AALBORG UNIVERSITY

STUDENT REPORT

ED5-3-E16

XXX

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AALBORG UNIVERSITY
STUDENT REPORT

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Preface

The project entitled *xxx* was made by two students from the Electronics and Computer Engineering programme at Aalborg University Esbjerg, for the P5 project during the fifth semester.

From hereby on, every mention of 'we' refers to the two co-authors listed below.

Aalborg University, November 17, 2016.

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Chapter 1

Introduction

1.1 Introduction

The theme of this semester's project lies within *Automation*. Automation can be simply described as being the use of diverse control systems for fulfilling a certain task with little to no human interaction. As known from the previous semester, a control system is an instrument which has the role of adapting the behaviour of a system according to a desired state, also knows as steady-steady or reference. Any control system has three components: measurement, control and actuation. Without one of these, automation would not be possible. Essentially, the measure reflects the current state of the system, the controller is the brain that given the measurement decides which action will be performed and the actuator is the one executing the action.

Project ideas around the topic of automation are unlimited, since it is so widely spread. Having discussed a few of them that would meet the semester's requirements, we finally decided to work on the control of a quadcopter. Our decision was, for the most part, based on the fact that the university had the required equipment available, which enabled us to start working on the project right away.

UAVs have been attracting attention for many decades now. Powered UAVs were, at first, utilized by the military to execute reconnaissance missions. Nowadays, they have found other uses, such as aerial photography, search and rescue, delivery, geographic mapping and more. While there are different types of UAVs, our focus is on the multirotors. Multirotor can be defined as a rotorcraft with more than two motors. Based on this, the four most common types are tricopter, quadcopter, hexecopter and octocopter, each having 3, 4, 6 and 8 motors respectively. Each type of multirotor has its ups and downs - more motors mean higher liftforce and more reliable stability, but they also increase both price and damage caused in case of an error. Due to their price, size and ease of setup, quadcopters are the most popular type. They are popularly referred to as drones. Our goal for the project is to design a control system that makes it possible for the quadcopter to be stable - hovering mid-air - and to also act according to the user's input - maneuvering. Basically, our input will be a certain height and the quadcopter will have to automatically adjust to that height and maintain its stability when no further inputs are given. A safety feature - obstacle avoidance - will also be implemented.

Chapter 2

Problem Description

Quadcopter control is a complex, yet interesting problem. One of the reasons why this control problem is challenging is the fact that a quadcopter has six degrees of freedom, but only four inputs which affects the linearity of the dynamics and makes the quadcopter underactuated. One other important thing to mention is that quadcopters, unlike ground vehicles, have very little friction that prevents their motion, so they have to provide their own damping in order to be able to stop or maintain stability.

This chapter will give a general overview on the pieces of technical equipment which we are using and show what the purpose of each one is. It will also present how our scopes - hovering and maneuvering - can be achieved by designing and implementing a control system. A solution in terms of the structure of our control system will be identified. We will also delve into the basic working principle of a quadcopter/flight dynamics.

2.1 Physical Setup

2.1.1 Motors

Controlling a quadcopter can be done efficiently by using high-quality motors with fast response, which will ensure more of a stable flight. The motors must also be powerful enough to be able to lift the quadcopter and perform the required aerial movements.

The motor that we are using is the Turnigy Multistar Brushless Motor seen in Figure 2.1.

Figure 2.1: Turnigy Multistar 2213-980 V2 Brushless Motor

2.1.2 Propellers

The propellers don't have such strict requirements as the motors. They are needed to be light and have a size and lift potential in order for the quadcopter to hover at less than 50% of the motor capacity. For our quadcopter, we are using plasting 10x4.5" propellers with light weight - 60g. They have a length of 254 mm and a pitch inclination of 114mm. They can be seen in Figure 2.2.

Figure 2.2: Hobbyking Slowfly Propeller 10x4.5

2.1.3 Electric Speed Controller

Electronic Speed Controller (ESC) is a widely used device in rotorcrafts. The purpose of an ESC is to vary the electric motor's speed. They also come with programmable features, such as braking or selecting appropriate type of battery. We need the ESC to have a fast response, for the same reasons mentioned for the motors in Section 2.1.1. The ESC that we are using is the TURNIGY Plush 30A which is shown in Figure 2.3.

Figure 2.3: TURNIGY Plush 30A Speed Controller

2.1.4 APM Flight Controller

ArduPilotMega (APM) is an open source unmanned aerial vehicle (UAV) platform which is able to control autonomous multicopters. It is illustrated in Figure 2.4. The system was improved uses Inertial Measurement Unit (IMU) - a combination of accelerometers, gyroscopes and magnetometers. The "Ardu" part of the project name shows that the programming can be done using Arduino open-source language.

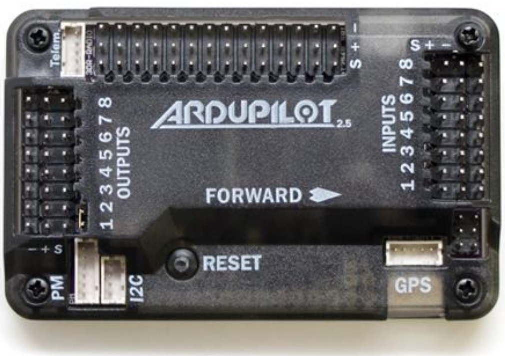

Figure 2.4: APM 2.5 board

2.1.5 Power Distribution Board

To reduce the number of connections straight to the battery, we used the a power distribution board made for a previous project. A board like this is an easy solution since it enables us to connect the four ESCs directly to the board and then connect the board to the battery.

2.1.6 Battery

To power up our quadcopter, we will use a TURNIGY nano-tech Lipoly battery, which can be seen in Figure 2.5. Higher voltage under load, straighter discharge curves and excellent performance are the factors that make it suitable for our project.

Figure 2.5: Turnigy nano-tech 6000mah 3S 25 50C Lipo Pack

2.2 Flight Dynamics

In order to put a working quadcopter together, it is important to understand the basic flight dynamics - the forces affecting the vehicle as well as the motors' speed effect. There are 4 main forces affecting quadcopter - or any airborne vehicle, for that matter - thrust, lift, draw and drop. See figure 2.6.

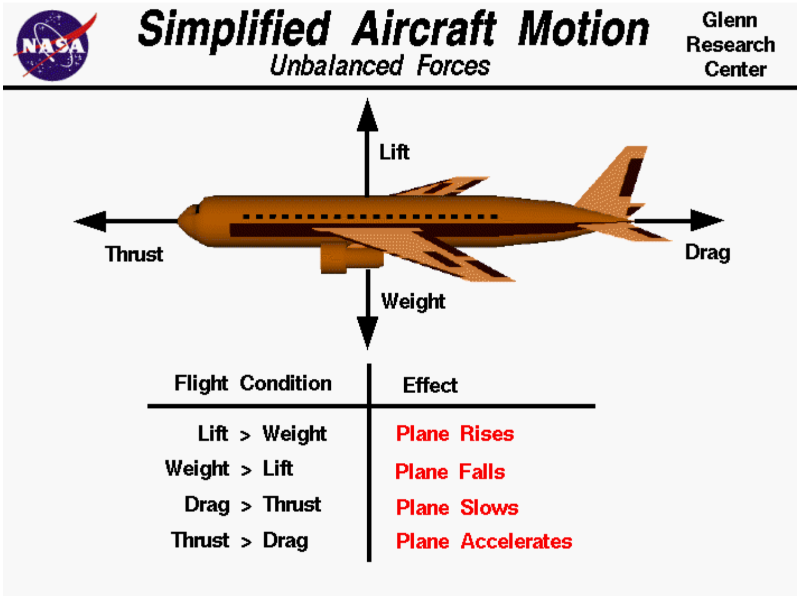

Figure 2.6: Forces affecting an airborne vehicle [1]

The drop - or the gravitational force - affects the vehicle at all times. As any object on Earth, its mass is driven towards the centre of the planet. This force, F_g, is always equal to: $F_g = mg$, where m is the mass of the drone and g is the gravitational constant.

The thrust is the force generated by the motors that is allowing the vehicle to move towards its heading. In case of a quadcopter, this force only exists when the force generated by the motors is uneven.

The lift force, following Bernoulli's principle, is created through a difference in the air pressure above and below the motor. Quadcopter's motors constantly generate lift force, which must be higher than the drop force in order for the vehicle to take flight.

Draw force is the resistance created by the air as the vehicle moves through it. It opposes the thrust force and therefore must be lower than the thrust force in order for the quadcopter to move on. In cases when is no wind, such as indoors area, this force can be disregarded due to lack of wind.

A powered off motors is only affected by the drop force and therefore stays on the ground. In order to lift it up, we need to understand the relationship between quadcopter and the thrust to weight ratio - or TWR for short. This ratio can be determined by equation F_t/F_g and describes the vehicle's ability to move up. With TWR expressed as a number, assuming that each motor generates equal amount of thrust, three cases can be identified:

1. TWR < 1: The gravitational force is higher than the lift force and therefore the quadcopter is drawn towards the ground.
2. TWR $= 1$: The forces are equal, causing quadcopter's altitude to stay constant.
3. TWR > 1: The thrust is higher than drop force, allowing vehicle to move upwards.

Therefore, in order to get a quadcopter up in the air, it is necessary to generate enough thrust for TWR ration to be higher than one. In order to land it, the TWR must be smaller than 1, allowing the quadcopter to move downwards.

Moving on, it is necessary to understand the effects that motor speeds have on the vehicle. While equal amount of force generated by every motor will result in a movement on vertical axis, differences in motor speeds will create a change in quadcopter's pitch, roll or yaw. These three motions can be seen in figure 2.7.

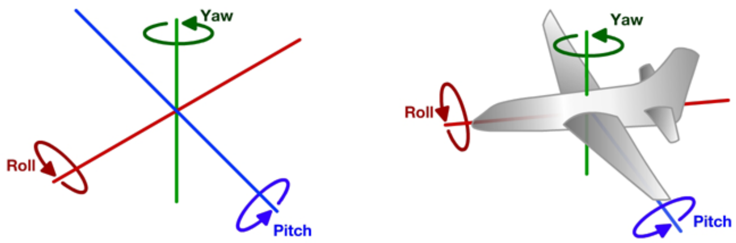

Figure 2.7: Pitch, roll and yaw motions in a 3-dimensional plane [2]

To examine the consequences of different motor speeds, let's assume there's a simple quadcopter with all 4 motors placed at equal distances from the centre. An example can be seen in figure 2.8.

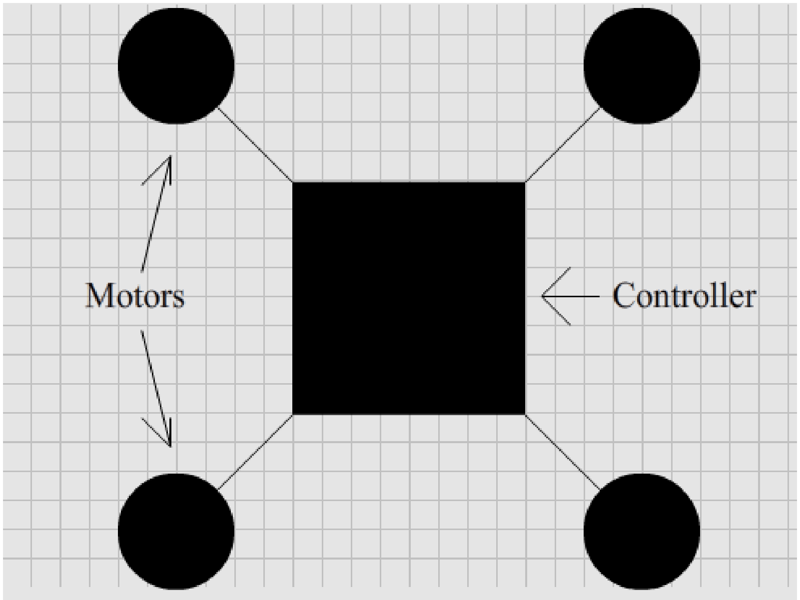

Figure 2.8: A quadcopter viewed from top

The direction of rotation and produced torque as well as the amount of force generated by the motors affect the quadcopter's movement. See figure 2.9 for an example in an idle - or hovering - position.

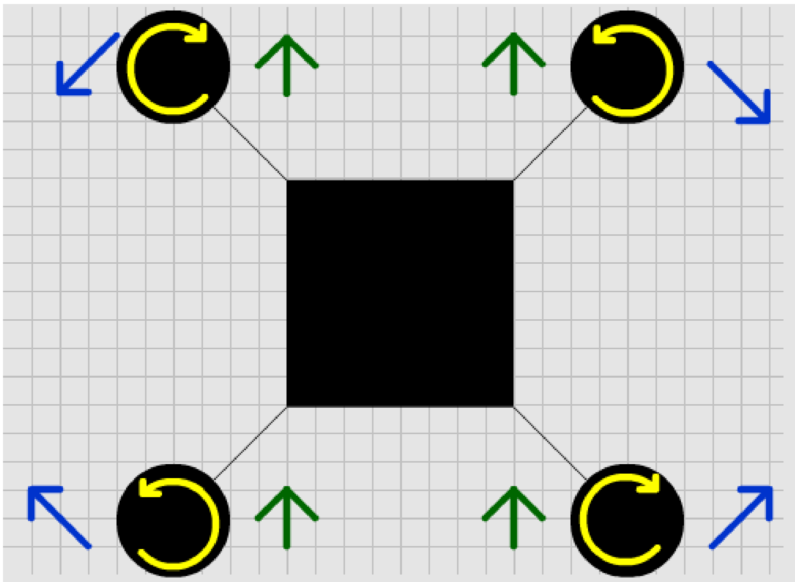

Figure 2.9: Motor direction overview

Here, the yellow arrows indicate the direction of rotation, the blue arrows show the direction of torque and the green arrows display the amount of force generated by the motors.

By controlling the speed at which the motors rotate, it is possible to change how quadcopter moves. Movement can be broken down in 3 separate sets of motor speeds:

1. If the two back motors rotate faster than the two frontal motors, the quadcopter will pitch forward. Switching the speeds will result in aft pitch. The required change in speeds for a pitch forward can be seen in figure 2.10.

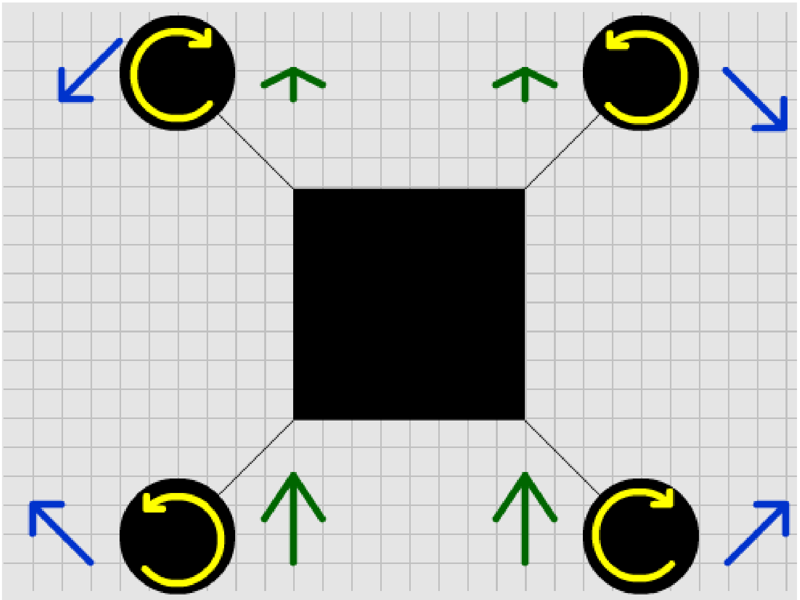

Figure 2.10: Motor RPM requirements for a pitch forward

2. If the two left motors have higher RPM than the two motors on the right side, the vehicle will roll to the right. Swapping the speeds differences will result in a roll to the left. See figure 2.11 for an example of a roll to the right.

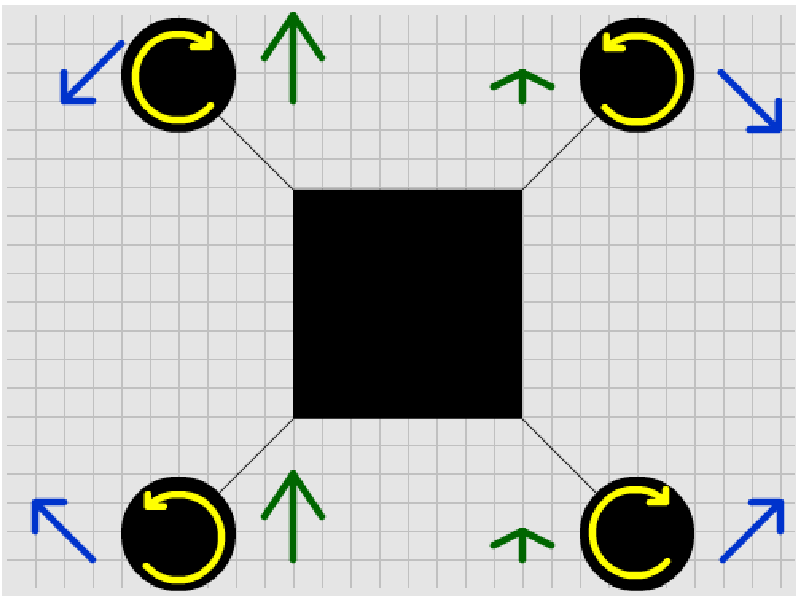

Figure 2.11: RPM requirements for a roll to the right

3. Increasing the speed of one of the diagonal pair of the motors will result in yaw to the direction of the torque of the motors. The copter will then spin

around its axis. Motor speed changes causing a yaw to the right can be seen in figure 2.12.

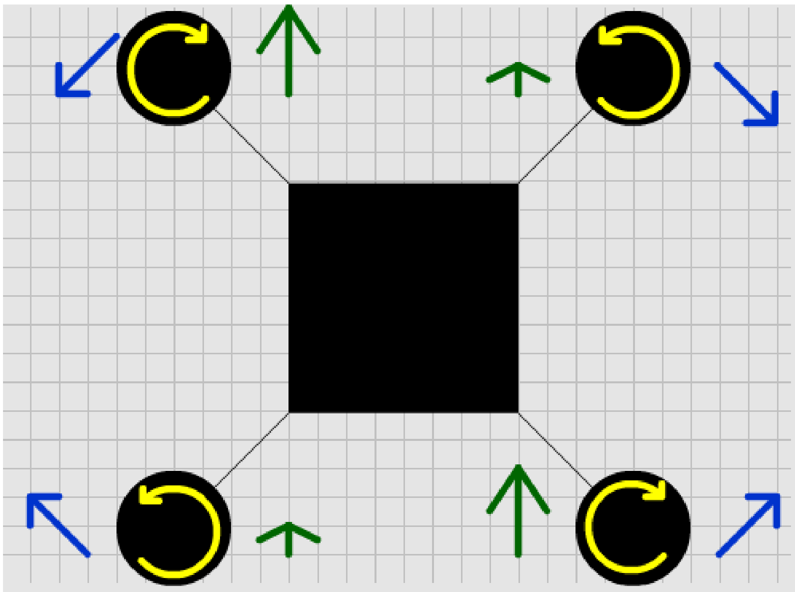

Figure 2.12: The two diagonal motors with increased RPM cause yaw to the right

Chapter 3

Mathematical Modelling

3.1 Motor Dynamics

In this chapter we will take a look at mathematical models that describe our quadcopter system. To begin with, we can identify an equation that describes torque generated by a motor:

$$Q = K_q I \tag{3.1}$$

Here, Q stands for torque, I - current and Kq - motor constant, relating current to the torque. Another equation can be identified as:

$$V = R_a I + K_e \omega \tag{3.2}$$

where V is the voltage, R_a is the motors armature resistance, K_e is the back EMF constant and ω is motor's angular rate.

We can then convert voltage into power in a steady state to get the following equation:

$$P = IV = \frac{Q}{K_q} V \tag{3.3}$$

P - power, which can be related to thrust by equating the power produced by the motors to the ideal power required to generate thrust by increasing the momentum of a column of air. This ideal power P_h, when hovering, can be found using the following equation:

$$P_h = T \upsilon_h \tag{3.4}$$

Here, T - thrust force and υ_h is the induced velocity when hovering. This velocity is the change in air speed which is induced by the motor blades with respect to the free stream velocity. However, to simplify the model and to reflect our testing conditions, this free stream velocity is set to zero due to lack of wind force. Using momentum theory, we can identify another equation:

$$\upsilon_h = \sqrt{\frac{T}{2\rho A}} \tag{3.5}$$

where ρ - air density and A is the area covered by the blade. This area is equal to π multiplied by R^2, which is the radius of the blade.

Since the torque is proportional to the thrust force generated by the motor with a constant ratio K_t, which depends on blade geometry, we can find the relation between the applied voltage and the thrust by combining equations 3.4 and 3.5:

$$\frac{Q}{K_q}V = \frac{K_t T}{K_q}V = \frac{T^{\frac{3}{2}}}{\sqrt{2\rho A}} \tag{3.6}$$

We then get the following equation:

$$T = \frac{2\rho A K_t^2}{K_q^2}V^2 \tag{3.7}$$

This final equation describes the relationship between the constants, applied voltage and the torque produced by the motors.

Chapter 4

Experiments

4.1 Initial Experiments

4.1.1 APM Frequency

Due to lack of proper documentation, it was necessary to do measure the frequency of the signals sent out by the flight controller. To do so, an oscilloscope was connected to one of the output pins of the board. Then, using the servo library, a signal was sent out. The interval between signals was found to be $20ms$, therefore, the frequency of the board is $50Hz$, as seen in figure ??.

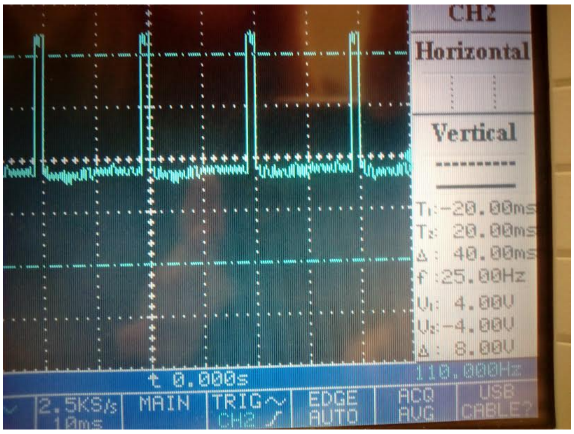

Figure 4.1: Oscilloscope measuring APM's frequency

The second experiment on the board was then made to determine how the flight controller handles the output signals during those $20ms$. First two outputs of the APM were connected to the oscilloscope, both utilizing the Servo library to send signals of length of $2000\mu s$. Results can be seen in figure ??.

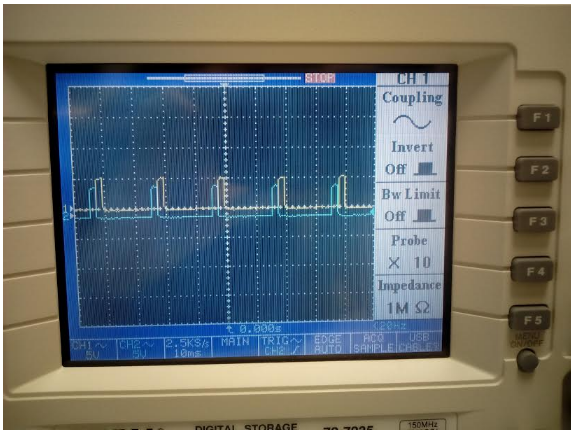

Figure 4.2: Readings of the two output signals

Then, by changing the length of the signals, two results were observed:

1. If the first signal is shorter than the second one, the second signal will still follow right after the first signal ends. In other words, the APM leaves no gaps between the outputs.
2. Since the board runs at the frequency of $50Hz$ and has a period of $20ms$, this leaves $\frac{20}{8} = 2.5ms$ maximum length for each output signal. The servo library is hard-capped at $2.4ms$ and thus is well within the limits of the board.

4.1.2 Expected and Real Motor Performance

The motors used in the prototype specify to be rated at K_v of 980. K_v is a constant describing the ration between RPM and the applied voltage and is expressed as $K_v = \frac{RPM}{V}$. Derived from this, voltage's effect on the RPM can be seen in figure **??**.

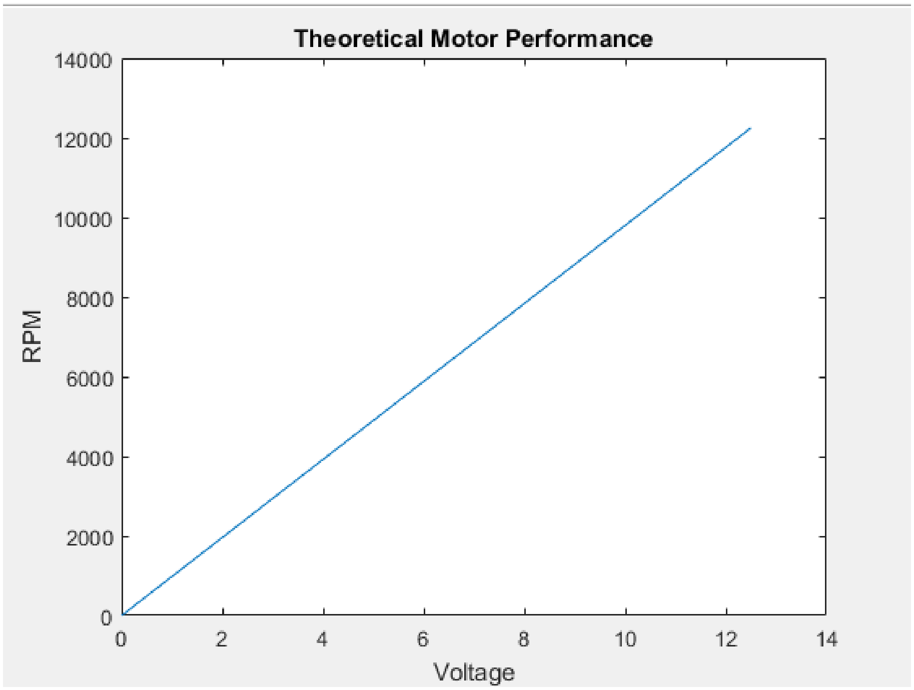

Figure 4.3: Expected motor performance

With a fully charged battery, the RPM is expected to be $980 * 11.1V = 10878RPM$.

In order to confirm this, the actual RPM was measured using SHIMPO DT-205 digital tachometer. EXPAND WHEN WE GET THE VOLTAGE

Chapter 5

Discussion

Chapter 6

Conclusion

Bibliography

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[2] Alex. The quadcopter : control the orientation. http://theboredengineers.com/2012/05/the-quadcopter-basics/. (Accessed 06/11/16).

Chapter 7

Appendix

7.1 Appendix code