

## I. Introduction

**This experiment is to test the thrust of replacing the parts individually, analyze the improvement, and decide whether it is a good one to consider when we design a combination of the parts for maximum thrust.**

In our research about removing three propellers and motors of Crazyflie, we found the original structure cannot provide enough thrust to lift the whole body by just one propeller: we measured the total thrust of the four propellers and divided by four to get a measure of the thrust of one propeller, 19g, which is less than the weight of the divide, 27g. Hence, in order to achieve our goal still using the Crazyflie platform since it is easier to implement, we decide to modify the physical structure by replacing the original parts by new ones that might provide more thrust to the body.

For example, to test different motors, we keep the other parts (batteries, propellers, etc) unchanged, and replace only the different motors alone to test their effects on the thrust. For different parts we will focus on different properties: for motor, we will focus on measurement of thrust and weight; for batteries, we will focus on capacity and weight; for propellers, we will focus on number of blades and efficiency (speed.) As thrust is our prime focus, we will also measure flight time.

## II. Components

### 1) Components under testing

1 Motors:

1 CL-0820-15 coreless motor (speed: fast) (27\$)

<https://micro-motor-warehouse.com/collections/all-motors/products/cl-0820-15>

compatible to:

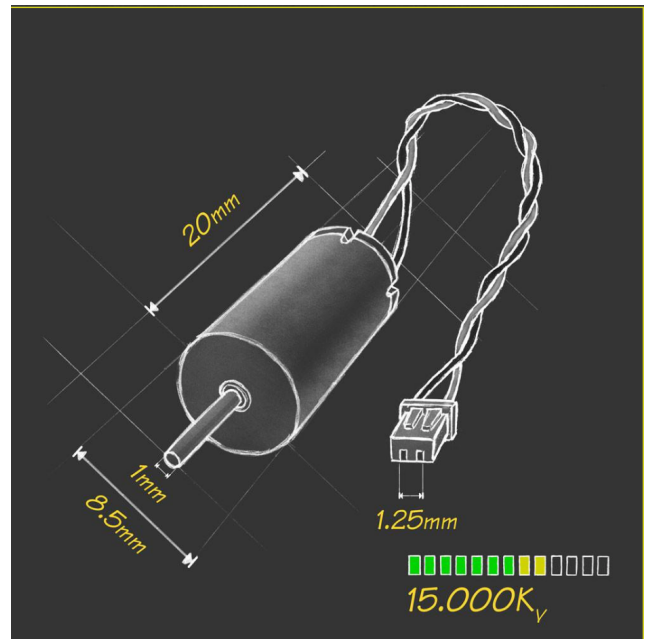
- AlienWii flight controller (plug'n'play)
- Hubsan 107C, 107D
- all other micro quads with 8.5mm motor holders

performance data:

- speed: 15.000Kv
- operating voltage: 1.5-3.7V
- max. thrust: 40g (direct drive, Hubsan X4 propeller)
- 2.75A max. load current at 3.7V (Hubsan X4 propeller)
- factory lifetime rating: 5-6 hours

dimensions:

- can diameter: 8.5mm
- can length: 20mm
- shaft diameter: 1mm
- shaft length: 5mm
- weight: 4.9g



2 CL-0720-14 coreless motor (speed: fast) (23\$)  
<https://micro-motor-warehouse.com/products/cl-0720-14>

specifications:

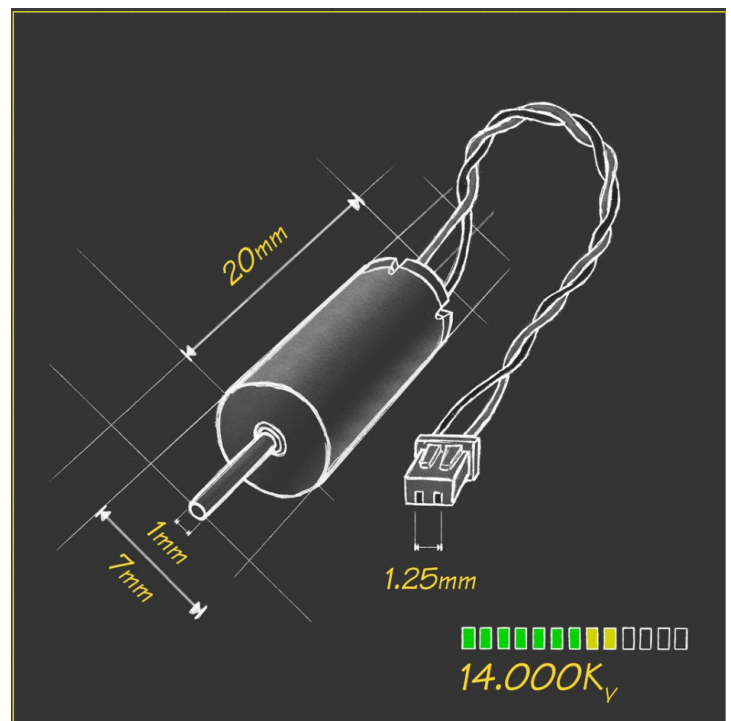
- speed: 14.000Kv
- operating voltage: 1.5-3.7V
- max. thrust: 26g (Hubsan X4 propeller)

propeller)

- 1.8A load current at 3.7V (Hubsan X4 propeller)
- lifetime rating: 5-6 hours

dimensions:

- can diameter: 7mm
- can length: 20mm
- shaft diameter: 1mm
- shaft length: 5mm
- weight: 3.4g



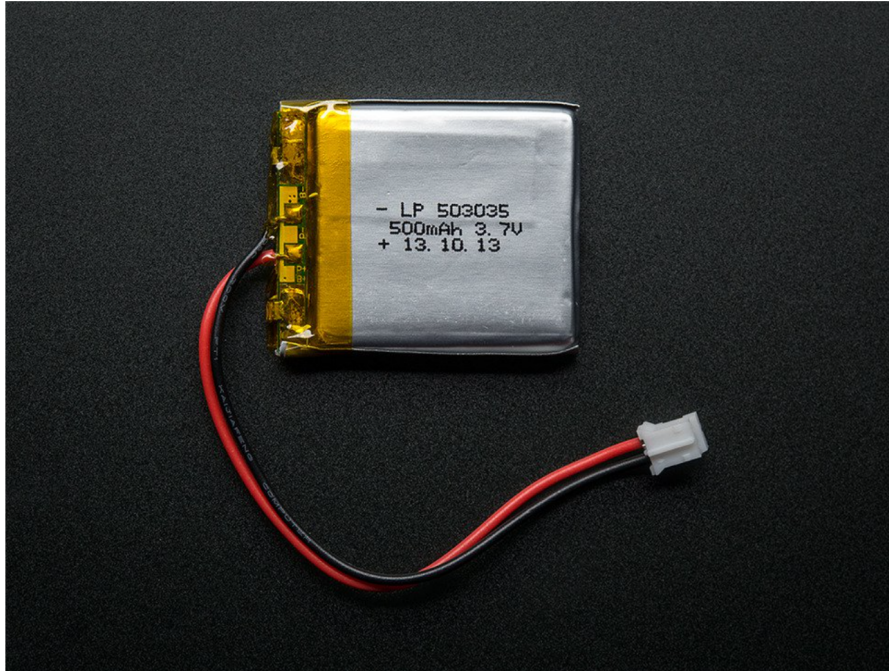
2 Batteries:

1 Lithium Ion Polymer Battery - 3.7v 500mAh (7.95\$)

<https://www.adafruit.com/product/1578>

Details:

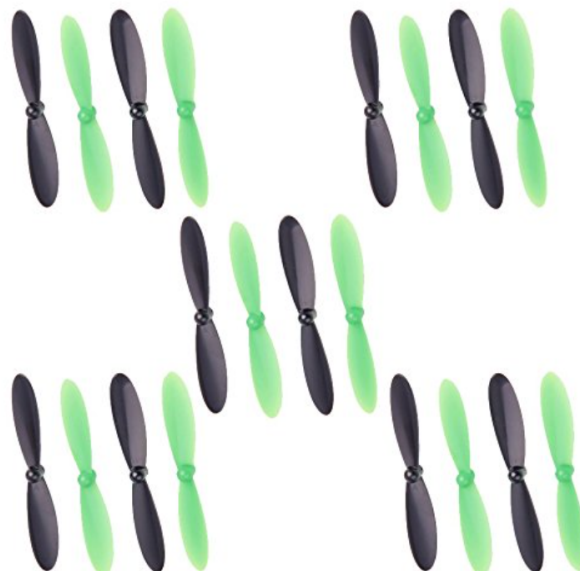
- Weight: 10.5g
- Size: 29mm x 36mm x 4.75mm / 1.15" x 1.4" x 0.19"
- Power Lead Length: 80mm / 3"
- Output: 500mAh at 3.7V nominal



3 Propellers:

1 Hubsan X4 H107C RC Quadcopter Spare Parts H107-A36 Rotor Propellers Blades Black and Green (5 Sets) (5.99\$)

<https://www.amazon.com/Hubsan-Quadcopter-H107-A36-Propellers-Blades/dp/B00M3ZANIO>



2 Hubsan X4 H107 Propeller Blades Props 5x COMBO Propellers SHIPS  
FROM USA B&W Color: Black+White Model (4.39\$)

[https://www.amazon.com/Hubsan-Propeller-Blades-Props-Propellers/dp/B00GZHI75C/ref=sr\\_1\\_3?ie=UTF8&qid=1501047198&sr=8-3&keywords=hubsan+x4+propeller](https://www.amazon.com/Hubsan-Propeller-Blades-Props-Propellers/dp/B00GZHI75C/ref=sr_1_3?ie=UTF8&qid=1501047198&sr=8-3&keywords=hubsan+x4+propeller)



3 Crazepony 16pcs 40mm Tri-blade 3 Blade Propellers for Mini FPV Racing  
Drones Multirotors Quadcopters (9.88\$)



Compatible with 7x20mm 8.5x20mm coreless motors  
Also fit with 0703 0705 etc brushless motors with 1.0mm shaft



[https://www.amazon.com/Crazepony-Tri-blade-Propellers-Multirotors-Quadcopters/dp/B0714BPGR4/ref=sr\\_1\\_4?ie=UTF8&qid=1501047397&sr=8-4&keywords=three+blade+propeller+micro](https://www.amazon.com/Crazepony-Tri-blade-Propellers-Multirotors-Quadcopters/dp/B0714BPGR4/ref=sr_1_4?ie=UTF8&qid=1501047397&sr=8-4&keywords=three+blade+propeller+micro)

## 2) Potential connection equipment

- a. 3D Printed Weights and Motor Mounts
- b. Scotch Transparent Tape
- c. Tekpower TP3003D-3 Digital Variable Triple Outputs Linear-type DC Power Supply
- d. SmartWeight Digital Pocket Scale
- e. Neiko 01409A Electronic Digital Caliper
- f. Long and Thin wire from Mechine Shop if necessary

(Links to find all of these components are attached at the end as well. )

### **Experiment setup:**

0 Using SmartWeight Digital Pocket Scale and Neiko 01409A Electronic Digital Caliper, measure the weights and dimensions of motors, batteries and propellers under testing to make sure they match with the data given in data sheet.

1 Remove the original battery and battery holder. Since we are not attaching anymore electronics to the crazyflie, it is fine to attach battery 1(Lithium Ion Polymer Battery - 3.7v 500mAh) simply by using the Scotch transparent tape.

2 Test connections between parts by performing simple flying tests including maximum thrust on all of the propellers. Before running the tasks on the Crazyflie Client, all of the LED lights on the crazyflie should light up as soon as it's connected to the laptop and switched on. As we change the forces of each motors on the Crazyflie Client software, the corresponding motor should change accordingly. If these tests failed, check the connections between battery, motors and propellers and the Crazyflie body, and the Crazyflie body to the controlling laptop; also check that the Crazyflie is fully charged by reading from the charge property from the Crazyflie Client software.

3 Glue the expansion board of the crazyflie to the selected weight using transparent tapes and measure the total weight using the scale. The weight of the object should be big enough so that it will stay on the load cell during the experiment (for reference, the thrust at 93.75% duty cycle is around 50g), but should be less than 100g, the capacity of the load cell. The weight we chose is shown in the following picture 1 and the weight is measured to be 70.32g.



Figure 1: Attached weight, 5-hour Energy, 70.32g

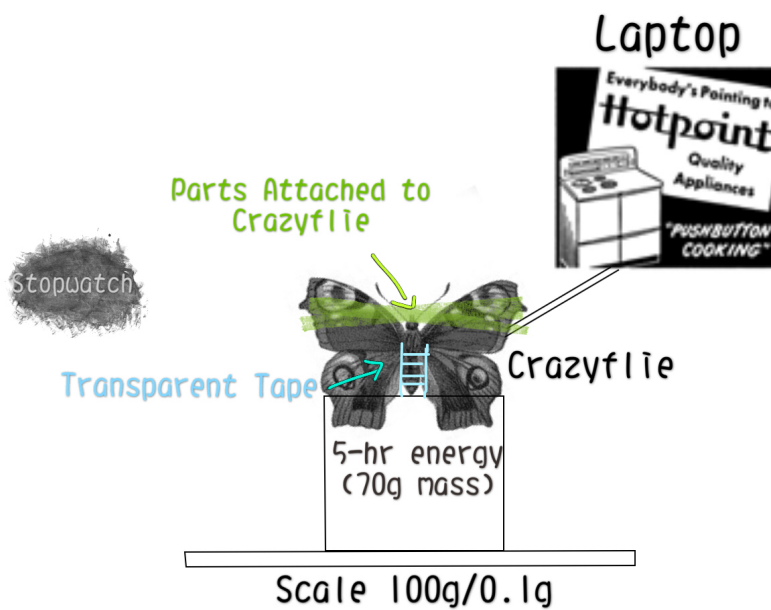


Figure 2: Picture illustrating the setup achieved in step 3

4 Adjust the PWM duty cycles by incrementing the 16-bit binary number representing the duty cycle from 0 to 65535 by steps of 256 through the crazyfly client and measure the weights read by the load cell respectively. The thrust at a specific PWM duty cycle is calculated by subtracting the weight reading at that duty cycle from the total weight of the object. In this case, the thrust is measured in units of gram force. To increase accuracy, stay for 3-4 seconds at each duty cycle, take several readings and calculate the average of these readings. In each measurement of the maximum forces on all of

the four motor, measure the lifetime of the battery: start the stopwatch when we change the parameters in the Crazyflie Client, stop the stopwatch when the Crazyflie Client shows the battery decays to 50% its full storage value. The lifetime at maximum forces is crucial to know for other steps and analysis.

5. Remove the weight attached in step 2. Remove battery 1 and plug back the original battery and battery holder, at this step the Crazyflie device is in its default position with all its original parts in its original places. Remove the four original motors by unplugging it from the connection wire, remove the original four motor mounts, and plug in the four 3D printed motor mounts (the dimensions and weight of this motor mount is shown in the following picture 2); plug in four motor 1(CL-0820-15 coreless motor) to the Crazyflie board. Keep the all the other parts unchanged.

6 Repeat steps 2-3 to perform flying tests and attach the weight.

7 Adjust the PWM duty cycles by incrementing the 16-bit binary number representing the duty cycle from 0 to 65535 by steps of 256 through the crazyflie client and measure the weights read by the load cell respectively. The thrust at a specific PWM duty cycle is calculated by subtracting the weight reading at that duty cycle from the total weight of the object. In this case, the thrust is measured in units of gram force. To increase accuracy, stay for 3-4 seconds at each duty cycle, take several readings and calculate the average of these readings. Among the above measurements of thrust, what we are interested in is the one using maximum force on all of the propellers, the other measurements are used to plot a best-fit curve to verify linear relationship between thrusts, to verify that we actually achieved maximum force (sometimes maximum is not achieved because of low power in battery of sudden change of forces.)

8 During step 7, measure the flight time of each level of forces up to four effective digits using a stopwatch: start the stopwatch when we change the parameters in the Crazyflie Client, stop the stopwatch when the Crazyflie Client shows the battery decays to 50% its full storage value. One person uses two stopwatches concurrently and take the average to ensure more accurate result. These values of flight time are used later to compare their properties.

9 In steps 7 and 8, if the motor power is too large, there might be a possibility that the original battery dies out too fast(within 1 second) for us to read the data on the scale for calculation of thrust. If this happened, unplug the original battery and attach battery 1(Lithium Ion Polymer Battery - 3.7v 500mAh) using Scotch transparent tape. Since we are testing the motors right now, battery is just a power source, which won't affect the results. Perform steps 7-8 again.

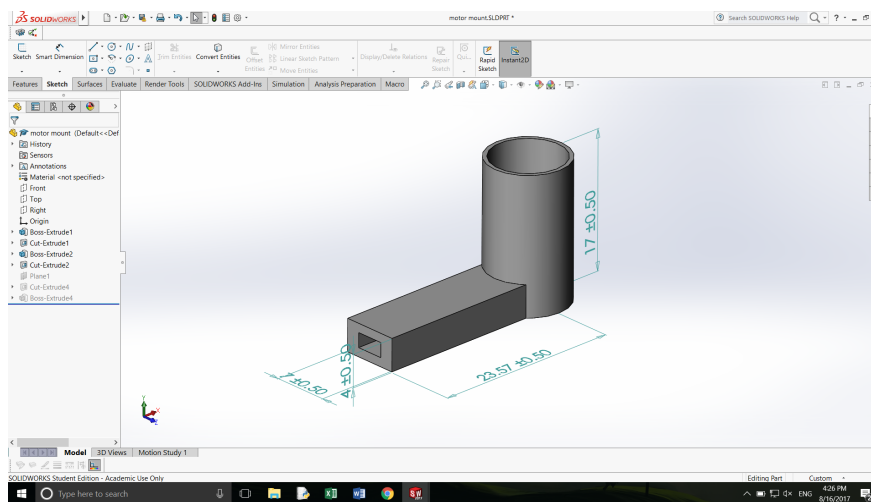
10 If battery 1(Lithium Ion Polymer Battery - 3.7v 500mAh) dies out too fast (within 2 seconds) again, unplug the original battery and connect the crazyflie board to the Tekpower TP3003D-3 Digital Variable Triple Outputs Linear-type DC Power Supply as shown in the following picture 3. To avoid additional masses produced by the alligator clips, attach the alligator clips to a long and thin wire to make sure the wire is loose, and won't add any tension onto the crazyflie body. Perform steps 7-8 again.

11 Remove the attached weight. Take off the four motor 1 and 3D printed motor mounts, reattach the four original crazyflie motor mounts, and attach four motor 2 (CL-0720-14 coreless motor.) Remove the power source(either the original battery, battery 1 or DC power source) from the crazyflie body, and reattach the original crazyflie battery. Repeat steps 6-10 for motor 2.

12 Remove the four motor 2, and reattach the default motors from the Crazyflie package. Put the original battery back, and replace the built-in propeller with propeller 1(Hubsan X4 H107C RC Quadcopter Spare Parts H107-A36 Rotor Propellers Blades Black and Green) Repeat steps 6-10 for propeller 1.

13 Repeat step 12 for propeller 2 (Hubsan X4 H107 Propeller Blades Props 5x COMBO Propellers SHIPS FROM USA B&W Color: Black+White Model) and propeller 3 (Crazepony 16pcs 40mm Tri-blade 3 Blade Propellers for Mini FPV Racing Drones Multirotors Quadcopters.)

During the experiment, make sure that the crazyflie is placed horizontally so that the thrust force is pointing up vertically. The cfclient provides real-time data of the pitch and roll angles of the crazyflie; adjust the position of it so that the pitch and roll angles are equal to or close to zero. The maximum accepted roll/pitch angles are 2 degrees; it will cause a  $1 - \cos(\pi/90) = 0.1\%$  error in measurement. This is shown in Figure 5.



**Figure 3: 3D-printed Motor Mount for Motor 1**

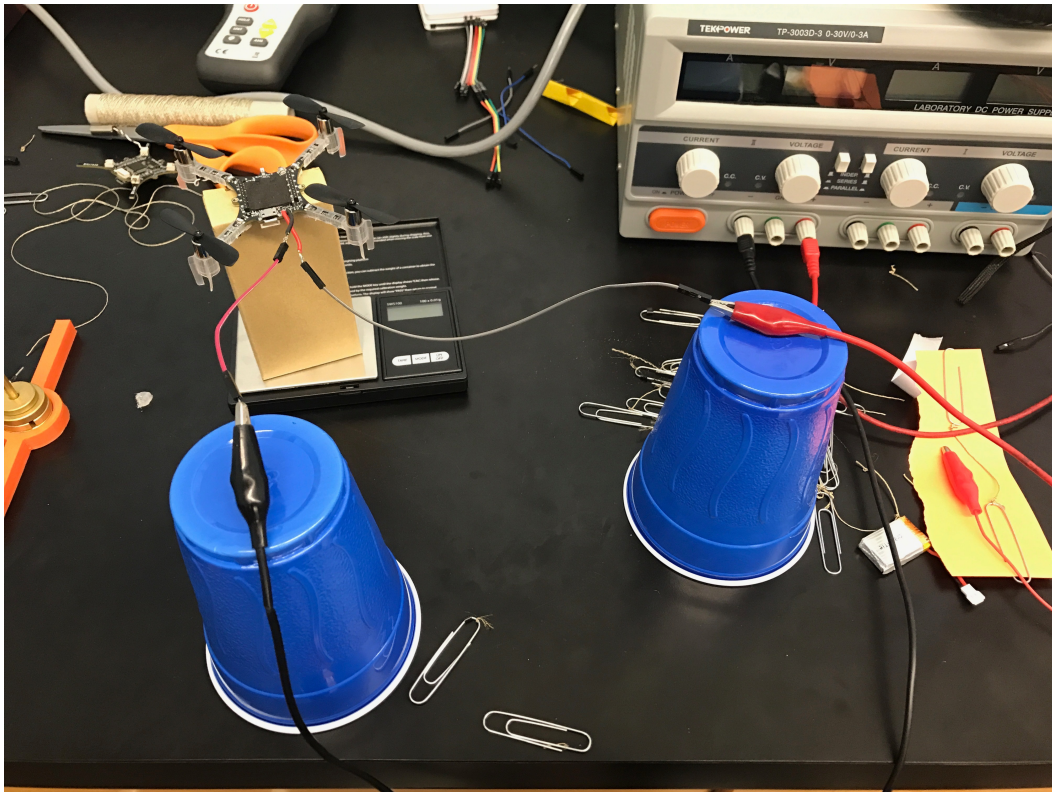


Figure 4: Setup for DC Power Source Connection

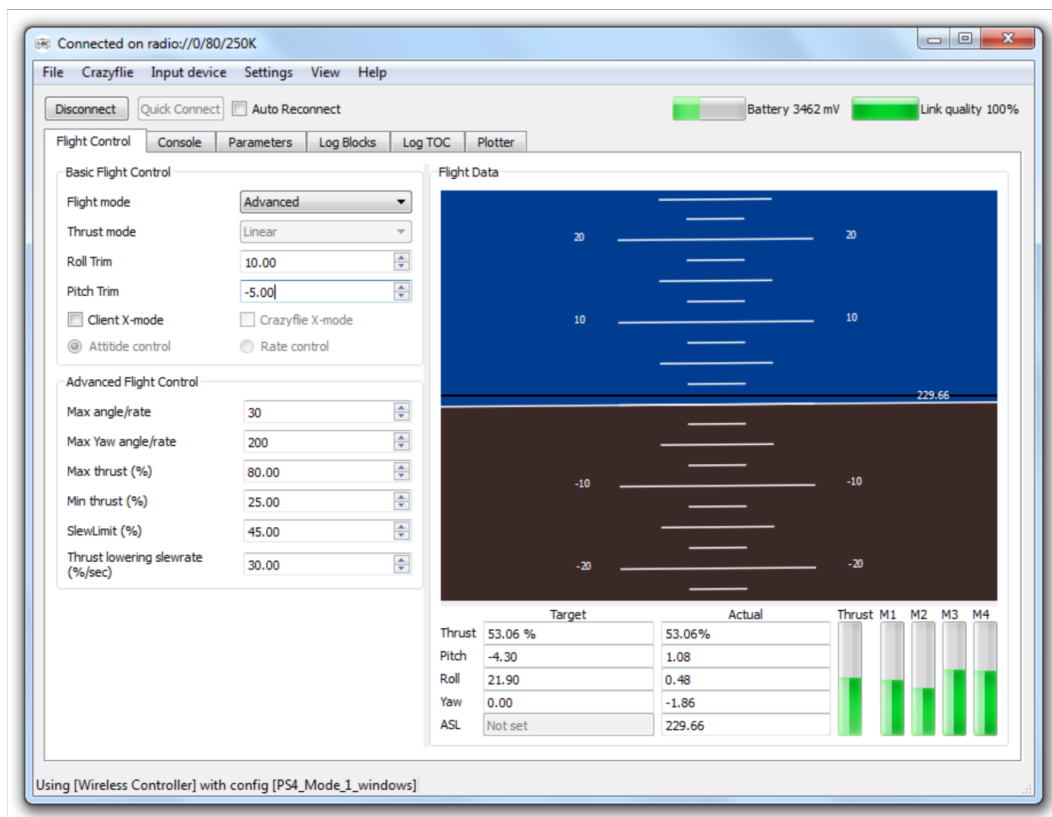


Figure 5: Crazyflie Client: Blue/Black area Shows whether the Device is Horizontal

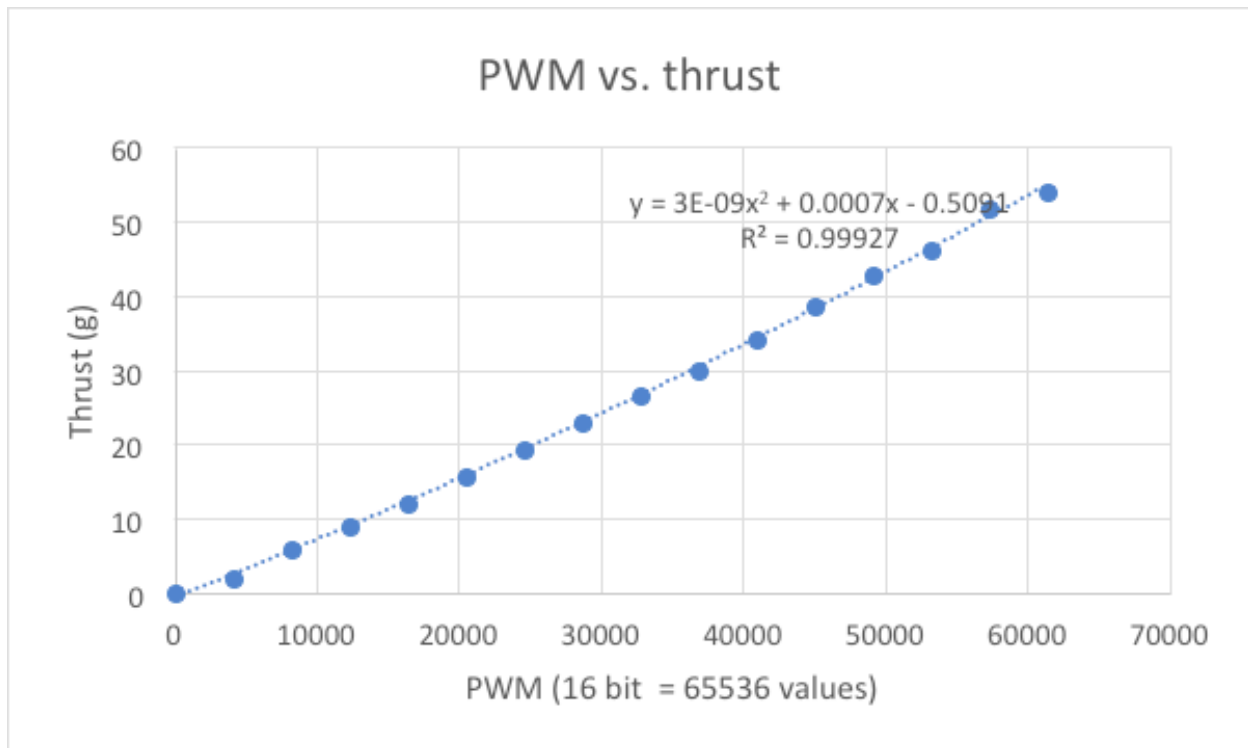
## Experimental Results and Data Analysis

Default Setting: Motor 0 Battery 0 Propeller 0

PWM Duty Cycle (%)	Thrust (automatic) (g)	Thrust (manual) (g)	Difference (%)
0		0	
6.25		2.11	
12.5		5.88	
18.75		9.11	
25		12.2	
31.25		15.84	
37.5		19.36	
43.25		23.04	
50		26.84	
56.25		30.1	
62.5		34.32	
68.75		38.82	
75		42.84	
81.25		46.34	
87.5		51.88	
93.75		54.07	

Crazyflie weight: 28.02g

Default PWM vs Thrust Graph





Experiment 1

Battery 1 Motor 0 Propeller 0

Total Weight: \_\_\_\_\_ g

PWM Duty Cycle (%)	Weight reading 1	Weight reading 2	Weight reading 3
0			
6.25			
12.5			
18.75			
25			
31.25			
37.5			
43.25			
50			
56.25			
62.5			
68.75			
75			
81.25			
87.5			
93.75			

Flight Time Measurement as 50% decay of total battery charge

PWM Duty Cycle (%)	Start 1 (s)	Stop 1 (s)	Flight Time 1 (s)	Start 2 (s)	Stop 2 (s)	Flight Time 2 (s)
0						
6.25						
12.5						
18.75						
25						
31.25						
37.5						
43.25						
50						
56.25						
62.5						
68.75						
75						
81.25						
87.5						
93.75						

Experiment 2

Motor 1 Battery 0 Propeller 0

Total Weight: \_\_\_\_\_ g

PWM Duty Cycle (%)	Weight reading 1	Weight reading 2	Weight reading 3
0			
6.25			
12.5			
18.75			
25			
31.25			
37.5			
43.25			
50			
56.25			
62.5			
68.75			
75			
81.25			
87.5			
93.75			

PWM Duty Cycle (%)	Start 1 (s)	Stop 1 (s)	Flight Time 1 (s)	Start 2 (s)	Stop 2 (s)	Flight Time 2 (s)
0						
6.25						
12.5						
18.75						
25						
31.25						
37.5						
43.25						
50						
56.25						
62.5						
68.75						
75						
81.25						
87.5						
93.75						

Experiment 2.1

Motor 1 Battery 1 Propeller 0 (if applicable)

This is only measured if the default battery of Crazyflie is not enough for motor 1.

Total Weight: \_\_\_\_\_ g

PWM Duty Cycle (%)	Weight reading 1	Weight reading 2	Weight reading 3
0			
6.25			
12.5			
18.75			
25			
31.25			
37.5			
43.25			
50			
56.25			
62.5			
68.75			
75			
81.25			
87.5			
93.75			

PWM Duty Cycle (%)	Start 1 (s)	Stop 1 (s)	Flight Time 1 (s)	Start 2 (s)	Stop 2 (s)	Flight Time 2 (s)
0						
6.25						
12.5						
18.75						
25						
31.25						
37.5						
43.25						
50						
56.25						
62.5						
68.75						
75						
81.25						
87.5						
93.75						



Experiment 3

Motor 2 Battery 0 Propeller 0

Total Weight: \_\_\_\_\_ g

PWM Duty Cycle (%)	Weight reading 1	Weight reading 2	Weight reading 3
0			
6.25			
12.5			
18.75			
25			
31.25			
37.5			
43.25			
50			
56.25			
62.5			
68.75			
75			
81.25			
87.5			
93.75			

PWM Duty Cycle (%)	Start 1 (s)	Stop 1 (s)	Flight Time 1 (s)	Start 2 (s)	Stop 2 (s)	Flight Time 2 (s)
0						
6.25						
12.5						
18.75						
25						
31.25						
37.5						
43.25						
50						
56.25						
62.5						
68.75						
75						
81.25						
87.5						
93.75						

Experiment 3.1

Motor 2 Battery 1 Propeller 0 (if applicable)

This is only measured if the default battery of Crazyflie is not enough for motor 1.

Total Weight: \_\_\_\_\_ g

PWM Duty Cycle (%)	Weight reading 1	Weight reading 2	Weight reading 3
0			
6.25			
12.5			
18.75			
25			
31.25			
37.5			
43.25			
50			
56.25			
62.5			
68.75			
75			
81.25			
87.5			
93.75			

PWM Duty Cycle (%)	Start 1 (s)	Stop 1 (s)	Flight Time 1 (s)	Start 2 (s)	Stop 2 (s)	Flight Time 2 (s)
0						
6.25						
12.5						
18.75						
25						
31.25						
37.5						
43.25						
50						
56.25						
62.5						
68.75						
75						
81.25						
87.5						
93.75						

Experiment 4

Propeller 1 Motor 0 Battery 0

Total Weight: \_\_\_\_\_ g

PWM Duty Cycle (%)	Weight reading 1	Weight reading 2	Weight reading 3
0			
6.25			
12.5			
18.75			
25			
31.25			
37.5			
43.25			
50			
56.25			
62.5			
68.75			
75			
81.25			
87.5			
93.75			

PWM Duty Cycle (%)	Start 1 (s)	Stop 1 (s)	Flight Time 1 (s)	Start 2 (s)	Stop 2 (s)	Flight Time 2 (s)
0						
6.25						
12.5						
18.75						
25						
31.25						
37.5						
43.25						
50						
56.25						
62.5						
68.75						
75						
81.25						
87.5						
93.75						



Experiment 5

Propeller 2 Motor 0 Battery 0

Total Weight: \_\_\_\_\_ g

PWM Duty Cycle (%)	Weight reading 1	Weight reading 2	Weight reading 3
0			
6.25			
12.5			
18.75			
25			
31.25			
37.5			
43.25			
50			
56.25			
62.5			
68.75			
75			
81.25			
87.5			
93.75			

PWM Duty Cycle (%)	Start 1 (s)	Stop 1 (s)	Flight Time 1 (s)	Start 2 (s)	Stop 2 (s)	Flight Time 2 (s)
0						
6.25						
12.5						
18.75						
25						
31.25						
37.5						
43.25						
50						
56.25						
62.5						
68.75						
75						
81.25						
87.5						
93.75						

Experiment 6

Propeller 3 Motor 0 Battery 0

Total Weight: \_\_\_\_\_ g

PWM Duty Cycle (%)	Weight reading 1	Weight reading 2	Weight reading 3
0			
6.25			
12.5			
18.75			
25			
31.25			
37.5			
43.25			
50			
56.25			
62.5			
68.75			
75			
81.25			
87.5			
93.75			

PWM Duty Cycle (%)	Start 1 (s)	Stop 1 (s)	Flight Time 1 (s)	Start 2 (s)	Stop 2 (s)	Flight Time 2 (s)
0						
6.25						
12.5						
18.75						
25						
31.25						
37.5						
43.25						
50						
56.25						
62.5						
68.75						
75						
81.25						
87.5						
93.75						



PWM Duty cycle vs. thrust graph for each components:

Potential problems and sources of error:

- 1) Bad connection of wires and laptop

To fix this, make sure to check the connections between crazyflie and laptop and the connecting wires,

- 2) Crazyflie body not horizontal

This problem can be detected on the screen of the crazyflie client when the black and blue region is not even as shown in Figure 4, if this happens, make sure to realign the crazyflie body so that the crazyflie client shows it's horizontal.

To fix this problem, tilt the Crazyflie body to different angles to finally make the Crazyflie Client displays that the boundary of the black and blue region is a horizontal line (as accurate as possible.)

- 3) Relative movement between crazyflie and weight

To fix this, consider another way of connecting the parts besides transparent tape. Possible solutions include hot glue, and creating a molding that fit the crazyflie body perfectly and then glue.

- 4) Maximum forces cause battery to discharge too quickly

To fix this, connecting to the DC power source is a good solution.

- 5) Calibration problems

Make sure to calibrate multiple times before starting the experiment.

## Reference

Dual Motor Modification:

[https://wiki.bitcraze.io/misc:hacks:dual\\_motors](https://wiki.bitcraze.io/misc:hacks:dual_motors)

<https://forum.bitcraze.io/viewtopic.php?f=6&t=348&hilit=motors>

Motor Upgrade:

<https://forum.bitcraze.io/viewtopic.php?f=11&t=1782&p=9089&hilit=upgrade+motor#p9089>

<https://forum.bitcraze.io/viewtopic.php?f=6&t=871&p=5014&hilit=upgrade+motor#p5014>

<http://frankpiesik.org/2014/06/01/crazy-experiments/>

Motors to purchase:

<https://micro-motor-warehouse.com/collections/all-motors/products/cl-0820-15>

<https://micro-motor-warehouse.com/products/cl-0720-14>

Batteries to purchase:

<https://www.adafruit.com/product/1578>

Propellers to purchase:

<https://www.amazon.com/Hubsan-Quadcopter-H107-A36-Propellers-Blades/dp/B00M3ZANIO>

[https://www.amazon.com/Hubsan-Propeller-Blades-Props-Propellers/dp/B00GZHI75C/ref=sr\\_1\\_3?ie=UTF8&qid=1501047198&sr=8-3&keywords=hubsan+x4+propeller](https://www.amazon.com/Hubsan-Propeller-Blades-Props-Propellers/dp/B00GZHI75C/ref=sr_1_3?ie=UTF8&qid=1501047198&sr=8-3&keywords=hubsan+x4+propeller)

[https://www.amazon.com/Crazepony-Tri-blade-Propellers-Multirotors-Quadcopters/dp/B0714BPGR4/ref=sr\\_1\\_4?ie=UTF8&qid=1501047397&sr=8-4&keywords=three+blade+propeller+micro](https://www.amazon.com/Crazepony-Tri-blade-Propellers-Multirotors-Quadcopters/dp/B0714BPGR4/ref=sr_1_4?ie=UTF8&qid=1501047397&sr=8-4&keywords=three+blade+propeller+micro)

Weight to attach:

[https://www.amazon.com/Hour-Energy-Drink-Berry-1-93/dp/B00MX5AWT4/ref=sr\\_1\\_8\\_a\\_f\\_it?ie=UTF8&qid=1503353133&sr=8-8&ppw=fresh&keywords=5+hour+energy+drink+berry](https://www.amazon.com/Hour-Energy-Drink-Berry-1-93/dp/B00MX5AWT4/ref=sr_1_8_a_f_it?ie=UTF8&qid=1503353133&sr=8-8&ppw=fresh&keywords=5+hour+energy+drink+berry)  
1.8\$