ALBATROSS: AN AUTONOMOUS, ELECTRIC MULTIROTOR FOR PERSONAL TRANSPORTATION

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ABSTRACT

Despite the continuous performance improvement on small airplanes and helicopters, aerial personal transportation is still very limited to few passionate amateurs and wealthy users who can afford extremely high aircraft acquisition, maintenance, and storage costs. Two other critical factors restraining the widespread use of personal aircraft are the need of dedicated take-off/landing areas and complex pilot licensing process. To address these limitations, a few companies and research teams are currently developing proof of concept prototypes of electric multirotors for personal transportation. This effort is backed up by recent technological developments on many key components such as controllers, electric motors, and batteries. The focus of this project is to design and manufacture a low-cost electrical multirotor with heavy-lift capability. Ultimately, we want to develop a small rotorcraft capable of both manual and fully autonomous flight. This paper summarizes the current results of our ongoing effort. In particular, we present results on the development of each subsystem with emphasis on stress analysis of the main structure and specific components, data of the motor/propeller static thrust test, and configuration of the power distribution.

Keywords: Flight; Aircraft Design; Multirotor; Automation.

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RÉSUMÉ

Malgré l'amélioration continue des performances des petits avions et des hélicoptères, le transport aérien personnel est encore très limité à quelques amateurs passionnés et utilisateurs fortunés qui peuvent se permettre des coûts d'acquisition, de maintenance et de stockage extrêmement élevés. Deux autres facteurs critiques limitant l'utilisation généralisée des aéronefs personnels sont la nécessité de disposer d'aires de décollage / atterrissage dédiées et d'un processus complexe de délivrance de licences de pilote. Pour remédier à ces limitations, quelques entreprises et équipes de recherche développent actuellement des prototypes de validation de principe de multirotors électriques pour le transport personnel. Cet effort est soutenu par les développements technologiques récents sur de nombreux composants clés tels que les contrôleurs, les moteurs électriques et les batteries. Dans ce scénario, une équipe composée par les auteurs s'est concentrée sur le projet de conception et de fabrication d'un multirotor électrique à faible coût avec une capacité de transport lourd. En fin de compte, nous voulons développer un petit avion capable de voler à la fois manuel et entièrement autonome. Ce document résume les résultats actuels de nos efforts continus.

En particulier, nous présentons les résultats sur le développement de chaque sous-système en mettant l'accent sur l'analyse des contraintes de la structure principale et des composants spécifiques, les données du test de poussée statique moteur / hélice, la configuration de la distribution de puissance. Ce projet a été sélectionné par la NASA comme lauréat du concours de recherche universitaire 2019. Il s’aligne notamment sur l’axe 6 de la Direction des missions de recherche aéronautique de la NASA: Autonomie assurée pour la transformation de l’aviation grâce au test initial d’autonomie des gros rotorcraft à usage civil.

Mots-clés : Flight; Aircraft Design; Multirotor; Automation.

INTRODUCTION

In recent years, advancements on personal aerial transportations vehicles, like small aircrafts and helicopters, resulted in more refined designs, improved safety, and better performance. Despite these improvements, the market for these small vehicles is still quite limited to few users. The reason for this lack of popularity might be attributed to several key factors. First of all, there are considerably high costs for the aircraft acquisition, maintenance, and storage. Secondly, both helicopters and, especially, small airplanes need dedicated spaces to take off and land. Finally, to pilot these aircrafts requires specific skills that must be acquired through a long, and costly, training process and, ultimately, a license. On the other hand, in the last decade, we have witnessed an exponential growth of the market and technology related to multirotor drones. Modern controllers, oftentimes supported by GPS navigation, allow users with limited training to easily control these vehicles. Several of these multirotors are now deployed to execute a variety of complex missions such as: surveillance, remote sensing, videography, agriculture, safety and rescue, transportation, etc. This scenario, begs the question: can this technological progress support the development of novel aircraft for personal transportation?

Most recently, few companies and research teams have been developing proof of concept prototypes of electric passenger multirotors [1] [2] [3]. Some of these companies are currently flight-testing their prototype vehicles for certification purposes. The most relevant projects have been developed by EHang, Volocopter, Workhorse (Surefly), Lilium, Joby Aviation, and Wisk. EHang 216, shown in Figure 1, utilizes sixteen motor/propellers in a coaxial configuration, placing two counter-rotating propellers directly on top of each other, to increase both thrust efficiency and thrust to space ratio while also providing contingency in the event of a motor/propeller failure. EHang’s design places the passenger above the rotors, inverted from the design seen used by Volocopter. The German multirotor company also places the ten rotors above the passenger, on a web-like upper frame as shown in Figure 2. Workhorse’s Surefly is a U.S. designed multirotor utilizing a diesel generator to power the electric motors. The Surefly also has a coaxial design similar to EHang, but the configuration is an "octo-quad,” using four arms and eight motors to generate lift [3]. The Lilium Jet has a total of 36 ducted fans, able to rotate ninety degrees as the vehicle transitions from takeoff to cruise [4]. Joby Aviation’s design also employs tilting rotors, though the Joby craft uses six large rotors to generate lift [5]. The aircraft designed by Wisk employs fixed wings to generate lift during cruise, with twelve motors to vertically lift the craft off of the ground [6].

In this project, the ATLAS Team (Advanced Transportation in Leading-edge Aerial Systems) has been formed to design and manufacture a battery-powered multirotor with heavy-lift capability to serve as a single-passenger aerial vehicle. The team is composed by SDSU undergraduate engineering students advised by mechanical engineering faculty. In 2019, the ATLAS Team was awarded by NASA as winner of the University Student Research Competition and received support to develop its project. The first year was dedicated to the preliminary design and initial structure assembly. Results of that effort have been presented in ATLAS: Advanced Transportation through Leading-edge Aerial Systems [7]. The second ATLAS Team, formed in 2020, is now dedicated to continuing the project by carrying out the following tasks: completing the original design, finalizing the assembly, performing indoor hover testing, attaining an FAA airworthiness certificate, and performing an outdoor flight-testing campaign. This paper outlines the current project status together with the main results of this team's effort.

Figure 1: EHang 216 [1]

Figure 2: Volocopter [2]

1. SYSTEM DESIGN/OVERVIEW

The main goal of this project is to develop an aircraft with the following specifications and characteristics:

1. Electric powered
2. VTOL
3. Payload = 100 kg (to carry a single human passenger)
4. Flight time ≥ 12 min
5. Capable of both piloted and autonomous flight
6. Parts cost ≤ $55,000 USD

For comparison purposes, Table 1 summarizes a similar set of specifications and estimated selling price of the competitor vehicles which are expected to be in the market in the following years.

Table 1. Existing multirotor personal aircraft specifications

Aircraft	**Payload** [kg]	**Estimated flight time** [min]	**Estimated price**
EHang 216	220	21	$336,000
Volocopter	91	27	$250,000
Surefly	181	60	$200,000

Our approach to the vehicle design is based on the following guidelines:

a. simplicity in its construction/assembly (high priority)
b. low cost (high priority)
c. extensive use of COTS parts/components (high priority)
d. aesthetic/style (low priority)

Among the most challenging tasks of this project is the selection of a controller compatible with an octocopter configuration and suitable for both piloted and autonomous flight modes. The criticality of such aspect has been tackled by dividing the vehicle development into two stages [7]:

I. A small demonstrator multirotor, named Hummingbird, was developed and tested utilizing the same flight control systems as the full-size rotorcraft. Hummingbird will be used to validate autonomous flight capability and safety in a controlled environment with low-risk trials, reducing the full-size rotorcraft testing time.

II. The large heavy-lifting rotorcraft, named Albatross, will be designed, manufactured, and tested. Albatross will be capable of carrying a 100 kg payload over short distances while operating with minimal, if any, pilot input. The aircraft will eventually undergo the FAA airworthiness certification process for flight testing.

In our design process of the vehicle, we have identified three main subsystems: flight controller, structure, and power/actuation. The flight controller was verified using Hummingbird and will integrate into the control system of Albatross smoothly when the full-scale multirotor is ready to be tested. Power distribution involves eight separate circuits consisting of four batteries in series to power each motor separately. The separate circuits allow for smaller gauge wire to be used, reducing mass and cost. The structure of Albatross was designed and manufactured according to a factor of safety of 1.5.

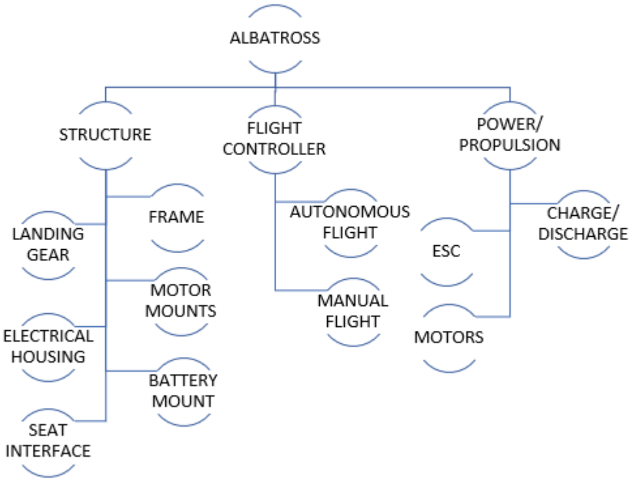
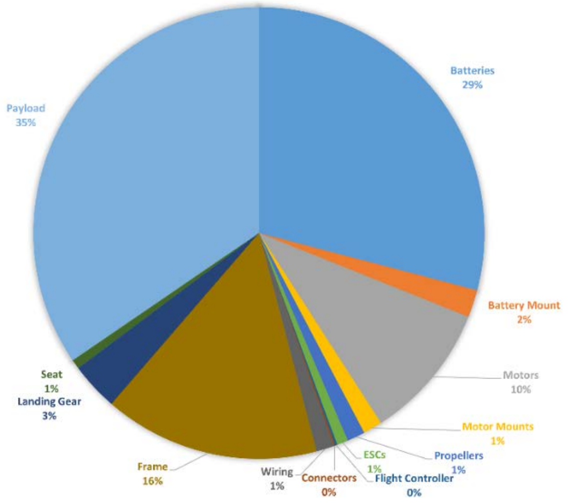


Figure 3: Albatross Subsystem Diagram

Figure 4: Concept design of Albatross

Figure 5: Albatross structure assembled

The concept design shows the "hashtag" design, utilizing straight beams rather than a circular frame, reducing mass and eliminating the central point of failure. Structural components were designed and simulated to satisfy the factor of safety desired. Physical testing has also been implemented to some structural components to ensure that simulations are accurate. The third main subsystem consists of the charging and discharging of the 32 batteries required to power Albatross. The system will be able to charge multiple batteries simultaneously to speed up the recharge rate and reduce wait time between flights.



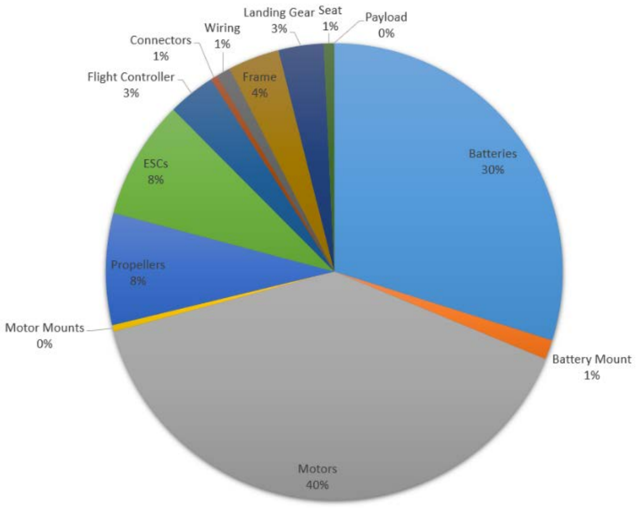


Figure 6: Albatross Mass Distribution (m_{tot} = 290 kg) Figure 7: Albatross Cost Distribution ($Cost_{tot}$ = \$22,132)

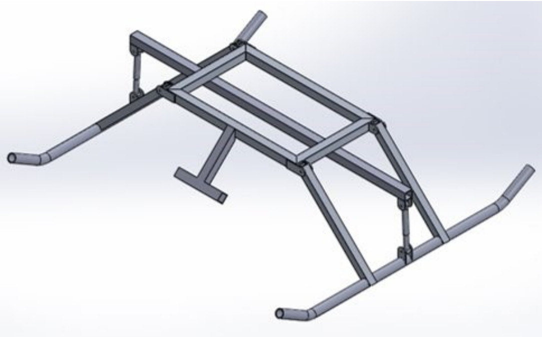
2. MECHANICAL SUBSYSTEM DESIGN

2.1. Main Frame and Cockpit

The main structure is configured for a single passenger below the rotor plane with the landing gear mounted below. This frame configuration has been selected as it reduces the number of joints at the bottom to four. The cockpit also serves as a roll cage for the passenger in the event of a rollover. The landing gear allows for a relaxed landing with a shock-absorbing element in case of a hard landing. The overall frame is designed with 5.08-centimeter square tubing with a wall thickness of 3.175 millimeters. The material is 6061-T6 aluminum, chosen because of its relatively high strength, workability, and low density. The motor arms expand 1.22 meters from the top square of the cabin. This allows for all eight motors and propellers to have 7.62-centimeters of clearance from tip to tip. These arms are also constructed from the same 6061-T6 aluminum. There are four sets of 4.88-meter arms to make up the hashtag configuration.

2.2. Landing Gear

The landing gear design is one of the major improvements from the previous year's design. As stated above, this design allows for a soft landing along with increased safety in case of a crash landing. The new design includes two FOX Float 3 shocks with an eye-to-eye diameter of 33 centimeters [8]. These shocks allow more force for impact with the given air pressure chamber acting as a traditional coil over spring. The shocks are attached to a 5.08-centimeter square tube that acts as the brace and attaches the landing gear to the cockpit. The shocks are also attached to 4.445-centimeter outer diameter pipe with a wall thickness of 3.175 millimeters. This design mimics helicopter skids.



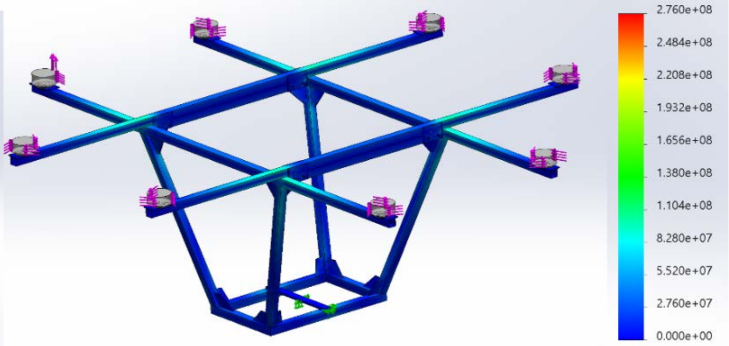


Figure 8 - Landing Gear Design Figure 9 - Full Frame FEA

2.3. Ad Hoc Joints and Motor Mounts

There are three joining mechanisms used. Most of the aluminum was metal inert gas (MIG) welded using a spool gun and a 5356-aluminum series filler wire with a compressed argon shield gas. The new additions to the project were welded with a 4043-aluminum filler wire with compressed argon shield gas. The rest of the multirotor is bolted together with grade eight stainless steel bolts and locking nuts. To verify the design of the frame prior to initial testing, the frame was analyzed using Finite Element Analysis. The frame was loaded with the maximum motor torque and 1.5x the maximum thrust of the motors, accounting for the worst-case thrust and torque combination for the frame and capturing any other flight load. As seen in Figure 9, the frame showed a maximum stress of only 170 MPa. This is well below the published yield stress of 276 MPa for the 6061-Aluminum frame [9]. The maximum deflection in the frame occurred at the end of the arms, where they deflected 33mm in the direction of the thrust. Deflection in the rotor plane was only approximately 3mm, which is reasonable compared to the 75mm spacing between the propellers.

Some of the most critical components of the system are the motor mounts. The motors must be securely fastened to the frame to ensure that thrust is properly distributed and that the motors do not detach during flight. To ensure the frame does not have stress concentrations, it will not be drilled into. Instead, the motors will be secured using clamp-style mounts. The design of the motor mounts is shown in Figure 10. To ensure the structural integrity of both the motor mount and the frame under a clamping force, the assembly was subjected to analysis through FEA. The results shown in Figure 11 show that the maximum stress in the motor mount is approximately 200 MPa. Again, this is below the published maximum stress of 276 MPa for 6061-Aluminum.

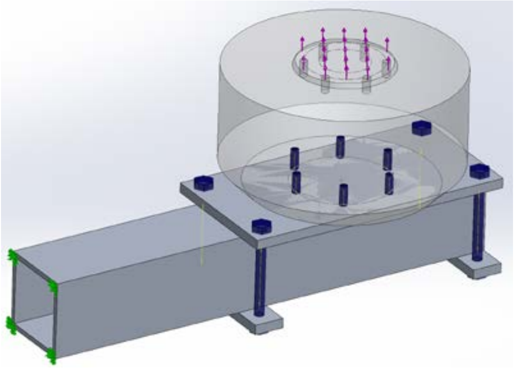


Figure 10 - Motor Mount Design

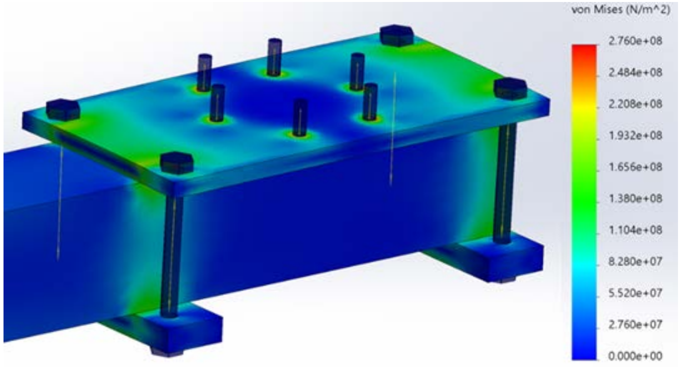


Figure 11 - Motor Mount FEA

2.4. Battery Mount

The battery mounting system was designed by prioritizing low mass, ventilation of batteries, and center of mass. As mentioned above, reduced mass was a major consideration when designing all parts of the system. While supporting 81.6 kilograms of batteries, the support was designed to have a mass on only 5.7 kilograms. Ventilation space between the batteries, along with forced airflow from the propellers, ensures that the batteries remain below the maximum operating temperature. The battery mount is a single tray which will be placed in the center of the rotorcraft below the rotor plane, keeping the system stable. A derivation determined that a one-meter free fall resulted in a seven times gravity force with an additional 1.5 factor of safety bringing the total force to eleven times gravity. The four corner brackets of the battery mount were held fixed, and the gravity load was applied.

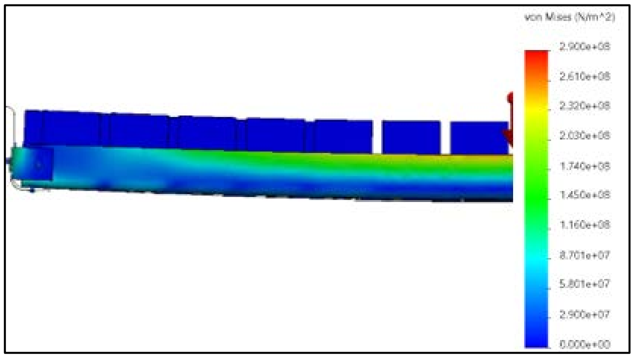


Figure 12: Battery mount frame stress

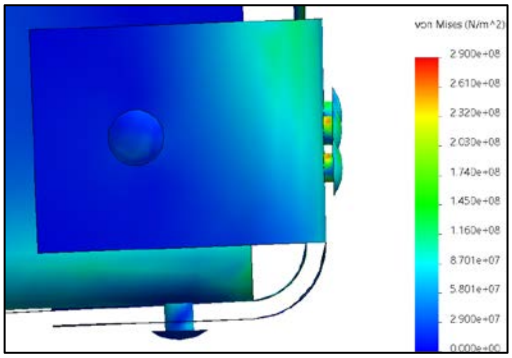


Figure 13: Detail on rivet stress

The load resulted in a maximum stress on the aluminum of 260 MPa, slightly below the 276 MPa tensile strength, leading to a safety factor of over 1.5 for a 1-meter free fall during a hard landing. Stress concentrations in the corners were offset with brackets riveted to the main frame. The corner brackets reduced stress in the mount but introduced new stress concentrations at the rivets. Stainless steel rivets were chosen to increase strength in the rivets where the stresses were most concentrated. A future iteration of the project that requires long term use would need to utilize aluminum rivets. The stresses could be decreased with a taller side flange, which was not used in this iteration to maximize the material on hand.

3. CONTROLS SUBSYSTEM

3.1. Flight Controller

A consumer-grade off-the-shelf control system will be used for this project. This is primarily due to the low cost, ease of use, and accessibility of consumer grade systems [7].

3.1.1. Pixhawk & UX

A Pixhawk PX2 Cube flight controller will [10] be used for the control systems of both *Hummingbird* and *Albatross*. This open-source controller was chosen due to program flexibility and community support of troubleshooting efforts. The Pixhawk system is optimized for multi-rotor craft, featuring autopilot systems, trajectory planning, battery monitoring capability, and a built-in Global Positioning System for location-based flight. The Pixhawk flight controller will simplify the control system implementation, allowing for more flight and mechanical system tests.

Figure 14: Pixhawk 2 Cube Flight Controller

The program QGroundControl will be used for the control system interface. User input will be sent from the QGroundControl interface to the flight control system through QGroundControl's internal protocols, simplifying the user experience. The program is optimized for Pixhawk operation and features location-based flight planning through a visual interface. The program also can be used on Android and iOS platforms, increasing the flexibility of the software and allowing for an in-cockpit user interface utilizing a cell phone or tablet [7].

Research into more capable autopilot systems is being done. Micropilot develops autopilot systems for larger scale multirotors and UAVs. Micropilot involves having redundant autopilots to ensure rider safety when a physical pilot is onboard. Micropilot deems itself more futureproof than that of Pixhawk and with built in redundancy, seems to be a potential option for Albatross.

4. POWER & PROPULSION SUBSYSTEM DESIGN

4.1. Propulsion

The propulsion system will consist of eight motors and propellers for the octocopter configuration. The propulsion system needed will allow Albatross to hover with the 100kg (220lb) payload with extra thrust for maneuverability within flight. The motor chosen for this aircraft was the MAD Component MAD TORQ M40 Pro 43 KV motor [11] paired with the Fluxer 47x13.1 propellers [7]. This combination will give a max thrust per motor of 70.4 kg (155.2 lbs). Overall max thrust of the aircraft will be estimated around 563 kg (1241 lbs). Verification of these numbers was done in the recent static thrust test.

A static thrust test bed was created to verify the data sheet from MAD Components with the desired motor and propeller. A data acquisition system was created to get live thrust data in kilograms and current draw from the motor. A large 200-amp shunt resistor was added to find the current draw at specific throttle percentages which could then be interpolated for all throttle percentages on an exponential curve. A 500 kg load cell paired with an Arduino was used to provide live thrust data in terms of throttle percentage. The values found from the thrust test were recorded to be compared with the data sheet, shown in Figure 15 with both thrust and current draw.

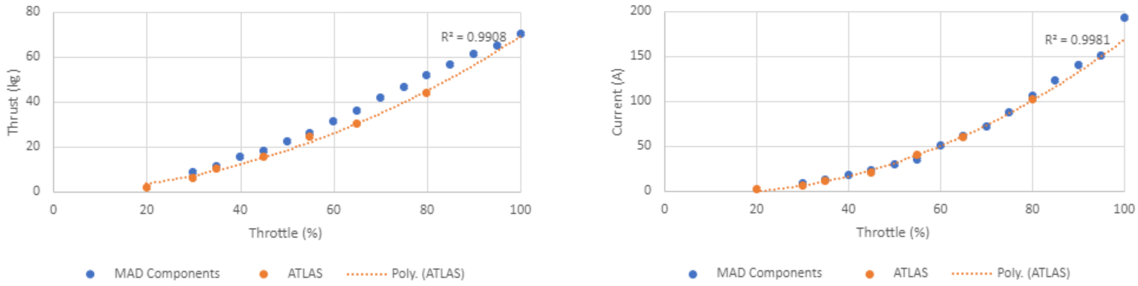


Figure 15: Experimental static thrust test results compared to manufacturer specifications, (Left) Thrust vs Throttle, (Right) Current vs Throttle

The overall result shows strong correlation between the two datasets. There is a slight decrease in thrust seen in the test data as compared to the manufacturer data, but that decrease can be partially attributed to the motor arm in the path of the propeller, obstacles in front of the propeller decreasing airflow, and wind interference. It can be assumed that MAD Components testbed setup minimized or eliminated any airflow restrictions in the path of the propeller. Other factors to skew the results of the thrust test data could be air properties such as temperature, humidity, and pressure changes due to elevation.

4.2. Energy Storage

To store the energy required for flight, many options were weighed, however, Lithium-polymer (Li-Po) batteries were selected due to their common use in small-scale multirotors. The discharge capability of Lithium-Polymer is much higher than competing battery chemistries, and they are available in many different voltages, capacities, and discharge rating. As the selected motors required around 100VDC, while the average Li-Po cell has a voltage potential of only around 4.2 V at full charge, it was determined that a 24-cell battery system would be required. However, no commercially available 24-cell (24S) batteries are currently available, so a series of lower-voltage batteries were connected in series to increase the effective voltage of the battery subsystem. A weighted design matrix was created to determine the most efficient configuration of batteries for Albatross. A collection of commercially available, high-capacity batteries was compared based on their mass, price, capacity, discharge (C) rating, and number of cells to determine the best solution for Albatross. Along with these large Li-Po batteries, common 18650 Lithium-Ion cells were included in the design matrix to compare to the other most commonly used battery chemistry.

The configuration that was ultimately chosen was a 20 amp-hour (Ah) 6S Li-Po battery. This design required 4 batteries in series to create the required voltage, with each set of four batteries powering a single motor, for a total of 32 batteries for the entire system.

4.3. Power Distribution

The power distribution subsystem will ensure that each motor has enough power to achieve liftoff and further. The decision to split up each motor into separate power subsystems stemmed from the potential voltage drop from pulling 200A from each motor, which in turn would be around 1600 amps from a single large battery pack. Four 20 amp-hour Lithium Polymer batteries in series will achieve the 100.8 volts (24S) needed for proper thrust output. Totaling thirty-two 20A batteries split between the eight motors. Figure 16 shows the wiring for one individual subsystem for a motor.

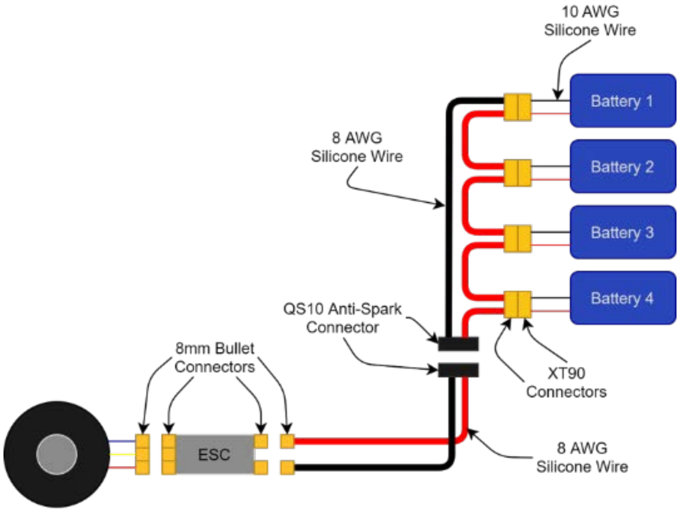


Figure 16: Power Distribution Wiring Diagram

Large QS10 connectors (Anti-Spark) are armed with resistors to eliminate sparking when connecting power initially. These QS10 connectors will be soldered to stranded copper 8-gauge wire [12] equipped to handle much more than the 200A load at full throttle.

4.4. Charging

With the designed battery back being a series of individual, smaller batteries, a custom charging system was required to charge the batteries as quickly as possible. For initial testing, a commercially available charger was used to charge each battery individually. This process was tedious, as only one battery could be charged at a time due to the cell limit of the charger. To charge more than a single battery at a time, a battery management system (BMS) was required to measure and protect each cell of the battery during charging. A variety of BMS circuits are available and can be used to charge batteries with a variety of different voltages. For Albatross, a 24S BMS with a rated current high enough to charge the selected batteries quickly was sourced. Though most BMS circuits can be used to charge and discharge the batteries, the BMS selected could only handle enough current to charge the batteries. A BMS with a rated current high enough to be used during discharge (flight) would have cost much more than the lower-rated BMS, so it was decided to manually monitor the batteries, rather than use a BMS for discharge.

To provide the voltage and current required to charge the batteries, two 50V DC power supplies were placed in series to create a 100VDC potential. These power supplies can continuously supply up to 52.1A, more than enough current to charge the batteries. However, the BMS circuits must dissipate any current not used to charge the batteries, which could be enough to overload the BMS boards. To limit the current of the power supplies, a simple voltage regulator circuit was designed to control the current-limit input of each power supply. This limit was set just below the maximum rating of the BMS boards, allowing the batteries to charge without overheating the BMS boards.

5. CONCLUSION

When Albatross is complete, airworthy, and fully tested, the ATLAS project will have shown that a battery-powered rotorcraft is a feasible and viable option for personal aerial transportation. The success of this project will also help convey to the general public that autonomous transportation by air is safe and reliable. By creating a heavy-lift drone capable of autonomously travelling short distances, Albatross has shown that the low-cost inner-city transportation need not be limited to the ground. As the world looks to solve the transportation problems of today, the transportation solution of tomorrow may be in the skies.

6. FUTURE TASKS

6.1. FAA Airworthiness Certification

With an experimental multirotor of this magnitude, new processes within the Federal Aviation Administration (FAA) will be taken to ensure the first flights of Albatross are safe and legal with proper regulations in place. The group will register the rotorcraft with an N-Number via the 8050-1 document given from the FAA. After an N-Number is assigned to Albatross, the group will undergo the certification process for a large UAS under the experimental category. Months of verification, documents, and meetings will ensure Albatross will have the proper legalities to fly in airspace. A Designated Airworthiness Representative will administer our certification upon our first take off. The multirotor will be certified under the 8130.34D Airworthiness Certification [13] emphasizing as an experimental aircraft. Being experimental will allow for further iterations without the re-certification process.

6.2. Dynamic simulations

We have already developed a complete Matlab/SIMULINK model of Albatross that reproduce the dynamics behavior of the rotorcraft under the control action of a PID controller. Preliminary simulations have shown that the chosen configuration (rotor/propeller combo, mass, geometry, etc.) is able to deliver satisfactory maneuverability performances. Further simulation will be carried out to assess the rotorcraft capabilities for the whole flight envelope inclusive of takeoff and landing maneuvers.

6.3. Design Optimizations

As with every design and design process, optimizations are being continually identified and considered. With the possibility of the ATLAS project continuing past this year, the team has identified many sources of improvement for a proposed ‘Albatross Mk2’. These include, but are not limited to:

- Frame redesign mass optimization
- Higher capacity/lower mass batteries
- Improved aerodynamics
- Redesigned and lighter landing gear
- Custom Graphical User Interface (GUI)

ACKNOWLEDGEMENTS

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