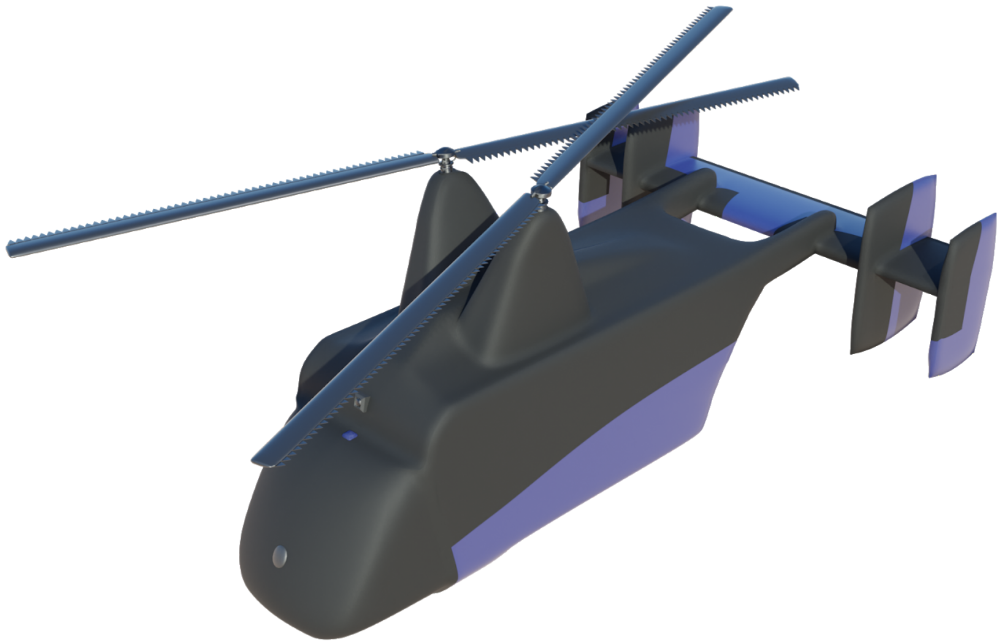
Drone-acharya



Submitted in Response to the Real World Design Challenge

Submitted by

Samaritan Aerospace Incorporated

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Executive Summary

Today, with a dramatic increase in online shopping, cities are being strongly affected (Oğuz, n.d.). Traffic has increased drastically on the streets, as have pollution levels (Charles, 1994). New York City has 1.5 million packages delivered within it everyday (Brian, n.d.). A similar phenomenon is taking place in all major cities in the world. Manual delivery is also an immense waste of human labour that could be employed in more productive areas (Ringbeck, 2019). This shows that in the online shopping system, the delivery is a highly inefficient process. To tackle this, the researchers propose a more highly automated system, whose basis lies in UAS (Unmanned Aerial Systems). The system consists of a ground-based component and a flying component. For the flying component, a rotary UAV (Unmanned Aerial Vehicle) has been proposed. By careful consideration of costs and timing, it has been demonstrated that one craft carrying three packages can do 3 deliveries within 15 minutes and return (Feist, 2018). This is better than any manual delivery system. Due to a strict mass limit, however, carrying three payloads required the empty mass to be within 10 kg. Here, consideration of battery size and weight shows the single rotor with a tail rotor to be ineffective and too heavy. Due to this, a design with two sets of angled intermeshing rotor blades has been used. Both blades are physically connected to make collision impossible. They are run by a single motor. The design of the hull has been inspired by the Kaman HH-43 Huskie (Walter, 2011). This proved especially effective in reverse-engineering very complicated calculations, usually accomplished only by software unavailable to a high-school team. After thorough research of components, a light and cheap set was arrived at. The UAV, by virtue of its mass distribution, is very balanced. Innovative navigation technologies have been used, including videogrammetry using camera data as well as a novel WiFi trilateration-based location determination system. Obstacle avoidance is being done by ultrasound and radar (Stimson, 1998). The operations system is also very efficient, preventing collisions and rushes. The delivery was carefully timed for the purpose of shortening it. The central hub was designed to maximise the rate of delivery. All operating costs, such as electricity for batteries, were considered and used to calculate the daily profit. The daily profit was used to calculate that the system could recover all costs within 7 days.

Specification Sheet

Criteria	Values
Maximum Takeoff Weight (MTOW)	25 kg wt. (including ballast margin for packages)
Wingspan (fixed-wing) or Max Width (other)	1.378 m
Maximum Airspeed during Mission	26.8 m/s (IAS)
Maximum Altitude during Mission	76.2 m (250 ft) AGL
Maximum Endurance of Aircraft (with all the 3 payloads)	40 min
Maximum Range of Aircraft	6.3 km

Table 1: Specification Sheet

1. Team Engagement

1.1 Team Formation and Project Operation

The team members are all members of the Aerospace Society of Delhi Public School, RK Puram. One member (the project manager) left the school and joined another after the formation of the team. The team has been composed of people with expertise in a wide variety of fields, ranging from research to engineering to design to business studies. Therefore, each area of the research and design process was handled by members who had expertise in it. However, the entire team shared a common vision and the mission of making a coherent and comprehensive design which adheres to the customers' requirements and offers an optimal configuration for the required task.

Aditya Swaminathan (Project Manager/ Physicist) is the team leader of the research group. He has an immense interest in theoretical physics and mechanical engineering. He is a senior member of Aeross (the school's extremely selective Aerospace Society) and Exun (the premier technology club in the country). He has participated in the Indian National Space Settlement Design Competition in the structural design department, led a team for the National Space Society Space Settlement Contest, and has drafted and submitted a research paper to the International Astronautical Congress. Currently, he is pursuing research on advanced ion thruster technology.

Advitya Singhal (Systems Engineer) is a member of the Aerospace Society of DPS RK Puram. He has experience in robotics and has built a variety of robots and competed with them in several competitions, giving him exposure to intercontinental standards of electrical and robotic system design. This gave him experience in picking UAS components that fit the required specifications, quality requirements and weight and dimensional limitations.

Karan Handa (Researcher) is a member of the Aerospace Society, DPS RK Puram. He is a senior student who has opted for the subjects Physics, Chemistry, Biology, and Math in his junior and senior years. He has taken many courses in academic writing and proves to be a big asset by making use of his writing skills. He is also a well-rounded individual whose diversity of interests includes aerospace engineering, electronics and research. Additionally, Karan is capable of using the entire Adobe Suite, for uses ranging from graphic design and illustrations to websites and document layouts. In school, he is a member of the Theatre Club, Exun, and Aeross. Karan's diverse interests and his yet vast expertise and outgoing personality contribute to the team's creative processes by encouraging the team to look beyond the scientific aspect of the challenge and keeping the team members open-minded about different ideas which can be integrated together to make sure the final product comes together in a way that the entire team is satisfied.

Om Gupta (Physicist) is a senior member of the Aerospace Society for DPS RK Puram. His senior and junior year subjects include Physics, Chemistry, Math and Computer Science. With five years of experience as a member of the club, his knowledge of the programs used for calculation and analysis have led to his ability to utilize the software in such a way that he can successfully manipulate algorithms to help the team. His experience includes being a Summit Finalist and Conrad Scholar at the Conrad Spirit of Innovation Challenge in the Aerospace and Aviation category. Additionally, he has served as Head of Engineering for the Asian Regional Space Settlement Design Competition. Further, working with the aerodynamic and mechanical elements of various other competitions has allowed him to apply a more comprehensive understanding of unmanned aircraft systems. It is his responsibility to oversee many varied aspects of the development process. In order to create an efficient, comprehensive, and technically viable solution, he has applied these experiences and skills in conjunction to contribute to the project with the goal of benefitting the team to the best of his ability.

Siddhansh Narang (Researcher) is a member of the Aerospace Society at DPS R.K Puram. He is a member of over 30 Virtual Airlines and Virtual Organizations and is engaged in developing airports in the Infinite Flight Simulator platform. He is an active member of the aviation society with patents in the field of aviation along with winning the first prize in the grade 10 individual category of NSS Space Settlement Competition 2020. He is also an active member of the Royal Aeronautical Society (RAeS). He has contacts with several pilots and personnel in the field of aviation. He does not confine himself to a single field, but, through extensive research, has provided innovative solutions to a variety of problems. His primary field of expertise is mission operations.

Ashvin Verma (CAD Specialist) is a senior member of the Aerospace Society and Exun. He has a plethora of experience from leading the design process in many international engineering design and innovation competitions, such as the NASA Ames Space Settlement Contest, International Space Settlement Contest and the Conrad Spirit of Innovation Challenge. Additionally, he has several technical skills, and has come 1st in inter-collegiate competitions, and emerged 2nd at an open hackathon, Angelhack, indicating his competence in a variety of fields from design visualisation to feasibility consulting.

Zohaib Ehtesham (Business and Cost Analyst) is a member of the Aerospace Society at DPS R.K. Puram. Zohaib has opted for Physics, Chemistry, Mathematics, and Computer Science as his elective subjects. He harbours a passion for coding and computer science. He also has interests in business and has studied different aspects of the same, thus was able to keep track of the development of various aspects simultaneously, almost single-handedly handling the entire cost breakdown and calculation and the business aspects.

1.2 Acquiring and Engaging Mentors

The researchers put in an immense amount of work and thought to acquire mentors. Specialists around the globe were contacted. Dozens of emails were written to anyone who the team thought could contribute their wisdom to the development of the design. Most of them, unfortunately, were either on vacation or extremely busy and unable to help. The team was advised to simply ask school teachers for help. The team put in a consistent effort over a long time to acquire industry professionals as mentors but to no avail. The researchers also tried to contact RWDC for mentors, but couldn't secure one. Finally, it was decided that the team, due to a lack of options, would have to deal with the disadvantage and proceed without a mentor, believing that the sole research efforts of the members would make up for the lack of guidance.

Throughout the project though, the researchers sought professional help. This was especially useful in acquiring justifying sources about autorotation. For this, a pilot, Mr. Wiggy G. helped a lot by providing some information from professional knowledge and experience. Mr G. is a General Aviation Pilot in the United States with over 1000 hours of flying under his belt in the C172. Soon he will be getting his commercial license and will begin flying for a major US carrier. Though he flies fixed-wing aircraft, he has a lot of knowledge across the field of aviation. His expert comments through an email correspondence helped the researchers significantly.

Advitya contacted his uncle, who was a civil engineer. He helped Zohaib with detailed calculations for construction costs. Beyond this, the team was constantly in contact with senior members and alumni of the Aerospace Society, who read the document and made invaluable suggestions.

The researchers did what they could with the resources they had and worked on despite the lack of an assigned mentor, solely dependent on extensive research, but feel that this does not stop them from making a good design.

1.3 State the Project Goal

This year's challenge requires the design of a UAS which can efficiently deliver packages (5kg, 0.5m × 0.5m × 0.25m) from a Central Hub to different locations within an 8km × 8km area. Effective design requires the researchers to decide their delivery locations and choose appropriate elements. A Payload Element choice must be made after careful consideration of the delivery process. Air Vehicle elements must be chosen while considering potential delivery locations. C3 Element choice must take into account external factors and distance from Central Hub. Support equipment choice depends on the Air Vehicle choice. It is up to the researchers to decide the locations suitable for delivery for their specific design. The UAS must also meet a set of safety requirements to operate within the city. The researchers are also required to design an efficient and safe delivery system and flight corridors for the UAVs. Teams will be "paid" based on the number of packages delivered in the service area in a day. The researchers must show that enough money is being made to cover more than operating costs. Fixed costs involving part choice and other design choices should be covered over time; there should be a reasonable period of ROI (Return on Investment). A good business plan is essential. Thus, the project goal is to design a solution that is profitable for the company and safe and convenient for the city.

1.4 Tool Set-up/Learning/Validation

Google Suite : Google Suite was arguably the most important tool used by the team members. It allowed the team to collaborate on a common document in real-time, despite being scattered over a city, for no additional cost. The universally accessible nature proved especially critical when the team leader had to move to another country midway through the designing process, making physical meetings impossible. Comments could be left on the pages and tasks assigned, reducing the temporal and spatial variation to a non-issue. Google Docs was used for writing the main body of the document, as well as typesetting and formatting content and images. Google Sheets was used for collaborating on calculations for rotor power and for delivery times.

Discord : Discord, the messaging application for gamers, became an essential tool for the team. Multiple discussions could take place simultaneously on a single server, simply separated into different channels. Voice channels could be left open for anyone to join, and one participating could either stop his own audio input or output, without affecting the others. The screen-sharing feature helped the team gain a common perspective and vision on the future of the project, where any member could stream his screen where the others would join via voice. Overall, it was far more useful than the average communication tool, especially because the team was unable to meet physically in its entirety. It was useful in creating junctures where all the team members could congregate, discuss the different aspects of the competition and assign roles on the basis of the strengths of the members and efficiently distribute and keep track of the work being done. Helping other members, discussing new ideas and suggesting edits was all done through Discord.

Fusion 360 : CAD or computer-aided design, is software for design and technical documentation of physical products, which replaces manual drafting. Additionally, it allows the computer to perform many complicated calculations simply, gives unique insights, and drastically improves productivity. The CAD specialist started by importing the mesh that had been made in Blender, and reconstructing it parametrically inside Fusion 360. He performed non-linear static-stress, structural buckling, and shape optimisation simulations, and assessed and modified our design and material selection according to the relations among the zones and their intensity.

Blender : Blender is a free, open source 3D computer graphics package, which we used for making the bash mesh, which we reconstructed in Fusion 360. Blender has very strong modelling capabilities, which supports parametric as well as mesh-based modelling. The modelling workflow is also very simple and fast, which made it a good choice for models of lesser significance.It has advanced ray-tracing capabilities for photorealistic rendering and accurate lighting. For this reason, it was also used for photorealistic depictions of the design.

Airfoil Tools : Airfoil Tools (website) is a website which consists of a compilation of scripts which carry out calculations, airfoil generation, etc. It has multiple tools such as airfoil search, airfoil plotter, airfoil comparison, etc. This helped find and compare airfoils.

1.5 Impact on STEM

The participants had experience participating in other engineering design competitions and expected the conceptualisation process to be relatively straightforward. However, they didn't expect the depth of knowledge that the competition required, which forced them out of their comfort zones and made them indulge in real learning and problem solving. Participation in this competition has allowed the researchers to experience real-life problem solving using tools used in the field, playing by its rules and simulating an industrial environment. It has also taught them how to find and understand research and to use the conclusions in their own concepts.

The researchers have varying career interests, but such hands-on experience has given them an appreciation for the field and discipline of Engineering. They learnt to balance and integrate objectives, constraints, and differing ideas together, for an optimal design.

The qualification of the team to an international stage has inspired students across the school to choose the science stream in senior secondary school, changing their perspective of engineering from textbook problems to solving exciting challenges, showing that even they can have an impact and use their education in unique ways. It has also led to the formation of many teams for other competitions, as students realize the breadth of opportunities available in high school. It has also led to renewed interest and engagement in STEM subjects classes, and upgradation of the lab facilities.

Document the System Design

2.1 Conceptual, Preliminary, and Detailed Design

2.1.1 Engineering Design Process[1]

Phase 1: Conceptual Design : This stage involved a thorough understanding of the challenge. With the additional requirements in the international challenge, an intensive individual and group reading of the new Challenge Statement (Including rereading the Detailed Background) was done. Three main types of UAV designs were considered during this phase *i.e.* fixed wing, rotary and hybrid. All were placed in the given scenario and tested for their suitability (at an appropriate scale) in terms of maneuverability, efficiency, size and complexity (and therefore costs and maintenance). The rotor based design was decided upon as the most effective for the required purpose. The team exchanged emails with the judges and managed to gain access to judges feedback for their first round proposal. An improvement roadmap was made and timely followed.

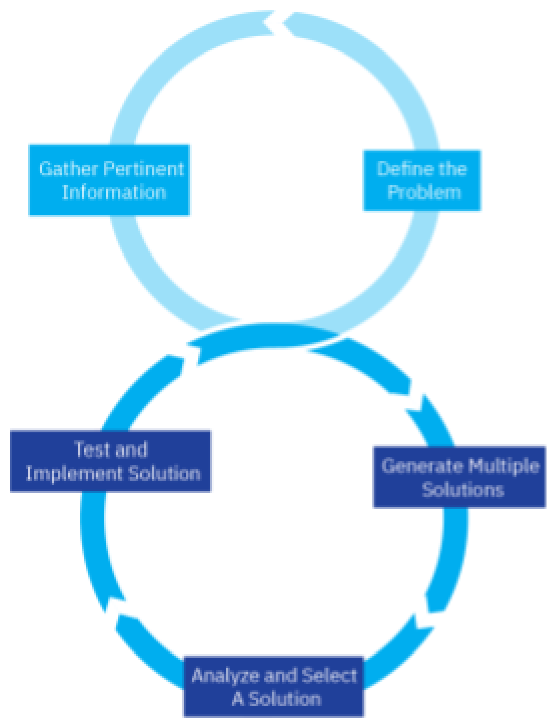

Figure 1: Engineering Design Process

Phase 2: Preliminary Design : The rotor based design itself had three main options- multiple rotors with control by varying motor speed, one or two rotors with control by varying the pitch (Smith, 2014), and an original method created by the team. Here too, basic

[1] Sketches have been remade digitally to improve viewability on the document.

designs of all three were made and considered. Due to its efficiency, load lifting capacity, smaller size, and maneuverability, the single/double varying pitch design was chosen.

Phase 3: Detailed Design : The final decision was between a single rotor or double rotor. Calculations were done for both. A dual rotor design presented two advantages. Firstly, the absence of a tail rotor means that nearly all the consumed power goes into producing thrust, and also greatly reduces noise, a key concern for operating in residential areas. Secondly, according to our calculations, dual rotors netted a decrease in total continuous power required; according to the disk actuator theory the power required per rotor is proportional to $\frac{3}{2}$ th power of thrust, and thus splitting the load between two rotors results in a lower net power requirement. Within this, angled intermeshing rotors were decided upon because they allowed for smaller body size and lay fewer constraints on rotor radius than in a design like the Chinook.

Overall, the process consisted of understanding a problem, researching, generating multiple solutions, and testing the final solution. This was carried out for multiple topics at various levels of detail. The process's strength lies in its sheer simplicity and immense effectiveness.

2.1.2 Conceptual Design

Airframe

There were four main designs considered at this initial phase. Before discussing them, however, one short argument must be stated which was important in selecting the design. This argument will be referred to in the Notebook multiple times.

The Kinetic Energy Argument : Kinetic energy for linear motion (an equivalent ½ $I\omega^2$ applies for rotation, so the argument for is identical) is given by ½ mv^2. This implies that increasing the velocity of a UAV uses more energy than increasing the mass by the same factor. Therefore, if the mass is halved and velocity doubled (the number of trips increase), the same amount of payload is carried across the same distance over the same total amount of time, but the amount of energy used is double (Mahesh, 2009). This is obviously an idealised situation, and there are many other factors in play such as UAV design, inefficiency, and external forces, but overall, the argument still applies and demonstrates that carrying more payload slowly is more efficient than carrying small packages faster. This is also the reason large payload weight is mentioned several times. The same argument demonstrates the higher efficiency of large slow-spinning rotors over small and fast rotors.

Returning to the list of conceptual designs:

Fixed Wing : The fixed-wing is the oldest method of flight (Shaw, 2014). The design has the greatest speed (Chapman, 2016) and can easily change altitude. Overall, it is very simple in terms of operations, and repairs and maintenance are relatively easy and cheap. It is not, however, the most manoeuvrable (McTavish, n.d.). This is an even greater problem due to its requirement of higher speeds, at which the plane needs shorter detection and reaction times to avoid obstacles. It is incapable of such swift movement due to its size (due to the large wingspans required to lift the heavy payload) and method of flight, and thus faces a greater risk of collision (McTavish, n.d.).

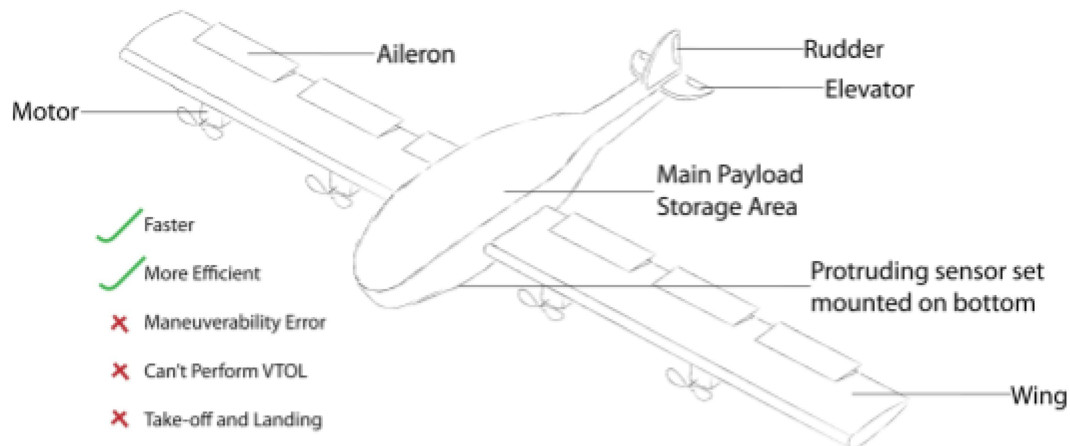

Figure 2: Fixed Wing Conceptual Sketch.

This presents a problem in navigating through a city. Also, while it may take off from the central hub with the aid of a catapult, landing within the required space presents a problem. Even if this is managed with the aid of nets, the UAV cannot take off again from the same amount of space without human aid at the delivery site to load it onto a catapult. A system of dropping payloads without landing is difficult and unpredictable at high speeds, which is also why the inability to hover is a serious concern. To prevent the aircraft from having to descend too low, it also requires parachutes on the packages, which add further weight and other complications.

Hybrid : The hybrid design combines the fixed-wing and rotary designs. Therefore, it has the speed and efficiency of a fixed-wing craft but can also carry out VTOL (Vertical Take-off and Landing) (Chapman, 2016). Just like the multirotor (discussed below), however, it is not as efficient as the fixed-wing. It faces the problem of maneuverability too.

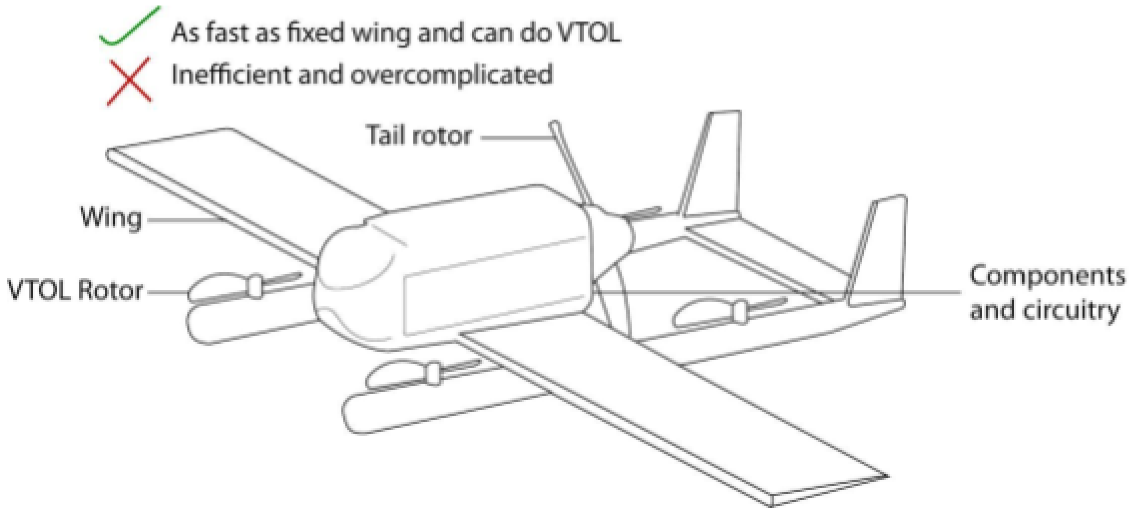

Figure 3: Hybrid Conceptual Sketch

It is also a more complex system, having to deal with both rotary and fixed-wing flight, each a very different method with its own requirements. This adds complications, a greater risk of possible problems during flight, and additional weight that renders it incapable of carrying as many packages as some other options can.

Multirotor : The multirotor with fixed rotor pitch is the most common type of UAV design, used frequently by amateurs for hobby drones. These have multiple small, fast-spinning rotors with fixed pitch. Motor speed of individual rotors is altered for stabilisation and control. The only reason for its popularity, however, is its mechanical simplicity (Gao, 2013), which allows it to be built and repaired with ease. They are not very stable, and the only way to make them work is by leaving complex stabilisation to algorithms such as the PID (Gao et al. 2013). This leads to an inherent instability which might come into play if

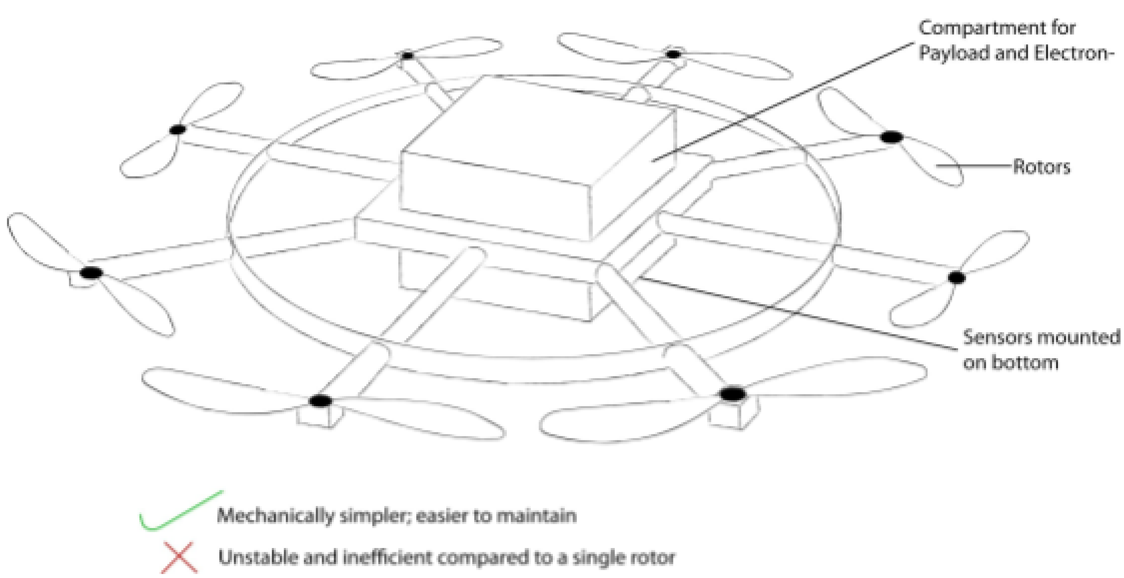

Figure 4: Multirotor Conceptual Sketch.

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situation is beyond the algorithm, and which then the pilot cannot handle either (the algorithm makes hundreds of small adjustments per second which is impossible for a human to do). The kinetic energy argument can also be applied to rotor blades, against the efficiency of multiple small and fast rotors.

Single Rotor : Single rotors are slower than hybrids and fixed-wing UAVs, but they are very effective in carrying heavier loads (GlobalUAV, 2018).

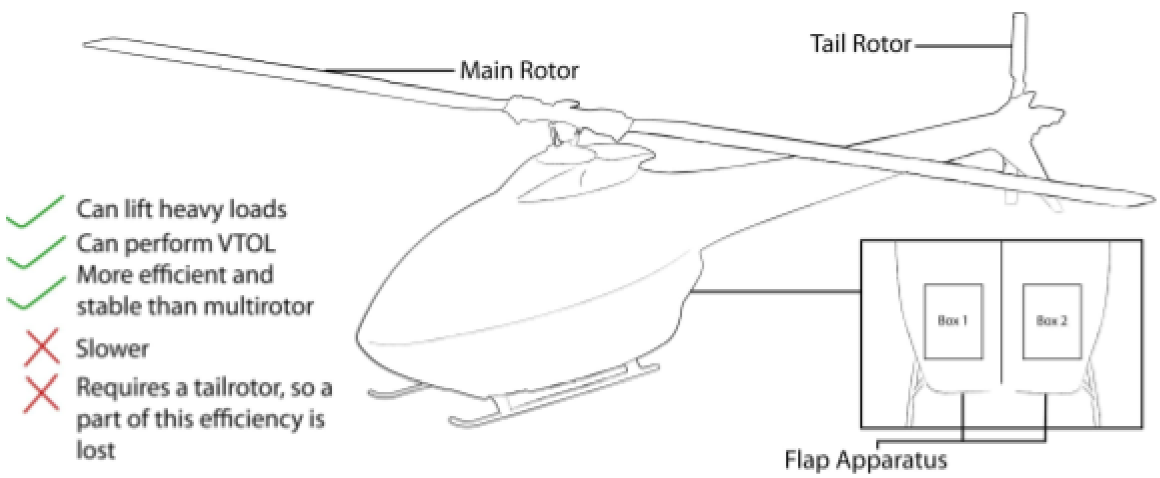


Figure 5: Single Rotor Conceptual Sketch.

They are more complex than multirotors (primarily due to the use of the swashplate mechanism for varying rotor pitch) but show greater efficiency and stability. Due to their lower speeds and ability to fly in any direction, they are maneuverable through a city and around obstacles (Maopolski, 1969). Due to their VTOL capability, they can land and take off from the required 3×3 m area.

Single Rotor with Vents : This original design was proposed by the team early in the design process. It used a single rotor to take in air, but distributed it with the aid of multiple regulated vents (Elan, 2019). This allowed for great control of tilt and direction by thrust vectoring while maintaining the single rotor's efficiency. Research revealed some examples of thrust vectoring in rotor based drones, such as in the prototype demonstrated by Maloney (2018), but a system with multiple thrust points was not found. Due to a lack of time and resources, the team was unable to build and test a prototype, and a purely theoretical model would not provide adequate verification for proposing it for large-scale commercial usage

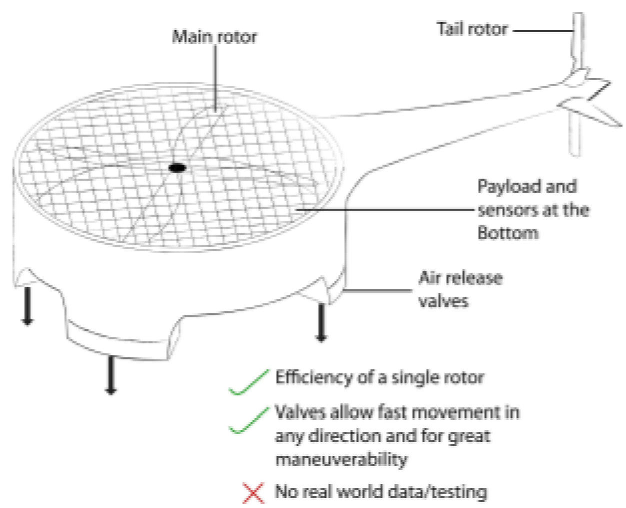


Figure 6: Single Rotor With Vents Conceptual Sketch.

Design	Advantages	Disadvantages
Fixed Wing	High speed; good fuel efficiency; can glide to safety in case of motor failure.	Lacks VTOL capability; low manoeuvrability.
Single Rotor	Can lift heavy loads; good maneuverability; better efficiency than multirotor; VTOL capability; can use	Lower speed than fixed wing or hybrid; mechanical complexity is greater than multirotor.

	autorotation in case of motor failure.	
Multirotor	Mechanically simple; has VTOL capability.	Inefficient compared to single rotor; lacks stability; no way of landing in case of failure of multiple motors.
Single Rotor with Vents	Has the efficiency, load capacity and VTOL capability of a standard single rotor; regulation through vents gives more control and maneuverability.	No real-world testing.
Hybrid	High speeds; good fuel efficiency; glide capability; VTOL capability.	Cannot lift heavier loads due to the use of multirotor for vertical flight; inefficient and unstable in vertical flight; high speeds are not very useful due to a lack of maneuverability in fixed-wing flight.

Table 2: Airframe Overview

Navigation

Effective navigation through the city required the UAS to follow the flight corridors in a particular path and maintain a minimum distance from all buildings. The team proposed multiple common and some new technologies to address this.

GPS is one of the most widespread navigation technologies. It requires communication with multiple orbital satellites and measurement of the time delay of signals (Brain & Harris, 2020). In urban areas, however, tall buildings and other obstacles prevent the UAV from establishing multiple strong connections. Nevertheless, the technology still gives a fairly accurate measurement of the position. Therefore, it was considered by the team. Another considered method was trilateration[2] using communication with radio antennas placed at several locations throughout the city, especially on tall buildings to avoid the signal being blocked (Signal Booster, 2019). This technology requires placing antennas on several buildings, which will require permissions whose granting is in ambiguity. The team also decided to use the data from the gyroscope and the accelerometer for more precise data.

Use of mobile towers and receiving position from the radar were also considered. But this too, required unhindered communication with at least two towers (Direction Finder,

[2] Involves the measurements of distances to various known points. Not to be confused with triangulation, which involves the measurement of angles.

2011), which may be a problem in the city, while radar has its own complications. These technologies were put into consideration and further researched.

Delivery Method

The kinetic argument made it clear that larger craft operating at slower speeds carrying multiple payloads would be more efficient than carrying single payloads at greater speeds. Several delivery methods were proposed.

The package could be dropped and the customer notified via a mobile application to collect it. This, however, raised concerns for theft (Shorr, 2019). Therefore, it was proposed that they could be reminded and asked to confirm a few days before the delivery, so they knew when the package was due to arrive.

The payload could be released from the UAV while flying over the delivery site, and then allowed to descend with a parachute, but this would increase the mass and cost per package. It might also risk misplacement, or incorrect landing.

The UAV could land at the delivery site and release the payload. Due to the customer's presence, this would require a way to indicate the minimum distance to be maintained from the UAS. Painting a circle around delivery sites was suggested.

Obstacle Avoidance

Safe operation requires the UAS to maintain a minimum distance from buildings and any other obstacles such as birds and other unwanted UAVs. It was considered that the main structure of buildings in the area and the major known obstacles such as towers, cables and signboards be added to a 3D map loaded into each craft. Location methods such as triangulation could allow the craft to determine its location on the map and thus know its position relative to buildings and allow prior awareness of these obstacles. This approach was discarded because comparing data with a 3D map in real time required very powerful hardware, which could not be placed onboard due to weight limitations, and remote servers would offer latency which is too high.

Other UAVs may be identified by transponders, and their location and velocities can be determined by analysis of the signal return time and Doppler shift in signals, and from the ATC. There may also be unanticipated moving obstacles such as birds and UAVs with damaged transponders. To respond to these, the UAV must possess sensors which can detect them from a long distance away to give the craft adequate time to respond. Several methods such as recognition from visual data by machine learning software and proximity sensors were suggested. The technologies in use could rely on ultrasound, RADAR or LiDAR. They each have their own advantages and were therefore further researched. It was decided to choose radar as the main sensor for obstacle detection because radar has the largest range. Radar sensors are also generally more compact than LiDAR sensors.

The team also decided to research further on the Skydio (https://www.skydio.com/) based visual sensor approach for real time 3D videogrammetry, navigation and obstacle avoidance.

Emergencies

Operating in an urban area requires a special emphasis on safety and having effective emergency procedures. Emergencies can be of several forms, including but not limited to damage to the antenna, the onboard internet connection, any of the sensors or hardware, the computer (onboard), motor, speed controller, etc can be damaged. Although it is planned to use multiple methods of communication, positioning and obstacle avoidance, this may still leave the UAV in a condition where it can not operate further. For such a situation, the UAV will attempt to land at a nearby location. For this, rooftop terraces could be useful because they will likely have space. It could use this, and the last verified location to gain the knowledge of its current location. With this approximate location information, it could further refine and verify the data by comparing visual data from the camera with previously obtained visual data of the area.

In case of motor failure, an emergency landing will take place. In the rotary design, motor failure would have to be responded to either by the presence of a backup motor or the use of autorotation. A fixed-wing aircraft can glide to safety.

In both these cases, the buzzer will emit a loud sound of 180 dB to warn nearby people of an emergency landing. In case the rotors/wings are damaged, their rotation could be stopped and a parachute released to bring the UAV down. The craft can be recovered by an emergency response crew.

2.1.3 Preliminary Design

Airframe

The variable pitch rotor design was chosen from the four choices compared in 2.1.2. This was due to its load lifting capacity, efficiency over multirotor, and better manoeuvrability, which is essential to fly through a city and deliver in residential areas. The Project Physicist had started working on some basic thrust calculations for the design, when it was noticed the 10-15% of the power was going to the tail rotor (Heli-Chair, 2016). The Business and Cost Analyst showed that profits could be improved dramatically if the UAV could carry multiple packages simultaneously. Since the maximum mass of the package was 5 kg, this required bringing the empty mass of the UAV under 10 kg (the calculations so far were on the fairly basic side, and the design was still subject to modifications). From some approximate component weight values, it was concluded that if the 10-15% power loss could be improved, a smaller battery could be used, reducing the empty weight and facilitating the addition of additional payloads. Removing the tail rotor would also reduce the weight of the craft, and also affect the CoM (Centre of Mass) and help bring it close to below the rotor mast.

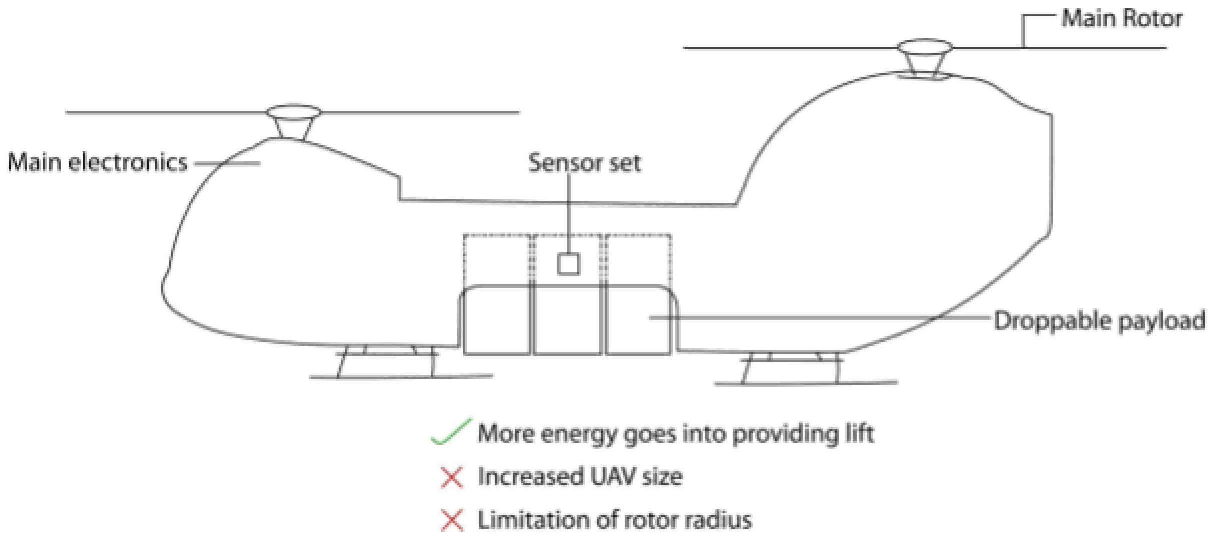


Figure 7: Separated Twin Rotors Preliminary Sketch

Firstly, a design with two rotors resembling the Chinook CH-47 was considered (Boeing, n.d). This, however, placed a limit on rotor size and increased the size of the UAV. It also increased the risk of collision while delivery because, due to the large distance between the rotors, the total area swept by them was larger. Inspiration for the final design was found in the Kaman Kmax (Trimble, 2017), a helicopter built for heavy lifting. It has a set of inclined intermeshing rotors spinning in opposite directions.

This removes the requirement of a tail rotor, motor and all its controls and connections. The tail, now a component purely for aerodynamic control and stability, can be shorter and much lighter (Chandler, Jay, 2014). Once this design was considered, other advantages came forth. The design produces lesser rotor vortex induced noise compared to more conventional helicopters. It also provides a larger disc area and greater stability.

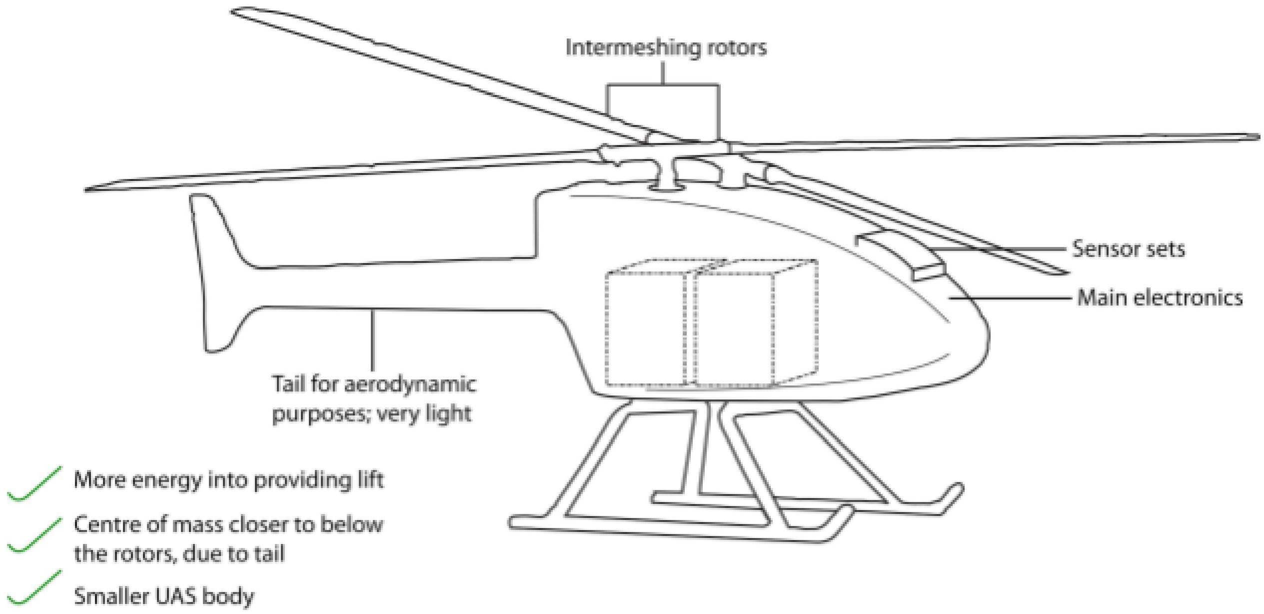


Figure 8: Intermeshing Twin Rotors Preliminary Sketch

Navigation

Trilateration with respect to different types of nearby objects was considered to be the main alternative to GPS. Specific methods were researched. The UAS would connect to multiple devices and use the time taken for a signal to be received back to find the distances to all the devices. With this information and some basic trigonometry, it is possible for the UAS computer to determine the position of the UAV to some degree of accuracy. (GISGeography, 2019).

GPS was researched to reach the conclusion that communication with a small number of satellites can still provide accuracy of a few metres (the exact figure depends on factors such as the number of satellites and signal strength). Though this allows the UAV to determine its location along a flight path, it is still inadequate for maintaining a minimum distance from buildings. While GPS also suffers from the urban canyon phenomenon, other technologies dependent on ground based transceivers are more strongly affected.

Cell phone towers, due to a dominant presence in the urban environment, can provide greater accuracy. This, however, depends strongly on the layout of the city. Often, due to differential signals transposing between towers (“bouncing signals”), the accuracy of triangulation is lowered, but other, more accurate methods such as AFLT (Advanced Forward Link Trilateration) can be employed, taking advantage of the motion of the UAV. WiFi positioning also functions by triangulation. The location of WiFi hotspots is known, and the distance can be determined by signal strength. The advantage here is that while there may not be enough satellites unblocked by city obstacles to communicate with, or that cell phone towers might be distant, there are virtually always nearby WiFi hotspots in an urban environment.

Videogrammetry using the real-time feed from the cameras was an alternative. It solves for a 3D environment from the sensor data. Though some of these designs provide more accuracy than others, there is a need for the UAV to have at least 2 ways in the absence of GPS for combined better accuracy and the availability of one of them in the absence of the other one.

Delivery Method

It was decided that availability of the customer be checked with him/her on the same day the package is received by the Hub *i.e.* two days before the delivery. Even before this, the approximate date of arrival of the package at the Hub will be obtained from the supplying company as soon as possible, and the customer will be informed of the delivery date. One night before the delivery day, before the manifest is prepared, the customer is asked for another confirmation through a mobile application/email, without which the delivery will not be added to the manifest. In the mornings, the manifest and flight plans can be prepared with the aid of computer programs an hour before the deliveries begin. These plans time deliveries for a uniform rate of delivery and avoidance of collisions.

For delivery itself, the UAV may slow down and descend to the delivery spot. A notification sent to the customer 10 minutes before the delivery will help ensure he/she is present at the site at the time of delivery. The UAV will hover over the area. On seeing the package, the customer can confirm the application, and the UAV can drop the package. The customer waits outside a marked boundary around the delivery area made to show the safe distance to the maintained. After the UAS leaves, the customer can come in and collect the package.

Obstacle Avoidance

Due to its ability to determine the position and velocity of obstacles (using Doppler shift in the radio waves), RADAR was chosen as the primary system for detecting obstacles. Size estimates can face minor inaccuracies because an obstacle's RCS (Radar Cross-section) may differ from its true size, but since most obstacles are not designed for stealth with absorbing paint and a deflecting shape, they will still be visible to the RADAR.

LiDAR operates on a similar principle as RADAR, but in the visible part of the electromagnetic spectrum. Due to a shorter wavelength than radio waves, the light waves can be used to detect finer details of the object and determine its size with greater accuracy, which is especially useful for analysing the close surroundings during delivery. LiDAR sensors are, however, much bigger than RADAR (with the same range), with much higher costs.

Another option for determining details is ultrasound. Ultrasonic sensors are available weighing just a few grams, which can determine details to a resolution of 1 cm. These rely on emitting ultrasonic waves and analysing their reflections off objects. This has a very short range and it can not be used for medium-to-long range applications.

The following table compares typical specifications from all three categories-

Criteria	**LiDAR**	**Radar**	**Ultrasonic**
Range	moderate range <120m	Has the farthest range <250m when cascaded	has really short range <20m
Accuracy	Very high because of the short wavelength of light	High, it will suffice for our purpose	Comparatively lower accuracy
Data update speed	Very fast	Very fast	874,030.49 times slower
Cost	Very high	Modest cost	Very low
Size	Very big and can't be used in this design	Small and compact and can be used in the UAV	It is the smallest
Weight	Heavy	Very Light	Very Light

Hardware required to process the data (comparatively)	Relatively better hardware with more energy requirements	General Hardware with moderate energy requirements	Hardware with low performance can also be used

Table 3: Comparison of Obstacle Avoidance Systems

RADAR was chosen for its ability to determine velocities accurately. It will be coupled with ultrasound (it can be implemented with much lighter sensors than LiDAR) for details, for a system that can determine the size, position and velocities of obstacles accurately.

Along with the radars, the team has decided to use neural networks along with cameras to assist in obstacle avoidance and real-time videogrammetry with the use of the powerful Nvidia Jetson TX2. This can also be used when the radar(s) are not functioning properly.

It was also decided that transponders would not be used, because the UAVs and instead have the location of other nearby UAVs sent to them live from the Hub.

Emergencies

The possibilities of an emergency or a situation where the UAV can not function properly have been minimised by the research team by using more than one ways for positioning,obstacle avoidance and contacting the hub. The emergencies have majorly been restricted to motor failure,malfunctioning of the computer, rotor damage, etc

The possibilities of landing on rooftops was researched further, and it was concluded that they are safer landing spots than crowded ground areas. Nevertheless, in the case of an autorotation landing, the loss of a certain amount of altitude is required to endow the rotors with adequate kinetic energy for flaring up for landing. Sometimes, empty and flat rooftops may not be present within the required altitude range, in which case landing on the ground is the only choice (a parachute will still not be resorted to because it results in lesser control while landing and a greater risk of collision). For this, the loud alarm will inform people of the landing, but people's reaction must not be completely relied upon due to its variance. Therefore, the UAV must also be able to locate the least crowded area in its vicinity. The chosen method to do so is Safe2Ditch, a software developed by NASA for this purpose. An advantage is that it can operate via the already present visual sensors.

Parachutes were considered for situations with rotor blade damage, when there is no other remaining option. The rotors will always be covered, so during all emergency situations, the rotors cannot hit objects from the sides. During parachute descent, however, they can still exert significant thrust, moving the UAV around in undesired directions and increasing the risk of collision. They may also snag and damage the parachute as it is deployed. For these reasons, the decision was taken to stall the rotor blades in a blade damage situation. This can be done with the aid of a motor brake. The stalling of rotors and the deplying of the parachute will not take place unless instructed by the operational or the safety pilot, with exemption to the case where there is no contact with the hub and the rotor blades are also damaged. This situation will be predicted by comparing the estimated path with the actual path. For emergencies, a loud sound must be emitted to warn nearby people. Loud and light variants of piezo buzzers were researched for this purpose and one was found that operated at 180 dB.

Launch and Recovery

Several launch and recovery systems designed to reduce take-off and landing area and give the craft an initial velocity are designed for fixed wing aircraft. Rotary craft must take-off and land with their own thrust. Due to their VTOL capability, they can land within small areas.

Due to the design of the package delivery process, the UAV, under normal conditions, takes off and lands only at its landing pad at the Hub. This is taken advantage of as the UAV is not equipped with any landing legs. Instead, the landing pad is specially equipped to receive it. To ensure alignment with the receiving apparatus, the UAV can use its cameras to detect and recognise coloured markers on the pad. In emergencies, when the UAV cannot land at the Hub, it can land on its belly, which is flat.

With all these considerations, the launch process was decided simply as placing the UAV on the helipad by any 2 workers with the help of a trolley. From there after all the ranging tests and other various conformations by the safety pilot, the operational pilot and the ATC, it shall hover and immediately clear the Hub. Only after it has moved away from the Hub will it begin its flight to cruising altitude, and proceed with its flight.

While landing, it will reduce speed and descent until it is close to the delivery location. Next, it can make a step descent to the location. Since for releasing the package it does not have to remain at the location for longer than 1-2 mins, hovering above the location is more efficient than landing. From 1 m above the ground, the package will be dropped, after which the UAV will leave the location. While landing at the Hub, it will slow down and come close to the landing area (similar to the take-off pad; launch stations are pre-assigned to UAVs by the ATC) and use a short step descent to reach the landing platform and touch down. Once it has stopped locomoting and the rotor blades have stopped spinning, it will be brought inside using the trolleys into the servicing block, close to the landing stations.

The team had also considered using conveyor belts for bringing the UAV inside, but the idea was dropped as for such a short distance using a conveyor belt would be inefficient. Therefore, rollers can be used instead.

Materials

A lot of UAVs use a combination of foam, fiberglass, metal and carbon fibre. In this case however, the composition has to be different.

The rotors, the surrounding protection, and the parts holding the motors support the UAV in the air, and undergo the most stress. They need to be very strong. The other parts are stressed due to repeated use but not as much. An all carbon fibre body appeared to be an attractive option, but weighed several kilograms higher than the required limit. It was decided that the rotors (due to aerodynamic stress), motor housing, the payload and battery containers (which make up over 80% of the total weight, and thus require stronger materials to hold them) be made of carbon fibre, and the rest of the components, bearing much lesser weight or aerodynamic stress be made up of a thick layer of EPP foam.

	Carbon Fibre	**Fibreglass**	**EPP Foam**	**PVC**	**Aluminium**
Ultimate Tensile Strength	3.5 GPa	3.445 GPa	0.003 GPa	0.052 GPa	0.310 GPa
Specific Gravity	1.8	1.522	0.09	1.45	2.7
Cost ($/kg)	22.07	1	5.55	1.17	4.5

Table 4: Comparison of Materials

Rotor Blade Selection

There are two primary types of airfoils under consideration for rotor blades- symmetrical and asymmetrical. Exact numbers require the comparison of particular airfoils, but the two general types may be compared qualitatively, as has been done below.

Factors	**Symmetrical**	**Asymmetrical**

Design	Equal curvature on top and bottom.	Greater curvature on the top side.
Lift	Lower lift. No lift at 0 AOA	Greater lift. Some lift at 0 AOA
Stability	Centre of lift remains more fixed during AOA changes, allowing for regular stable changes in AOA.	Centre of lift varies with AOA, creating instability with AOA changes.
Blade Stress	Low	High. Centre of pressure is higher up the chord line, exerting greater torque.
Structural Requirements	The blade can handle the stress with a slight twist.	The blade needs more strengthening.
Cost	Low	Production costs are high due to shape and strengthening required.

Table 5: Comparison of Rotor Blades

A lot of the disadvantages of asymmetrical airfoils were present in earlier decades, but have now been dealt with. Considering all this (most importantly lift/drag ratios), blades with asymmetric airfoils were decided upon.

2.1.4 Detailed Design

Airframe

The overall design of the body was considered with the payload in the centre, near to and below the rotors, with a conical/hemispherical shape at the front to make the shape more aerodynamically streamlined. It was also decided to put the main electronics in the front, and to have the payload CoM slightly behind the rotor mast to balance out the electronics. During the design phase, some sketches were made, and, from past research, it became clear that the main body was taking a form surprisingly similar to the Kaman HH-43 Huskie. The Huskie was further researched, and it was found that an OH-43D design had been converted to UAV configuration, known as the QH-43G. Since the shape of the fuselage, scaled down, fit the requirements (and the original sketches) identically (with a few small modifications), it was decided that it would be used. The helicopter has undergone a lot of real world testing, and Kaman has tested it to an extent beyond the scope of this project. Therefore, its performance is better verified. For these reasons, the body of the UAV will take the shape of the Huskie.

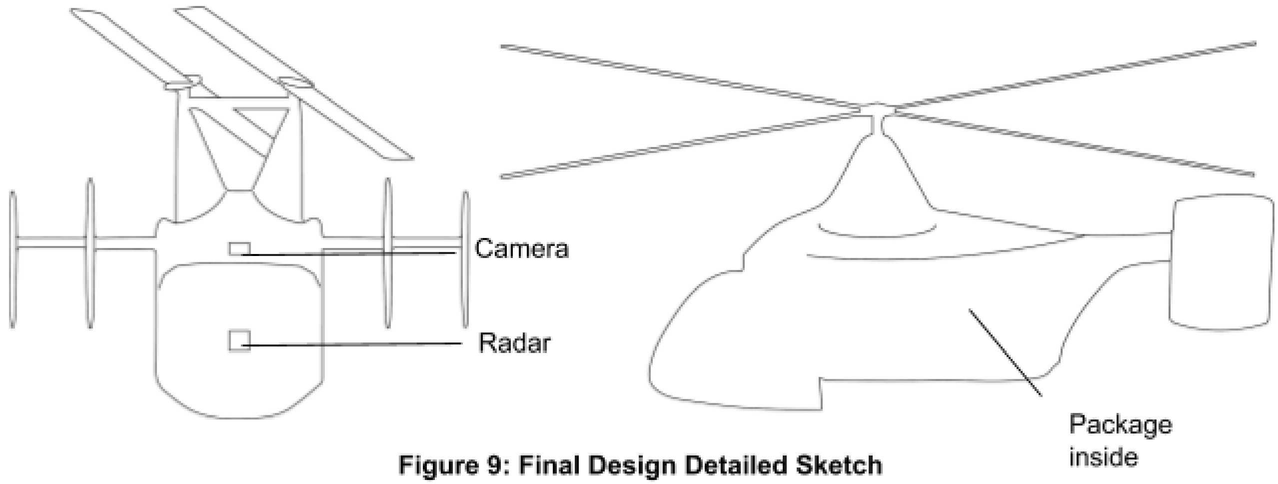


Figure 9: Final Design Detailed Sketch

Rotor Blade Selection

Choosing the final airfoil was tricky. The inspiration of the design of the UAV had been the Kaman Huskie, which employed the NACA 23012 airfoil. This choice by Kaman was unusual for two reasons-

➔ Old rotorcraft airfoils are usually symmetric. This is because symmetrical airfoils have less movement of the center of lift with the angle of attack, and so that is desired in the design of a helicopter rotor with a cyclic and collective pitch which is continuously changing (Kamas, 2009).

➔ The Huskie has intermeshing rotors, which face a wide spectrum of angle of attacks and CP (Centre of Pressure) changes. This requires stability from the airfoil, hence symmetric airfoils seem to fit better at first glance (Kaman, 2020).

Upon further research (Barth, 2018), it was found that due to the availability of sturdier and stronger materials, asymmetric airfoils have been employed in modern rotorcraft due to their high lift/drag ratio. Stability of the rotorcraft is also taken care of, as the asymmetric airfoils are made with strong, stable materials like carbon fibre. Also, since the payload packages have variable weight, high LD (Lift/Drag) ratio asymmetric airfoils were considered instead of speed factors. These factors are adequately in favour of asymmetrical airfoils that these were chosen, despite the arguments made in the previous section (those primarily affected older helicopters, and can now be dealt with, as mentioned above).

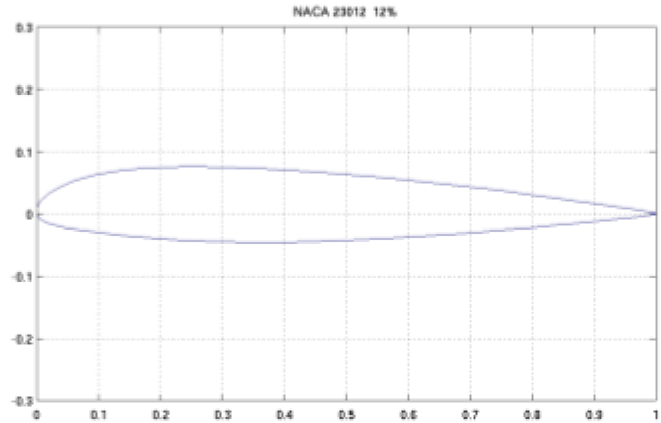


Figure 10: NACA 23012

The fact that the Huskie used it, however, was not adequate justification for using an airfoil, since multiple factors change with scale differently (almost never linearly) and therefore such design aspects from large helicopters may not be directly qualified for usage in UAVs. Therefore, other asymmetric airfoils which operated at high Reynolds numbers (>1,000,000) with high LD ratios were considered, like EPPLER 325 AIRFOIL, NACA 22112, MARSKE PIONEER IID ROOT AIRFOIL, but the best LD ratio was achieved by NACA 23012 (NACA, n.d.).

Airfoil	**Max Cl/Cd**	**Thickness**
EPPLER 325 AIRFOIL	88.2 at α=9°	12.6%
NACA 23012	96.8 at α=8.75°	12%
NACA 22112	89.4 at α=9.25°	12%

Table 6: Airfoil Comparison

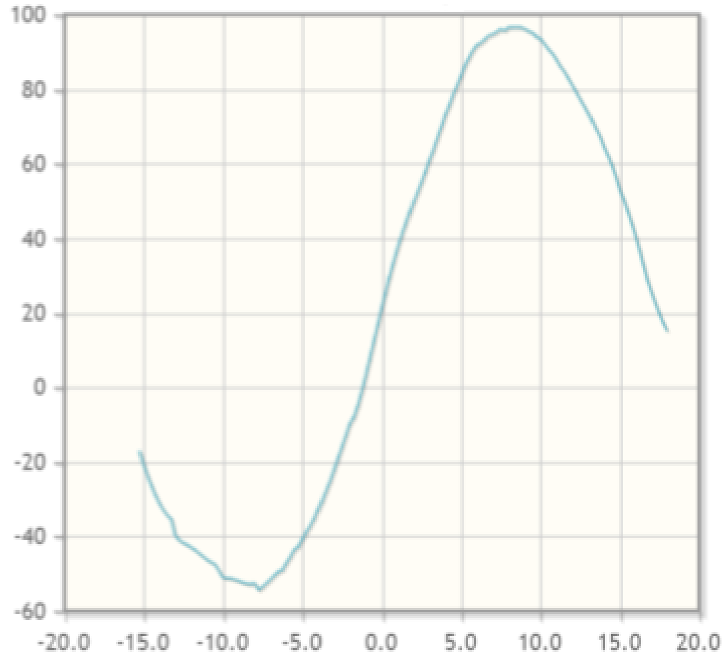


Figure 11: Cl/Cd v Alpha for NACA 23012. Obtained from XFOIL.

The rotor blades also have a slight variation across their length, with a change in the thickness of the airfoil. Therefore, the airfoil at the root is NACA 23011 and that at the tip is 23012.

Most of the noise produced by helicopters comes from the spinning rotors, due to the formation of vortices. One of the most important goals in the project is to make UAV deliveries a standard part of urban life. For this, it must be made as comfortable for customers and other urban residents as possible. Therefore, noise levels must be minimised. The intermeshing rotor design itself generates less noise than conventional helicopters. Further, a recently proposed solution was found, which involves putting a spoiler on the trailing edge of the rotor blades. This decreases noise levels and also improves efficiency (Tafoya, 2007).

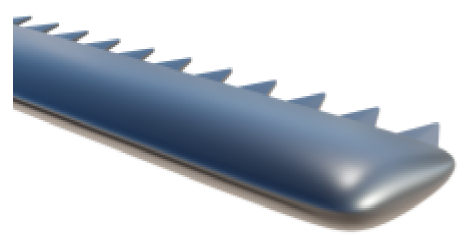


Figure 12: Rotor Blade Spoilers

Components

The design process was carried out under the difficult goal of effectively carrying 3 payloads per mission, thus placing a severe 10 kg limit on the empty mass (including the batteries). This is the reason the weight of materials and components has been among the most important criteria while the team made our final selections. Lithium polymer batteries will be used, due to their high energy density, despite their greater cost.

The team used a minimalistic approach for choosing components, taking each requirement for functionality and trying to accomplish it in the least amount of sophistication and weight. This approach led the researchers to the Xiaomi 4K Mija action camera as the main front camera, along with a 3-axis gimbal due to its constant 4K at 30 frames per second stream, and lower cost versus the de-facto standard GoPro Hero 7, and to use a Sony Xperia XA's rear camera as the fish eye cameras for the obstacle avoidance and real-time 3D mapping (inspired by Skydio). The technology makes use of neural networks. It has been demonstrated very successfully in Skydio drones

Instead of a Raspberry Pi and Navio2 in concurrence (the initial choice), the researchers decided to use the NVIDIA Jetson TX2, as it has 8GB of RAM, Dual-core Denver 2 64-bit CPU and quad-core ARM A57 complex and 1.3TFLOPs of compute power, allowing us to run robust Reinforcement Learning models on the device itself, as the latency to the cloud server is too much for real-time operation.

Cellular networks have regular fees, however they enable us to use reliable and existing infrastructure, with high bandwidth. Antennae will be present as a backup system and will be used in case the internet connection is slow. The Unlimited Premium℠ plan by Spirit was chosen to provide a stable onboard internet connection because of its high bandwidth, cost efficiency, and reliability.

Materials

Due to its higher strength-to-weight ratio than other materials often considered for UAVs, carbon fibre will be used for the critical components This will make them very strong and rigid, and also lower the influence of temperature variation. The usage of EPP foam for other components will reduce their weight and their influence in shifting the CoM. Carbon fibre will be used only in the

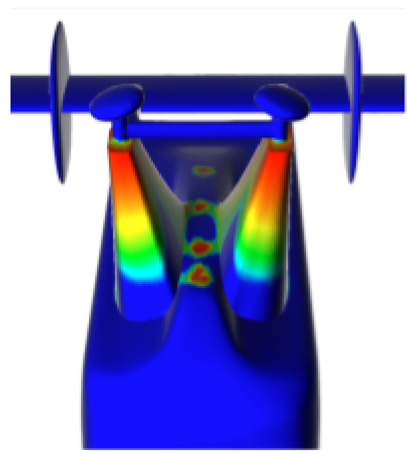


Figure 13: Static Stress Simulation Results

upper surfaces from which the packages and battery are suspended.

For more information on how to distribute the materials, a non-linear static stress simulation was carried out on Fusion 360, with the load on the frustums holding the rotors, and constraints for the attachment points for the packages and batteries. The results of which are shown on the right. Therefore, carbon fibre will be used in the upper surfaces from which the packages and battery are suspended. The distribution is shown in Figure 14, where light grey is carbon fibre, black is EPP foam.

Figure 14: Material Distribution.

Inside the body, small sections of EPP foam will be used to hold various components in place. In addition to its low weight, it will also cushion vibrations from the UAVs operation, which is especially useful for the more delicate electronic equipment. Some vertical carbon fibre rods will also be driven through the EPP foam, to make the UAV capable of standing upright in emergencies.

Obstacle Avoidance

For obstacle avoidance, the research team went through all usable sensors and it was decided that for short-medium range the imaging sensors will be used, these will help in obstacle avoidance and 3D videogrammetry.

For medium–long range, ultrasound was found to have shorter range, reduced reliability, slower polling rate and less precision and thus it was eliminated. LiDAR does not support very long range functions while having a considerably lighter weight, thus, it was also eliminated.

The following radar sensors were researched properly:

Criteria	**AWR1843**	**AWR1243**	**AWR2243**	**AWR1243 BOOST cascaded (automotive)**	**Bosch long range radar (automotive)**
Range	<150m	<160	<40m	<250m	<250m
Weight	2g	2g	2g	200g	240g

Cost/unit	$55	$36	$53	$299	$350
Hardware Required	Standard I2C,UART can be used	Standard I2C,UART can be used	Standard I2C,UART can be used	Special Board from Texas Instruments is required.	Special hardware required
Power	1.2v, 100mA	1.2v, 100mA	1.2v, 100mA	7.5W	4W
Precision (velocity, distance)	High	High	High	Very High	Very High

Table 7: Comparison of Radar Systems

It was decided that the AWR1243BOOST and the Bosch LRR will not be used as they are heavy and expensive and multiple cannot be placed on the UAV for complete coverage.

Therefore, the researchers ended up choosing the AWR1243 for its comparatively low power consumption, long range, low cost, easy usage, light weight and higher precision than what will be required on by the UAV. The comparatively smaller range will be accommodated by mounting them on servo motors which will rotate and increase the range. Calibration will ensure correct interpretation of data. Five such sensors will be placed on the UAV, one each on the left side, the right side, the tail, at the bottom and infront.

2.1.5 Lessons Learned

The team members had participated in a lot of international science and aerospace engineering related competitions in the preceding few years, and therefore felt that this one would be fairly easy after all the experience acquired in the past. However, soon after beginning, they realised that this one was much more difficult. It was connected much more to the real world, and required far better research to develop a solution, for it had to be capable of flying even in real life. There was a large amount of work to be done, and little idea of how to go about it.

The first task was to make a schedule. Team members lived in different places, and it was impossible for them all to meet each other physically. Therefore, after an engineering design process was decided upon, the schedule was made in Google Sheets, and formulas were used to connect it to a Gantt Chart. Through this, team members learned more about making an effective schedule and staying on track on work.

The team also extensively read the Notebooks of past winners, most prominently the Galaide. Written sections were compared directly to the Galaide to assess whether the level of detail was adequate.

Team members also learnt how to use professional software such Fusion 360, which allowed the running of advanced simulations, which were used to study aspects such as structural stress and airfoils. These are skills which will be useful to the researchers later in life.

Finally, writing a good Notebook was also a major task. Drafts of sections were edited multiple times, unnecessary content removed, and more detail added where required, and sentence structure, grammar and spelling improved. Proofreads were done to make it as close to perfect as the team could.

2.1.6 Project Plan Updates and Modifications

After studying different engineering design processes, the team was faced with several problems. After thoroughly examining the engineering design process, a flaw was unravelled. It was found that the pace at which the team was working on would not be fast enough. Time was allocated to the research of efficient ways of organization. The research concluded in the result that a schedule was necessary. The schedule must have the following properties.

- ➔ It must be universally accessible
- ➔ It must be easy to interpret
- ➔ It must be easy to use and modify
- ➔ It must be satisfying, encouraging, and motivating to complete.

This led the researchers to narrow graphical representation to entries on Google Sheets. This took care of properties (1) and (2). Additional research was done to see which graphical representation of timelines would be most encouraging for workers to follow. Optimising efficiency required us to consider both emotional and cognitive stability. This finally narrowed down to a Gantt chart. The Gantt chart had the following advantages-

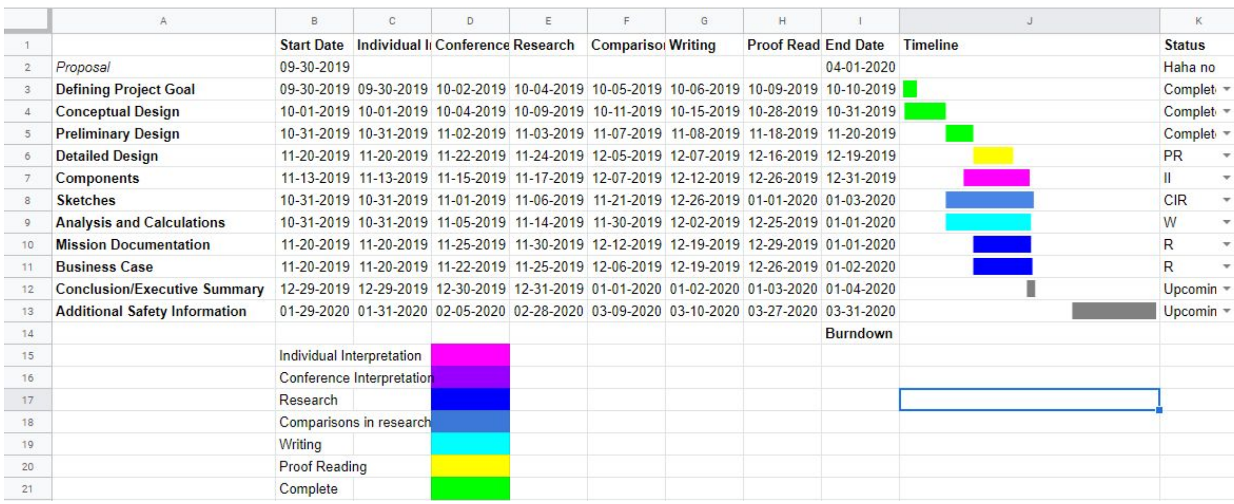
- ➔ A steady sense of progress was observed
- ➔ Any missed deadlines could be easily extended while preserving structure.
- ➔ It could be made colorful and appealing to the brain.

The use of Google Sheets to create a Gantt chart required proficiency. The finished product operated in the following way-

The individual tasks under *Project* were divided into different phases. The Gantt chart was then programmed to adjust its color according to the status of the task. This was done using the following code -

```
=SPARKLINE({int(Cx)-int($B$2),int(Ix)-int(Bx)},{"charttype","bar";"color1","white";"color2",if(Kx="Complete","#00ff00",if(Kx="II","magenta",if(Kx="CI","#9900ff",if(Kx="R","blue",if(Kx="CIR","#4a86e8",if(Kx="W","cyan",if(Kx="PR","yellow",if(Kx="upcoming","grey"))))))));"max",int($I$2)-int($B$2)})

where x is variable row number
```



	A	B	C	D	E	F	G	H	I	J	K
1		Start Date	Individual I	Conference	Research	Compariso	Writing	Proof Read	End Date	Timeline	Status
2	*Proposal*	09-30-2019							04-01-2020		Haha no
3	**Defining Project Goal**	09-30-2019	09-30-2019	10-02-2019	10-04-2019	10-05-2019	10-06-2019	10-09-2019	10-10-2019		Complet
4	**Conceptual Design**	10-01-2019	10-01-2019	10-04-2019	10-09-2019	10-11-2019	10-15-2019	10-28-2019	10-31-2019		Complet
5	**Preliminary Design**	10-31-2019	10-31-2019	11-02-2019	11-03-2019	11-07-2019	11-08-2019	11-18-2019	11-20-2019		Complet
6	**Detailed Design**	11-20-2019	11-20-2019	11-22-2019	11-24-2019	12-05-2019	12-07-2019	12-16-2019	12-19-2019		PR
7	**Components**	11-13-2019	11-13-2019	11-15-2019	11-17-2019	12-07-2019	12-12-2019	12-26-2019	12-31-2019		II
8	**Sketches**	10-31-2019	10-31-2019	11-01-2019	11-06-2019	11-21-2019	12-26-2019	01-01-2020	01-03-2020		CIR
9	**Analysis and Calculations**	10-31-2019	10-31-2019	11-05-2019	11-14-2019	11-30-2019	12-02-2019	12-25-2019	01-01-2020		W
10	**Mission Documentation**	11-20-2019	11-20-2019	11-25-2019	11-30-2019	12-12-2019	12-19-2019	12-29-2019	01-01-2020		R
11	**Business Case**	11-20-2019	11-20-2019	11-22-2019	11-25-2019	12-06-2019	12-19-2019	12-26-2019	01-02-2020		R
12	**Conclusion/Executive Summary**	12-29-2019	12-29-2019	12-30-2019	12-31-2019	01-01-2020	01-02-2020	01-03-2020	01-04-2020		Upcomin
13	**Additional Safety Information**	01-29-2020	01-31-2020	02-05-2020	02-28-2020	03-09-2020	03-10-2020	03-27-2020	03-31-2020		Upcomin
14									**Burndown**		
15		Individual Interpretation									
16		Conference Interpretation									
17		Research									
18		Comparisons in research									
19		Writing									
20		Proof Reading									
21		Complete									

Figure 15: Gantt Chart

The following Gantt chart was the result of this effort, thus ensuring that team members would be engaged and willing to complete the proposal outside of the monetary gains of a $50,000 scholarship, and simply for the sake of knowledge and the potential contribution of a viable future technology, especially given current (March 2020) circumstances (Covid-19) requiring the use of portable means of delivery. Further communication and updates were done in the form of bi-weekly calls on discord. Tasks were also assigned through the “task assigning” functionality of Google Docs by adding a comment followed by a “+” sign before the name.

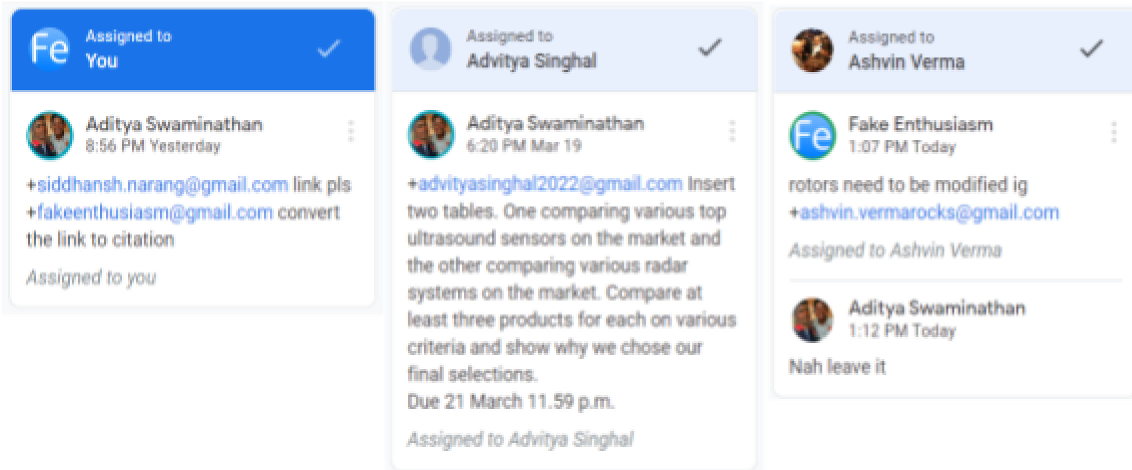


Figure 16: Task Assignments in Google Docs.

2.2 Selection of System Components

2.2.1 Payload Selection

Spring Loaded Package Release Mechanism

The three packages will be suspended from their tops, which will have hooks. They will be attached to hinges, each of which will have a movable or loose part connected to a thread and spring. When the servo moves clockwise, the thread will be tugged and the loose-part will disengage, allowing the hook to come free, and drop the package.

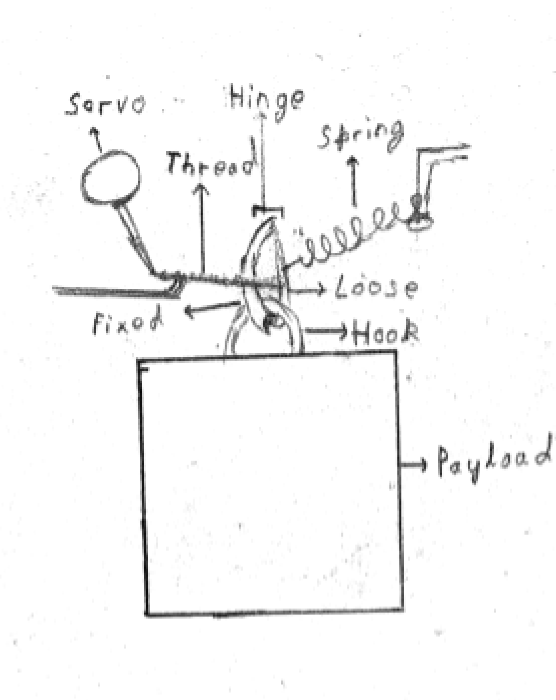


Figure 17: Package Release Mechanism

Corona DS339HV Digital Metal Gear Servo 5.1kg / 0.13 Sec / 32g

These servos will be used for releasing the spring-loaded mechanism to release packages. Their power consumption will be negligible since they will only be used once each during the flight and only momentarily.

Name	Quantity	Mass	Cost
Release Mechanism	3	120g	$100 (estimated)
Servo	3	32 g	$8.25
Total	**6**	**152g**	**$108.25**

Table 8:Payload Selection

2.2.2 Air Vehicle Element Selection

Xiaomi YDXJ01FM Mi 4K Action Camera, 2.4” Touchscreen WiFi Sports Camera with Sony Image Sensor, 145° Wide Angle 4K/30fps

This was selected as the UAVs main camera, mounted in the front. It has a low power requirement of 2.25W. It uses Sony CMOS IMX317, with an aperture of f.2.8. This makes it capable of capturing 4k video at constant 30 frames per second. It also has a wide 145° wide angle lens along with 3 axis gyroscopic stabilization which is quite effective. All this helps in proper execution of the 3D videogrammetry algorithms. The camera has been designed handling low light operation, adventure and can handle extreme outdoors conditions, making it suitable for mounting on the UAV.

Sony IMX 258 based rear camera of Sony Xperia XA ultra

These were selected as the vital fish-eye cameras which will be placed on the UAV for obstacle detection and efficient real time mapping. They use CMOS based Sony IMX 258 along with a wide view lens and the aperture of f/2.0, which will help run the 3D photogrammetry software onboard for navigation and obstacle avoidance.

Texas instruments AWR1243 Radar.

A lot of radar sensors are available on the market. The AWR1243 has been chosen because of its light weight, long range, high precision, low power consumption, etc.(advantages listed in section 2.1)

Global Positioning System (GPS) Sensor

NEO M8N was chosen as the main GPS sensor because of its high precision, low power consumption, lightweight body and the ability to run GPS, GLONASS (global navigation satellite system), BeiDou and Galileo simultaneously. It provides some verification.

SparkFun 9DoF IMU Breakout - LSM9DS1 and SparkFun IMU Breakout - MPU-9250

The research team decided to use these sensors as each one of them provides 3 axis gyroscope, 3-axis magnetometer and 3 axis accelerometer with very low power consumption and very light body. Both of them would be combined for better precision.

Digikey MS5611-01BA Barometric Pressure Sensor

This sensor was chosen as the barometric (altitude) sensor because of its low power consumption, light weight, and high accuracy. Adding it is affordable due to negligible mass, and yet it can provide additional confirmation to trilateration position data. It will be used along with the GPS to get the altitude and as an alternative in case GPS is not available. Adding it is affordable due to negligible mass, and yet it can provide additional confirmation to trilateration position data.

Turnigy 20000 mAh 6S 12C Lipo Pack and Turnigy 1000mAh 6s 65C Lipo Battery Pack

The motor has a very large power consumption compared to other components. This battery has been chosen to meet the motor's requirement of 22.2V, and with 20000mAh along with a 22.2V 2650mah battery while connected in parallel can provide 38-40 minutes of flight (Turingy, n.d.), and power the onboard electronics (that being the primary purpose of the smaller battery). Given that the longest missions last under 17 minutes, it gives a backup flight time margin of 22-24 minutes. A battery any larger will have greater weight, and will also be needless, given the fact that 22000mAh is adequate to complete the mission with 3 deliveries.

Rotor Blades

The rotor blades are custom made with carbon fibre.

Scorpion SII-4020-420KV Motor

From the power figures calculated for hovering and cruise (hovering was considered as it required greater thrust), this motor was chosen for its maximum continuous power output of 1500W (Scorpion, n.d.). This allows it to simultaneously power both rotors via a gear assembly. The motor allows swift acceleration to the maximum speed while cruising, and maintaining an effective hover.

FrSky Neuron 60 BL-32 60A Brushless ESC (3-6S)

This will be used as the speed controller for the motor. It can handle 60A continuous current and 100A of peak current. This also has a battery elimination circuit (BEC) which can give a seperate 8.4V-7A supply, which is enough to power all the other components.

Amongst the few ESC options this one was chosen because of the unmatched quality of HobbyKing products and the presence of a battery elimination circuit.

Corona DS339HV Digital Metal Gear Servo 5.1kg / 0.13 Sec / 32g

These servos are very powerful and they will be used in controlling the Swashplates.

Cytron 8 channel servo controller SC08A

This is a small and powerful servo controller which can assist the nVidia Jetson TX2 to control the servos. IT can run up to 16 servos with ART interference.

Body

The body will be made of EPP foam, with carbon fibre for the critical components.

HXT900 Micro Servo 1.6kg/ 0.12sec

This servo will be used to control and increase the range of the radar. This will also be used as the parachute servo. The radar placed at the tail will not have a servo motor.

Component Name	Quantity	Total Mass	Power usage	Total Cost
Xiaomi Mi 4K Action Camera	1	55g	2.25W	$89
IMX 258 based rear camera of Sony Xperia XA ultra	7	7g	2.9W	$105
AWR1843 Radar, Texas In.	5	15g	6W	$180
SparkFun IMU Breakout - MPU-9250	1	neg.	0.01W	$12
SparkFun 9DoF IMU Breakout - LSM9DS1	1	neg.	0.01W	$14
Digikey MS5611-01BA Barometric Pressure Sensor	1	neg.	0.02W	$105
EO-M8N u-blox	1	Neg.	0.756W	$16
HXT900 Micro Servo 1.6kg/ 0.12sec	4	36g	6.24W	$20
Turnigy High Capacity 16000mAh 6S 12C Lipo Pack w/XT90	1	2015g	N.A.	$184
Scorpion SII-4020-420KV Motor	1	288g	553W [3]	$479
FrSky Neuron 60 BL-32 60A Brushless ESC (3-6S)	1	56g	13.4W [4]	$55

[3] This is the average power. It has been calculated taking into account the changing weight during the flight and the motor efficiency which is around 87%.

[4] Released as heat

Cytron 8 channel servo controller	2	120g	1.8W	$30
Corona DS339HV Digital Metal Gear Servo 5.1kg / 0.13 Sec / 32g	6	192g	11.52W [5]	$49.5
Rotor Blades (including spoilers)	4	360g	N.A.	$292
Body	1	5100g	N.A.	$268.35
Wiring	1	50g	N.A.	$16
Total	**37**	**8294g**	**599.466W** [6]	**$1914.85**

Table 9:Air Vehicle Element Selection

Emergency Equipment

Mace 180dB Personal Alarm

Most of the buzzers used in hobby drones are often for locating a crashed drone, and are not loud enough as alarms. Personal alarms were investigated, and some were found which could emit 130 dB. These alarms were quite heavy, at around 50g, but it was realised that removing their outer covering and other included features would put the buzzer itself at about 20g (Mace, n.d.).

16 ft Ultra Light Parabolic Parachute

Most parachutes capable of handling a 25 kg UAV were very heavy. The Ultra Light Parachute, however, is unusually light due to its choice of materials. It is capable of reducing the UAV to a 15ft/s descent (Rocketman, n.d.).

HXT900 Micro Servo 1.6kg/ 0.12sec

This light servo is attached to the parachute, and opens it upon receiving the command during an emergency (ParachuteDrone, n.d.).

Component	Quantity	Mass	Cost
Mace 130dB Personal Alarm (only the buzzer inside)	1	30g	$15
16 ft Ultra Light Parabolic Parachute	1	365g	$360
Parachute Servo(HXT900)	1	25g	$8
Total	**3**	**420g**	**$383**

[5] Power only considered for six, because payload release servos are used only once each and momentarily.
[6] Excluding battery.

Table 10: Emergency Equipment

2.2.3 Command, Control, and Communications (C3) Selection

Ground Station

Turnigy T6A-V2 AFHDS Mode 2 2.4GHz 6Ch Transmitter w/Receiver along with TBS Crossfire micro Tx Rx bundle.

The research team decided to use the mentioned controller along with the TBS Crossfire, which gives it very low latency and a very large range of 40km. Other options for 5.6 km range (farthest distance) had the same cost, so were avoided.

5.8GHz 48CH FPV AV Receiver (RC832)

This will be used as the receiver for the telemetry and the video from the UAV. Instead of audio, telemetry will be transferred.

Lenovo Thinkpad

The Lenovo ThinkPad is well known for its reliability in industry applications. The ThinkPad X1 Carbon Gen 7 will be used, as it has an i7 processor, 16GB RAM and a PCIe SSD boot drive. It will be used in the ground station to monitor the UAV.

Onboard

Eachine TS832 Boscam FPV 5.8G 48CH 600mW 7.4-16V Wireless Transmitter and FPV 5.8ghz 11dbi High-gain Panel Antenna Aerial 200mw

This will be used as the main transmitter to transmit video from the main front camera of the UAV to the control station. This has a range of 5 km but with the mentioned antenna the range increases to 8 km.

Huawei E3372 LTE 4G CAT4 USB Modem (E3372H-153) with US Mobile 4G LTE SIM

Huawei E3372 LTE 4G Cat4 USB Modem US Mobile SIM and the plan allows us to transfer sufficient data over the internet and as a backup in the case the radio fails. The plan allows 5GB of 4G LTE data/mod. The SIMs can be recharged in case the high speed data is exhausted.

Flight Controls

nVidia Jetson TX2

Despite being an embedded device, the TX2 is fast and power-efficient, rated at 7.5W with 8 GB RAM, and 256 CUDA cores, and 32 GB Storage. Its firmware is supported by Linux, allowing us to easily develop and deploy our RL solution.

Name	Quantity	Mass[7]	Cost
Turnigy T6A-V2 AFHDS Mode 2 2.4GHz 6Ch Transmitter w/Receiver along with TBS Crossfire micro Tx Rx bundle	1	3.5g	$150
5.8GHz 48CH FPV AV Receiver (RC832)	1	N.A.	$30
Lenovo Thinkpad	1/3[8]	N.A.	$533.3
Eachine TS832 Boscam FPV 5.8G 48CH 600mW 7.4-16V Wireless Transmitter and FPV 5.8ghz 11dbi High-gain Panel Antenna Aerial 200mw	1	22g	$14.5
nVidia Jetson TX2	1	90g	$479
Huawei E3372	1	30g	$47
US Mobile SIm with %GB/mo 4G LTE	1	neg	$25
Total		**145.5g**	

Table 11: C3 Components Selection

Component Type	Total Mass	Total Cost
Payload	152g	$108.25
Air Vehicle Elements	8303g	$1914.85
Emergency Components	420g	$383
C3 Components	145.5g	$1278.83
Total	**9011.5**	**$3684.93**

Table 12: Total Mass and Cost of UAS

[7] Mass of only the onboard part is considered.
[8] 1 Thinkpad will be used to control 3 UAVS

2.2.4 Support Equipment Selection

Flight line equipment- There are generators required in the event of a power outage. With the capacity to deliver power upto 4000W, these can minimize disruption of services in the event of a power outage in the hub and satisfy all the needs.

Emergency Equipment- Trailers which will be strategically deployed all around the city, concentrated at the hub. In the event of any emergency, these trailers quickly respond to and proceed to the last known location of the UAV. They will feature all the necessary equipment required to rescue a UAV with a response time of two minutes. So the entire grid will be covered and quick extraction and retrieval of UAV can take place.

Solar Panels- The entire complex will be powered by the electricity generated by the solar panels. In the case of any cloudy weather, government-provided electricity will be used to meet internal demands.

Operational Closure- The hub will feature ample operating space for all staff. The safety pilots, load operators and the ATC controllers will operate out of a temperature controlled environment owing to the sensitive equipment present. The UAV maintenance staff will be working on the UAVs in the workshop at the centre of the launch floor, and the package handlers will have a dedicated building for the sole purpose of package sorting and packaging. Each staff member will be given a laptop to access overall operational status and receive instructions. The ATC will have a full equipment set including radars, and the safety pilots will have a setup of a joystick and a monitor giving a live feed from the camera.

2.2.5 Human Resource Selection

Number of Personnel	Category	Wages[9]
9	Safety Pilots	$3,543.75
9	Maintenance/ Aircraft Launch and Recovery	$3,543.75
9	Payload Operators	$3,543.75
8	Package Handlers	$1,350.00
2	Package Collectors	$337.5
7	Air Traffic Manager	$2756.25

[9] The wages are the total wages of both the sets of workers

6 (3 teams)	Emergency Rescue and Response Team	$1012.5
Total		**$16087.5 per day**

Table 11: Human Resource Selection

The working day will be 9 hours (0800hrs to 1700hrs) and will consist of 2 shifts of 4.5 hrs which will have separate workers. It will have 30 mins of preparation, 30 mins of packaging and 2:30 mins of break, one for each shift of workers. The workers will be paid a wage 1.25 times the wage specified in the detailed background, which will let them have a wage of 39.375 hours while working for only 31.5 hours (7 days a week). It will help the workers to work the job for 7 days a week, and also helps the company to abide by labour laws while having 7-day work weeks.

The description of the employees are as follows:

- **Safety Pilots:**

They will be observing UAV flight at all times. They will be monitoring the flight of the UAV and the event of an emergency, they will take manual control of the UAV. They will be FAA-certified and will be in accordance with all the regulations as stated in Part 107.

- **Maintenance/ Aircraft Launch and Recovery:**

They will be responsible for ensuring that the UAVs are in flying condition. It is their job to facilitate the loading and unloading of containers of the UAV, and replacement of batteries after every flight. Furthermore, they will check flight control surfaces, flight systems and conduct repairs and maintenance checks. They also have to ensure frequency deconfliction.

- **Payload Operator :**

They will ensure that the right package is sorted into the right box and that the packaging is properly done and then pack them into their specified containers for loading into the UAV.

- **Package Handlers:**

They are responsible for moving the packages from package sorting to the launch bays for loading into the UAVs.

- **Package Collectors:**

They will collect packages from the customers in the event of an error in package handling by the company or for a return.

- **Air Traffic Manager:**

They will be responsible for coordinating the take-off and landing of aircraft from the central hub. They will prioritize an aircraft low on fuel, or requiring an emergency landing. They will monitor all civilian and military frequencies and will control UAS operations. In the case of any airspace closure, they will re-route the UAVs away. They will also be responsible for real-time weather updates and management of UAV traffic.

- **Emergency Response Teams:**

These are 3 teams formed of pairs, which will be deployed all over the city. They will be responsible for immediately responding to any emergency declared by the UAVs. They will be strategically located so that their response time is less than 2 minutes and they can quickly balance.

2.3 Component Placement and Complete Flight Vehicle Weight Balance

As can be seen from the top view figure, all components have been distributed equally across lines of symmetry down the length of the body. The only place where this is not the case is in the set of circuitry around the NVIDIA Jetson. In this area, however components were placed in a way that their centre of mass still remained along the centre line. From this, it can be known that the CoM (centre of mass) is not inclined towards any side.

To determine the coordinates along the y-z plane, the CAD software was used, along with some manual calculation (due to the use of multiple hull materials). Calculations revealed the CoM to be **8.8 cm** from a datum line taken at the main rotor mast.

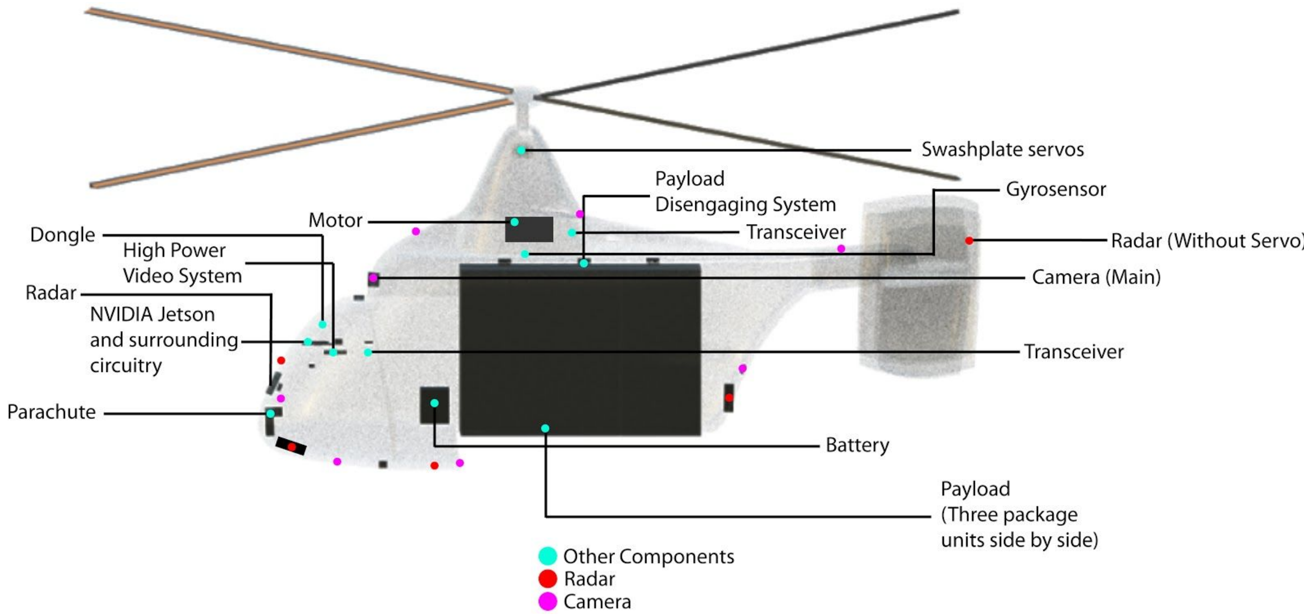


Figure 18: Side View Of The UAV With The Hull Made Transparent To Show The Placement Of Components And The Centre Of Mass (Rotor Blades Coloured For visibility).

2.4 Operational Maneuver Analysis

Hover

In order to determine the power requirement for hovering, disk actuator theory can be used, according to which an expression for the ideal power required to drive a rotor can be determined in terms of the thrust required, the density of the ambient air, the vertical velocity of the rotors and the area swept out by the blades.

$$\text{Power} = Tu_{\text{disk}} = \frac{1}{2}Tu_0\left[\left(\frac{T}{A_{\text{disk}}u_0^2\frac{\rho}{2}}+1\right)^{\frac{1}{2}}+1\right]$$

This is the ideal power, and in reality the requirement is about 15% higher than this. Putting in the values for a stationary UAV near sea level, and adding a 20% margin on top for extra safety results in a hover power requirement of roughly 1.4 kW, compared to the 1.5 kW peak output of the motor driving the rotors.

Though this formula is applicable to a more standard single rotor configuration, it is known from Fernandes, 2017 that using the same power estimation techniques on dual coaxial rotor designs results in a slight overprediction when compared to reality. As the intermeshing configuration used by the UAV is quite similar to a coaxial configuration, especially considering the low displacement of the rotors, it is safe to say that these estimations will hold, and any deviation will be on the side of safety.

Constants:		
Acc. due to gravity	9.81	m/s
Ambient air density	1.22	kg/m^3
Pi	3.14	
Parameters:		
Final margin	20	%
Total mass	25	kg
Blade length	1.51	m
Thrust to weight ratio	1	
power		W
speed	0	m/s
Calculations:		
rotor thrust	**245.25**	**N**
required power	**1.36**	**kW**

Figure 19: Spreadsheet Used for Thrust Calculations

Climb

The principle in maximising the efficiency of the UAV in climb is similar to a rocket launch. Every second spent hovering is energy being wasted in countering gravity, and in addition the power required to maintain flight goes down with airspeed as the horizontal speed of the vehicle increases. Therefore, it is desirable to get up to cruise speed as quickly as is possible given the performance of the UAV and the surrounding obstacles. Hence, the climb will occur in two stages:

Vertical ascent: The UAV will remain perfectly horizontal with the rotor at maximum thrust to begin accelerating upwards. During this phase, it will also yaw towards the direction of the next target or as dictated by the flight path.

Horizontal acceleration: The UAV will pitch down and accelerate to cruise speed, while maintaining maximum rotor power and a constant (but lower) vertical speed.

Final ascent: the UAV will maintain cruise speed while still keeping rotor power at maximum, and thus climb at a gradually increasing rate until it reaches cruise altitude.

The transition from stage one to two will take place when two conditions are met. First, the UAV must be above a designated minimum vectoring altitude, considered here at 20 m or approximately 66 ft. Second, the UAV must clear any obstacles along its climb path with a sufficient margin, so a minimum safe horizontal acceleration start altitude must be cleared.

For maximum load, the weight will be equal to mg ie. 25 kg × 9.8 m/s^2 = 245 N. The thrust from the rotors need to balance this force in a climb. Knowing the other parameters in the equation used in the previous subsection, u_0 can be obtained. For the motor's maximum power output of 1.5 kW, the climb speed is then 2 m/s, 4.4 m/s, and 7.3 m/s at 25 kg, 20 kg, and 15 kg gross weight respectively.

Now, for the horizontal acceleration phase, the UAV will pitch forward slightly, thus reducing the vertical component of the rotors' thrust. Simultaneously, a horizontal component of the thrust will start acting on the UAV, accelerating it sideways. However, as the vertical speed drops, the power required to drive the rotors will also decrease as per the above equation, and thus thrust can be increased to maintain a lower vertical speed. It can be seen that for a vertical speed of 1.5 m/s, the UAV will be able to generate ~270 N of thrust, thus allowing it to maintain its vertical velocity while also gaining lateral velocity. So, the UAV will gradually pitch over as its vertical velocity decreases. For our selected climb rate in this phase, this will result in a maximum pitch angle that can be calculated as follows:

In order to maintain vertical velocity-

$$T_v = mg$$

$$\Rightarrow T \cos\theta = mg$$

$$\Rightarrow \theta = \cos^{-1}\left(\frac{mg}{T}\right)$$

$$\Rightarrow \theta = \cos^{-1}\left(\frac{25 \cdot 9.8}{270}\right) = 24.9°$$

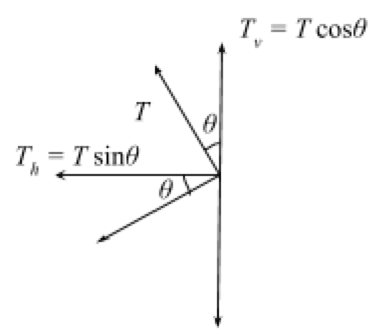


Figure 20: Climb vector diagram.

As the UAV accelerates horizontally, two competing effects will come into play. Parasitic drag and profile drag will increase with velocity, while induced drag will decline, and total drag will decrease, as will the power required to maintain vertical speed as the UAV approaches cruise speed. Thus, in order to maximize climb efficiency, the UAV will subsequently follow the control rules given in the table below:

Condition	Power	Horizontal speed	Vertical speed
Horizontal acceleration start	maximum	increasing	maximum
Cruise speed reached	maximum	26 m/s	variable (higher)
Cruise altitude reached	variable (lower)	26 m/s	0 m/s

Table 13: Climb Control Rules

From this the minimum climb angle from the point of reaching cruise speed can be obtained:

At minimum climb rate after reaching cruise speed:

$$\tan\theta = \frac{|v_y|}{|v_x|}$$

$$\Rightarrow \tan\theta = \frac{2}{26}$$

$$\Rightarrow \theta = \tan^{-1}\left[\frac{2}{26}\right]$$

$$= 4.4°$$

Finally, the minimum safe horizontal acceleration start altitude can be determined by drawing a line at this angle to the ground from the site onto the cruise path, and raising it such that it just touches the top of any obstacle lying along the flight path. As the acceleration to cruise speed will take several seconds during which the climb angle will be much higher, the UAV will fly a trajectory above this line, thus guaranteeing that it will clear any obstacles on the line.

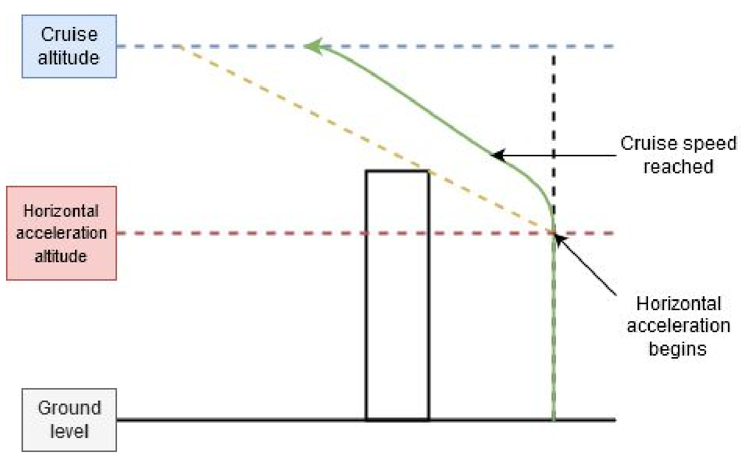


Figure 21: Cruising Altitude Diagram

Cruise

Due to the many, many disparate factors, foremost of which is induced drag from the rotors, it is impossible for the team to directly calculate the cruise power required by the UAV. However, given the significantly more accurate hover power figure, an estimate can be extrapolated by comparing the ratio of hover to cruise thrust requirements for a design whose values are known. For instance, Ibrahim & Jaafar, 2008 found that for their theoretical 4-seater helicopter, the power required for hovering is ~195 bhp (which, when calculated by the team's method using their specifications, came within a reasonable margin of their result). On the other hand, for forward flight at 85 ft/s, the required power dropped to ~100 bhp, resulting in a ratio of 1:0.52 for hover vs cruise power.

Given the UAVs hover power requirement at max load of 1.4 kW, multiplying by 0.52, rounding and normalizing gives us a cruise power of ~0.73 kW. Due to the inaccuracy of this method, the rated cruise power is set to be 0.75 kW for the purposes of operational planning, thus leaving a comfortable margin for error on top of what is already built into the hover power calculation, though actual cruise power is expected to be lower in practice.

Thus, the team estimates cruise power at 25 kg, 20 kg, 15 kg, and 10 kg gross weight to be 0.75 kW, 0.54 kW, 0.36 kW, and 0.21 kW respectively.

Descent

$$v_f^2 - v_i^2 = 2as$$

$$\Rightarrow s = \frac{-v_i^2}{2a}$$

$$\Rightarrow s = \frac{-26^2}{2\cdot(-2.4)} = \mathbf{140.8\ m}$$

Taking a safe descent rate of 6 m/s, the UAV will take just over ~10 seconds to descend from cruise altitude to a target site. In this time, it needs to shed all of its horizontal velocity, starting from a cruise velocity of 26 m/s, while also coming to a stop over the site. To ensure maximum efficiency, the UAV must remain in cruise as long as possible, and hence deceleration should begin at the same time as descent, as long as no obstacles lie along the flight path. So, if setting the deceleration rate to a little over 2.4 m/s (this is the average deceleration rate required, so sustained deceleration rate will need to be higher), the stopping distance required using the laws of motion can be obtained as well as the upward pitch and power during the descent as follows:

To maintain descent rate-

$$T_v = mg$$

$$\Rightarrow mg = T\cos\theta \quad \text{- I}$$

To decelerate at 2.5 ms^{-1},

$$T_h = ma$$

$$\Rightarrow T\sin\theta = ma \quad \text{- II}$$

Dividing I by II,

$$\frac{T\,sin\theta}{T\,cos\theta} = \frac{ma}{mg}$$

$$\Rightarrow \tan\theta = \frac{a}{g}$$

$$\Rightarrow \theta = \tan^{-1}\left(\frac{a}{g}\right)$$

$$\Rightarrow \theta = \tan^{-1}\left(\frac{2.4}{9.8}\right)$$

$$\Rightarrow \theta = \mathbf{13.76°}$$

Substituting $\theta = 13.76°$ into II yields-

T = **252.3 N**

By calculating the power required for this thrust level as before, the team can ascertain that the rotors will require 1.46 kW to maintain it while the UAV is stationary, well within its capabilities. Furthermore, in practical use, power required will be even less than this; in the first few seconds of deceleration, lower induced drag will mean less power is required to drive the rotors, while parasitic drag will provide part of the retarding force, reducing the thrust needed to be provided by the rotors themselves.

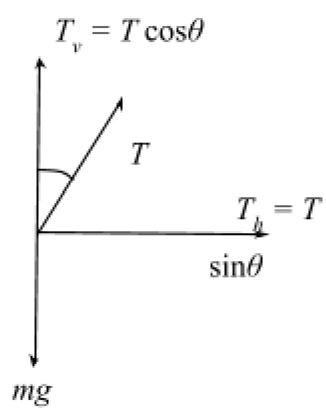


Figure 22: Descent Vector Diagram

In case of a high obstacle lying along the flight path, the start of descent can be delayed, although in this case horizontal deceleration will still have to begin at a distance of 120 m from the target site in order to minimize the pitch angle and ensure that the UAV is in a stable regime. This only changes the time required for the descent phase, and not any maneuvering characteristics or stresses.

Turns

Referencing back to the method the team used to calculate the required power for cruise, a function that gives the percentage of hover power at a particular airspeed can be extrapolated from the given data. Using polynomial regression, the team obtained an expression for the power P (in kW) required by the theoretical 4-seater helicopter in Ibrahim & Jaafar, 2008 study to maintain flight at a particular forward velocity v (in m/s) for any v between 0 and 30 m/s:

$$P = 144.0 - 1.196v - 0.9726v^2 + 0.06640v^3 - 0.001798v^4 + 0.00001781v^5$$

Since the power required at hover for this helicopter is given by $P_0 \approx 144$ kW, the expression for the required power at a given speed as a fraction of hover power becomes

$$k = \frac{P}{P_0} = \frac{1}{144}(144.0 - 1.196v - 0.9726v^2 + 0.06640v^3 - 0.001798v^4 + 0.00001781v^5) \quad \text{— I}$$

where v is in meters per second and the units of P and P_0 are the same. Now, consider the UAV to be in a banked turn at a roll angle of θ degrees and a forward speed of v meters per second. Then, for a given turn radius of r meters, the centripetal force required to maintain the turn is given by

$$F_C = \frac{mv^2}{r} \quad \text{— II}$$

At the speeds the UAV is operating, centripetal force due to drag will be negligible, and hence the entire required centripetal force can be assumed to be provided by the rotors. So, the team gets

$$F_C = T\sin\theta \quad \text{— III}$$

Now, from the earlier disk actuator theory-based rotor power formula, the team can write an expression for the power required to hover in terms of thrust as follows:

$$P_0 = 1.2\sqrt{\frac{T^3}{2A\rho}}$$

where A is the area swept out by the rotors and is the ambient air density. The 1.2 factor is added as a 20% safety margin. Now, in order to convert this power requirement to a value corresponding to the velocity of the vehicle during the turn, the team can use the conversion factor by multiplying both sides by eq. I:

$$P_0 \cdot \frac{P}{P_0} = 1.2\sqrt{\frac{T^3}{2A\rho}} \cdot k$$

Or, on rearranging,

$$T = \sqrt[3]{\frac{2A\rho P^2}{1.2^2 k^2}} \text{ — IV}$$

Using eqs. III and IV in eq. II, the team gets

$$\sqrt[3]{\frac{2A\rho P^2}{1.2^2 k^2}} \cdot \sin\theta = \frac{mv^2}{r}$$

As A, ρ, P, and m are constant in practice, the team can combine them as well as the 2 and 1.2^2 factors into a single variable C such that

$$Cr\sin\theta = v^2 k^{\frac{2}{3}} \text{ — V}$$

$$C = \frac{1}{m}\sqrt[3]{\frac{2A\rho P^2}{1.2^2}}$$

Now, in order to maintain altitude, the vertical component of the thrust from the rotors must balance the weight of the UAV, ie.

$$F_V = mg = T\cos\theta \text{ — VI}$$

Also, on dividing eq. I by eq. V, the team gets

$$\tan\theta = \frac{v^2}{rg} \text{ — VII}$$

By converting the above to $\sin\theta$, putting eqs. I and VII in eq. V, and rearranging, the team finally obtain an expression for the turn radius in terms of forward speed:

$$r = \frac{v^2 k^{\frac{2}{3}}}{\sqrt{C^2 - g^2 k^{\frac{4}{3}}}}$$

We can also get the bank angle and load factor (G force) from eq. VII as

$$\theta = \tan^{-1}\left(\frac{v^2}{rg}\right)$$

$$n = \sec\theta$$

The team then used the Python library *matplotlib* to chart the variation of these quantities with velocity at the vehicle's maximum gross weight of 25 kg and at the maximum power output of the motor, yielding the following graph:

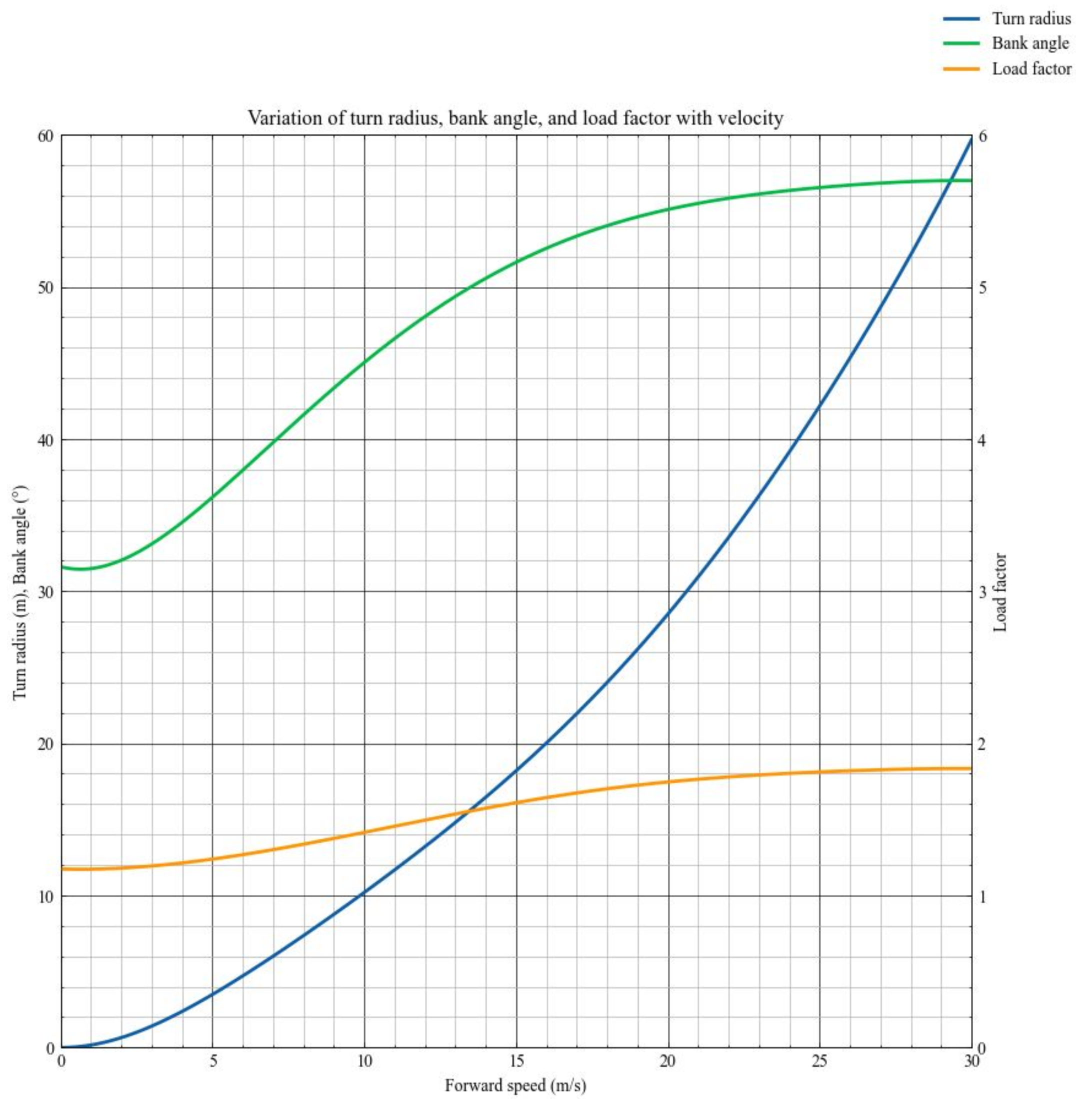
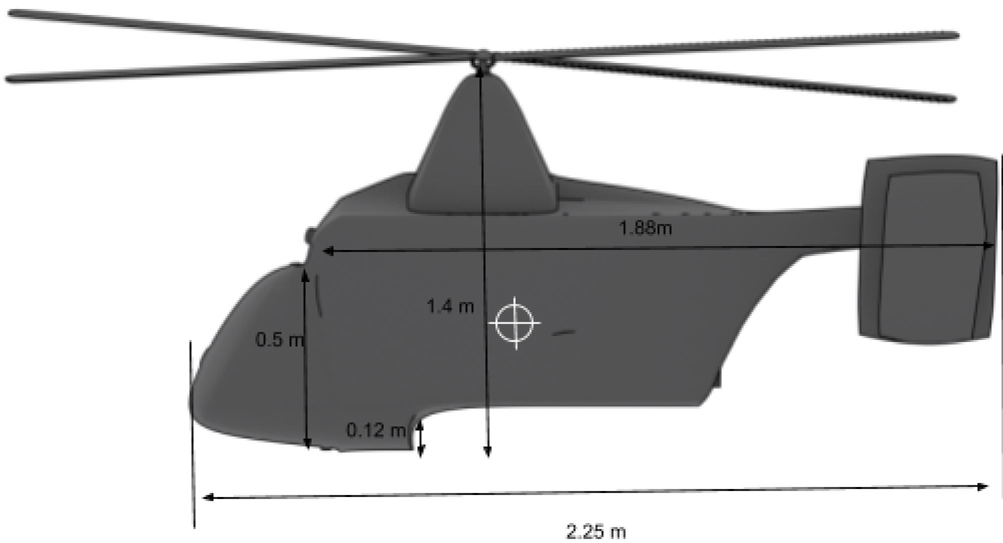


Figure 23: Turns Plot

As can be seen from the above plot, in its entire operating range of up to 26 m/s velocity, the UAV in a maximum banked turn never exceeds a bank angle of 60° or a load factor of 2. Hence, the limits on turn speed are imposed not by structural or aerodynamic constraints, but by the available turn radius. This also means that the UAV can safely undertake evasive maneuvers at cruise speed without a possibility of damage from external loads. Inside the city, the team expects available turn radius to typically be around 10 m, which correlates to a turn speed of a little under 10 m/s at full load, accounting for the extra distance required to roll and level out during the maneuver.

2.5 Three View of Final Design



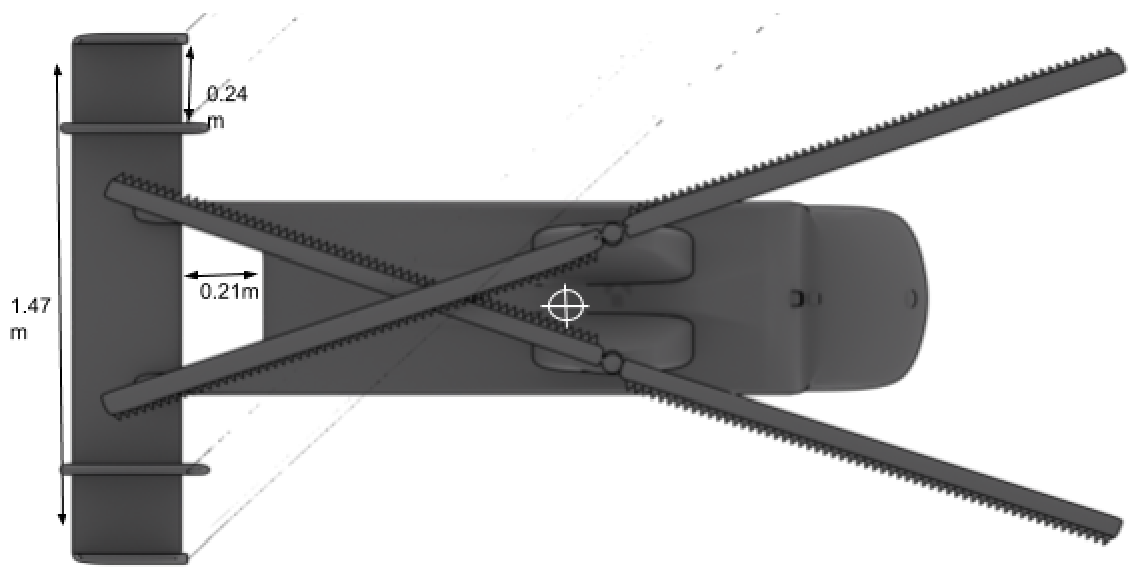


Figure 24: Three-View of Final Unmanned System Design (Centre of Mass Also Indicated).

3. Document the Missions

3.1 Concept of Operations

3.1.1 Pre-Mission

The working day will start at 0800 hours and will end at 1700 hours. Packages will be received at the Hub latest by the morning on the intended date of delivery (if received later, packages will be accommodated on the next day). On the delivery day, in the morning, packages will be sorted into groups of three, determined by proximity of their delivery locations. The packages will be wrapped in bubble wrap and/or cardboard (depending on package) for integrity during flight and the one metre drop at the delivery location.

Customers will be required to download a mobile application (or use the company's website) to receive notifications regarding their delivery. The application will be equipped with a machine learning based chatbot, capable of text-based and verbal communication. Its ability to handle various requests will improve over time. Its architecture will consist of-

➔ Intent and entity recognition

➔ Reinforcement learning based conversational state inference and policy training

➔ Natural Language Dialogue generation module

It will be able to handle rudimentary queries, and help reduce the number of customer support personnel. It will provide 24/7 support without any delay. In case it faces a situation for which it is unprepared, or is unable to understand the customer, it will pass the request on to a human operator (the emergency response team, who will mostly be unoccupied). The situation will help train it further. All conversations will be recorded and analysed for improvement of the chatbot and checking for improper behaviour on the customer's part.

Customers will be asked to confirm availability before delivery. In the Hub, FishBowl Inventory, a Warehouse Management System, is used for package management and database operations.

At 0530 Local Time every morning, a computer algorithm, under the direction of a planning crew, will generate flight plans for each UAV during the whole day. This will be done while the package handlers will be preparing the hub. METAR (Meteorological Routine Weather Report) data for the day, TFRs (Temporary Flight Restrictions) and NOTAMs (Notices to Airmen) for the local airspace will be factors. Deliveries are spread evenly throughout the day to avoid excessive rush at any time. Early planning of all flight routes for the day allows prior knowledge and avoidance (by adjusting flight timings) of possible collisions. Flight planning software by Garmin and Honeywell are used here, such as Garmin Pilot and Next Generation Flight Management System (NGFMS) by Honeywell. Various road intersections, landmarks, and other points will be marked as waypoints, and their exact locations as well as required flight altitude will be determined. This eases planning and also navigation for the UAV because it has more reference points for comparison. All flight routes are along predefined flight corridors.

The boxes are sent to launch stations three hours before the estimated time of departure. They will be inspected again and verified with the manifest. On the flight deck, the UAV will be present without batteries (removed) and the payload (dropped). Fresh batteries are added and the payload attached. Inspections are carried out. Finally, the departure of the UAV is checked with the ATC. After confirmation, it is moved on the protruding launch platform, from where it takes off.

3.1.2 Flight to Delivery Location

Upon take-off, the UAV enters the vertical ascent phase, and, if necessary, also rotates to face the direction of its intended flight route. After clearing the surroundings, it accelerates horizontally, and thus reaches cruise speed (26.8 ms^{-1}) and altitude (200 ft). While flying, the UAV determines its location by using a combination of GPS and trilateration from verified nearby WiFi networks. Then, it will use location data to compare with the map and remain on the assigned route. Buildings and their heights are marked on the map, allowing the UAV to know its position relative to the buildings and thus avoid them by changing the altitude, if required. The map also contains information on major known obstacles in the path, so most of these can also be avoided in this manner. It will also have the locations of all the UAVs that may cross over the UAVs path.

However, there are some unknown obstacles, some of which may also be moving, such as birds and unlicensed hobby drones. Therefore, the UAV also uses obstacle detection systems. It is equipped with radars on the front and back. These cover an angle around the front and back directions, which are the most important at high speeds. The AWR1243 can detect objects and their velocity from a distance of at least 150m (for small obstacles, it may increase with increase in obstacle size). At top speed, this provides the UAV over 5.5 seconds to react to a still obstacle, though lesser if the obstacle is flying directly towards the UAV. This way, there is adequate time for the UAV to perform one of a set of pre-programmed dip/turn avoidance manoeuvres (depending on the speed and direction of the obstacle). In case the pilot must take control, there is a high resolution front camera, along with small fish-eye cameras that cover the other directions. In case of loss of trilateration systems and the GPS (which is very rare), the UAV uses the data from the 3 axis gyroscope, magnetometer and the accelerometer.IN such a scenario the cameras can also be used to study each frame in real time and give an approximate location(along with the 3 axis gyroscope, magnetometer and accelerometer). The ATC monitors all UAVs. Any changes in METAR or new TFR/NOTAMs are immediately sent to the UAVs and the pilots monitoring them, along with instructions for changes in flight paths. The pilot constantly monitors the UAV and is ready to take over if required. Communication between the UAV and the ground station will be through a long range radio system capable of delivering a range of over 14km). The UAV will transmit motor telemetry, sensor data, and location information to the ground station, while the ground station will send mission changes, locations of other nearby UAVs, flight corrections and other instructions to the UAV. The UAV also communicates with other UAVs in the form of transponder signals. The signal strength, direction and Doppler shift allow determination of the UAVs' location and velocity, which is useful to add to the data already provided by the ATC. All aircraft in the airspace below 2500 ft will be required to tune in to the Hub's ATC transmission frequency (possibly enforceable by a NOTAM, if permission is granted by the FAA and city authorities). This will be different from the frequencies used by aircraft and airport ATCs, since the information is irrelevant to high-flying passing aircraft. The UAVs route will follow flight corridors, and a minimum distance of 20 m will be kept from buildings at all times.

3.1.3 Package Delivery

Upon reaching the delivery neighbourhood, the UAV will reduce speed and descend gradually, till it is 20 m directly above the delivery spot. Then, it will descend vertically, and finally hover one metre above the delivery spot. Since delivery spots are pre-designated, they all have a circle painted around them to indicate the minimum safe distance. The required package is dropped. The wrapping during the preparation stage protects it from damage due to the impact from this short drop. The risk of theft will be eliminated by the fact that the customer's presence will be guaranteed by him/her (by the medium of multiple confirmations required through the mobile application at various times prior to the delivery; absence after these will be considered the customer's responsibility). Breaching the minimum distance will cause the UAV to take off immediately for safety reasons. The person who breaches the perimeter will be liable for inquiry and legal action. The customer will collect the package after the UAV departs. Between delivery locations (which will be in the same neighbourhood, due to flight planning), the craft will fly at an altitude of 50 ft at half the cruise speed.

3.1.4 Return Flight to Hub

All packages are delivered on a strict schedule. The schedule does, however, leave a margin of a few minutes on every mission to accommodate delays. After the last delivery, the UAV will return to the Central Hub. On the return flight, the UAV will be much lighter, due to the lack of payload. Therefore, during this time, the battery consumption will be lower. Upon reaching the Hub, the UAV will slow down and descend. It will reach the designated landing spot and await ATC approval. The ATC regulates arrivals and departures by using Standard Terminal Arrival (STAR) and Standard Instrument Departures (SID) to prevent clogging of landing space and confusion for arriving UAVs. If, due to a snag, there is a delay, the UAV will be required to hover at a designated location. After receiving approval, it will descend vertically onto the landing pad, which is equipped for the landing (since the UAV has no landing legs). From there, it will be rolled into the launching/receiving station.

3.1.5 Post-Mission

Once the UAV has landed, its rotors will be allowed to stop. Then, it will be brought inside the launching/receiving station. Here, its motor will be allowed to cool down. The battery will be removed. An inspection of the sensors will take place. A tablet will be connected to the main computer, which is connected to the other components. This will allow a check of all the electronics. The motor, rotors, and structural components will be examined separately. Then, fresh batteries are put in and the packages attached. The batteries will be checked again to make sure they are adequately charged. Then, the UAV will be ready to receive the new payload and battery.

In general, a UAV is put through various kinds of tests at different times. If these hinder its operating time, a backup UAV covers for it. 2 backup UAVs will always be there along with some spare parts like tails, rotors, etc.

Check Type	Features
Class A	Done after every flight, it is very short and a tablet will also help along

	with physical inspection. Includes thorough checking of all the flight controls and checking that each component is fully functional.
Class B	Done after every fortnight. An extensive check including checking the motor and performance, and replacement of any part.
Class D	This is done only if a UAV develops a major snag while in flight. If such an incident happens, the UAV is removed from active service and is carefully examined to find the cause. After it has been fixed, it is tested for a week and performs test flights. Then once it has been certified for commercial use, it enters back into active service.

Table 14: UAV Inspection Types

3.2 Urban Flight

3.2.1 Flight Corridors

Flight corridors restrict the region through which the UAVs can fly, and thus reduce nuisance caused to residents. The flight corridors follow major roads, and therefore UAVs will not fly above houses and other buildings. Flight over crowded areas will be monitored more closely. To encompass all conditions, we assume the presence of an airport. Flight corridors will avoid the glideslope of the runways. Since the cruise altitude is 200 ft, all non-fixed operators in the vicinity (especially helicopters) will be instructed to stay clear of the flight corridors or fly over them at a higher altitude. Special emergency craft such as police or rescue helicopters will be given the right of way, and all UAVs in the area will receive immediate instructions to change flight path to avoid them.

The figure below illustrates the chosen flight corridors. For the scope of this Notebook, due to the lack of information on airports or how crowded areas are, the primary basis for choosing the flight paths here is ease of accessibility to neighbourhoods. The neighbourhoods have been labelled on the map for reference in 4.1.1.

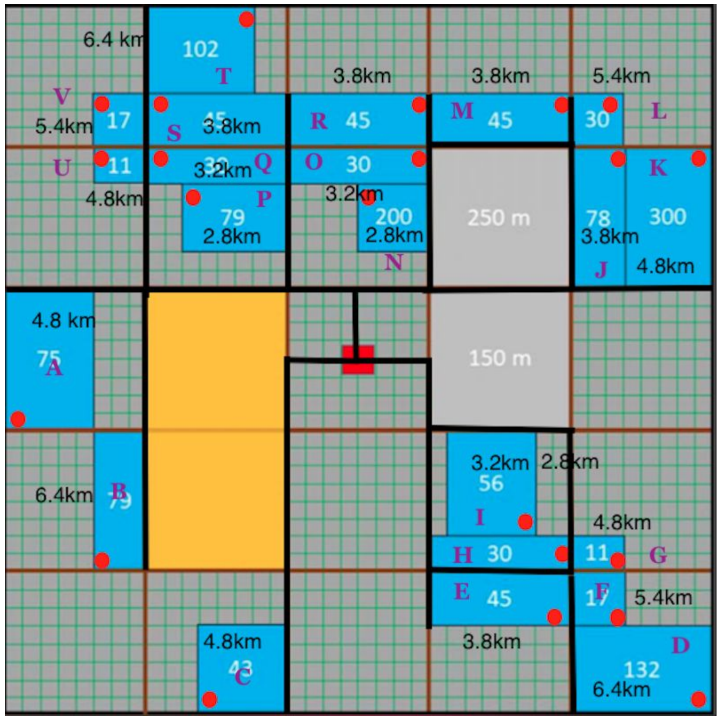


Figure 25: Flight Corridors

3.2.2 Flight in Delivery Neighborhoods

Within delivery neighbourhoods, the UAV will fly at only 13 m/s (half the cruise speed) and at 50 ft, since gaining and losing altitude and speed for these short and quick flights between deliveries is pointless.

While cruising, the UAV is high enough that its noise emission does not reach annoying levels. It spends only a few minutes within a neighbourhood, where its altitude is low enough for it to cause annoyance. Considering the size of neighbourhoods, the speed of the UAV, and assuming an even distribution of deliveries in the neighbourhood, it can be seen that the average person will only hear the sound of a UAV in approximately 5 second intervals 5-10 times a day. This is not much of a nuisance in itself. The rotor blade spoilers bring down noise emissions further, which makes the UAV package delivery system more welcome in the urban area.

3.2.3 Flight Logistic

Handling 27 UAVs is a challenge for the Hub, and requires well-made procedures and division of work. The Hub contains nine launching/receiving stations, each having 3 UAVs assigned to it, and each being connected to a landing pad. Though considering the flight times, it is theoretically possible to have four to five UAVs per station, this requires mechanical efficiency on the part of the crew operating the station, and perfect timing in all aspects. Therefore, a margin must be accommodated and instead a value of 3 UAVs per station has been chosen. Each station is operated by two people who receive the UAV, prepare it, and launch it again.

Due to a strict assignment of two UAVs per landing pad, a system of alternation is followed where one UAV carries out a mission while the other is being prepared at the Hub. This system ensures that an arriving UAV will always have an available landing pad and receiving station, with a time margin to spare. This removes delays and prevents clogging up of the work. In case landing pads are not available due to a snag, the UAV will be sent instructions to fly around the hub in predesignated holding patterns. This is preferred over hovering in place since power usage is lower at speed, and hence gives the UAVs more endurance in case of an extended hold time.

UAVs are flown using an algorithm, but to ensure safe flight, they are constantly monitored by the operational pilot, who may take over control if necessary. Most of the time, however, the pilot must merely watch a screen showing telemetry along with visual footage. They need only take over if the system raises an alarm due to any values exceeding set parameters or if they notice any discrepancy. Therefore, one pilot can easily monitor three UAVs. The pilot gets short breaks at a few points when all of their UAVs are at the Hub to prevent fatigue and ensure alertness.

In case of an emergency, all crew members who handle that UAV and emergency response trailers in the area are alerted. Attempts are then made to either fix the problem or to make a landing at a hub, or on a rooftop.

3.3 Mission Requirements

3.3.1 Guidance without GPS

Due to the urban canyon phenomenon, GPS is not the primary navigation system for the UAV. A small GPS sensor is placed since it has almost negligible size, mass and electric consumption, and it can provide approximate data. However, for the most part, the UAV operates using WiFi trilateration. This will not be intrusive on residents' privacy, nor will it use their resources, since the triangulation method only measures signal strength, and does not even connect. Then, when the UAV is flying, it can trilaterate from a large number of WiFi hotspots, which are abundant in an urban environment. If, in an emergency, this system fails an algorithm can analyse camera footage and estimate location data or the data from the 3 axis gyroscope,magnetometer and accelerometer can also be used. (explained in 3.1.2). Pilots constantly receive location data from the UAV. This, combined with the camera footage and data from various sensors, provides adequate information for proper monitoring and flying the UAV if necessary. Information is sent and received using the radio, but the internet is maintained as backup.

3.3.2 Obstacle Avoidance

The UAV is equipped with radar sensors for obstacle avoidance. The radar has the capability of detecting objects and their velocities from a range of 150m (small-medium objects). The radars are also connected with a servo to increase their range of operation. After an obstacle is located, it's velocity is analysed and maneuvers are made accordingly. The UAV has a cruise speed of 26 m/s. The TI AWR 1843 can detect objects up to a 150 m distance from the UAV, along with the magnitude of the velocity. If the object is stationary, the UAV at maximum operating speed has 5.5 seconds to take evasive maneuvers. In case the object is mobile, the available time to take evasive maneuvers will be reduced, however due to the UAV's high velocity, it will have a high amount of leverage when maneuvering, and a TCAS-style avoidance decision can be taken by the flight computer which will safely allow it to avoid the obstacle. The most common flying obstacles in the city are birds. The worst case scenario can have a bird flying directly towards the UAV. In this case, if the average velocity of the bird is assumed to be 22 m/s (a fairly fast bird), then the relative velocity of the bird is 48 m/s and given the radar range, the UAV has over 3.8 seconds to take evasive actions, which is sufficient (especially, since the bird is flying directly toward it; it must only deviate slightly). All other scenarios will be less critical and the reaction time available to the UAV will be more, allowing it to easily evade.

3.3.3 Beyond Line of Sight

The UAV has excellent capabilities for operating beyond line of sight. In fact, once it is kept at the launch pad, it can complete the whole mission, return and land without having any need to be seen with the eye. Firstly, it's exact location is always known due to its navigation system. Also, it captures a large amount of information about its surroundings in the form of visual and radar data. It has a high resolution front camera with image stabilisation, along with 7 fish-eye cameras on the top and bottom and the radar sensors. All this information is sent real time to the pilot, who can monitor it at all times from a computer.A small 2 dimensional map will be used by the UAV,the map will have the flight paths of the UAVs it might intersect with.In case there is an update in the flight path of any UAV, all the required UAVs will be updated using the radio or internet.Finally, an attempt will be made to acquire permissions from city authorities to access existing closed circuit cameras surveillance and traffic cameras, to for more footage of a UAV if required in the case of an emergency and for its further investigation.

3.3.4 Fuel/Charge Reserve

The UAV uses ultra-light lithium polymer batteries for power, and these can be easily fit into the UAV and can provide extra flight time of 15 mins. Given that the maximum time required to complete one round of deliveries is 15 minutes, the UAV has a reserve charge of at least 15 more minutes. This accounts for real world scenarios like adverse weather conditions and long landing queues, or delay at the delivery location due to some unwanted reasons. This requirement nearly doubled flight time, and made weight management a much bigger challenge. In the end, through careful work, the weight was brought just under the limit with barely enough left for a margin. This was still a very difficult task.

3.3.5 One Engine Out Condition

The UAV is powered by only one motor. In case it fails, the UAVs algorithm will alert the monitoring pilot to take control, and controls it for the few seconds in between.The pilots will be receiving the telemetry too and they can also figure out if there is such a condition. They will then attempt to land by autorotation. Immediately, the pilot (or the algorithm, depending on the timing) will ease the collective. As the UAV goes through a controlled descent, its rotor blades gain kinetic energy. Though rooftops are preferred for landing, they may not be present at a desirable location or altitude, so landing on the streets is a possibility. The pilot will be aided in finding the emptiest landing spot by Safe2Ditch, which will be further cleared up as the very loud alarms in the UAV will be activated to alert pedestrians. When the UAV comes close to the ground, the pilot pulls on the collective and flares up to use all the accumulated kinetic energy in the blades to provide a gentle landing. Though it lacks landing legs, the UAV has a flat base, on which it can rest, as an emergency response team comes to collect it. The carbon fibre rods driven through the foam will help it stand.

3.3.6 Emergency Landings

Emergency landings can be required in a number of situations. These include loss of all external communication, failure of motor and damage to rotor blades. If any of these occur near the Hub, then there will be an effort to make a landing at a landing pad or at least within land acquired for the Hub, to avoid public inconvenience, damage and danger to civilians. An emergency landing is an area outside the Hub will be the absolute last resort, to be avoided as often as possible. However, despite their rarity, such landings will have to be conducted. In case of motor failure, autorotation will be used, as is explained in 3.3.5. If the blades are damaged, they will be stopped using the motor brake. Then, immediately, a parachute will be released from the nose of the UAV, and the UAV will slowly descend. If external communication systems fail, the UAV will no longer be able to receive instructions to the Hub, or send any information. It will also not be able to use WiFi triangulation, which leaves it to GPS and the 3 axis gyroscope, accelerometer and magnetometer sensor for location determination. In this case, it will first stop, and hold its positions as fast as possible. It uses the Skydio 3D videogrammetry software along with the 3 axis sensors to figure out its position relative to the last known position, and thus determine its current position. The system's accuracy allows the UAV to reach the Hub if it is nearby. If it is far from the Hub, it will use Safe2Ditch to analyse camera footage and land at the nearest safe location. In all these cases, a loud 180 dB buzzer will alert all nearby people.

Such emergencies will be taken very seriously and will undergo detailed investigation. Any omissions regarding safety procedures will be subject to inquiry to avoid the same problem occuring again.

3.4 Regulations and Additional Safety

The UAV complies with almost all the FAA guidelines given in Part 107 of the FAA charter. The UAV weighs under 25kg and cruises at 200 ft, well within the flight ceiling of 400ft for UAVs. Operations take place in daylight hours only between 0600 hours and 1800 hours. The UAV yields the right of way to all other aerial vehicles including helicopters and aircrafts. The cruise speed of the UAV is 26 m/s and UAV operations only take place in airspaces above class bravo with necessary ATC permission.

Regulation §107.31 states the remote pilot in command, the visual observer (if one is used), and the person manipulating the flight control of the UAV must be able to see the UAV throughout the entire flight in order to locate the UAV at all times. The UAS is non-compliant. However, the solution proposed provides the UAV with full BLOS flight capabilities. The UAV features cameras on all sides with a high resolution camera in the front of the UAV. This ensures that high definition video of the UAV flight is streamed to the pilot at the Hub and the pilot is able to monitor the UAV flight at all times. Furthermore the position of the UAV is tracked through trilateration and GPS. Section 3.3.3 discusses the function of the UAV beyond the visual line of sight in detail.

Regulation §107.33 states that UAV must remain in the VLOS of the remote pilot and the visual observer in accordance with regulation §107.31 and that the airspace should be scanned for any potential collision hazard by the remote pilot, visual observer and the person manipulating the flight controls. The pilot may not directly see many obstacles, so the UAS is non-compliant. To account for this, however, the UAV will be equipped with AWR radar sensors which are specifically designed for operation by autonomous vehicles. Furthermore, the UAV also features a trained Reinforcement Learning system for real-time obstacle avoidance and potential threat recognition, eliminating any chance of collision during flight. Section 3.3.2 discusses obstacle avoidance in detail.

Regulation §107.37 states that each small unmanned aircraft must yield the right of way to all aircraft, airborne vehicles, and launch and reentry vehicles (Yielding the right of way means that the small unmanned aircraft must give way to the aircraft or vehicle and may not pass over, under, or ahead of it unless well clear). The UAS is in compliance.

Regulation §107.39 states that the UAV may not fly directly above any persons not a part of the UAV operations. The UAV is non-compliant, since it flies over roads, however it poses low risk as the chance of any malfunction in the UAV is very less and the UAV employs softwares such as Safe2ditch to prevent risk of any collateral damage to the people.

4. Document the Business Case

4.1 Cost Analysis

4.1.1 Operating Costs

Factor	Daily Cost	Notes
Employee wages[10]	$16,087.5	2 shifts will be there working at 1.25 times the stated wage in the Detailed Background(see 2.2.5).
Infrastructure maintenance	$98.2	2049 m^2 at $17.5/$m^2$/year (Facility Services Partners, Inc. (FSP), 2014). Includes solar panel and warehouse costs.
Packaging material	$3525.00	Assuming 1 m^2 package area, 282 53×0.3 m rolls/day required @ $12.5/roll. Three layers of bubble wrap will be used.
Insurance premium	$6943.75	Insurance for unforeseen damages; 5% of daily revenue as insurance premium.
Batteries	$261.4	4 batteries/UAV w/ 27 UAVs and 350 cycles/battery set; 1 battery set consumed/76 days at $184/battery set.
4G communication	$25	30 lines of the 5GB/month plan at $25/line/month.
inFlow inventory software	$2.63	Light plan at $79/month. Other software used is FOSS, hence not included.
Miscellaneous budget	$300	Added to account for unforeseen expenses and rise in costs of consumable items.
Electricity	$28.1	Assuming 2 cloudy days/week where solar panels at 25% capacity, other inconsistencies and power spikes the total extra energy required was assumed at around 1640kWh/week. At $0.12/kWh it amounts to $196.8/week.
Total	**$27,272.00**	

Table 15: Operating Cost

No major deviation was observed in the cost of flying UAV to different locations for package delivery. The only difference was found to be in the electricity consumption but as

[10] excluding the cleaning staff.

the cost of electricity is no longer a major operating expense, it isn't considered here. Therefore, there will be only a negligible difference in operating cost in delivering the consignment to different neighborhoods at different distances.

Neighbourhood	Average Distance	Time (in seconds-one way)
A	4.3	188
B	6.7	295
C	3.8	170
D	5.4	247
E	2.9	136
F	5.3	244
G	3	149
H	2.5	121
I	4.3	188
J	5.1	218
K	4.9	220
L	5.4	239
M	3.8	180
N	4.3	188
O	4.3	188
P	4.3	188
Q	6.5	280
R	3.8	179
S	5.4	239
T	5.1	218
U	5.9	248
V	5.1	218

Table 16: Neighbourhood-based Time Estimations

Although the operating cost has only tangential dependence on the distance, the deliveries in neighbourhoods in Zone 2 will generate more revenue as they will give $25 more per delivery. The team plans to deliver all the packages in a day but in case if there is any issue the team will give priority to the neighbourhoods in Zone 2. The total time difference to return from the closest neighbourhood in Zone 1 and the farthest neighbourhood in Zone 2 is only 5.3 minutes. The team analysed why this is a profitable strategy.

Assume the running time is 8 hours and the team has to choose between the zones to deliver the package. If the team considers Zone 1, the total number of trips will be 25 as it takes an average of 19 minutes to deliver the cargo in Zone 1, and the total revenue generated will be $3750 [$50 × 3 × 25] per UAS. Alternatively, for Zone 2, the total number of trips which will be possible will be 20, as it takes an average of 24 minutes to deliver the cargo in Zone 2, and the total revenue generated will be $4500 [$75 × 3 × 20] per UAS. Hence delivery in Zone 2 is more profitable, especially as the operating time decreases.

According to the Orlando Utilities Commission, the annual power usage for buildings similar to ours operating 40 hrs/week is 15 kWh/year/ft^2. For our building with a total floor area of 956 m^2 or 10290.3 ft^2, the annual usage should be approximately 154,354.5 kWh. However, since we are operating 63 hrs/week, this value increases to a total of 243,108.3 kWh. This corresponds to an average usage of 666 kWh/day, or an average instantaneous power use of 74 kW during operation for the building alone. In addition, assuming that during an average trip UAVs use 60% of their rated battery capacity, over 500 trips they will require a total energy of 244.2 kWh over the course of the day. Splitting this value over the 9 hour operational period, this adds another 27 kW of instantaneous power draw to the equation. Adding some additional usage for the warehouse and inefficiency during the conversion from DC to AC and vice versa, the team reached an estimate of 105 kW average continuous power usage, though it may spike higher at times.

4.1.2 Fixed Costs

The first component of the fixed cost will be the construction costs associated with the hub design, for which the team consulted an expert. A decision was reached to construct a circular building with a radius of 10m and vertical of 2.85m per floor. The building would have 3 floors with an ATC (Air Traffic Control) tower at the top. The building will be surrounded by a turf net which will catch the UAV if there is a malfunction in the UAV during launch or landing. The materials which will be used for construction of the building was calculated to be $258,679 and the labour cost was calculated as $128,574. Epoxy resins were used in patches on the floor from which the UAVs will be launched.

For the floor, it was decided to add epoxy resin for the following reasons:

1. It offers a hard wearing durable surface able to withstand heavy and continuous traffic.
2. Resists oil stains and water.
3. Easy to clean.
4. Creates a specular high gloss surface to improve visibility under aircraft.

Hence, the total cost for construction of the building will be $387,253. Assuming the conditions of a city such as New York into account, we will be using government electricity during overcast weather conditions for 2 days a week, as an analogue for all power outages/inefficiencies in a week. The cost of material for construction of the warehouse is $20,370 and the cost of labour will be $10,124. Hence, the total cost will be $30,494. The cost of tables, racks and shelves will be $6,000. The cost of each UAS is $3,684.93 as detailed in section 2.2. Therefore, the cost of 29 UASs (27 + 2 backup) will be $106,862.

The cost of the air conditioning was estimated to be around $20,000. Furnishing was also considered, and it was estimated to be around $10,000 dollars. Other miscellaneous costs were estimated to be $16,500 for 55 battery chargers each at $109 and other things like trolleys, tolls,etc.

3 shelters (support vehicles) from the detailed background ($5000 each) will be taken. All the shelters will be scattered across the map, to minimise the time taken to retrieve the UAV in case of an emergency landing. So the total cost of the trailers and the UAS' is $121,863. The cost of solar panels per watt in Washington was found to be $2.69 (Sara Matasci, 2019) [after 26% federal tax credit for solar energy]. The average power input required by the building, batteries and the electrical equipment over a 9 hour functioning day was estimated at 62kW. The area covered by the solar panels (with an efficiency of 12% at 25°C) will be 933.33 m^2, easily fitting in the unused area around the building (SolarMango, n.d.). Hence the total cost of solar panels is $188,300, which can give 70kW to accomodate for energy spikes. In the case there is extra energy output from the solar panels, it will be earthed. The solar panel will produce DC, which will be converted to AC using 3 SolarEdge 25kW Three Phase on grid 25,000W Solar Inverter costing $1,530 each, this will amount to $4,590. The total fixed cost will be $785,000.

4.1.3 Profit Analysis

Fixed cost focus

In order to maximize long term profits, the team sought to reduce maintenance costs as much as possible through investing in better technology through fixed costs. This included the decision to use all-electric powered aircraft, a decision which although means that more expensive components and materials are required to the significantly lower energy density of batteries when compared to fossil fuels, results in a greatly reduced ongoing cost of fuel. The team also invested a greater amount of land area into solar power generation. This, despite very high setup costs, cuts down power costs — which would have otherwise been the main driver of operational cost — is reduced to a fraction of its original value. So, in this way, despite a higher break even period, the team seeks to maximize the long term profits of the operation.

High volume operations

It was decided to have UAVs carry multiple payloads as it would decrease the delivery time. The team decided to deliver maximum possible packages in a day because of the high earning of $50 per delivery, which will also help us attain the volume bonus in far less time. Though the requirement to have multiple UAVs (to handle greater delivery demand) and space to store them will increase the initial fixed cost, this will tremendously increase the daily revenue, and would decrease the time taken to reach break-even on investment.

Use of EPP foam for construction

The material used for making the UAV will be mostly made up of EPP foam instead of carbon fibre, which will reduce the fixed and maintenance cost of the UAV enormously. Furthermore, the lower density of this material allows for a payload fraction of 60%, and a cruise speed that is key in allowing for the large amount of deliveries which is integral to the team's business strategy.

Profit calculations

The UAV will be delivering 1,075 packages in the neighbourhoods situated in Zone 2 and hence the team would be generating $80,625 daily as the revenue per package is 75$. The neighbourhood in Zone 1 will provide $21,250 daily revenue, as 425 packages will be delivered in the area and the revenue generated per package will be $50. The company will be generating $101,875. As the team will be delivering 1500 packages it will receive all the volume bonuses. The volume bonus were as follows:

- 50 Packages → $500
- 100 Packages → $1,500
- 500 Packages → $10,000
- 1,000 Packages → $25,000

Hence the company will be given $37,000 as a volume bonus. Hence, the total revenue generated will be $138,875.

As detailed in section 4.1.1 the total operating cost is $27,272 which includes the daily wages, maintenance cost, cost of the packaging material, management software, 4G communication subscription for 27 lines and insurance. The daily net income was calculated to be $138,875–$27,886. Hence the company will be able to make $110,990 in one day, and hence $3,329,700 in 30 days' time.

4.1.4 Break Even Analysis

We began by taking initial fixed costs into account which were $785,000. Then, operating costs were taken into consideration which are $27,272 daily. With a profit of $111,603 daily, as the revenue will be $138,875, we will be able to reach the break even point in an estimated 7 days. Of course, we assume sub-ideal conditions for achieving this, as while we try our best, we cannot account for every additional delay or miscellaneous addition to the cost. However, we have allocated some portion of our operating budget to miscellaneous costs.

The team was able to receive all the daily bonuses, which was a huge help in reaching the breakeven point as they increased the daily revenue by 30.8% and will by itself cover all the operating costs.

4.2 Cost/Benefits Analysis and Justification

The team looked upon many risk factors and found solutions to deal with them. Dealing with risk factors increases the fixed cost, but ensures the smooth functioning of the system and provision of quality service to the city.

➔ The team decided to have 3 shelters, which will speed up the extraction of UAVs and hence the UAV repairs will start faster.

➔ The company will buy electricity from the government only if the solar panels are not able to generate electricity due to cloudy weather, or in case of other outages.

➔ In case a package is to be returned, the package collector will retrieve the cargo while the corrected package will be delivered via one of the backup UAVs. The customer will have another option of getting a refund instead of replacement, which will be done online. This will not hamper the daily routine of the regular UAVs, as only the backup UAV is used.

➔ In case the company is not able to deliver consignment due to harsh weather conditions or other unforeseen circumstances, inconvenience will be caused among the customers as their package was not delivered within time. They will be given a discount/coupon from a third party—advertisers—for the next delivery instead of a refund to keep them engaged with the service.

➔ The team decided that the employees will be working in shifts, and if a person is not able to work due to medical or personal reasons, the employee from another shift will be allowed to work for overtime.

➔ The team also planned to keep a turf net around the building to catch the UAVs, in case of possible malfunction during take off and landing.

➔ Instead of having contingency costs to pay for unexpected damages, the team planned to get insurance service by providing them 5% p.a of the annual revenue obtained. This will add onto the operating cost, but will be cheaper in the long run compared to a dedicated contingency fund.

➔ Instead of making the whole UAV of carbon fibre, the team decided to include EPP foam in the parts of the body which will face reduced aerodynamic stress, to reduce cost and collision impact on cargo and components.

➔ UAV does not work on fuel but on electricity, which is a much more environmentally acceptable and economically reliable option.

High cost of Solar Panels

Despite the high fixed-cost of solar panels, which increase our fixed cost, delaying our break-even point, we have decided to use it in order to support sustainable development, and eliminate operating costs of generating or sourcing electricity for the most part.

5.Conclusion

Drone-acharya is a highly innovative solution to a large number of problems caused by manual delivery of packages. From a central Hub, packages are delivered to various locations in the urban area. Right from the Hub to the moment the package is delivered, the design of all things and processes has been optimised and set for the highest efficiency, safety and customer satisfaction.

The UAS consists of extremely carefully chosen components which provide good quality at a lower cost. The airframe has been picked for maximum efficiency and minimum noise. Noise has been further reduced by using an electric motor and by adding spoilers to the rotor blades. Further, the way the UAV reaches and then approaches the neighbourhood minimises the nuisance caused to city residents.

On the customer's side, the whole process is very convenient. The customer is given multiple chances to provide confirmation and thus ensure his/her presence during the delivery. Safe distances are marked at the delivery location, and procedures designed to make the process smooth and safe.

The delivery of packages, right from their arrival at the Hub, is developed into a very efficient process. The unique design of the Hub allows take-offs from higher altitudes. Adequate land has been left around the Hub to reduce noise outside the company's land. Inside, most of the area has been allocated to solar panels which, though expensive, make the Hub almost self-sufficient in electricity supply and are thus a step towards sustainable development.

Safety has been the highest priority in the design on the UAV. It is equipped to handle several different types of problems. If it must make an emergency landing, it has adequate indicators to warn civilians.

Overall, the entire system is aimed towards eventually replacing present-day manual delivery systems therefore meets up to them in terms of urban acceptance and customer convenience. Therefore, it can be expected to eventually find its way into and become a normal part of city life.

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