An Exploration of Hybrid Unmanned Aerial Vehicle Design

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SUMMARY

The goal of this project was to design a drone capable of meeting real-world delivery applications. In order to establish a baseline of requirements from which to base the design off of, we chose to pursue the application of urgent medical supply delivery to a 911 caller faster than an ambulance could provide. To make this a reality, the most essential qualities for the drone design to possess was speed, range, vertical take off and landing (VTOL) capabilities, and payload capacity. After much research and many design iterations, we decided that a hybrid between a fixed-wing plane and a quadcopter drone would enable us to meet the high-level requirements to achieve mission success. Throughout the first semester of this project, we focused on building normal quadcopters to familiarize ourselves with the technology and design work. Once we mastered the basic framework of drone design, in the second semester, we pivoted towards integrating the fixed-wing airfoils and a pusher-propeller onto the quadcopter to test how much more speed, efficiency, and payload capacity could be achieved.

RESEARCH & DEVELOPMENT

Inspiration

With drone delivery becoming an increasing reality in our world, our team set out to find a market where we could save lives using drones. After weeks of research, we learned that SCA (Sudden Cardiac Arrest) was the leading cause of death for people over the age of 40.

A victim's chance of survival decreases 10% every minute; in other words, they only have around ten minutes to receive aid until their survival rate drops to 0%. To help reduce the amount of deaths, our team decided to build a drone capable of delivering AEDs (Automated External Defibrillators) to patients suffering from SCA within the ten minute time window.

We needed a drone that could deliver an AED to remote locations where victims are far away from hospitals and local ambulances. This lead us to focus on 3 essential design specifications:

1. Speed - The final version of the drone should fly at 100mph, which is the maximum speed allowed by FAA regulations
2. Range - The drone must be capable of reaching a 30 mile radius
3. VTOL - Vertical takeoff and landing. This is essential in order to deliver and pick up packages in tough to reach places.

4. Payload Capacity - We are planning to use a small AED on our drone which weighs about 2 pounds.

Although these are the specs we want for our final iteration, this year we focused on building a functional hybrid quadcopter, rather than trying to meet the specifications above.

Existing Technologies

Exploration of hybrid drone technology has rapidly expanded over the recent years, and therefore has taken many shapes. Aircraft can be piloted with an on-board human, using radio-control, or autonomously.

They can be used for leisure, industry specific sensory data applications (cinema cameras, crop maintenance, military surveillance), or payload delivery.

Figure 1: 'Cora' by Wisk

Figure 2: 'Wing' by Google

Figure 3: UberEats' drone

Theory

The advantages UAVs have over the transportation options today is the ability to get from point A to point B in a straight line quickly, efficiently, and autonomously. There are two established types of UAVs to consider, VTOL (vertical take-off and landing) drones, and fixed wing drones, each having their own advantages. The third type is a hybrid between both fixed wing drones and quadcopters. Figure 4 below shows that hybrids end up being the dominant technology for many applications.

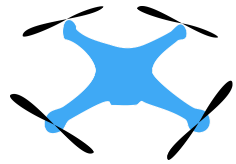
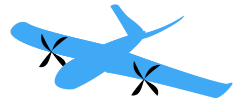
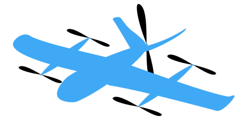
UAV Capability Matrix	 **Vtol**	 **Fixed Wing**	 **Hybrid**
Speed	✖	✔	✔
Range	✖	✔	✔
Efficiency	✖	✔	✔
Payload Capacity	✔	✖	✔
Stability in Harsh Conditions	✖	✔	✔
Malfunction Recovery Safety	✖	✔	✔
Vertical Takeoff/ Landing	✔	✖	✔
Ease of Use	✔	✖	✖
Size / Portability	✔	✖	✖

Figure 4: A comparison of capabilities of the three types of UAVs

Analysis

Airfoils generate lift when propelled forward, and drones generate forward movement when propelled upward. Can we combine these two features to create a more efficient aircraft? How much energy do we save? How much faster does this make us? What if we add a thrust-vectored propeller? These are the questions we set out to answer.

The initial analysis we made was a free-body-diagram force-balance on the steady state velocity of a quadcopter and hybrid drone. Figure 5 below illustrates our approach.

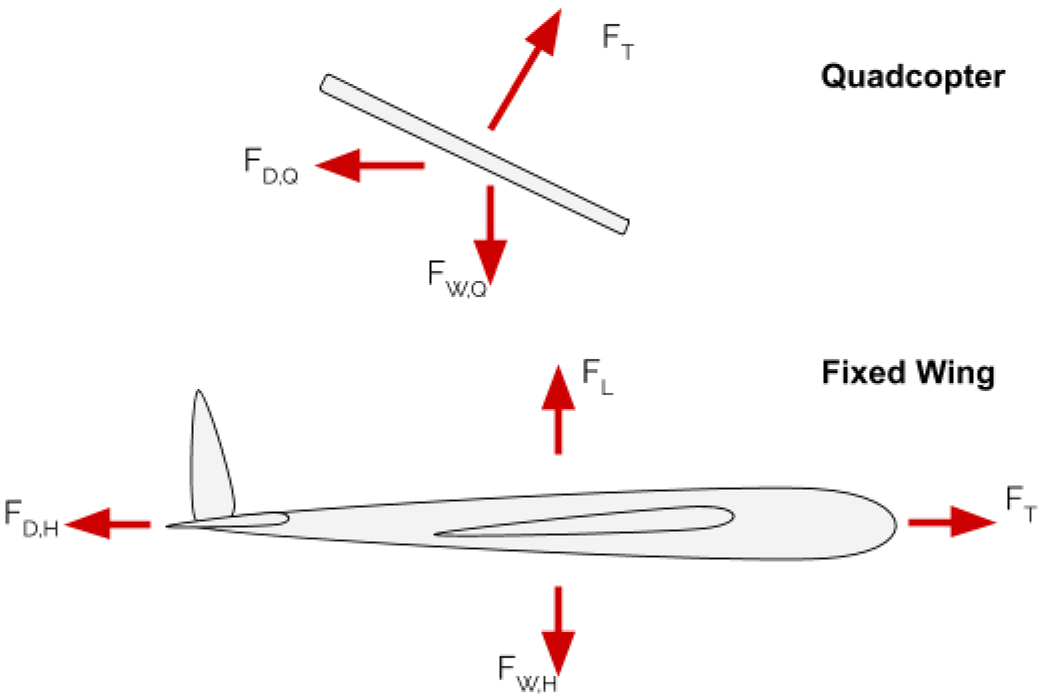


Figure 5: Free Body Diagram of Drones

Given an identical thrust force, power, and airframe (other than the wings), we related the velocity of a quadcopter and a hybrid at cruise. This means that parameters such as mass and maximum thrust are the same for both. Assuming no vertical motion and constant horizontal velocity, we know the sum of the forces along these axes is zero. Starting with the quadcopter:

$$F_{D,Q} = F_T\ sin(30) = \frac{F_T}{2} = \frac{1}{2}\rho S_Q U_Q^2 C_{x,Q} \qquad (1)$$

Rearranged:

$$\frac{F_T}{\rho} = S_Q U_Q^2 C_{x,Q} \qquad (2)$$

Now for the hybrid drone:

$$F_{D,H} = F_T = \frac{1}{2}\rho S_H U_H^2 C_{x,H} \qquad (3)$$

Rearranging to solve for the velocity:

$$U_H = \sqrt{\frac{2\,F_T}{\rho\,S_H\,C_{x,H}}} \qquad (4)$$

Substituting equation 2 into equation 4, we get:

$$U_H = \sqrt{\frac{2\,S_Q U_Q^2 C_{x,Q}}{S_H\,C_{x,H}}} \qquad (5)$$

Simplifying, this becomes:

$$U_H = U_Q \sqrt{2 \frac{S_Q C_{x,Q}}{S_H C_{x,H}}} \qquad (6)$$

This tells us that the difference in speeds depends on the increase in planform area and coefficient of drag. While the planform area will most certainly have to become larger due to the wings, if the horizontal cross section can be optimized the coefficient of drag can potentially be reduced for a hybrid. Assuming $S_Q = S_H$ and $C_{x,Q} = C_{x,H}$, then U_H is $\sqrt{2}$ times greater than U_Q, or 41% greater. A more realistic assumption would be $S_Q C_{X,Q} / S_H C_{X,H}$ = 75%, which would give us a velocity roughly 25% quicker. This also means we can get 25% more range with the same amount of power as a quadcopter. We wanted to test this theory in reality with our prototype, however, given the COVID-19 situation, we were not able to get flight test results.

DESIGN, PROTOTYPES & TESTING

Manufacturing Methods

Throughout the duration of this project, manufacturing has always posed a challenge, as the success of our drone flight was highly linked to the quality of the manufacturing and fabrication. We used commonplace hand and power tools, such as allen keys and drills, to fabricate various aspects of the drone with standardized hardware. For each rendition of our design, we utilized 3D printing additive manufacturing technology to print the structural components of the drone. For future iterations, if attempted, will use higher quality materials for greater structural integrity and decreased weight, such as carbon fiber tubes and plates. However, due to the minimal costs and ease of manufacturability associated with using 3D printing, we were able to rapidly produce multiple parts as well as spares for our early design attempts, allowing us to constantly churn out new parts with "OK enough" structural properties for flight. Although these parts would break pretty easily when crashing the drone during flight testing, the fact that we would always have multiple spares allowed us to replace the broken parts very quickly.

For V1, the 3D printed components included the main structural body where the electronics were placed, and the four motor arms where each motor/propeller would be placed. For V2, the design changed quite a bit, and the structural components requiring 3D printing included the main fuselage and electronics housing, the fixed wings, and the four motor arms protruding from the wings. These designs will be discussed in greater detail in a later section. We used *Creality Ender-3* 3D printers to print all structural parts using PLA as our filament of choice. By tinkering with infill density settings, print temperature and speed, and other configuration options, we were able to find the perfect settings for mass-producing parts for our purposes.

Another important aspect of the manufacturing process was the electronics configuration. Several design iterations involved changing placement of electronics or adding holes/conduits into 3D printed structural parts in order to add ease of wired connectability between electronics. All electrical connections were enforced using plugs or soldered connections. Throughout the entire project, it is clear that most roadblocks came from the lack of being able to create strong electrical connections. These obstructions in our manufacturing occured from not having the proper type of solder material, or just not being careful/precise enough with our solder placement.

Commercial Off-the-Shelf (COTS) Parts

After reading some drone-racing literature, we were essentially introduced to all the starting components we would need: a flight controller (FC), electronic speed controller (ESC), a battery, some motors and rotors.

XRotor provided a very convenient FC and ESC combo that was easy to integrate, compatible with many commercial sensors, and was designed to be used with Betaflight.

Betaflight is an open source flight controller configurator. It allows you to calibrate and configure various features based on your system design, sensor suite, and transmitter capabilities. Shown below is a component breakdown of all COTS components used in our drone.

Part	Brand
Flight Controller	XRotor Flight Controller F4 G2 w/OSD
ESC	Hobbywing XRotor Micro 60A 6S 4-in-1 BLHeli32 ESC FPV Drone Racing
Motor (4x)	Rs2205-2300kV
Propellers (16x)	DALPROP 16pcs Cyclone T5046C 5046 3 Blades
Lipo Battery	GOLDBAT 1300mAh 4S 100C 14.8V Softcase Lipo Battery Pack

FPV Camera	RunCam Swift 2 600TVL CCD FPV Camera Integrated OSD 2.1mm Lens FOV 165 Degree DC 5-36V
Antenna	FOXEER FPV Antenna Lollipop V3 Super Mini RHCP Antenna 5.8G 2.5dBi SMA Male and Female RP-SMA Male
Receiver	FPVKing Flysky FS-iA6B Receiver 6-Channel 2.4G 6CH
VTX	Team BlackSheep TBS UNIFY PRO 5G8 V2 (SMA)
Transmitter	Turnigy 9X 9Ch Transmitter

Figure 6: COTS Component Breakdown

Wiring Schematic

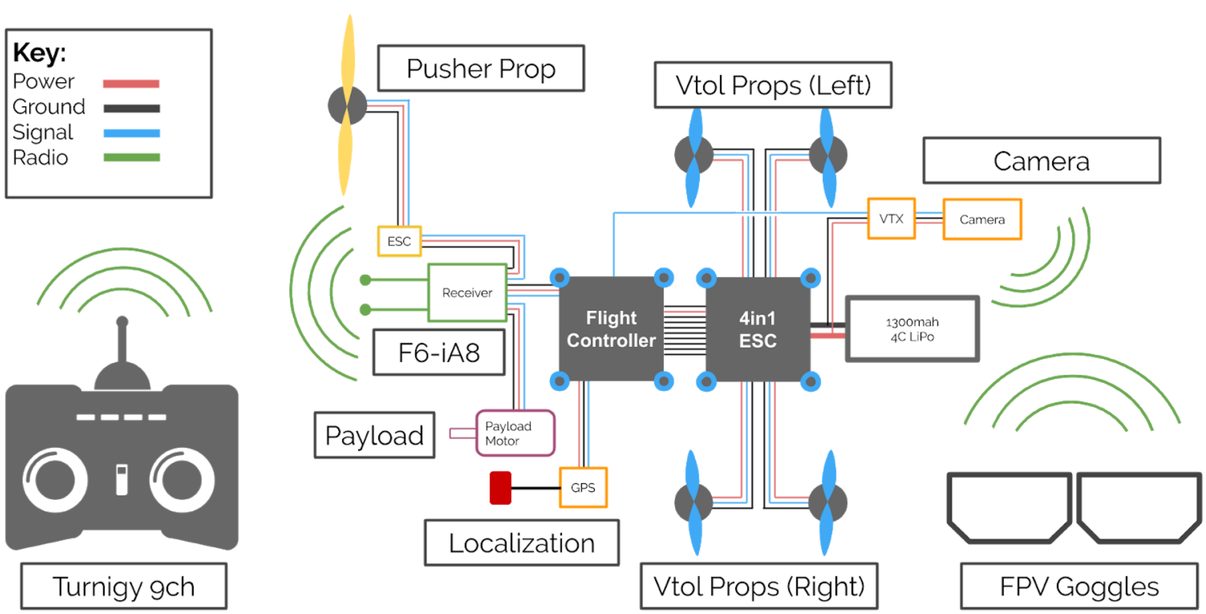


Figure 7: Wiring Schematic

After deciding on building a hybrid, we decided on the following wiring schematic. We use components used commonly in competitive quadcopter racing, and with some slight hardware modification, we are able to integrate a pusher prop which acts independently of the system. Since we have VTOL props already installed, there is no need for ailerons or empennages since we still have the ability to control pitch, yaw, and roll. This drastically simplifies the system. In further iterations, we'd like to have props that act as both VTOL props and pusher props depending on whether or not the plane is in cruise mode. We didn't do this because it would require a complicated feedback system.

V1.0

Our first prototype was just to test our ability to build a drone from scratch, which none of us have ever done. We created a simple quadcopter, which used the same flight controller and motors that we would eventually use for our hybrid quadcopter.

Figure 8: V1.0

The design focused on ease of access and replaceability. Quadcopter frames are generally made out of carbon fiber, or some other strong composite. We decided to 3D print our frame, despite PLA being much more brittle. This allowed us to make modifications as we built. The drone was also built to be easily replaced since we would all be learning to fly for the first time on it.

The first iteration was designed to be crashed. The arms are significantly weaker than the body, so that in the case of a crash, an arm will break and absorb the impact before fracturing the body. The arms are easily replaced by removing two locking pins and replacing the broken arm with a new one. The battery was accessible through the bottom, and all the electronics were accessible through the top.

V1.1

Whenever we crashed our V1.0, the motor arms would break nearly every time. In order to reduce these common fractures, we shortened the motor arms in order to reduce the maximum torque stress per crash. We also added a rib feature to both sides of the motor arms. As a result of these new design edits, the fractures occurred less frequently and we were able to spend more time in the flight testing phase.

V1.2

We modified our quadcopter frame using drills and electrical tape to see if we could get the camera, FPV, and GPS. The goal was to see if we could fly the drone using FatShark FPV goggles, and track the location. Unfortunately, we never took an image of V1.2 and never modified the cad to demonstrate our changes.

V2.0

V2 was our first attempt at a hybrid fixed wing UAV. In order for our two systems to work together independently, we ensured that the plane flies level to the ground with a slope of zero and an angle of attack of zero when cruising. We use the feedback system provided in betaflight along with the gyroscope in our flight controller to make sure that the drone is level throughout the cruise.

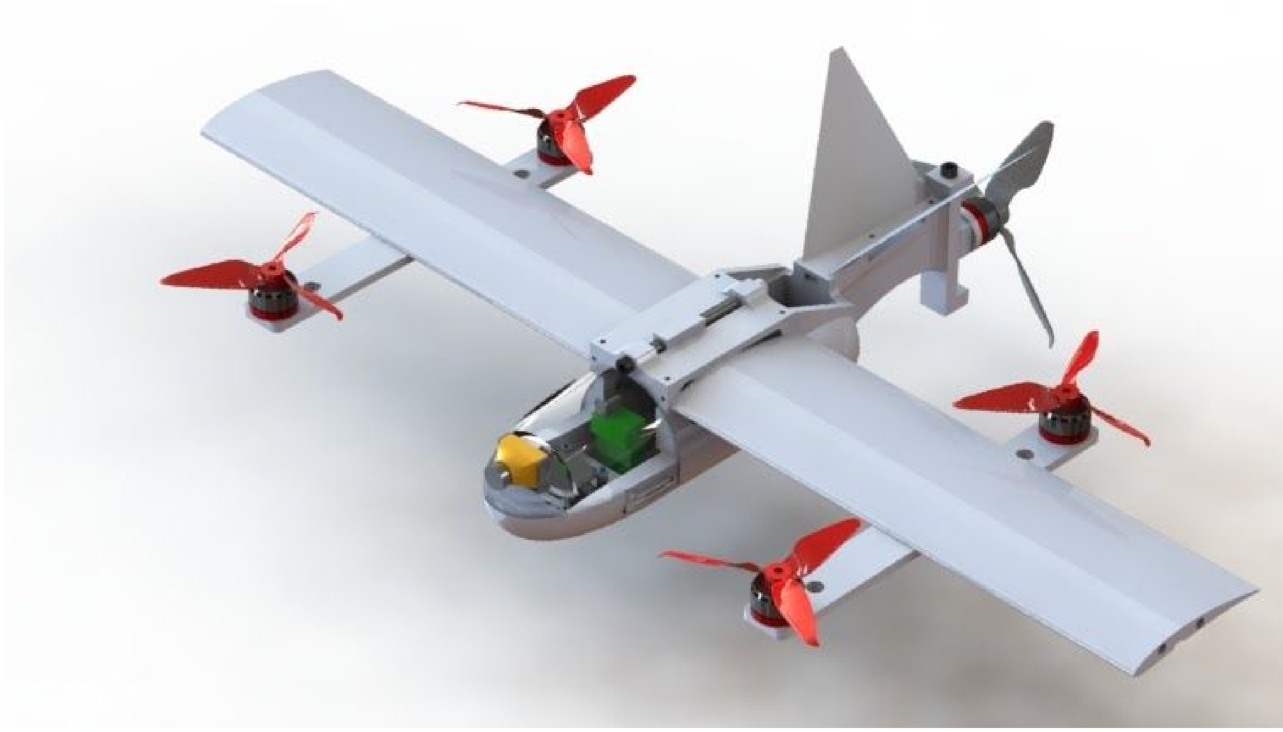


Figure 9: V2.0

Adjustable Airfoil Assembly

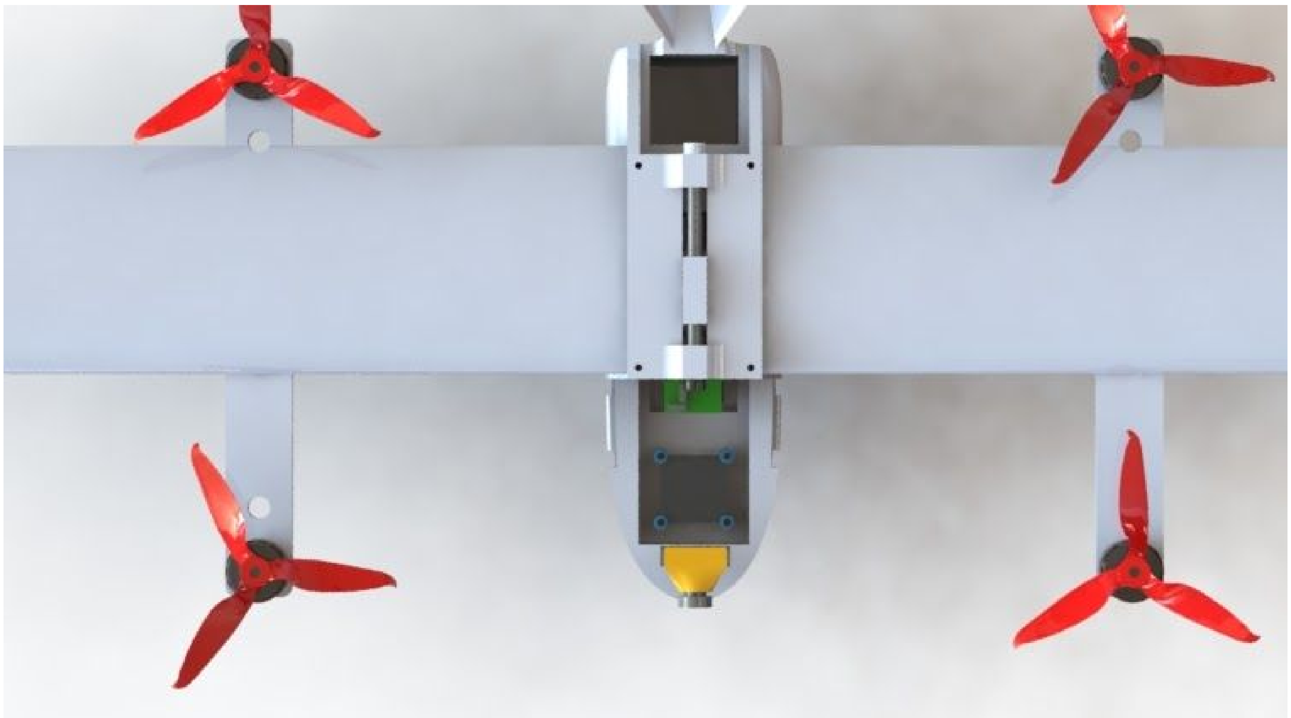


Figure 10: Overhead View of Airfoil Adjustment Mechanism

The airfoil assembly is built out of 4 PLA wings, with a 2% infill, compared to the rest of the drones 20% infill. This is to keep the wings as light as possible. The wings are supported structurally by two ¼ in dowel rods that run horizontally through the entire airfoil assembly. The wing is split into 4 pieces for easy replaceability.

In order to empirically find and control the center of mass of the aircraft, the wing assembly needed to be adjustable. The props are mounted such that they are equidistant from 25% of the chord length. The center of gravity of the system is aligned at 25% of the airfoil chord; however, since we weren't certain about the weight distribution with all of our componentes, the airfoil assembly is mounted on a threaded rod which can be threaded in order to tune the weight distribution.

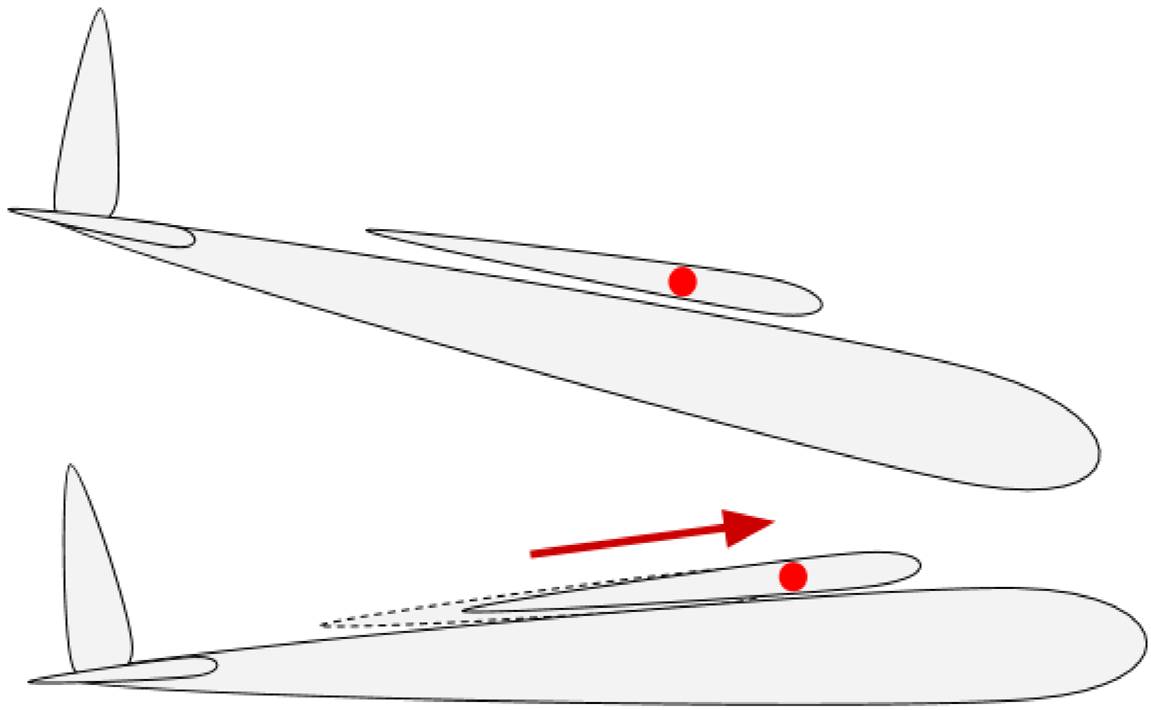


Figure 11: Depiction of Adjustable Airfoils

We found the center of gravity by fixing the aircraft wings at 25% of the chord length. This is indicated by the red dot. If the aircraft wasn't level, the airfoil was adjusted such that the body had zero slope. In the example above, the airfoil was too far back, so we adjusted it forward. We now know exactly where the center of gravity is in the horizontal plane.

Thrust Motor Assembly

The center of thrust must go through the vertical center of mass of the drone in order to eliminate pitching moments. The rear pusher motor was mounted on a sliding rod, similar to the airfoil system. Once the horizontal center of gravity is found, the wing tips are pinned along the center of gravity, and the rear is pushed until there is no moment. The diagram below shows how the thrust motor mount location was decided.

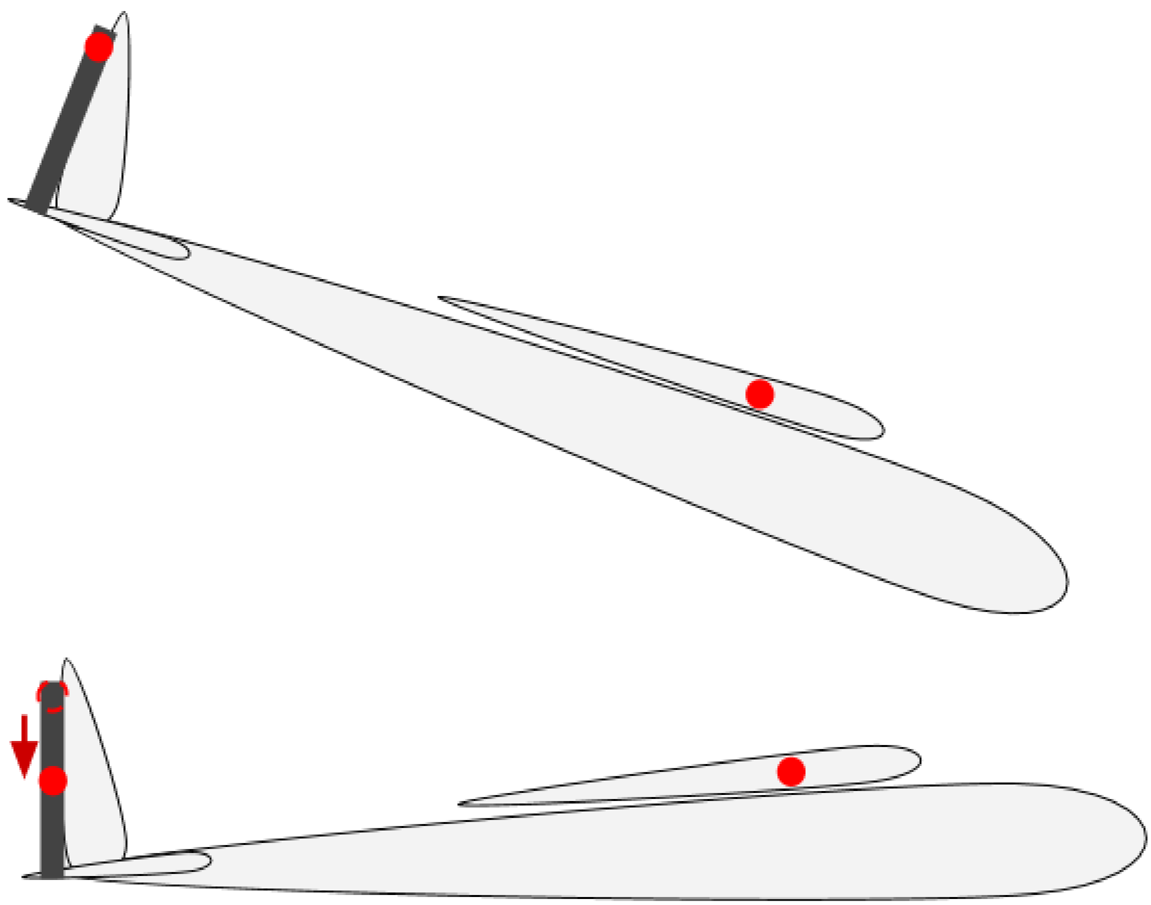


Figure 12: Depiction of Adjustable Back Propeller

Electronic Housing

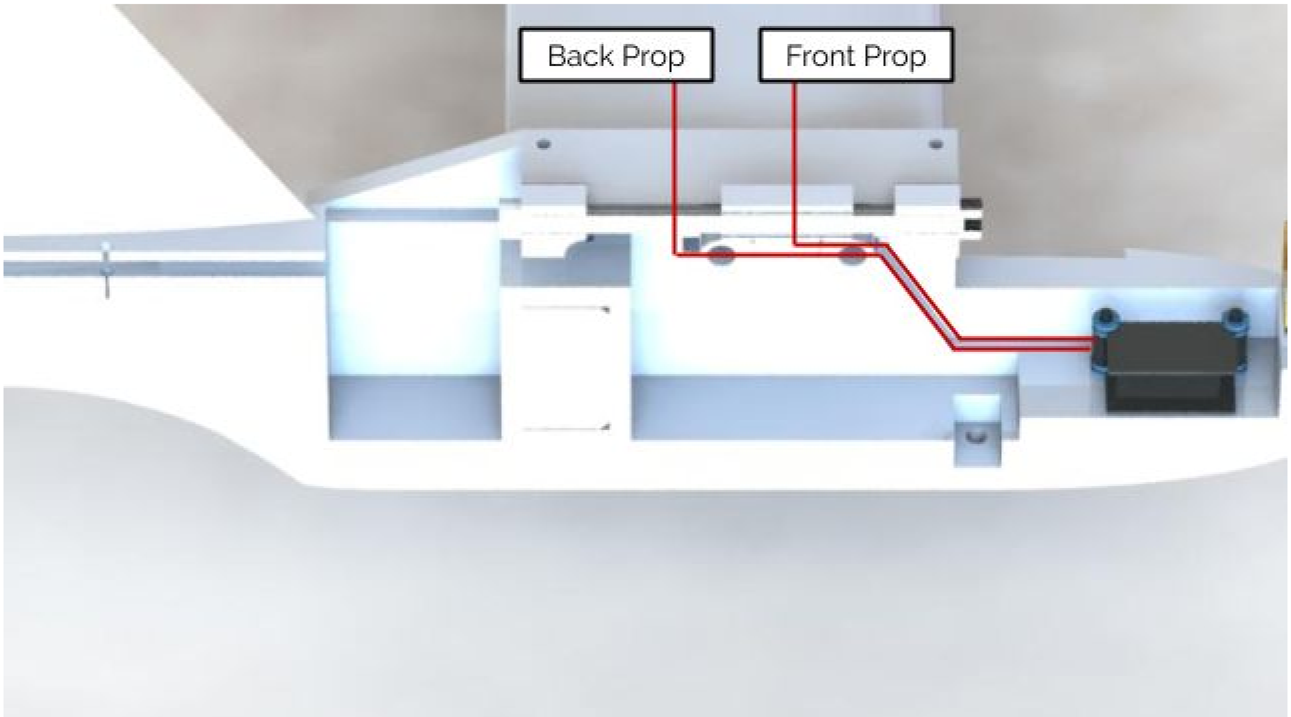


Figure 13: Depiction of Interior Electronic Housings

In this iteration we concealed all our wires since we were already familiar with the schematics and knew we wouldn't need to do as much maintenance. Channels are cut out of the frame to allow wires to pass through the walls. The prop wires then exit the fuselage through a slit which leads directly into the airfoils.

BUSINESS VENTURE

Hoplite

While this was primarily an engineering project, there was also serious consideration in turning it into a business venture. The initial driving factors for the research and design that went into this project have hard facts suggesting that this would be a successful endeavour. The following reiterates the primary problem that the drone concept would be providing a solution to by ultimately saving lives. The company name for this project is Hoplite.

Every year 360,000 Americans experience out-of-hospital sudden cardiac arrest (SCA), of which 90% will not survive. This healthcare crisis is the leading cause of death in the United States for people over 40, and chance of survival is primarily dependent on the victim's proximity to a hospital or an automated external defibrillator (AED). Every minute that someone is in SCA without an AED reduces their chance of survival by 10%. It takes between 8 and 12 minutes for first responders to arrive on the scene, reducing the survival chance to 0% - 20%.

Our solution to this problem is to deliver AEDs to people in SCA up to 3 times faster using medical delivery drones. The high speeds our drone can fly at will allow it to reach someone in need far quicker than an ambulance could, which could amount to saving 130,000 American lives every year. The general idea is for a 911 dispatcher to send the drone to the location of the caller, with an ambulance on the way as well. By getting the drone there before the ambulance, the AED can be applied several minutes before first responders get there. Equipped to our drone will be a small monitor where a teledoctor will be on a live stream. From their end, they will be able to assess the situation and give the bystanders clear and concise instructions on how to help the patient with the delivered equipment.

Our target market is EMS companies that operate in high population rural areas. Since the rural areas are the regions where travel is most constrained by land features, this is where the drone's ability to avoid obstacles is most appealing. In addition to the AED, the modular design of our drone allows us to expand to different medical devices such as EpiPens and other emergency supplies. This will allow EMS companies to have multiple revenue streams using our drones. Furthermore, the improved VTOL hybrid design of our drone is significantly faster and more efficient than competitors.

Figure 14: Potential Product Offering

COVID-19 Pivot

The novel coronavirus (COVID-19) has quickly become a global crisis and delivering tests to everyone who needs it is currently impossible. Americans everywhere must first see their general practitioner to get signed up for a test, schedule a time for a drive-thru test, then await results as they are transported to labs with the right equipment. During this potential multi-week process, unwitting patients will inevitably infect others. Once the self-administered COVID-19 test kits that are currently being developed are readily available, our private and federal delivery infrastructure will struggle to distribute them effectively. As we approach the peak of the number of cases affected by the virus, it will become more and more important to expedite the process by which people receive test results while still keeping them isolated from the rest of the public.

Our solution is to deliver these test kits via drone within Tompkins County. This will supplement the current municipal delivery infrastructure while reducing the contact necessary in producing test results and mitigating the spread of the virus. Our plan is to target those most vulnerable in hard to reach places.

By delivering test kits to people at their homes using drones, it completely eliminates the risk of human interaction with a potentially contaminated test kit. In other words, it cuts out the middleman and ultimately ramps up the pace at which these test kits can be distributed. The envisioned delivery procedure is as follows: the test kit will be equipped to our drone's payload carrying mechanism and delivered to the patient's home directly. The test kit will be deployed from the payload mechanism in the patient's front yard or equivalent. Once the patient has completed the test, they will then request a pickup drone, which will arrive shortly. The patient will leave the test kit outside. The pickup drone, which has not had any contact with anyone, will then come pick up the test kit.

Our initial target market is the population in rural areas, who may be located far away from medical centers or delivery routes. This demographic also tends to be much older and more economically vulnerable, which during this crisis translates to a larger desire to stay at home. With 15% of the county's 105,000 people being age 65 or older and 17% living in poverty, we estimate a demand for over 20,000 tests in Tompkins County from people with a greater desire to stay at home and less means to drive to testing centers.

The feedback received so far is encouraging for future development of this business idea and we may pursue it further in the near future.

ACKNOWLEDGEMENTS

Matt Ulinski - We would like to thank Matt for his steady help and guidance throughout the duration of this project. As our advisor, Matt played a large role in helping us design our initial concepts and schedule of deliverables. He was also incredibly valuable in helping us obtain our commercial parts and making sure we had all the necessary supplies and facilities that were needed during the prototyping and manufacturing phases of our journey. Matt kept us grounded throughout the entire academic year and also connected us with multiple other individuals who were helpful to our endeavour.

Andrea Ippolito & Alex Hagen - We would also like to thank Andrea and Alex for taking time out of their busy schedules to provide entrepreneurial guidance for our business venture. The hours they spent helping us refine our pitch decks and competition strategies were invaluable to us.

APPENDIX

Individual Contributions

<u>Max Kester (Sr.)</u>

Project:

Firstly on the design, I researched existing technologies and theories to influence the design and features of our drone. Using Joaquin's SolidWorks, I analyzed and iterated our CAD models and supported 3D-splicing efforts to prototype parts. Next, I was working on the hardware integration of our purchased parts. Soldering wires and boards, fastening sensors and actuators to the airframe, and performing tolerancing during assembly.

Report:

Regarding this report, I contributed most to the research and design V2 sections.

<u>Leo Andriuk (M.Eng)</u>

Project:

For this project, I was largely involved on the systems engineering and business development side, forming a concept of operations through research and detailing requirements to be met in order for the drone to add value in the lives of everyday people. I also helped with manufacturing and fabrication of the drone throughout design iteration.

Report:

For the report, I contributed by writing the summary, manufacturing methods, and business venture sections. We all worked together to create figures and format the report properly.

Joaquin Jerez (M.Eng)

Project:

I did most of the CADing since I had the Solidworks on my computer. I was also heavily involved in mechanical/electrical prototyping. We split almost everything evenly.

Report:

I focused on the hybrid theory and comparison between quadcopters, fixed wings, and hybrids. I also wrote a good portion of the prototype section.