Optimized Quadcopter Design

An Analysis and Guide to the Components for Design and Flight

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How to start:

Before deciding on any components, the size and type of quadcopter must be chosen. There are thousands upon thousands of different components and most are only suited for a certain task. Furthermore, some components require other pieces specifically rated to handle, for example, a certain type of motor. Every part is paired together to make a quadcopter that either has a longer flight time, can lift more weight; can do acrobatics, or many more applications.

The Quadcopter's capabilities lie primarily in the size of the craft. The measurement is taken from the motor shafts on opposite sides. While many other different sizes and classifications exist, there are three main sizes; Small, less than 300mm, Medium, greater than 300mm, and large, greater than 600mm. The small quadcopters can only carry very little weight, in effect the reduced weight also makes them very responsive and great to play with and control. However, you can't do very much more with them. Medium quadcopters are great for most all applications. They can carry a variety of on board sensors, and many also have camera and gimbals mounted underneath. Depending on how you make it, medium sized quadcopters can either be very lightweight and acrobatic, or a bit heavier and great for steady filming. Finally, the larger quadcopters allow for larger blades and motors, so they can carry greater weights; however, they are slower and more sluggish because they take more time to accelerate.

When building a quadcopter, it is important to research every component chosen to determine whether the craft will ultimately fly well. A good tool to help you with this is a site called http://ecalc.ch/. This tool will give a very rough estimate of how a Quadcopter will perform based on a combination of different components.

The remainder of this guide will focus on the components used on a medium sized test platform and research quadcopter. It will go over a general description to explain each component so an informative decision can be made on which part is best for each type of quadcopter. Each section will also give an overview of how the components chosen performed with the research quadcopter.

Frame:

Figure 1: Frame from Hobbyking.com

For the first time, it is suggested to buy a prebuilt frame when deciding on the one. If there isn't a frame that satisfies the requirements for a design, a custom built frame may be needed. When choosing or designing, make sure the frame is lightweight and strong enough to handle hard landings or a crash. By now a decision should be made on the size, so deicide upon or design a frame within the size range that has the proper type of material and style suited for the task.

There are many different types of materials. Carbon fiber is probably the strongest and most lightweight, however it is very expensive and difficult to modify. Another type of material is glass fiber. It is lightweight and a lot cheaper; however it isn't as strong and can bend easily. Another common material is aluminum. It is easy to design with, fairly inexpensive, and easy to modify; however, it is a lot heavier than the previous materials. Decide which material best suites the task, and work from there.

The frame used (see Figure 1) in the research quadcopter is *Turnigy Talon* carbon fiber frame at 500mm. This frame is pretty resilient, lasting though many hard landings and couple of crashes. However, after many tests and usage, cracks begin to form where the motor mounted clamped onto the carbon fiber tube. The motor clamp would sometimes spin on the tube so to fix this it was tightened harder, which ultimately led to the cracks forming and furthered the problem. For further testing, a custom built frame will need to be designed and fabricated.

Quadcopter Motors:

Figure 2: Turnigy Motor

There are a lot of different factors to consider when choosing the motor for a quadcopter. First, they are not the typical brushed inrunner type motors commonly seen. A special type of motor identified as a brushless outrunner has to be used for optimal efficiency. Additionally, the Kv of the motor, max wattage rating, and resistance has to also be considered.

Brushless motors require a special controller and have three wires instead of two. Unlike brushed motors, the name implies there is no brush to switch the polarity as the shaft turns. This is handled by a brushless controller, and helps eliminate power loss to increase efficiency.

In outrunner motors (opposite of inrunner motors), the coils of wire are stationary, while the outer casing with the magnets spins. The controller controls the coils to change the magnetic field which causes the casing to spin. This setup helps to increase the rotational inertia of the motor. All outrunner motors also have a central shaft that goes through bearings in the middle of the coils. Depending on the motor some shafts end right at the top of the casing with a propeller mount that attaches directly to the outer case. Other types have a shaft that extends beyond the case with a propeller mount that attaches to the shaft. Each motor should come with its own propeller mount.

Other factors to consider are the Kv, wattage ratings, and resistance of the motor. Kv is a measure of revolutions per minute of the motor per volt (RPM/V) with no load. For example, if you have a motor with 1240Kv like the one pictured; a 12 volt battery has a max RPM of 14880. Typically smaller motors will have a higher Kv, but will be unable to provide as much torque. On the other hand, larger motors have a lower Kv and provide more torque. Also, larger motors often require a higher battery voltage to maintain a high enough RPM. Additionally, the battery voltage used is limited by the max wattage of the motor. Motors using higher voltages will pull a lot more power, and if this goes over the max wattage of the motor, the motor will overheat. Many different factors contribute to how much power the motor will pull. The voltage battery, the size of the propellers, and the internal resistance all play a part. To determine the max wattage it is easiest to use http://ecalc.ch/ to get an estimate of wattage used at full power. Ensure the calculated wattage drawn will not go over the max wattage of the motor when deciding the best one for you.

The *Turnigy Aerodrive SK3* - 2826 – 1240Kv (see figure 2) provided sufficient power despite one mishap. It provided adequate lift to hover at a little under 50% power and had a propeller mount attached directly to the casing which helped eliminate some vibration. Unfortunately one of the motors failed while testing for unknown reasons. It started spinning erratically. When I disarmed the quadcopter it started smoking which could indicate a failure with the Speed controller but the Speed controller tested fine afterwards.

Electronic Speed Controller (ESC):

Figure 3: Brushless ESC

A brushless motor requires a brushless Electronic Speed Controller (ESC). If it looks similar to the one above and has three wires going to the motor it is most likely a brushless ESC. When choosing the right ESC `for you motors, you must first determine the max amps pulled (either listed on the specifications of the motor, or calculated using http://ecalc.ch/). Then choose an ESC with an amp rating greater than the max amps pulled by the motor. Additionally, BEC, SBEC, UBEC, and OPTO identify if a separate circuit is included in the ESC.

A BEC stands for a battery eliminator circuit. A BEC takes any battery rated by the ESC and regulates five volts to the red wire of the signal (PWM) cable. The five volts is used to power the controller, receiver, servos, and any other devices that use five volts. Anything with BEC in the name, such as UBEC and SBEC, will do the same task, some are more efficient than others, and they are all typically switching regulators. The amp rating of the BEC must be greater than the amps used to prevent damage to the circuit, and avoid brown outs. If it is labeled as OPTO, that means there is no BEC in the ESC. These are typically cheaper, and there are often identical models with and without the BEC. You only need one ESC with a BEC for each quadcopter, and it is suggested that you do not have multiple BEC's powering the controller. If there are four ESC's each with a BEC, it is suggested to pull out the red wire from the PWM cable of each of them.

Most all ESC's have a way to program them in order to change some settings like low voltage cutout, battery type, or a brake mode that brakes the props when unpowered. Each ESC has a specific way to program it and most suppliers sell an optional programming card. It is also possible to program it with the receiver and transmitter by listening to beeps that tell the options, but that can be difficult. Furthermore, to change direction, simply flip two of the three wires going to the motor. DO NOT flip the input.

The ESC pictured (see figure 3) is *Hobbyking 20A Blueseries Electronic Speed Controller*. This ESC worked well though it got a little hot after extensive use. As mentioned above with the motor, there was a time when the motor smoked and died which could've been caused by this ESC, but it worked fine afterwards.

Propellers:


Figure 4: Two Propellers

Most Quadcopter Propellers have two blades with a few rare ones with three. The main factors that go into propeller choice are length and pitch. Length and pitch are typically indicated respectively as "10x4.5" or "1045" with the first two digits being length in inches and the second two digits being pitch. If it acted as a screw, pitch is how many inches it would screw with one rotation.

Two clockwise (CW) spinning props and two counterclockwise (CCW) spinning props are needed for most types of quadcopters. Each prop with the same rotation are mounted on opposite corners. This keeps the quadcopter from spinning around since the motors cause a torque on the arm from spinning. In a similar way, yaw is controlled by increasing the power to one pair, while decreasing the power to the other, creating a difference in torque to rotate the craft.

When choosing the propeller length you have to keep in mind the Kv of the motor. Higher Kv typically means a small propeller is used. Smaller props typically use less current and are easier to speed up and slow down, which allows for a more responsive craft. In turn, larger props are normally paired with lower Kv motors, are more efficient, and can carry heavier loads. They also take a little bit longer to change speeds, but are a little more stable.

Pitches commonly lie between 3" and 5" range. A higher pitch means that it can provide more thrust, but requires more motor output. Lower pitches are more efficient, but provide less thrust. It is a tradeoff to determine the pitch that best fits your needs.

Before flying the quadcopter, the propellers must be balanced. Unbalanced propellers create significant vibrations that can throw off sensors and lead to uncontrolled flight. There are many methods to balance propellers with the following being a fairly basic one:

1. Have the quadcopter firmly strapped to a surface.
2. Hook up the receiver to each motor one at a time and use your transmitter to control speed. Alternatively, some flight controllers have a built in motor test function available.
3. Bring it to full speed and see, hear, and/or feel the vibrations caused by the spinning propeller.
4. Stop it, and cut a piece of tape and firmly attach it on one side of the propeller. Turn it on again and see if it improves the vibrations.
5. If it does, try adding a bit more or removing some. If it doesn't try switching the side of the propeller you put the tape on.
6. Keep repeating these steps for one motor until satisfied the vibrations are minimal. Then repeat for all other motors.

The propellers pictured (see Figure 4) are 10" x 4.5" propellers. These propellers worked well for the craft, but took a bit of balancing to keep them from vibrating too much. Quite a few broke from crashes, but otherwise they performed flawlessly. Make sure to buy spare propellers as these are usually the first thing to break.

Lithium Polymer (LiPo) batteries:

Figure 5: LiPo Battery

For Quadcopters the optimal type of battery is a lithium polymer (LiPo). It is both lightweight and can supply high currents. However, LiPo's are a lot more dangerous than common household batteries if handled improperly. The factors to consider when buying a LiPo are cell count (battery voltage), milliamp hours, and C rating.

LiPo batteries all have an average voltage around 3.7 volts. This can go up to 4.2 at full charge, and should go no lower than 3.0 to avoid ruining the battery. Labeled on each LiPo should be something like 3 Cell, 4S1P, or 5S2P. This indicates how the cells are arranged, and tells you the type of voltage for the battery. The "S" stands for series of cells and the "P" stands for parallel. Most batteries only are just arranged in series. To find the voltage, multiply the series of cells by 3.7volt. For example a 3S1P or 3 cell battery arranged in series will have an average voltage of 11.1volts. The voltage battery needed is based on your motor/ propeller setup. Larger motors will allow and sometimes need higher voltages, while smaller ones can run on lower voltage. Choose the battery and voltage based on what the motor and propeller combination need to run most efficiently.

The flight time of the battery depends on the amp hours on the battery. These can range anywhere from 500milliampere hours (mAh) to 10,000mAh. This indicates how many constant amps it can provide in one hour before being fully drained. For example a 3,000 milliamp hour battery can provide 3 amps of current with any voltage battery for 1 hour. Similarly, if the load is a constant 6 amps you will drain the same battery in a half hour. Oppositely, a 1.5 amp load will drain the battery in 2 hours. Reversing this equation will indicate average current a quadcopter pulls by timing how long it flies.

The C rating tells you how many amps it can provide by multiplying the C by the milliamp hours. A battery with 20C and 3000mAh can supply 60amps at one time. If the quadcopter requires more than the max current, a higher capacity battery (mAh) or a higher C rating is needed. A C (burst) is often listed which specifies a higher C rate that can be maintained for a limited time. The max current should never go over the max C burst rating, and the hover current needed should be well below the constant C rating. Additionally, ensure the connectors and wires can handle the current needed as well.

It is important to note that these batteries can be very dangerous. LiPo fires are very serious and can be very destructive. Do not use ones that look disfigured or bulging, and don’t just throw them in the trash. Rather, send old or damaged ones to proper battery recycling facilities. Also, ensure charging only happens with chargers specifically designed for LiPo batteries, and be in the room to monitor them while they charge. Fire safe bags for storage and transport are highly suggested.

The 3000mAH battery above (figure 5) gave a flight time of about 15min for the quadcopter at hover. The original connectors were replaced by Anderson PowerPole. These are very good types of connectors and have no female/male ends. PowerPoles also come in many different sizes to handle a variety of current loads. This battery had no problems and performed flawlessly.

Flight Controller and Software:

Figure 6: Pixhawk Flight Controller

There are many different options for flight controllers. Most all of them should work just fine, but others have improved functionality and more features. More expensive ones typically have better sensors and more features.

Most all flight control boards have built in sensors. The boards have an accelerometer for measuring acceleration, a gyroscope for measuring rotational angular velocity, a barometer to measure height from pressure, and a magnometer for a compass. Using integral and derivative equation with the raw values from these sensors; X, Y, and Z orientation of the quadcopter can be calculated. The sensors are not perfect, so sensor value drift sometimes occurs; however, by using the different sensors together, the controller is able to eliminate most drift so the pilot never has to worry about the sensors being off. Unfortunately, since the Magnometer and Barometer rely completely on outside sources like magnetic fields and air pressure, uncontrolled environments may cause large sensor error. For example, wind or pressure changes can cause the quadcopter to go flying up for no apparent reason if using altitude control.

The *pixhawk* controller pictured (figure 6) was tested by a partner who determined it to have the most reliable sensors. It is quite expensive for starters, but it has almost every feature available at this time. It has ports for two telemetry modules, GPS, CAN, A separate Magnometer, i2C, SPI, and a couple of more features. It also has software to allow for addition of custom modules. It comes with a voltage monitor with a built in BEC, and buzzer, and a safety switch. This controller is recommended if the project has the budget for one, though a cheaper alternative like *Multiwii* or *KK2* will also work.

Ardupilot software is used on the quadcopter with the *pixhawk* board. This is very well developed control software that provides functionality for many different accessories, with optional autonomous flight mode, gimbal control and much more. Additionally, *Mission Planner* was used both as a ground station, and for programming and calibrating the flight controller. *Mission Planer* is very effective software for the quadcopter, and it also provides functionality for many different types of crafts and controllers. The site http://ardupilot.com/ is a good place to start when looking into *Ardupilot* software and compatible ground stations, *QGroundControl* being another good ground station alternative.

Accessories:

While a pilot can manually fly a quadcopter with just a flight controller, basic framework, and electronics, additional components are needed for more functionality. These accessories allow the pilot to better stabilize the quadcopter, provide monitoring from a ground station, autonomous control, camera control, and much more. It is highly suggested, though not required, to have at least a telemetry module and a GPS module.

Telemetry will be able to give you real time data to a ground control station. It also allows commands to be sent from the ground stations to control other modules autonomously. Paired with a GPS unit, flight plans can be created while flying for autonomously controlled flight.

A GPS module will gives real time flight location data up to 2-3 meters accuracy. This allows for tracking and/or logging of the flight while in air. It is also essential for any autonomous flight control, or to keep the quadcopter hovering in one place with no user input or adjustments.

If the quadcopter has a camera, a gimbal helps to control the camera independently of the craft. It stabilizes the camera despite any changes in the quadcopters orientation, and helps to dampen vibrations. The flight controller can handle the stabilization autonomously, and the transmitter can control any desired changes in camera angle.

3DRobotics has an optional optical flow sensor that works with the *pixhawk.* This tracks the ground movement using a camera to send very accurate X and Y velocity to the flight controller. This helps improve stability and keeps the quadcopter in one place much more accurately than GPS can.

ESC's have a low voltage cutoff set by default, however it is better to have an audio or visual warning first using a power monitoring circuit. Some voltage monitoring circuits send data to the flight controller that can handle controlled low battery failsafe landings, while others attach onto the LiPo's balance plug and beep when the cells or low. A few even have a built in BEC which allows having ESC's without BECs (OPTO).

Lastly, Lights can do more than look cool. They can be great visual indicators of the orientation of the craft. They can also send other signals or flash to warn the pilot is anything's wrong.

Transmitter and Receiver:

There are several different types of transmitters and receivers. It is important to have a reliable transmitter over long distances otherwise control of the craft might be lost. Every controller should have a listed range, but this is only under the best conditions with no obstructions. There are also two different types of how controllers encode the data sent, PPM or PCM.

Figure 7: Futuba Transmitter

Pulse Position Modulation (PPM) and Pulse Code Modulation (PCM) both accomplish the same task. However, PPM is the analog version while PCM is the Digital version. PCM takes additional encoders and decoders to handle the data signal; therefore this type is more expensive. However, it doesn't have to deal with interference as much and it is easier to setup a failsafe. Additionally, if it loses a packet of data it can hold the last signal for a small amount of time before initiating failsafe. PCM is the better option if it is affordable.

The transmitter pictured (figure 7) is made by *Futuba*, transmitter model T14SG. It has PCM encoding and a nice display. There were no connection problems with this model and it comes with a lot of optional functions. Futuba is a good maker of quality transmitters if it is affordable. Otherwise, *Turnigy 9x* is a good cheap alternative.

Preflight Checks:

Before thinking about flying, the pilot must ensure every part of the quadcopter is functioning properly, especially the failsafes. Failsafes act to ensure the quadcopter doesn't just fly away, or fall out of the sky. Additionally, proper calibration is necessary to ensure a smooth flight and to avoid crashes.

Flight controllers won't arm the quadcopter until a minimum set of requirements are met. For one, the quadcopter has to be properly calibrated, with a small acceptable level of variance. Additionally, advanced flight modes will often require GPS lock to start flying. To arm most l controllers, push the throttle down and all the way to the right. The four blades should all spin very slowly. To disarm it, push the throttle down and to the left.

Before flying, ensure all motors are spinning freely, and the Propellers are sufficiently balanced for minimal vibration. Furthermore, make sure all bolts are tight, and everything is tied or taped down firmly.

Failsafes are necessary before flying and often have to be setup properly. Two main failsafes include one for loss of signal, and one for low battery. If the signal is lost the quadcopter should automatically land. Test this by turning of the transmitter at hover in a controlled environment, to see whether the quadcopter slowly descends. If it does not land, follow the instructions from the software's manual to set it up with the controller. Secondly, to avoid falling out of the sky at low battery, a voltage monitor is necessary to alert the flight controller of low voltage. This way the controller will auto land instead of falling out of the sky when the ESC's low voltage failsafe enables. If the low voltage battery failsafe is disabled on the ESC's and the flight controller, the battery can be ruined.

When first testing, go out to an open field to have space to test in. First users will need time to get the feel of the quadcopter, and will likely crash a couple times before getting the hang of it, so make sure to have spare parts and a solid design. Good luck flying!

Flight Results:

Using the components discussed and pictured above with the research quadcopter worked fairly well. Being in Oklahoma, wind is a very big problem when flying the quadcopter. In more than one occasion, height control was lost, and was only gained back after turning off altitude control. Otherwise outside tests were very successful, until the quadcopter frame started cracking like mentioned in the frame section. It allowed the motors to rotate and while quadcopter would still fly, the frame would start spinning since the propellers provided a sideways thrust.

There were also many tests with the GPS module. Attempts at autonomous flight control were made; however, after reaching the destination the quadcopter would fly around erratically trying to maintain a more accurate position than it could. This eventually caused a couple of crashes forcing these tests to be put on hold. On the other hand, the more simple GPS hold position mode maintained accurate position in the air with very little trouble. Movement was a bit slower with this controlled mode, but it didn't have any problems and maintained and accuracy of about 2-4 meters with wind.

Flight time varied with the different batteries used and how aggressively it was flown. The 3000mAh battery as mentioned above provided about 15min hover flight time. Smaller batteries provided a lot less. Flight time typically ranged between 8min to 15min.

There are a few ideas for further research. First off, a new frame has to be designed to fix the problems with the current one. Secondly, more flight tests with autonomous control will need to be made, possibly with more accurate GPS or an optical flow sensor. Finally, if a very stable quadcopter can be built, there are plans to work on, improve, and add more features to the autonomous control function of the quadcopter.

References and Useful Sites

Part suppliers:

http://www.hobbyking.com/

http://3drobotics.com/

Online Quadcopter Calculator:

http://ecalc.ch/

Controller software:

http://ardupilot.com/