive Low Profile Heatsink	292062	ADL Embedded Solutions	1
	DC-DC Converter	DC1U-1VR	OceanServer Technology	1

	On/Off Switch	19-00027-00	OceanServer Technology	1
	ATX DC-DC Converter	DC123SR	OceanServer Technology	1
	ATX and Disk Power Cable	19-00014-00	OceanServer Technology	1
	Mini Battery Management Module	BB04SR	OceanServer Technology	1
	Wireless N Pocket Router	DAP-1350	D-Link	1
	Fiber Optic Gyroscope	DSP-3000	KVH Industries	1
	Portable Power Battery	NL2044HD22	Inspired Energy	2
	Red LED	RL5-R12120	superbrightleds.com	8
	MP-04/08 TO DCX CONVERTER (RAW DC) CABLE	19-00026-20	OceanServer Technology	1
	DC IN PS150 DUAL JUMPER CABLE	19-00195-12	OceanServer Technology	1
	Gigabit LAN Cable	100-9720	ADL Embedded Solutions	1
	USB, 4 Port Cable	100-9725	ADL Embedded Solutions	1
	ADL Power w/ cap	100-9700	ADL Embedded Solutions	1
	VGA Analog Cable	100-9715	ADL Embedded Solutions	1
	Keyboard/Mouse Cable	100-9644	ADL Embedded Solutions	1
	ADL Battery Option	100-9655	ADL Embedded Solutions	1

APPENDIX B. FLOATING SPACECRAFT SIMULATOR ASSEMBLY GUIDE

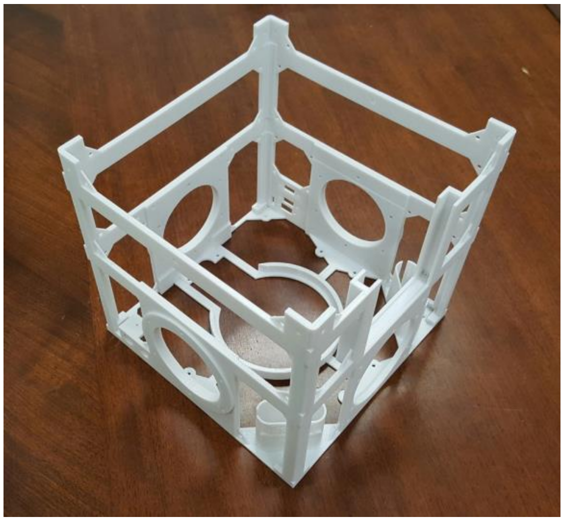
Step (1) Create the following 3D printed parts at the Space Systems Academic Group

i. 1 – Level 1
ii. 1 – Level 2
iii. 1 – Level 3
iv. 1 – Level 4
v. 2 – Battery Rings
vi. 2 – Transducer Rings
vii. 4 – Attachments for Level 3
viii. 3 – Air Bearing Support Mounts

Note: It will take a few days, because it uses about 2.5 canisters of material

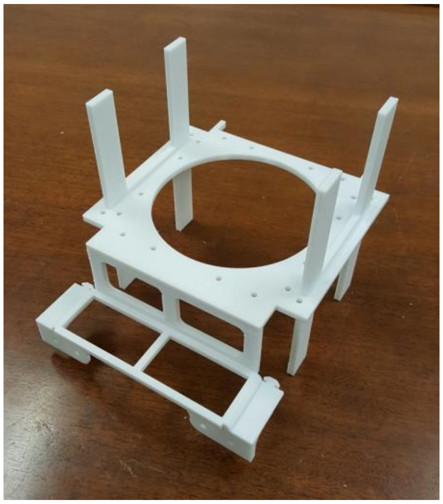
Step (2) Create 3 air bearing support mounts using the 3D printer in the Spacecraft Robotics Laboratory.

Step (3) Remove excess material from the 3D printed parts from Step (1) (pictures of parts with excess material removed)

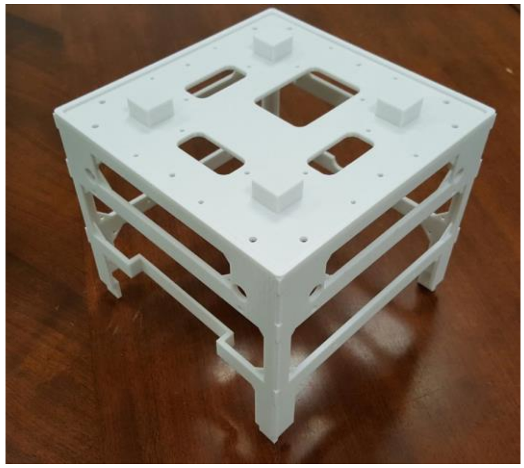


(Level 1)

(Level 2)

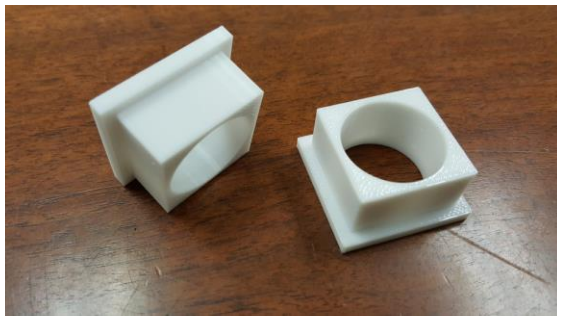


(Level 3)



(Level 4)

(Battery Rings)



(Transducer Rings)

(Air Bearing Support Mounts)

(Attachments for Level 3)

Step (4) Retrieve the preassembled Base (pictured below)

Step (5) Using 10x hex nuts and 10x button head cap screws, attach Level 1 to the preassembled Base using the pre-cut holes.

(hex nut/ button head cap screw)

(Level 1 and Base attached)

Step (6) Insert the Peachtree scale as pictured below and insert Level 2 on top of the Peachtree scale.

(Peachtree scale)

(w/ scale inserted)

(w/ Level 2 inserted on top of scale)

Step (7) Gather the following pieces/items to assemble the tank filler attachment.

Step (8) Unscrew the feeder/inlet valve from the regulator and remove/clean the regulator and valve of left over teflon tape material.
(NOTE: be careful when removing the valve, there is a silver bolt inside. DO NOT LOSE IT)

(Ninja Regulator) (regulator with removed valve)

Step (9) Add teflon tape to the feeder/inlet valve and both ends of the gold extension.

(gold extension and valve with teflon tape)

(valve with bolt mentioned in the note)

Step (10) a) Screw one end of the gold extension into the ninja regulator (where feeder/inlet valve was removed).
b) Screw the female hex coupling to the other end of the gold extension.
c) Screw the feeder/inlet valve into the other end of the female hex coupling. *(NOTE: ensure the bolt is inserted in the valve before installation)*
d) Apply teflon tape to the top of the regulator

Step (11) Screw the aluminum flathead to the top of the regulator and apply teflon tape to the bottom.

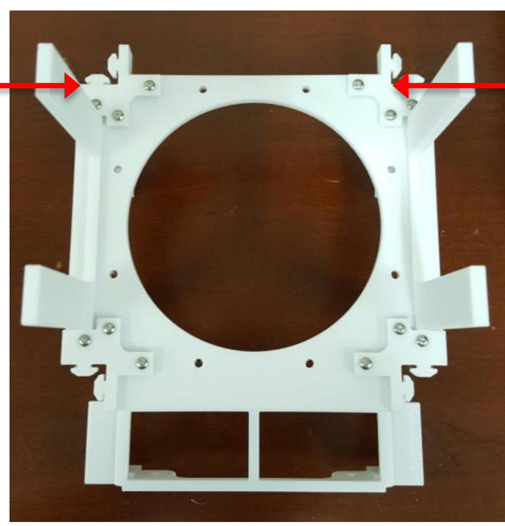
Step (12) Screw the assembled tank filler attachment to the air tank.

Step (13) Retrieve the 4 attachments for Level 3 as well as 4 sets of screw, nut, and washer. Install these to the four corners of Level 3 as shown below.

(Attachments for Level 3)

(screw, nut, washer)

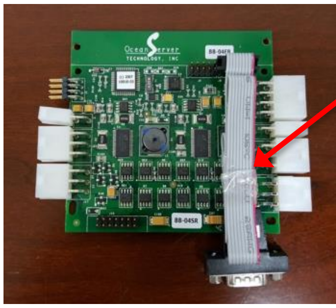
Rear attachment



Rear attachment

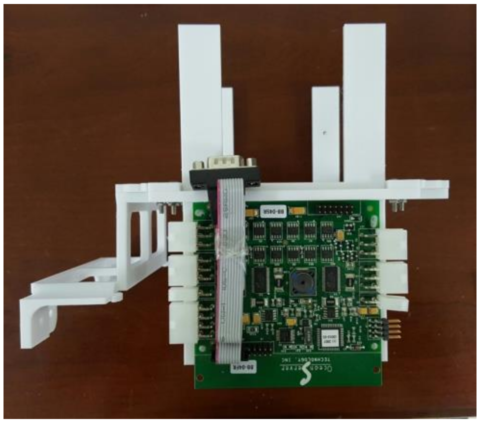
(NOTE: attaching 2 in the rear is sufficient; do not need all 4)

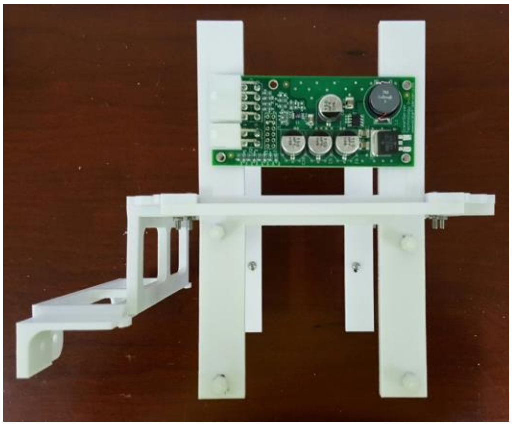
Step (14) Retrieve the Mini Battery Management Module and the DC-DC Converter. Use these as templates to drill the holes onto the Level 3 on the right side in preparation for installation.



(Mini Battery Management Module)

(Remove the attached cable; not needed)

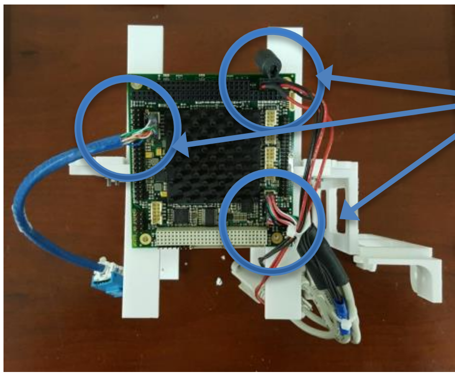




(Mini Battery Management Module (lower half) and DC-DC Converter on upper half)

(Note: mark where the holes need to go using the circuit cards and drill it)

Step (15) Retrieve the Intel Atom CPU. Use this as a template to drill holes onto the Level 3 on the left side in preparation for installation.



These 3 cables should already be pre-attached.
-Gigabit LAN cable
-USB, 4 Port cable
-ADL Power w/cap

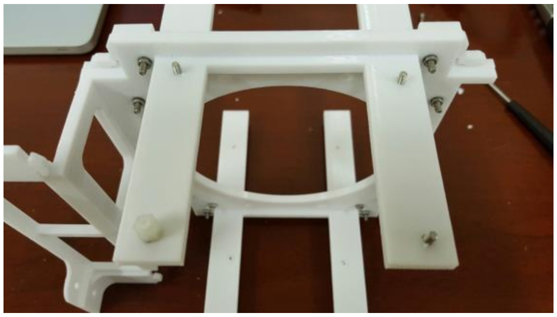
(CPU will eventually be installed in the center of the left side of Level 3)

Step (16) Once the holes have been drilled on both sides of Level 3, use the hardware (bolts, nuts, spacers, washers) pictured below in preparation for the various circuit card installations. The screws will be inserted into Level 3 pointing outward and then the spacers will be screwed on.

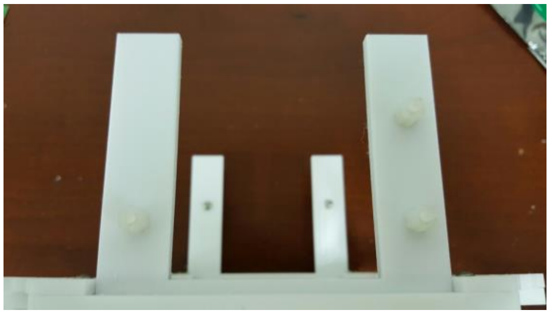
(7 sets for the right side: bolt, nut, plastic spacer)

(4 sets for the left side: bolt, washer, aluminum spacer)

(screw the nut all the way onto the bolt for the 7 sets and slide the washers on for the other 4)



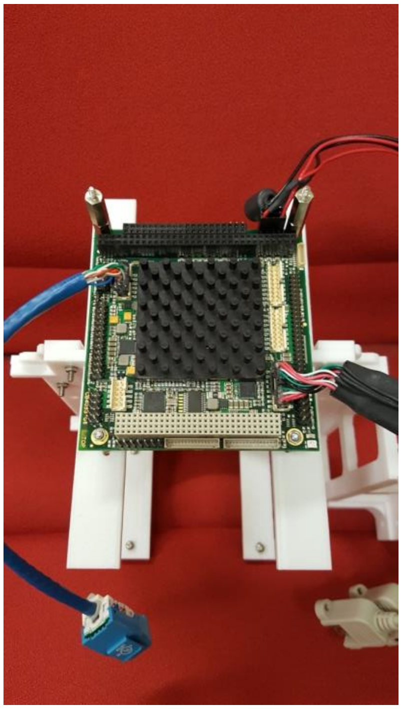
(bottom right)



(top right)

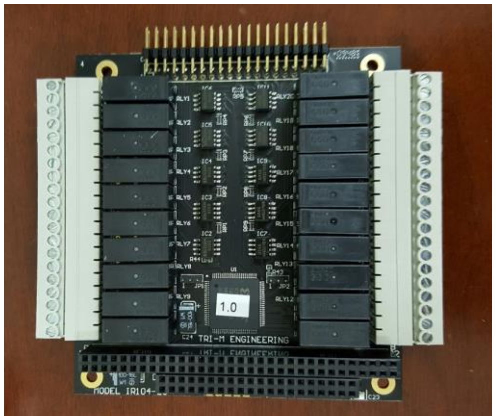
(left side)

Step (17) Retrieve the Intel Atom CPU, 2 nuts, and 4 aluminum spacers. Install the CPU onto Level 3 using the hardware as pictured below.

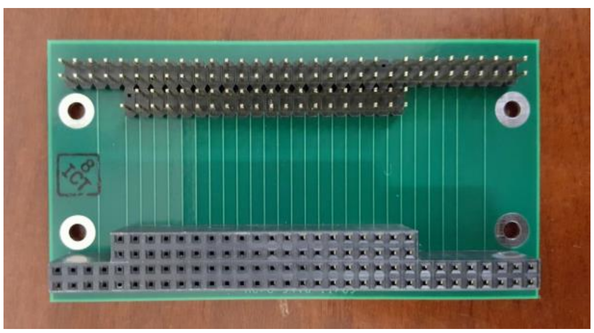


(bolts used on the bottom, 2x spacers on each side on top)

Step (18) Retrieve the Relay Board, Extender, and Plus Connectors. Attach the Extender to the bottom, back of the Relay Board and attach the Plus Connector the male end of the Extender.



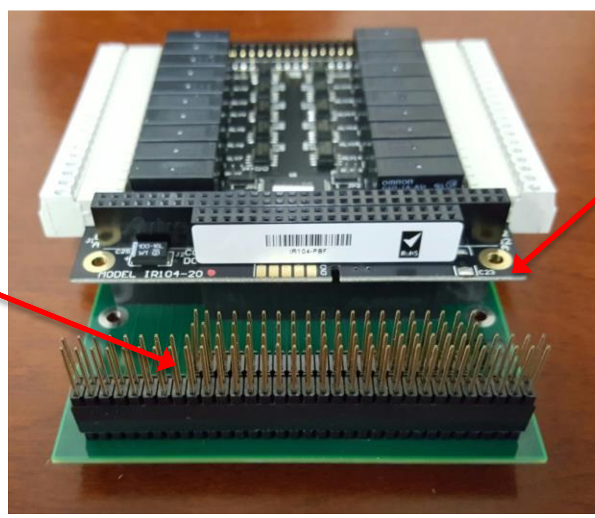
(Relay Board)



(Extender)

(Plus Connectors)

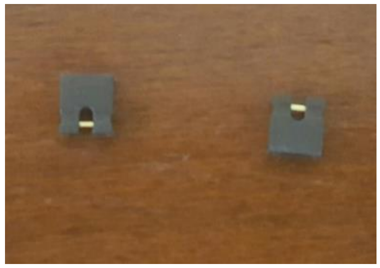
Plus Connector attached to Extender



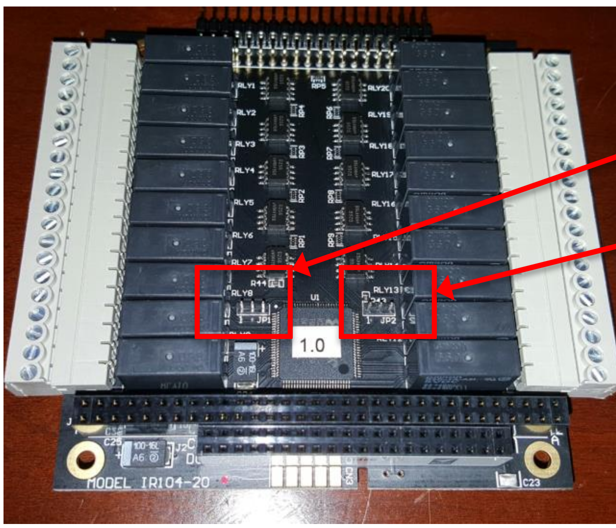
Extender attached to Relay Board

(Relay Board, Extender, Plus Connector all attached)

Step (19) Retrieve the jumper cables that came with the Relay Board. Find JP1 and JP2 on the Relay Board. Both JP1 and JP2 will have 3 pins. Attach the jumper cables to the outboard pin and the center pin on both JP1 and JP2 as pictured below. The inner pins should remain exposed.

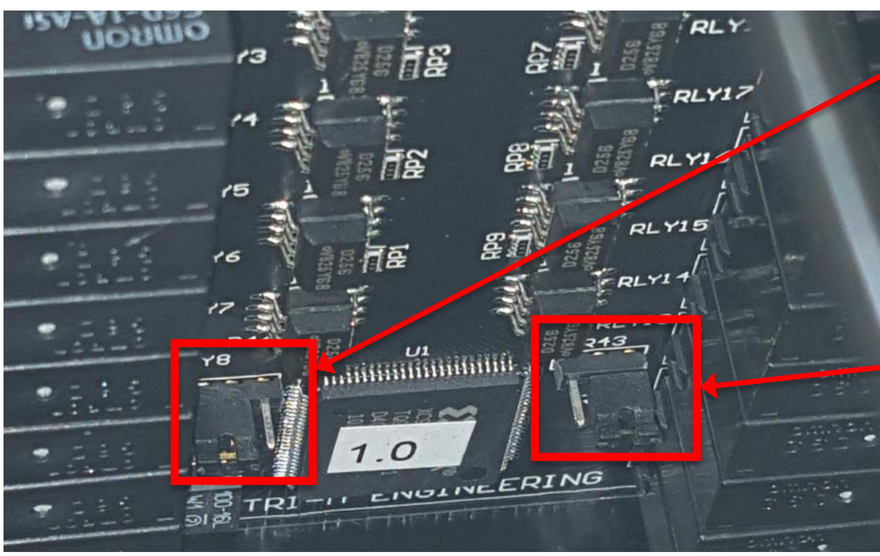


(jumper cables)



JP1 (jumper cables not attached)

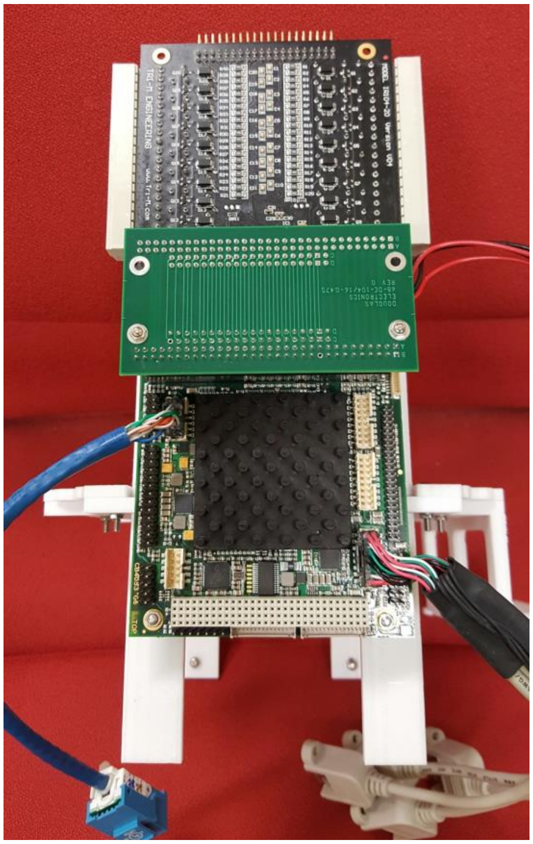
JP2 (jumper cables not attached)



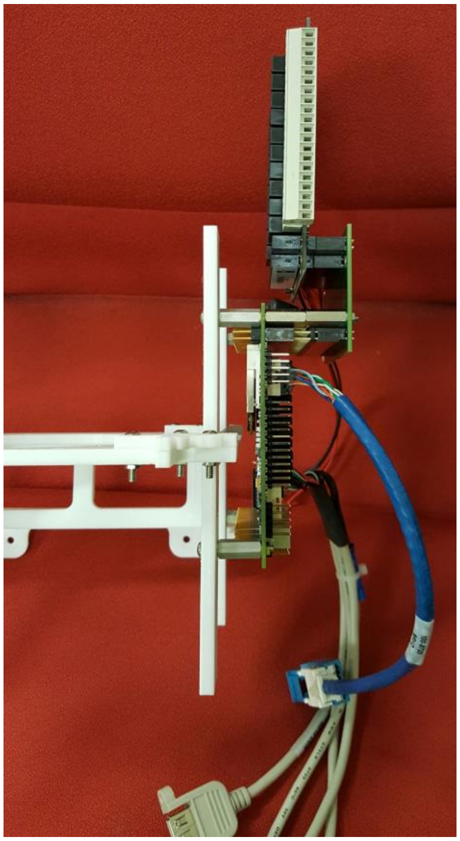
JP1
(jumper cables attached)

JP2
(jumper cables attached)

Step (20) Attach the assembled piece from Step (18) to the top of the CPU as shown below using 2 nuts.

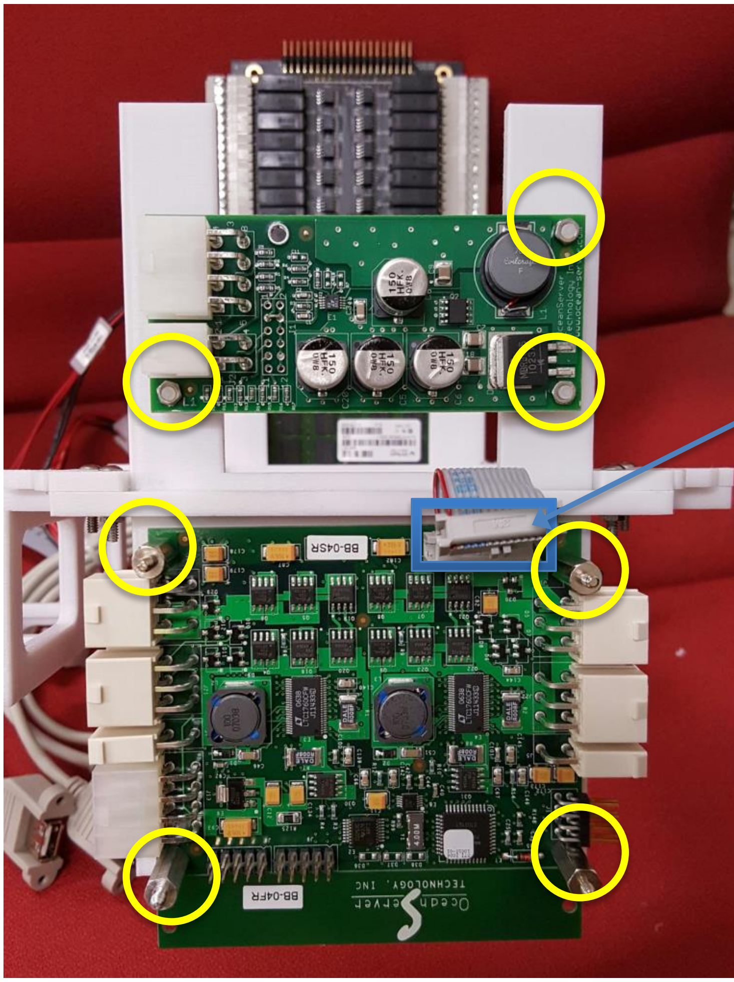


(frontal view)



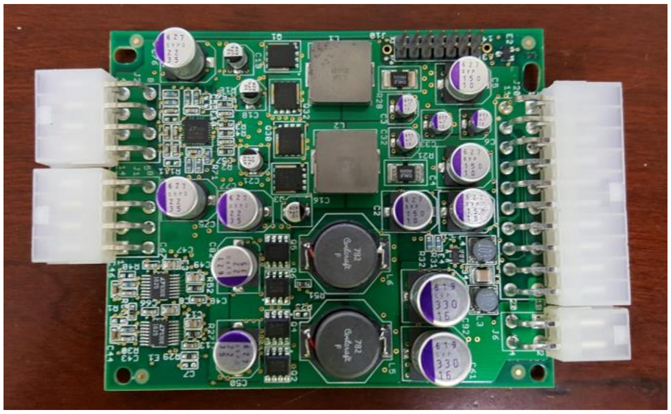
(side view)

Step (21) Attach the DC-DC Converter to the top half of the right side of Level 3 using 3 nuts and attach the Mini Battery Management Module to the lower half using 4 aluminum spacers. Also, ensure that the Expansion Connector is attached to the Mini Battery Management Module.

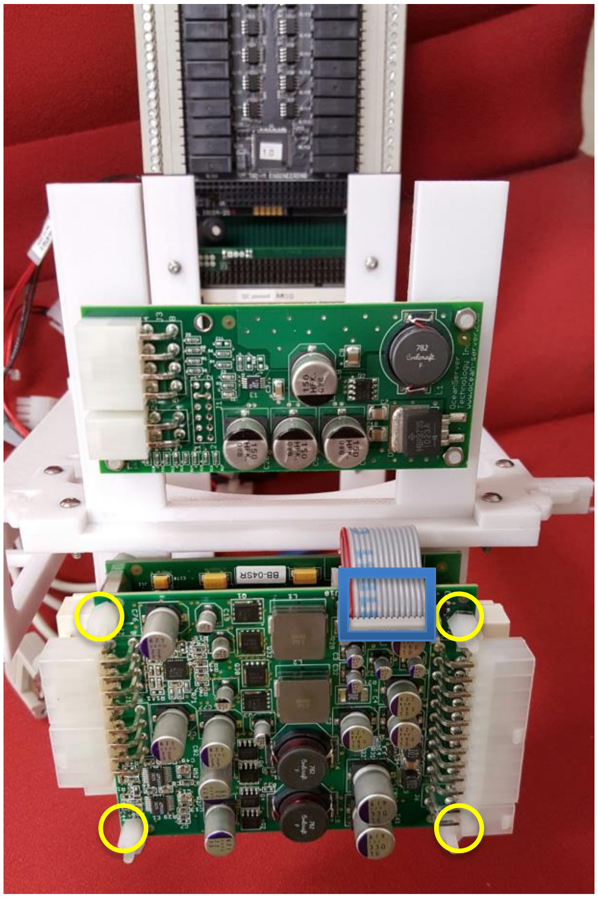


Expansion
Connector

Step (22) Attach the ATX DC-DC Converter on top of the Mini Battery Management Module using 4 plastic spacers and attach the free end of the Expansion Connector to the ATX DC-DC Converter.

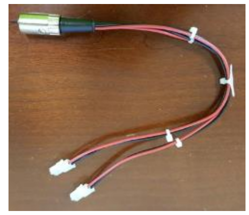


(ATX DC-DC Converter)



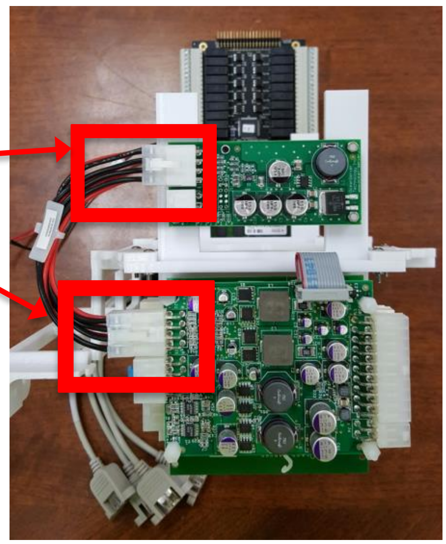
Step (23) Retrieve the DCX Converter Cable and the Dual Jumper Cable. Attach the DCX Converter from the DC-DC Converter to the ATX DC-DC Converter as pictured below. Additionally, attach the Dual Jumper Cable to both sides of the Mini Battery Management Module as pictured below.

(DCX Converter Cable)

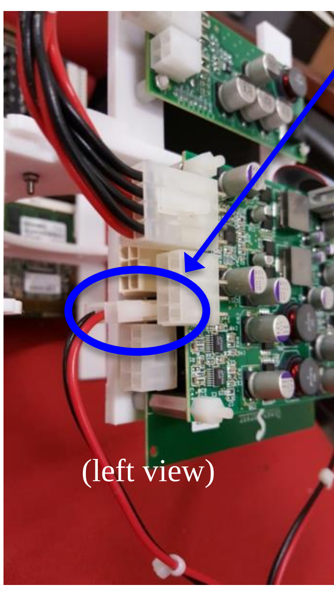


(Dual Jumper Cable)

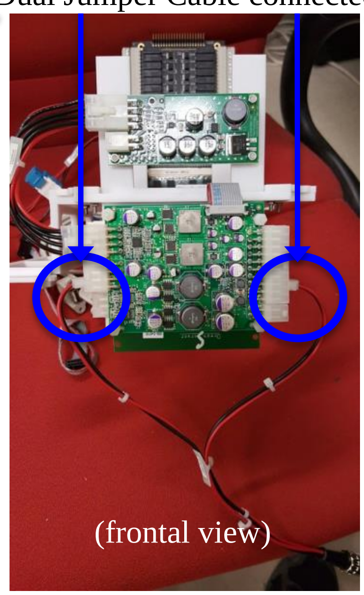
DCX Converter Cable connected



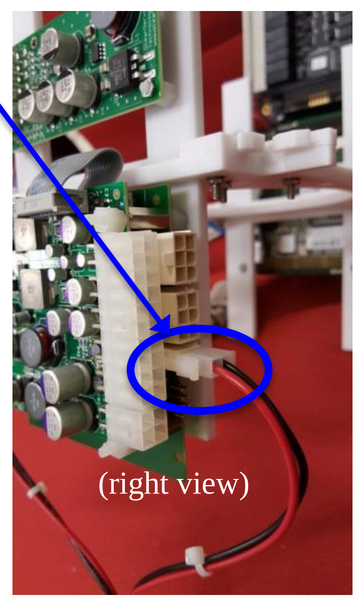
Dual Jumper Cable connected



(left view)

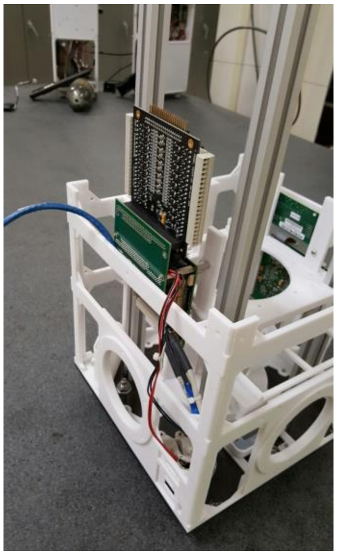


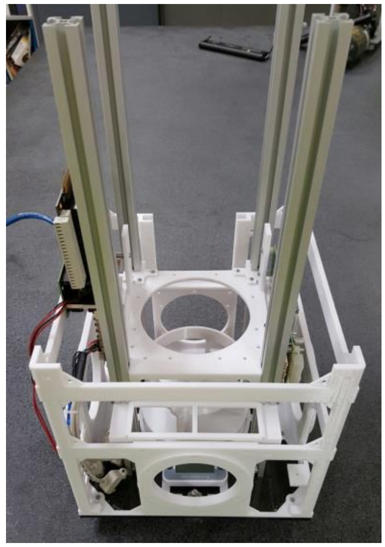
(frontal view)

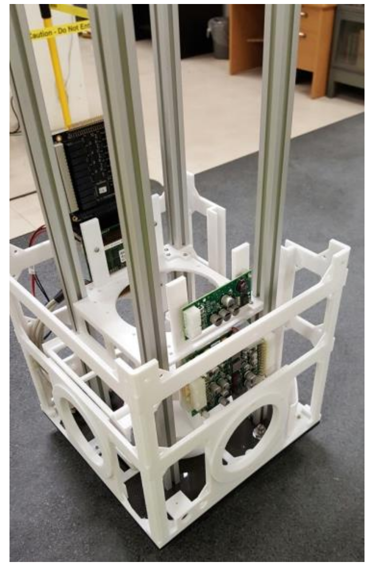


(right view)

Step (24) Insert the assembled Level 3 onto the base, aligning it to the aluminum rails as required. (Note: this may be difficult and will most likely not slide in easily.)

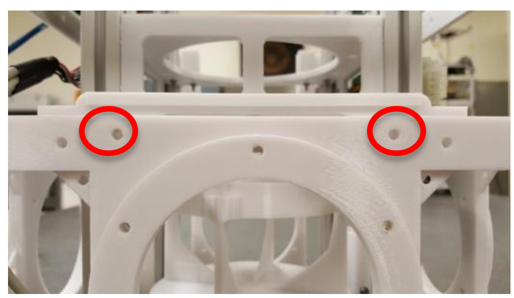

(left angled view)


(frontal angled view)

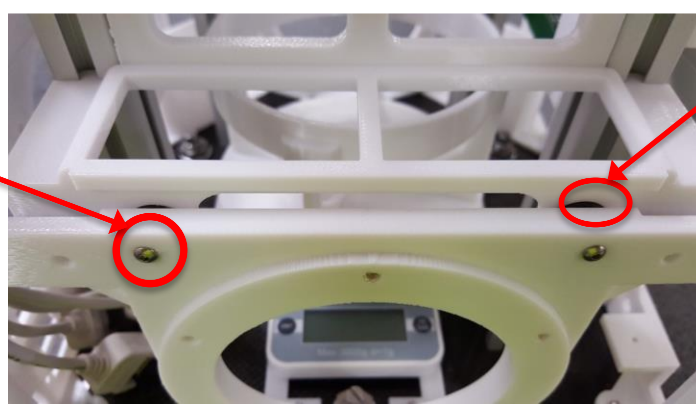

(right angled view)

Step (25) Align the inner holes on the front of Level 3 to the inner holes on the front of Level 1. Use 2 sets of 2 washers, a bolt and a nut to attach Level 1 to Level 3.


(hardware required)


(inner holes aligned)

bolt



2 washers placed in-between Level 1 and Level 3

<u>Step (26)</u> Gather the following pieces to assemble the Air Regulator and apply teflon tape to the screw ends of the necessary pieces

<u>Step (27)</u> Arrange the pieces as pictured below and attach them in the order preferred

Step (28) Gather the pieces pictured below to assemble two Pressure Regulator Assemblies and apply teflon tape to all screw ends

Step (29) Assemble the air outlet valve x2

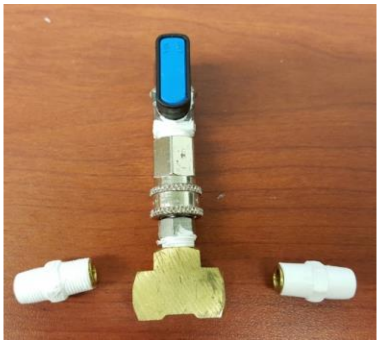
Step (30) Assemble the 4-way piece x2

Step (31) Attach the aluminum flathead to the bottom of the 4-way piece x2

Step (32) Attach the pressure regulator to the assembled piece in Step (31) x2

Step (33) Get x2 male to male screws, wrap in teflon tape and screw onto the Air Regulator

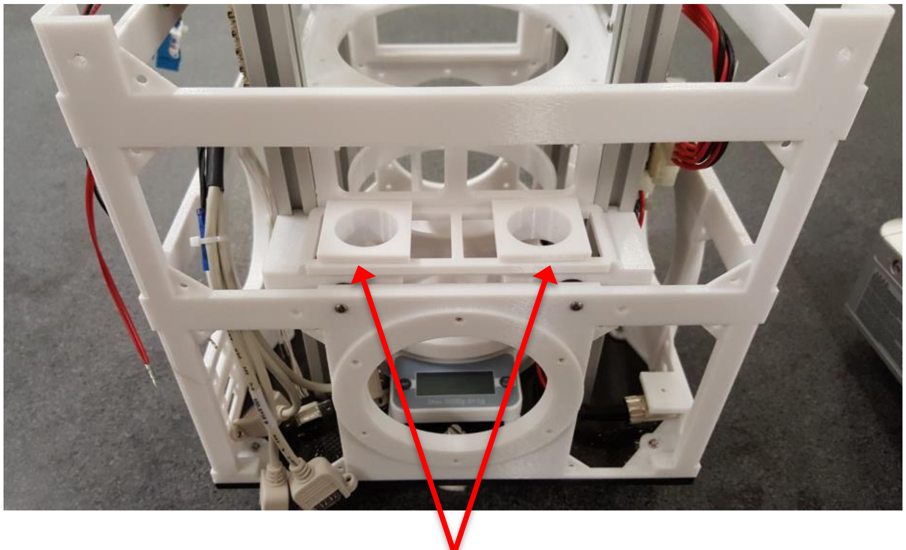

step (a)


step (b)


step (c)

Step (34) Attach the two Pressure Regulator Assemblies to the Air Regulator Assembly

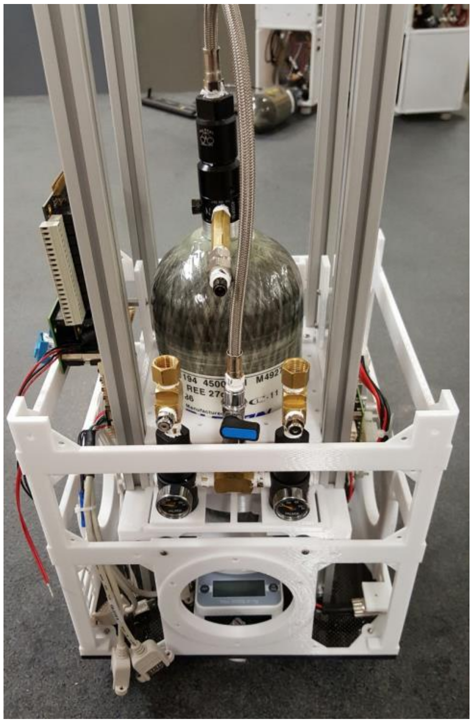
Step (35) Insert the Transducer Rings onto the front of Level 3 as shown below.



(Transducer Rings inserted)

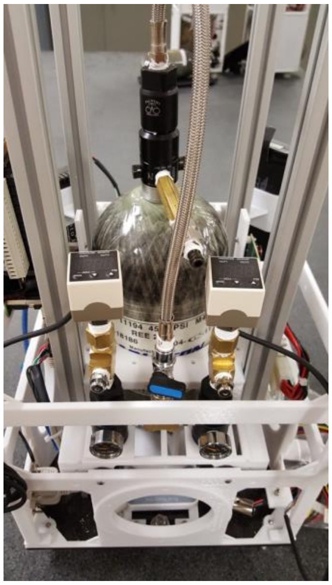
Step (36) Retrieve the stainless mesh hose and apply teflon tape to both ends. Attach the hose to the Air Regulator Assembly and to the tank filler attachment as pictured below.

Step (37) Insert the tank through Level 3 and onto Level 2 and insert the Pressure Regulator Assemblies into the Transducer Rings.
(Note: you may need to adjust the Transducer Rings)



Step (38) Retrieve two pressure sensors and attach them to each Pressure Regulator Assembly.

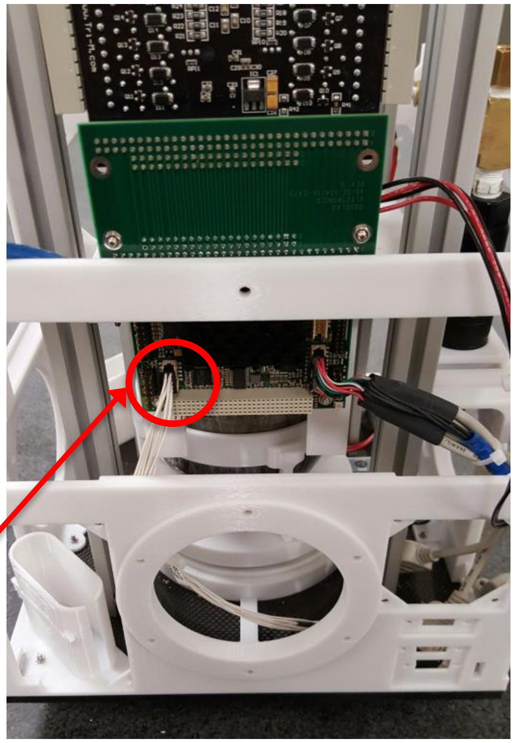
(pressure sensor)



(Pressure sensors attached)

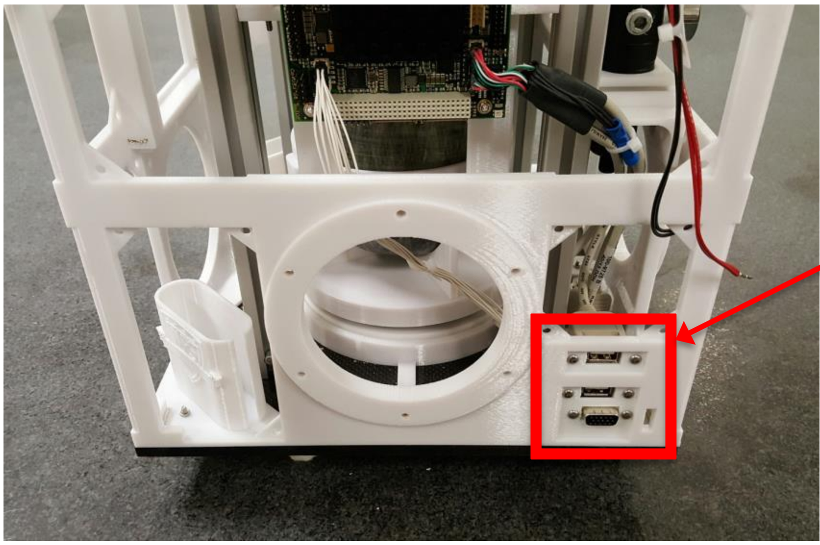
Step (39) Attach the VGA Analog Cable to the CPU if it was not already attached.

(VGA Analog Cable)



VGA Cable attached to CPU

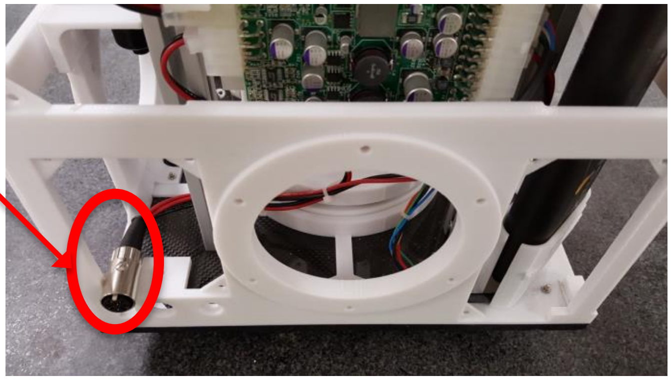
Step (40) a) Attach the VGA end of the cable to the bottom slot on the left side of Level 1 using 2 screws and 2 nuts.
b) Attach any 2 of 4 USB ports to the remaining two slots on the left side of Level 1 using2 screws for each. The remaining two will be left unconnected.



From Top to Bottom
1) USB port
2) USB port
3) VGA port

Step (41) Locate the free end of the Dual Jumper Cable that was attached to the Mini Battery Management Module and unscrew the cover of the cable.

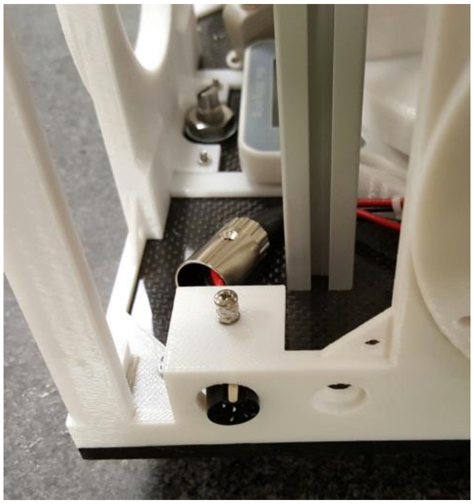
Free end of Dual Jumper Cable



Cover of cable unscrewed

Step (42) a) Separate the cover from the cable itself by my pushing the cover back.
b) Insert the cable into the pre-cut hole and screw it in place using one screw and a combination of nuts and washers as needed.

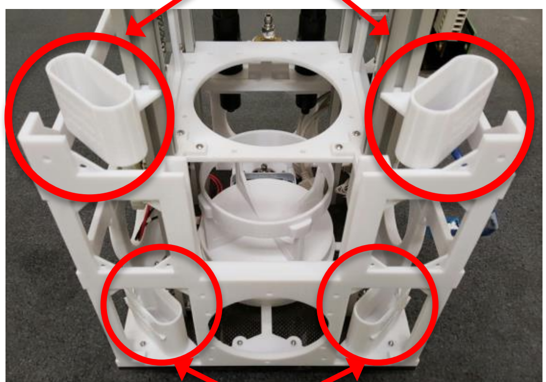
step (a)



step (b)

Step (43) Insert the Battery Rings onto the railing, ensuring that they are directly above the battery base holder (pre-cut into Level 1). The Battery Rings should be inserted to the top of Level 1.

Battery Rings

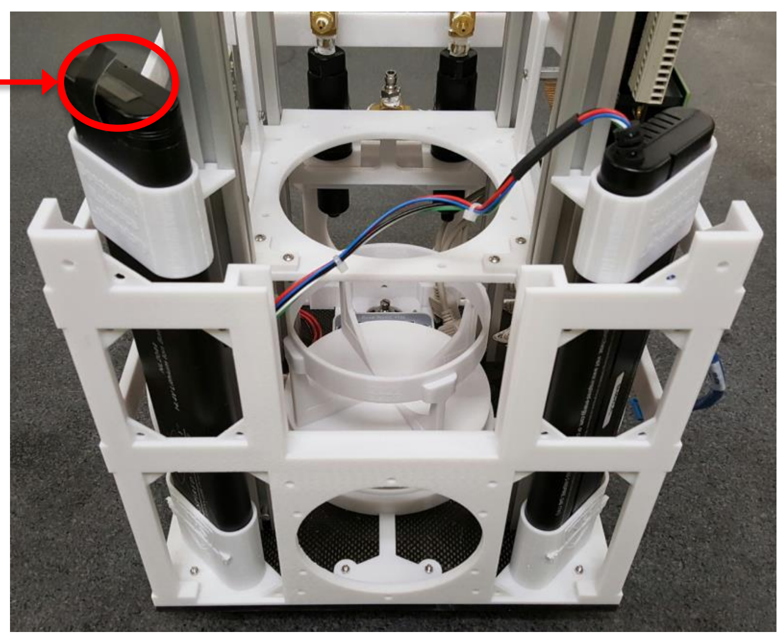


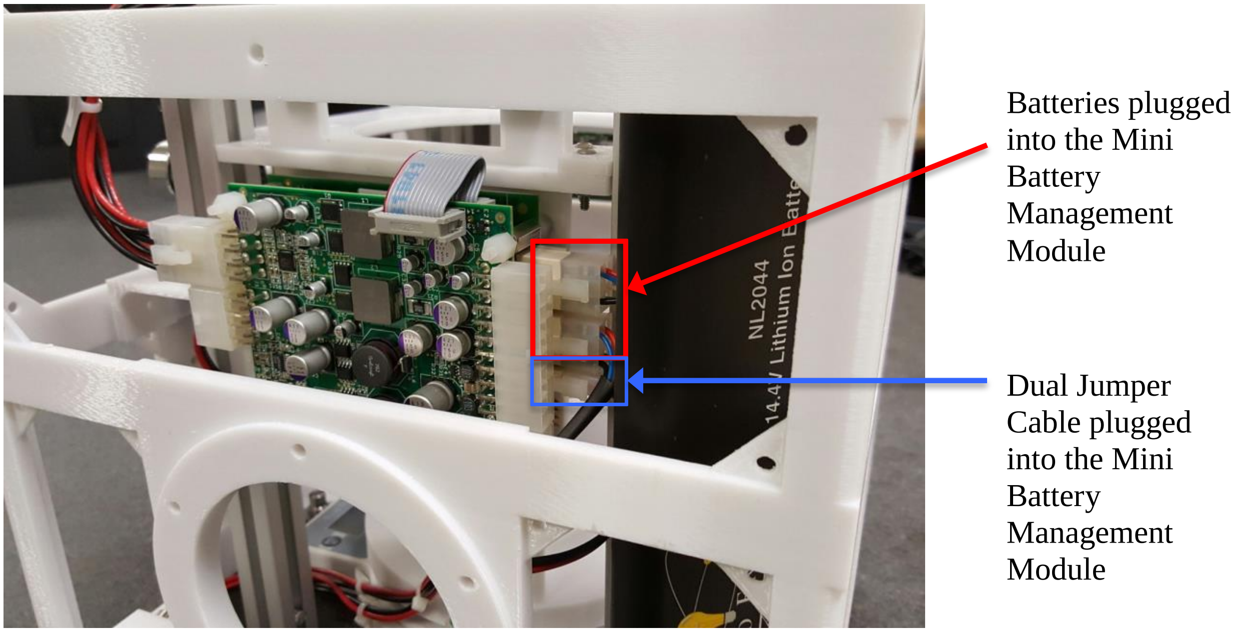
Battery base holder

Step (44) Retrieve two portable batteries and insert them through the Battery Ring and onto the battery base holder.

a) Insert one battery with the charge indicator facing up.
b) Plug both batteries into the right side of the Mini Battery Management Module (directly above the location where the Dual Jumper Cable is plugged in).

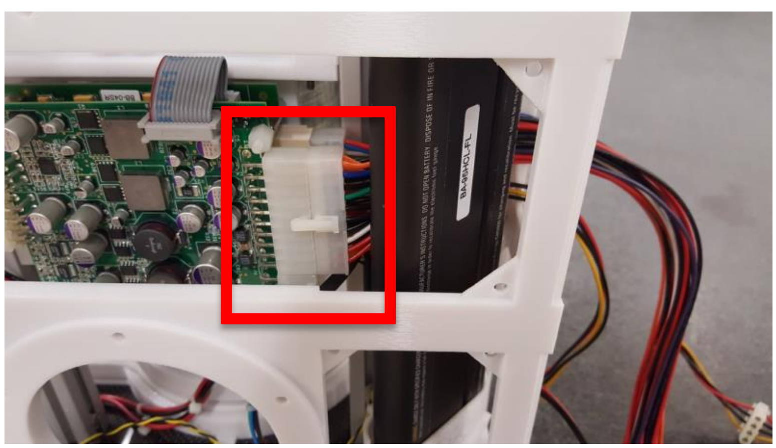
Battery charge indicator





Step (45) Attach the ATX Disk Power Cable to the right side of the ATX DC-DC Converter.

(ATX and Disk Power Cable)



(ATX and Disk Power Cable attached)

Step (46) Retrieve the on/off switch assembly.

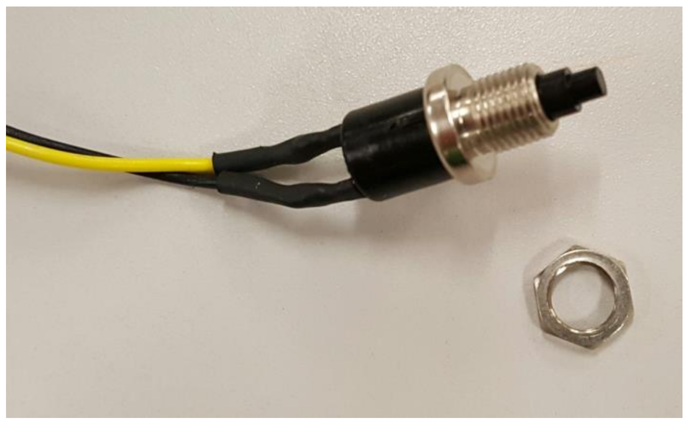
a) Unscrew the nut that was pre-attached to the on/off switch

b) Plug it into the Mini Battery Management Module on the right side, below where the Dual Jumper Cable is plugged in (there will be an 8-pin connection). When looking at the 8-pin connection head on, the on/off switch assembly will connect to the two, bottom, left pins as pictured below.

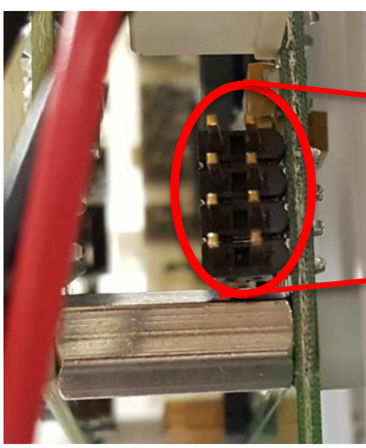
c) Insert the switch assembly through the pre-cut hole next to the Jumper Cable

d) Screw the on/off switch assembly in place using the nut that it came with.

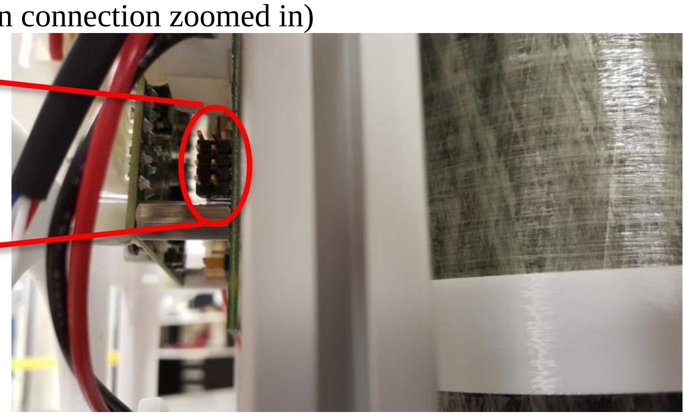
(on/off switch assembly)

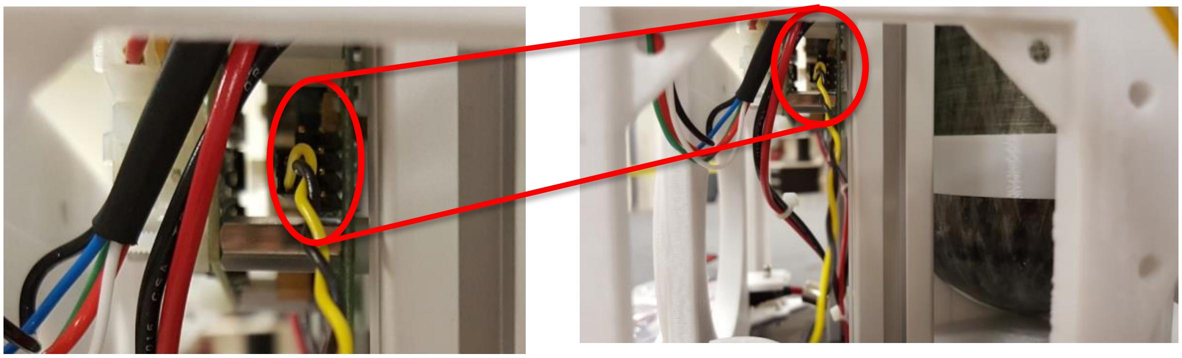


(nut removed from assembly)

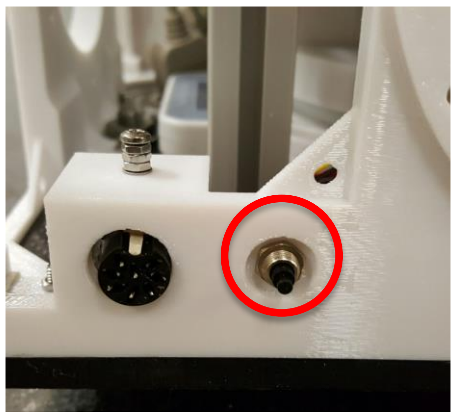


(8-pin connection zoomed in)



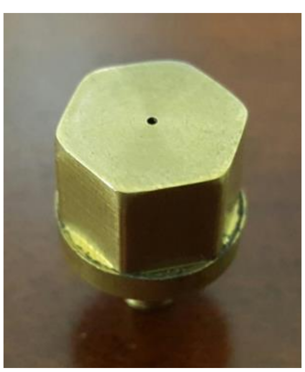


(on/off switch assembly connected to the two, bottom, left pins)



(on/off switch assembly attached to base of Level 1 next to Jumper Cable location)

<u>Step (47)</u> Retrieve 8 solenoid valves, 8 thruster fittings, 8 brass pipe fittings, and teflon tape. Apply teflon tape to ends of each thruster and pipe fitting. Then install a thruster and pipe fitting to each solenoid valve.
(NOTE 1: Prior to applying teflon tape to the pipe fitting, ensure it screws into the solenoid valve easily. If it does not, it is has the wrong threading.)
(NOTE 2: Ensure that the thruster fitting is installed on the solenoid valve indicating "OUT" and the pipe fitting is installed on the side labeled "IN")

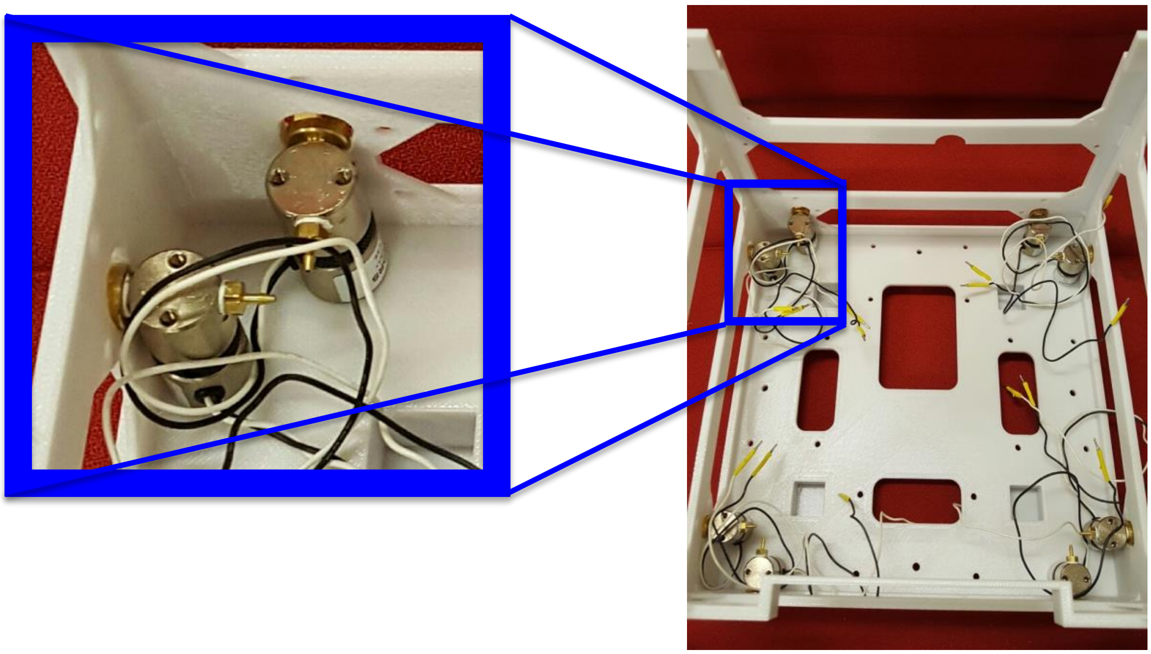


(thruster fitting)

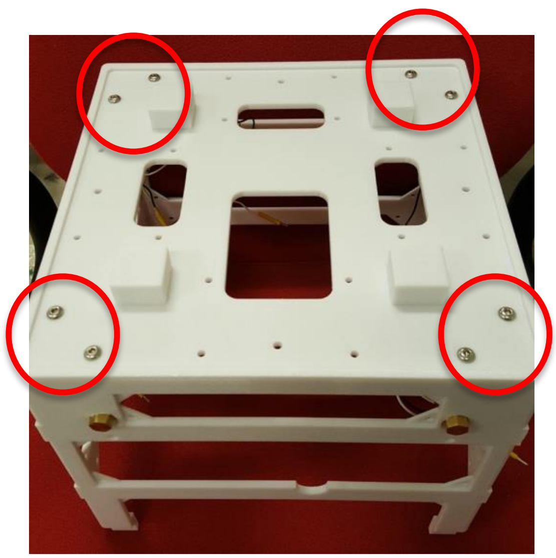
(brass pipe fitting)

(parts installed)

Step (48) Using 8 screws, install the assembled solenoid valve to the top, inside of Level 4 as pictured below.

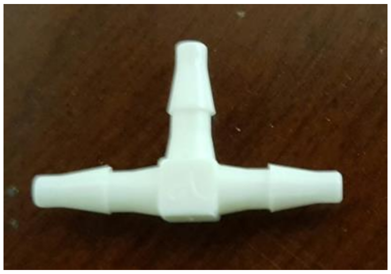


(inside view of Level 4 with valves installed)

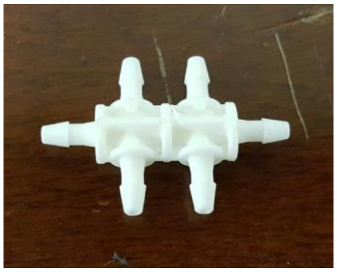


(top view of Level 4 with valves screwed in)

Step (49) Retrieve one three-way tube connector, two six-way tube connectors and cut the following amount of plastic tubing:
-8 pieces of 4.5 inch length
-2 pieces of 2.5 inch length
-1 piece of 10 inch length



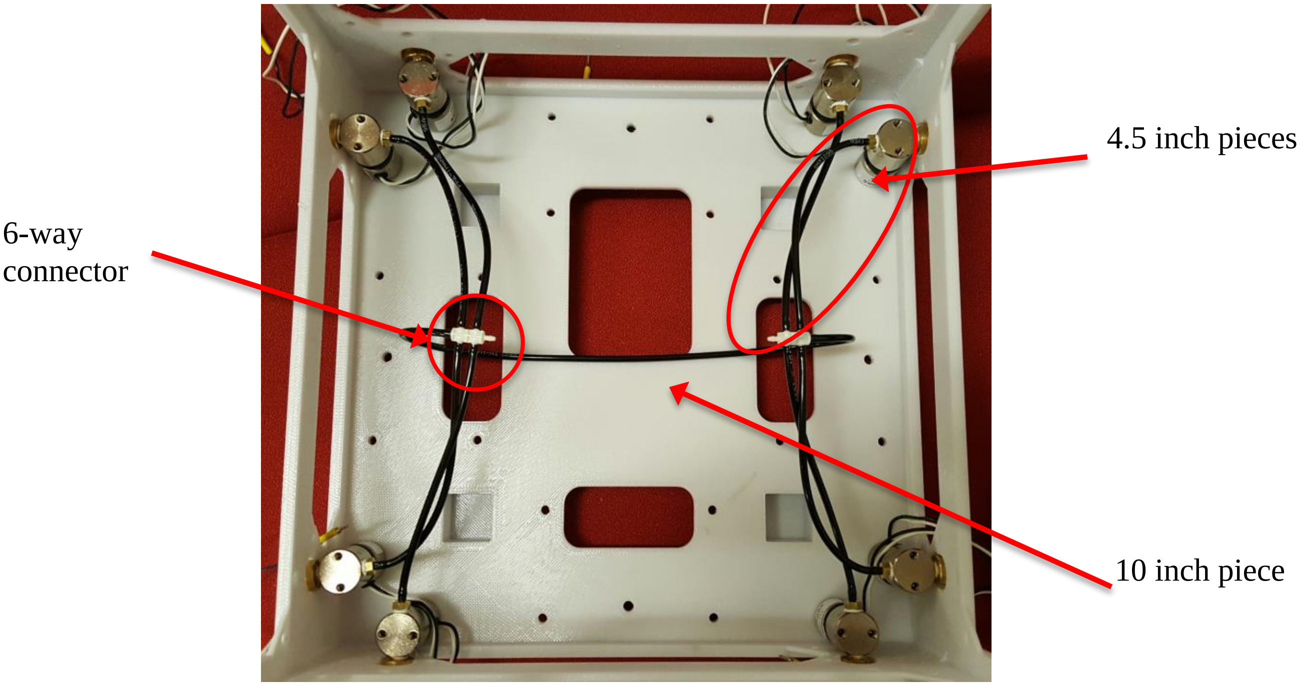
(3-way connector)



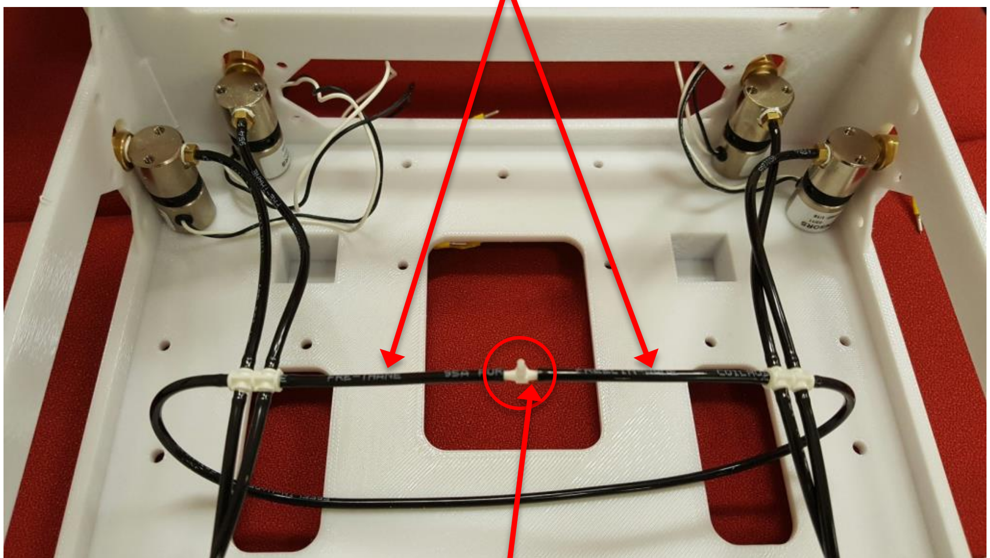
(6-way connector)

(plastic tubing)

Step (50) a) Connect the 4.5 inch pieces to the brass pipe fittings on the solenoid valves.
b) Attach the free ends to the parallel connections on the 6-way connector (one for the left four and one for the right four).
c) Use the 10 inch piece to the connect the two 6-way connectors (connect them using the ends directed outward).
d) Attach the two 2.5 inch pieces to each of the 6-way connectors (connect them using the ends directed inward).
e) Attach the two free ends of the 2.5 inch pieces with the 3-way connector, ensuring the center connection remains free.



(2.5 inch pieces)



(3-way connector)

<u>Step (51)</u> Using two brass pipe fittings, attach them to each end of the micro-solenoid valve. (apple teflon tape to the brass pipe fittings before screwing them into the micro-solenoid valve.

(micro-solenoid valve and two brass pipe fittings)

(after assembly)

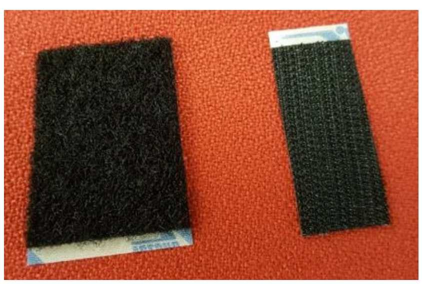
Step (52) For the air filter assembly, use two brass adapters, two brass pipe fittings, and a finite filter. Apply teflon tape to both the adapters and pipe fittings before assembly.

(finite filter)

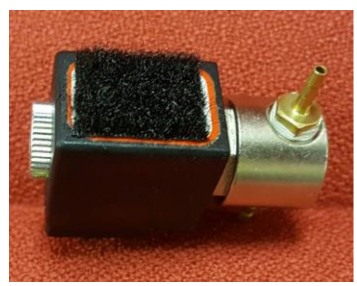
(brass adapters and pipe fittings)

(assembled air filter)

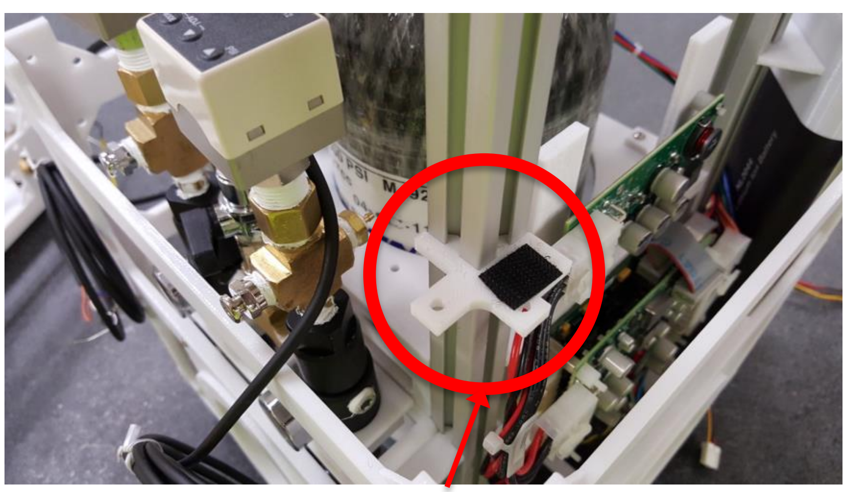
Step (53) Install a Level 3 Attachment to the front right aluminum rod as shown below. Then apply a set of velcro tape (cut size accordingly) to the top of the Level 3 Attachment and the micro-solenoid valve as shown below.



(velcro tape set)

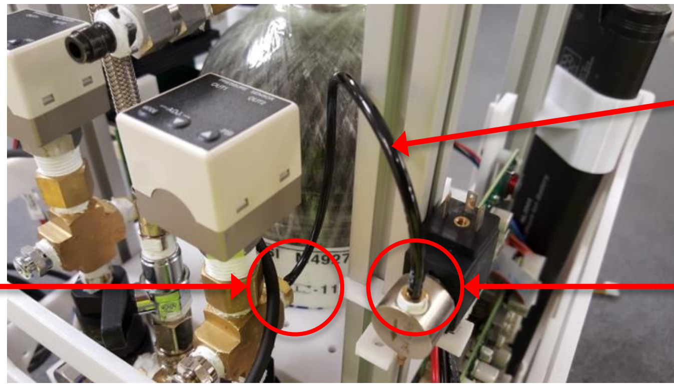


(micro-solenoid valve with velcro tape)



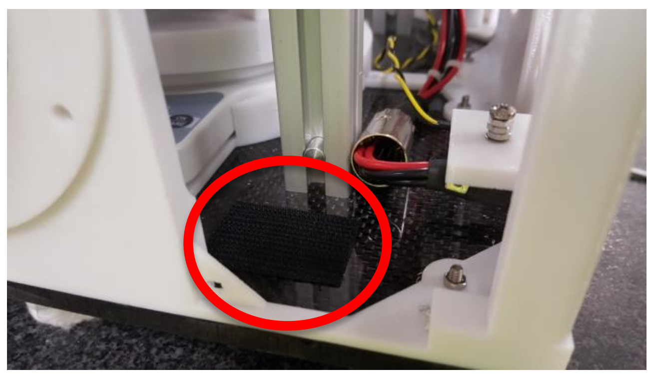
(Level 3 Attachment installed with velcro tape)

Step (54) Attach the micro-solenoid valve to the Level 3 Attachment using the velcro attached (the orifice label should be facing outward with the inlet side facing up and outlet side facing down). Cut a 7 inch piece of plastic tubing and attach it from the inlet side of the micro-solenoid valve to the outlet of the Pressure Regulator Assembly closest to it (of the two assemblies, the one on the right).



Step (55) a) Cut an 11 inch piece of plastic tubing and attach it to the inlet side of the air filter.
b) Apply velcro tape to the bottom of the air filter (ensure the flow label is visible) and at the bottom of the pre-assembled base (behind the jumper cable connection and in front of the aluminum rod) as shown below.

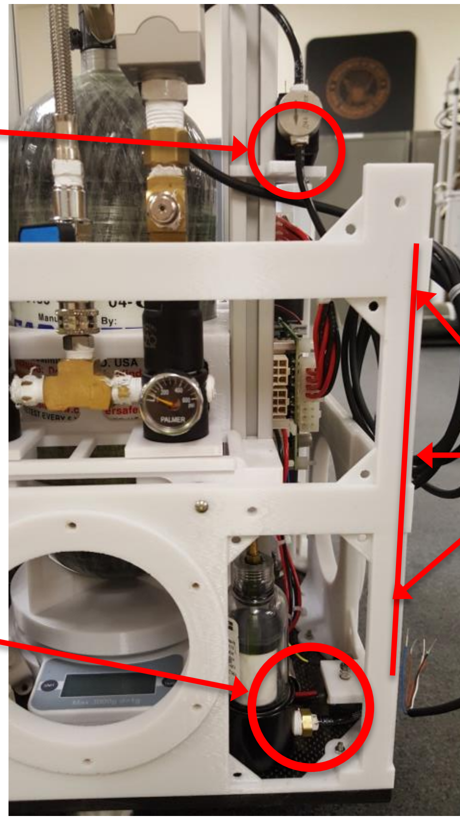
-plastic tubing attached at inlet and velcro applied to bottom



(Velcro taped to the base)

Step (56) Attach the free end of the 11 inch plastic tubing from the air filter to the outlet side of the micro-solenoid valve.
(Optional: route the plastic tubing along the corner of Level 1 using velcro as necessary to keep it neat)

plastic tubing attached to outlet of micro-solenoid valve



Optional: plastic tubing routed along the corner edge of Level 1

plastic tubing attached to inlet of air filter

Step (57) Retrieve a 3-way connector and cut the following lengths of plastic tubing: 1.5 inch, 10 inch, and 12 inch. Attach the 10 inch piece to the left, 12 inch to the center, and 1.5 inch to the right of the 3-way connector. Lastly, attach one end of the quick release connection to free end of the 10 inch piece.

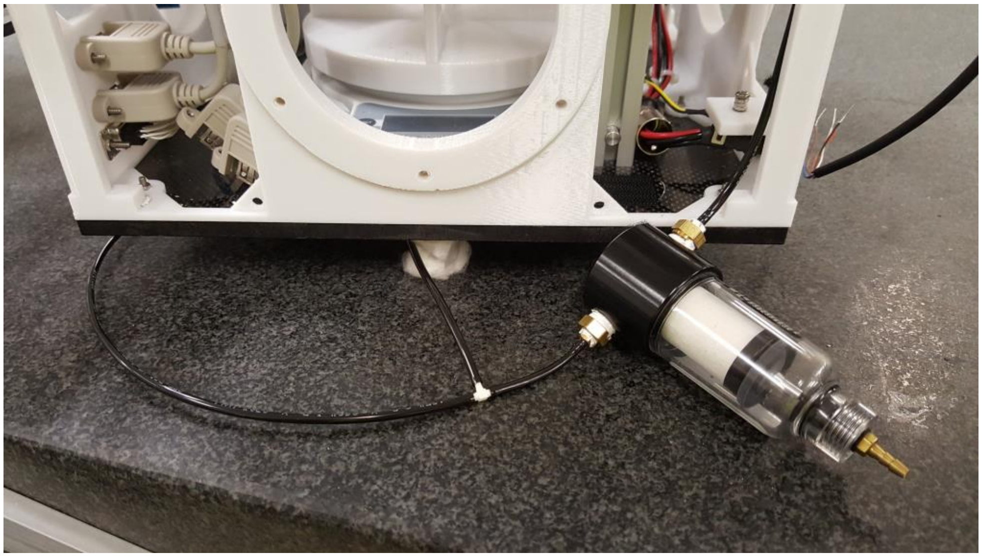
(3-way connector)

(quick release connection)


(use one end to attach to the 10 inch piece)

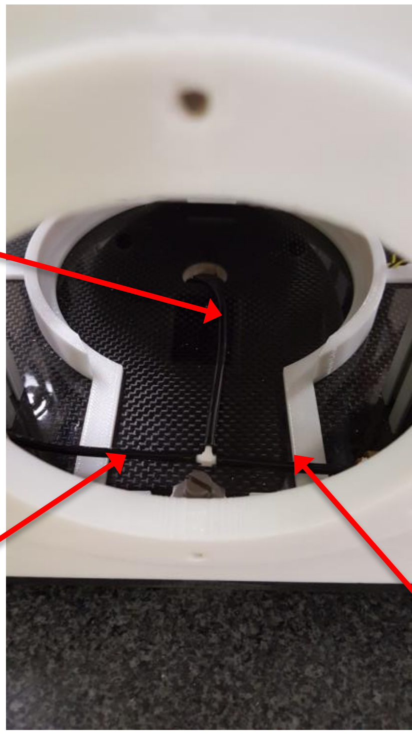

(all pieces attached)

Step (58) Attach the free end of the 1.5 inch tubing to the outlet of the air filter.



Step (59) Routing the plastic tubing.

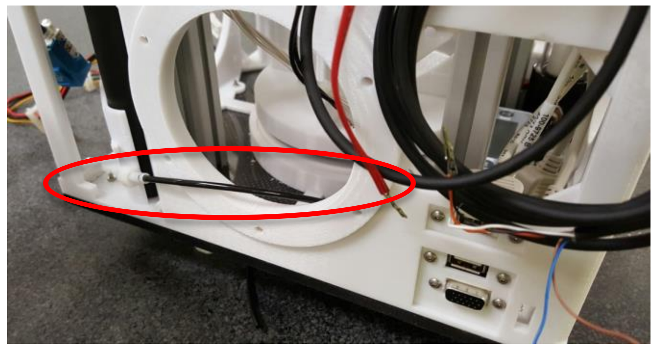
a) Attach the air filter to the base using the velcro applied previously.
b) Ensure all the tubing is internal to Level 1
c) Remove the air tank, lift the scale up and route the center, 12 inch plastic tubing through the hole found in the center of the base.
d) Route the 10-inch piece with the quick release connection through the large hole on the left of Level 1.



12 inch piece

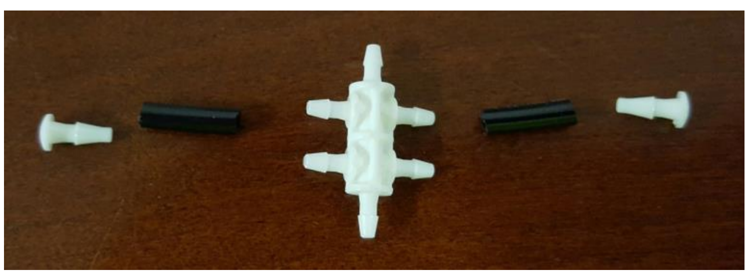
10 inch piece

1.5 inch piece connected to air filter

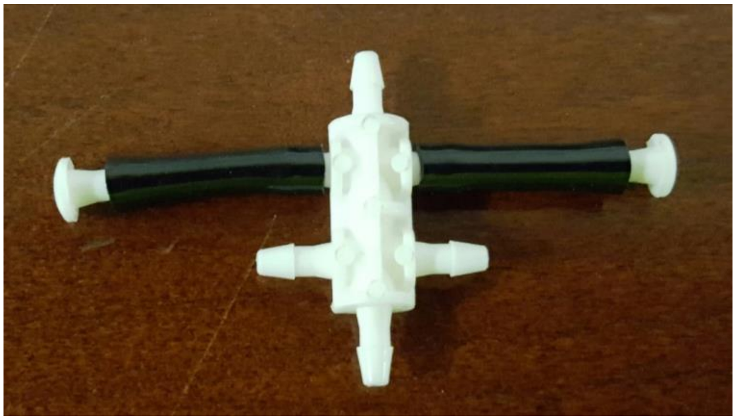


(10 inch piece through left hole in Level 1)

Step (60) Retrieve a 6-way connector, two tubing plugs, and cut two 0.5 inch pieces of plastic tubing. Assemble them as shown below.



(before assembly)



(after assembly)

Step (61) Attach the assembled part from Step (60) to the free end of the 12 inch tubing that was routed through the center of the base.

Step (62) Disconnect the batteries from the Mini Battery Management Module.

Step (63) Locate the cable attached to the pressure sensors. Strip the cable as necessary to expose the wires within. There will be five wires colored brown, blue, orange, black and white. Brown is the positive end and blue is the ground. All other wires are not needed and can be grouped together and covered with heat shrink tubing.

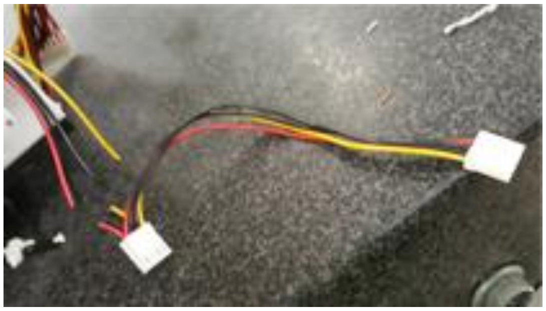
(cable stripped to show wires)

(the unneeded wires grouped together)

(unneeded wires covered with heat shrink tubing)

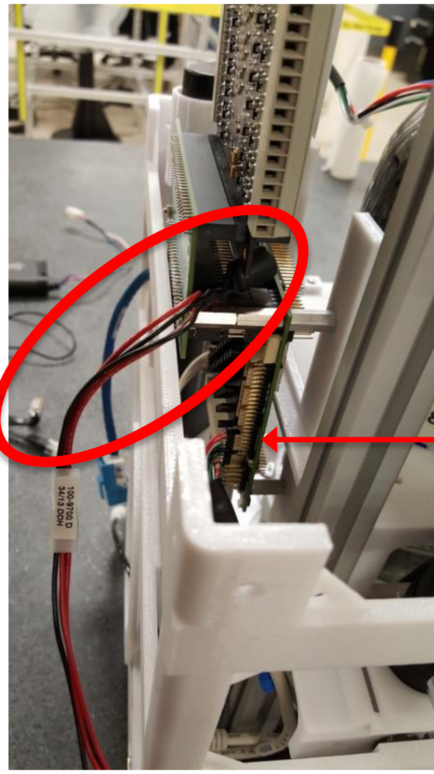
Step (64) Combine the two cables from the pressure sensors by grouping the positive (brown) ends together and the negative (blue) ends together.

Step (65) Cut the unneeded ends of the ATX and Disk Power Cable as shown below.



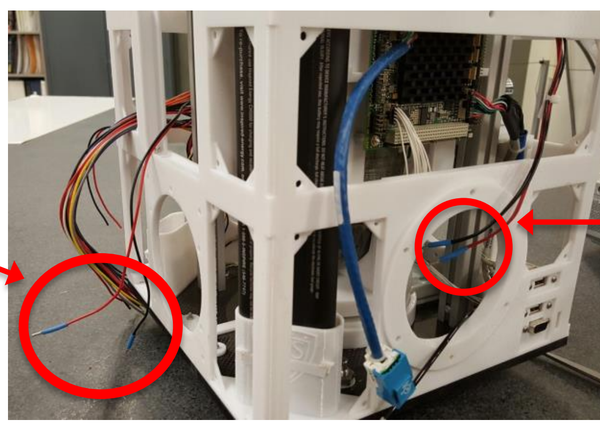
Step (66) Select a yellow and a black wire from the ATX and Disk Power Cable. Yellow wires provide approximately 12 volts and the black cable is ground. Attach female crimp connectors to a yellow and a black wire and male crimp connectors to the blue and brown wires from the pressure sensors. Connect the positive and negative ends respectively (brown to yellow and blue to black). Use heat shrink tubing as necessary.

Step (67) Locate the power strip attached to the CPU. Attach female crimp connectors to the red and black wires on the power strip. Select a black and red wire from the ATX and Disk Power Cable and attach male crimp connectors. Connect the same colored wires together. (Note: route the wires as necessary and use heat shrink tubing to keep it tidy)



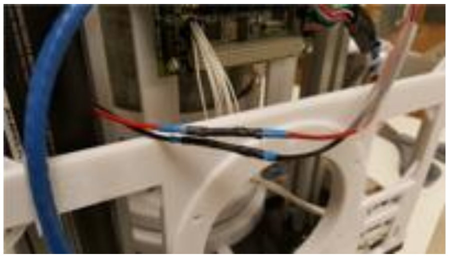
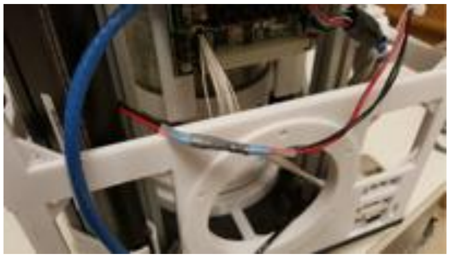
Power strip

CPU



Red/black wire from ATX and Disk Power Cable

Red/black wire from power strip

(black and red wires connected and heat shrink tubing used)

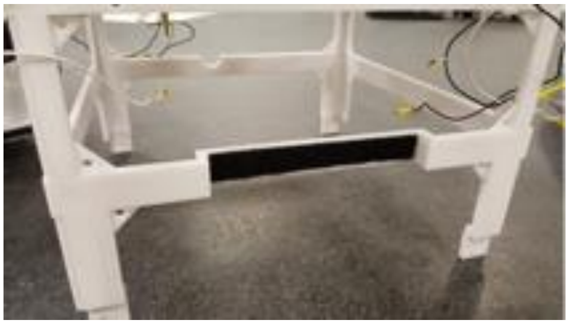
<u>Step (68)</u> Retrieve the D-Link Wireless Router and apply velcro to the back of it.

(wireless router)

(velcro applied to back)

<u>Step (69)</u> Apply velcro to the back of Level 4 where the wireless router will attach.

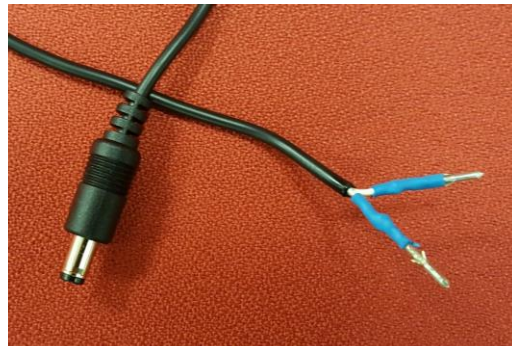
(back of Level 4)



(velcro applied to back of Level 4)

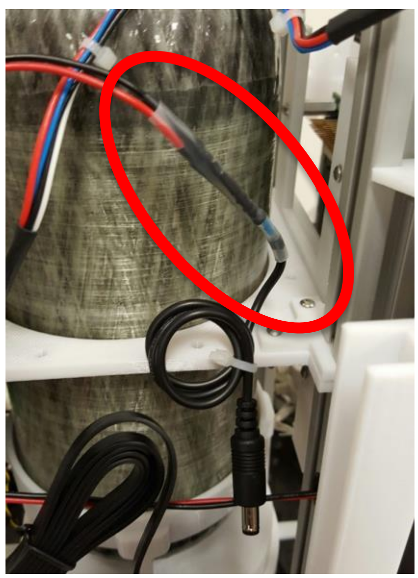
Step (70) The D-Link Router comes with a USB Power Cable. Cut the USB end off and strip the cable to expose the wires underneath. The inner white wire is the positive end and the wires surrounding are ground. Attach male crimp connections to both ends. Use heat shrink tubing as necessary.

inner wire outer wire

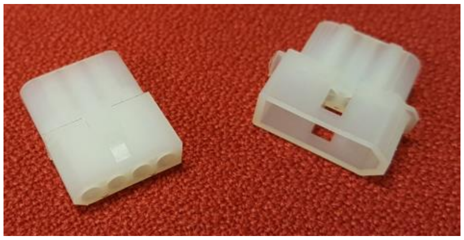


Male crimp connections installed

Step (71) Select an unused black and red wire from the ATX and Disk Power Cable and install female crimp connections. Then connect the red and black wires to the respective wires on the power cable for the wireless router from Step (70). Use heat shrink tubing as necessary.

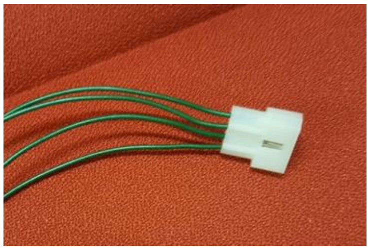


Step (72) Retrieve 2 sets of quad quick release connections and 8 pieces of green wire. Attach male crimp connections to the wires and insert 4 wires into each female quick release connections as shown below.



(a set of quick release connections)
(male: left | female: right)

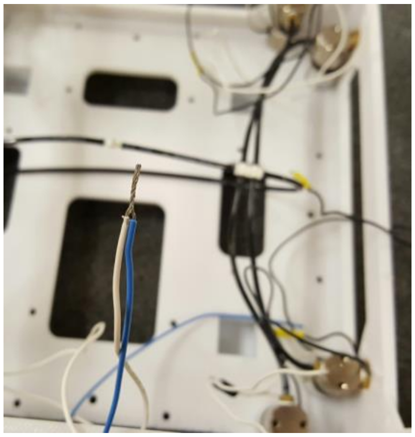
(green wire with male crimp connection)



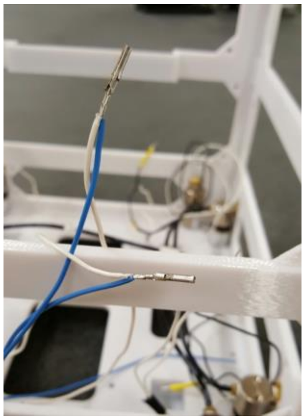
(4 wires attached to female connection)

(inside view after assembly)

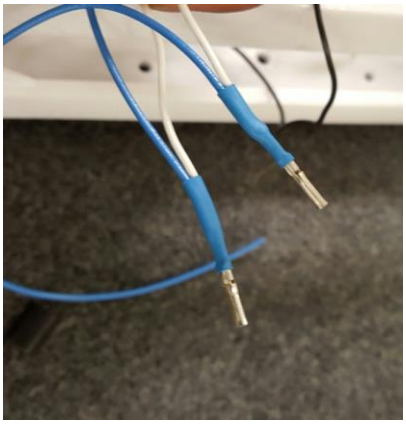
Step (73) Retrieve 8 pieces of blue wire (color does not really matter). Strip one end on each cable and attach them to each positive (white) wire from the 8 solenoid valves attached to Level 4. Once twisted together, crimp a female connection to it and heat shrink as necessary.
(Note: the blue wire we will later be used to connect the LED lights.)



(wires twisted together)

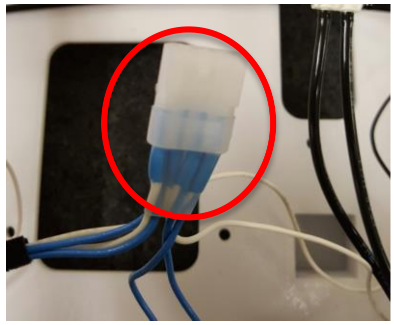


(female crimp connection)

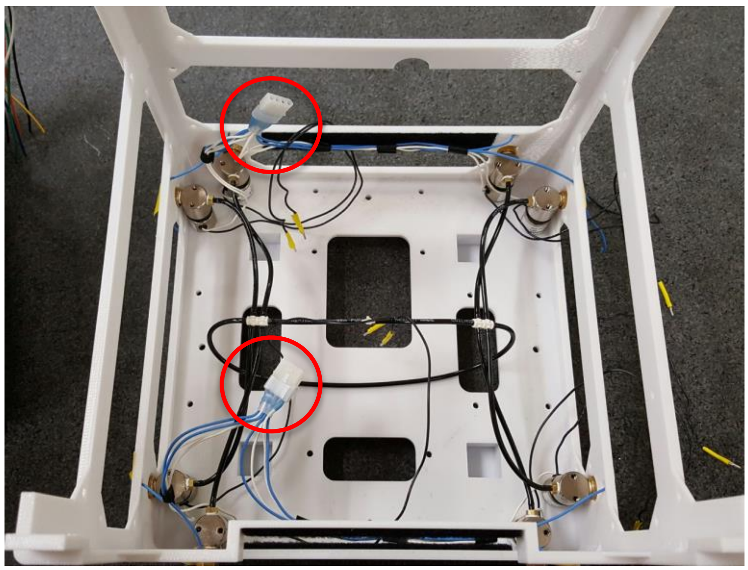


(heat shrink applied)

Step (74) Using the 2 male quick release connections from Step (72), insert 4 sets of the positive wires from Step (73) into each male connections.

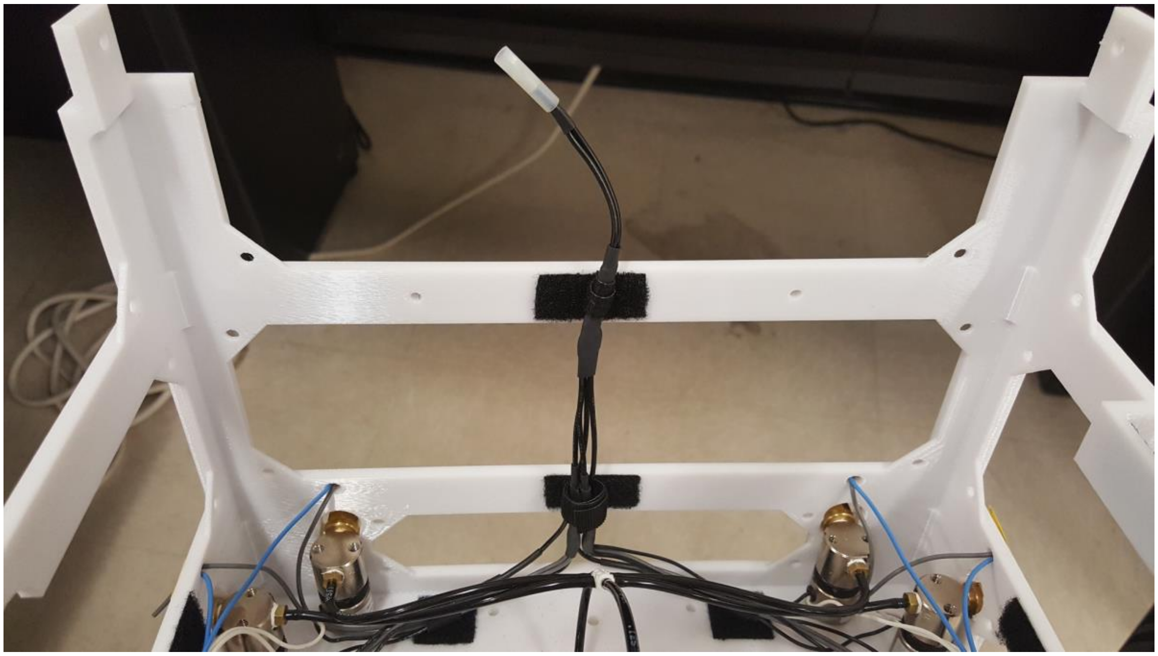


4 sets of wires inserted into male end of quick release connection



Step (75) For each black (ground) wire on the solenoid valves attached to Level 4, retrieve a piece of grey wire and attach/twist them together similar to Step (73). Goal is to combine all of the 16 ground wires into one wire. Strip, combine, and heat shrink as necessary to achieve this. Once completed, attach a female crimp connection followed by a single male quick release connection. (Note: the grey wire we will later be used to connect the LED lights.)

(female: left | male: right)

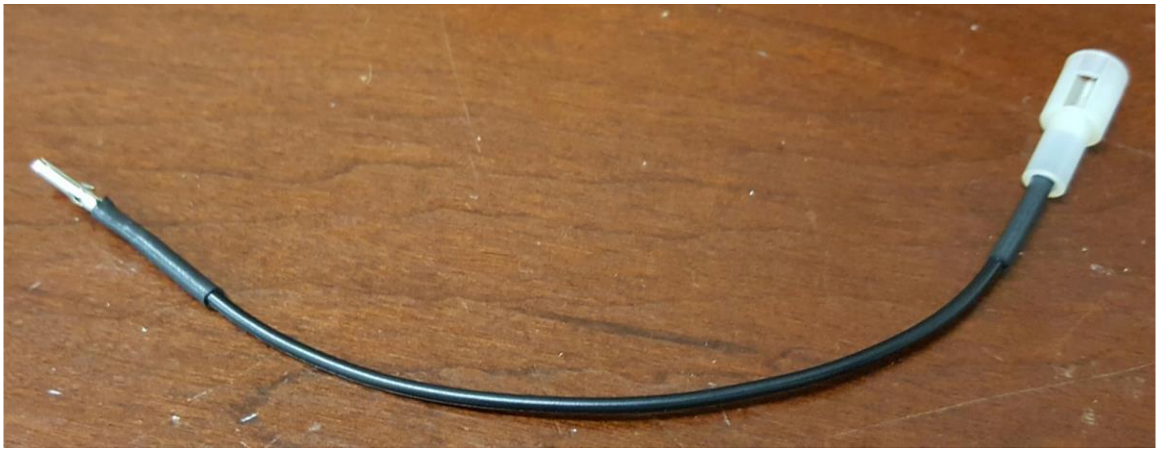


(all 16 ground wires combined into a single connection)

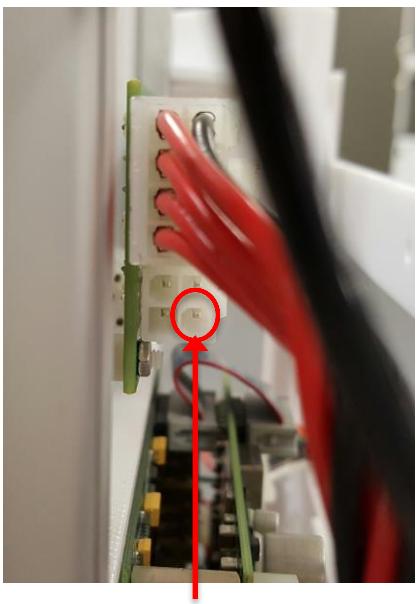
Step (76) Retrieve a short piece of black wire. Strip both ends and attach a male crimp connection on one end and a female crimp on the other. Attach the single female quick release connection from Step (75) to the male crimped end. Attach the female crimped end to the bottom right slot of the DC-DC Converter as shown below.

(wire with both ends stripped)

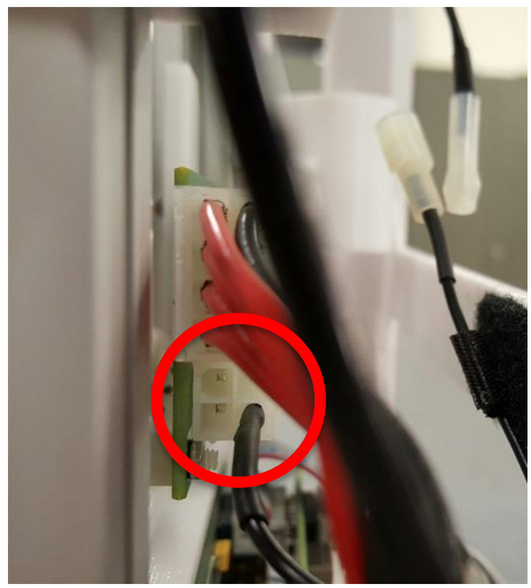
(crimp connections attached)



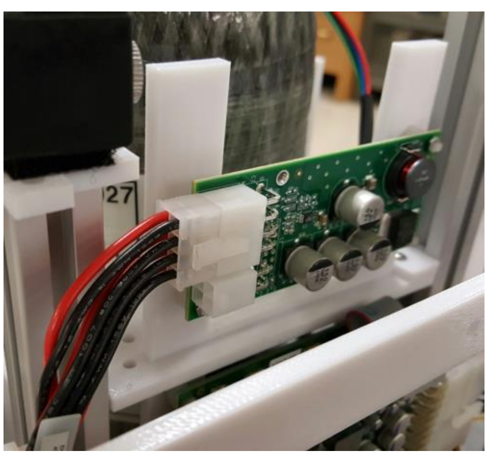
(female quick release connection attached to the male crimped end)



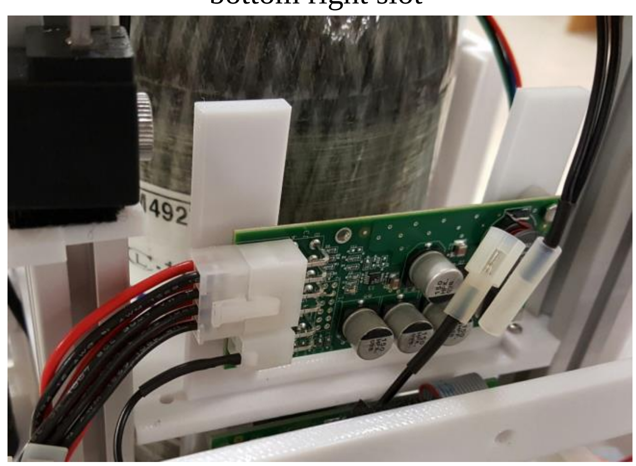
Bottom right slot



Wire attached to
bottom right slot

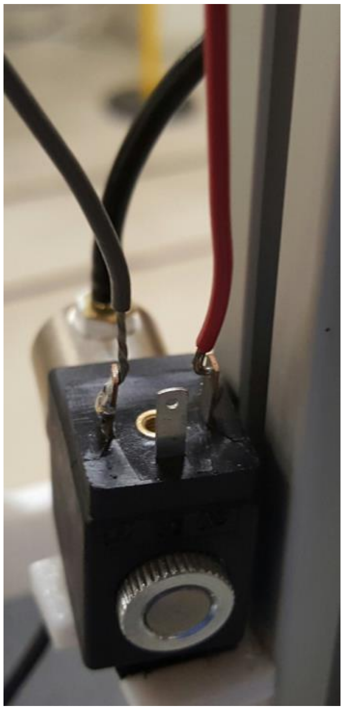


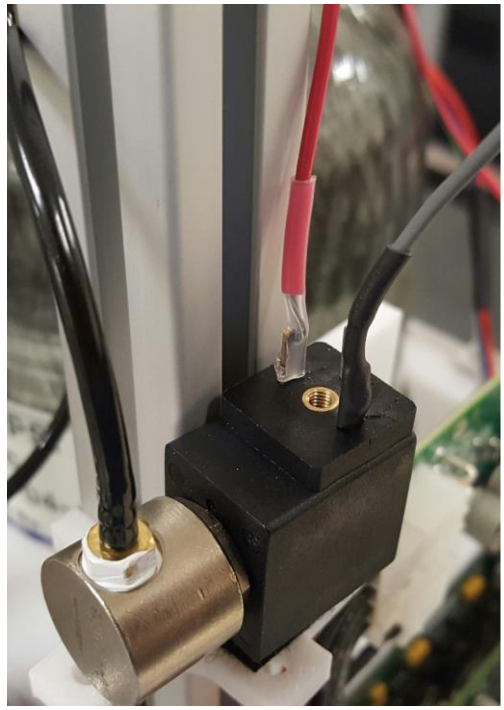
(wire unattached)



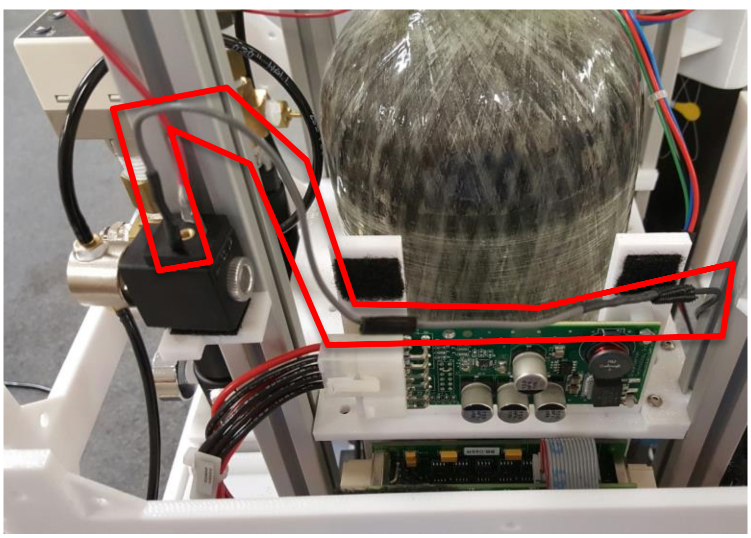
(wire attached)

Step (77) Retrieve a red and black wire for positive and ground ends. Solder these wires onto the micro-solenoid valve to its respective connections as shown below. Apply heat shrink tubing as necessary.

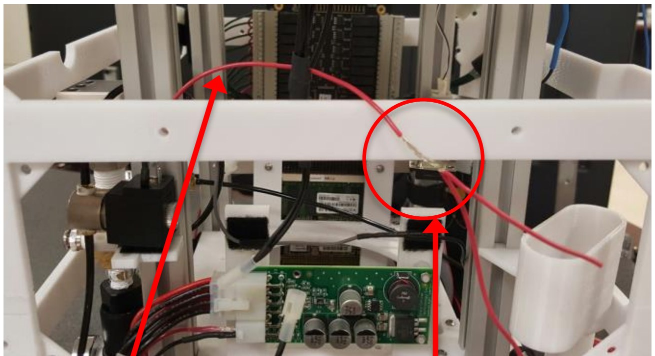

(wires soldered on)


(heat shrink tubing applied)

Step (78) Pick a black wire from the ATX and Disk Power Cable and attach it to Black (ground) wire from the micro-solenoid valve. Use heat shrink tubing as necessary.

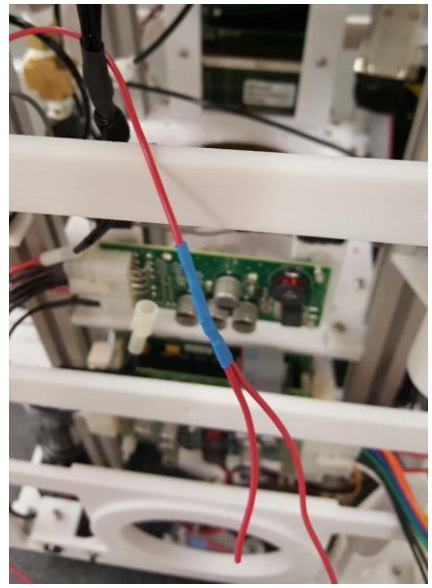


Step (79) Cut two pieces of red wire (be liberal with the length), and attach it to the red wire connected to the micro-solenoid valve and use heat shrink tubing.



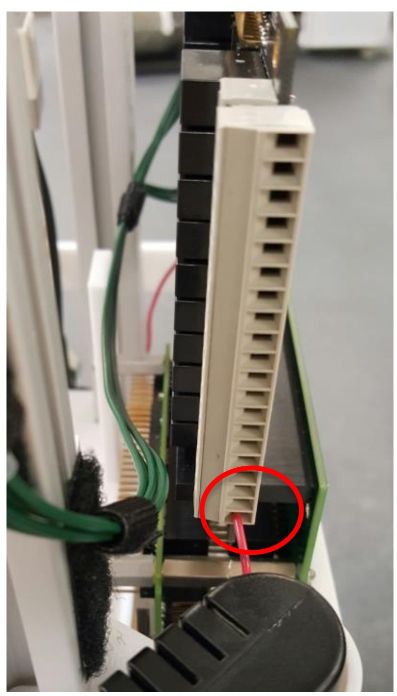
Red wire from micro-solenoid valve

2 red wires attached to red wire from solenoid



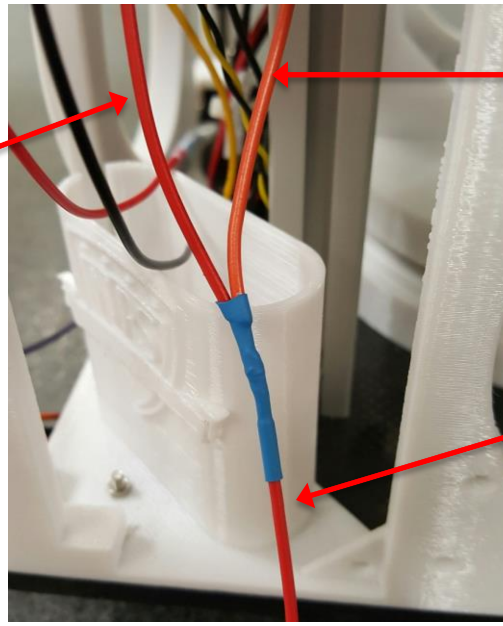
(heat shrink tubing applied)

Step (80) Route one of the red wires from Step (79) to the Relay Board and attach it to RLY11, which is the bottom connection on the left side. The other red wire will be connected directly to a switch in a later step.



Step (81) Select a red wire from the ATX and Disk Power Cable and attach 2 red (or orange) wires to it. Use heat shrink tubing as necessary.

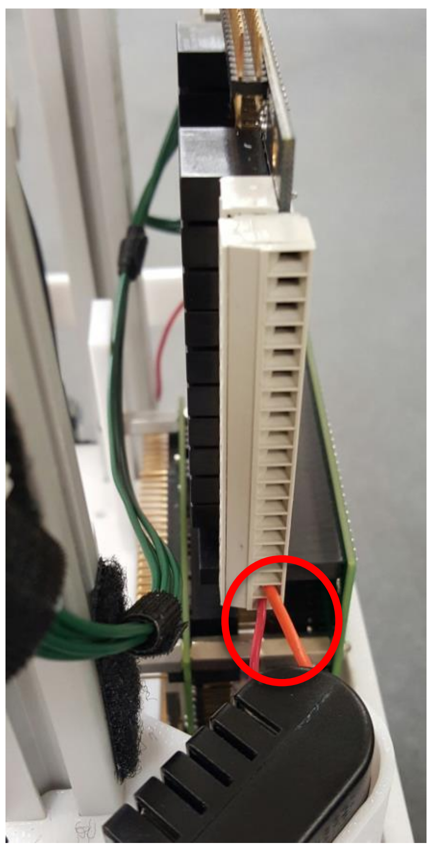
Red (5V) wire from ATX and Disk Power Cable



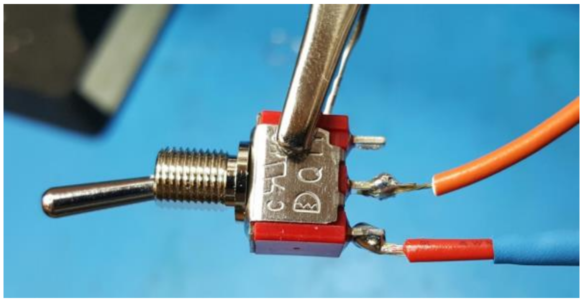
Will attach to Relay Board in later step

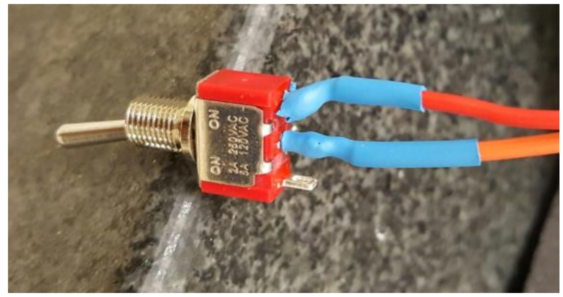
Will attach to switch in later step

Step (82) Route the orange wire from Step (81) to the Relay Board and attach it to the spare slot in RLY11.

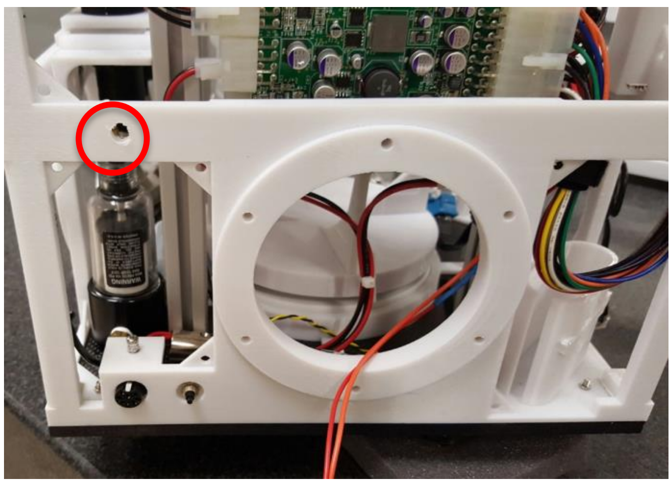


<u>Step (83)</u> Retrieve the switch. Using the remaining wires from Step (79) and Step (81), solder one of the wires to an end connection (does not matter which one) and the other wire to the center connection. Use heat shrink tubing as necessary.

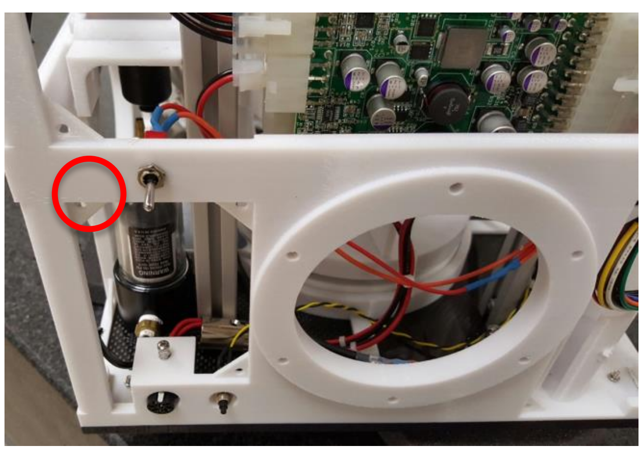




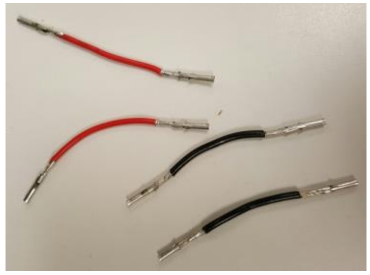
<u>Step (84)</u> Drill a hole for the switch as indicated below.



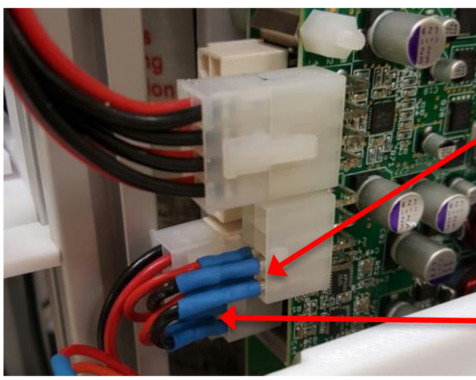
<u>Step (85)</u> Insert the switch through the hole drilled and hold it in place with a nut.



Step (86) Cut 2 short pieces of black wire and 2 short pieces of red wire. Strip both ends on all wires and attach female crimp connections to the ends and use heat shrink tubing as necessary.

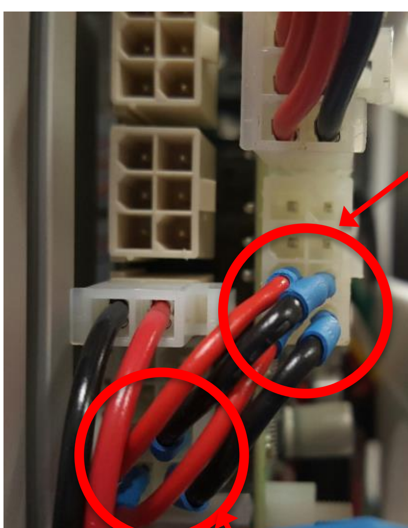


Step (87) Connect the black wires on the left of the ATX DC-DC Converter on the bottom right 2 slots and connect the red wires to the left of those black connections. Then connect the opposite ends of the wires in the same fashion to the Mini Battery Management Module. Three different views are shown below.



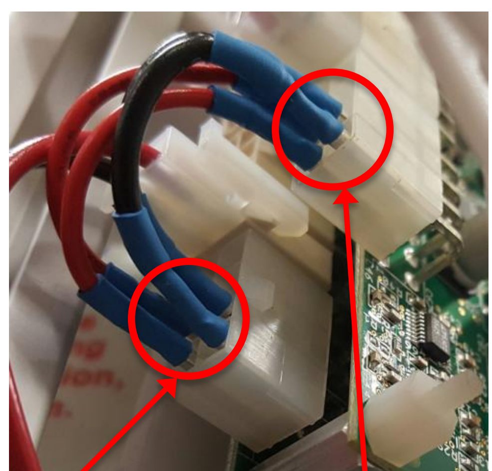
Connected to ATX DC-DC Converter

Connected to Mini Battery Management



Connected to ATX DC-DC Converter

Connected to Mini Battery Management



Connected to Mini Battery Management

Connected to ATX DC-DC Converter

Step (88) Cut two pieces of plastic tubing. This will be used to connect the remaining Pressure Regulator Assembly to the solenoid valves attached to Level 4. Retrieve a quick release connection and attach a plastic tubing to each end. Attach one end of the tubing to the remaining Pressure Regulator Assembly and the other end to the remaining end of the 3-way connection on Level 4.

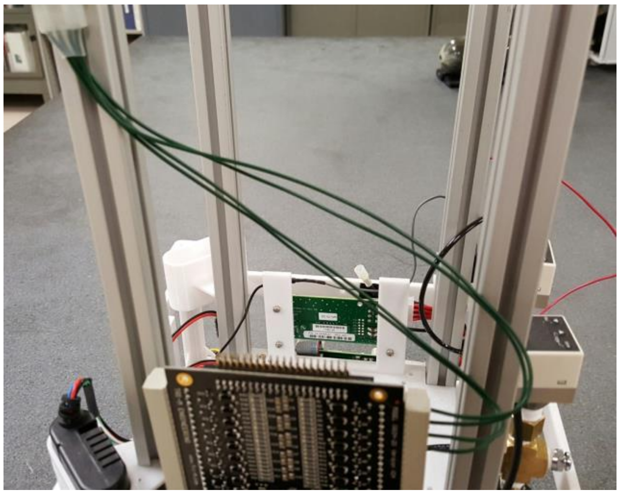
Tubing attached to Pressure Regulator

Tubing attached to 3-way connection

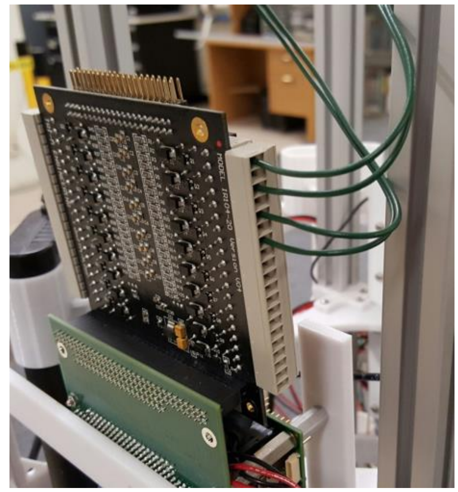
Step (89) Cut 8 pieces of green wire. Strip both ends of the wire and attach a male crimp connection to one end on each wire. Retrieve two female quad quick release connection and insert 4 wires (male crimped end first) into each female quad quick release connection. Use heat shrink tubing as necessary.

(require a set of 2)

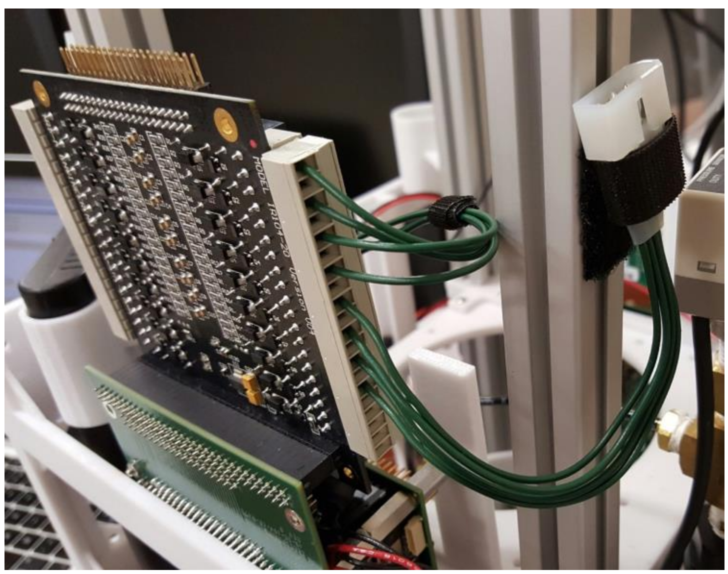
Step (90) Use one set from Step (89) and attach the free ends to the right side of Relay Board in connections RLY1 – RLY4. Use the remaining set to connect to RLY5-RLY8. (Note: each RLY position has 2 connections, ensure you are skipping every other connection.)



(first set connected)



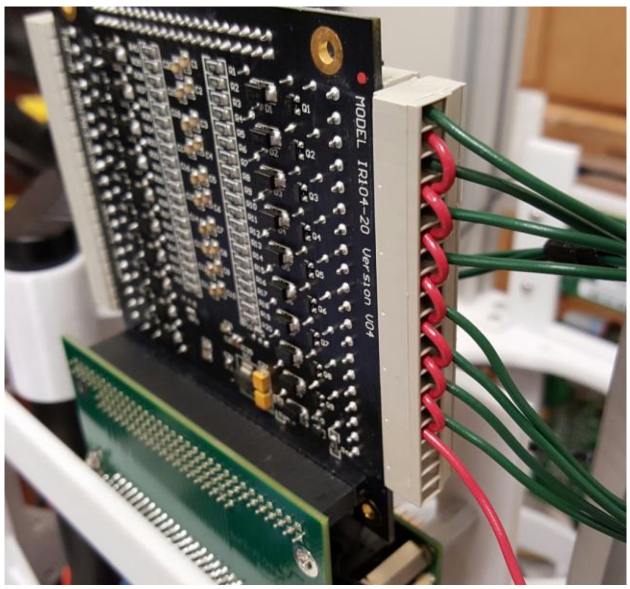
(first set connected to every other slot)



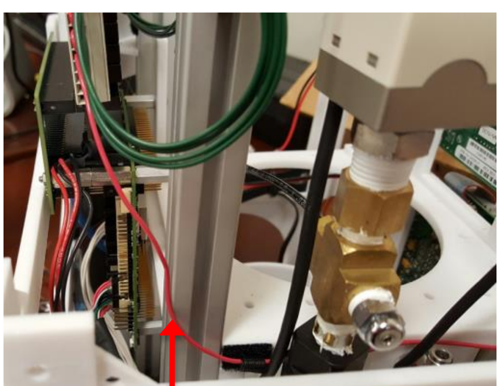
(Second set connected)

Step (91) Cut 7 short pieces of red wire and strip both ends. Also, cut one long piece of red wire that will reach the DC-DC Converter from the Relay Board. Connect the short red wires to the remaining slots from RLY1 - RLY8 as shown below. Connect the long red wire to RLY8.

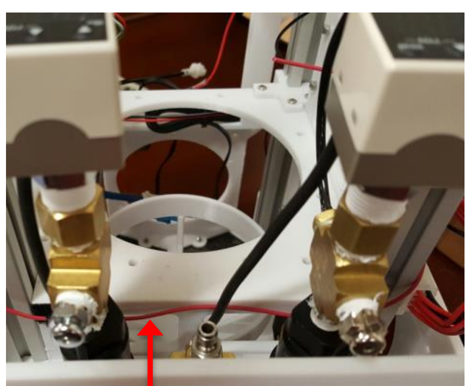
(short red wire with ends stripped)



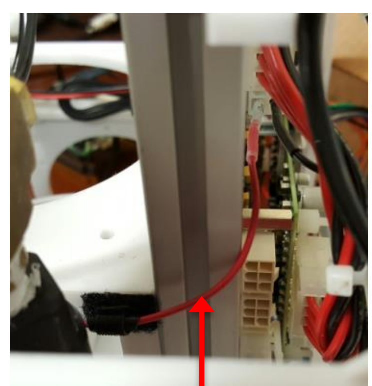
Step (92) Using the free end of the long red wire connected to RLY8, attach a female crimp connection. Use heat shrink tubing as necessary. Once complete, connect the female crimped end to bottom left slot of the DC-DC Converter (next to the ground connection from Step (76)).



Red wire from RLY8 connection



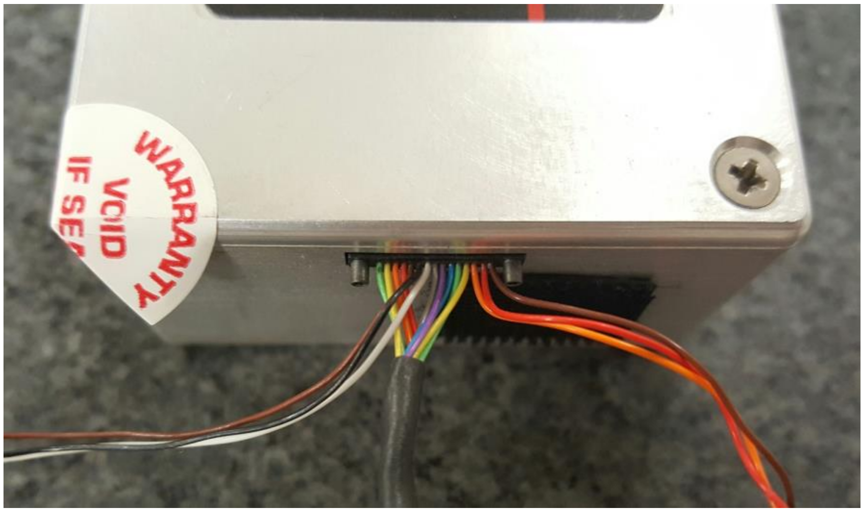
Red wire routed through



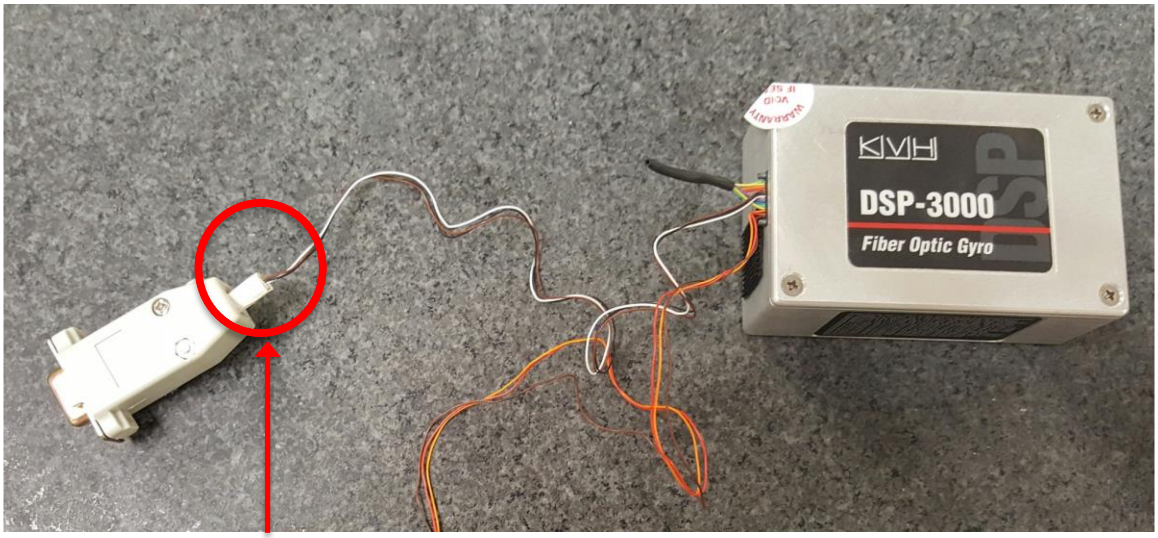
Red wire connected to bottom left slot on DC-DC Converter

Step (93) Retrieve a Fiber Optic Gyro. Most of the wires on the gyro will not be used so they can be heat shrunk together with the exception of the following wires: black, white, both brown wires, the far right red wire and the far right orange wire as shown below.

(Fiber Optic Gyro)

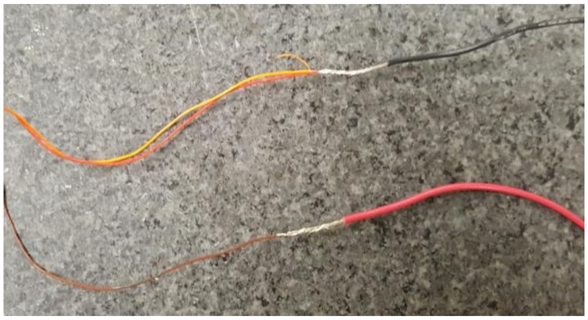


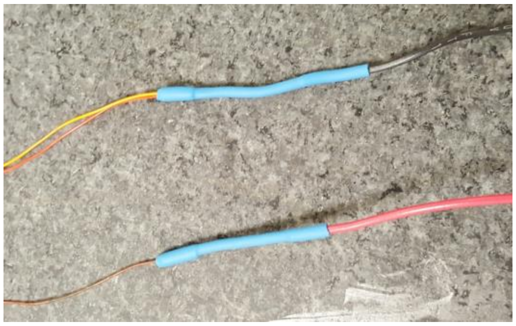
Step (94) Group the black, white and the left brown wires together and attach it to a female VGA cable connector.



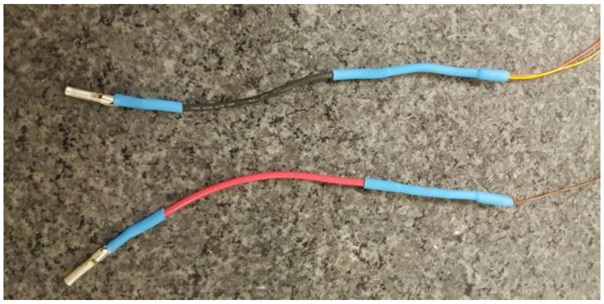
The black, white, and left brown wires attached to a female VGA cable connector.

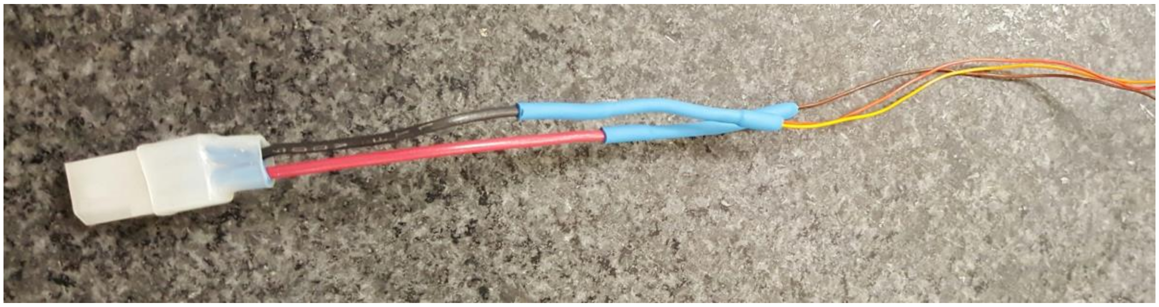
Step (95) Cut a piece of red and black wire. Connect the red wire to the brown wire. Connect the black wire to both the orange and red wire on the gyro. Apply heat shrink tubing.



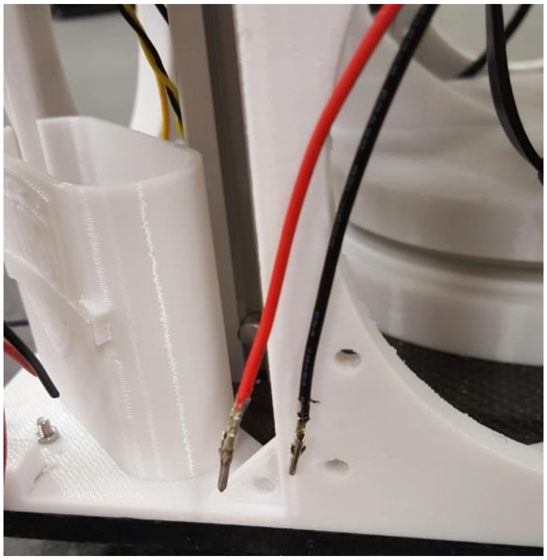


Step (96) Attach a female crimp connection to the ends of both the black and red wires. Then attach a dual male quick release connection.





Step (97) Using a black (ground) and red (5V) wire from the ATX and Disk Power Cable, attach male crimp connections to both wires. Then attach those wires to a dual female quick release connection. This will connect to the wires in Step (96).

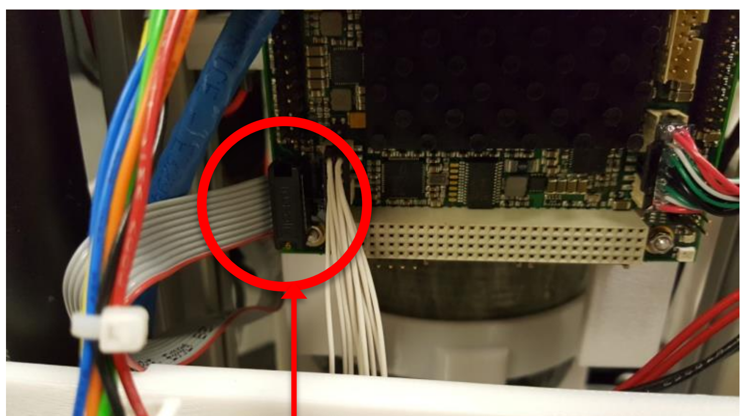


(male crimp connections attached)

(w/ female quick release connection)

Step (98) Retrieve a COM1 Ribbon Cable (VGA connection) and attach it to the CPU as shown below. Ensure that the red
strip is at the bottom. This will connect to the VGA cable from Step (94).

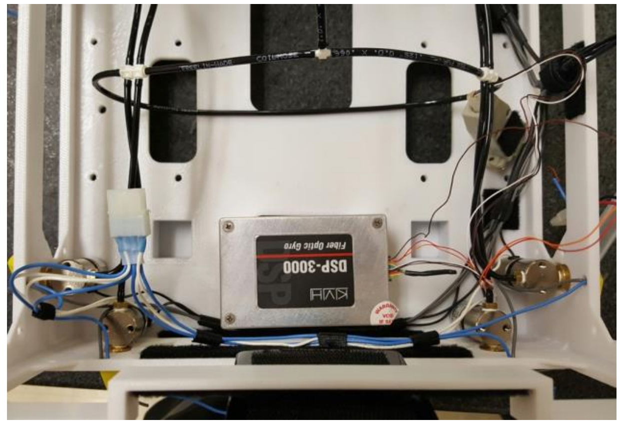
COM1 Ribbon Cable



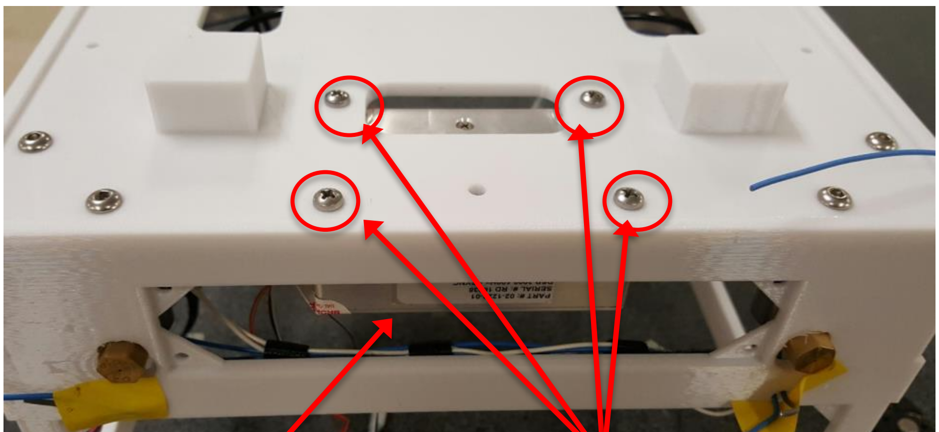
COM1 Ribbon Cable attached to heatsink
(red wire on bottom)

Step (99) Using 4 screws, attach the gyro to the inside, top, and back of Level 4.

(4 screws needed)



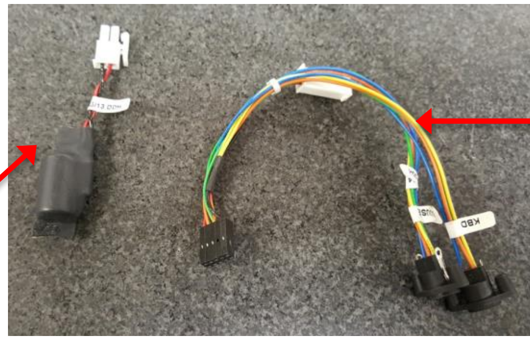
(Gyro attached, inside view)



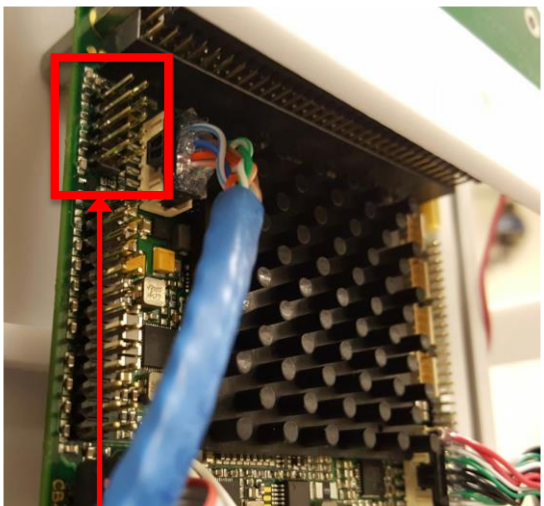
(Gyro attached. Outside, top view) (screws attached to gyro)

Step (100) Retrieve the Keyboard/Mouse Cable and the ADL Battery Option. Attach the Keyboard/Mouse Cable to upper left set of pins on the CPU. Ensure that the red wires are on top as shown below. Once the cable is attached, attach the ADL Battery Option to the cable.

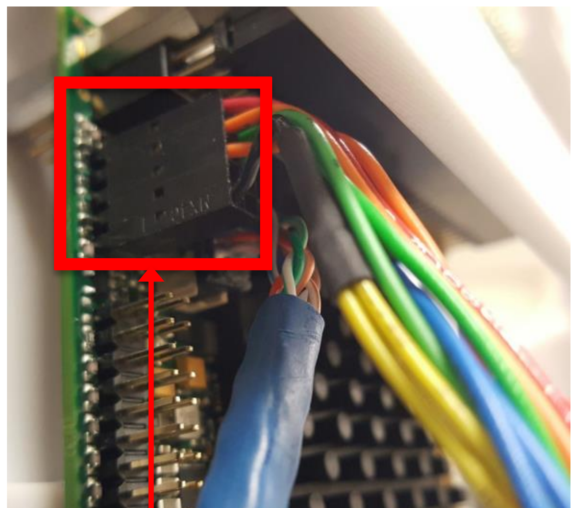
ADL Battery Option



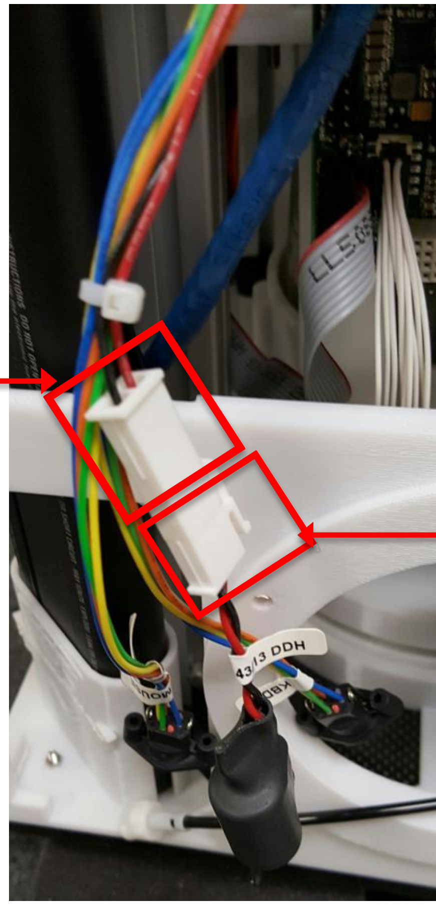
Keyboard/Mouse Cable



Location where Keyboard/Mouse Cable will be attached



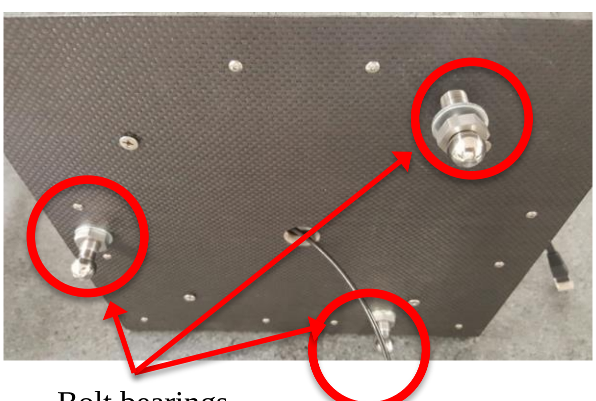
Keyboard/Mouse Cable attached



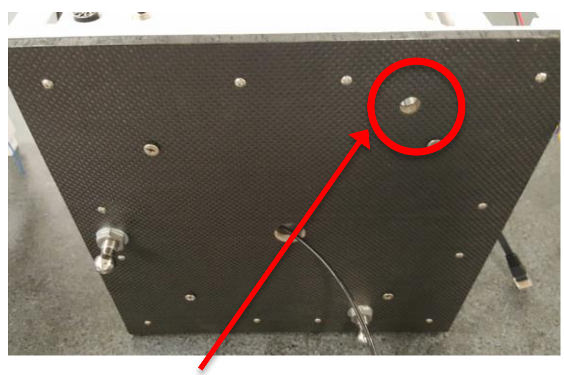
Keyboard/Mouse
Cable Connection

ADL Battery Option
Connection

Step (101) Lay the robot on its side and remove the 3 bolt bearings. Make sure to keep the washers and nuts nearby for the next step. Each bolt bearing should have 2 washers and 2 nuts.
(Note: remove parts as necessary to make it easier to lay the robot on its side: air tank, Level 4, etc.)



Bolt bearings



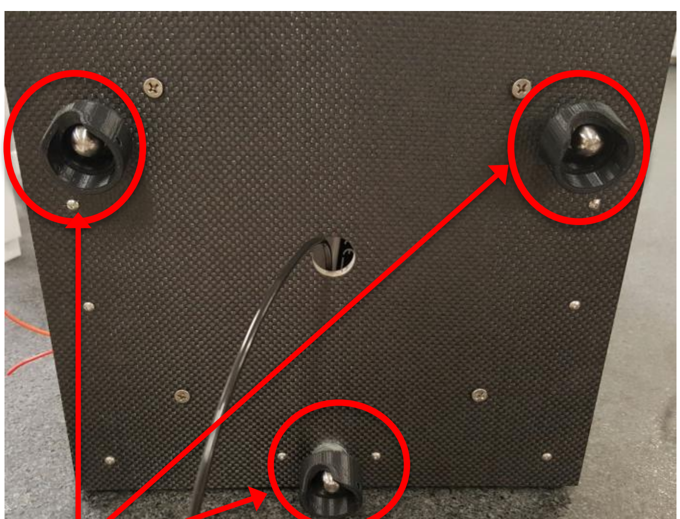
One bolt bearing removed

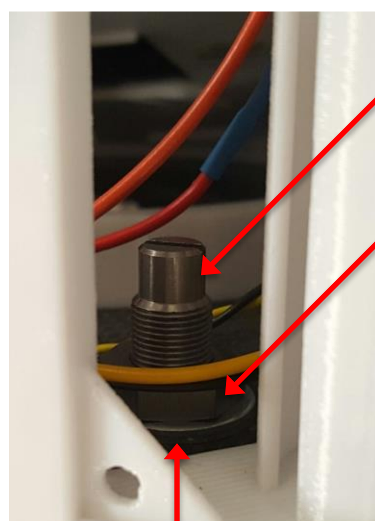
Step (102) Ensure all the washers and nuts have been removed from the bolt bearings. Slide on an Air Bearing Support Mount to each bolt bearing and then screw a nut on followed by a washer.

(bolt bearing with all washers and nuts removed)

(Air Bearing Support Mount attached followed by a nut followed by a washer)

Step (103) Slide the pre-assembled bolt bearing from Step (102) from the bottom up into the 3 pre-drilled holes on the base. Use a washer and nut to hold it in place.





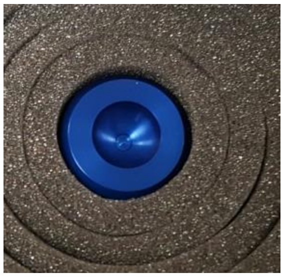
Bolt bearing

nut

Bolt bearings with attachments inserted

washer

Step (104) Retrieve 3 air bearings and 3 brass pipe fittings. After applying teflon tape to the brass pipe fittings, attach one to each air bearing.



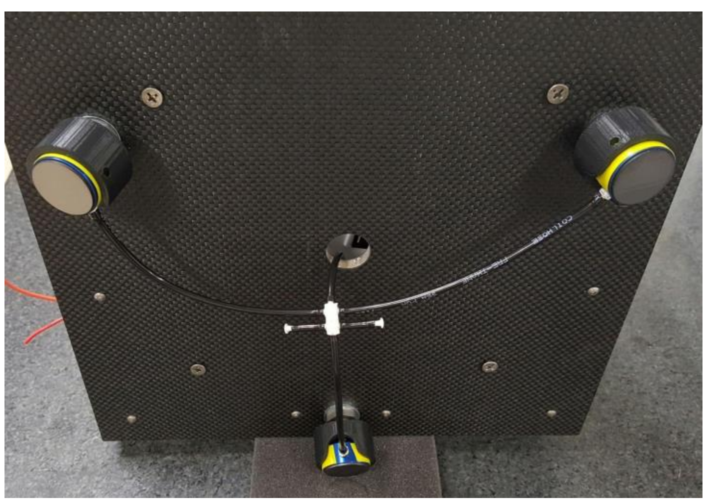
(air bearing: top view)

(air bearing: side view)

(brass pipe fittings)

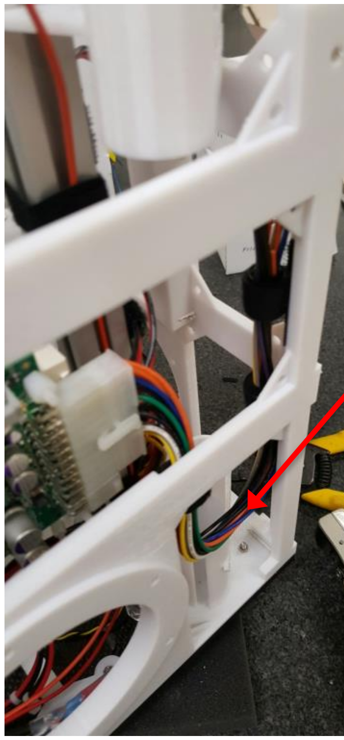
(air bearing with pipe fitting attached)

Step (105) Attach the assembled air bearing in Step (104) to the bolt bearings on the base. Apply one layer of electrical tape, if needed, on the side of the air bearings to keep it stationary within the Air Bearing Support Mount. Attach plastic tubing to each air bearing and connect it to the available fittings from Step (61).



(after assembly | note: used yellow electrical tape to keep the air bearings in place)

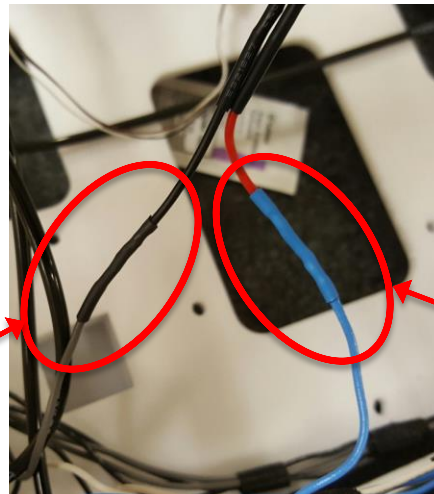
Step (106) Group the remaining wires from the ATX and Disk Power Cable and neatly stow them away.



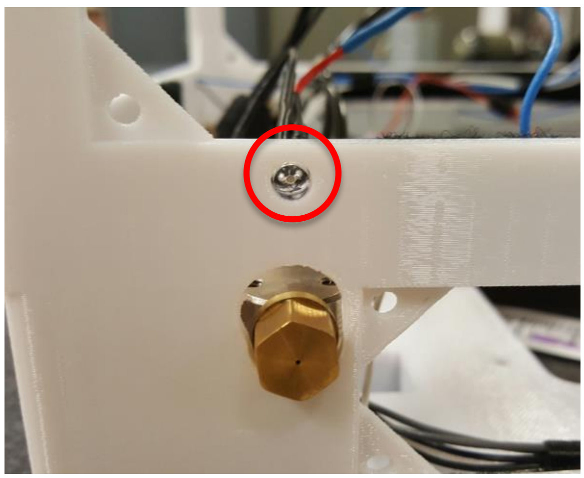
Wires grouped using velcro straps

Step (107) Retrieve 8 LED lights. Attach the red wires from the LED to the blue wires from Step (73) by twisting the stripped ends together and applying heat shrink tubing. Do the same for the black wires on the LED and the grey wires from Step (75). Once complete, insert the LEDs to its respective pre-drilled slots underneath the thrusters.

(LED lights)



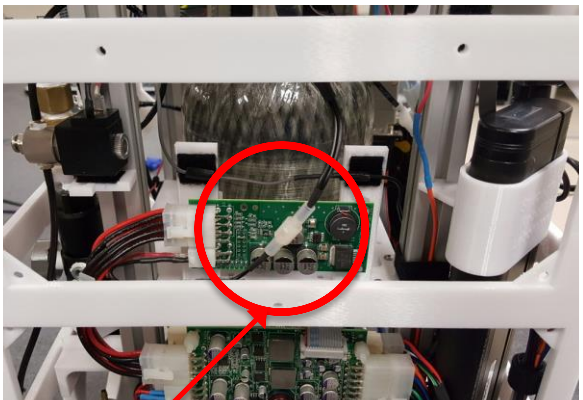
(complete 8 sets of these, one for each thruster)


(LED light inserted)

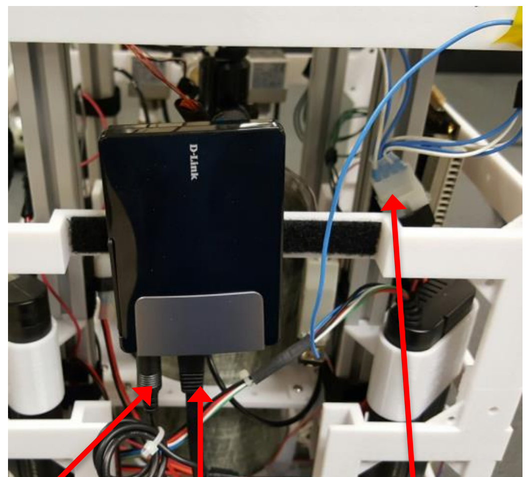
Step (108) Re-connect the two batteries to the Mini Battery Management Module.

FINAL STEP Attach Level 4 and ensure the following 8 connections are made.

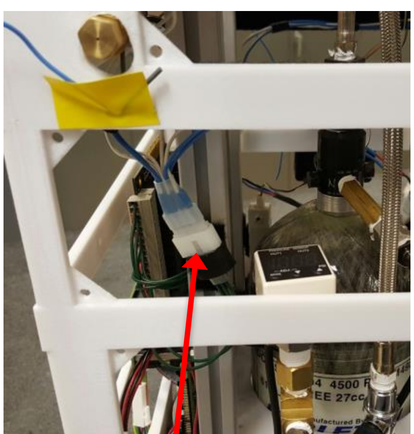
1) Ground connection for all solenoid valves.
2) Power connection for wireless router
3) Ethernet connection for wireless router
4) Power connection for solenoid valves for group 1
5) Power connection for solenoid valves for group 2
6) Power and Ground connection for gyro
7) Air connection from transducer assembly to air tank
8) VGA connection for gyro



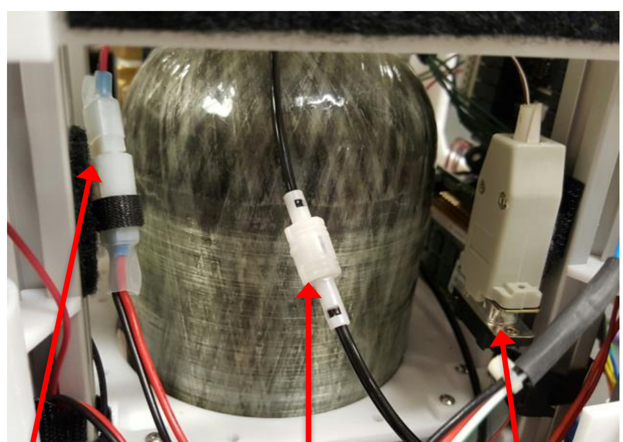
Connection 1



Connection 2 Connection 3 Connection 4



Connection 5



Connection 6 Connection 7 Connection 8

Calibration

1) Turn the robot on and ensure the pressure sensors light up and indicate zero pressure.
2) Slowly open the air inlet valve while monitoring the pressure reading.
3) Ideal pressure is between 60 and 90 psi.
4) Use a hex key to adjust each pressure regulator as necessary.

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