Independent Drone Project

Building a Drone Utilizing CAD, FEA, Iterative Prototyping, and Betaflight Tuning.

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Abstract:

The goal of this project was to build a functional quad copter drone capable of stable flight leveraging an engineering skillset, all while treating the project as a rigorous engineering endeavor. This included a bill of materials, a timeline, designing the drone's frame, and justification for each action taken. Overall, the project encountered hurdles from every step. Some were entirely user errors, like poor solders, and others were inevitable, such as software issues. Some errors, however, were due to inexperience in engineering projects, such as GD&T or weight and size considerations. These errors were extremely valuable to learn from firsthand. The result of the project was a successful controlled flight; however, a critical failure of an ESC has grounded the project for the time being. While this is unfortunate, this is not a stopping point for this project but rather a simple part replacement.

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Introduction:

This report documents the design and construction of a drone, which was built as a personal project during the summer break in between semesters. The motivations of this project were to tackle an engineering project without guidance and to satisfy personal curiosity. This project was meant not to be an informal side project, but rather a strict, well documented, and rigorous project that would better mimic real life. A scope was established with the conception of this project, and every design decision was documented thoroughly. Along with this, there was also a tangible goal for success for each step of the drone assembly.

The scope of this project, from the start, has been well defined; the final drone design was intended to be handheld, and flown via line of sight. Additionally, the weight of the drone was monitored to comply with FAA regulation. Drones that weigh more than 250g must be registered with the FAA [1], so keeping the drone under 250g was essential. For the design of the drone, I decided to model the drone's frame using SolidWorks, but elected not to build the flight controller manually to avoid scope creep. Additionally, a timeline was decided after initial research as part of the scope, which was a total of 6 weeks from start to finish. The timeline for this project was as follows: week 1 was research, week 2 was computer assisted design (CAD) modeling, week 3 was frame testing and software familiarization, week 4 was assembly, week 5 was flight testing, and week 6 was reserved for delays and final touches. This was primarily to avoid the feeling of a side project, but rather to make this an active project that required near constant work, which better mimics an actual engineering project.

Methodology:

At the beginning of this project, the parts were researched and chosen based on the clear scope that had been developed. These parts were then compiled into a complete Bill of Materials, which can be seen in appendix D. For this design project, a 4000kv brushless motor and the propellers built for it were chosen due to the motor's relatively low power, matching the scope of the handheld drone. A 3S 850mAh LiPo battery was also chosen to complement the motor. The selected flight controller was the Speedy Bee 405AIO, which has many DIY friendly features like integrated electronic speed controllers (ESCs), BetaFlight software support, and a compact size that serves well for smaller builds. Over the course of the project 3 prototypes were created.

The frame of the drone was a completely original work created with a combination of CAD and additive manufacturing, specifically 3D printing. The drone's frame was split into three parts, the main body, the body's lid, and modular arms. The main body was designed in a basket shape with a size of 70mm×70mm×25mm, but later iterations increased the size to 85×85×30, which let components fit better. The arms are 50mm long overall, featuring a hollowed-out well for the motors to be mounted and 2 screws to mount the arm to the main body. This decision allows for broken arms to be isolated and requires only a single arm to be made, not the entire frame. The entire design was optimized for easy assembly, requiring 12 m3x8mm screws, with 4 for the lid and 2 for each arm.

For the 3D printing of the frame, specific choices were made to maximize the strength of the drone's frame while minimizing weight. All three parts of the frame were printed using PLA+, which was chosen due to material availability at the time. Additionally, the frame was printed with a 30% infill, which means the printed part has 30% of the normal density of the printing material, and a gyroid pattern which is a great choice for strength in all directions. Supports were used, but only on overhangs that were over the build plate. This design decision stopped supports from printing in hard-to-reach places, which was easier for assembly but slightly reduced strength because of inefficient first layer bonding on some overhangs. Some other minor print settings included a nozzle temperature of 215° C and a build plate temperature of 65° C. Once the frame was printed, the edges were sanded, and the supports were removed.

Analysis and Results:

The drone frame was analyzed using both finite element analysis (FEA) and real-life testing. While FEA testing was only performed for the final design, each prototype was tested in real life. The tests performed were a drop test at various heights, a load test for both the frame and the arm, and weighing the drone to ensure flight was possible. The drop tests were conducted on concrete, starting at one foot and increasing in increments of one foot each time until a height of six feet. While the drone was not dropped with a simulated load weight, it is believed that the rough concrete mitigated this potential source of error in testing. The load tests performed for the main body and the arm were a load of 200lb and a load of 2lb respectively. These tests can be seen in appendix A. The weight of the frame did not have a strict value in mind, but for flight to be possible (and responsive), a weight of 50-100g was required for the full frame.

The first prototype passed all the load tests but could not be assembled because the intended screw holes were not wide enough and screws were stripped during assembly. The first prototype also failed the weight requirement with a weight of 46g, just under the lower limit. The second prototype was able to be assembled, increased in size for better part accommodation, and passed every test except the drop test, which had an arm break on the 6ft drop due to a force concentration, all while weighing 96g. The third prototype increased the strength of the arm and the connection while shaving weight and resulted in the same experimental outcome as the second prototype while weighing 88g. It is worth noting that the severity of the break, while the same in nature, decreased in severity from the second and third prototype. While these breaks do showcase a failure point, breaking at the arm connection is preferred due to the modular nature of the arm, and therefore is not a failure structurally. Since the electronics inside the main frame are worth far more than the motor and arm, even if the motor is permanently damaged that is a better outcome than the overall body receiving a large impact and breaking. Images of these breaks can be seen below in Figure 1a and 1b.

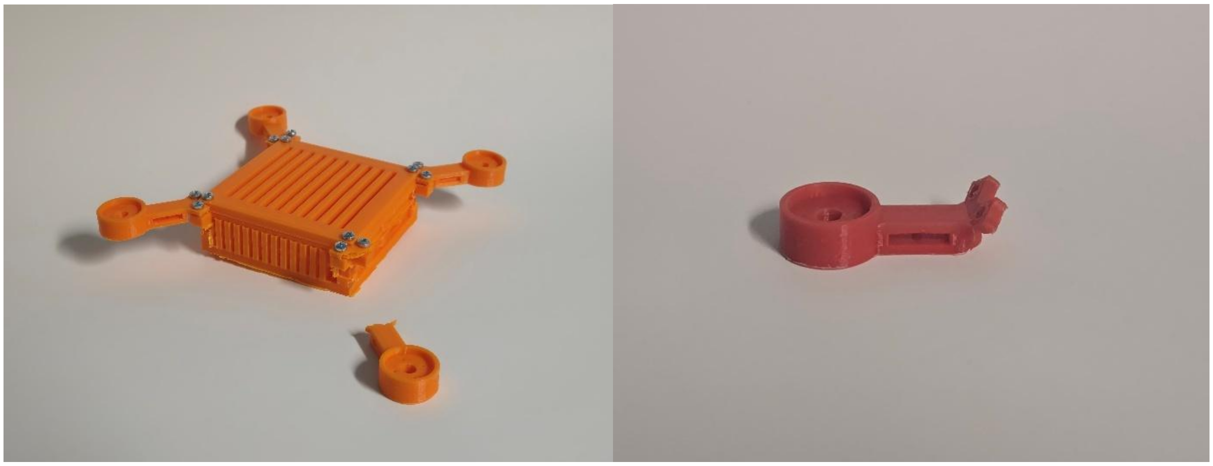


Figure 1: Drop Test Breaks – (a) Prototype 2, (b) Prototype 3

For the final design, FEA testing was implemented with five studies overall: two on the arm and three on the body. For the arm, studies were run for lift forces and torque from the motor, with the failure load and torque found to be 7.885 lbf and 15.76 lbf ·in respectively. According to the manufacturer, the chosen motor's maximum thrust on a 4S LiPo battery per motor is 290g [2]. For a 3S battery setup like the one in this project, a maximum lift of about 200 g or 0.44 lbf is more practical, which is way below the failure point of the arm. The torque generated by the motor was calculated using Equation 1, which can be seen below.

$$T = thrust \ \times r_{propeller}$$

Since the propeller for this project has a 2.5-inch diameter, the total torque produced by one motor is 0.55lbf ·in, which is well below the yield strength of the arm as well. While the arm performed very well on the FEA analysis, it is worth pointing out that the failure point in FEA also correlates with real life very well. This can be seen below in Figure 2.

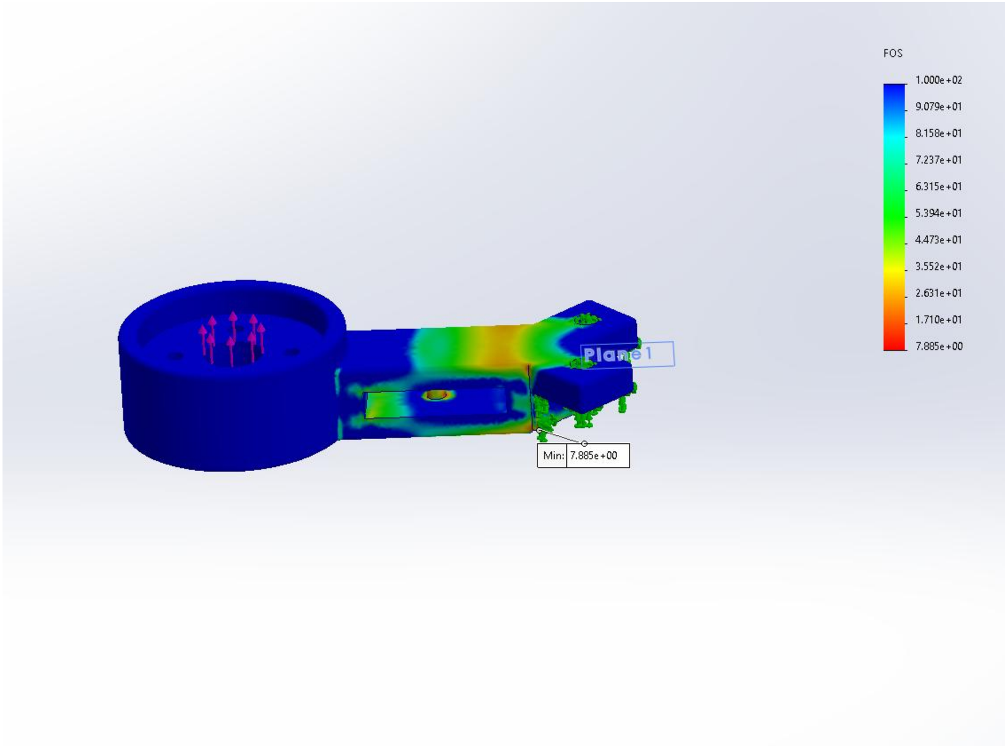


Figure 2: FEA Analysis Failure Points for Lift

For the body, similar studies were run concerning lift and torque on the connection where the arm attaches, and a study was run on the load that the base of the drone frame could withstand. For the lift and torque studies, the main connection point had a failure load and torque of 122.3 lbf and 8.895 lbf·in respectively. For the load study, the analysis showed a maximum load of 111.6 lbf. This particular result was interesting since real load testing showed that the frame survived loads of 200 lbf. Because of this discrepancy, further load testing was conducted, and it was found that the drone body could withstand over 285 lbf of load without breaking. This highlights the differences between FEA analysis and real testing.

Challenges and Conclusion:

During this project, there were many engineering challenges that had to be overcome. From frame design to thermal issues on the flight controller, every step had a major issue that needed to be addressed. During the initial frame design, many issues were discovered after manufacturing the frame. From the size of the frame to the size of the screw holes to the design of the arms, each piece was fine in theory but turned out to not work practically due to things like GD&T. Soldering was also a major hurdle, since I have little soldering experience. The wiring diagram for this project can be seen in appendix B. The connection wires for the battery and the wires to the motors were a large gauge, which was a challenge to solder properly with the small flight controller pads. Additionally, since this system underwent crashes during flight tests and the wires were bent to accommodate space, often solders became undone and the whole assembly had to be taken apart. During the soldering process, an ESC was fried internally on the flight controller due to an undiscovered short, which has ceased flight.

When there wasn't a mechanical issue, there was a software issue. Building a drone has some complexities that are hidden inside the software used, which was Betaflight, like determining the spin of the motors, or correctly accounting for the offset of the flight controller. Some other examples of technical difficulties I faced during this project were the motors creating lift upon arming even without throttle, connecting the transmitter to the receiver, or determining the cause of RX loss. A more comprehensive list of errors and the solutions I found can be found in appendix C.

Despite the many hurdles I faced, this project has given me very valuable experience on every part of an engineering project. From choosing parts to optimizing the frame to mechanical and software error handling, I encountered just about every error I could and learned how to effectively solve problems and build intuition. Despite these many errors, the project's goal of building a stable drone capable of flight was accomplished, which can be seen in the media section of the project's GitHub. For future work on this project, the next step would be to replace the flight controller due to the fried ESC, and future upgrades could include a First Person View (FPV) camera and a 4S LiPo battery.

References:

[1] FAA – Recreational Drone Registration Guidelines

https://www.faa.gov/uas/getting_started/register_drone

[2] BETAFPV - Lava Series 1506 Brushless Motors

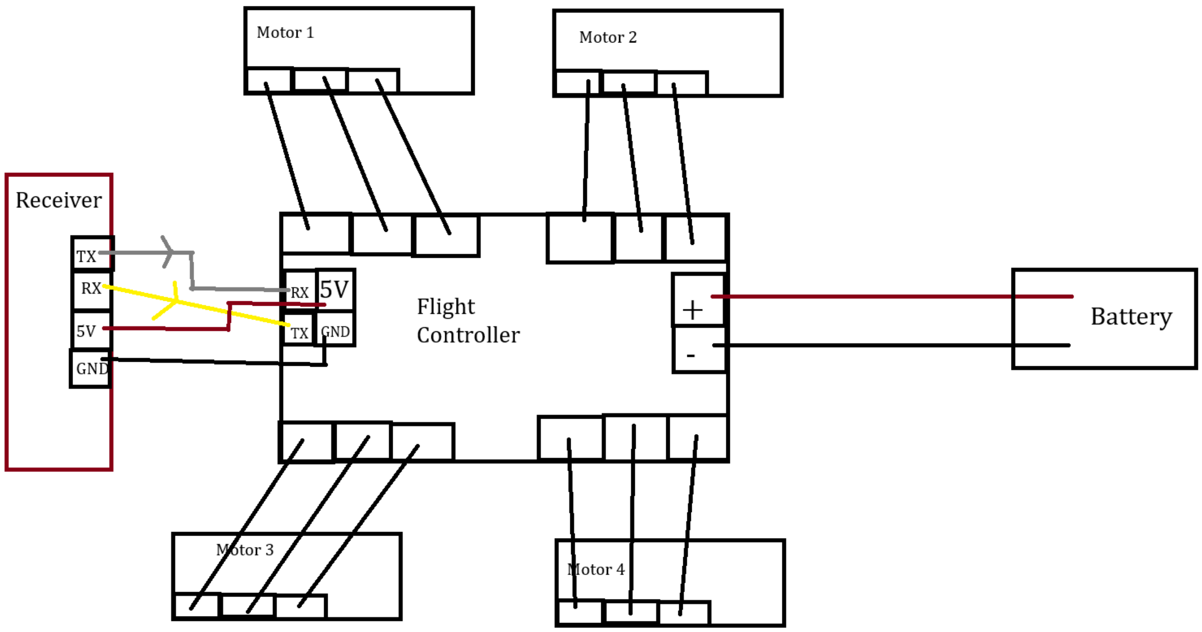
https://betafpv.com/collections/brushless-motors/products/lava-series-1506-brushless-motors

Appendix A: Load Testing

Arm withstanding 2lb of load

Body withstanding 200lb of load

Appendix B: Wiring Diagram



Wiring Diagram for the Flight Controller Made in MS Paint

Appendix C: Error and Solution Table

Error:	Solution:
Drone Frame was Too Small	Dimensions increased from 70x70x25mm to 85x85x30mm
Screw holes were too small	Screw holes increased from 2.5 to 2.6mm
Frame too heavy	Support pillars decreased in size; air vents increased in size and quantity
Arms were stress concentration points	Not addressed; arms designed to break before frame
Drone produced lift even with no throttle	PID tuning turned off before certain % throttle, dshot_idle_value decreased
UART 3 port fried during soldering causing RX Loss in CLI	Switched to UART 5
No room for battery in drone frame	Battery wrapped in foam and electrical tape, strapped to bottom.
Flight controller overheating	Unable to be addressed; caused by soldering mistake and fried internal component
Drone drifts in flight testing	Center of mass shifted until drift was manageable
Motor wires are too short to solder	Flight controller mounted at 45-degree angle for ease of access
Final Drone Prototype was 4 grams over 250g weight limit	Air vents on non-load bearing regions expanded to reduce material

Appendix D: Bill of Materials

Item	Cost	Link
Soldering Iron Kit	17.99	https://a.co/d/6YskGMB
Test Kit	18.99	https://a.co/d/98i73YK
Solder	11.99	https://a.co/d/1helH4b
Flight Controller	59.99	https://a.co/d/hUkwHap
Transmitter	52.99	https://a.co/d/3yBquBF
Receiver	23.99	https://a.co/d/6LJXERT
Motors	14.99×4	https://betafpv.com/collections/brushless-motors/products/lava-series-1506-brushless-motors
Propellers	2.50×3	https://betafpv.com/products/gemfan-d63-3-blade-propellers-1-5mm-shaft?_pos=1&_sid=51054b8a4&_ss=r
3S LiPo Batteries	29.99	https://a.co/d/i0Bczd0
Battery Charger	9.68	https://a.co/d/9skja1B
Velcro Straps	8.99	https://a.co/d/4vgneQ5
XT30 Battery Connectors	9.99	https://a.co/d/9tj3u2S
Total	312.05	