3D Printed Quadcopters

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Abstract

The principle objectives of the following project were twofold. First, it sought to inquire into the underlying physics of quadcopter drones and the fundamentals of 3D printing. Second, it attempted to determine whether additive manufacturing is a viable option for constructing a quadcopter. To accomplish the former goal, a rudimentary model was assembled so as to be easily replicable by amateurs and hobbyists. For instance, it lacked any auxiliary sensors beyond the most basic that are required for quadcopters to operate stably. During the design and assembly processes, it was confirmed that additive manufacturing is optimal for constructing quadcopter vehicles, as it enables versatile customization of the design, is relatively inexpensive, and incorporates highly flexible and durable materials. Moreover, polylactic acid (abbreviated PLA), one of the two most common plastic composites available was determined to be more suitable than acrylonitrile butadiene styrene (abbreviated ABS) for 3D printing quadcopters, given that it caused fewer complications during the printing process.

1 3D Quadcopters

In recent years, drones have rapidly grown more commonplace in almost every facet of daily life. Quadcopters, or aerial vehicles propelled by four rotors, in particular have enjoyed enormous popularity over the past decade in a wide range of fields, due to their user-friendliness and countless other advantages. They serve as indispensable tools for hobbyists, military organizations, realtors, law enforcement agencies, and countless other professionals that benefit from quadcopters’ seemingly unlimited potential. It is abundantly clear that quadrotor aircraft, along with other drones, will only continue to grow ever more integral to an increasingly automatized world.

Yet, despite their prevalence, quadcopters are highly complex vehicles that require extensive knowledge to fully comprehend. The following experiment attempts to investigate their applications and the
physics and flight mechanisms underlying their operation. Furthermore, it attempts to determine the obstacles involved in creating quadcopters via additive manufacturing. Research inquires into propeller design, flight stability and efficiency, electronic stability control to optimize the drone’s performance, and contrasts between quadcopters and single-rotor helicopters. In order to accomplish the latter goal, an experimental approach is taken. A simple quadcopter is assembled from 3D-printed components and research into the printing process and computer-simulated stress tests is conducted, so as to develop a model easily constructible by any hobbyist or amateur.

During the design process, the quadcopter’s frame must be developed in compliance with a number of constraints. For one, the 3D printer available is unable to produce items that exceed six inches in length, width, or height, such that it is necessary to design a chassis that can be printed in and assembled from multiple parts. To maximize the payload the vehicle is able to support, its frame must be extremely light, as is generally the case for most aircraft. Finally, the model must be drafted as expeditiously as possible.

Although the main goal is to design a simple quadcopter for recreational purposes, the model can be easily adapted to other applications through constructional modifications. For instance, a photographer filming aerial shots of a landmark might use a larger and stronger version of our design that can stably support a camera. An educator might teach a lesson on wind currents using the quadcopter to show how wind speed affects a moving object. In this case, a smaller, lighter model would be most suitable. Quadcopters have many uses beyond being simply recreational and these uses can be discovered through extensive research.

2 3D Modeling and Quadcopters

Figure 1: The assembly of the quadcopter.

Quadcopters are multirotor helicopters propelled by four rotors, each of which is horizontally oriented to generate lift. As seen in Figure 1, the propellers are aligned horizontally to the ground. In most cases, they use two pairs of fixed propellers. Two rotate clockwise while their counterparts rotate counterclockwise. By changing each propeller’s rotational speed, it is possible to generate varying thrust, propelling the quadcopter along any trajectory desired. A torque, or net force that induces the quadcopter to rotate about its central axis, can be produced through similar means. Because of this unique design, quadcopters possess a far greater and more versatile range of motion than conventional, single-rotor helicopters.
2.1 3D Printing

3D printing, also known as additive manufacturing, is the process of converting a digital design into a tangible model. Thin layers of a material are formed one on top of the other which creates the specified object, all under computer control. This can be seen in Figure 2. With the use of 3D printing, virtually any imagined object can be produced in real life. 3D printable models can be created using a computer aided design package or 3D scanning tool. Among the many modeling softwares available, the most prevalent are those in the Autodesk suites, such as Inventor, AutoCAD, and SolidWorks. Since 3D printers rely on successive cross sections of the final part to ensure accurate results, the digital mesh needs to be checked for hidden errors that may cause the print to fail. Once the file is run through an application and checked for holes, a software will process the model by “slicing” the model into a series of thin layers. If the file is problem-free, the software will produce a G-code file which contains instructions tailored to a specific 3D printer. When the model is ready to be printed, the data is sent to the 3D printer and through a computerized process, and the object is created.

2.2 3D Printing Processes

The most common additive manufacturing processes are fused deposition modeling, or FDM, selective laser sintering, or SLS, and stereolithography, or SLA.

Stereolithography is the process of using a source of light, most commonly a precision laser or DLP projector, to cure cross sections of a 3D model in a UV-sensitive liquid polymer [1]. As the polymer cures and hardens, the print is displaced, and another layer of polymer is cured directly on the previous layer. The primary advantage of SLA is that it can produce highly accurate and detailed parts. However, it requires a large amount of post processing. In addition, because the polymer is UV sensitive, parts created using SLA cannot be exposed to sunlight for large amounts of time or else they will become brittle and then break. This is undesirable because quadcopters will be constantly exposed to sun, which means that SLA is not ideal.

Selective laser sintering is the process of using a laser to trace and melt a layer of polymer or metal powder. Once a layer is completed, the entire build platform, including both the sintered and unused powder, is lowered and another layer is laid on top. The process is then repeated. SLS has many advantages including the ability to produce parts in a wide variety of materials. This is desirable because one would be able to produce a quadcopter in a material that balances strength and weight best. In addition, SLS does not require support structures, which means that more complex objects can be created in a single print. However, SLS requires a very specialized environment and specific tools to produce prints. Unfortunately, a lab with these capabilities was not available during the creation of the quadcopter.

Fused deposition modeling is by far the
most prevalent 3D printing process. FDM is the process of using an extruder to trace layers of a 3D model while extruding a melted thermoplastic. The most common thermoplastics used in FDM are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). FDM is the most accessible 3D printing technology because unlike SLS, FDM does not require a specialized environment. Because they can be created from relatively simple and inexpensive parts, FDM printers are the most common type of printers. Although FDM is limited to thermoplastics, the final product’s qualities can be easily modified through different slicing settings such as layer height, wall width, and infill density. However, parts created from FDM are generally not as dimensionally accurate as those from other methods and their strength is only limited to the strength of thermoplastics.

2.3 ABS vs PLA

3D printing filaments vary greatly in chemical and physical properties. Two plastics, ABS and PLA, are the most commonly used plastics by hobbyists, educators, and manufacturers. They share a few similarities since they are both thermoplastics, which means they become soft and malleable when heated and return to a rigid solid state when cooled [2]. Furthermore, you can repeat the process without affecting the durability and integrity of the material. While both filaments are used in the process of 3D printing, specific variations set them apart.

ABS is generally a very durable and strong plastic. Furthermore, it is flexible and has a great heat resistance (Refer to Figure 3). The filament, depending on the brand, ranges in tensile strength from 35 to 45 MPa [3]. These specific properties are ideal for most projects. However, ABS must be printed on a very hot print bed. If the printing surface does not reach the proper temperature, the filament will not stick to the plate properly or extrude properly. This causes problems to arise: the 3D print will come out deformed or the printer could possibly be damaged. ABS is the cheapest plastic of the two filament types and is widely used for various purposes. Due to the properties of this material, it can be sanded from jagged edges to smooth curves. Additionally, printed or broken parts can simply be pieced together with ABS glue. The filament, when hardened, is soluble in acetone.

Nevertheless, there are still many drawbacks to ABS. It is extremely toxic, and the fumes it produces when printing are harmful to the environment and anyone nearby [4]. When exposed to moisture, spools of ABS swell, and air pockets form with the filament. Upon printing, the plastic bubbles at the tip of the nozzle which reduces the visual quality and strength of the 3D printed part. ABS will curl upwards when in direct contact with the printing bed which causes corners to be rounded off. Most importantly, the filament shrinks significantly when cooling because it cools very rapidly and contracts. The design must take into account this shrinkage and be scaled. Guesswork is involved and requires multiple prints in order to ensure proper sizing of the model.
On the other hand, PLA is a biodegradable, non-toxic thermoplastic. This makes it more environmentally friendly than ABS. The filament typically has a tensile strength of 60 MPa. PLA is tough, but tends to be brittle when cooled. Unlike ABS, PLA is printed at relatively low temperatures, around 160 degrees Celsius - 220 degrees Celsius, and is very slow to cool. When PLA is exposed to moisture, physical properties change, such as color, strength, and density. Compared to ABS, PLA warps much less. Furthermore, PLA is known for its ability to print sharp, detailed prints at high speeds.

While ABS filament produces a stronger quadcopter, issues arose while printing with this particular plastic. As discussed earlier, without a hot enough plate, ABS will not stick properly and pull off the surface. During printing, the model will deform and fail. Instead of sticking to the plate properly, the material would move, resulting in excess strips of printed ABS attached to the design. Albeit possible alternatives could have been taken, the materials necessary to make these changes were not available at the time. As a result, PLA was chosen as the filament for the 3D printed quadcopter. Although it was not ideal, PLA has many properties that aided the printing process. The filament heats up easily, making it easy to print detailed designs well with sharp corners. PLA shrinks less than ABS. Therefore, designing a model on a computer is simpler than scaling a model because one does not have to account as much for shrinkage. Additionally, PLA can be printed at a faster pace with no complications.

2.4 Benefits of 3D Printing
3D printing requires a relatively low expense budget for any quadcopter hobbyist. It allows the designer to personalize his/her own model through multiple methods. For example, one can directly edit the file digitally or adjust the printer’s settings, such as speed, fill percentage, and resolution, to affect the properties of the model. The filaments all have different properties that can add strength or flexibility. Furthermore, it is a very productive and accurate manufacturing method. The 3D printing machine itself is affordable and durable. Due to its ability to build a model from the bottom up, 3D printers can produce shapes that cannot be fabricated any other way. Because additive manufacturing only uses material that will be in the final product, little to no waste is produced.

As seen in Figure 4, traditional forms of machinery often leave up to 90 percent of metal wasted. However additive manufacturing generates far less waste to begin with [7]. Additionally, 3D printing provides a cheaper alternative to replacing broken parts. Instead of having to wait for a week or longer for a single piece of a store-bought quadcopter to come in the mail, a 3D printed copter can have any broken part reprinted in a few hours for a fraction of the cost. The printed objects are mass producible because they can be made on various printers and the parts are easily replaceable. If a 3D part were to break, all one would have to do to replace it is print a new one.

2.5 Benefits of Quadcopters

Quadcopters are easy to manufacture and are sold at an affordable price. These quadcopters utilize four propellers which means that the product has a lot of power to be able to lift off the ground [8]. The device can easily take on a small load. Furthermore, only having four propellers means that the quadcopter has great maneuverability and thrust in comparison to other copters.

For example, a tricopter is unbalanced and hard to maneuver due to its undistributed weight over three motors. On the
other hand, a hexacopter which has six motors and propellers has an increased speed and greater power than a quadcopter due to its larger size. However, its dimensions make the copter harder to fly in tight spaces while its controls are much more complex. Meanwhile, the eight motor and propeller copter, the octocopter, is a fast, agile device that can reach exceptionally high elevations. Since it is so large in size, the battery life is often far less than that of the quadcopter. Similar to the hexacopter, the octocopter is very challenging to maneuver. Ultimately, quadcopters are far better than other type of copters. Their size and mobility is just right, which means that the devices can have more applications. Quadcopters, moreover, are inexpensive and thus suitable for novices and hobbyists, in consideration for whom this project’s model was designed.

3 Methods/Experimental Design

3.1 Physics

A quadcopter’s propellers generate lift, a force perpendicular to the ground that counter-balances the vehicle’s weight to keep it aloft. Adjacent propellers must rotate in opposite directions in order to cancel out lateral and vertical forces and thereby prevent the vehicle from unstably spinning in place (Refer to Figure 5). Because horizontally oriented propellers add significantly to a quadcopter’s weight, they are highly inefficient and unfavorable. Instead, to move in a horizontal direction, the vehicle must generate a net force parallel to the ground by creating an imbalance of forces between its four propellers [9].

One pair of adjacent propellers produces more lift than the other, inducing a torque, or twisting force, along either the vehicle’s roll or pitch axes [10].

Figure 5: This is a diagram that displays the direction of each spinning propeller on the quadcopter.

Figure 6: The imbalance of forces from the propellers drives the quadcopter laterally. [11]

Now, with the quadcopter angled and the propellers still creating a net force perpendicular to the quadcopter, the net force has a slight horizontal component which
can drive the quadcopter in a lateral direction (Refer to Figure 6).

Quadcopters have physical limitations. The upward force created by the four propellers must be stronger than the gravitational downward force caused by the weight of the whole structure itself. This then limits the equipment that can be added to the quadcopter. Stronger motors usually tend to be heavier motors, which cannot be supported by a device designed for small motors.

Even larger-scale quadcopters are unable to support the load of a heavy motor and battery because the frame’s strength and weight must increase to accommodate the heavy additions as well. The thrust gained from the heavy duty motors is less than the weight gained from the new frame and battery. That is why using quadcopters as a method of transportation is not possible with today’s technology.

The number of propellers affects the amount of load the quadcopter can carry, as well as its stability and maneuverability. First, as previously stated, the upward force that counteracts the gravitational pull is only generated by the spinning propellers. Therefore, the more propellers there are, the more overall lift the quadcopter receives. Because there are more points around the quadcopter that can generate a torque, the quadcopter becomes less dependent on each single propeller, which means it is more stable.

Also, more propellers can create more variable directions to move in, making the quadcopter more maneuverable as well. Due to budget limitations, only four propellers are used in this model to understand the other aspects of quadcopters. Adding propellers increases the amount of supplies required to run the motors as well as the complexity of the whole quadcopter. One would require something to control the motor, as well as the battery power sufficient enough to run an additional motor. If a drone were to have more propellers, the propellers would need to be at all times, which would convolute the movement commands. However, each motor would require less power. The addition of more propellers would also increase the cost of the project, which is limited.

3.2 Design Process: Foundation

Figure 7: These were the two potential designs of the quadcopter.

The quadcopter’s design primarily consists of elements from two Thingiverse models. The chassis of the first model (Model 1 in Figure 7) consisted of several compartments along with four connections to attach the motor arms. Each motor arm had a hollow cylinder with one open end and one closed end with several slits, which were designed to hold the screws that attached the motors. This model’s primary advantage was its flexibility in motor mounting because the slits allowed for different mounting orientations and dimensions. However, a major problem to this design was its multi-layered compartment design because each compartment consisted of a ceiling and floor with empty space between. This posed a major problem to the printing process be-
cause we were using fused deposition modeling. FDM builds new layers of a print on top of previous printed layers, so it will not print well when there is an empty space. In addition, the design’s compartments had very thin walls, which limited the group’s capabilities in modifying the strength of the resulting print through adjusting density and wall thickness [12].

The second model (Model 2 in Figure 7) consisted of a flat mesh with hexagon shaped cutouts. It was split into four separate parts to allow users to print it in separate prints so that no piece would be too large for the printer’s maximum volume. This model was the most apparent in the final design of the quadcopter. However, the motor mounting points were not sized correctly for the motors. But, unlike the first model, this model was flat and did not have any overhangs, which means it would be very easy to print on a FDM printer. In addition, this model was easier to print and assemble because it was split into four parts. Furthermore, the uneven edges allowed for each part to be securely fastened to the other parts.

3.3 Design Process: Modeling

The final quadcopter included the motor mounts from the first model and the mesh chassis of the second model. The program chosen for cutting these parts from each model was Netfabb because of its mesh cutting features and reliable boolean operations. The cylinder of the motor mount was first cut from the model of the entire arm to reduce the polygon count, thereby making it easier to work with. Then, a basic pipe was created with the exact dimensions of the motors. The model of the motor mount was stretched to fit the pipe and then the difference was taken into account for the final motor mount. In addition, the second model was re-scaled to fit the print bed of our 3D printer. Finally, boolean addition was performed on the modified version of the second model and the motor mount to produce the final body of the quadcopter. Although the body was able to be modified from the original files, the landing gear needed to be designed from scratch to accommodate the smaller chassis. A digital caliper was used to measure the inner diameter of a hexagon on the quadcopter to the nearest hundredth of a millimeter. This hexagon shape was recreated using polylines in Autodesk 123D and extruded to 5.5 mm (the thickness of the body of the quadcopter). A similar hexagon was then created and extruded to 40 mm, which was the desired height of the landing gear. These two parts were combined and printed four times.

3.4 Design Process: Printing

Being very large flat prints, each quarter of the quadcopter had to be printed very carefully to prevent warping. When cooling, plastics will shrink, which will cause printed parts to peel off of the build plate while the printer is still printing. This was countered by printing a brim around edges of the quadcopter to increase its surface area on the print bed and putting glue on the print bed to increase surface adhesion. In addition, the usage of each part was considered when setting the slicing parameters of each print. Overall, the quadcopter must be light in order to reduce unnecessary strain on the motor but maintain the strength needed to sustain a crash or hard landing. Using the model of the stress gradient, the infill density was increased in more stressed areas to increase the strength and rigidity in those areas. In addition, to account for the shrinking of each print as a whole, each part was sliced at 102% scale.
4 Results/Discussions

The quadcopter is based on designs found on an online repository [13]. The design process of modifying and combining existing designs significantly expedited the project’s design phase because of the ability to merge the most advantageous aspects of each model. Many designs were considered but ultimately, a combination of several models was created. The resulting model was four sections of flat mesh with many honeycomb cutouts across the body (Refer to Figure 8). This design maximized its structural strength while minimizing its weight and made it easier to print.

4.1 Stress Testing

The designer must consider various factors such as strength and deformation before choosing a model. While beginning a print immediately after finding a quadcopter design is ideal, the factors must be taken into account. A stress test can be done through various programs to see how the model will perform with a load. For the chosen honeycomb design, a test was run to examine possible deformation. One of the quarters of the quadcopter’s body was selected at random. From there, a load was placed on the motor’s mounting point and the corner opposite - the point where all of the quarters meet in the center of the quadcopter - was set as a fixed point.

Figure 8: This is the final 3D model of the quadcopter.

Figure 9: This is an example of the deformation of the quarter.

Figure 10: This is the strain gradient on a quarter.

As pictured in the Figure 9, piece B is the design without any applied stress, and piece A is the design with the maximum amount of stress applied. The section began to curl at the ends as more force was applied in the upward direction, simulating the moving propeller’s pull on the piece. Figure 10 shows where the stress disperses throughout the model. The red displays the area that absorbs most of the amount of stress, while the blue reveals the area that is barely affected by the load. Therefore, the motors will generate stress near their
mount points but little to no stress on the center of the quadcopter where all of the electronics lie.

4.2 Failures

While constructing the quadcopter, there were many issues. The first issue that appeared was the fact that ABS would not stick to the plate. While the printing bed was hot enough, the ABS filament would not stick to the plate. Test pieces of both PLA and ABS were printed to compare which was stronger. However, the ABS model would not print well. Therefore, the material was switched to PLA. While PLA is a weaker material, the design was modified to ensure that the quadcopter would be strong enough. It was pertinent that the quadcopter could be assembled in a relatively easy manner and the printability of the parts is very important. This is due to the goal of the project which is to create a simple quadcopter that a beginner could assemble. The primary issue when this quadcopter was being sliced was accounting for the shrinkage during the printing process. The motor mount needed to be tight enough to securely fasten the motor while not being too small to restrict its movement. Another problem the group ran into was that the wires that protrude perpendicularly from the motor were not accounted for in the modeling process, so there was no hole in the cylindrical motor mount for the wires to pass through.

We fixed this through another iteration of the design by removing a rectangular area from the wall of the motor mount to create an area for the wires to escape (shown in Figure 11 print 2). The last error in the iterations before the final model was that the cylindrical motor mount was too high, which was problematic because the motors were outrunner motors and would scrape against the edges of the mount. This was fixed by removing the top centimeter of the motor mount (shown in Figure 11 print 3).

After a few more trials and errors in 3D printing, the final four pieces were printed. Since FDM printers are generally not very dimensionally accurate, it was hard to connect the pieces together. While the pieces were supposed to snap together, they had to be glued together instead (Refer to Figure 12).

Not only were there problems in the printing process, but multiple issues arose when constructing the actual quadcopter. The first main issue was that there were
no manuals or specifications for the Arducopter, the flight controller used in this project which commands the overall quadcopter. The proper connections were found, but they were scattered in various forums and video tutorials. Because the equipment used were not exactly the same, multiple educated guesses were performed while connecting the wires. While using the two firmwares installers recommended for Arducopter, Mission Planner and APM Planner, there was a bad barometer health error which could not be troubleshooted. There was no adequate support or cases online where the barometer had bad health so no solution was found. Eventually, a loaned Pixhawk, another flight controller, was implemented. Additionally, one of the motors for the propeller was defective which drained the budget for repurchasing another set.

5 Conclusion

Additive manufacturing is an extremely effective tool for quadcopter enthusiasts designing their own vehicles. 3D printing is ideal due to its affordability, the freedom it grants designers to readily customize their unit, the flexibility and durability of the materials used in the 3D printing process, and its environmental friendliness. Although ABS plastic is superior in strength and durability to PLA, the latter was found to present fewer complications during the printing process and therefore to be preferable for inexperienced designers. Moreover, quadcopters were determined to be a superior alternative in this case to other multi rotor helicopters, which suffer from issues in stability, maneuverability, and battery life. When designing a frame, stress tests are imperative to perform in order to determine the location of structural weak points where vibration and mechanical stress must be mitigated. Other hobbyists might improve the design herein developed by foregoing the purchase of a flight transmitter and instead operating it directly from a computer, further reducing the device’s cost. A camera might also be added, which, though raising the cost of the quadcopter, would allow it to be flown at a greater distance from its operator.

Figure 13: This is the final 3D quadcopter.

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