University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Conceptual Design Document (CDD)

VORTEX: Vertically Optimized Research, Testing, & EXploration

September 28th, 2020

1 Information

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Nomenclature

TWR Thrust to weight ratio

COTS Commercial off-the-shelf products

RAP-Cat Rapid Acceleration Pneumatic Catapult

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2 Project Description

2.1 Project Overview

The Integrated Remote and In-Situ Sensing (IRISS) group at the University of Colorado Boulder currently utilize a fleet of unmanned aircraft to collect atmospheric data in order to improve the conceptual model of supercell thunderstorms. These unmanned aerial vehicles (UAVs) are launched into flight from a catapult system mounted to the top of an automobile or from a bungee rail system. The IRISS group has expressed desire for an alternative to this fleet of UAVs: a vertical takeoff and landing (VTOL) drone. The launch sites of the UAVs currently utilized are restricted to wide open spaces to allow for belly landings in open fields. A VTOL capability would allow IRISS to launch in a wide variety of locations, including heavily wooded areas and coastal regions. IRISS desires the vertical takeoffs and landings to be completely autonomous– not requiring any input from the pilot. Further, the IRISS team desires a UAV capable of one hour of cruise time, including an additional takeoff and landing during the mission. The replication cost for one VTOL UAV must be under $1000, excluding the avionics package. The successful completion of this project will further the IRISS group's effort in reducing false alarm tornado warnings and improving detection of potentially lethal storms.

2.2 Objectives

1. **Flight** - The aircraft shall be capable of vertical takeoffs and landings. In between takeoff and landing the aircraft shall be able to maintain a steady hover, transition from vertical flight mode to horizontal flight mode, and transition back to vertical flight mode from horizontal flight. As a customer requirement, stability in 5-7 m/s is expected but does not need to be validated as part of this project.

   Verification: Before the aircraft is assembled, the motors and propellers shall be tested on a static test stand to prove that a thrust to weight ratio (TWR) greater than 1 can be generated. Then the transition mechanisms and software will be tested while the aircraft is fixed to the ground to demonstrate functionality. Next a tethered flight will be conducted to show that steady hover can be achieved. The aircraft will then be tested with the RAP-Cat launch system to demonstrate compatibility. Finally, full flight regime will be tested demonstrating full transition of flight modes starting from both vertical takeoff and launch from the RAP-Cat.

2. **Budget** - The final aircraft design shall have a production cost below $1000 per unit, per customer request. This is to increase the ease of manufacturing and production of multiple aircraft. This budget does not include the standard avionics kit provided by the customer but does include the Drak wing kit.

   Verification: During the design process, material costs will be tracked and monitored to ensure that a production model does not exceed the desired amount. After design and testing is complete, a materials cost sheet will be created for the final production aircraft, and the resulting cost shall be below $1000.

3. **Endurance** - The aircraft shall have an endurance total of 1 hour at cruise conditions along with two vertical takeoffs and landings. This will be broken up into two flights involving a takeoff, a 30 minute cruise, and a landing.

Verification: The propulsion system shall be tested at the required thrust output equivalent for 1 hour cruise and 2 takeoffs and landings. The test will be conducted for approximately 1 hour and 15 minutes on a stand in simulated flight conditions. Once the test is concluded the battery will be measured demonstrating it has a remaining capacity equal or greater than 15%

4. **Airframe** - The aircraft shall be constructed using the RiteWing Drak wing set. The final product shall require fewer than 20 hours of work time to be assembled. The airframe shall also be able to withstand RAP-Cat takeoff forces of up to 5G of acceleration as well as potential incidental forces up to 10G.

   Verification: A Drak kit shall be used as the basis of any design. By modeling potential materials to withstand the expected forces, materials with insufficient properties will be ruled out. After a material is selected, prototypes will be created of the physical components and tested under the expected loads, demonstrating the ability for airframe to withstand necessary forces. An assembly guide will be created to document the process of making a unit

5. **Avionics & Sensors** - The aircraft shall have all motors and actuators integrated with the flight controller and shall have all non-native sensors integrated with the avionics system.

   Verification: The successful integration of the sensors will be confirmed by showing that flight controller receives data from sensors, as well as demonstrating the ability to actuate all control surfaces and control individual motor thrusts.

6. **Autonomy** - The customer has requested the vehicle be capable of performing a fully autonomous takeoff and landing procedure, being able to navigate to waypoints using an autopilot system, as well as have the capability for a pilot to manually resume control at any time.

   Verification: Through a series of individual tests, the system shall display the capability to control all relevant systems while mounted to a test stand. The full mission profile can be demonstrated while mounted, including flight mode transitions.

7. **Safety** - The aircraft shall be capable of executing a "return to loiter" function where it returns to the last known good location and flies in circles if a loss of telemetry occurs for over 90 seconds. The aircraft shall also be capable of terminating flight immediately if requested by the operator.

   Verification: The aircraft autopilot shall demonstrate proper functionality by abandoning the mission profile and attempting to return to the ground station upon a manual telemetry loss, while mounted to a static test stand.

Table 1 shows the specific levels of success for each project objective. Level 1 describes the verifications that can be performed on individual subsystems through modeling or static testing. Level 2 is a step up in execution-level for validation, including tests such as a tethered 2m hover. Level 3 indicates the highest level of success and is validated primarily through deonstrated flight or full-scale testing (catapult launch). Level 3 also signifies that all the customer's requirements have been fully met. The following section lays out the criteria for the verification of each objective.

Table 1: Objectives Table for Levels of Success

	Level 1	Level 2	Level 3
Flight	Show on a static test stand that the propulsion system is capable of producing enough thrust to provide a TWR greater than 1	Maintain tethered hover at 2 m of altitude for 30 seconds as well as demonstrate capability to transition to horizontal flight while aircraft is mounted to a test stand	Aircraft shall demonstrate takeoff ability via RAPCat launch system as well as demonstrate full transition from vertical to horizontal flight modes.
Budget	The aircraft shall cost no more than \$1250, not including IRISS avionics package.	The aircraft shall cost no more than \$1000, not including IRISS avionics package.	The aircraft shall cost no more than \$900, not including IRISS avionics package.
Endurance	The propulsion system shall maintain required thrust output for the equivalent of 1 hour cruise and 2 takeoffs and landings (approximately 1 hr 16 minutes) on a static test stand in simulated freestream conditions of 18 m/s with >15% battery remaining	-	Demonstrate 1 hour of flight cruise as well as 2 takeoffs and landings
Airframe	A finite element analysis of the modified airframe will be performed to demonstrate that it can withstand the required forces with a FOS of 1.7	The aircraft will have full integration capabilities with RAPCat launch system, and show that it can withstand the forces due to acceleration.	The airframe shall withstand axial and lateral forces up to 10G.
Avionics & Electronics	All motors and actuators shall be successfully integrated with the flight controller. The telemetry link shall be maintained with less than 25% packet loss within 1 km of the ground station.	All external (non-native) sensors are successfully integrated with the avionics system. -	-

Autonomy	Both the VTOL and fixed-wing modes have valid dynamic models to ensure active stabilization is possible. Ensure that the chosen avionics package interfaces successfully with propulsion system, sensors, and connectivity with ground station.	The aircraft can autonomously execute a takeoff and landing.	The aircraft shall autonomously execute a full mission profile, transitioning between flight modes, and land within a 1.5 meter radius of a target location.
Safety	The aircraft shall have an autonomous return to loiter function if telemetry is lost for an extended period (90 seconds) as well as capability to terminate the flight immediately upon command from the GSE		-

2.3 Concept of Operations

The primary focus of this project is the successful implementation of a VTOL system on the Drak wing set. As this vehicle will share the same Drak base of the RAAVEN platform, it will maintain its current capabilities with the RAPCat launch system with no additional transportation or launch infrastructure required to accommodate the VTOL version. Once the system is transported to its operational location, it will be configured for flight by connecting the on-board computer to a ground station (e.g. a laptop computer) and uploading the desired mission profile. After the computer is configured, the vehicle is set up for deployment with any necessary launch hardware before executing a vertical takeoff or RAPCat launch. Once airborne, the vehicle will transition to a horizontal flight mode and engage in standard mission operations. Once mission operations are complete, the vehicle will perform a vertical landing at a specified target location, within 1.5 meters of the target. A successful mission profile will consist of two cruises of 30 minutes each with a vertical takeoff/landing in between at a specified location for a total of 1 hour endurance with 2 takeoff and landing procedures without replacing any batteries or receiving any further human input.

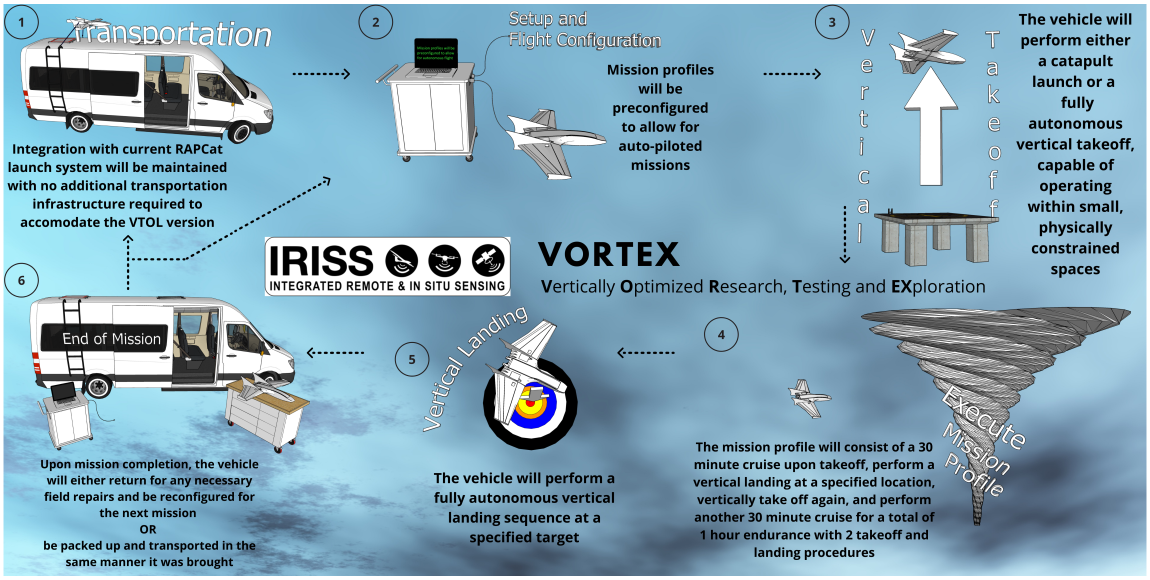

Figure 1: Concept of Operations

2.4 Functional Block Diagram

The functional block diagram shows the subsystems and connections between the subsystems that are needed to fulfill the objectives of the VORTEX project. The arrows between boxes represent the connections or communications between subsystems and their components. All of the functional requirements' needs are satisfied by one of the subsystems in the FBD, such as the battery supplying power or the Mechanisms section for the propulsion requirement. Many of the necessary avionics needed for this project are provided by the IRISS team. This consists of a printed circuit board designed to do the necessary power conditioning and signal support for the Pixhawk Cube, S.bus reciever, GPS unit, a Pitot-tube connection and probe, a ground station transmitter for flight data, and peripheral boards for additional hardware connections. The Pixhawk cube provided will fit the need of this project as it has two 32bit microprocessors, 3 total inertial measurement units(IMUs), 14 total servo outputs, and allows for various additions through UART, I2C, or CAN communication protocols. The various hardware listed above are part of the avionics package block of the FBD seen below.

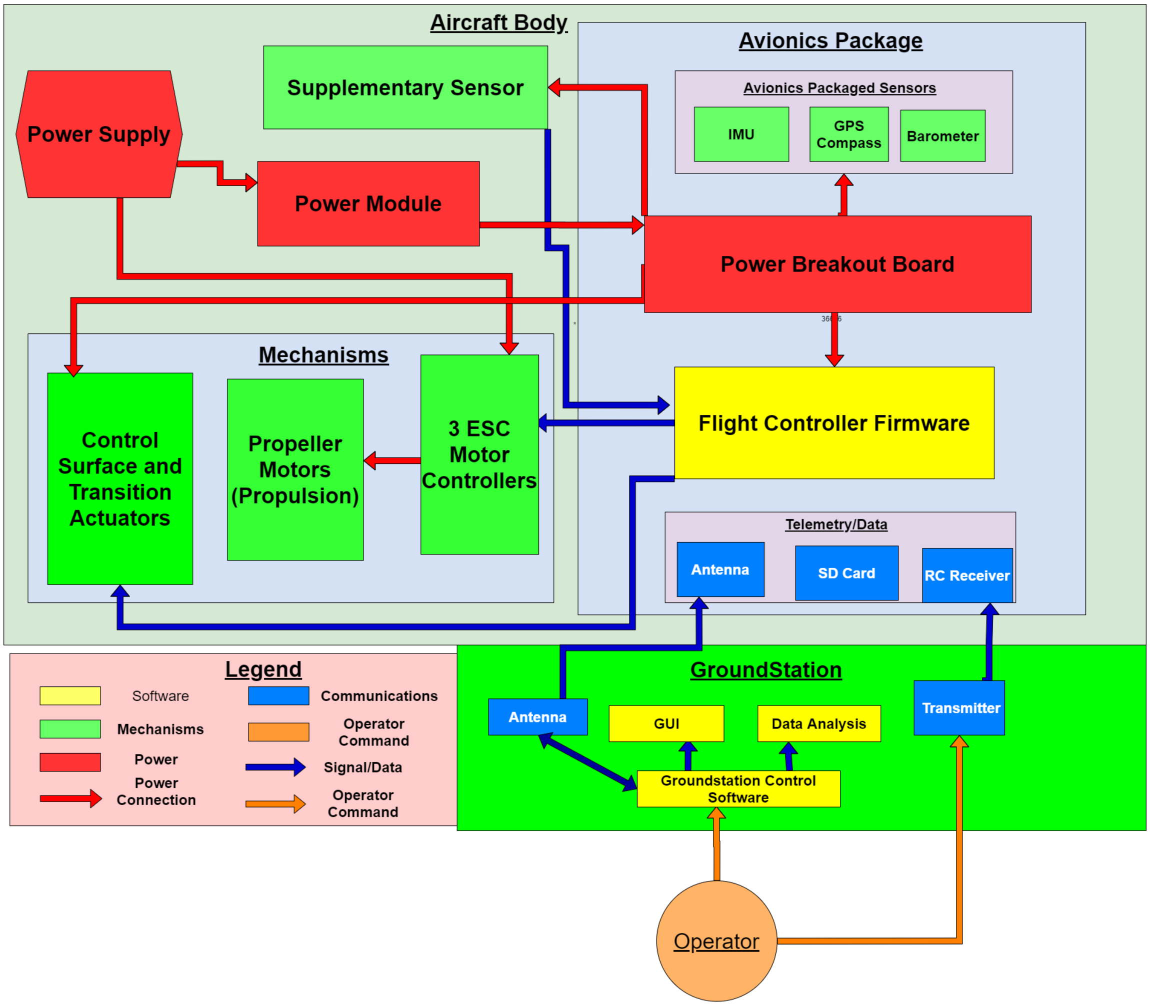

Figure 2: Functional Block Diagram

2.5 Functional Requirements

In order for this project to succeed, a series of requirements have been set and ranked by importance. The following section describes in detail each design requirement that must be met in order for the respective functional requirement to be considered successful. All of the requirements chosen for this design were interpreted from customer requests, which allowed the team to better define the design space.

FR1: The aircraft shall be a VTOL conversion of the COTS Ritewing RC "Drak" airplane kit

FR2: The aircraft shall have an endurance of one hour in addition to two takeoffs and landings

FR3: The aircraft shall be able to autonomously execute all aspects of its mission from takeoff through landing.

FR4: The aircraft shall maintain communication with the ground station up to a distance of 2km. (In this context, maintaining communication is indicated by <50% packet loss)

FR5: The aircraft shall be capable of carrying a 0.5 kg payload.

FR6: Aircraft shall be capable of taking off from existing RAPCat launch system.

3 Design Requirements

Each previously stated functional requirement can be broken down into design requirements. Completion of individual design requirements represents smaller achievements in the process of satisfying the overarching functional requirement. In order to ensure each design requirement is satisfied, it must be verifiable. In the tables below, a design requirement can be tested by *demonstration* (e.g. through a flight test) or by *inspection* (e.g. a visual inspection). *Analysis* shows an alternative method to testing that relies on functioning models.

Table 2: **Functional Requirement 1 Flow-Down**

FR1: The aircraft shall be a VTOL conversion of the COTS Ritewing RC "Drak" airplane kit		
	Requirements	**Verification and Validation**
DR1.1	The aircraft shall be able to sustain hover using its own thrust system	***Demonstration:*** Aircraft will execute a steady level hover within a 1m radius. ***Analysis:*** Stability of hover will be proven during these hover tests along with dynamic models, while thrust from motors will be validated on a static test stand.
DR1.2	The aircraft configuration is capable of VTOL to horizontal flight transition	***Demonstration:*** The flight controller will rotate thrust vector from horizontal to vertical and vice versa on a static test stand and/or during flight.
DR1.3	All components shall mount to a modified Drak airplane kit	***Inspection:*** All necessary VTOL hardware and control surfaces will be integrated into the Drak kit.
DR1.4	Modified kit shall require fewer than 20 person-hours to assemble a full unit - customer has expressed interest in producing multiple units if the design is successful and meets all other requirements.	***Demonstration:*** Describe an assembly process and guide that can reasonably be followed in approximately 20 hours if all required components are available.

Table 3: **Functional Requirement 2 Flow-Down**

FR2: The aircraft shall have an endurance of one hour in addition to two takeoffs and landings.		
	Requirements	**Verification and Validation**
DR2.1	The aircraft shall possess an internal power system capable of powering all electronics necessary for a single flight.	***Inspection:*** Each hardware component of the power system is enclosed inside the aircraft. ***Demonstration:*** Actuators and motors shall be tested to verify they are receiving power.
DR2.2	The propulsion system shall support sustained horizontal flight for a minimum of one hour at standard operating loads	***Demonstration:*** During flight or a static test imitating flight conditions, the propulsion system will function for an hour.
DR2.3	The propulsion system shall be capable of 2 takeoffs and 2 landings without replacement of battery	***Demonstration:*** During a static test the propulsion can generate the required thrust for 2 takeoffs and 2 landings on a single battery
DR2.4	The propulsion system shall generate sufficient and sustained thrust to overcome the expected drag forces on the aircraft in vertical and horizontal flight	***Demonstration:*** During a static test, the propulsion system will generate thrust exceeding the predicted force models in separate vertical and horizontal configuration.
DR2.5	Power system shall have >10% capacity remaining on completion of mission	***Inspection:*** After the mission or full duration static test, the remaining power will be measured to be greater than 10% of full battery capacity.
DR2.6	Aircraft can complete entire mission on one set of batteries without charging or replacing	***Demonstration:*** The aircraft is able to complete a full mission or static test equivalent without power alteration or replacement.
DR2.7	Aircraft cruise speed shall be at least $16\frac{m}{s}$	***Inspection:*** The flight speed during cruise will be reported to be greater than or equal to $16\frac{m}{s}$ from the ground station equipment. ***Analysis:*** Model shows that horizontal flight stall speed is $<16\frac{m}{s}$.

Table 4: **Functional Requirement 3 Flow-Down**

FR3: Aircraft shall be able to autonomously execute all aspects of its mission from takeoff through landing.		
	Requirements	**Verification and Validation**
DR3.1	The aircraft shall autonomously takeoff once operator starts flight.	***Demonstration:*** When prompted, the flight controller will execute the vertical takeoff without further input from the pilot.
DR3.2	On-board flight controller shall control propulsion system and flight surfaces.	***Demonstration:*** The flight controller will make the necessary adjustments without pilot input when the aircraft is perturbed on a test stand and/or in flight.

DR3.3	The aircraft shall autonomously transition from vertical flight mode to level flight	***Demonstration:*** The aircraft shall demonstrate transition from vertical to horizontal flight mounted on a static stand without input from the pilot.
DR3.4	Vertical accuracy of <10cm is desired in takeoff and landing when below GPS altitude of 5m.	***Demonstration:*** Prove <10 cm resolution in data reported in electronics test moving the designated sensor away from a fixed point over 30s.
DR3.5	The aircraft shall be capable of completing the mission profile without pilot input after initial flight configuration.	***Demonstration:*** The flight plan established on the ground station will successfully transfer to the aircraft, and the aircraft will execute it without further input from the pilot.
DR3.6	The aircraft shall be able to recognize ground station location and distances with 2m accuracy relative to GSE.	***Demonstration:*** Affirm relative location of ground station electronics with avionics package from 50m distance.
DR3.7	The aircraft shall autonomously transition from level flight to vertical flight.	***Analysis:*** Effectively model transition in coding program that utilizes the dimensional derivatives and does not show failure in nominal conditions. ***Demonstration:*** Successfully takeoff vertically and transition to horizontal flight mode without pilot input.
DR3.8	The aircraft shall autonomously land at target location.	***Demonstration:*** The aircraft will land without input from the pilot within a 1.5m radius.

Table 5: **Functional Requirement 4 Flow-Down**

FR4: The aircraft shall maintain communication with the ground station up to a distance of 2km. mission		
	Requirements	**Verification and Validation**
DR4.1	GS shall be capable of receiving commands and recording telemetry from onboard sensors	***Demonstration:*** A ground test will be performed to prove that the GS receives telemetry data from the sensors.
DR4.2	GS shall be capable of sending user defined flight profiles to the aircraft	***Inspection:*** Flight profiles are successfully uploaded to the aircraft prior to takeoff
DR4.3	The aircraft shall have a maximum of 25% packet loss up to 1km	***Demonstration:*** A ground test of varying distances up to 1 km shows that the packet loss never exceeds 25%
DR4.4	RC transmitter and receivers must be built in for emergency manual pilot control	***Inspection:*** Aircraft has RC transmitters and receivers ***Demonstration:*** A pilot can assume control of the aircraft during flight, functionality can be proven on a static stand

DR4.5	Sensor data must be able to get sent to GSE both in real time and stored in SD card	***Demonstration:***After a ground test, GSE data matches the data stored on the onboard SD card.

Table 6: **Functional Requirement 5 Flow-Down**

FR5: The aircraft shall be capable of carrying a 0.5 kg payload.		
	Requirements	**Verification and Validation**
DR5.1	Aircraft is capable of lifting 0.5kg payload and a .13kg probe in vertical and horizontal flight modes.	***Demonstration:*** The aircraft will be able to lift 0.5kg mass during a steady hover test as well as during horizontal flight. ***Analysis:*** Using propulsion system data, prove the lift capability of the aircraft in both modes is sufficient to lift the combined airframe and payload weights.
DR5.2	Aircraft controllability accounts for presence of payload.	***Analysis:*** Using aerodynamic system data and modeling, show that the flight characteristics (controllability, modal behaviors) are still acceptable with and without the payload.

Table 7: **Functional Requirement 6 Flow-Down**

FR6: Aircraft shall be capable of taking off from existing RAPCat launch system.		
	Requirements	**Verification and Validation**
DR6.1	Interface successfully with launch rail/tow hook after addition of VTOL components	***Inspection:*** The 3D model of the VTOL aircraft shall show the potential for integration with the rail and tow hook.
DR6.2	Withstands 5G acceleration from RAP-Cat without plastic deformation of airframe	***Analysis:*** A model of the aircraft under the predicted forces of launch will show no plastic deformation.
DR6.3	Begin flight in level flight mode via RAPCat launch	***Demonstration:*** In a limited flight test, show that the aircraft is able to take-off from the existing launch infrastructure after VTOL modifications are made.
DR6.4	No modification of existing launch infrastructure	***Inspection:*** No modifications shall be made to the RAP-Cat launch system.

4 Key Design Options Considered

4.1 VTOL Configuration

For the general VTOL configuration, it was decided that looking at more broad ideas for systems would run the risk of not being fully representative in comparison if done head to head without further consideration for the specific implementation. Likewise, the motor configuration within each broad system was a wide enough topic for concern that to merit a close look of its own. In order to consider the configuration options as completely as possible, the configurations were divided into the larger configurations (tilt motor, tail sitter, hybrid, and tilt wing) and then broken out into individual motor configurations as applicable.

4.1.1 Tilt Rotor

The tilt rotor VTOL system is characterized by having one or more rotors physically rotate their orientation with respect to the airframe. The advantage of this system is that the traditional flight modes of horizontal and hovering flight can be separated into independent regimes. No considerations have to be made for changing the orientation of the airframe when transitioning from one flight mode to another, as in the tail sitter configuration, for example. Another benefit is with regards to dead weight. While not carrying as little dead weight as the tail sitter, the added mechanism for tilting the motors adds less weight than what is required for the tilt wing or the additional motors of the hybrid system. The downsides of this system are primarily the increased complexity and risk that is introduced by the actual tilting mechanism. Whatever tilting device is chosen, it will not only have to have to lock in place for the stresses of hovering and flight, but be able to quickly and safely transition to each mode every time, and have fine controllability for stability in hover. There is additional risk that if a motor fails mid transition, the entire mission could fail; potentially at the cost of the airframe itself. This is a general consideration for any UAS, but the modifications made during this project have some potential to increase this risk. This transition period will also require extra considerations for modeling and controls, because of the dynamic nature of flight in that regime.

Description	**Pro**	**Con**
Less dead weight in flight/hover compared to hybrid	x	
Airframe attitude is constant for all flight modes	x	
More dead weight in flight/hover compared to tail sitter/tilt wing		x
More moving parts compared to tail sitter		x
Hover transition phase will be difficult to model		x
Can't independently optimize motors/propellers for cruise and hover		x

Table 8: Pros & Cons of Tilt Rotor in General

1. Tri-Motor
   A Tri-Motor design allows for two of the propellers to act as the main form of thrust at the front of the aircraft during fixed wing mode, while the back propeller can be used as a pusher to help with flight, or stow away to reduce drag contribution. In VTOL mode, all three motors would point vertically and function as a tri-copter. Tri-Copters are a commonly used design, and many flight control firmwares have the capability to control this configuration. Control is achieved by changing the rotation speed[36] of the motors or rotating the motors in different directions. This allows for yaw, pitch, roll, and translational control. Tri-copters require only three motors making it the most mass and cost efficient option of the tilt rotors. The Drak wing kit already utilizes a rear motor mount, so only two additional motors would need to be mounted, decreasing the complexity of manufacturing.

Figure 3: A tri-motor aircraft system [37]

Description	Pro	Con
Fewer propellers and motors, less mass compared to quad and quint	x	
Can make use of existing motor mount system	x	
Can utilize asymmetric propeller configuration to create differential thrust and yaw control	x	
Need to balance asymmetric moment in both hover and cruise		x

Table 9: Pros & Cons of Tri-Motor Tilt Rotor

2. Quad Motor
   The quad motor tilt rotor configuration would be similar to a quad copter that is attached to wings and can rotate its motors for horizontal flight. This comes with a wealth of documentation and control options for hover control, considering the popularity of quad copter systems. The advantage of this over the tri motor is that the thrust requirement per motor in hover is lower. This means less stress on the motors, both in terms of instantaneous load and over the course of the motor's lifetime. Another advantage this has over both the tri and quint motor systems is that there is no asymmetric moment generated from having more propellers spinning one way or the other. Subsequently, there are no extra design considerations for maintaining orientation. The main downside is that there are more motors than the tri system - more servos, more mounting hardware, and more points of failure. Specifically, the existing Drak wing kit mounts a single motor at the rear, which is a part of the existing kit that this design would be unable to use or take advantage of.

Figure 4: Quad Motor VTOL hybrid model [38]

Description	Pro	Con
Well known flight dynamics	x	
Balanced motor torques	x	
Less stress on each individual motor in hover	x	
More complexity compared to tri-motor		x
4 motors for cruise flight is likely to be inefficient, resulting in dead weight and added drag of motors that are not operating		x
Mounting system will have to handle additional weight on spars compared to tri-motor		x

Table 10: Pros & Cons of Quad Motor Tilt Rotor

3. Quintuple Motor
   This design would be similar to the quad motor design, but featuring an additional vertical motor/propeller used during takeoff and landing. This would allow smaller, more efficient motors to be used during the horizontal phase of flight, as they would not need to produce as much individual thrust during VTOL. One motor can be interfaced with the preexisting motor mount on the Drak; however, mounting 4 additional motors would make this the most complex to manufacture for the tilt rotor category. The additional mounting structures and number of motors would also make this the heaviest and most expensive configuration of the tilt rotors. The fifth motor must also be accounted for when looking at stability and control of the aircraft as this motor can make the aircraft unbalanced depending on the placement of the other motors.

Description	Pro	Con
5th motor can interface with existing motor mount	x	
5th motor can offset lift in hover	x	
More complex than both tri and quad motor configs		x
5th motor torque must be countered for stability		x
Most additional weight and complexity of mounting to spars		x
5 motors for cruise flight is likely to be inefficient, resulting in dead weight and added drag of motors that are not operating		x

Table 11: Pros & Cons of Quint Motor Tilt Rotor

Figure 5: Quint Motor VTOL hybrid model [39]

4.1.2 Tail sitter

A tail sitter configuration is a mechanically simpler option that relies on a modified control scheme to transition to horizontal flight and a sufficiently powerful propulsion system to enable it to hover with only two motors. Using the flow of propwash over the control surfaces, a puller tail-sitter configuration has sufficient control authority when in hover mode. Pusher tail-sitters would require additional control mechanisms such as gimbals or thrust vectoring due to the lack of this flow. Tail sitters offer the least amount of hover control due to a larger cross sectional area in the direction of the wind. A tail sitter configuration would require the least amount of moving parts needed for transition between horizontal and vertical flight modes, and therefore less structural modifications. However, transitioning from horizontal to vertical flight for landings would be difficult to control, as the wings will stall when pitching up. A tail sitter would also be the least likely to have dead weight in the form of unused motors because most designs of this nature have all of the motors in use for the entire flight.

Description	Pro	Con
Least number of moving parts	x	
Less propwash due to motors being further off the ground	x	
Less likely to have dead weight in the form of unused motors	x	
Pullers can use air over control surfaces for control in hover mode	x	
Hover transition will be more complex due to dependence on aerodynamic forces to change attitude		x
Fewer motors handle lifting vehicle in hover (more stress)		x
More sensitive to wind		x

Table 12: Pros & Cons of Tail Sitter in General

1. Quad Motor - Puller

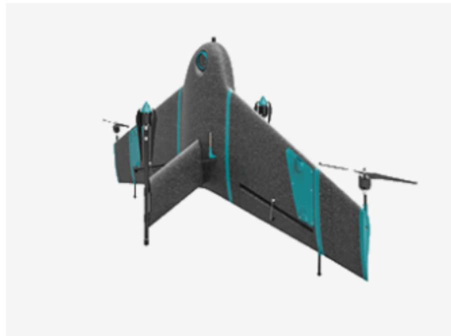

Figure 6: Quad Motor Puller Tail Configuration [40]

Quad motor tail sitter is characterized by having four motors in a forward facing cross or x configuration. This allows for additional stability in hover mode since the dynamics will be similar to that of a quadcopter. A downside is that not all motors will be needed for cruise flight, so there is additional weight and drag that is not contributing to thrust or lift.

Description	**Pro**	**Con**
Additional motors simplify stability in hover	**x**	
Can have different types of motors; 2 can be dedicated lifters, 2 can be cruise motors	**x**	
Motors not used for cruise will be dead weight in forward flight		**x**
Additional structural strength considerations from mounting 2 additional motors		**x**
Additional drag from structure & unused propellers during cruise		**x**

Table 13: Pros & Cons of Quad Motor Tail Sitter

2. Dual Motor - Puller

Figure 7: Dual Motor Puller Tail Sitter Configuration [15]

This system would consist of two motors mounted forward of the wings. While there would be a lost dimension of control due to the motors being coplanar, they would blow air over the control surfaces even in VTOL mode, which would provide the controllability needed for stable hover. The downside to this is that all of the thrust needed to offset weight in hover would be supplied by those motors; and they would have to work in both cruise and hover modes.

Description	**Pro**	**Con**
Motors won't interfere with RAPCat	**x**	
Balance will be more of a concern in hover		**x**
Stability concerns from lifting with two motors in hover		**x**

Table 14: Pros & Cons of Dual Motor Puller Tail Sitter

3. Dual Motor - Pusher

   This configuration has two motors behind the aircraft creating thrust. Unlike a puller configuration, propwash over the control surface and wings would not be as big an issue as most puller configuration. Pusher motors are not as efficient due to the disturbed air flowing off the control surfaces, and the difficulty in maintaining stability due to the relative position of the center of thrust and the CG is a draw back.

Description	**Pro**	**Con**
Least stable in hover		**x**
More work needs to done to interface with Drak airframe		**x**
Stability concerns from lifting with two motors in hover		**x**
Landing structure will need to accommodate props and motors		**x**

Table 15: Pros & Cons of Dual Motor Pusher Tail Sitter

4. Single Motor - Pusher

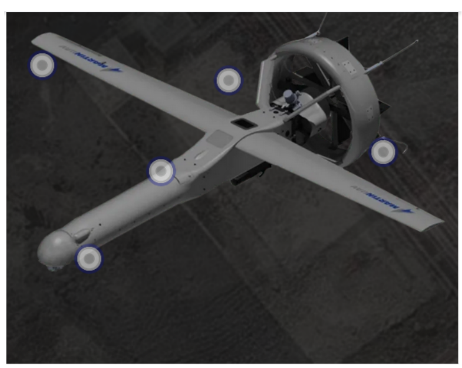

Figure 8: One Pusher Motor Tail Sitter Configuration [41]

The single motor pusher configuration would require the least modification to the Drak kit itself since the standard thrust system for the retail wing set is a single pusher. Propwash does not contribute to control authority in the manner that a puller does, but instead will require alternative methods to maintain control authority, and potentially modification of flight control firmware code. There are solutions to this issue but they are complicated, such as a gimballing thrust system or multiple fans/fins to direct thrust in real-time to maintain stability. There are a lot of drawbacks to this design, but the lack of complexity regarding modification of the wing kit is highly desirable.

Description	**Pro**	**Con**
Similar in config to stock Drak motor	x	
Balance will be more of a concern		x
Won't be able to use existing control surfaces in hover mode		x
Hover mode control system will be more involved		x
Single motor will need to provide all required thrust for vehicle		x
Landing system will need to accommodate props		x

Table 16: Pros & Cons of Single Motor Tail Sitter

4.1.3 Hybrid

The hybrid system or lifter/pusher system can be thought of as taking a standard horizontal flight system and adding additional fixed orientation lift fans to enable the VTOL capacity. In general, this system benefits from being able to have dedicated subsystems for both vertical and horizontal flight regimes, which can be independently optimized. Downsides of the configuration primarily come down to the endurance requirement of this project, with the motors that do not function in flight contributing significant amounts to drag and reducing cruise efficiency.

Description	**Pro**	**Con**
Motors don't need to change thrust direction	x	
Easier hover transition	x	
Can easily configure hover and cruise motors/props separately	x	
Easy to integrate into current design and model	x	
Dead weight in cruise/hover from unused motors for other function		x
Increased drag from orientation/position of propellers during cruise		x
High cost, most complexity and moving parts		x

Table 17: Pros & Cons of Hybrid System in General

1. Quad Lift Motor, Single Cruise Motor (4L1C)

Figure 9: 4L1C Hybrid configuration [42]

This configuration is the most straightforward option, offering the balanced controllability of a quadcopter, and the simple controls of a single pusher plane. With four lifting motors and one cruise motor, this is referred to as the 4L1C configuration. The design also features simple manufacturability, with two symmetrical arms being added to the structure of the aircraft. This model also allows for simpler dynamic modeling and not having to account for the uneven torques of a tri-motor configuration.

Description	**Pro**	**Con**
Balanced thrust in hover	x	
Could utilize existing motor mount for pusher	x	
More dead weight in cruise		x
Mounting system needs to accomodate placement of four additional motors		x

Table 18: Pros & Cons of 4L1C Hybrid System

2. Tri Lift Motor, Single Cruise Motor (3L1C)

   This configuration features a similar layout to the 4L1C, but with three motors instead of four. Hence, 3L1C. The use of three motors instead of four causes an imbalanced moment that must be accounted for - there must always be two motors moving in one direction and one in the other, so the controls system will need to account for this, such as with motors that can tilt past vertical and cause a yaw, or by sizing the propulsion system to naturally balance out the moments. There is also the necessary consideration of added complexity from having different mounting systems for the front and rear motors, as they would need to be designed and validated separately.

Description	**Pro**	**Con**
Less parasite drag during cruise than 4L1C	x	
Need to balance asymmetric lift in hover		x

Table 19: Pros & Cons of 3L1C Hybrid System

4.1.4 Tilt Wing

A tilt wing configuration utilizes wings that adjust their angle of attack independently from the airframe. One of the advantages of this system is the lack of dead weight and parasite drag which increases cruise efficiency. Unlike the tilt rotor and hybrid configurations, the motors for the tilt wing configuration are either along the wing or at the wing tips and therefore do not require significant external structures. Another advantage is the tilt wing configuration allows the use of control surfaces during hover which can help provide some extra control and stability. However, the tilt wing configuration comes with several drawbacks. The first issue would be the complexity of integrating this system with a pre-built aircraft. The next problem is that even with the aid of control surfaces during hover, the configuration of the motors makes the hover controls limited without additional parts. Another disadvantage would be the large motor (or motors) that would be needed to rotate the wings, mostly negating what would be saved in dead weight. In existing models, the transition from vertical to horizontal flight is slow. Finally, without additional parts, the wings would have to sit in line with the center of mass or the resulting moment would have to be countered.

Description	**Pro**	**Con**
Added mass of tilt mechanism does not increase drag as much as unused propellers	x	
Can use control surfaces in hover configuration	x	
Complex to manufacture and operate		x
Slow transition phase that can be difficult to model		x
Large motor required to rotate entire wing while under load		x
Motors in vertical flight mode need to either be in line with CoM or the resulting moment needs to be countered		x
Would require offset of lift generated by vertical wing in hover mode		x
Susceptible to disturbances in vertical flight		x

Table 20: Pros & Cons of Tilt Wing in General

1. Inboard Motors

Figure 10: In Board Tilt Wing Configuration [43]

The inboard tilt-wing configuration utilizes motors that are mounted perpendicular to the leading edge of the wings at about the mid-span. Instead of rotating the individual motors to perform vertical takeoffs and landings, the entire wing rotates upward with the motors remaining in the same position relative to the wing. During horizontal flight, the wing acts as it would for a fixed wing aircraft with motors that can provide additional thrust if necessary. The tilt wing does not require as many servos/actuators as the similar tilt rotor configuration, however it requires one much larger, more complex tilting mechanism that must rotate the entire wing along with all the motors. Since the entire wing is rotating in vertical flight mode, the aircraft is much more susceptible to disturbances due to the large cross sectional area of the wings when tilted. However, just like in horizontal flight mode, the streamlines from the propellers will flow along the wings efficiently in vertical flight mode and the motors can provide more power to lift the aircraft. Since the streamlines flow smoothly, there is no loss of lift or vertical down force created due to down-wash generated by the motors in vertical flight mode that can be found in tilt rotor configurations.

Description	**Pro**	**Con**
Less stresses on the wing spar	**x**	
No loss of lift due to unwanted prop-wash in vertical flight mode	**x**	
Less moment control authority in hover		**x**

Table 21: Pros & Cons of Inboard Motor Tilt Wing

2. Wing Tip Motors

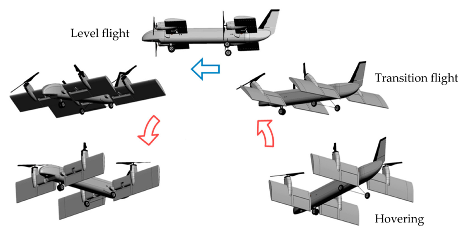

Figure 11: Wing Tip Tilt Wing Configuration

A tilt wing configuration requires less servos and actuators for transition between flight modes, and having wing tip motors is a valid option for accomplishing this task. There will be two motors creating thrust, but the drawbacks are plentiful. The bending moments on the wings will be significant, the yaw would be almost uncontrollable in case of an engine failure, and there will have to be a large rudder to counteract large polar moments.

Description	**Pro**	**Con**
More often used by other tilt wing configurations	x	
Propellers accelerate flow over wingtips, reducing likelihood of wingtip stall	x	
More stress on wing spar		x

Table 22: Pros & Cons of Wing Tip Motor Tilt Wing

4.2 Landing Sensors

Performing two autonomous takeoffs and landings at desired targets set in the ground station software is a critical project element, so the chosen sensor package must be tailored to the desired avionics package and electronics that operate the aircraft. The current IRISS avionics package provided to the VORTEX team contains a GPS/compass that interfaces with Pixhawk Cube, an internal barometer, and an internal IMU. These can provide the altitude measurements in flight necessary to support and perform the base IRISS mission requirements, but a supplementary sensor is required to accurately measure relative altitude to the ground and land in a controllable manner. This section will point out the key benefits and differences in LiDAR, RADAR, and Sonar to find the best option for relative altitude determination. This trade study focuses on complexity of integration, precision and accuracy, volume and mass, cost, and resiliency to all expected low-wind flight conditions.

4.2.1 LiDAR

Figure 12: A LiDAR Sensor [11]

LiDAR sensors measure distance by repeatedly sending light towards an object, the ground in this case, and calculates distance through measuring the time that it takes for the light to travel to and reflect back from the ground. There are a few off the shelf LiDAR sensors with multiple ready to use capabilities like obstacle filtering over rough terrain, compatibility with the provided microcontroller, measurements in the desired range, and accurate altitude readings which allow for largely autonomous execution. Due to these characteristics and the fact that the readings are not affected by speed, wind, changes in pressure, noise, terrain or air temperature make it a great choice to use[12]. These sensors have been field tested and are highly regarded in the autonomous vehicle community.

Description	**Pro**	**Con**
Very high sampling rate	**x**	
Ready to integrate with Avionics Package	**x**	
Typically very Small with Housing Units	**x**	
Issues with Metal/Reflective Objects		**x**
High Data Processing Requirements		**x**
Affected by Heavy Vegetation		**x**
Typically More Expensive		**x**
Refracting Issues Over Bodies of Waters		**x**

Table 23: Pros & Cons of LiDAR

4.2.2 Micro Radar

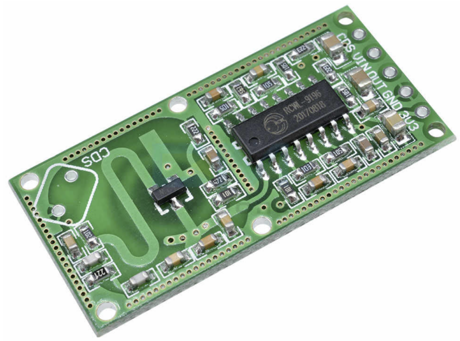

Figure 13: A Micro Radar Sensor [17]

Radar altimeters use radio waves to measure distance of an object. Radar altimeters are a well known tool in aviation. Bulky radar altimeters were used in civilian engine power aircraft but have been optimized and sized down to work well in battery powered autonomous vehicles. They are typically highly accurate, have high sampling rates, and many retail micro radars have software capabilities that greatly increase their efficacy. However, they are not as commercially available at affordable prices as LiDAR and Sonar sensors, but they do have the added benefit of more accurate readings over water. Unfortunately, they are also susceptible to signal interference and are typically expensive.

Description	**Pro**	**Con**
More durable than other sensors	x	
Measures distance and speed	x	
Microwaves unaffected by harsh weather conditions	x	
Adjustable operating frequency	x	
Ready out of the box	x	
Larger and heavier than other sensors		x
Not as accurate as other sensors		x
Shorter distance range compared to other sensors		x
Must be kept clear of debris		x
Data processing requires more processing power		x

Table 24: Pros & Cons of Micro Radar

4.2.3 Sonar

Figure 14: A Sonar Sensor [23]

Sonar sensors are often used in autonomous vehicle applications. They use a reliable and well tested time of flight algorithm that measures the time it takes for a ultrasonic signal to be reflected back to the sensor. They are typically small and relatively cheap and have the added benefit of not being hindered by reflective surfaces and water. However, they are sensitive to pressure effects and temperature swings, and often are meant for highly accurate readings at smaller ranges, compared to those that are desired for this project.

Description	Pro	Con
Less expensive than laser sensors	x	
Comes with software installed	x	
Minimally effected by dust, debris, smoke, and color	x	
Can detect highly reflective objects	x	
Shorter measurement ranges		x
Larger and heavier than other sensors		x
Accuracy effected by temperature		x
Accuracy effected by soft/irregular shapes		x
Dead zone issues		x

Table 25: Pros & Cons of Sonar

4.3 Battery Chemistry

The drive train of any fixed wing UAV or multi rotor drone is completely dependent on the power source. Drone technology has been limited in the last decade because of motor and battery size and performance limitations. Choosing the correct battery for a VTOL configuration is challenging because there is generally a trade off between energy storage (endurance) for horizontal flight and discharge rate (burst) for high energy vertical flight. Below, different types of battery chemistry are compared for their potential use in a VTOL aircraft. This study is limited to the value each specific chemistry contributes to the design.

4.3.1 Lithium Polymer (Li-Po)

Lithium Polymer (short for lithium-ion polymer) batteries are very popular in many consumer electronics. These rechargeable batteries use a polymer electrolyte instead of a liquid electrolyte compared to other lithium types. Chemically, this allows for a high specific energy with low weight (high energy density). Because of their cell structure, they are adaptable batteries in their size and shape, and are known for high capacities and high discharge rates. These batteries are used for most RC aircraft for these reasons, but require special attention to safety when charging and discharging (the electrolyte used can burst if mistreated). More downsides include short lifespans (100-300 charge cycles) [31] in high intensity usage. Li-pos are organized in cells in hard or soft cases. Recently, Li-po batteries have become affordable but are still expensive compared to other battery types. The limiting factor for a VTOL design with this battery is needing a high capacity endurance in horizontal flight.

Description	Pro	Con
Lightweight	x	
Low profile and flexible design	x	
Industry standard	x	
Short lifespan		x
Expensive to manufacture		x
Safety risk if damaged/punctured		x

Table 26: Pros and Cons of Lithium-Polymer Battery Composition

4.3.2 Lithium-Ion (Li-ion)

Lithium ion batteries are another battery type used in portable and consumer electronics. This battery chemistry is known for its very high energy density (based on standard 3.6V 18650 cell). Because of this, lithium ion batteries are found in many phones, some electric cars, and some aerospace applications. Unlike other batteries, Li-ions can maintain one of the highest specific energy and highest capacity (low internal resistance and good coulombic efficiency) [32]. Another advantage is these batteries generally have a long cycle and shelf life, and they have safer recharge and discharge characteristics (as opposed to Li-pos). On the other hand, there are limitations to rapid charging, thermal integrity sensitivity, and many shipping regulations. The reason Lithium ions are not as popular is Li-pos in RC electronics is their low discharge rate. Although they can store higher capacity, they lack rapid discharge used for multi rotor drones or vertical takeoff vehicles. The limiting factor for a VTOL design with this battery is needing a high current draw in vertical take off with a low current discharge battery.

Description	Pro	Con
High energy density	x	
Low self-discharge rate	x	
Long lifespan	x	
Low maintenance	x	
High efficiency	x	
High safety risk		x
Expensive to manufacture		x
Suffer from 'aging effect'		x
Can be subject to transportation regulations in large quantities		x

Table 27: Pros and Cons of Lithium-Ion Battery Composition

4.3.3 Nickel Metal Hydride (NiMH)

Nickel Metal Hydride are another battery type used in high-current-drain applications such as digital cameras and hybrid cars because of their low internal resistance. Although less expensive than lithium ion counterparts, nickel batteries are much heavier and larger. In terms of battery capacity, Li-on and NiMH have a similar performance (although Li-ions can discharge faster)[30]. Nickel Metal Hydride batteries are not as sensitive to extreme climates so can be used in those settings. These batteries are not as much as a safety hazard as Li-pos if not charged or discharged correctly. In addition, both low efficiency and short lifespan makes these batteries unpopular for use in drones and RC planes. The limiting factor for a VTOL design with this battery is the large weight and size of the battery (not ideal for endurance drones).

Description	Pro	Con
Low cost	x	
Slightly higher energy density than Ni-Cd	x	
Environmentally friendly (recyclable)	x	
Low safety risk	x	
High maintenance		x
High self-discharge rate		x
Relatively low efficiency		x
Heavy		x
Short lifespan		x

Table 28: Pros and Cons of Nickel-Metal Hydride Battery Composition

4.3.4 Nickel Cadmium (NiCd)

Another rechargeable battery, Nickel Cadmium batteries have a common use for applications needing constant terminal voltage discharge. Being very robust, these batteries are used for extreme environments. A disadvantageous characteristic for this battery is the memory effect, which requires close attention to charging and discharging. During subsequent use after recharge, voltage will drop (dead battery) at that level where charging began. They have a much longer lifetime with more charging cycles (1000+)[33]. Compared to lithium ion, these batteries are cheaper (about 40% compared to Lithium ion) with the disadvantage of less capacity and energy density. The limiting factor for a VTOL design with this battery is the lower energy density, heavy weight, and high maintenance (not ideal for endurance drones).

Description	**Pro**	**Con**
Long lifespan	x	
Low cost	x	
Available in a wide range of sizes and performance options	x	
Robust, durable and perform well in extreme environments	x	
Low energy density		x
Suffer from 'memory effect'		x
Relatively high self-discharge rate		x
Environmentally unfriendly (contains toxic metals)		x

Table 29: Pros and Cons of Nickel-Cadmium Battery Composition

4.3.5 Lithium Iron Phosphate (LiFePO4)

This rechargeable battery is very similar to the characteristics of a lithium polymer battery. Typically used in solar energy systems, golf carts, and electric motorcycles, this is one of the safest batteries and does not ignite during abusive handling or discharge. In terms of environmental safety, these batteries are nontoxic and recyclable. Since LiFePO4 is so similar to Li-ion chemical structure (modified cathode material), it has many inherited characteristics such as high energy density and lightweight. LiFePO4s have both very long life cycles (2000-3000 charge cycles) and can reach 100% depth of charging (as opposed to Li-pos)[34]. Its energy density is slightly lower than other lithium ion 18650 cells and is heavier and bulkier. These batteries are usually paired with high discharge rates and reasonable capacity. The limiting factor for a VTOL design with this battery is the weight of the batteries.

Description	**Pro**	**Con**
Extreme life cycle	x	
Extreme safety behavior	x	
High energy density	x	
Environmentally friendly (uses non-toxic metals)	x	
Poor performance in low temperatures		x
Slightly lower cell voltage compared to other Lithium batteries		x
High comparative weight per cell		x
Not industry standard		x

Table 30: Pros & Cons of Lithium Iron Phosphate

4.4 Flight Controller Firmware

Autonomous aircraft require a flight controller capable of accurate analysis of sensor data and manipulation of other subsystems. From this, every flight controller is limited not only by its hardware, but by it firmware package. IRISS expressed a desire to continue the use of components in their current avionics package. It has been developed to operate a with a Pixhawk Cube flight controller. Keeping this in mind, it is important that the firmware functions on the provided Pixhawk Cube. If the firmware requires supplementary microcontrollers to operate, that cost will be added to the project's budget and make it difficult to stay below $1000. The firmware chosen should be ready to handle autonomous flight and preferably operate with the customers previously used ground station software systems or similar graphic user interface. It is critical to the project that the firmware is capable of controlling the chosen VTOL configuration as well as the fixed-wing flight mode or else project will be at risk of failure. Ideal firmware have well developed open-source code that already feature advanced controls algorithms and can support a variety of different functionalities and configurations.

4.4.1 ArduPilot

After 11 years, the ArduPilot Project has become an advanced, fully-featured and reliable open source autopilot software system that has both volunteer and professional developers. Originally developed for 8 bit ARM-based microcontroller units (MCUs), it is now used for 32 bit MCUs, capable of controlling a wide range of vehicles and configurations such as boats, rovers, drones, fixed-wing planes, and everything in between. The firmware can run on PixHawk and Linux based boards, making it a viable option for a wide range of controllers. ArduPilot is also an application that was based on the PX4 Native Stack firmware[13], so it will have no issue running on the Pixhawk Cube. ArduPilot also comes with ground control station (GCS) support for Mac OSX, Windows, and Linux with various accessible GUI's for each that allow for mission planning and setup such as assigning waypoints, sensor calibration, vehicle set-up, and real-time flight data reporting[14].

Description	**Pro**	**Con**
Has the most VTOL configurations developed	x	
Fairly advanced control algorithms	x	
Supports full autopilot systems already.	x	
Extensive forum and developer documentation	x	
Currently used by the customer and has loiter function desired	x	
Functions on hardware provided	x	
Written in C++ and Python	x	
Open-source licensing, code needs to be shared as open		x

Table 31: Pros & Cons of ArduPilot

4.4.2 PX4

PX4 is an open source flight control software for a wide range of airborne vehicles. Derived from the DroneCode collaborative project, PX4 is compatible with the QGroundControl GCS and is capable of controlling multi-rotor vehicles in drone, fixed wing, and VTOL configurations. PX4 is free to use and can be modified under the BSD 3-clause license. This differs from ArduPilot in that any source code modifications done by companies or private parties is not required to be released as open source information. This code is written in C++, a language with which the team is familiar. PX4 has many functionalities that make it more suited for autonomous aircraft.

Description	**Pro**	**Con**
Has basic autopilot functions	x	
Works on a range of configurations/vehicle types	x	
Designed to work with Pixhawk Cube provided by customer	x	
Works with a range of flight controllers	x	
Easy to set up new flight configurations	x	
Written in C++	x	
BSD License		x

Table 32: Pros & Cons of PX4

4.4.3 iNav

iNav is a revamped version of CleanFlight with improved navigation functionalities and is widely used in autonomous vehicles and applications. It specializes in "Follow Me" vehicle applications, so the control and software algorithms are complex and implement substantial control authority. It has documentation on how to interface with over 25 flight control boards and the source code is available online. The code is primarily written in C and assembly language, which is not a strength of the team. It supports GSC on multiple operating systems, however it has spent less time in development than its competitors.

Description	**Pro**	**Con**
Robust navigation system including waypoint tracking, supports both multirotor and fixed wing aircraft	x	
Heavy Documentation	x	
Supports cheaper flight boards than ardupilot	x	
Many GSC options, uses barometer and GPS	x	
Open source and free	x	
Mainly written in C and assembly		x
Less developed		x
Not familiar to customer		x

Table 33: Pros & Cons of iNav

4.4.4 PaparazziUAV

The PaparazziUAV project is a widely used flight control firmware that has many capabilities for a range of UAVs. This project has some of the most capable control software available, but this becomes more computationally demanding of the current flight controller and may require additional hardware. It supports a variety of vehicle configurations, including some VTOL. PaparazziUAV has its own GCS and flight simulations that can operate on Linux, Windows, or Macintosh to operate the Paparazzi suite. The software has a lot of in-depth documentation online with its own wiki-based setup guide, but requires much more setup and modification for the features desired in this project. Modification to the software will have to done in C++, which is possible for the team.

Description	**Pro**	**Con**
Works well with multi-rotor airframes Supports a complete UAV system, including simulation	x	
Autonomous flight is primary focus	x	
Open source and free	x	
Not possible to alter mission mid flight		x
Requires development of new firmware functions		x
GCS is less accessible		x
Written in OCAML and C		x

Table 34: Pros & Cons of PaparazziUAV

5 Trade Study Process and Results

5.1 VTOL Configuration

In order to decide the VTOL configuration, a variety of considerations had to be considered to make sure that the chosen option was the best for this mission. A complicating factor for choosing the baseline is that there are many different options within each configuration. In order to combat this, the trade study was broken out into the four major configurations, tilt rotor, tail sitter, hybrid and tilt wing. The comparison was done within each of these configurations for manageability, but the criteria were universal. At the end of these 4 studies, the chosen design was the one with the highest overall score.

Cost here refers to the cost of motors, propellers, ESCs and any additional structure that would be included in a given VTOL configuration.

5.1.1 Criteria and Weight Assignment

Criteria	Weight (%)	Rationale
Risk	20	The risk associated with each configuration is a big factor in deciding which to use. Risk grows with the number of potential failures from added structures and components, or the general technical complexity of systems.
Manufacturing/Complexity	15	How many modifications and the time required to do them a is critical criteria.
Weight	10	Number of added structural components and motors greatly effect the total weight of the system, which is important to keep in mind when attempting to fly.
Hover Control	20	A configuration's control during VTOL mode is a deciding factor as steady level hover is a design requirement.
Cruise Efficiency	30	The configurations complexity, power draw, weight, and more will have direct impacts on cruise efficiency. A 1 hour cruise endurance is a critical project element.
Cost	5	The customer has provided a budget for per-unit cost on a finished product, but the budget may have some flexibility and is thus weighted lightly with respect to the other sections.
Total	100	

Table 35: Rotor Configuration Weighting

5.1.2 Scale Assignment

Due to the nature of many criteria being hard to assign objective values to at this point, the values were assigned to each option relative to the other options in the study. For the options reading "N/A", values were interpolated between the other options. Cost refers to the additional hardware that is required to allow VTOL configuration compared to a standard assembly of the Drak.

VTOL Configuration Criteria Standards					
Criteria	**1**	**2**	**3**	**4**	**5**
Risk	Many points of failure. VTOL system is technically complicated with many pieces.	N/A	Moderate amount of points of failure.	N/A	Minimal points of failure. Design is proven with extensive examples.
Manufacturing / Complexity	Requires difficult and time-consuming modification to aircraft body. Spars for tilting, spars/tails to hold rotors.	Requires modification to wings and bodies to hold rotors.	Moderate modifications, but requires a tail boom, or jutting structure.	N/A	Minimal modifications, ideally a bracket that can be simply put on. Makes use of existing mounting points in Drak wing kit.
Weight	Extensive additional structure	4 motors	3 motors, moderate additional structure	2 motors	1 motor, minimal additional structure
Hover Controllability	Minimal control authority from VTOL system. Easily destabilized, even in no wind.	N/A	Moderately control authority from VTOL system. Requires some modification of control software.	N/A	VTOL system has control authority with a wide margin in all conditions. Doesn't rely on control authority from control surfaces.
Cruise Efficiency	Many drag elements not contributing to propulsion.	N/A	Few drag elements not contributing to propulsion.	N/A	No drag elements not contributing to propulsion, few additional drag elements at all.
Cost	$700 or more	$500-$700	$300-$500	$100-$300	$100 or less

Table 36: Scale Assignment for VTOL Configuration

5.1.3 VTOL Configuration Trade Matrix

Criteria	Weight	Options		
		Tri	Quad	Quint
Risk	20	2.5	2.5	2
Manufacturing / Complexity	15	4	3	2
Weight	10	4	3	1
Hover Controllability	20	5	5	4
Cruise Efficiency	30	4	3	2
Cost	5	3	2	1
Total	**100**	**3.85**	**3.25**	**2.25**

Table 37: Tilt Rotor Trade Study

Criteria	Weight	Options			
		Quad	Double Push	Double Pull	Single
Risk	20	2	1.5	4	1
Manufacturing / Complexity	15	1.5	1	4	5
Weight	10	2.5	2.5	4	5
Hover Controllability	20	3.5	1	2	1
Cruise Efficiency	30	2.5	4	4.5	5
Cost	5	2	4	4	3
Total	**100**	**2.43**	**2.30**	**3.75**	**3.30**

Table 38: Tail Sitter Trade Study

Criteria	Weight	Options	
		4L1C	3L1C
Risk	20	4	4
Manufacturing / Complexity	15	2	3
Weight	10	1	2
Hover Controllability	20	5	5
Cruise Efficiency	30	1	2
Cost	5	1	2
Total	**100**	**2.55**	**3.15**

Table 39: Hybrid Trade Study

Criteria	Weight	Options	
		Inboard Motors	Wingtip Motors
Risk	20	1	1
Manufacturing / Complexity	15	1	1
Weight	10	3	2.5
Hover Controllability	20	2.5	3
Cruise Efficiency	30	5	5
Cost	5	2	2
Total	**100**	**2.75**	**2.80**

Table 40: Tilt Wing Trade Study

The final configuration was chosen between the winners of each sub trade study.

Options	Tri Tilt Rotor	Double Pull Tail-sitter	3L1C Hybrid	Wingtip Motor Tilt Wing
Score	3.85	3.75	3.15	2.80

Table 41: Final Results of VTOL Configuration Trade Study

5.2 Landing Sensors

5.2.1 Criteria and Weight Assignment

Before beginning the process of selecting a landing sensor package, the team had to decide what aspects of the sensor package are most important to completing our project goals. Complexity as well as accuracy and consistency are the most crucial criteria. A sensor package that requires several pieces of external hardware and substantial software development in order to interface with the existing avionics system might not be worth the time and effort to implement. To optimize a vertical landing, the sensor must be able to measure altitude data accurately and consistently in variable weather conditions. An issue with the altitude sensor (a barometer) internal to the provided flight controller package is a decrease in accuracy in windy conditions due to pressure variations. The next critical factor is size and weight. A heavy sensor package could alter the center of gravity of the aircraft and affect its stability. Cost, like in any engineering decision, must be considered and is especially important due to the projects budgetary goals. Finally, the sensor package's resiliency to damage and need for recalibration needs to be measured and weighed. The weight assignments for these criteria are outlined below in Table 42.

Criteria	Weight (%)	Rationale
Complexity	25	The ease of interfacing the landing sensor with the existing avionics package is very important, as a sensor that requires extra hardware and software development adds extra work and weight.
Accuracy and Consistency	25	The sensor must be capable of capturing data with enough accuracy to ensure safe autopilot controlled takeoff and landing. The sensor must be able to consistently capture altimeter data in non-ideal conditions (e.g. wind and dust debris).
Size and Weight	20	The heavier and larger the sensor package is, the more of a negative affect it has on the center of gravity location and more additional space it requires.
Cost	15	The sensor package must not be so expensive as to push the project over budget and therefore restrict other design choices on a cost basis.
Resilience	15	It is critical to have sensors that are capable of bearing the forces exerted on it during all testing and mission flights. Constant recalibration and/or replacement needs to be avoided.
Total	100	

Table 42: Landing Sensor Trade Study Weighting

5.2.2 Scale Assignment

Landing Sensors Criteria Standards					
Criteria	**1**	**2**	**3**	**4**	**5**
Complexity	N/A	N/A	Requires an external processor for computations and sensor interfacing. Requires external hardware for mounting.	Requires external processor and sensor mounting to interface with avionics system. Does not require external hardware for mounting.	Interfaces directly with the avionics system and uses the internal avionics package MCU to handle all necessary computations.
Accuracy and Consistency	Sensor accuracy greatly effected by adverse weather conditions.	N/A	Sensor fairly accurate in most weather conditions.	N/A	Sensor very accurate in all weather conditions.
Size and Weight	Sensor package significantly impacts CG location and thrust required.	N/A	Sensor package moderately impacts CG location and thrust required.	N/A	Sensor package minimally impacts CG location and thrust required.
Resiliency	Delicate sensor package, requires extra consideration for safe mounting. Requires frequent recalibration.	N/A	A more rugged sensor package. Better handles flight loads and debris. Requires occasional recalibration.	N/A	Sensor package unaffected by flight loads and debris. Recalibration seldom required.
Cost	Sensor package results in high cost to budget.	N/A	Sensor package results in moderate cost to budget.	N/A	Sensor package results in low cost to budget. <100

Table 43: Scale Assessment of Landing Sensors

5.2.3 Trade Matrix

Criteria	Weight (%)	Options		
		LiDAR	**Micro Radar**	**Sonar**
Complexity	25	3	3	3
Accuracy and Consistency	25	4	5	2
Size & Weight	20	5	3	5
Resiliency	15	4	5	2
Cost	15	5	3	5
Total	**100**	**4.1**	**3.8**	**3.3**

Table 44: Landing Sensor Trade Matrix

5.3 Battery Chemistry

Battery chemistry is essential in providing the correct amounts of voltage, current, and capacity to the aircraft design. Without proper batteries, the aircraft will have insufficient stored energy and will be unable to fly for the required duration. When constructing a trade study, it is important to study which battery types will meet these requirements. Upon initial assessment, 5 different rechargeable battery types were found that are common in electronics including lithium polymer, lithium ion, nickel metal hydride, and nickel cadmium. The two most common in drone and UAV batteries were lithium ion and lithium polymer. The three additional batteries were explored to meet the unique needs of the VTOL aircraft. The most important criteria for this trade study were cost, battery lifespan, discharge capacity, energy density, and safety. Ideally, we want high battery density for efficient and light power, balanced discharge capacity for vertical (high) and horizontal (low) flight, and reasonable lifespan, cost, and safety. Online research and videos explained each property of the batteries and their characteristics as electronic power sources. The rationale for each criteria weight is seen below in the weight assignment table as well as further analysis in the trade matrix.

5.3.1 Criteria and Weight Assignment

Criteria	Weight (%)	Rationale
Energy Density	25	High energy density is critical to have the highest battery capacity while maintaining the lowest weight, which allows the aircraft to achieve a one hour flight time with a lightweight aircraft.
Discharge Rate	20	The ability of the battery to provide enough current for the high demands of VTOL functionality - in order to produce enough power, the battery and wiring system must be capable of handling sufficient current.
Cost	20	Battery cost tends to correspond directly with performance, and a high performance battery will be more expensive. Although this performance is essential to the project, there is a limited project budget. The cost will be a large limiting factor, but performance is weighted higher than cost.
Lifespan	20	A cycle of a battery is defined as a full battery being discharged to empty and charged to full capacity again. Over time after charging and discharging the battery so many times, the capacity of the battery will slowly decrease. The lifespan of the battery is the number of cycles that the battery can go through before it needs to be replaced where maximizing the number of cycles is important so that a new battery does not need to be purchased as often.
Safety	15	Different battery types have different discharge properties. Some batteries may become unusable if they drop below a certain voltage. Other batteries may be dangerous to the user, so proper safety precautions must be made. Because of this, safety is weighted low because vehicle performance takes precedent.
Total	100	

Table 45: Trade Study 3 Weighting

5.3.2 Scale Assignmnent

Battery Chemistry Criteria Standards					
Criteria	**1**	**2**	**3**	**4**	**5**
Discharge Rate (per cell)	0.5C	1C	2C	5C	10C
Energy Density	0-30 Wh/kg	30-60 Wh/kg	60-90 Wh/kg	90-120 Wh/kg	$>$ 120 Wh/kg
Cost (per cell)	250 $/kWh	200 $/kWh	150 $/kWh	100 $/kWh	50 $/kWh
Lifespan (discharge cycles)	Battery shows significant wear (loss of charge capacity) after 250 or fewer cycles	Battery lasts 250-500 discharge cycles without significant capacity loss	Battery lasts 500-750 discharge cycles without significant capacity loss	Battery lasts 750-1000 discharge cycles without significant capacity loss	Battery lasts 1000 or more cycles without showing significant degradation of charge capacity
Safety	Battery presents a high risk to the user - sensitive to overcharging, overheating, impacts, etc.	N/A	Battery is safe if handled and stored according to manufacturer's instructions, low risk of overcharging or damaging at low charge states	N/A	Battery is very safe - Can withstand extreme conditions, impacts, etc.

Table 46: Scale Assessment of Battery Composition

5.3.3 Trade Matrix

Criteria	Weight	Options				
		Li-Po	**Li-ion**	**NiMH**	**NiCd**	**LiFePO4**
Discharge Rate (per cell)	20	5	2	2	3	3
Energy Density	25	2	5	2	1	2
Cost battery (per cell)	20	3	2	4	3	2
Lifespan (discharge cycles)	20	1	4	3	4	5
Safety	15	2	3	4	3	4
Total	**100**	**2.6**	**3.3**	**2.9**	**2.7**	**3.1**

Table 47: Battery Chemistry trade matrix

5.4 Flight Controller Firmware

Autonomous aircraft require robust flight controller firmware that allow for accurate operation of all the system. Table 47 lists the weight and criteria used to conduct a trade study in order to select a firmware package. The customer expressed a strong preference for the VORTEX team to use the existing firmware utilized in other IRISS UAVs to simplify integration of the VTOL with the rest of the fleet. Thus, customer preference is weighted heavily. Aside from customer preference, functionality is also crucial, because successful flight depends on having an effective firmware foundation controlling the aircraft. As it is possible that the VORTEX team will need to alter some aspect of the firmware, having readily available resources and documentation on the firmware is very useful. These three selection criteria are considered the most important. The ability for the firmware to easily interface with the flight controller is critical, however it is weighted less because it is known that each firmware package in question does interface to some extent with the flight controller. Also, most firmware is written in languages the VORTEX team is familiar with (C++, Python).

5.4.1 Flight Controller Firmware Criteria Standards

Criteria	Weight (%)	Rationale
Functionality	30	The flight controller firmware package must be designed to fulfill the full range of requirements for mission success. Integration with the firmware package, having a capable and approachable GSC, and capability to control VTOL configurations are the the most critical element when choosing an appropriate firmware package.
Resources	30	Access to online resources that detail the use and capabilities of each firmware package is critical to successfully executing a mission. A firmware that has an extensive site for forums, tutorials, and open information, especially on VTOL flight configurations, will be very helpful.
Customer Preference	25	This final project is meant to integrate into the customer's existing aircraft systems, so the firmware choice should fall in line with the customer's preference to minimize difficulty of integration.
Hardware/Software Interface	15	A flight controller firmware that is easily integrated with the chosen avionics package, ground station software, and flight planner is critical to minimize weight and number of electronic connections and mechanisms.
Total	100	

Table 48: Firmware Trade Study Weighting

5.4.2 Scale Assignment

Flight Control Firmware Criteria Standards					
Criteria	**1**	**2**	**3**	**4**	**5**
Functionality	Firmware cannot handle autonomous flight and is only for RC applications.	Control laws for both fixed-wing, transition modes, and hover mode have to be written from entirely from scratch.	Software and control laws require extensive modification. Firmware is difficult to physically interface with avionics package.	Requires some changes to software to interface with avionics package. Has standard control algorithms for configuration.	Capable of switching between horizontal and level flight modes out of box. Supports our specific configuration with advanced control algorithms.
Resources	No open-source information or tutorials. Hard to use software, does not interface with GSE software,language is complex.	Software/firmware cannot be altered GSE software does not work with the flight control system well. Some open source information	N/A.	Alterations to software is possible and fairly intuitive. Backed up with forums, tutorials, on website/online. Language is complex but understandable	Adjustable control through interface with GSE software. Language is simple and intuitive, resources for all flight modes can be found. Plentiful documentation
Customer Preference	Doesn't take into account the customers option used for ground station software. Would require significant alteration from customer's existing workflow	N/A	Interfaces with provided GSE Differs from existing platform used by customer but functionality is usable for mission.	Integrates into customers' choices for flight controller and ground control software.	Compatible with existing IRISS workflow, familiar to team for the purpose of further development
Hardware and Software	Functions on only specific operating systems,requiring the purchasing. Requires significant reworking of software.	N/A	Interfaces with provided GSE hardware with minimal extra hardware to purchase. Requires creating basic UI, some learning curve to software.	N/A	Doesn't require any additional hardware for operation besides what will be provided Fully developed UI, plug-n-play functionality, easily understandable software.

Table 49: Scale Assessment of Flight Controller Firmware Criteria

5.4.3 Flight Controller Firmware Trade Matrix

Criteria	Weight	Options			
		Ardupilot	**PX4**	**iNav**	**PaparazziUAV**
Functionality	30	4	4	3	5
Resources and User Interface	30	5	5	3	3
Customer Preference	25	5	3	1	1
Hardware/Software Interface	15	5	4	3	3
Total	**100**	**4.7**	**4.1**	**2.5**	**3.1**

Table 50: Stabilizer and Control Surface Configuration

6 Selection of Baseline Design

6.1 VTOL Configuration

The selection of a VTOL configuration is key to taking the first steps in meeting the requirements of this project. The primary elements that will be critical to a successful design are hover control and cruising efficiency. Battery and motor efficiencies exist in a reasonably well-defined range, so the major contribution to cruise efficiency will come in the consideration of the total drag on the aircraft. In a close race that was ultimately determined by hover control, the "tri tilt rotor" configuration was chosen. This design features two forward motors and a rear motor. In VTOL mode, all three propellers thrust downwards and the vehicle is controlled in a similar manner to a standard quadcopter. In horizontal flight mode, the two front motors tilt 90°and provide thrust for forward motion. The third propeller tilts 90°towards the rear, and the folding propeller automatically stows, allowing reduced contribution to drag. The folding propeller required for this design comes at the cost of propeller efficiency and therefore power consumed, but will have no impact on the actual cruise efficiency as it will not be operating during cruise.

6.2 Landing sensors

The trade study results show that a LiDAR sensor is the most appropriate choice for meeting the requirement of autonomous landing, with a score of 4.1/5. Since some of the sensors could require an additional processor to allow for accurate in-flight calculations of relative altitude, this solution that has already been integrated in the current avionics package. The LiDAR sensor also proves to be the best option as it can recognize objects below, regardless of if it's flat, and the accuracy of measurements are less susceptible to wind and temperature fluctuations when compared to Sonar. While micro radar sensors are more reliable than LiDAR sensors in environments with highly reflective surfaces, a reliable micro radar with adequate range is outside of the budget of the project. Furthermore, a LiDAR sensor has been used through I2C with the avionics package provided and similar devices have been found. LiDAR is most helpful in satisfying design requirements 3.4 and 3.8, being the vertical accuracy and landing autonomously, respectively. Overall this sensor has proven to be the most effective solution in appealing to the requirements of the project.

6.3 Battery Chemistry

The battery chemistry results showed a close lead for Lithium ion, surpassing Lithium Iron Phosphate and lithium polymer. Lithium ion is the most reasonable for this design considering the amount of endurance that is required. Most other battery types will require expensive and heavy battery packs that will exceed budget in order to meet a 1 hour flight time. Estimating the aircraft will weigh about 9-14 pounds, the main trade off is having high capacity discharge when in vertical flight, and long discharge times at low current for horizontal flight. Since Lithium ions are capable of long endurance with low discharge current, the challenge will be designing a battery that can supply sufficient current to the motors in order to have the necessary 6-8 kg of thrust. Lithium-ion batteries have superior safety and lifespan. Theses batteries also vary in cost, and further research is needed to determine the proper type of lithium ion. If a lithium ion battery configuration or battery pack is not feasible, the second option (Lithium Iron Phosphate) will be evaluated in terms of its endurance, relying on the fact that it also has sufficient current discharge capabilities to meet the mission requirements.

6.4 Flight Control Firmware Design Option

A critical part of this project is the autonomous operation of takeoff and landing procedures. The design options were scored on their existing assets and features. The criteria for the scoring were created based on the needs of the project and what the firmware should accomplish. The firmware trade study results show that ArduPilot is the most appropriate firmware for this project, with a total score of 4.7/5. Although not being ranked the highest in functionality, ArduPilot has enough capabilities to meet the requirements for both the VTOL and fixed-wing flight modes. Paparrazi UAV's list of possible configurations is just much more vast. The vast documentation and resources available for ArduPilot make it a very attractive option for straightforward implementation. PX4 scored second highest at 4.1/5. PX4 is an excellent alternative, because it is designed for the Pixhawk Cube and the BSD license allows for modifications to be kept private, as opposed to the GPL license requiring ArudPilot modifications to be open source. Although PX4 is a valid option, ArduPilot is more appropriate for this project due to customer preference,which was a heavily weighted criteria. Since the IRISS team already uses ArduPilot in other UAVs in their fleet, using ArduPilot will make integration in their end much easier. ArduPilot is known to handle multiple propeller configurations as well as interfacing with external microprocessors. Also, it is well known that ArduPilot's autonomous flight plan functions well and can be easily customized. These aspects of ArduPilot are helpful for accomplishing Functional Requirements 3 and 4, pertaining to autonomous flight and ground station communication, respectively.

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