Optimization of a Quad Rotor Aircraft for a Stable Flight

Sadath Hussain, Arjun Puttabakula, Mannat Kaur and B.S. Raju

Abstract--- A quad copter is multi-rotor copter with four arms, each of which has a motor and a propeller at their ends. Quad copters do not require mechanical linkages to vary the rotor blade pitch angle as they spin, which simplifies the design and maintenance of the aircraft. The use of four rotors allows each individual rotor to have a smaller diameter than the equivalent helicopter rotor, allowing them to possess less kinetic energy during flight. This reduces the damage caused, should the rotors hit anything. Hence an attempt is made to study the flight parameters and also to perform various experiments on the quadcopter in order to ascertain the effect of these experiments on quadcopter and how it alters the performance characteristics such as stability in flight, load carrying capacity, power consumption, battery life etc. Thus, the effects which enhance the performance characteristics of a quadcopter for its stability are the end results of the paper.

Keywords--- Quadcopter, UAV, RC Aircraft, Tuning, Pitch Profiles, Thrust Profiles & Curve Optimization

I. INTRODUCTION

A single rotor machine, in comparison with a multi rotor machine, is much more stable and efficient. The main reason that multi rotor machines are popular as small drones is because of their mechanical simplicity [1,2]. A quadcopter uses four motors which are connected to four fixed-pitch props which are literally propellers attached directly to motors, a sum total of a single moving part for each of the four props. This makes them extremely simple (and therefore low cost), also very easy to control. In order for a quadcopter to remain stable in the air, it must individually adjust the thrust produced by each of its props. If the props on one side are producing more thrust than the other, the quadcopter tilts to one side. With fixed-pitch propellers, the only way for it to adjust the thrust is to speed up or slow down the propellers [3].The various experiments to be performed will include performance variation due to different thrust profiles, different propeller sizes, different pitch of the propeller and testing the efficiency of the control board by performing self-level test. The behavior of quadcopter due to these experiments will give us a better understanding of its functioning and help us easily stabilize the quadcopter for any configuration. The quadcopter is made of glass fiber having total dimensions of 550 x 500 mm, Emax MT3510 brushless motors each having a payload capacity of 1.7kg at maximum configuration are attached to each arm of the X configuration quadcopter individually powered by Emax 30A Brushless Electronic Speed Controller (ESC). The propeller sizes vary from 12 - 15 inches depending on the desired payload capacity. The flight parameters are controlled by Hobby king KK2.1 Multi-rotor LCD Flight Control Board With 6050MPU And Atmel 644PA. The quadcopter is controlled by a Fly Sky FS-T6 2.4ghz Digital Proportional 6 Channel Transmitter and Receiver System. Power to the motors and the control board is provided by Turnigy 5000mAh battery which

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provides sufficient battery to fly the quadcopter for 20 minutes approximately [7].

UAVs are playing a very major role today in the aviation industry. They are finding a lot of applications which are discussed in chapter 11 of this report in detail. Our source of inspiration for this report comes one of the "TEDTalks" given by Raffaello D'Andrea on the "Astounding Athletic Power of Quadcopters" A lot of universities across the world are performing experiments and building quad copters and doing extensive research on then to improve their applications and usability. Vijay Kumar and et al., have worked on these robots for the various applications and issues with respect to stability [5]. The various papers published by Y. Bouktir, M. Haddad, T. Chettibi on the topic "Trajectory planning for a quadrotor helicopter", Gabriel M. Hoffmann, Haomiao Huang, Steven L. Waslander, Claire J. Tomlin under the topic "Quadrotor Helicopter Flight Dynamics and Control: Theory and Experiment", MongkhunQetkeaw A/L Vechian under the topic "Wireless Control Quadcopter With Stereo Camera And Self-Balancing System" and various other papers helped us to get a deeper understanding of the topic. In order to tune the quadcopter, a basic knowledge of the various controllers is essential to implement in the quadcopter which has been the elemental in building the foundation of it. Manuals present on the Hobby King website also helped in setting up the flight control board which otherwise would have been impossible for novices. Going through various RC forums such as RCgroups, RCuniverse and RCindia we were not only able to trace out the solutions most of our technical and experimental errors but also avoid the mistakes made by others.

A. Tuning the Flight Control Board for a Stable Flight

The KK2.1 board by Hobby King is equipped with advanced controls which can tweak by the user to affect the flight parameters to obtain a stable flight. The parameters vary from one quadcopter to another. The user must adjust these parameters by trial and error method to identify which settings work best for the quadcopter. Let us detail some of the flight control board parameters and settings for easy setup of the flight control board. KK2.1 Board PI Tuning-tuning is the most important part of getting the quadcopter to fly right. Without tuning, the quadcopter is very hard to control. PI tuning is accomplished on this board by setting gain variables used by the firmware loaded on the board. The gain variables are set through the LCD menu system on the board. Correctly setting these variables helps the quadcopter fly much better. The creator of the Hobby King KK2.1 flight control board Rolf Bakke aka Kaptein KUK gives very specific directions on setting the gain variables to do PI tuning. Our team followed his directions to tune the quadcopter.

a. P Gain

The P gain stands for Proportional. This is the gain that applies to how much we are out-of level.

- If we are level, then each motor is driven with the current throttle position (T).
- If we are 1 degree out of level, then each motor is driven with T + (P * 1).
- If we are 2 degrees out of level, then each motor is driven with T + (P * 2).

b. When the P Gain is too LOW?

- If the P gain is way too low, then we simply will not be increasing the thrust enough to level the quadcopter back. It will want to flip over.
- If the P gain is slightly too low, then it will be controllable, but drift excessively. It will take a longer time to get back to level.

c. When the P Gain is too HIGH?

- If the P gain is too high, the quadcopter will wobble (oscillate) because it will compensate too much when going out of level and overshoot, meaning it will go back to level quickly, but then continue and get back out of level the other way, and so on. It is important that the P gain is not too high when trying to fly level, but also when the stick inputs change, when there are gusts of wind or when it is coming down vertically, in the turbulence of the propellers. If the P gain is just a bit on the high side, it will be rock solid flying level, but then it gets out of control when you try any aggressive maneuver.

B. What is I Gain?

I gain stands for Integral, which is a fancy way of saying "over time". This is the gain that applies to how long we are out-of level.

- If we are level, then each motor is driven with the current throttle position (T).
- If we are 1 degree out of level, then each motor is driven with T + (P * 1).
- If we are 1 degree out of level for 0.5 second, then each motor is driven with T + (P * 1) + (I * 0.5).
- If you hold your quadcopter in your hands and tilt it, the corresponding motor should spin up. This is the P gain. If you hold it there and the motor speed keeps increasing, this is I gain's contribution.
- Note that how I gain is implemented can vary, but the effect described here is valid nonetheless.

a. When I Gain is too LOW?

If I gain is way too low (or 0), then the quadcopter may not be able to get back to level and drift if an external force (like wind) is applied, which is not a major problem and thus we should start tweaking the gains with I set to 0.

b. When I Gain is too HIGH?

If I gain is too high, the effects are similar to having the P gain to high, but even more dramatic. The quadcopter will wobble (oscillate) because it will compensate too much when going out of level and overshoot, meaning it will go back to level quickly, but then continue and get back out of level the other way, and so on. The effect will be more dramatic because I gain applies over time, so it will take longer to realize it is past level and reduce (and reverse, by then) its effect. If the I gain is just a bit on the high side, your quadcopter will be stable, but you'll notice that if you try to move in one direction (forward hopefully) for some time it will tend to gradually level off and automatically pitch back when you center the controls. While stable, this will make it more difficult to precisely control the final position of your quadcopter when you stop.

C. What is the D gain?

Some controllers may have an additional D gain. It is not extremely useful for quadcopters (the mathematical proof of this is outside the scope of this article), but may be present in some controllers. The D gain stands for Derivative, which is a fancy way of saying "over speed". This gain works differently than the previous two in that it will work against them to prevent the problems (oscillations) that occur if they (the P and the I gains) are too high, while still keeping the benefits of their high values: stability and speedy recovery. This can be seen as a damping factor.

- If we are level, then each motor is driven with the current throttle position (T).
- If we are 1 degree out of level, then each motor is driven with T + (P * 1).
- If we are 1 degree out of level for 0.5 second, then each motor is driven with T + (P * 1) + (I * 0.5).
- If we are 1 degree out of level for 0.5 second but in the process of getting back to level at a speed of 2 degrees per second, then each motor is driven with T + (P * 1) + (I * 0.5) - (D * 2).

In simple words if you are out of level, the P and I gains kick in to bring it back. As you quadcopter start moving back to level (but not there yet), the D gain will turn down the throttle to partially cancel out the P and I gains' effect so that it doesn't overshoot and start wobbling.

D. PI Gain Defaults

The default PI gain values that came on ourboard loaded with version 1.5 firmware were set as follows:

“Roll/Pitch P-gain: 50

Roll/Pitch I-gain: 25

Yaw P-gain: 50

Yaw I-gain: 50

Before starting the tuning process, Set the gains and limits to the following values:

Roll/Pitch P-gain: 30 (For a small 25cm size set to 20)

Roll/Pitch P-limit: 100

Roll/Pitch I-gain: 0

Roll/Pitch I-limit: 20

Yaw P-gain: 50

Yaw P-limit: 20

Yaw I-gain: 0

Yaw I-limit: 10"

So, according to his instructions, we went into the first menu item called "PI Editor" and changed all of the variables to the values above. We did not change any of the limit values during the tuning process [4].

a. Roll and Pitch Tuning

The right and left roll angle of the quadcopter is controlled by the radio's aileron stick movement. This is done by moving the right stick on my Mode 2 radio right and left. The forward and back angle of the quadcopter is controlled by the radio's elevator stick movement. This is done by moving the right stick up and down. By default the KK2.1 links the tuning for roll and pitch together and I left it that way for my quad.

1. Roll/Pitch P Gain Tuning

Increase Roll/Pitch P-gain by 10 (5 or less for a small aircraft) at a time, and test your aircraft response by hovering and move the left stick in short and fast movements. As increase in the gain the following observation are made:

- The aircraft reacts faster and feels more connected to the stick movement and wander less on its own.
- The aircraft may oscillate for a short time. Usually a few oscillations, but may be more if gain is high. If it oscillates continually the gain is too high.
- The aircraft may be harder to land, it bounces back when touching down.
- The aircraft may climb.

When the aircraft has a good response and does not oscillate or climb when testing, P-gain is good. When the "left stick" is above, he is using a Mode 1 radio, where the roll and pitch are set up on the left stick. We use a Mode 2 radio where the pitch and roll are on the right side, since we moved the P gain value up by 10 it became more responsive. When we got the P value up to 80 the quad was much more responsive to the stick movement which was considerable.

2. Roll/Pitch I Gain Tuning

- Trim it level.
- Fly fast forward and center the stick.

If it levels itself, increase I-gain. , If it stays in attitude, I-gain is good.

Alternatively setting I gain to 50-100% of P-gain does the trick.

Here, we started with an I gain of 40 which was 50% of the 80 we chose for the P gain. When we got to 60, we noticed it would hold the angle we set by moving the right stick from side to side or forward and back.

b. Yaw Tuning

The rotation of quadcopter is controlled by the radio's rudder stick movement. The rudder is controlled by moving the left stick on my Mode 2 radio right and left.

1. Yaw P Gain Tuning

Increase Yaw P-gain by 10 (5 or less for a small aircraft) at a time, and test your aircraft response by hovering and move the Yaw control stick until it have yawed about a quarter of a circle, and then center it. As increase in the gain the following observation are made:

- The aircraft start and stops faster.
- The aircraft overshoots less.
- The aircraft may start to climb or descend.

When the aircraft has a good response, has a minimum of overshoot and does not climb or descend, P-gain is good.

Alternatively, set it to 100% of Roll/Pitch P-gain". Hence we have set the P gain to 60 which caused the aircraft to stay level while yawing.

2. *Yaw I Gain Tuning*

"Increase Yaw I-gain by 10 (5 or less for a small aircraft) at a time, do the same test as above. When the aircraft overshoots even less, I-gain is good. Alternatively, set it to 100% of Yaw P-gain.

If you have a small and not dangerous aircraft, you can disturb it around the yaw-axis and see if it returns. Increase if not. It is generally good to keep the gain values in the low range. Excessive gain may introduce vibration and control issues." We also set the yaw I gain to 60 to match the P gain.

Self-Leveling in KK2.1 Board

First thing about self-level in quadcopters is to choose how to activate and deactivate it. This is available in mode settings, self-level. Choose "AUX" or "STICK". Choosing "AUX" will let you activate and deactivate self-level just by using a switch. In our quadcopter we use the channel 5 in flight control board to activate and deactivate self-level either during the flight or before the flight. If you choose "STICK", you turn on the self-level mode by holding the aileron to the right while arming or disarming it. Turn it off by pushing the aileron to the left while arming or disarming it. This is usually not advisable since it is not possible to turn on or off self-level when the quadcopter is in the air. But choosing "AUX" gives you the flexibility to activate or deactivate self-level at any point of time.

Fig 1.1: KK2.1 Board Mode Settings to Choose Self-Level Activation Method

Fig 1.2: Self-Level Settings Menu in KK2.1 Board

P gain in self-level settings must not be set too high or too low. The correct P gain settings will be achieved by train and error. P limit refers to how much control you want in your hands of the quadcopter. Higher the value, the more control the controller gets over the quadcopter and vice versa."ACC Trim Roll" and "ACC Trim Pitch" refers to trimming the values to roll and pitch of the quadcopter in self-level mode. If the quadcopter is pitching in the front in self-level mode, then "ACC Trim Pitch" value had to be adjusted to reduce that effect. The same concept applies to "ACC Trim Roll" also. These values vary from one quadcopter to another and one can attain proper values only by trial and error method [6]. The tunings are shown in the table 1.1.

Table 1.1: Experimental Readings for Attaining Stable Flight

Trial No.	P Gain	P Limit	Acc. Roll	Acc. Pitch	Observations
1.	100	20	0	0	Quadcopter pitching forward, relatively stable enough.
2.	100	20	0	0	Pitching forward, set ELE to +2
3.	100	20	0	0	Pitching forward, set ELE to +4
4.	100	20	0	0	Pitching forward, set ELE to +7
5.	100	20	0	0	Pitching backward, set ELE to +6
6.	100	20	0	5	Pitching forward and towards the right.
7.	100	20	0	6	Pitching forward and towards the right.

8.	100	20	0	7	Pitching forward
9.	100	20	0	9	Pitching forward and left.
10.	100	20	0	7	Pitching forward and left.
11.	100	20	0	11	Pitching forward.
12.	100	20	0	3	Pitching left.
13.	100	20	3	3	Pitching forward intensely.
14.	100	20	0	1	Forward pitching reduced relatively.
15.	100	20	-7	-7	Slightly pitching forward. Much more stable.
16.	100	20	-7	-15	Pitching forward and towards the left.
17.	100	20	-7	7	Barely pitching forward. Very stable.
18.	100	20	-8	7	Unstable.
19.	100	20	-7	7	Quadcopter stable. When pitch adjusted to backwards excessively.
20.	100	20	-7	7	Elevator set to +13. Lifts vertically after initial adjustments.
21.	80	30	-7	7	Going backwards. Extremely sensitive.
22.	100	35	-7	7	Very stable. Very good controls.
23.	100	35	-7	7	Continued stable flight.

After tuning the quadcopter KK2.1 board to the above settings, the quadcopter was much easier to control than it was during the first flight. Hence, quadcopter tuning is very important to attain stable flight. It is advisable for first time fliers to leave the other settings in the flight control board untouched. The main setting and tuning of the quadcopter revolves around the above explained points.

II. EXPERIMENTS PERFORMED ON QUADCOPTER

With respect to the various mechanical aspects a series of experiments were conducted on the quadcopter to understand the actual performance by varying certain parameters. The various experiments performed on the quadcopter are as follows,

A. Propeller Size and Pitch

- Propellers are classified by length and pitch. For example 9×4.7 propellers are 9 inch long and has a pitch of 4.7.
- Generally, increased propeller pitch and length will draw more current. Also the pitch can be defined as the travel distance of one single propeller rotation. In a nutshell, higher pitch means slower rotation, but will increase your vehicle speed which also use more power.
- When deciding on length and pitch, you need to find a good balance. Generally a propeller with low pitch numbers can generate more torque. The motors don't need to work as hard so it pulls less current with this type of propeller. If you want to do acrobatics, you will need torque propellers which provide more acceleration and it puts less pressure on the power system. Lower pitch propellers will also improve stability.
- A higher pitch propeller moves greater amount of air, which could create turbulence and cause the aircraft to wobble during hovering. If you notice this with your quadcopter, try to choosing a lower pitched propeller.
- When it comes to the length, propeller efficiency is closely related to the contact area of a propeller with air, so a small increase in propeller length will increase the propeller efficiency. A smaller propeller is easier to stop or speed up while a larger

propeller takes longer to change speeds (inertia of movement). Smaller propellers also means it draws less current, that is why hexacoptors and octocopters tend to use smaller props than quadcopter of similar size.

- For larger quadcopters that carry payloads, large propellers and low KV motors tend to work better. These have more rotational momentum, and will more easily maintain your aircraft's stability.

Table 2.1: Propeller Pitch and Size Experiment Readings

Sl No.	Propeller Size	Trial No.	Time taken to cover the following distances (in seconds)		
			100m	150m	200m
1.	12 X 4.5	1	15	21	31
		2	16	21.5	32
		3	15	23	30.5
2.	13 X 4	1	17	27	35
		2	18	26	37
		3	16	25	34
3.	13 X 10	1	10	15	22
		2	11	16	23
		3	12	17.5	23.5
4.	14 X 10	1	10.5	15	21
		2	11	15.5	22.5
		3	11.5	16	22.5

From the above table it is observed that the as the pitch of the propeller is more, when the time taken to reach the distance goes on decreasing.

The readings of the experiment are depicted in a graph as shown below. The X-axis represents distance covered by quadcopter and Y-axis represents time taken by the quadcopter to reach that distance. We can see from graph 10.1 that the variation across all the propeller sizes and pitch is a linear graph.

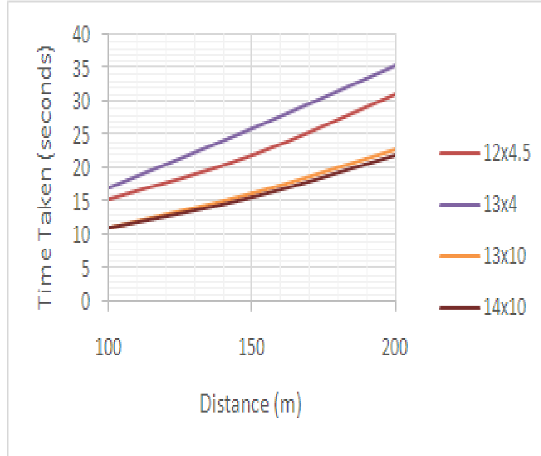

Fig 2.1: Propeller Pitch and Size Experiment (Taking Average Values)

From the above graphs it can be seen that

- Propeller of 13x4 takes more time to cover the distance when compared to other propellers.
- Though the propellers 13x10 and 14x10 have different lengths, their pitches are similar.
- The graphs of propellers 13x10 and 14x10 are almost coincide. It can be inferred that the distance travelled by the quadcopter in unit time is almost the same for these two propeller configurations.
- Propellers of larger pitch consume more power. Hence propeller of 12x4.5 was selected as it ensured maximum flight time and battery life, without compromising on the performance of the quadcopter.

It is concluded that the linear velocity of the quadcopter is solely dependent on the pitch of the propeller and not its length.

B. Minimum Thrust Requirement

This experiment is performed to check the payload carrying capacity of the quadcopter. The weight to be lifted is attached to the quadcopter. The readings for different propeller sizes is tabulated as shown below.

These calculation are done assuming a linear throttle curve graph.

Table 2.2: Minimum thrust Requirement Experimental Readings

Sl No.	Propeller	Trial No.	Thrust required to lift up 0.5 Kg	1 Kg	1.5
1.	12 X 4.5	1	82	90	98
		2	83	91	98
		3	81	91	98
2.	13 X 4	1	70	83	91
		2	68	80	90
		3	71	82	91
3.	13 X 10	1	69	80	89
		2	71	81	90
		3	71	80	89
4.	14 X 10	1	57	68	79
		2	59	71	81
		3	60	70	82

From the readings above, it can be observed that as the propeller length increases, the efficiency increases and this can be observed from the decrease in amount of throttle required to lift the quadcopter from the ground.

The readings of the experiment are depicted in a graph as shown below. The X-axis represents weight added on the quadcopter and Y-axis represents trust required to lift the quadcopter from the ground. We can see from graph 10.2 that the graph is linear.

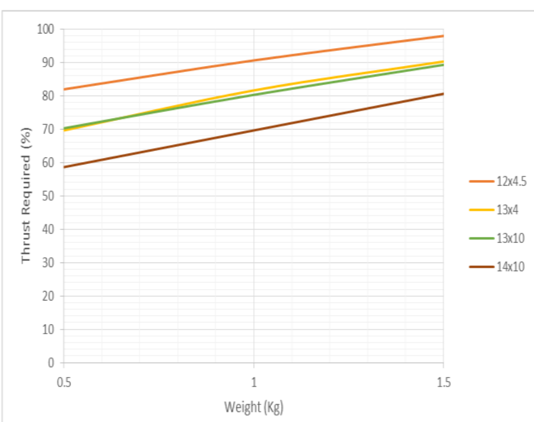

Fig 2.2: Minimum Thrust Requirement Experiment (Taking Average Values)

From the above graphs it can be concluded that

- Propeller of 12x4.5 requires the largest amount thrust to produce lift.
- Though the propellers 13x4 and 13x10 have different pitches, their lengths are similar.
- The graphs of propellers 13x4 and 13x10 are almost coincide. It can be inferred that the thrust required to lift unit weight is almost the same for these two propeller configurations.
- Propellers of larger length consume more power. Though the thrust required by propeller of 12x4.5 is more, the power consumed is comparatively less when compared to the other propellers. Hence propeller of 12x4.5 was selected as it ensured maximum flight time and battery life, without compromising on the performance of the quadcopter.

It is concluded that the thrust required for lifting the quadcopter and any payload attached to it is solely dependent on the length of the propeller and not its pitch.

C. *Conclusion Drawn by the Cumulative Result*

As the length and pitch of the propeller increases, the power requirements of the quadcopter also increase. Any person who wishes to fabricate a quadcopter must first keep in mind, its desired speed and payload capacity and then perform further calculations based on these parameters. Failure to do so may affect flight performance and also damage the quadcopter. For our experiments and applications, 12x4.5 was found to be the ideal propeller size. Propeller of 12x4.5 also bolstered good control and optimal experimental results which have been documented in the report.

III. Optimizing the Throttle Curve for Better Control

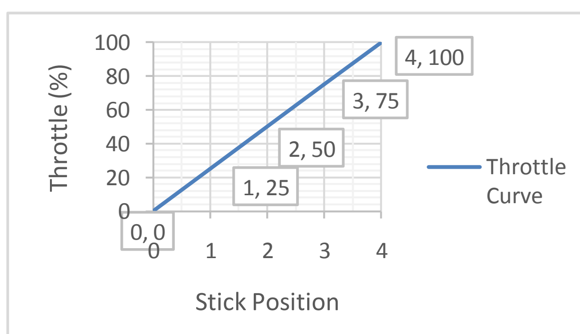

Fig 3.1: Linear Throttle Curve

- The default Throttle curve in Fly Sky T6 is as shown in the figure above.
- However this curve poses certain difficulties during take-off and landings.
- During take-off, minimum throttle being 72%, the sticks position is almost towards its end, the controller experiences problems controlling the quadcopter as limited area is available for control from threshold to full throttle.
- During landing, any value less than 72% will cause the quadcopter to fall off midflight, which may damage the components and the affect future flights. To resolve this issue the throttle curve was modified.

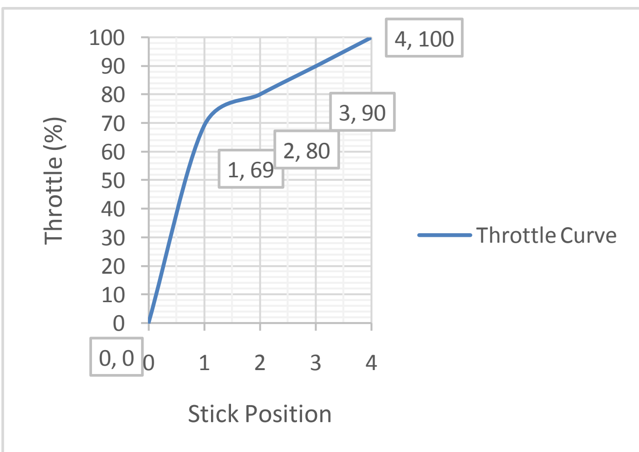

Fig 3.2: Modified Throttle Curve

Experimenting with this graph reduced the problems of controlling the quadcopter after takeoff as a large area of control was available to controller after passing the threshold frequency. However, landings were still bumpy and rough as the area of control below the threshold frequency was not sufficient.

An attempt was made to optimize the curve again, keeping in mind that an equilibrium must be maintained between the stick position and the throttle.

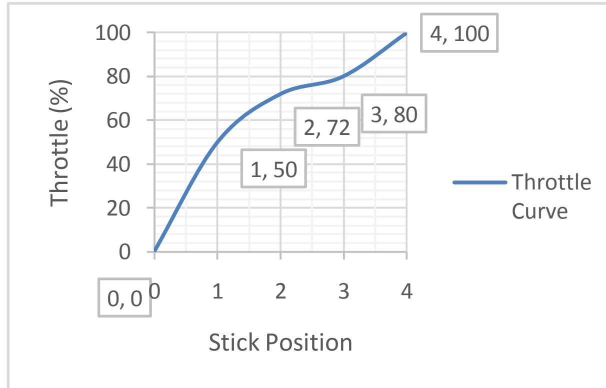

Fig 3.3: Final Throttle Curve

By choosing the throttle curve as shown above it can be concluded that

- Threshold position was set at half position of the stick and then a gradual increase was provided up to 100% thrust.
- A slightly longer, gradual decrease was provided on the other end so that smoother landings can be achieved (landings are much more important than takeoffs). Hence, the throttle curve chosen above is ideal to ensure that both the landings and takeoff of quadcopter are smooth.

IV. Conclusion

Even though building a quadcopter looks simple, in actual practice and for first timers, building a quadcopter from scratch is a long process. A lot of theoretical knowledge and through research is important before finalizing on the components to be purchased. This research will go a long way in helping you build a quadcopter which will serve your purpose and give you exactly what you need. With proper care and research all these problems can be overcome initially and can be corrected properly in order to optimize the stability of the quadcopter. The final quadcopter is as shown in the figure 4.

Fig. 4: Final Quad Copter Assembly

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