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Vertical Flight Society (VFS) 8th Annual Student Design Competition

Senior Honors Project

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Abstract

Every year the Vertical Flight Society (VFS), a professional society for vertical takeoff or vertical lift vehicles, sponsors a student design competition in order to foster innovation and interest in vertical flight technology. The University of Portland sponsored a five-person mechanical engineering team to compete in the 8th annual Micro Air Vehicle (MAV) Student Challenge. The team created an MAV that was capable of transporting a bag of sand from one set area to another. This required the development of a vehicle body, component selection, and testing. While the competition was ultimately cancelled, the team was successful in the creation of a vehicle.

Applications of VTOL UAVs and MAVs

The use of Vertical Take-off and Landing (VTOL) are widespread and interest is continually growing. A vertical takeoff aircraft is much more flexible than other forms of aircraft, as theoretically it can take off and land almost anywhere. Applications include military use, projected personal transportation, package delivery, emergency rescue and land survey. Interest in the development of a personal VTOL vehicle, or a “flying car”, has been peaking in the last few years, with Uber announcing their intent to develop a fleet of VTOL vehicles in Dallas, Los Angeles and Melbourne starting in 2023 (Uber Elevate 2020). Human transport, however, is only a small part of the many applications of VTOL vehicles, particularly when considering Unmanned Aerial Vehicles (UAVs).

A UAV is a vehicle without a pilot abord. Levels of autonomy can range from being under complete control of a human operator or be fully autonomous using onboard computers and preset objectives. To be clear, a UAV need not also be vertical takeoff. There are many examples of fixed wing UAVs, often used for survey and monitoring purposes. Depending on the sensors on board, high resolution maps can be created of ground surfaces, allowing for targeted identification of potentially archeologically significant sites (Zorich 2019). UAVs can also be used for agriculture in order to monitor crop growth, pinpoint irrigation problems, and target pesticide application (Meola 2020).

A micro air vehicle (MAV) is a small air vehicle. The definition ranges from country to country. In Canada, a vehicle must be less than 2 kg to qualify, while the US defines it as being less than 25 kg (Federal Aviatio nAdministration 2015). The applications and designs of these vehicles range wildly, from photography, advanced defense, and disaster relief. Current MAVs in production have been used to inspect military targets and search for roadside bombs. MAVs fitted with radiation sensors were also used after the Fukushima Daiichi nuclear disaster to monitor the site (Army Technology n.d.). The MAV space is also one that is highly dynamic and often bioinspired. This inspiration can take a physical design shape, seen in flapping wing or claw like perching mechanisms, or it can take a more abstract shape. Flocking, schooling, or swarming behavior is of particular interest as it provides unique sensing, information processing and action opportunities.

Barriers to Adoption

Despite design innovations, there are two central issues yet to be solved for MAVs. The first is stability in challenging conditions, such as storms. Unlike larger aircrafts, which rely on their weight and wingspan to maintain stability in rapidly changing conditions. Particularly when considering emergency search and rescue applications, where weather conditions may preclude a manned vehicle, stability in the face of buffeting winds, low temperatures and rain is critical to performance. To a less life-threatening degree, the same is applicable for package delivery.

Regardless of weather conditions, delivery deadlines must be hit, and maintaining stable flight is critical.

Another central challenge to MAV technology is flight time. Since the lift of the vehicle is limited by its rotor size, the maximum battery size is somewhat limited. In addition, the larger the battery carried, the shorter the flight time, as the motors draw more current to carry the vehicle. Active flight time is most usually measured in minutes, not hours. This puts a massive limit on the distance an MAV can travel and limits its usefulness. Innovations in the field are needed that radically improve vehicle efficiency. This could take the form of lightweighting, whereby components are reduced in weight, or by an increase in motor/rotor efficiency.

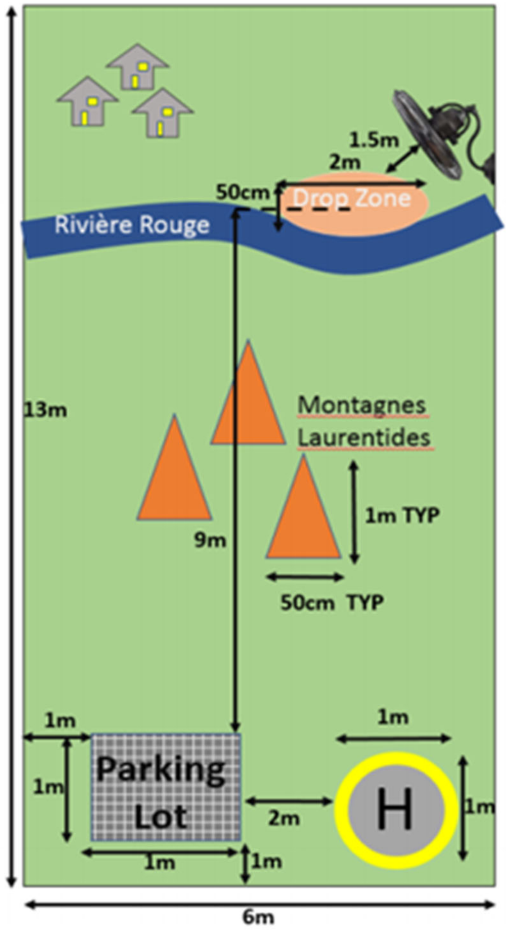

Figure 1: Provided Schematic of Competition Field

The Challenge

The VFS Student Design Challenge is constructed with the above technical challenges in mind. For the 2020 competition, the challenge was centered around a potential emergency flooding scenario, specifically a dam breath on the Riviere Rouge. In order to provide disaster relief to a mountain town, sandbags needed to be delivered to the banks of a river, before a storm arrived. This storm, initiated halfway through the competition, at the 5 minute mark, was to be modeled using an industrial fan. The proposed competition field can be seen in figure 1 (Vertical Flight Society).

Design Criteria

In order to create a working prototype ready for competition, a design criteria table was made using the rules published by the Vertical Flight Society ((Vertical Flight Society). Distinctions were made between qualitative and quantitative descriptions, and related subsystems were grouped.

Table 1: Design Criteria Table

Qualitative Description	Quantitative Description	Importance	Consequences
Physical Requirements			
Any number of rotors/propellers	>1	5	-
Size	<45 cm or 17.7" in any dimensions	1	DQ
Weight (including batteries)	<500 g (17.6 oz)	1	DQ
Robust (able to take a drop)			
Ability Requirements			
Vertical takeoff and landing, hover		1	
Flies Indoors	Flies <15 ft in the air	1	
Able to pick up package	up to 30 g, ~1 oz	1	
must take off and land safely on helipad	within 3 ft	2	
must hover for 10 seconds before and after pickup (static pickup	10 s hover	3	
climb over a 6 ft barrier	6 ft	4	
climb over a high net (4 ft) and below a barrier 2ft	> 2 ft flight	2	
Able to pick up package from braided loop, statically		1	
Must be able to not drop package		1	DQ
Able to be flown for at least 10 minutes	10 minutes	3	
Complete the distance	130 ft	2	
Carry packages	20-30 g	1	
Able to be flown out of the line of sight of the pilot		1	DQ
FPV Goggle Use		4	
Landing Gear			
Stable hover		1	DQ
Must be able to remain in competition zone, follow a straight line	<3 ft out	1	DQ
Electronic Requirements			

Onboard cameras	>1 camera is allowed	1	
No gasoline engines (electric only)		5	
Target recognition capability using on-board camera system		1	
Controls Requirements			
Onboard flight stabilization		2	TB
Onboard RC kill switch or remote operation button command to cut all power		1	DQ
Standard communication (2.4 gz)		4	
Stable roll/pitch performance		2	
Nice to Haves			
Modular		3	
Quick Connects to allow easy component replacement		2	
Clean Wire Management		4	
Ruggedness		4	
Field Readiness		5	
Potential for sensors		3	
Good sensor integration and craftsmanship		4	

Control Components

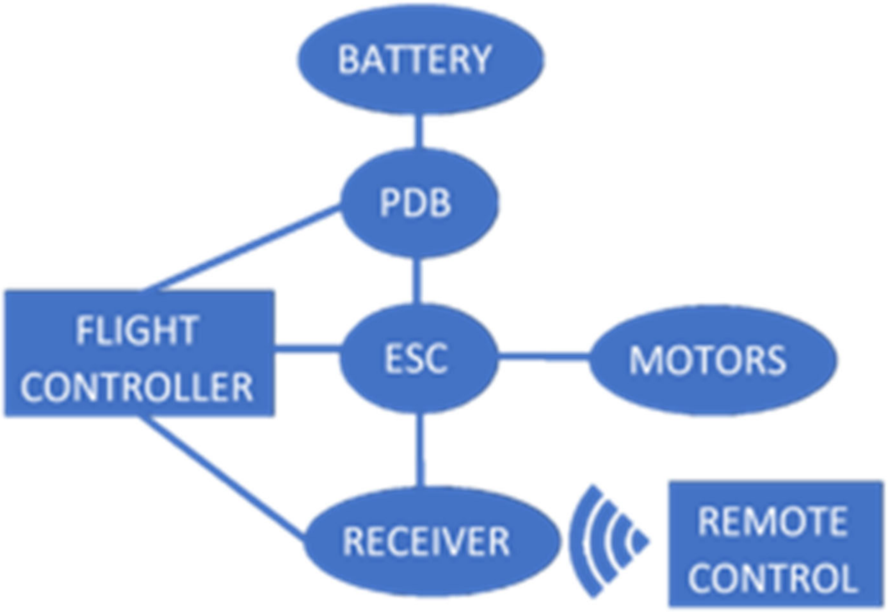

Fig. 2: Overview of Component Communication

Figure 2 above describes the relationships between key electrical and controls components that power and communicate with the vehicle. At the top is the battery, connected to the PDB, or power distribution board. The battery used was a LiPo, a lithium-ion polymer battery that is popular due to its relative lightweight. The voltage of these batteries ranges from 3.3 V to 22.2 V, depending on how many cells are included as part of the battery. The higher the voltage, the more power they can put out. For this competition, the battery was limited to a three cell, or 3S battery with a voltage of 11.1 V.

Connected to the battery is the power distribution board (PDB). The PDB acts as a regulator and can output different voltages to different parts of the circuit. It communicates with the ESCs (electronic speed controllers) and the flight controller. It powers the flight controller using a 5 V out, as the flight controller would be damaged by a higher voltage. The connection to the ESC is regulated by the flight controller, which sends a control signal to regulate the voltage sent to the ESC. A control signal is very small compared to the current used to power devices and uses changes in frequency to communicate a condition. The team selected the PDB used as it came as a part of the flight controller package and was known to effectively communicate with the flight controller.

The flight controller is the most significant part of the vehicle and can be thought of as the “brains” of the vehicle. It processes inputs from onboard sensors in order to stabilize flight by modulating motor outputs. It also takes remote controller (RC) inputs and processes them into motor outputs, maneuvering the craft. The selection of this component was highly linked to the software used. Different flight control software have different intended uses, ranging from autonomous vehicle research to drone racing. With these intended uses come limitations. More research oriented softwares, such as PX4 and ArduPilot have more flexibility in terms of integrating sensors and actuation components, but do not have integrated first-person view (FPV) capabilities. Other software oriented towards racing have this FPV capability but are less flexible when integrating components. The software was chosen first, as it would limit the type of flight controller available for use. A decision matrix was made, shown below, in order to determine the most optimal flight control software.

Table 2: Selection Matrix for Software

	Weight (1-10)	PX4	Comments	ArduPilot	Comments	BetaFlight	Comments
Altitude Hold	10	10	Explicit Flight Mode for this that does not use GPS	9	Explicit Altitude hold mode	4	Self-leveling modes available, Sonar integration is not available in a flight mode
Ability to fly well without GPS	10	5	Hefty drift reported	1	GPS is a central part	10	No attempt to "map"
SONAR integration	7	10	Able to easily integrate a number of different rangefinders	5	analog sonar capability	4	No functional altitude hold mode
Video Integration	4	6	Switching possible	1	requires separate relay/processor	10	able to route through the flight controller
Support / Troubleshooting	5	4	Least out of all of them	10	Ivler	7	Good Forums
Flexibility of Flight Modes	6	6	Multiple kinds of stabilization modes	6	Multiple kinds of stabilization modes, GPS based	7	Fewer options than others, modules not modes.
Precision of Tuning Control	6	8	Precise options available	9	Exact PID and roll rate establishment	8	PID available
Open Source	1	10		10		10	

Optical Flow Integration	4	10		10		4	Able to use serial ports, but no clear input
Ease of Use	4	1		5		5	
		402		349		379	

As shown above, PX4 was the most applicable software, finding a balance of ease of use with integration flexibility and a critical capability of non-GPS reliance. This decision significantly limited the flight controllers available to three models, shown below.

Table 3: Selection Matrix for Flight Controller

	Weight	PixHawk Racer		PixHawk Mini 4		PixHawk 4	
Fast Processing	10	10	4 khz, 32 bit interface	10		10	
SONAR integration	8	3		10	2 I2C ports	10	Explicit and Present
Current Sensor	2	10	present	5		0	
Black Box	2	10	micro SD	10		0	
Integrated OSD	1	0		0		0	
Integrated Camera Switching	1	0		0		0	
Serial Ports	10	2	Not good outs	8		10	Lots and varied
Weight	6	10	10.4	9	7 g	3	15.8 g
Safety Switch	8	5	optional	0		0	
Wifi	2	10	Flash with Wifi	0		0	
Radio Telemetry	10	10	works with FrSKY	10		10	works with FrSKY
		404		444		398	

Ultimately, the PixHawk Mini 4 was selected for its relative lightweight and having enough ports to integrate possible LIDAR or SONAR units in addition to hook controls.

An electronic speed controller (ESC) is a circuit that controls and regulates the power sent to the ESC. It has a high impact on the maneuverability and flight performance of the vehicle. It is also one of the most robust electrical components on the vehicle, as it distributes a large (amps, versus milliamps) amount of current. In order to minimize weight, a four-in-one ESC was chosen. ESCs can also be purchased per motor, allowing for flexibility in the number of motors. There are three electric lines that come from the ESC, a voltage in, a pulse width modulation (PWM) and a ground. The PWM is the signal line, communicating with the motor. ESC choice was largely driven by weight and by the current drawn by each motor. A detailed description of the communication between components can be seen below.

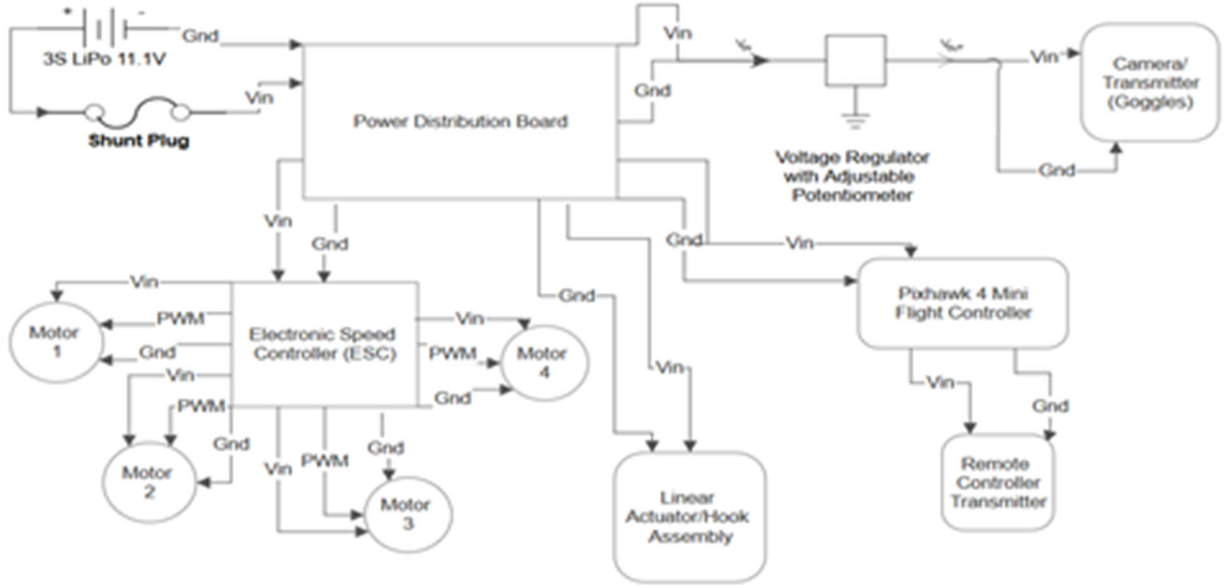

Figure 2: Final Electrical Diagram

Motor and Rotor Selection

The motor choice was a delicate balance of thrust, weight, and power draw. The larger the motors, the more thrust they could provide, increasing flight speed, carrying capacity and maneuverability. The increase in thrust, however, also increased the power drawn and the batter weight, decreasing flight time. Online data from MiniQuad Test Bench (Harrell) were used to compare to compare the power draw, thrust, and weight of commercially available motors, providing a standardized test setup that company provided specification sheets do not. After crawling through data sheets and aiming for a thrust to weight ratio of 1:4, or approximately 4000 g of thrust. The Lumenier RX 2206-11 2350 Kv motor was chosen, due to its relatively high efficiency. The thrust to weight ratio is critical to the flight performance of the quadcopter. If the maximum thrust of the vehicle is only itself, it would not be able to "push" itself around and would be simply buoyant like a hot air balloon. The higher the thrust to weight ratio, the more acrobatic maneuvers are possible.

Rotors are a similarly key part of the performance of the vehicle and have a high impact on the performance of the motors. Data from MiniQuad Test Bench was again used to predict rotor performance. If a rotor is too heavy or large for a motor, then the efficiency is significantly reduced. If a rotor is too small, or light, then the thrust produced by the motor is significantly reduced. Rotors were selected using the following data. Aiming for a minimum power useage while still hitting 900-1000 g of thrust per motor.

Table 4: MiniQuad Test Bench Data for Lumenier RX2206 2350kv (Harrell)

Rotors	Thrust (g)	Power Used (W)	Thrust (g)/Watt
HQProp 4x4	636	207	3.07
HQProp 4x4.5	726	257	2.82
HQProp 4x4x3	736	243	3.02
Diatone Ghost 5x3	842	220	3.82
HQProp 5x4GF	903	262	3.44
GemFan 5x4.5	985	288	3.42
HQProp 5x4x3	1046	317	3.30
GemFan 5x4.6	1055	350	3.01
King Kong 6x4	1261	369	*3.41*

The thrust values found online were then compared to theoretical values calculated by simple momentum theory (Anderson, John David), shown below in equations 1 and 2, where ***hp_{actual}*** is the wattage consumed per motor, disk area, ***A***, was defined as 19.63 in2, pounds of thrust required per motor, ***T***, was defined as ¾ lbs/motor, and a *Figure of Merit**, FM,*** of 0.6 was assumed to have a more conservative estimation. The disc loading, shown in Equation 2, was calculated using a rotor diameter, ***d***, of 5".

$$hp_{actual} = \frac{T\sqrt{DL}}{38(FM)} \qquad \text{Eq. 1} \qquad DL = \frac{F}{A} = \frac{T}{\pi\left(\frac{d}{2}\right)^2} \qquad \text{Eq. 2}$$

The team found a final calculated power of 57.53 Watts/motor, which totals to about 230 Watts. The initial flight time estimate with a total vehicle weight of 3 lbs was found to be 7 minutes.

Physical Design

A quadcopter design was chosen as it balances stability with a minimal power draw. An increase in motors increases flight stability and total lift capability but comes with additional weight and power draw requirements. In order to maintain quadcopter performance in the case of a catastrophic crash, the team wanted to develop a modular design that could have pre-prepared spares of wing assemblies on hand. This could take two forms, a fully modular design where each arm had a single motor attached, and a semi-modular design that attached a side to the baseplate, composed of two motors. The performance of the two designs were compared using ANSYS, a finite element analysis software. The software breaks down a solid model into extremely small finite units, or elements, and shows how they interact and stretch when a force is placed at a location on the model. The results can be seen below. What the team was looking for in these models was the total deflection. This reflects the stiffness of the design. If a quadcopter arm is not stiff then any “push” by the motor would result in the arm vibrating instead of translating or rotating the entire craft.

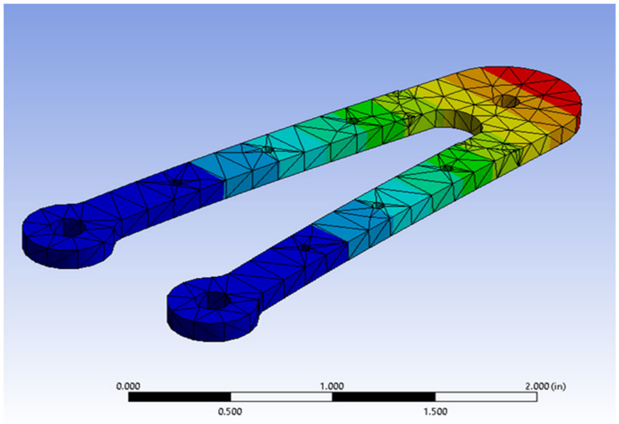

Figure 3: ANSYS of Modular Arm

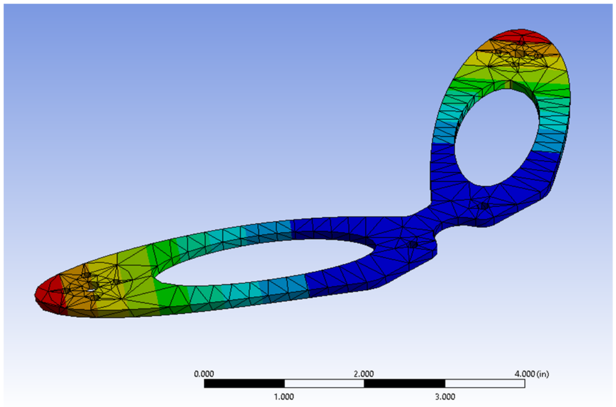

Figure 4: ANSYS of Semi-Modular Arm

The two designs were modeled to be as similar as possible, with the same plate thickness and material used for both designs. The force was also standardized. According to the model, the maximum deflection was of the fully modular arm was found to be 0.0135", while the deflection of the semi-modular arm was 0.0075”. To verify the model’s findings, the team printed out the designs in plastic using 3-D printing. A test was completed using a spring-based force gauge to

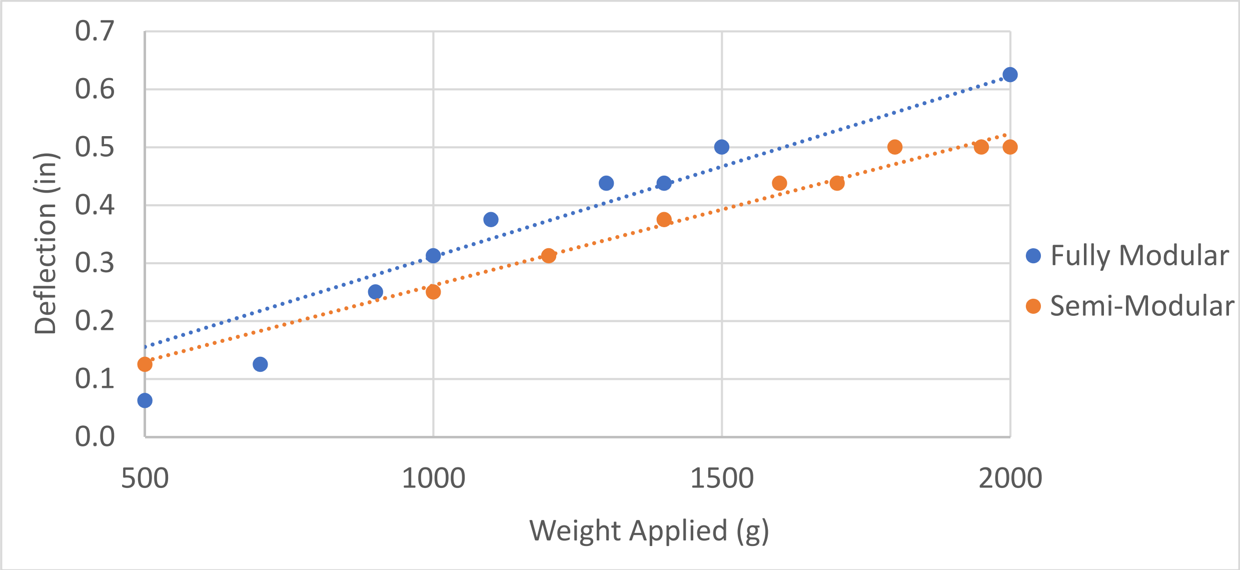

Figure 5: Comparative Deflection of Wing Designs

compare the deflection of the two designs when loaded from 500 to 2000 grams, after which both designs catastrophically failed. The deflection of the arm was measured using a ruler, leading to high uncertainty of 0.02”. With this uncertainty in mind, the two designs were only differentiated by the differences in weight. Since the semi-modular design used fewer fasteners than the fully modular design, it reduced the weight of the vehicle by 44 g, as described in the table below.

Table 5: Comparative Weights of Modular and Butterfly Designs

	Weight of PLA Printed Arm Per Side (g)	**Total Weight of Fasteners Needed (g)**	**Total Weight as Tested (g) (x4 motors)**
Fully Modular	7	12	76
Semi-Modular	10	6	32

Once the semi-modular design was selected, additional simulation was conducted using ANSYS in order to determine whether the magnitude of stress would be within the allowable range for carbon fiber. Carbon fiber is difficult to model using conventional software approaches, as it is anisotropic. This means that the strength and “stretchiness” of the material varies with the orientation. Metals, such as aluminum are isotropic, meaning their material characteristics are the same in every dimension. A factor of safety (FOS) of 2 was included in this analysis to account for the inaccuracies in the model. The team found that if the carbon fiber sheets were 1/8” in thickness the wing would stiff and strong enough to repeatedly carry flight loads with minimal deflection. The calculated deflection of the wing using a load of 876 g, or the maximum thrust of the selected motor, was 0.0084”. The maximum stress was found to be 969.8 psi, well below the ultimate tensile stress of carbon fiber, 500,000 psi. The stress analysis is also useful in that it predicts where failure might occur. For this competition, the likely breaking points, seen in orange, were ideal sacrificial spots, as they were unlikely to harm the motors if broken and would allow for easy removal of the fasteners used.

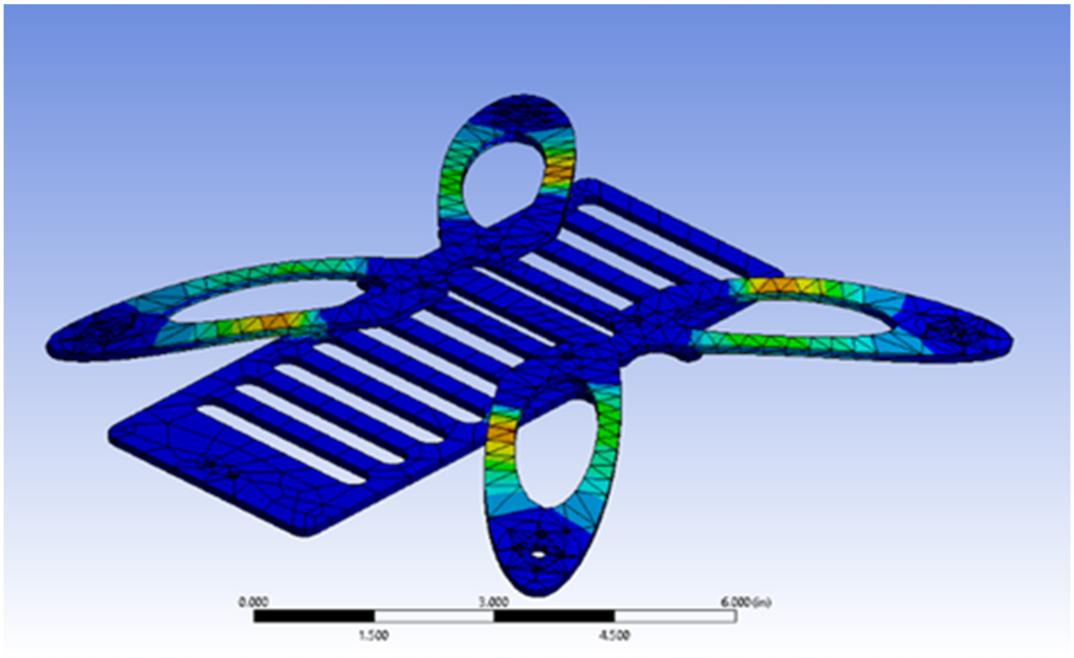

Figure 6: Stress Analysis of Final Design

Test Results

Before the competition, testing was undertaken to ascertain the true lift capability and flight time of the vehicle. The flight time ranged from 3 – 5 minutes, depending on how aggressively the vehicle was flown and how long it held the sandbag to be delivered. The target weight of sand to be delivered was 1.5 lbs, but the vehicle was unsuccessful in lifting this weight. A reduced weight of 1 lb was effectively used. The final weight of the vehicle unloaded was also significantly higher than anticipated, 1.5 lbs versus 1 lb. This could account for the decrease in estimated flight time. The power draw of additional components, such as the camera circuit and pickup mechanism are prime suspects for the decreased flight time, as is the replacement of the originally selected rotors with ones that provided additional thrust. Despite these setbacks, the team was largely successful in its goals of creating a working entry to the VFS competition.

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