PLAN-E Design Report
ME 171E

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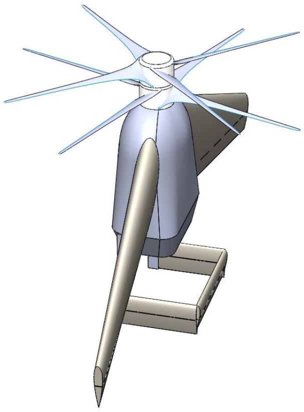
1 Executive Summary

Our mission is to empower birth control users through regularly scheduled monthly pill delivery, reducing emissions through optimized multi-stop routes via aerial robot, by four students, in seven weeks. We accomplish this mission through autonomous one-way flight with 10x 20g birth control packages payload on a 17-mile, 10-stop route, using the sea-breeze effect, with precision ballistic drop delivery.



Our project is a novel interpretation in the drone-delivery space for several reasons. Firstly, instead of delivering a single unique item, we are delivering ten identical, lightweight items to ten customers. Our problem therefore involves optimizing a delivery route given a map with 10 customers. Secondly, our trip is one-way. Drone redistribution teams will collect the post-flight drones from designated pickup locations and bring them back to the takeoff location (not unlike LimeBike). Given the one-way nature of our mission, we seek to use the 'sea-breeze' effect to extend our drone's range, which will play into the route optimization algorithm. Finally, range, rather than speed, is the driving factor of our design, as the delivery cycle is regularly scheduled. This novel interpretation of the drone-delivery problem led us to an ultimately unique design that is likely applicable to other business models in the future.

In our proof-of-concept scaled delivery demo, we were able to deliver 3 pill packets to 3 unique customers each 50 meters apart. From our drop altitude of 10 meters, we were able to control the accuracy of our delivery radius to 1.0 m. The delivery sequence was actuated by the pilot remotely through the transmitter.

Our final design is a contraprop with two active rotors during hover and one during cruise that weighs approximately 6 kg with a payload capacity of 0.5 kg. The unmanned aerial vehicle (UAV) requires 12.4 N of thrust during cruise and 32 N per prop during hover. With the addition of the XRotor and XFLR5 designs, our aircraft's range is approximately 95 kilometers, consuming 502 W during hover and 360 W during cruise.

Figure 1: PLAN-E in hover (top left) and cruise configuration (bottom right)

2 Our Mission

Figure 2: Team 2 and Mission Ideation

Team 2 hosted an additional brainstorming session outside of the hours spent in class, and narrowed a set of fifty initial ideas down to five final ideas using a round-robin process of elimination. Our five final drone delivery ideas included immediate epipen delivery, reducing the at-home storage of a drug in short supply, a walk-home-safely drone equipped with safety tools and a recording device, jumper cable service for stranded vehicles in remote locations, and N-95 mask delivery for neighborhoods at risk for wildfire, reducing the delivery-related risks to human life. The following is our trade-off table.

	Weight	**Walk Home Safely**	**Epipen**	**Birth Control Pills**	**Jumper Cables**	**Wildfire Masks**
Feasibility (Technical)	**40%**	1	4	4	2	3
Scalability/Users	**10%**	5	4	5	3	2
Impact/Need	**20%**	5	5	4	2	4
Efficiency (goal)	**10%**	2	3	3	2	4
Uniqueness of Problem/Solution	**10%**	5	3.5	3.5	3.5	3.5

Safety (Risk of Failure)	**5%**	2	1	5	4	1
Safety (Drone Danger)	**5%**	2	2	2	1	4
Total Score		**2.8**	**3.8**	**3.9**	**2.3**	**3.2**

Table 3: Mission Ideation and Tradeoff Table

Our decision criteria included two different safety factors, one for the consequences to human life if the delivery could not be completed, i.e. how much extra danger are the recipients put in if the delivery is not completed, and the other for the risk to human life if the drone were to malfunction. Our remaining factors included the feasibility to manufacture and implement our mission, the potential energy and manufacturing efficiency of our solution, originality, as well as potential for impact and number of prospective users. Our idea for monthly, multi-stop birth control delivery scored the highest, due to its relative safety, scalability, and impact.

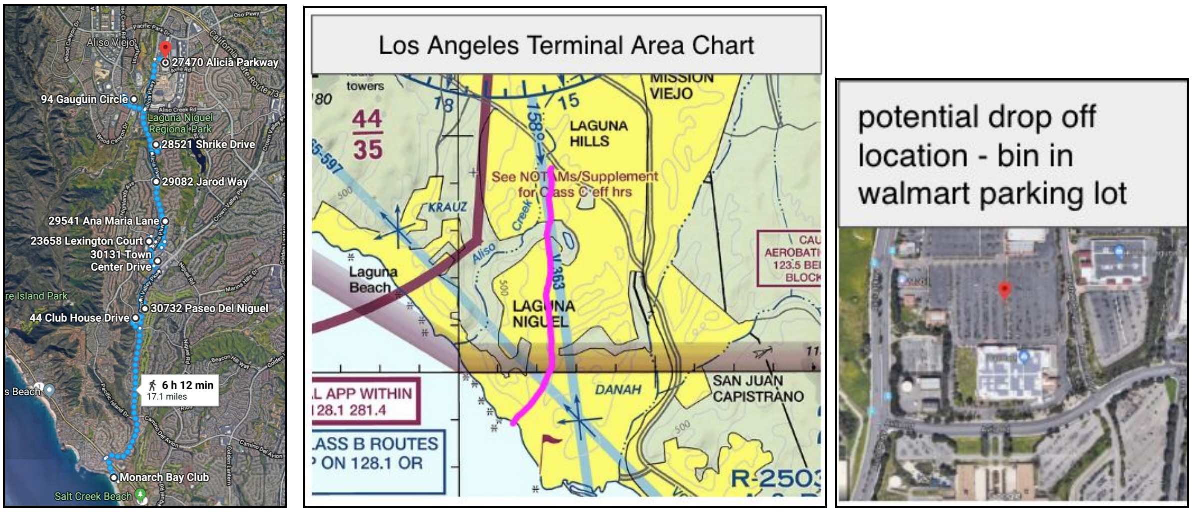


Figure 4: Mission Route, Including Airspace Diagram and Dropoff Location

We chose Lagunita Niguel, Lagunita Hills, and Mission Viejo, just south of Los Angeles and clear of LAX International Airport airspace, for our 10-stop birth control delivery. A sea-to-inland route during the daytime allows our drone to utilize a sea-breeze tailwind to enhance the range of our unmanned aerial vehicle (UAV).

Flight Route Optimization

A key aspect of our delivery mission is flight route optimization for several customers across a map. To solve this flight route optimization problem, our team seeks to input drone range, customer locations, takeoff and landing locations, and the wind velocity vector into an algorithm which outputs a route optimized for the maximum number of customers reached. Below is an illustration of a sample decomposition of this real-world problem into a manageable computer problem. Given a set of points and a fixed distance (range available), calculate the route between two points (takeoff and landing) which maximizes the number of customers reached.

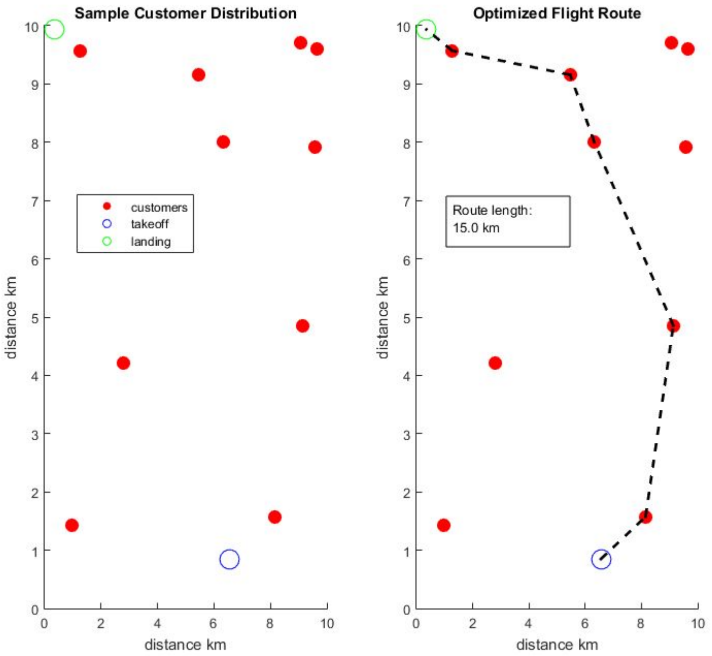


Image 5: Sample Flight Route Optimization Graphic

While we did not actually code a solution to this problem, we theorized how it might have been solved in ‘pseudocode.’ Our approach was a dynamic programming solution which would treat distance as an integer (meters, for resolution). The program would start at the takeoff point and attempt incrementally larger distance values until it was able to reach another point. It would leap-from from point to point, storing the maximum number of points reached for various combinations, while decreasing the ‘available range remaining’ as it progresses down the path. The path would be stored in a secondary table, and the ‘solution’ could be found by backtracking through this secondary table once the landing location was reached. Limitations to this current model include that it does not minimize the distance in a possible solution, rather stops once it reaches the landing point node. (Or states ‘flight route impossible’ if the range is insufficient.) It also neglects the effect of tailwind, which would increase the range of our drone dramatically. Our model could be expanded significantly to include tailwind effects, and also using multiple drones in concert to serve the maximum number of customers. Finally, our model could even suggest pickup sites for our redistribution crews to stage in anticipation for our delivering drones.

3 Systems Engineering

We began our systems engineering process by fully defining our mission through objective and needs statements and subsequently defining the structure and flow associated with our UAV flight and the work to be done throughout the quarter.

Project Objective Statement

The 'Project Objective Statement' is a brief description of what has to be done with what resources (Design System Engineering Lecture 7). Our project objective statement:

Empowering birth control users through regularly scheduled monthly pill delivery, reducing emissions through optimized multi-stop routes via aerial robot, by four students, in seven weeks.

Mission Need Statement

The 'Mission Need Statement' is a concise description of the functions that the project's result will have to perform (Design System Engineering Lecture 7); our mission statement follows:

Autonomous one-way flight with 10x 20g birth control packages payload on a 17-mile, 10-stop route, using the sea-breeze effect, with precision ballistic drop delivery.

Functional Flow Diagram

Our functional flow diagram (Design Systems Engineering Lecture 7) displays the sequence of steps involved in flying our drone, broken down into overall process step, actions, modal changes, and desired inputs.

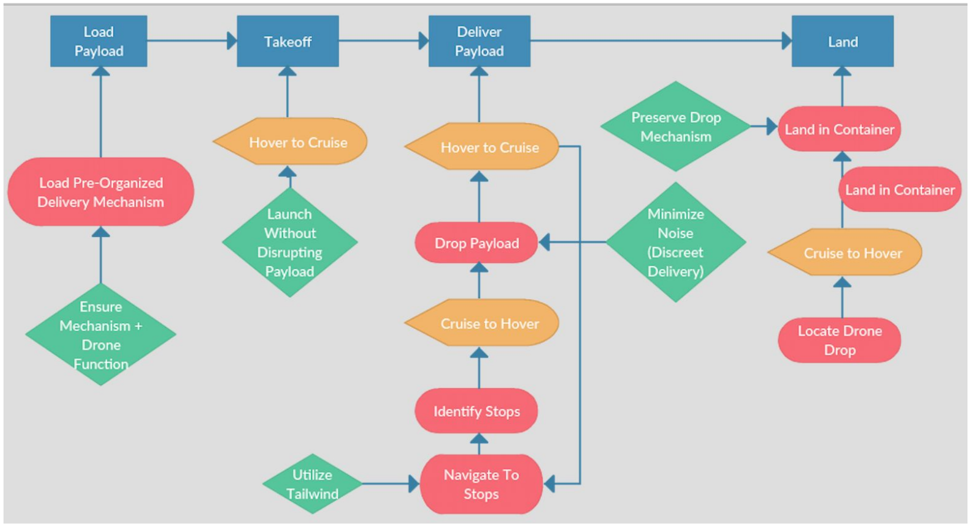


Figure 6: Functional Flow Diagram

Functional Breakdown Structure

Our functional breakdown structure (Design Systems Engineering Lecture 7) displays overall tasks involved in flying our drone, broken down into overall process, actions, and desired secondary steps.

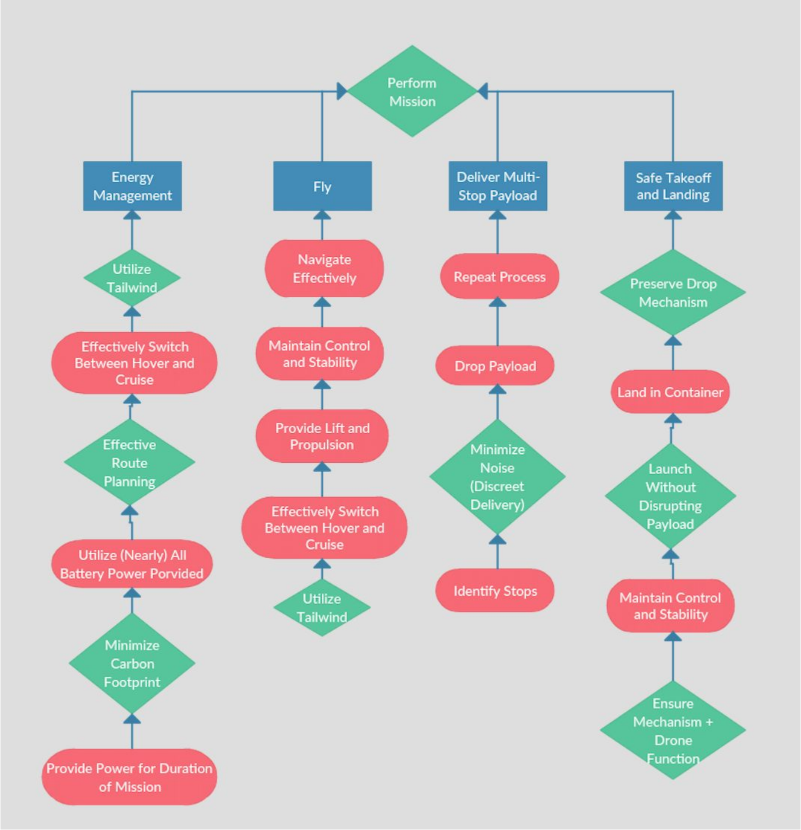


Figure 7: Functional Breakdown Structure

Requirements Discovery Tree

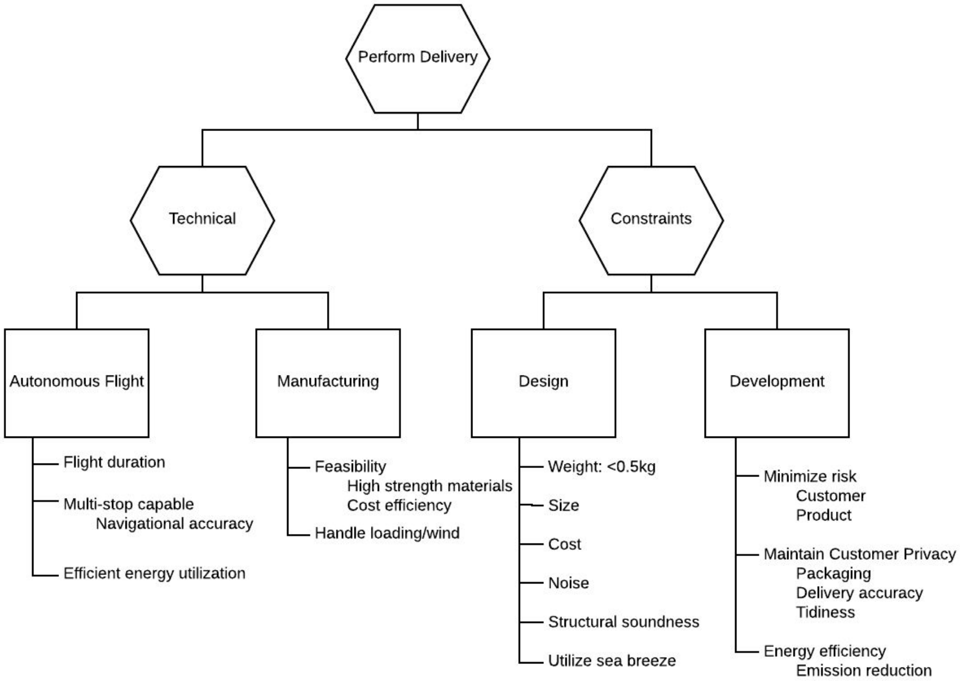


Figure 8: Requirements Discovery Tree

Work Flow Diagram

The ‘Work Flow Diagram’ connects required ‘project activities’ via inputs and outputs, navigating design opportunities by being mindful of process. (Design System Engineering Lecture 7).

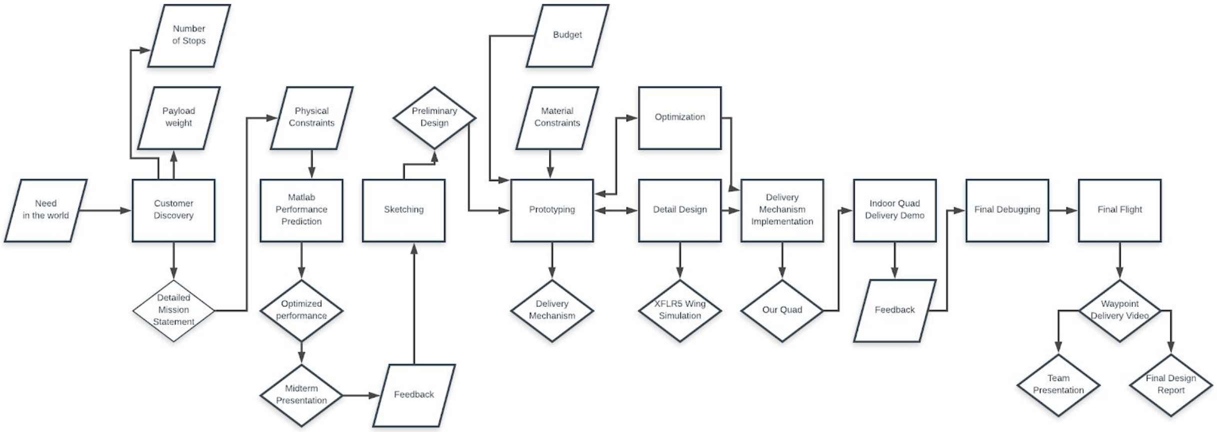


Figure 9: Work Flow Diagram

Work Breakdown Structure

The 'Work Breakdown Structure' outlines group 'project activities' in general phases of the project, to create work packages based off the Work Flow Diagram. (Design System Engineering Lecture 7).

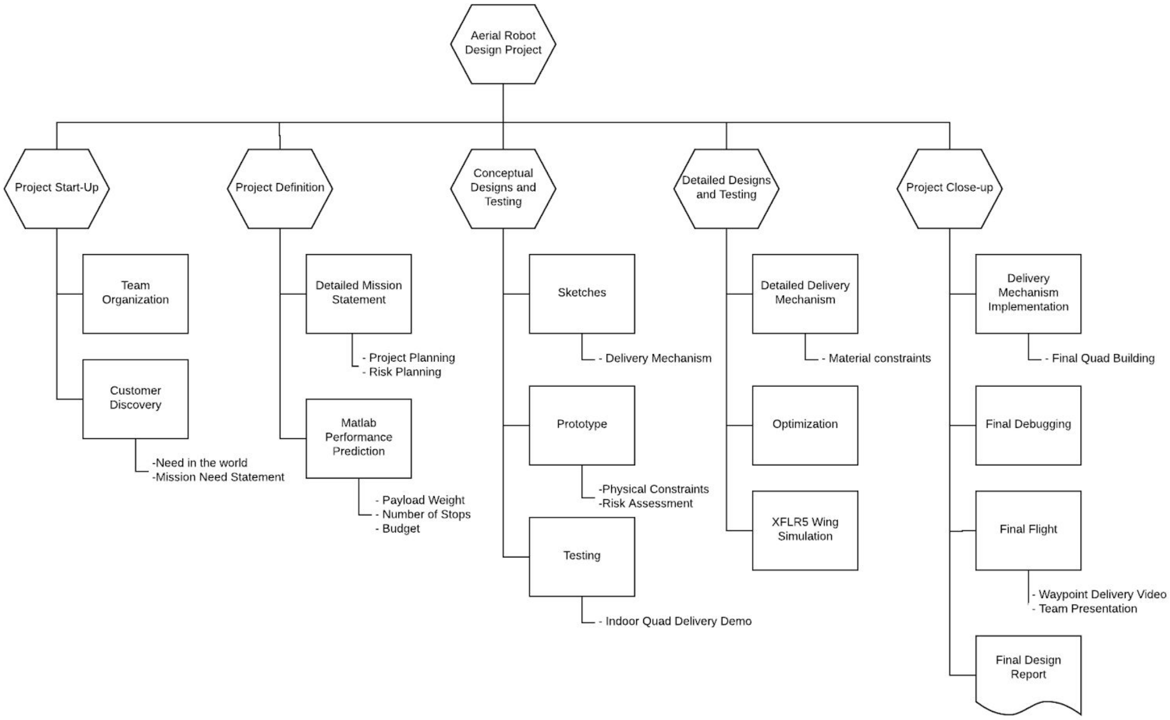
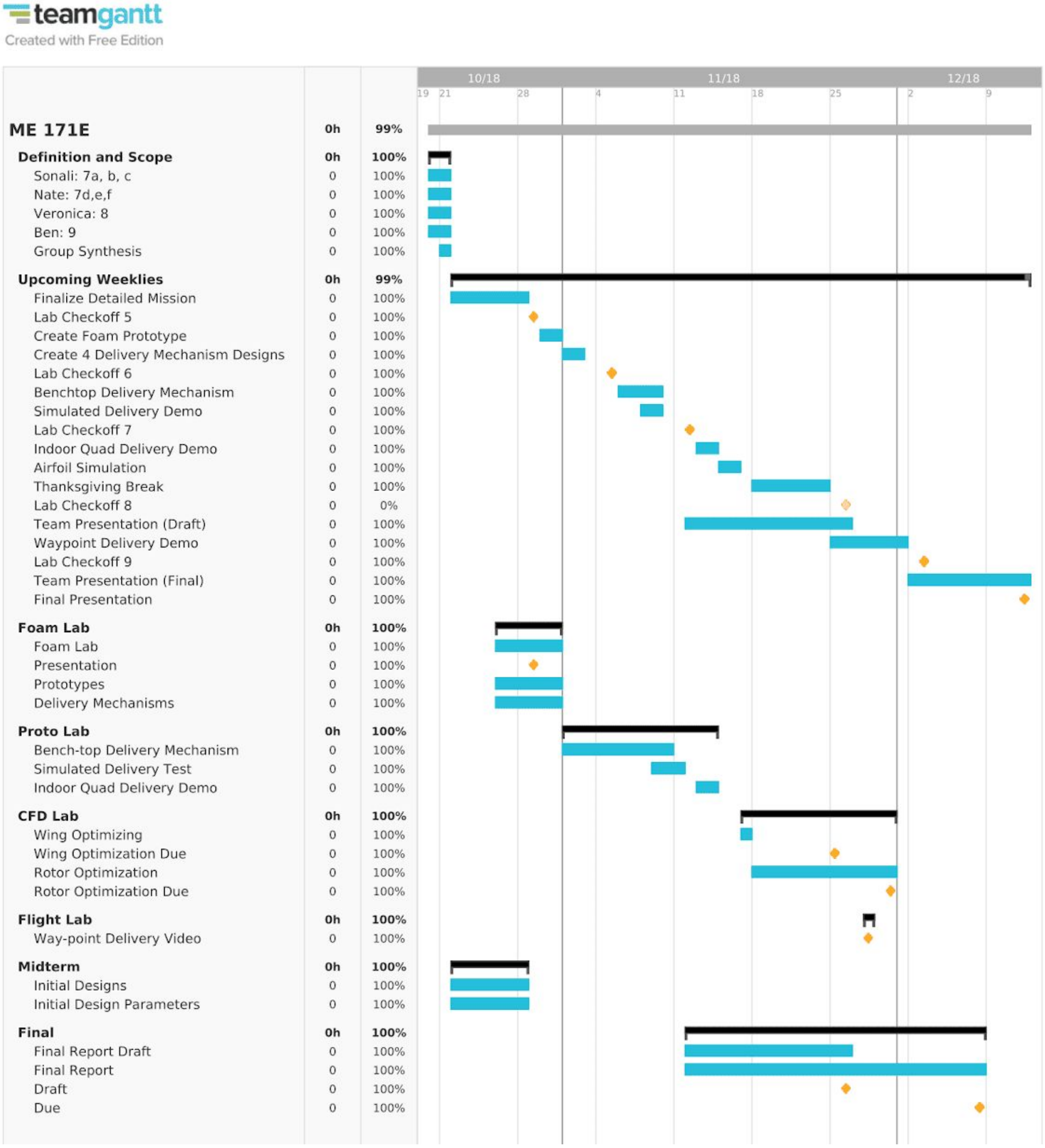


Figure 10: Work Breakdown Structure

Gantt Chart



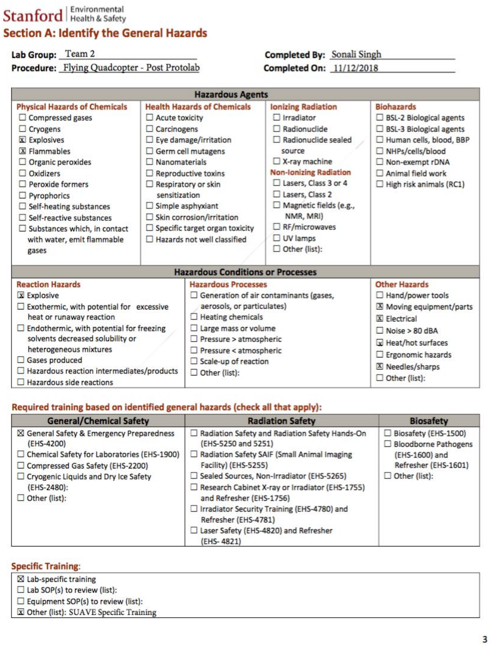
ME 171E	**0h**	**99%**
Definition and Scope	**0h**	**100%**
Sonali: 7a, b, c	0	100%
Nate: 7d,e,f	0	100%
Veronica: 8	0	100%
Ben: 9	0	100%
Group Synthesis	0	100%
Upcoming Weeklies	**0h**	**99%**
Finalize Detailed Mission	0	100%
Lab Checkoff 5	0	100%
Create Foam Prototype	0	100%
Create 4 Delivery Mechanism Designs	0	100%
Lab Checkoff 6	0	100%
Benchtop Delivery Mechanism	0	100%
Simulated Delivery Demo	0	100%
Lab Checkoff 7	0	100%
Indoor Quad Delivery Demo	0	100%
Airfoil Simulation	0	100%
Thanksgiving Break	0	100%
Lab Checkoff 8	0	0%
Team Presentation (Draft)	0	100%
Waypoint Delivery Demo	0	100%
Lab Checkoff 9	0	100%
Team Presentation (Final)	0	100%
Final Presentation	0	100%
Foam Lab	**0h**	**100%**
Foam Lab	0	100%
Presentation	0	100%
Prototypes	0	100%
Delivery Mechanisms	0	100%
Proto Lab	**0h**	**100%**
Bench-top Delivery Mechanism	0	100%
Simulated Delivery Test	0	100%
Indoor Quad Delivery Demo	0	100%
CFD Lab	**0h**	**100%**
Wing Optimizing	0	100%
Wing Optimization Due	0	100%
Rotor Optimization	0	100%
Rotor Optimization Due	0	100%
Flight Lab	**0h**	**100%**
Way-point Delivery Video	0	100%
Midterm	**0h**	**100%**
Initial Designs	0	100%
Initial Design Parameters	0	100%
Final	**0h**	**100%**
Final Report Draft	0	100%
Final Report	0	100%
Draft	0	100%
Due	0	100%

Figure 11: Gantt Chart

The Gantt chart plans ‘Work Breakdown Structure’ tasks by dividing project into marked key milestones and review points.

<u>SHARP Analysis</u>

Screenshots of our Hazard Assessment for Research Procedures, required to thoroughly fill out prior to a test flight of our UAV, follow:



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Section A: Identify the General Hazards

Lab Group: Team 2
Procedure: Flying Quadcopter - Post Protolab
Completed By: Sonali Singh
Completed On: 11/12/2018

Hazardous Agents

Physical Hazards of Chemicals
- ☐ Compressed gases
- ☐ Cryogens
- ☒ Explosives
- ☒ Flammables
- ☐ Organic peroxides
- ☐ Oxidizers
- ☐ Peroxide formers
- ☐ Pyrophorics
- ☐ Self-heating substances
- ☐ Self-reactive substances
- ☐ Substances which, in contact with water, emit flammable gases

Health Hazards of Chemicals
- ☐ Acute toxicity
- ☐ Carcinogens
- ☐ Eye damage/irritation
- ☐ Germ cell mutagens
- ☐ Nanomaterials
- ☐ Reproductive toxins
- ☐ Respiratory or skin sensitization
- ☐ Simple asphyxiant
- ☐ Skin corrosion/irritation
- ☐ Specific target organ toxicity
- ☐ Hazards not well classified

Ionizing Radiation
- ☐ Irradiator
- ☐ Radionuclide
- ☐ Radionuclide sealed source
- ☐ X-ray machine

Non-Ionizing Radiation
- ☐ Lasers, Class 3 or 4
- ☐ Lasers, Class 2
- ☐ Magnetic fields (e.g., NMR, MRI)
- ☐ RF/microwaves
- ☐ UV lamps
- ☐ Other (list):

Biohazards
- ☐ BSL-2 Biological agents
- ☐ BSL-3 Biological agents
- ☐ Human cells, blood, BBP
- ☐ NHPs/cells/blood
- ☐ Non-exempt rDNA
- ☐ Animal field work
- ☐ High risk animals (RC1)

Hazardous Conditions or Processes

Reaction Hazards
- ☒ Explosive
- ☐ Exothermic, with potential for excessive heat or runaway reaction
- ☐ Endothermic, with potential for freezing solvents decreased solubility or heterogeneous mixtures
- ☐ Gases produced
- ☐ Hazardous reaction intermediates/products
- ☐ Hazardous side reactions

Hazardous Processes
- ☐ Generation of air contaminants (gases, aerosols, or particulates)
- ☐ Heating chemicals
- ☐ Large mass or volume
- ☐ Pressure > atmospheric
- ☐ Pressure < atmospheric
- ☐ Scale-up of reaction
- ☐ Other (list):

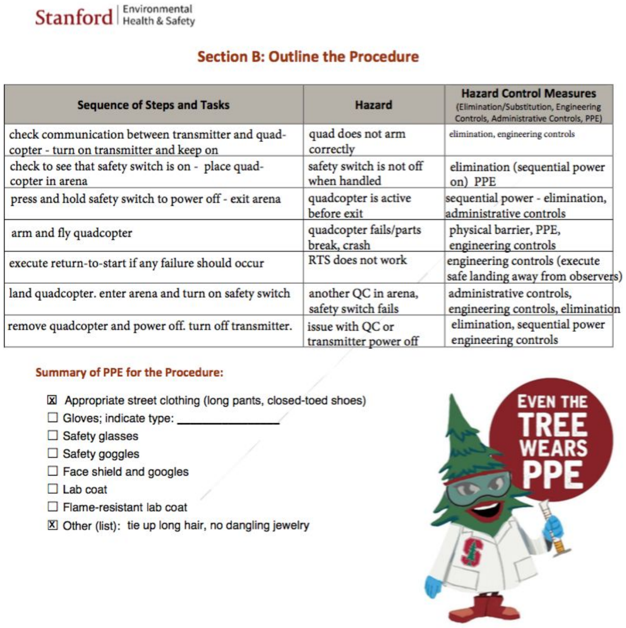
Other Hazards
- ☐ Hand/power tools
- ☒ Moving equipment/parts
- ☒ Electrical
- ☐ Noise > 80 dBA
- ☒ Heat/hot surfaces
- ☐ Ergonomic hazards
- ☒ Needles/sharps
- ☐ Other (list):

Required training based on identified general hazards (check all that apply):

General/Chemical Safety	Radiation Safety	Biosafety
☒ General Safety & Emergency Preparedness (EHS-4200) ☐ Chemical Safety for Laboratories (EHS-1900) ☐ Compressed Gas Safety (EHS-2200) ☐ Cryogenic Liquids and Dry Ice Safety (EHS-2480): ☐ Other (list):	☐ Radiation Safety and Radiation Safety Hands-On (EHS-5250 and 5251) ☐ Radiation Safety SAIF (Small Animal Imaging Facility) (EHS-5255) ☐ Sealed Sources, Non-Irradiator (EHS-5265) ☐ Research Cabinet X-ray or Irradiator (EHS-1755) and Refresher (EHS-1756) ☐ Irradiator Security Training (EHS-4780) and Refresher (EHS-4781) ☐ Laser Safety (EHS-4820) and Refresher (EHS- 4821)	☐ Biosafety (EHS-1500) ☐ Bloodborne Pathogens (EHS-1600) and Refresher (EHS-1601) ☐ Other (list):

Specific Training:
- ☒ Lab-specific training
- ☐ Lab SOP(s) to review (list):
- ☐ Equipment SOP(s) to review (list):
- ☒ Other (list): SUAVE Specific Training

3



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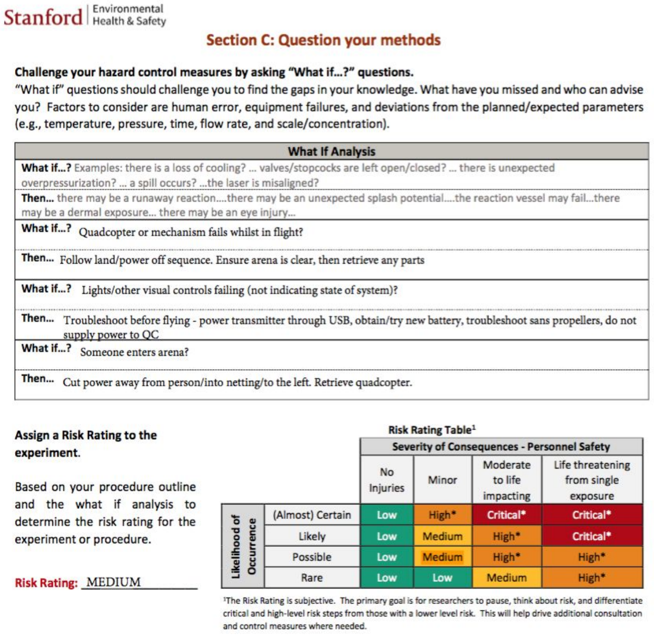
Section B: Outline the Procedure

Sequence of Steps and Tasks	Hazard	Hazard Control Measures (Elimination/Substitution, Engineering Controls, Administrative Controls, PPE)
check communication between transmitter and quad-copter - turn on transmitter and keep on	quad does not arm correctly	elimination, engineering controls
check to see that safety switch is on - place quad-copter in arena	safety switch is not off when handled	elimination (sequential power on) PPE
press and hold safety switch to power off - exit arena	quadcopter is active before exit	sequential power - elimination, administrative controls
arm and fly quadcopter	quadcopter fails/parts break, crash	physical barrier, PPE, engineering controls
execute return-to-start if any failure should occur	RTS does not work	engineering controls (execute safe landing away from observers)
land quadcopter. enter arena and turn on safety switch	another QC in arena, safety switch fails	administrative controls, engineering controls, elimination
remove quadcopter and power off. turn off transmitter.	issue with QC or transmitter power off	elimination, sequential power engineering controls

Summary of PPE for the Procedure:

- ☒ Appropriate street clothing (long pants, closed-toed shoes)
- ☐ Gloves; indicate type: ______________
- ☐ Safety glasses
- ☐ Safety goggles
- ☐ Face shield and googles
- ☐ Lab coat
- ☐ Flame-resistant lab coat
- ☒ Other (list): tie up long hair, no dangling jewelry



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Section C: Question your methods

Challenge your hazard control measures by asking "What if…?" questions.
"What if" questions should challenge you to find the gaps in your knowledge. What have you missed and who can advise you? Factors to consider are human error, equipment failures, and deviations from the planned/expected parameters (e.g., temperature, pressure, time, flow rate, and scale/concentration).

What If Analysis
What if…? Examples: there is a loss of cooling? … valves/stopcocks are left open/closed? … there is unexpected overpressurization? … a spill occurs? …the laser is misaligned?
Then… there may be a runaway reaction….there may be an unexpected splash potential….the reaction vessel may fail…there may be a dermal exposure… there may be an eye injury…
What if…? Quadcopter or mechanism fails whilst in flight?
Then… Follow land/power off sequence. Ensure arena is clear, then retrieve any parts
What if…? Lights/other visual controls failing (not indicating state of system)?
Then… Troubleshoot before flying - power transmitter through USB, obtain/try new battery, troubleshoot sans propellers, do not supply power to QC
What if…? Someone enters arena?
Then… Cut power away from person/into netting/to the left. Retrieve quadcopter.

Assign a Risk Rating to the experiment.

Based on your procedure outline and the what if analysis to determine the risk rating for the experiment or procedure.

Risk Rating: MEDIUM

Risk Rating Table[1]

Likelihood of Occurrence		Severity of Consequences - Personnel Safety			
		No Injuries	Minor	Moderate to life impacting	Life threatening from single exposure
	(Almost) Certain	Low	High*	Critical*	Critical*
	Likely	Low	Medium	High*	Critical*
	Possible	Low	Medium	High*	High*
	Rare	Low	Low	Medium	High*

[1] The Risk Rating is subjective. The primary goal is for researchers to pause, think about risk, and differentiate critical and high-level risk steps from those with a lower level risk. This will help drive additional consultation and control measures where needed.

<u>Figure 12: SHARP Analysis</u>

4 Configuration

Our team produced four midterm configuration designs with varying qualities and capabilities.

The Contra(Ception)

2 Contra-Prop Tilt-Wing-Body

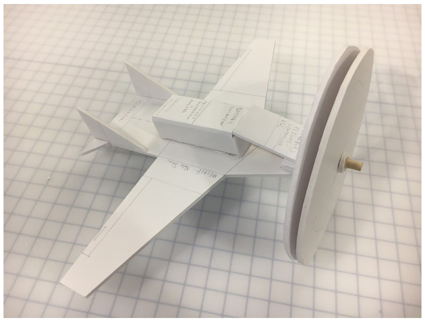


Figure 13

This small and semi-conventional design has a tilt-wing body which allows for rapid hover-to-level transition. The design is optimized for cruise and ‘good enough’ for hover. The maximum range was 46 km. Disadvantages included that it was difficult to control, had a CG shift, had large propellers, and was mechanically complex.

The Vertik00Ler

8 Prop Tilt-Wing-Body

Figure 14

The large design of the Vertik00ler allows space for many different propeller configurations. The large props mean low RPM, and there are no complicated parts. The maximum range achieved was 44 km. Disadvantages include a greater safety risk (due to the large and heavy design), higher cost, an a reduced ease of operation.

Pro-pill-sion

4 Props (Hover) + 4 Props (Cruise)

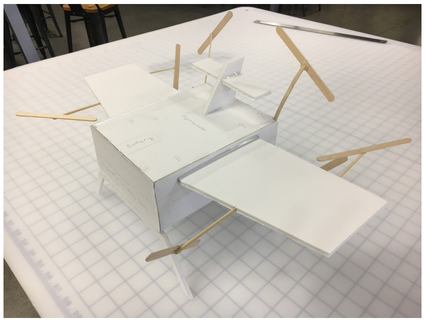


Figure 15

The Pro-pill-sion is small, compact, and simple. It sports a fast hover-cruise transition, has a maximum range of 18 km, and the CG does not shift during cruise. Disadvantages include idle (unused) props which add weight and add drag, and a lower range.

Tilt-Win(nin)g

4 Prop Tilt-Wing

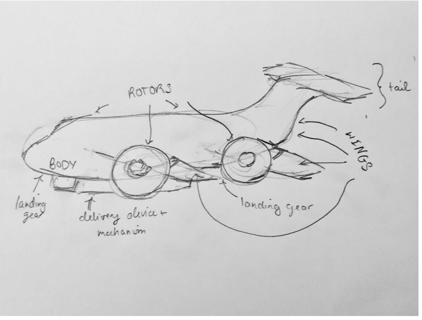


Figure 16

This design is efficient and non-disruptive during take-off and landing (it allows for conventional runway takeoffs) and has a range of 27km. Disadvantages include an expensive transition, reduced hover control, reduced safety during package drop, an incompact structure, and a complex mechanical system.

	Contra(ception)	**Vertik00ler**	**Pro-pill-sion**	**Tilt-win(nin)g**
Range (km)	46	44.4	19	27
Mass (kg)	6.22	14.62	5.17	5.68
Wingspan (m)	1.0	2.0	1.0	1.0
Cruise Rotors	1	8	4	4
Hover Rotors	2	8	4	4

Table 17: Performance Specifications of Midterm Configuration Results

These results informed our trade-off table. In our table, we weighted mission range, efficiency, feasibility, and ease of transition as the most important factors. However, our ‘fit with delivery mechanisms’ criteria ended up pushing the Contra(Ception) into the winning position. As we developed our delivery mechanism, we realized that having gravity act in the same direction as our ejection was exceedingly helpful. Only Vertik00ler and Contra(Ception) satisfied that criteria, being tilt-body aircraft.

Criteria/Design	**Weight %**	**Contra(Ception)**	**Vertik00ler**	**Pro-pill-sion**	**Tilt-win(nin)g**
Efficiency	15	5.0	3.0	2.5	3.0
Mission Range	25	3.0	5.0	3.0	3.0
Cost	5	3.0	2.0	4.0	4.0
Footprint (Environmental)	5	3.0	3.0	2.0	3.0
Fit with Delivery Mechanism	5	4.0	5.0	5.0	4.0
Feasibility (Manufacturing)	15	3.0	2.0	5.0	3.0
Ease of Transition	15	4.0	4.0	5.0	3.0
Safety	5	2.0	2.0	2.0	2.0
Fit With Chosen Delivery Mechanism	10	5.0	4.0	1.0	3.0
Total /5		**3.7**	3.6	3.4	3.3

Table 18: Drone Configuration Trade-Off Table

Given the results of our trade-off table, we chose to move forward with the Contra(ception) tilt-wing-body design.

Figure 19: Initial Contra(Ception) Configuration Design

Constraints on our robot are determined by our mission. Given the multi-stop delivery requirement, total hover time (which significantly reduces range) must be sufficient to complete the delivery sequence at 10 stops. Therefore, we chose a hover time of 175 s (17.5 s per customer, which was proven to be more than enough in our delivery mechanism tests). This should compensate for transition time. Other constraints include a 1.0 meter wingspan (to be maneuverable in urban spaces and easily redistributable), and a payload mass of more than 0.5 kg. Given our initial delivery scenario, our drone also needs to achieve a range of 40 km (with a safety factor of 1.5, ignoring the positive effects of the sea-breeze effect).

We optimized our design for the following parameters: number of propellers, payload mass, cruise velocity, wingspan, aspect ratio, propeller diameter, and hover time. The findings were relatively straightforward. Number of propellers was reduced for cruise (as cruise requires less thrust). Wingspan was maximized, thus 1.0 m (our constraint). Aspect ratio was optimized at around 6, and velocity at around 25.3 ms^{-1}. Range increased with propeller diameter, which is why we ended up with a 0.48 m diameter prop.

Geometric	**Value**	**Mass**	**Value**	**Propeller**	**Value**	**Aero**	**Value**
Chord Length	16.7 cm	Payload	1.5 m	No. Props	1,2	Cruise	25.3 m/s
Wingspan	1.0 m	Battery	4.00 kg	Name	APC 9x6	Hover time	175 s
Area	0.17 m^2	Total	6.22 kg	No. Blades	2	Level Time	23.6 min
Aspect Ratio	6			Diameter	0.47 m	Range	35.8 km
AirFoil	23112						

Figure 20: Critical Performance Specifications Chart

5 Wing Design

The final design of the PLAN-E wing includes a main wing, elevated tail, and double-fin extending from the bottom of the tail, as shown in Figure 21 below. Battery mass, payload, and body masses were modeled as point masses.

Figure 21: Screenshot of XFLR Simulation of PLAN-E Wing

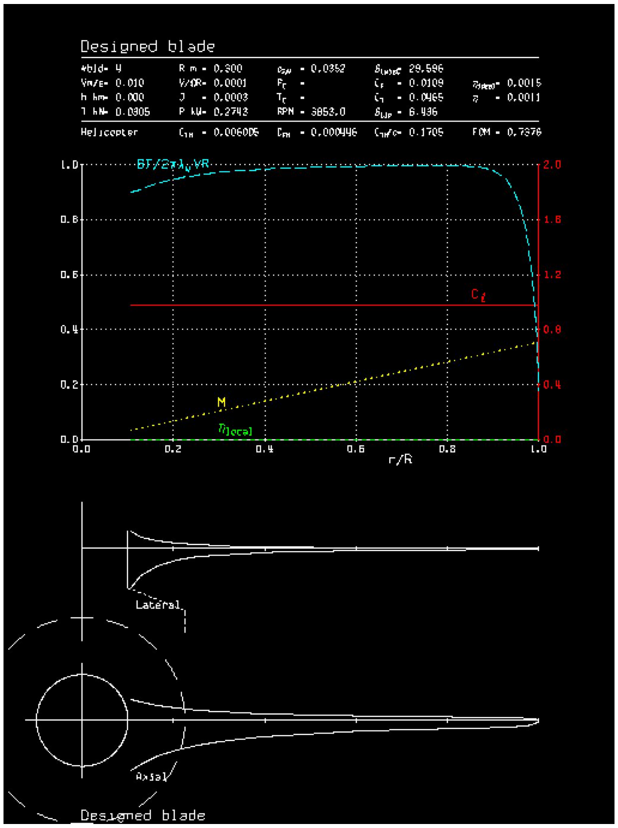
Our initial polars indicated a Cm-alpha curve with a negative slope, indicating stability; however, our curve displayed a negative Cm at zero. To shift the Cm-alpha curve of the wing, the dihedral and twist angles of the wing were altered, with final angles of two and five degrees, respectively. The locations of the point masses were also shifted, to change the tilt of the wing at our angle of attack. Lastly, we selected NACA 23018 as our final airfoil, with a slightly thicker and more uniform profile, to increase our Cm. At our desired lift coefficient of approximately 0.97, our angle of attack (AoA) for this wing is four degrees. At our AoA, the Cm-alpha curve shows a Cm value of 0.002, extremely close to zero. Our design did not converge for AoAs greater than four degrees.

Figure 22: Screenshots of Polars from the Final Design for PLAN-E in XFLR5

Our final wing design provided a drag coefficient of 0.064, which replaced the initial value for CD0 in our midterm code. The resulting re-analysis resulted in an overall increase in our flight range of five meters, from 46 km to 51 km.

6 Rotor Design

Our rotor and wing design processes were iterative and dependant upon our converged solution for the wing design, resulting updates to our midterm code, and subsequent alterations.



```
Designed blade
#bld= 4       R m = 0.300      σpw  = 0.0352     β0.75= 29.596
Vw/E= 0.010   V/ΩR= 0.0001     Pc   =            Cp   = 0.0109     ηideal= 0.0015
h km= 0.000   J   = 0.0003     Tc   =            CT   = 0.0465     η     = 0.0011
T kN= 0.0305  P kW= 0.2743     RPM  = 3852.0     βtip = 6.436
Helicopter    CTH = 0.006005   CPH  = 0.000446   CTH/σ= 0.1705     FOM   = 0.7376
```

Figure 23: XRotor Curves and Geometry for Chosen Design (Left: Hover, Right: Cruise)

Our final solution involved four blades and utilized the NACA 4412 airfoil. Changes are summarized in the table below. Contraprops utilize two rotors, and our design involves using both for hover and only one for its cruise. Values shown below are per propeller. Tradeoffs were made to increase our lift coefficient, leading to slightly higher power consumption than predicted in our initial CFD analysis. We utilize a rotor design with four blades, in part to enhance our UAV's ability to utilize the tailwind provided by the sea breeze along its inland route.

Change to Airfoil	Designation	Phover (per prop, kW)	Pcruise (kW)
2 to 3 Blades	Number of Blades	0.380	0.381
3 to 4 Blades	Number of Blades	0.374	0.374

0.200 to 0.300	Tip Radius	0.363	0.367
Slightly Less Steep Spline	Blade Chord Distribution	0.304	0.365
Shift Upward in Curve	Blade Twist Distribution	0.251	0.360

Table 24: Summary of Rotor Modifications

Our ultimate design was more efficient than both our midterm design, which consumed approximately 1,380 W during hover and 750 W during cruise; however, our ultimate design consumed more power than our initial CFD lab design, which consumed 480 W during hover and 250 W during cruise. Our final optimized rotor here consumes 502 W during hover and 360 W in cruise, likely due to an increase in our desired lift coefficient between parts one and two of our CFD lab, from approximately 0.75 to 0.97. This was coupled with a significant increase in the thrust required per propeller during both cruise and hover - leading to a more expensive final optimized rotor than our first CFD lab might have suggested, but a more efficient vehicle than predicted in our midterm, with a range of 95.24 km, Cp_{hover} = 0.0299 and Cp_{lift} = 0.0159.

Figure 25: Final PLAN-E Rotor Geometry with Four Blades and a Tip Radius of 0.3 m

7 Delivery Mechanism Design

For our mission, our team prototyped four different delivery mechanisms that could hold at least 10 pill units of 8.6cm x 5.4cm, and approximately 0.5cm thick. These were our initial designs:

- The Spring-Stapler: the pill units are stacked and pushed to one side by a spring which holds them in place. There is a narrow gap, the size of a pill unit, on the bottom of the box. An actuator pushes down the pill unit through the gap and delivers it.
  Because the spring holds the units in place, this configuration works horizontally and vertically.

Figure 26: The Spring-Stapler Prototype

- The Rotary: the units are stacked vertically in a box with open bottom. A gear at the bottom holds the units in place and rotates to deliver one of them while keeping the other units in place.
  This mechanism needs to be vertical since gravity is keeping the units in place.

Figure 27: The Rotary Diagram

- The Vending: inspired by vending machines, the units are stacked linearly in a helical pivot rod which rotates and pushes the units forward until they fall out of the open front. This design can also be modified to a linear actuator, like the one on the right.

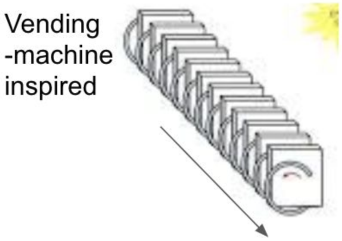


Figure 28: The Vending Diagram

- The Turnstile: the units are arranged in a circular pattern that rotates. A foldable one way latch covers the bottom hole when rotating in one direction and allows for the unit to be delivered when rotating in the opposite direction.
  This mechanism allows for out-of-sequence delivery, but it is less space efficient than the other three designs.

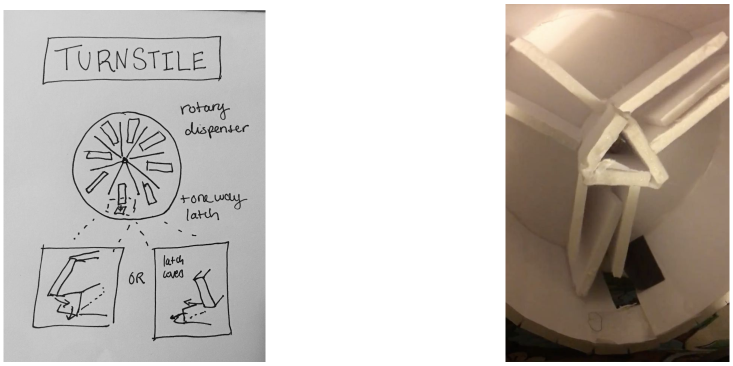


Figure 29: The Turnstile Diagram and Prototype

After prototyping and testing our four delivery mechanisms, we made a trade-off table with the design criteria relevant to us. Our most important factors were the manufacturing feasibility and the complexity of the actuation.

Criteria/Design	**Weight**	**I**	**II**	**III**	**IV**
Description		Spring-stapler	Rotary	Vending	Turnstile
Spatial Efficiency	10%	2.5	3	3	2
Allows for Delivery Out of Sequence	10%	2	2	2	5
Weight	20%	3	5	4	4
Feasibility (Manufacturing)	30%	3	3	3	3
Few Additional Parts/Actuators	30%	3	5	5	4
Score (X/5)		2.9	**3.9**	3.7	3.6

Figure 30: Delivery Mechanism Trade-Off Table

Delivery Mechanism Design

Our final delivery mechanism combines the best features of both the Rotary, our winning choice, and the Spring-Stapler. It has a capacity of 10 complete pill units. Each pill unit consists of a 1cm thick pill packet and an additional .5cm spacer to ensure appropriate spacing and uninterrupted delivery during operation. The latch is carefully designed to fit snugly into the gap created by the spacer, pulling on the bottom pill packet while it rotates while keeping the upper one contained inside. A tilted ledge on the opposite side to the latch keeps the unit in place, and allows it to slide out when the latch is in the right position.

The rod which holds the latch is attached to a 90 degree servo, which is programmed to three positions: high, neutral, and low, as shown in Figure 31.

We adapted a compression spring, from the Spring-Stapler design, so that the pill packets stay in place when PLAN-E is in cruise.

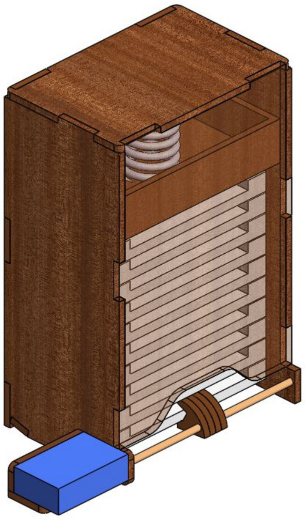


Figure 31: Delivery Mechanism and Internal Component View

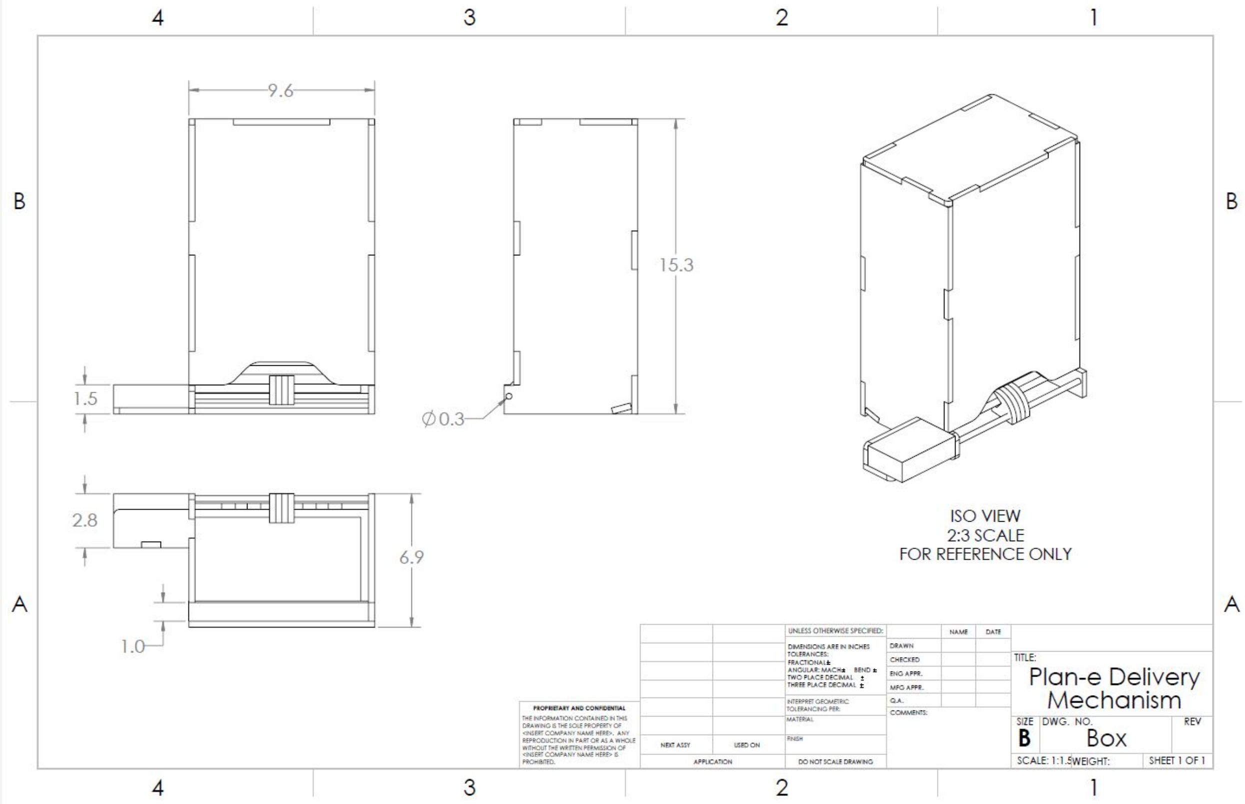


Figure 32: Delivery Mechanism Engineering Drawing with Relevant Dimensions

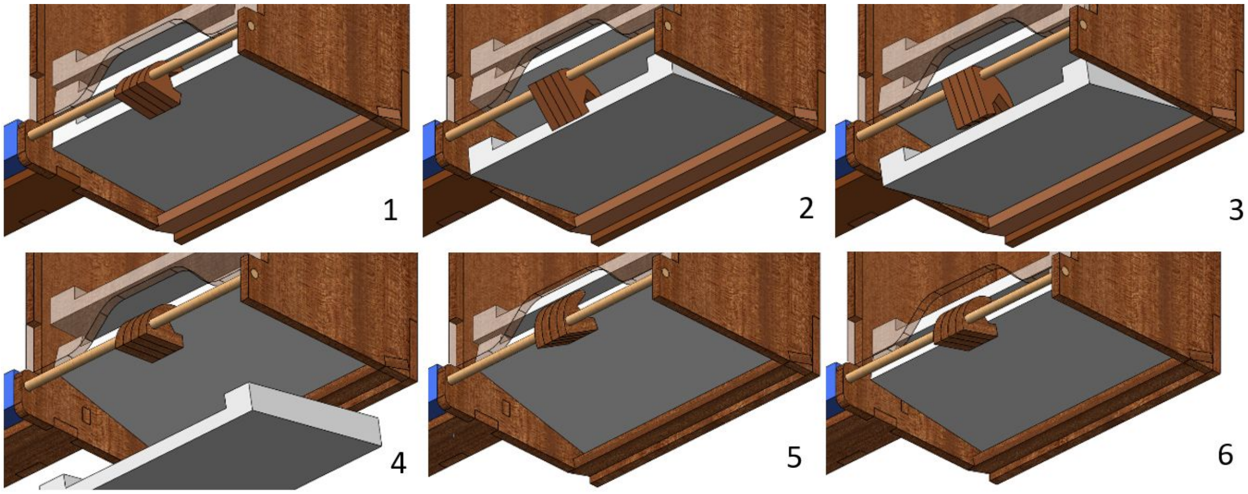


Figure 33: Delivery Mechanism Motion Study

Built Delivery Mechanism

We adapted our delivery mechanism design to the quadcopter configuration used for flight testing. We reduced the height of the box to 7 centimeters, to fit five pill units. Since we did not tilt the quadcopter horizontally, like our tilt-body configuration would in cruise, we did not have to add the spring and pusher to keep the units in place. Figure 34 shows the three different latch positions to deliver one pill unit.

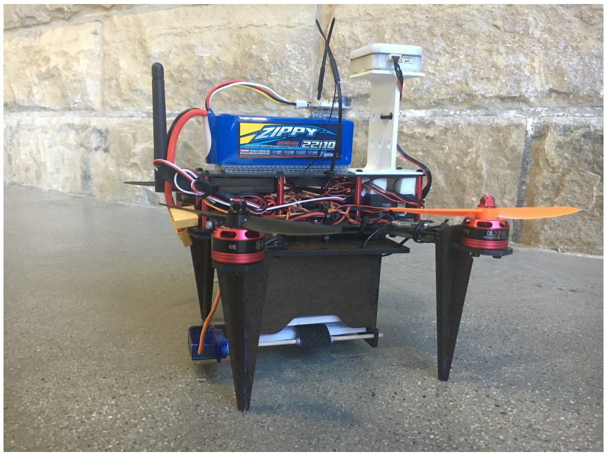
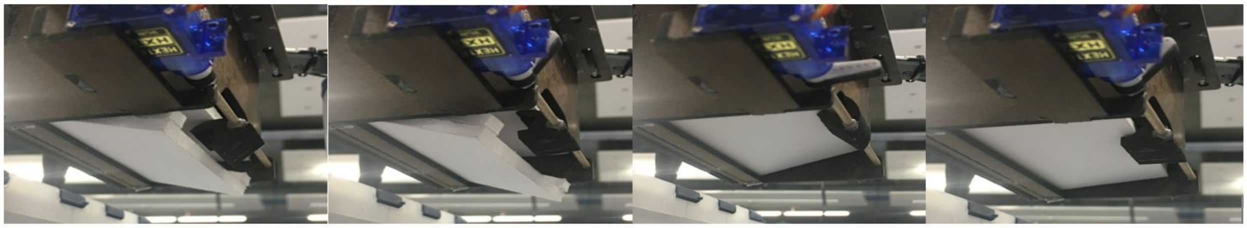


Figure 34: Built Delivery Mechanism Mounted on Quadcopter



Low Neutral High Neutral

Figure 35: Built Delivery Mechanism Action Sequence

This scaled down delivery mechanism was made from ⅛” duron and and had a mass of 230g. By leveraging more mass efficient materials such as carbon fiber, this mass could be cut considerably, increasing the range and payload capacity of our aircraft.

8 Scaled Outdoor Demonstration Flight

Our actual mission involves or drone flying to several delivery points and delivering the pill-packet payload. Our scaled delivery demo was designed to be a ‘proof-of-concept’ that our delivery mechanism was indeed capable of delivering pill-packets to multiple locations. Therefore, our mission objective was to deliver 3 packets at discrete and controlled locations and times.

Figure 36: Outdoor Flight Path

Our flight plan in Mission Planner consisted of three automated round trip flights at an altitude of 10 m AGL between two points 50 m apart (shown above), with pill-packed deliveries closer to the staging area (Point 8). Each pill-packet delivery sequence was actuated by the pilot remotely during a 10-second loiter period.

Sequence	Takeoff	1	2	3	4	5	6	7	8	9	Land
Control	Pilot	Auto	Auto	Remote	Auto	Auto	Remote	Auto	Auto	Remote	Pilot
Action		Fly to 7	Fly to 8	Loiter + Deliver	Fly to 7	Fly to 8	Loiter + Deliver	Fly to 7	Fly to 8	Loiter + Deliver	

Figure 37: Mission Planner Waypoint Sequence

‘Remote’ control denotes that the transmitter was used to control the servo while the drone was still flying autonomously. Our delivery mechanism was actuated by a Turnigy micro-servo which was connected to our UBEC for power and the PixRacer for signal. The pilot then actuated the servo from the transmitter during the delivery sequence.

Given our relatively small payload (including the delivery mechanism), no PID tuning from default parameters was needed.

Figure 38: Outdoor Flight Delivery Test Action Sequence

Our scaled delivery demo mission was successful in that all pill packets were delivered under control at the desired locations and times, followed by a successful landing.

9 Final Design

Having made the decision to move forward with the Contra(Ception), we then turned out attention to optimizing the parameters of the final design. This included body, rotor, and wing shaping and sizing. The final parameters are described in the performance specification chart at the end of this section, and renders of the final configuration in CAD are included below:

Hover Configuration

Two rotors spinning in opposite directions

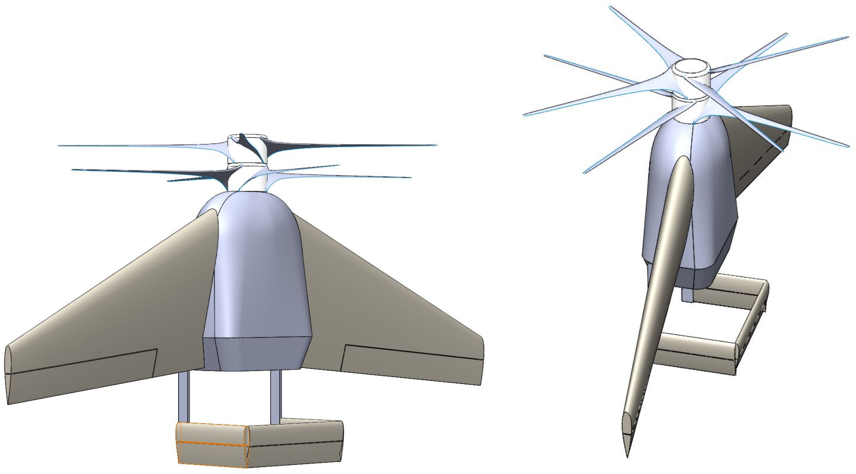


Figure 39

Cruise Configuration

Folded back rotor

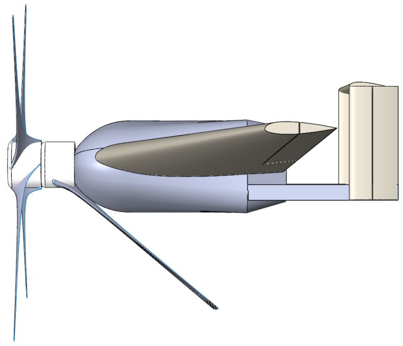


Figure 40

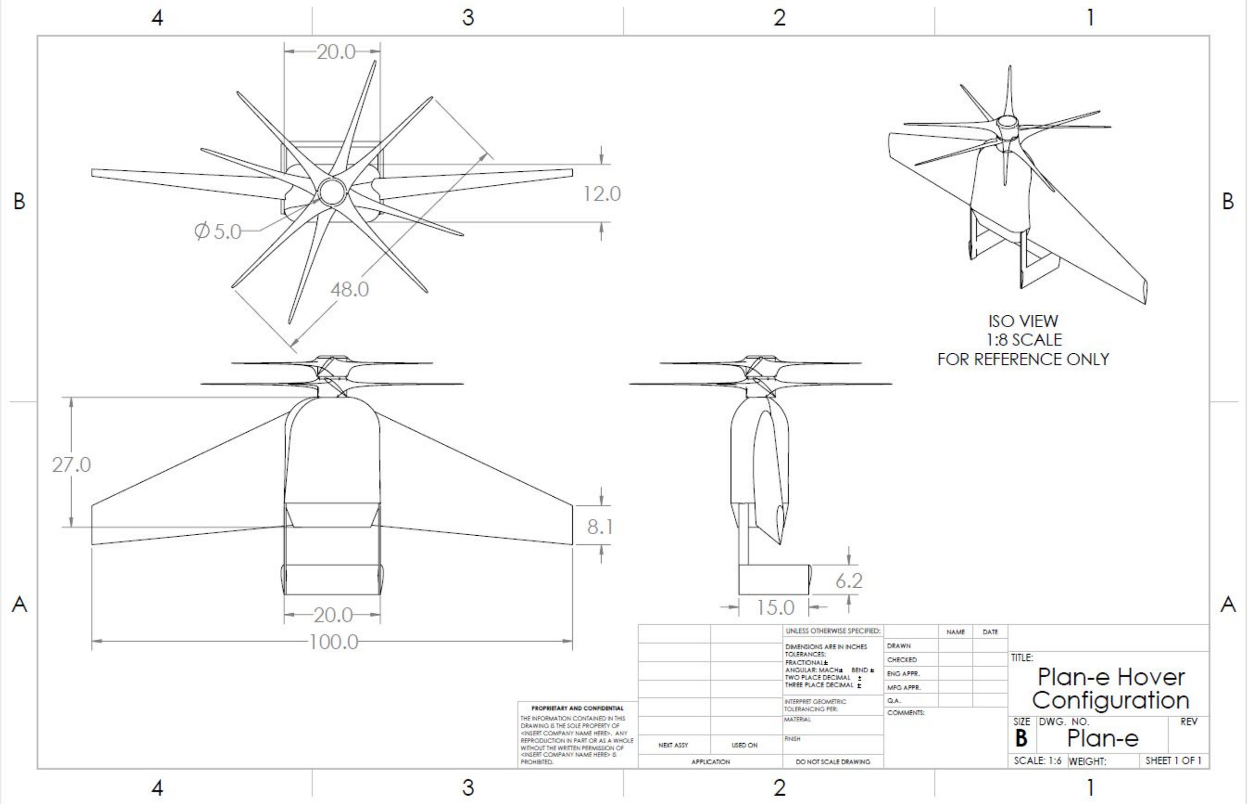


Figure 41: PLAN-E Engineering Drawing with Relevant Dimensions

Our final design incorporates a contraprop into a relatively standard model airplane sized aircraft. With a wingspan of 1 meter, PLAN-E is small enough maneuver in the tight spaces of the city but large enough to easily carry our intended payload with good efficiency. The design has traditional ailerons for roll control, but uses a less standard raised twin-boom tail to hold the single elevator and twin rudders. The elevator is positioned at the top of the booms to avoid interference from the body. A more traditional elevator would find its airflow obscured by the body directly in front of it, giving it poor control authority, but this design allows for the elevator to sit in the flow and retain control authority regardless of the orientation of the aircraft. Additionally, both the elevator and stabilizers function as landing gear.

The control surfaces do not only provide control authority during cruise. We have taken a page out of 3D Aerobatic aircraft and designed our system for full control authority during hover. Due to its large diameter propellers, PLAN-E's propwash causes airflow over the elevator, ailerons, and rudder during hover. This allows for maneuvering during hover to counteract gusts, obstacles, and any other possible issues. It also allows PLAN-E to transition to hover by apply full elevator while keeping roll and yaw control through the maneuver.

The innovation in this design comes from incorporating the contraprop, a difficult and rare propulsion system for full-scale aircraft, into a drone. The contraprop offers an additional 5 to 16 percent efficiency gain over a standard propeller, and this is extends our range, increasing both the distance and number of houses we can deliver to.[1] While the added weight and complexity of a contraprop system can offset the aerodynamic benefits, we are confident that the benefit of the system outweighs the cost since we have the additional consideration of hover. By increasing our effective disk area, the contraprop significantly improves hover efficiency compared to a normal single prop design.

Given the unique nature of our propulsion system for drones of this size, finding a suitable motor was critical. In the end, we settled on the Himax CR 5025, shown in Figure 42. According to the manufacturer's specifications, this motor has a static thrust of 17lbs (75.6N), which puts us well above our required hover thrust of 64.65N which allows a thrust-to-weight ratio greater than one, a margin necessary for hover control, climb, and other conditions (such as gusty conditions).

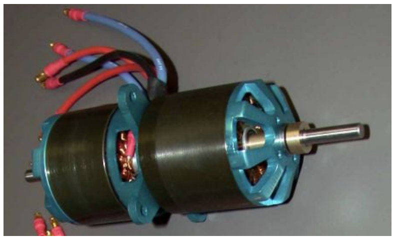


Figure 42: Himax CR 5025 Contraprop motor

Component arrangement

Figure 43: PLAN-E Internal Components' View

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[1] https://www.rcgroups.com/forums/showatt.php?attachmentid=2815700

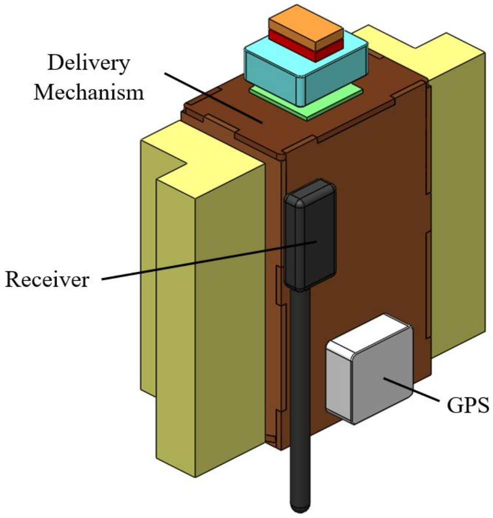

Figure 44: PLAN-E's Electronics and Delivery Mechanism Arrangement

Our main internal design constraint was adequately fitting all necessary components around our large internal delivery mechanism. Other concerns were keeping the battery and avionics separate to avoid interference, placing our avionics at the front of the aircraft, and of course properly balancing our center of pressure and center of mass to achieve and maintain stability throughout the mission.

Given the above constraints, the avionics are mounted in the tapered section of the fuselage and the power board is directly behind them. Due to the taper, there is less space in the front than in the back so we chose to put the smaller components there which also matches up well with our desire to locate the avionics in the nose. Behind this is the power distribution board, located between the batteries and the components that require power.

Behind this sits the delivery mechanism and the batteries. The design calls for the delivery mechanism to be located in the aft of the aircraft, and the space between the delivery mechanism and the fuselage walls is filled by the battery. Thanks to the weight of our propulsion assembly and the low weight of our delivery mechanism and payload, we still have our center of gravity ahead of our center of pressure, and thus a moment coefficient that decreases with alpha and is approximately zero at our cruise angle of attack.

Performance Specification Chart

Size, Weight, & Performance	**Value**	**Units**
Empty Weight	6.09	kg
Payload Capacity	0.5	kg
Wingspan	1.00	m
Cruise Speed	25	m/s
Cruise Range	95	km
Payload Mass	0.50	kg
Battery Mass	4.02	kg
Wing Mass	0.21	kg
Propulsion Mass	0.90	kg
Body Mass	0.96	kg
Total Mass	6.22	kg
Power and Prop		
Battery Capacity	1.74e+06	J
Propeller Configuration	4-Bladed Contra	
Propeller Diameter	0.60	m
Number of Propellers (Hover)	2	
Number of Propellers (Cruise)	1	
Hover Specifications		
Thrust Required	64.65	N
Thrust Per Prop	32.32	N/prop
RPM Required	3853	RPM
Total Power	502	W
Cruise Specifications		

Cruise Speed	25	m/s
Thrust Required	12.4	N
Thrust Per Prop	12.4	N/prop
RPM Required	4883	RPM
Total Power	360	W
Advance Ratio	0.518	
Propeller Efficiency	81	%
Wing Parameters		
Aspect Ratio	6.1	
Wing Root Chord	0.270	m
Wing Area	0.164	m^2
Average Operating Re	2.91e+05	
Operating AoA	+4.0	Degrees
Operating CL	0.97	
Operating Glide Ratio	14.13	
Operating Power Factor	13.4	
Taper Ratio	4.50	
Wingtip twist	0.00	Degrees
Wing Sweep	34.8	Degrees
Wing Airfoil Name	NACA 23018	
Stall CL	1.0	

10 Future Directions

With a completed design schematic for our robot, the next logical step would be to build our first test model and begin testing. Important testing considerations include flight stability, noise levels, range, and payload capacity. In the event that any of these, or other design parameters, present themselves as issues, more simulations can be run and more test models constructed until the issue is resolved. Once we have a working production model, we can move onto the route optimization.

While we know the general implementation of our route optimization algorithm, the specifics have not yet been implemented. We would need to acquire accurate daily weather information for our flight area and automatically incorporate that into our code. Luckily, NOAA provides a weather service which offers predictions of the winds at various points throughout the day and publicly offers their data for download. We can fetch this data at the start of every day and feed this into our optimization algorithm to determine the appropriate route for that specific day given that the path is constrained by visiting all of the necessary stops.

With the technical elements of the project completed, work would need to be done on the business side. While drone delivery is not a radical concept, our specific mission has some logistical and legal hurdles to overcome.

On the logistics side, we need to create and maintain the services that repair and retrieve our drones after their flights. Since the drones land at a designated location at the end of their mission, they must be returned to the start of the route to be prepared for the next day. This requires logistical oversight to ensure that the drones are collected and returned on time so that they can be serviced and ready for their next flight.

On the legal side, there are currently restrictions in place for the packaging and delivery of birth control pills. These restrictions would likely hamper our ability for timely birth control delivery.

Despite these issues, this project offers a new vision for commercial aerial drone deliver. By utilizing a design more in the vein of an aircraft than a drone, our range and payload capacity are extended beyond a typical aerial robot of this size. With further designs and a larger scale craft, the delivery market could be radically altered.