



DEGREE PROJECT, IN MECHATRONICS , FIRST LEVEL  
*STOCKHOLM, SWEDEN 2015*

# Camera Surveillance Quadrotor

EMIL HJELM, ROBERT YOUSIF

KTH ROYAL INSTITUTE OF TECHNOLOGY

INDUSTRIAL ENGINEERING AND MANAGEMENT





**KTH Industrial Engineering  
and Management**

**Bachelor's Thesis MMKB 2015:9 MDAB062**

## **Camera Surveillance Quadrotor**

Emil Hjelm  
Robert Yousif

Approved  
2015-05-27

Examiner  
Martin Edin Grimheden

Supervisor  
Fredrik Asplund

### **ABSTRACT**

A quadrotor is a helicopter with four rotors placed at equal distance from the crafts centre of gravity, controlled by letting the different rotors generate different amount of thrust. It uses various sensors to stay stable in the air, correct readings from these sensors are therefore critical. By reducing vibrations, electromagnetic interference and external disturbances the quadrotor's stability can increase.

The purpose of this project is to analyse the feasibility of a quadrotor camera surveillance system by optimizing the handling of vibrations, video signal and external disturbances for a quadrotor. The quadrotor will be flown through first person view and should be able to hover at 10 meters altitude in a radius of 3 meters. Only sensor readings will be optimized, not data processing. The flight controller used will be a MultiWii Pro which has an accelerometer, a gyroscope, a magnetometer, a GPS and a barometer.

By balancing motors and applying vibration dampening material between the motors and the frame vibrations were reduced by 73 %. Electromagnetic interference to the magnetometer was made negligible when the magnetometer had a distance of 3 cm from the power circuit. Video signal was improved by applying a LC-filter. Isolating the barometer improved calculations for the altitude.

The quadrotor's position could be locked within a radius of 4 meters and its altitude could be locked in an interval of 2 meters.

The quadrotor cannot be considered stable enough for automatic camera surveillance, however with software improvement it could be.

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KTH Industriell teknik  
och management

## Kandidatarbete MMKB 2015:9 MDAB062

### Kameraövervakningsquadrotor

Emil Hjelm  
Robert Yousif

Godkänt

2015-05-27

Examinator

Martin Edin Grimheden

Handledare

Fredrik Asplund

## SAMMANFATTNING

En quadrotor är en helikopter med fyra rotorerna placerade på lika avstånd från farkostens masscentrum, kontrollerad genom att låta de olika rotorerna generera olika mycket lyftkraft. Den använder sig av flera olika sensorer för att hålla sig stabil i luften, korrekt avläsning från sensorerna är därför kritiskt. Genom att reducera vibrationer, elektromagnetisk störning och externa störningar kan quadrotorns stabilitet öka.

Syftet med detta projekt är att analysera möjligheten för ett quadrotorkameraövervakningssystem genom att optimera vibrationer, videosignal och externa störningar för en quadrotor. Quadrotorn ska styras genom FPV (First Person View) och kunna hovra på 10 meters höjd inom en radie av 3 meter. Endast sensorläsning kommer att optimeras, inte hantering av data. Microcontrollern som används är MultiWii Pro som har en accelerometer, ett gyroskop, en magnetometer, en GPS och en barometer.

Genom att balansera motorer och lägga på vibrationsdämpande material mellan motorer och ram kunde vibrationerna minskas med 73 %. Elektromagnetisk störning på magnetometern gjordes försumbar med ett avstånd på 3 cm från kretskortet. Videosignal förbättrades genom att filtrera strömtillförseln till kameran med ett LC-filter. Isolering av barometern gjorde att höjdbereäkningarna förbättrades.

Quadrotorns position kunde låsas inom en radie på 4 meter och dess höjd kunde låsas inom ett intervall på 2 meter.

Quadrotorn kan inte anses vara tillräckligt stabil för automatisk kameraövervakning, men med förbättring på mjukvaran skulle den kunna bli det.

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## PREFACE

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First and foremost we would like to thank our supervisor Fredrik Asplund for his valuable feedback and ideas. We would also like to thank the rest of the students at the institution of mechatronics and finally the MultiWii community for the software used in this project.

Emil Hjelm, Robert Yousif

Stockholm, May 2015

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## NOMENCLATURE

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*This chapter denotes and describes the symbols and abbreviations used in this report.*

### **Symbols**

<b>Symbol</b>	<b>Description</b>
$r$	Radius (m)
$U$	Voltage (V)
$R$	Resistance ( $\Omega$ )
$I$	Current (A)
$Ih$	Capacity (Ah)
$n$	Rounds per minute (RPM)
$K_v$	Voltage proportionality constant ( $\frac{RPM}{V}$ )
$C$	Discharge rate ( $h^{-1}$ )

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### **Abbreviations**

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FPV	First Person View
FOV	Field Of View
ESC	Electric Speed Controller
IMU	Inertial Measurement Unit
PID	Proportional Integrative Derivative
CMOS	Complementary Metal Oxide Semiconductor
CCD	Charge-coupled Devices
RC	Radio Control
OSD	On Screen Display
GPS	Global Positioning System

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# 1 INTRODUCTION

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*This chapter describes the background, purpose, scope and method for the degree project.*

## 1.1 Background

A quadrotor is a helicopter with four rotors placed at equal distance from the crafts centre of gravity, controlled by letting the different rotors generate different amount of thrust. It has simple mechanics, great manoeuvrability and can even be made autonomous (DHL, 2014). Because of their flexibility they are used in many different areas and for many different missions. They are used by police (Harnesk, 2015) (TT, 2014), filmmakers (Aerosight, u.d.) (SpiderAerialFilming, u.d.), researchers (D'Andrea, 2013) and hobbyists to name a few.

Camera surveillance today is mostly stationary and locked at certain heights and angles making the surveillance limited. That is where the quadrotor could be used as a compliment to the stationary cameras. A camera attached to a quadrotor that could travel to a specific point of interest at any given time to provide surveillance would therefore be of interest.

To create a camera surveillance quadrotor that is powerful, safe and cheap, several factors must be analysed and optimized. Vibrations in a quadrotor can make sensor readings difficult, and the footage from its camera can become too blurry to accurately use. A non-optimized video signal from the quadrotor will cut out frames from the video feed and render the video feed useless.

## 1.2 Purpose

The purpose of this project is to analyse the feasibility of a quadrotor camera surveillance system by optimizing the handling of vibrations, video signal and external disturbances for a quadrotor. The surveillance comprises an overview of a scene from a distance to give a clear idea of movements, body characteristics and unusual activity. To accomplish this the quadrotor should be flown through FPV and be able to hover at 10 meters altitude in a radius of 3 meters. These numbers reflects a wide camera image that can cover big areas and still be close enough for details mention above.

For the quadrotor to lock a certain position in three dimensions it needs some sensors to make this possible: a gyroscope and an accelerometer are used to make the quadrotor levelled, these sensors are sensitive to vibration; a GPS to lock the certain position in the horizontal plane, the GPS needs a magnetometer to know which direction the quadrotor is headed and the magnetometer is sensitive to electromagnetic disturbances; a barometer to lock the quadrotor in the vertical plane, the barometer is sensitive to rapid changes in air pressure and temperature. The camera system to send a live video feed to the base, the camera system is sensitive to rapid changes in voltage and current. To create a stable camera surveillance quadrotor readings from these sensors must be accurate.

## 1.3 Scope

The scope of this report is limited to how vibrations, electromagnetic disturbances and external disturbances affect the stability of a quadrotor, and minimizing their effect on

the system. Sensors used will be limited to accelerometer, gyroscope, magnetometer, barometer and GPS.

Control and filtration of signals will not be optimized, but analysed to some degree. Standard filtering and control settings provided by MultiWii (MultiWii, u.d.) will be used to ensure a stable flight.

The components for the quadrotor will be limited by the material supplied by the department of mechatronics and a budget of approximately 1000 SEK. The time frame for the project is limited to the spring semester of 2015.

## **1.4 Method**

To examine the feasibility of a quadrotor camera surveillance system, a quadrotor will be built. The quadrotor will operate using the opensource software MultiWii.

Vibrations, video signal and disturbances will be optimized and the stability will be measured. Details regarding how these disturbances were minimized can be seen in 3.5 Optimization and tests. Stability will be defined as how well the quadrotor can stay in one spot.

A Bluetooth module will be installed for debugging purposes. It will contribute with in flight data for analysis and live feedback to the base.

## 2 THEORY

*This chapter presents the theoretical framework that will create the base for this degree project.*

### 2.1 The dynamics of a quadrotor

To understand how the quadrotor behaves a theoretical framework must be established.

#### 2.1.1 Mechanics

The quadrotor hovers by making all four rotors generate equal amounts of thrust, and turns by allowing some rotors to generate more thrust than the rest. It has six degrees of freedom around which it can navigate: The rotational axes yaw, roll and pitch, and translational along all three respectively, illustrated in Figure 1.

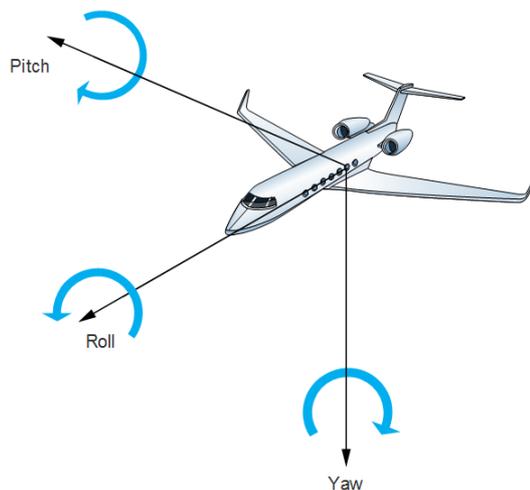


Figure 1. Illustrating yaw, roll and pitch axis.

A regular helicopter has a big rotor to generate thrust and a small tail rotor to offset the torque generated by the big rotor. Without a tail rotor the helicopter would not be able to control its spin around its yaw axis. On a quadrotor this torque is offset in a different way. Two of the rotors on opposite sides from each other rotate clockwise and the other two rotate counter clockwise, see Figure 2. This way the total torque generated by the two pairs of rotors cancel each other out. A quadrotor can be flown in two different formations: Either “X-formation” or “+ -formation”, also shown in Figure 2.

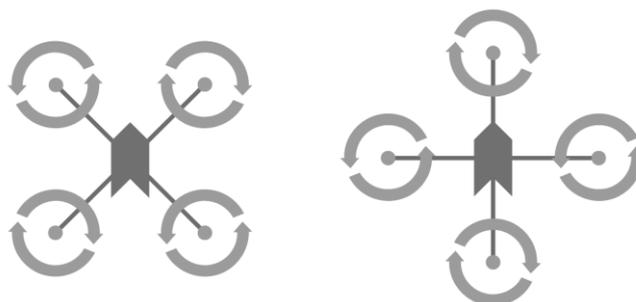


Figure 2. Rotor direction when hovering, Left: X-formation, right: +-formation.

By making one pair of rotors generate less torque than the other pair the quadrotor will turn since the total torque will not equal zero. To stop the quadrotor from changing altitude the total thrust must be the same, i.e. one pair of rotors must generate more thrust and the other pair equal amount less thrust, as illustrated in Figure 3.

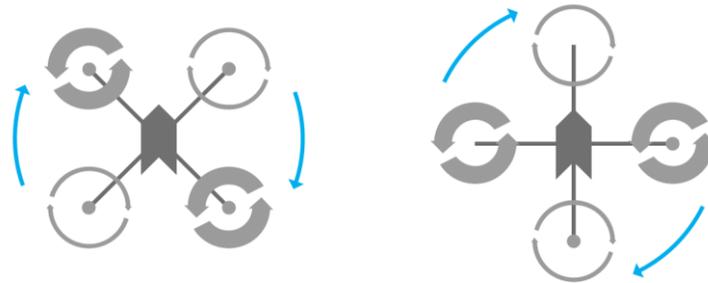


Figure 3. Rotor direction and speed when turning. X and +-formation respectively.

To control the pitch of the quadrotor only one rotor has to generate more thrust and the opposite rotor must produce equal amount less thrust. This makes the quadrotor tilt and thus the overall thrust will be split into a vertical component and a horizontal. The horizontal component causes the quadrotor to travel forwards or backwards depending on which rotor is generating more thrust. The vertical component will be smaller than before and to keep the quadrotor at the same height it has to let all rotors generate more thrust, shown in Figure 4.

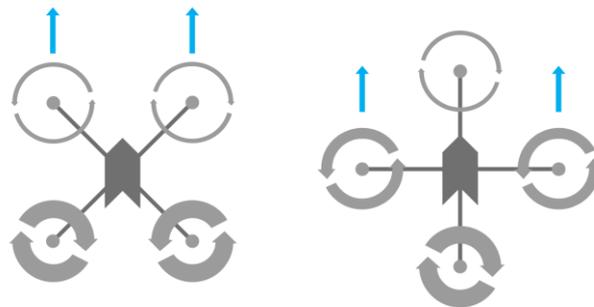


Figure 4. Rotor direction and speed when tilting forward. X and +-formation respectively.

Finally, controlling the roll of the quadrotor is done the same way as controlling the pitch, just using the other pair of rotors, see Figure 5.

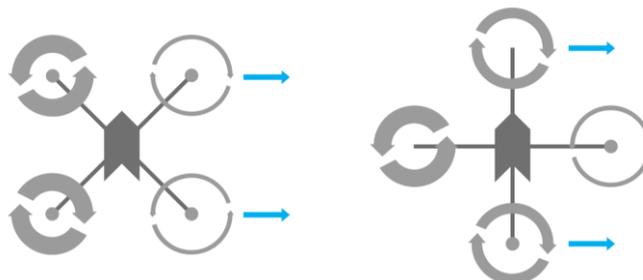


Figure 5. Rotor direction and speed when rolling. X and +-formation respectively.

### 2.1.2 Kinematics

To derive the dynamics of a quadrotor two frames in which the quadrotor will operate will be introduced. The inertial frame and body frame. The inertial frame is defined by the

ground with gravity pointing in the negative z-direction. The body frame is defined by the orientation of the quadrotor with the rotor axis's pointing in the positive z-direction, illustrated in Figure 5. (Luukkonen, 2011) (Gibiansky, 2012)

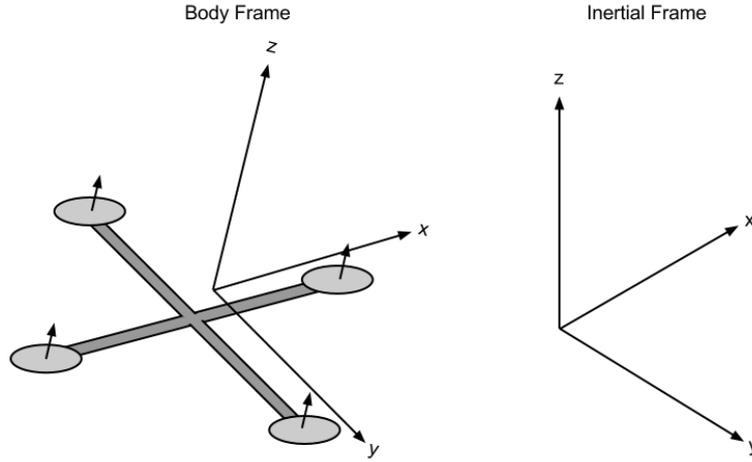


Figure 6 Body and inertial frame of the quadrotor. (Gibiansky, 2012)

The absolute position and the velocity of the quadrotor is defined in the inertial frame with  $\xi$  and its derivative  $\dot{\xi}$ .

$$\xi = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \dot{\xi} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} \quad (1)$$

The angular position of the quadrotor yaw, roll and pitch and its angular velocity is defined as  $\eta$  and  $\dot{\eta}$

$$\eta = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}, \dot{\eta} = \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \quad (2)$$

To convert these angular velocities into the angular velocity vector  $\omega$  the following relation can be used.

$$\omega = \begin{bmatrix} 1 & 0 & -S_\theta \\ 0 & C_\phi & C_\theta S_\phi \\ 0 & -S_\phi & C_\theta C_\phi \end{bmatrix} \dot{\eta} \quad (3)$$

Where  $S_x = \sin(x)$  and  $C_x = \cos(x)$  so that  $\omega$  is the angular velocity in the body frame.

The body frame and the inertial frame can be related by a rotation matrix  $R$  which goes from the body frame to the inertial frame. (Luukkonen, 2011) (Gibiansky, 2012)

$$\mathbf{R} = \begin{bmatrix} C_\phi C_\psi - C_\theta S_\phi S_\psi & -C_\psi S_\phi - C_\phi C_\theta S_\psi & S_\theta S_\psi \\ C_\theta C_\psi S_\phi + C_\phi S_\psi & C_\phi C_\theta C_\psi - S_\phi S_\psi & -C_\psi S_\theta \\ S_\phi S_\theta & C_\phi S_\theta & C_\theta \end{bmatrix} \quad (4)$$

For a given vector  $\bar{v}$  in the body frame, the corresponding vector in the inertial frame is given by  $R\bar{v}$ .

### 2.1.3 Electrical

To be able to generate torque the quadrotor needs electric motors on every rotor. For almost all quadrotors brushless motors are used because of their high efficiency, increased reliability, reduced noise, longer lifetime and reduction of electromagnetic interference compared to brushed motors. (Dirjish, 2012) (Miller, 2010) The torque  $\tau$  generated by a motor can according to (Gibiansky, 2012) be calculated as

$$\tau = K_t(I - I_0) \quad (5)$$

where  $I$  is the input current,  $I_0$  is the current when there is no load applied and  $K_t$  is the torque proportionality constant. To calculate the voltage  $U$  the following equation can be used,

$$U = IR_m + \frac{\omega}{K_v} \quad (6)$$

where  $R_m$  is the motor resistance,  $\omega$  is the motors revolutions per minute and  $K_v$  is a proportionality constant showing how many revolutions per minute the motor produces given a certain voltage. If the motor resistance is assumed to be negligible the power consumed by the motor can be calculated as

$$P = IU = \frac{(\tau + K_t I_0)\omega}{K_t K_v} \quad (7)$$

Further simplifying the model it can be assumed that  $K_t I_0 \ll \tau$  and thus we get

$$P = \frac{\tau\omega}{K_t K_v} \quad (8)$$

as showed by (Gibiansky, 2012).

## 2.2 Components

The quadrotor consists of different components, where almost all components depend on each other. Therefore it is important to have a stable system where all mechanisms are compatible with one another.

### 2.2.1 Frame

The frame is the base for all other components on the quadrotor. It needs to be solid and at the same time absorb vibrations from the motors. It also needs to be lightweight for longer flight times, but still durable in case of a crash. The lightest and strongest (stiffness-to-weight) materials used today are composite, carbon fibre and glass fibre. Glass fibre is cheaper in most cases and also non-conductive which means it will resist the flow of electric charge and will not respond to electrical fields. It will not interfere with radio signals, which is good for the antennas mounted on the quadrotor. (GW-Composites, u.d.) A wooden frame is also an option; it is very cheap and takes up vibrations well, but is heavy. Aluminium is in between composite fibre and wood in relation to cost and weight, but it is fairly conductive and may interfere with the radio signals.

### 2.2.2 Motors

The motors are very dependent on the whole system. To work properly the motors need to be compatible with the battery, ESC (Electric Speed Control), propellers and the frame. The motors need to be powerful enough to lift the quadrotor and make it manoeuvrable. A rule of thumb is that if the motors can provide twice the thrust of the total weight the craft will have enough power for stability. (Liang, 2013) There are some attributes to look at when choosing a motor:  $K_v$ -value, described as the amount of revolutions per minute/voltage

$$n = K_v \cdot U \quad (9)$$

Other important factors are the amount of power the motor will be able to produce, the maximum amount of current the motor will draw and under what voltage it is most efficient.

In order to not produce vibrations a motors geometrical centre and centre of mass needs to coincide.

### 2.2.3 Propellers

Propellers are measured in diameter and pitch. Pitch is the distance one propeller will drill the air in one rotation, see Figure 7. Higher pitch generates more thrust at the cost of energy. Depending on the motors and the propeller shape the quadrotor will have different properties. With large propellers the motors will generate much thrust at low rotation speeds, but the agility of the quadrotor will be reduced in comparison to small propellers and high rotation speeds. (Liang, 2013) Large propellers also require more powerful motors which contribute to more weight and bigger batteries.

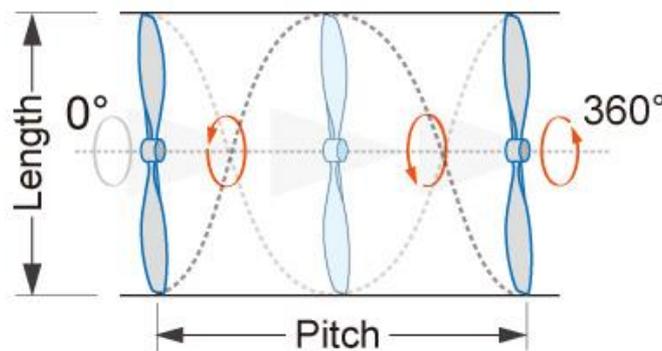


Figure 7. Illustrating the pitch of a propeller. (Anon., u.d.)

### 2.2.4 ESC (Electric Speed Controller)

The purpose of an ESC is to control each motor separately; it controls the amount of current the motor will receive from the battery. To manoeuvre the quadrotor in the air each motor needs to behave individually when performing different tasks. To work properly the ESC needs to provide enough current to the motor, depending on the properties of the motor.

### 2.2.5 IMU (Inertial Measurement Unit)

An IMU ordinarily consists of a gyroscope and an accelerometer but its properties depend on the area of use. An accelerometer measures the orientation of the body with reference to the surface of the earth, and a gyroscope measures the body's angular speed. In flight

control IMUs often have many other sensors such as a magnetometer and a barometer. A magnetometer measures the strength and the direction of the magnetic field around the instrument, and a barometer measures the pressure in the air to estimate the height.

### 2.2.6 Microcontroller

The microcontroller is a single integrated circuit computer which is used in all kinds of applications today. It can be seen as the brain of the quadrotor which communicates with all of the other parts. It also contains the software used to calculate how the quadrotor should behave to be stable.

### 2.2.7 GPS (Global Positioning System)

A GPS is used to determine the location of a GPS receiver. This will give any vehicle with a GPS receiver the ability to know its location and can be used as a tool for navigating.

### 2.2.8 Battery

A battery contributes with power to an electrical system. What defines the specifications of a battery is its voltage  $U$ , capacity  $Ih$  measured in the unit Ah, and the discharge rate  $C$ . The maximum amount of current that can be continuously drawn from the battery is according to (MIT, 2008) defined as

$$I_{max} = Ih \cdot C \quad (10)$$

which is measured in the unit A.

### 2.2.9 FPV camera and RC communication

FPV is used to control a vehicle remotely from a pilots view with a camera that transmits the video from the vehicle to a receiver on the ground. Cameras with a CMOS or CCD image sensor are commonly used. Neither technology has a clear advantage in image quality. On one hand, CCD sensors are more susceptible to vertical smear from bright light sources when the sensor is overloaded; high-end CMOS sensors in turn do not suffer from this problem. On the other hand, cheaper CMOS sensors are susceptible to undesired effects that come as a result of rolling shutter. (Litwiller, 2001) A radio transmitter and receiver between 2.4 GHz to 5.8 GHz are commonly used for communication between the vehicle and the pilot. Each action the RC will be able to do will take up a channel so the number of functions depends on the number of channels the RC have. Minimum requirement to control a quadrotor is a 4-channel RC (throttle, yaw, pitch and roll). Controlling the quadrotor and receiving the footage from the camera requires two transceivers.

Radiofrequencies are used today almost everywhere. This means that applications using the same frequencies have a tendency to disturb each other. One of the most usual frequencies is 2.4 GHz which is used as a standard in wireless networking, microwaves, remote controls and car alarms just to name a few. To minimize disturbance, there are different channels to operate in so that overlapping can be avoided. (Intel, 2012)

### 2.2.10 Bluetooth

Bluetooth is a wireless technology used to transmit data over a short range. This makes it possible to replace the cabled serial port so that data can be exchanged wirelessly.

### 2.2.11 LC-filter

A LC-filter is an electric circuit where electricity oscillates between a capacitor  $C$  and an inductor  $L$ . The filter can store electric energy, the capacitor stores energy in the electric field between its plates in relationship to the voltage, the inductor stores energy in its magnetic field in relationship to the current through it. This is used to even out the voltage and current from an unstable power source, such as a battery used to power up motors.

## 2.3 Software

The software on a quadrotor serves two main functions, filtering measurements from the IMU and calculating new speeds for the rotors.

### 2.3.1 Automatic control system

A PID controller is used to get the observed results closer to the preferred results, a closed loop control system. This is done by regulating the feedback, how the feedback is regulated depends on the PID values. (Glad & Ljung, 2006) The PID controller uses reference values and data from the quadrotor's IMU to send new values to the ESCs. See Figure 8.

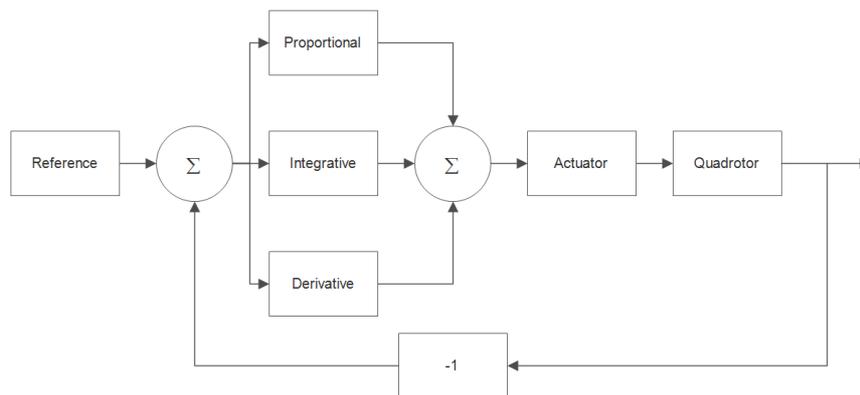


Figure 8. Control diagram for a quadrotor.

The proportional part multiplies the given error by the proportional gain constant,  $K_p$ . A large  $K_p$  will result in a large change of the output from the control system.

The integral part is proportional to both the magnitude of the error and the duration of the error. The accumulated error is multiplied by the integral gain constant  $K_i$ .

Finally, the derivative part determines the change of the error over time and multiplies this rate by the derivative gain constant  $K_d$ . (Glad & Ljung, 2006)

### 2.3.2 Filters

To reduce the effect of noise, data from the sensors must be properly filtered. Filters can for example take a median value from several data points to avoid one bad value from being considered reliable.

Filters can also be used to cut off and pass signals above and below certain frequencies.

### 2.3.3 Arduino code

The Arduino language is all in C and C++ but also includes the big Arduino library. The Arduino software also includes a compiler that transforms the written code to machinery instructions. (Arduino, u.d.)

## 3 DEMONSTRATOR

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*This chapter describes the developed demonstrator and the work process behind it.*

### 3.1 Problem formulation

The goal with the quadrotor is to get an accurate and stable surveillance camera in the air. It needs to be able to hover at 10 m altitude within a radius of 3 m. To do this, there are some disturbances that need to be taken into account. The types of disturbances limited by the scope are vibrations, electromagnetic and external.

#### 3.1.1 Vibrations

The stability of the quadrotor depends on the readings of the sensors. If the data collected from these sensors is disturbed by vibrations from the motors, the quadrotor will be hard to manoeuvre. Reducing the vibrations on a quadrotor is therefore essential for the equipment to work right.

Motors are not manufactured perfectly, and thus their geometrical centre and centre of mass do not align perfectly. This will induce vibrations at high motor speeds.

#### 3.1.2 Electromagnetic interference

Electromagnetic interference can originate both locally from the electronics and from outside disturbance i.e. power lines, solar magnetic storms and radio transmission just to name a few. (DiBiase, 2011) The most affected systems on the quadrotor are the camera feed and the magnetometer.

The camera transmitter takes power from the same battery as the motors on the quadrotor, the discharge current from the battery fluctuate due to the quadrotors fluctuating power consumption. This affects the current and voltage that flows to the camera transmitter, therefore the image will flicker.

The quadrotor uses a compass to know what direction it is heading. This compass can be easily disturbed by electromagnetic interference like an outside power supply line or locally from the quadrotors circuit board.

#### 3.1.3 External disturbances

To be able to lock the quadrotor in one position, the accuracy of the GPS needs to be very stable. The GPS manufacturer can only guarantee a precision within  $\pm 3$  meters. Other sensors will be used simultaneously to achieve stability.

To measure the height the quadrotor uses a barometer. The barometer measures the pressure and the temperature of the air, compares it with the ground and then estimates a probable height. The sensor is sensitive to sudden movements in the air it measures and to sunlight, these disturbances can make the approximated height differ a lot, this can be a big problem when this sensor is used to manoeuvre the motors for a stable levelled flight.

### 3.2 Hardware

The frame of the copter can be seen as the base for all other components. The copter will fly in an X-formation in order for the camera to have a clear view. The frame used is a

Hobbyking X550. (HobbyKing, u.d.) It has a glass fibre base where most of the electronics will be mounted since glass fibre is non-conductive. The arms are of aluminium which is cheap, light and robust. The base of the frame consists of two glass fibre plates with each arm squeezed in between, see Figure 9.



Figure 9. HobbyKing X550 frame. (HobbyKing, u.d.)

The top plate carries the flight controller and the middle plate carries the camera and the GPS. The circuit board is placed between the two lower plates and on the bottom side of the lower plate the battery, RC receiver, FPV transmitter, Bluetooth module and the switch for the battery will be placed.

The propellers are made of hard plastic. According to Ecalc a 10 inch propeller gives the best motor efficiency when hovering. See Appendix A: Ecalc values.

### 3.3 Electronics

The software Ecalc (Mueller, 2015) was used to approximate the copters abilities such as flight time, maximum speed, thrust power, efficiency and more to make sure the requirements are met. See Appendix A: Ecalc values. Although these numbers are theoretical this gives a good overview of the quadrotoer's properties.

#### 3.3.1 Motors, ESC and battery

The motors supplied from the institution were of model Turnigy C3530-1100 ( $K_v = 1100$ ) together with the ESCs Tower Pro MAG8 25 A. Tests show that these motors operate most efficiently at 11.1 V. (FlyBrushless, u.d.) According to equation 9 this will give our motors a theoretical maximum RPM of

$$n = K_v \cdot I = 1100 \cdot 11.1 = 12210 \text{ RPM} \quad (11)$$

Given that the motors are most efficient at a voltage of 11.1 V a 3S LiPo battery was chosen. The motors have a maximum power draw of 20 A each. This means that the battery has to be able to continuously give at least 80 A. A battery that can discharge at least 100 A continuously provides enough leeway given that the microprocessor, camera system, RC receiver and bluetooth also need some current. A battery with 5500 mAh and 30 C meet the above requirements for a maximum continuous current draw according to equation 10.

$$I_{max} = I_h \cdot C = 5500 \cdot 10^{-3} \cdot 30 = 165 A \quad (12)$$

Although the average current drawn will be much lower.

### 3.3.2 Microcontroller, GPS and Remote Control

The microcontroller used is MultiWii pro and it consists of an Atmega 2560 microprocessor, ITG3205 Triple Axis Gyro, BMA180 Accelerometer, BMP085 Barometer, HMC5883L Magnetometer, servo output for camera control and a connection for a GPS module, see Figure 10. The controller is powered up from the ESCs with 5V, see Appendix C: Complete circuit. The GPS used is a MTK 3329 GPS module.

The Remote Turnigy 9XR with the FrSky transmitter and the FrSky receiver was supplied from the academy. The remote communicates through 2.4 GHz and supports at least nine channels.

The four first channels will be used to control the movement of the quadrotor: throttle, roll, pitch and yaw as seen in Figure 10 below.

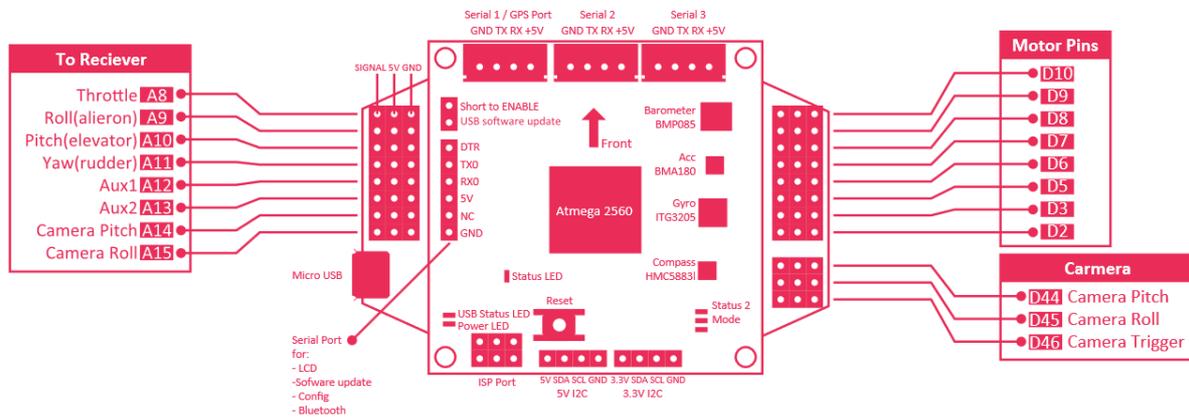


Figure 10: Connection Plan for MultiWii Pro (HobbyKing, u.d.)

### 3.3.3 FPV system

The FPV communication is done wirelessly with a SkyZone RC305 5.8 Ghz receiver and a SkyZone TS353 5.8 Ghz transmitter (HobbyKing, u.d.). In between the transmitter and the circuit a LC filter will be placed for noise cancelling.

The camera used is a Mini CMOS FPV 520TVL 0.008LUX 17x17x24mm (PAL) camera with 120 degrees FOV. This camera is used to provide a live video feed and to provide a video signal to optimize. A GoPro HD Hero 2 will be used to record higher quality footage.

### 3.3.4 Bluetooth module

The Bluetooth module HC-06 is used to communicate with the microprocessor, the main use is to collect data from the sensors for study and to configure flight modes in the field.

### 3.3.5 Circuit board

To provide the components with electricity a simple circuit board was made, see Figure 11. Each ESC is soldered to a corner of the board and battery and transmitter is connected to the VCC and GND pins.

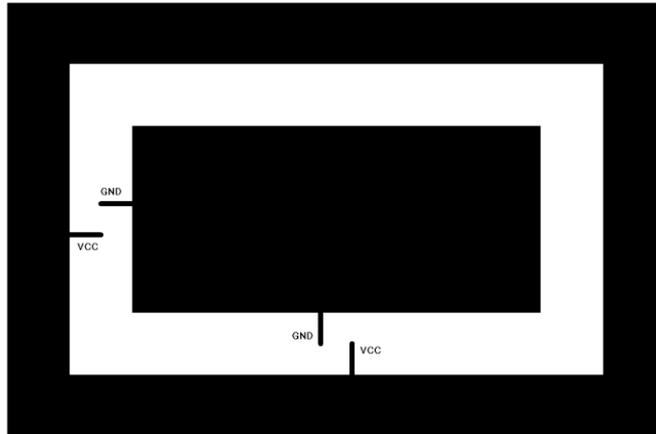


Figure 11. Circuit board.

### 3.4 Software

All the software used on the quadrotor is Arduino based and open source. The code was downloaded from the MultiWii software page (MultiWii, u.d.) and was then edited to work for this project (Appendix). A graphical user interface (GUI) was also provided. (MultiWii, u.d.)

To achieve stability in flight the quadrotor uses a PID-controller (Khoroshko, 2013). The processor will calculate new values for each ESC so that each motor will generate correct amount of thrust. A schematic of the PID-controller can be seen in Appendix B: PID-controller.

### 3.5 Optimization and tests

This chapter will describe how the quadrotor was tweaked and optimized. When testing the accuracy of the different sensors, flight test were made by manual and automatic control, then the logged data was compared with the expected from what was physically seen.

#### 3.5.1 Vibrations

To make the motors vibrate as little as possible their geometrical centre and centre of mass must align. A small piece of tape was attached to a motor on one side and vibrations were measured using an accelerometer. This changed the centre of mass slightly. To find the amount of vibrations the root mean square value was calculated using values obtained from the accelerometer. After some adjustments the optimal position and amount of tape was found. When the motor was balanced a vibration dampener (VD) in the form of compressed cotton was attached between each motor and the frame. This was repeated for all four motors. See 3.6.1 Vibration reductions.

#### 3.5.2 Electromagnetic disturbances

To reduce flickering in the video a LC-filter was built. A capacitor with 1 mF connected to an inductor. This gave the camera system more evenly distributed current and voltage. Results before and after the LC-filter was implemented can be seen in 3.6.2.1 Video signal.

The magnetometer is essential for the quadrotor to know what direction its heading, when using the GPS as feedback for a position hold, small disturbances to the

magnetometer can affect the stability. When arming the motors with oscillating throttle it affected the magnetometer. To decrease the impact of disturbance to the magnetometer it was moved further away from the main power cables. Results can be seen in 3.6.2.2 Magnetometer.

### 3.5.3 External disturbances

The barometer was very unstable out of the box. There are two factors disturbing the barometer; airflow and temperature. The airflow can come from both the quadcopter and from weather circumstances and the temperature can differ a lot when direct sunlight hits the barometer. Two tests were made, see 3.6.3 Stability. One test with the barometer naked and one with isolation mounted over the barometer. These tests were made under windy weather conditions, around 7 m/s.

When using GPS Hold the quadrotor is supposed to stay in one certain position. To do so, the quadrotor also uses the magnetometer and the barometer. The GPS used for this quadrotor comes with a certainty of  $\pm 3$  m. The quadrotor was flown to a specific point with a measured distance to home position before initiating position hold. The quadrotor's distance to home was then logged. Results can be seen in 3.6.3.2 GPS.

## 3.6 Results

Here the results from the optimized system will follow. The final build of the quadrotor in flight can be seen in Figure 12 below.



Figure 12. Quadrotor operational in flight.

The final circuit can be seen in Appendix C: Complete circuit.

### 3.6.1 Vibration reductions

The results from the vibration measurements as described in 3.5.1 Vibrations can be seen in Figure 13 - Figure 16 for each motor respectively. The vertical axes shows the RMS values for each direction x, y, z and the horizontal axes shows tape position on the motor where the circumference of the motor is divided into six sections. The tape pieces used had an area of approximately 1 cm<sup>2</sup>, and small pieces had an area of 0.5 cm<sup>2</sup>.

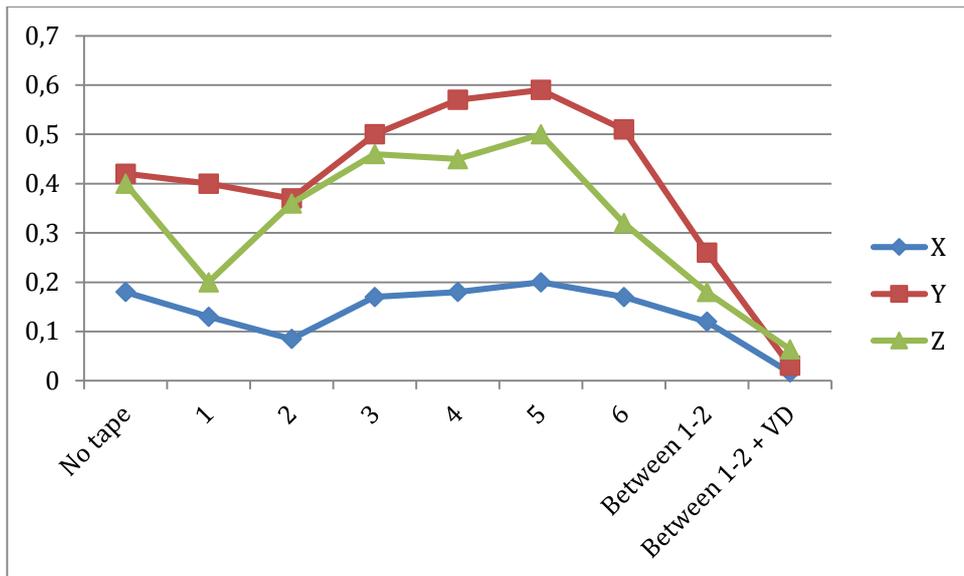


Figure 13 Graph of vibrations for motor 1 as a function of different tape positions and with vibration dampener (VD).

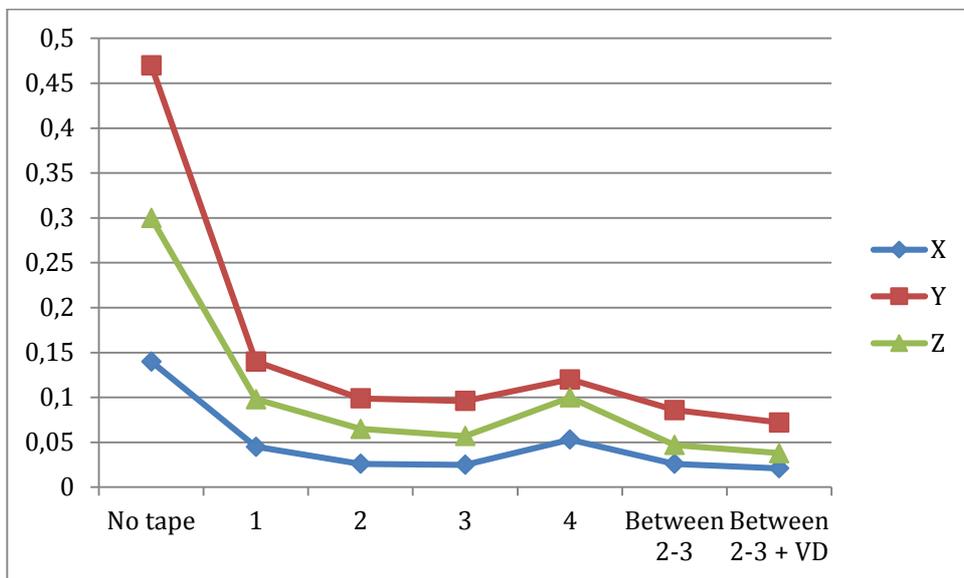


Figure 14 Graph of vibrations as a function of tape position for motor 2.

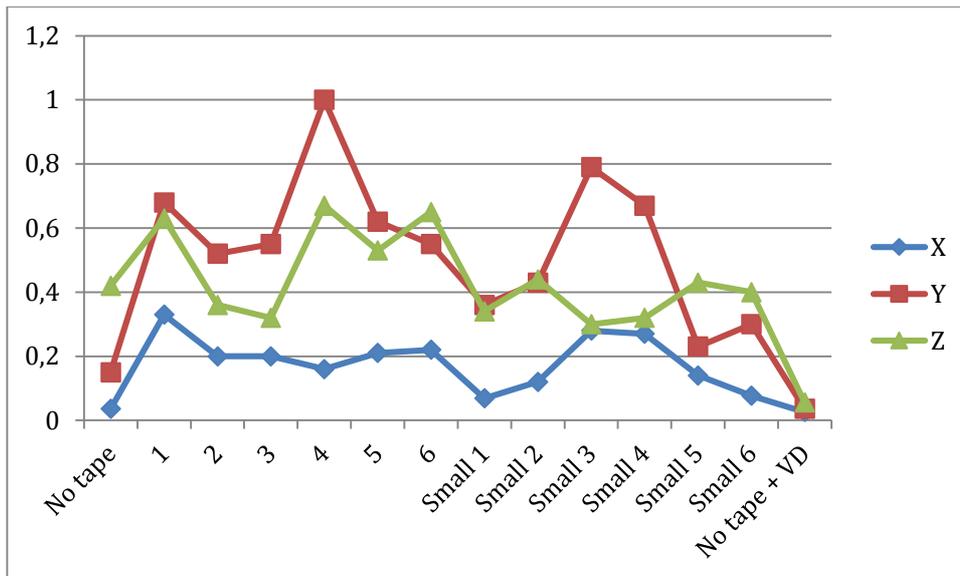


Figure 15 Graph of vibrations as a function of tape position for motor 3.

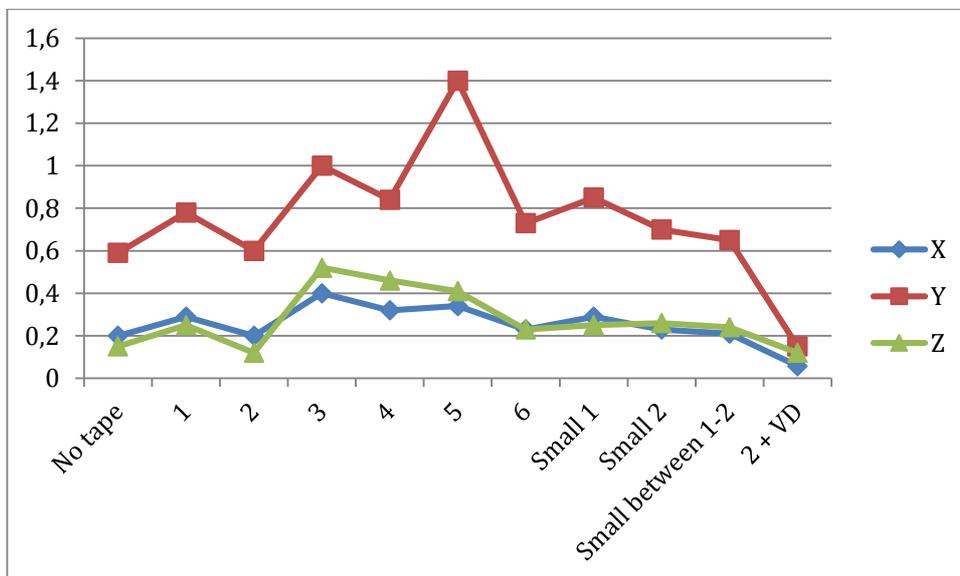


Figure 16 Graph of vibrations as a function of tape position for motor 4.

On average, vibrations were reduced by 73%.

### 3.6.2 Electromagnetic interference

Two forms of electromagnetic disturbances were improved; disturbance to the video signal and disturbance to the magnetometer.

#### 3.6.2.1 Video signal

The pictures below shows what kind of flicker that could occur during a live video stream, the pictures on the left is without the LC-filter and the pictures on the right is with the LC-filter.

The first two pictures are taken when the quadrotor is stable on the ground with armed motors (motors spinning at their lowest RPM).



Figure 17: Picture of grass without LC-filter (left) and with LC-filter (right).

As seen in the in Figure 17, sharpness and colour was improved by the LC-filter.

To make a fair comparison, screenshots have been taken in flight of the worst kind of flicker that could be seen, see Figure 18.



Figure 18: In flight flicker without LC-filter (Left) and with LC-filter (right).

The image without the LC-filter shows great lack of quality, colour and sharpness, whereas the right image shows an improved picture quality.

### **3.6.2.2 Magnetometer**

With the microcontroller 1 cm from the circuit board clear signs of magnetic disturbance could be confirmed, see Figure 19.

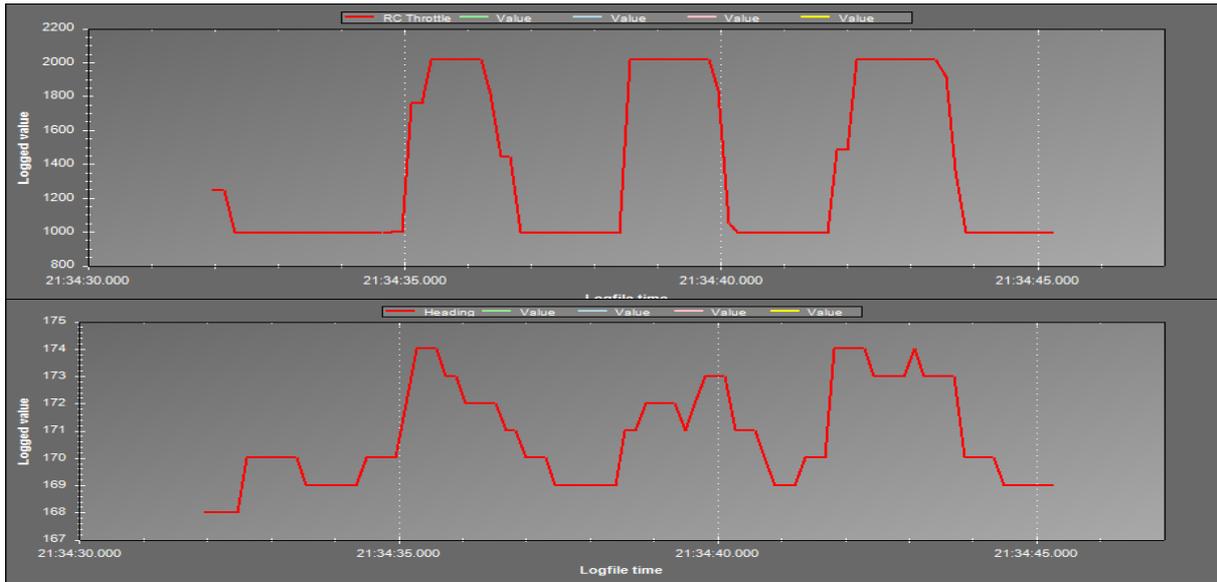


Figure 19: Magnetic direction in degrees (bottom) influenced by throttle (top).

The magnetic direction changed from 168 degrees to 174 degrees from low throttle to full throttle, a difference of 6 degrees.

This compared with the microcontroller placed 3 cm from the circuit board, Figure 20.

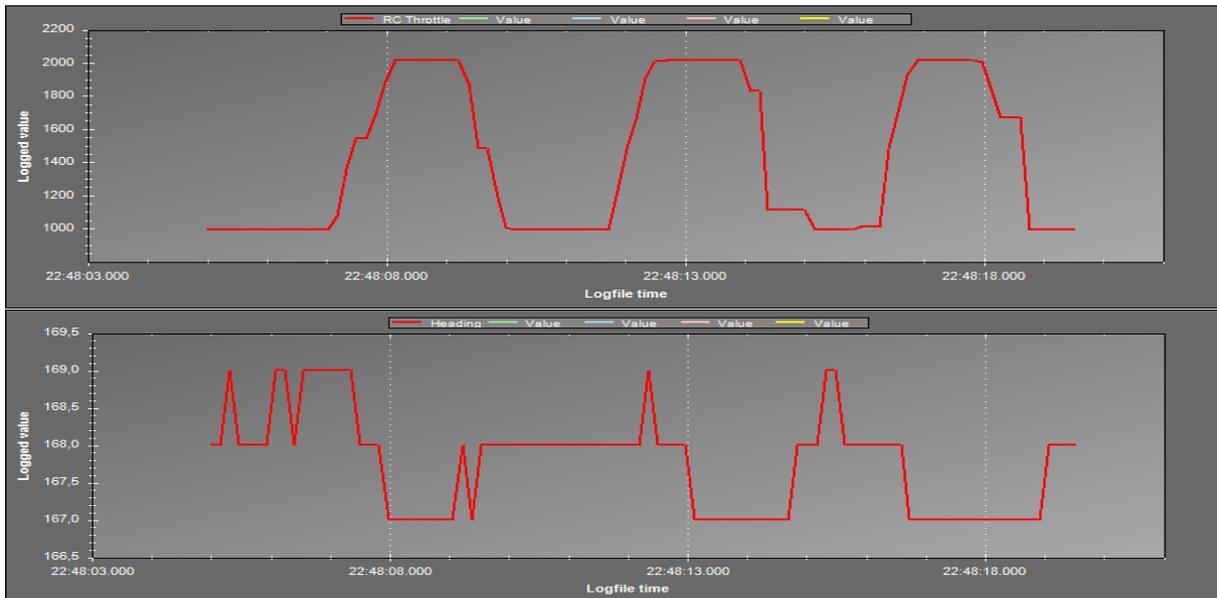


Figure 20: Magnetic direction in degrees (bottom) influenced by throttle (top).

The magnetic direction differed between 169 degrees to 167 degrees, which is a difference of 2 degrees. A clear improvement from earlier results.

### 3.6.3 Stability

Regarding stability in the air, both the barometer and the GPS were tested. Barometer for auto-level and GPS for position hold.

#### 3.6.3.1 Barometer

The two figures below shows measurements of the tests. Altitude hold was activated at 6 m without isolation to the barometer and 10 m with isolation.

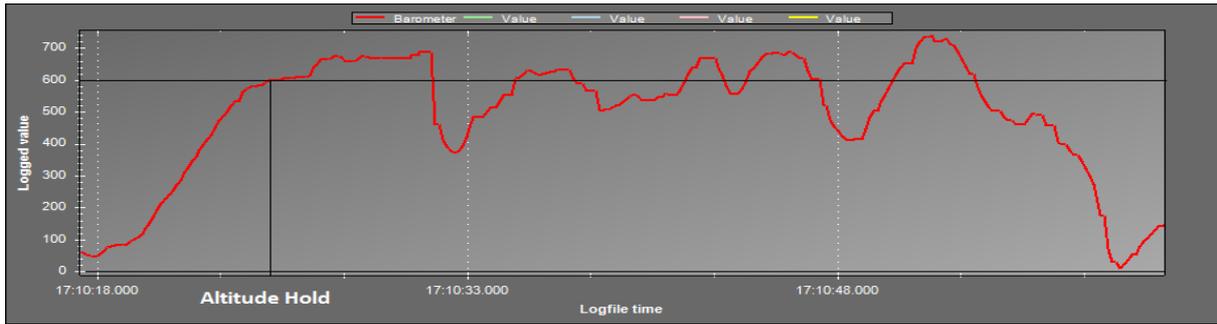


Figure 21: Altitude Hold without the barometer isolated, y-axis in cm

Figure 21 shows that the altitude oscillates around six meters and never gets to a stable point. At one point it shows that a large change in the altitude was registered, this was however not observed visually.

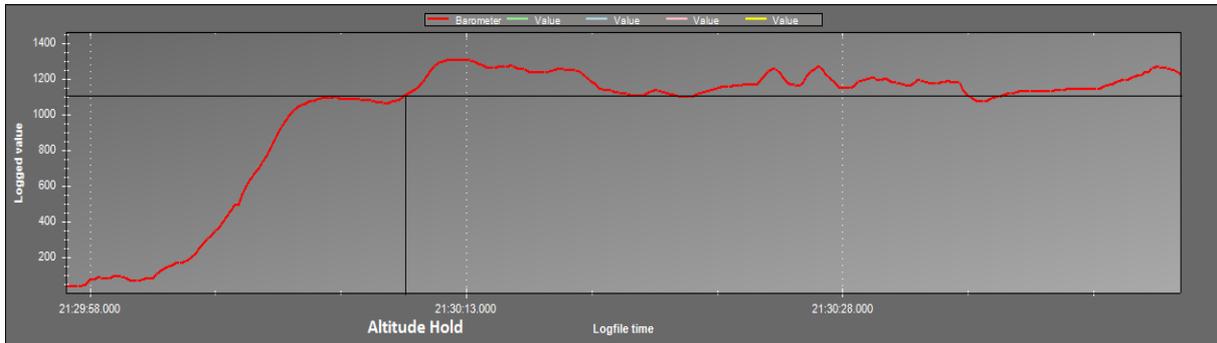


Figure 22: Altitude Hold with the barometer isolated, y-axis in centimetres

Figure 22 shows a more stable curve, the oscillation decreases, this difference comes from isolating the barometer. Observations could be made visually that the registered data was much more accurate due to the isolation.

### 3.6.3.2 GPS

Figure 23 below shows the distance to a pre-set home position over one minute when the quadrotor had position hold activated.

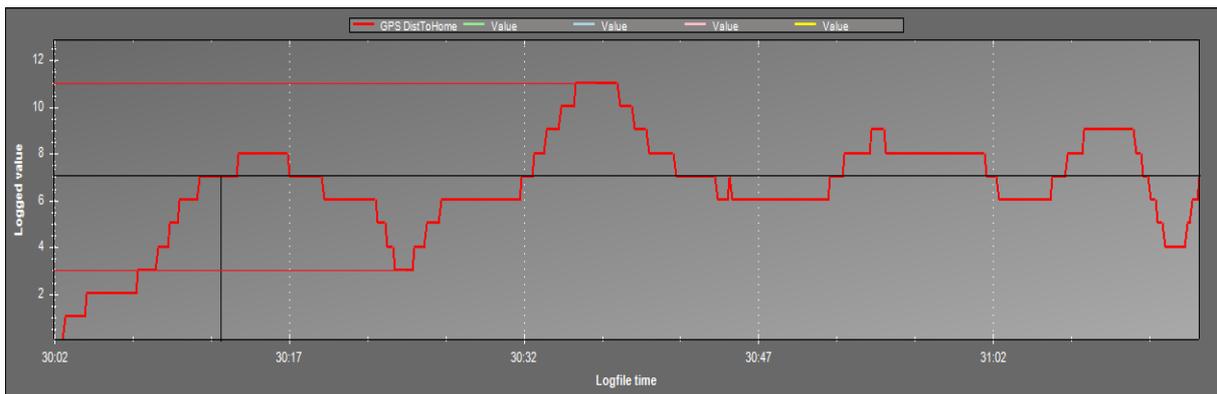


Figure 23: Position Hold using GPS, Barometer and Magnetometer, y-axis in meters

With a distance of 7 m from home position, position hold was initiated and the distance from the preset position could differ up to 4 meters, this test was conducted with an outside wind of 7 m/s.

## 4 DISCUSSION AND CONCLUSIONS

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*This chapter discusses the results gathered and concludes whether camera surveillance via quadcopters is feasible.*

### 4.1 Discussion

The quadrotor can be seen as a system with output and input information. The input information is the raw data collected from the sensors and the output is the processed data that is sent to the ESCs to then control the motors. The methods used to improve the quadrotor were focused on the hardware and the sensor readings, i.e. input information. Disturbances from internal and external factors were minimized. All the improvements were made by reducing the disturbances to the input data.

All the logging came from the microcontroller, the only reference to control this data were eye measurements. While measuring with the eye it is reasonable to expect that errors of up to 1 m could have been made when estimating the quadrotor's position. Optimal tests would have had another way to confirm logged data. For example measuring the altitude of the quadrotor with a barometer would ideally be compared with an absolute measurement. At low altitudes it is easy to see if the quadrotor is stable in space but one cannot be certain at higher altitudes.

The tests were made under special circumstances as seen in the results. Some tests were made under hard weather circumstances while others were made in a more controlled environment. However conclusions can be made that improvements have been made to the sensor reading according to the purpose. For a more accurate conclusion more tests should be made to ensure their validity.

To use a quadrotor for camera surveillance a better camera than the one used would be needed. However since the purpose of this project was to minimize the disturbances, the quality of the camera did not really matter.

When controlling the quadrotor manually in windy conditions, still keeping it steady, logged data showed that the GPS and the barometer worked very well with small deviations. The quadrotor knew its position in all three dimensions with good precision, but when the flight mode was switched to an automatic mode the quadrotor would not hold its position as well as it theoretically could. This implies that the quadrotor is not suitable for automatic surveillance with just the sensor reading improvements, however if the processing of data can be optimized the quadrotor will most certainly be able to perform automatic missions. If the sensor readings are correct then the problem lies within the processing of data.

### 4.2 Conclusions

The purpose of this project was to see if it was possible to build a quadrotor and optimize it for camera surveillance. Without any calibration or improvements the quadrotor experienced a lot of disturbance; the quadrotor was difficult to control.

Improvements were made to the input sensor data and results show that the accuracy was good enough for the quadrotor to know its own position in the three dimensional plane. It can therefore be asserted that reduction of vibrations, electromagnetic and

external disturbances has a big impact on quadrotor stability. Only improving sensor readings is however not enough to make a camera surveillance quadrotor accurate enough. Further improvements to the software processing the data must be made.

The surveillance quadrotor could be used to cover big fields or as a standby camera that would engage when the stationary surveillance detects something unusual. It could also be used in emergency situations to estimate a fire for fire fighters or a crime scene for the police.

## 5 RECOMMENDATIONS AND FUTURE WORK

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*This chapter gives recommendations for more detailed solutions and further improvements for continued work to further analyse the feasibility of camera surveillance via quadcopters.*

### 5.1 Recommendations

When flying a quadrotor and experiencing disturbance, there are many factors that could be the source of these disturbances. It is therefore important to log as much data as possible and analyse it. That would save a lot of time during troubleshooting.

The troubleshooting could be divided into two areas, the raw data and the processed data. If the raw data is incorrect then it will be very hard to find the problem in the processed data, it is therefore important to start with improving the raw data.

### 5.2 Future work

The new observed data from the sensors are now more precise and similar to the expected. Improvements can now be made to the software in regards to processing the input information so that the quadrotor can behave more precisely.

Also more tests should be made under different circumstances and with independent measuring instruments such as absolute altitude and position log to confirm the height, position and heading.

Autonomous flying could be improved by installing more components in addition to the already existing ones. A laser to get more accurate distances can be installed in all directions to be able to fly with distance feedback indoors. An OSD (On Screen Display) could be used for more feedback from the microcontroller like battery status, distance to base, direction to base, altitude, motor status and much more.

A waterproof chassis could be mounted on top of the base of the frame that would enable the quadrotor to operate in rain.

Camera gimbal for both regulated and manually controlled camera, to get more stability and be able to get a stable camera feed in great velocities.

It would also be interesting to analyse a quadrotor base and a system with several quadrotors were a quadrotor can deploy automatically and return to base to recharge its batteries automatically.

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# APPENDIX A: ECALC VALUES

<b>General</b>	Motor Cooling: medium	# of Rotors: 4 flat	Model Weight: 1000 g 35.3 oz	incl. Drive	Field Elevation: 500 m ASL 1640 ft ASL	Air Temperature: 25 °C 77 °F	Pressure (QNH): 1013 hPa 29.91 inHg	
<b>Battery Cell</b>	Type (Cont. / max. C) - charge state: LiPo 5000mAh - 65/100C - normal	Configuration: 3 S 1 P	Cell Capacity: 5000 mAh	Total Capacity: 5000 mAh	Resistance: 0.002 Ohm	Voltage: 3.7 V	C-Rate: 65 C cont 100 C max	Weight: 139 g 4.9 oz
<b>Controller</b>	Type: max 30A	cont. Current: 30 A	max. Current: 30 A		Resistance: 0.008 Ohm		Weight: 40 g 1.4 oz	
<b>Motor</b>	Manufacturer - Type (Kv): Turnigy D3530-14 (1100)	KV (w/o torque): 1100 rpm/V	no-load Current: 1.6 A @ 8 V	Limit (up to 15s): 315 W	Resistance: 0.077 Ohm	Case Length: 30 mm 1.18 inch	# mag. Poles: 10	Weight: 73 g 2.6 oz
<b>Propeller</b>	Type - yoke twist: GWS	Diameter: 10 inch	Pitch: 4.7 inch	# Blades: 2	PConst: 1.18	Gear Ratio: 1 : 1	<input type="button" value="calculate"/>	

<b>Remarks:</b>	<b>Battery</b>	<b>Motor @ Optimum Efficiency</b>	<b>Motor @ Maximum</b>	<b>Motor @ Hover</b>	<b>Total Drive</b>	<b>Multirotor</b>
Load:	17.06 C	Current: 15.55 A	Current: 21.32 A	Current: 4.17 A	Drive Weight: 956 g	All-up Weight: 1000 g
Voltage:	10.59 V	Voltage: 10.60 V	Voltage: 10.42 V	Voltage: 10.97 V	33.7 oz	35.3 oz
Rated Voltage:	11.10 V	Revolutions*: 10035 rpm	Revolutions*: 9364 rpm	Throttle (linear): 32 %	Current @ Hover: 18.67 A	add. Payload: 1713 g
Capacity:	5000 mAh	electric Power: 164.9 W	electric Power: 222.1 W	electric Power: 45.7 W	P(in) @ Hover: 185.0 W	60.4 oz
Energy:	55.5 Wh	mech. Power: 129.8 W	mech. Power: 172.3 W	mech. Power: 24.1 W	P(out) @ Hover: 96.6 W	max Tilt: 68 °
Flight Time:	3.5 min	Efficiency: 78.7 %	Efficiency: 77.6 %	Efficiency: 52.8 %	Efficiency @ Hover: 52.2 %	max Speed: 62 km/h
Mixed Flight Time:	10.2 min		est. Temperature: 56 °C 133 °F	est. Temperature: 38 °C 100 °F	Current @ max: 85.28 A	38.5 mph
Hover Flight Time:	15.3 min			specific Thrust: 5.47 g/W 0.19 oz/W	P(in) @ max: 946.6 W	with Rotor fail:
Weight:	417 g 14.7 oz				P(out) @ max: 689.3 W	
					Efficiency @ max: 72.8 %	

Figure 24: Calculations with 10 inch propellers

<b>General</b>	Motor Cooling: medium	# of Rotors: 4 flat	Model Weight: 1000 g 35.3 oz	incl. Drive	Field Elevation: 500 m ASL 1640 ft ASL	Air Temperature: 25 °C 77 °F	Pressure (QNH): 1013 hPa 29.91 inHg	
<b>Battery Cell</b>	Type (Cont. / max. C) - charge state: LiPo 5000mAh - 65/100C - normal	Configuration: 3 S 1 P	Cell Capacity: 5000 mAh	Total Capacity: 5000 mAh	Resistance: 0.002 Ohm	Voltage: 3.7 V	C-Rate: 65 C cont 100 C max	Weight: 139 g 4.9 oz
<b>Controller</b>	Type: max 30A	cont. Current: 30 A	max. Current: 30 A		Resistance: 0.008 Ohm		Weight: 40 g 1.4 oz	
<b>Motor</b>	Manufacturer - Type (Kv): Turnigy D3530-14 (1100)	KV (w/o torque): 1100 rpm/V	no-load Current: 1.6 A @ 8 V	Limit (up to 15s): 315 W	Resistance: 0.077 Ohm	Case Length: 30 mm 1.18 inch	# mag. Poles: 10	Weight: 73 g 2.6 oz
<b>Propeller</b>	Type - yoke twist: GWS	Diameter: 12 inch	Pitch: 4 inch	# Blades: 2	PConst: 1.18	Gear Ratio: 1 : 1	<input type="button" value="calculate"/>	

<b>Remarks:</b>	<b>Battery</b>	<b>Motor @ Optimum Efficiency</b>	<b>Motor @ Maximum</b>	<b>Motor @ Hover</b>	<b>Total Drive</b>	<b>Multirotor</b>
Load:	23.34 C	Current: 15.55 A	Current: 29.17 A	Current: 3.79 A	Drive Weight: 956 g	All-up Weight: 1000 g
Voltage:	10.40 V	Voltage: 10.60 V	Voltage: 10.17 V	Voltage: 10.98 V	33.7 oz	35.3 oz
Rated Voltage:	11.10 V	Revolutions*: 10035 rpm	Revolutions*: 8451 rpm	Throttle (linear): 22 %	Current @ Hover: 15.15 A	add. Payload: 2740 g
Capacity:	5000 mAh	electric Power: 164.9 W	electric Power: 296.6 W	electric Power: 41.6 W	P(in) @ Hover: 168.1 W	96.6 oz
Energy:	55.5 Wh	mech. Power: 129.8 W	mech. Power: 218.2 W	mech. Power: 20.1 W	P(out) @ Hover: 80.5 W	max Tilt: 74 °
Flight Time:	2.6 min	Efficiency: 78.7 %	Efficiency: 73.6 %	Efficiency: 48.4 %	Efficiency @ Hover: 47.9 %	max Speed: 50 km/h
Mixed Flight Time:	10.1 min		est. Temperature: 73 °C 163 °F	est. Temperature: 38 °C 100 °F	Current @ max: 116.68 A	31.1 mph
Hover Flight Time:	16.8 min			specific Thrust: 6.01 g/W 0.21 oz/W	P(in) @ max: 1295.2 W	with Rotor fail:
Weight:	417 g 14.7 oz				P(out) @ max: 872.8 W	
					Efficiency @ max: 67.4 %	

Figure 25: Calculations with 12 inch propellers

# APPENDIX B: PID-CONTROLLER

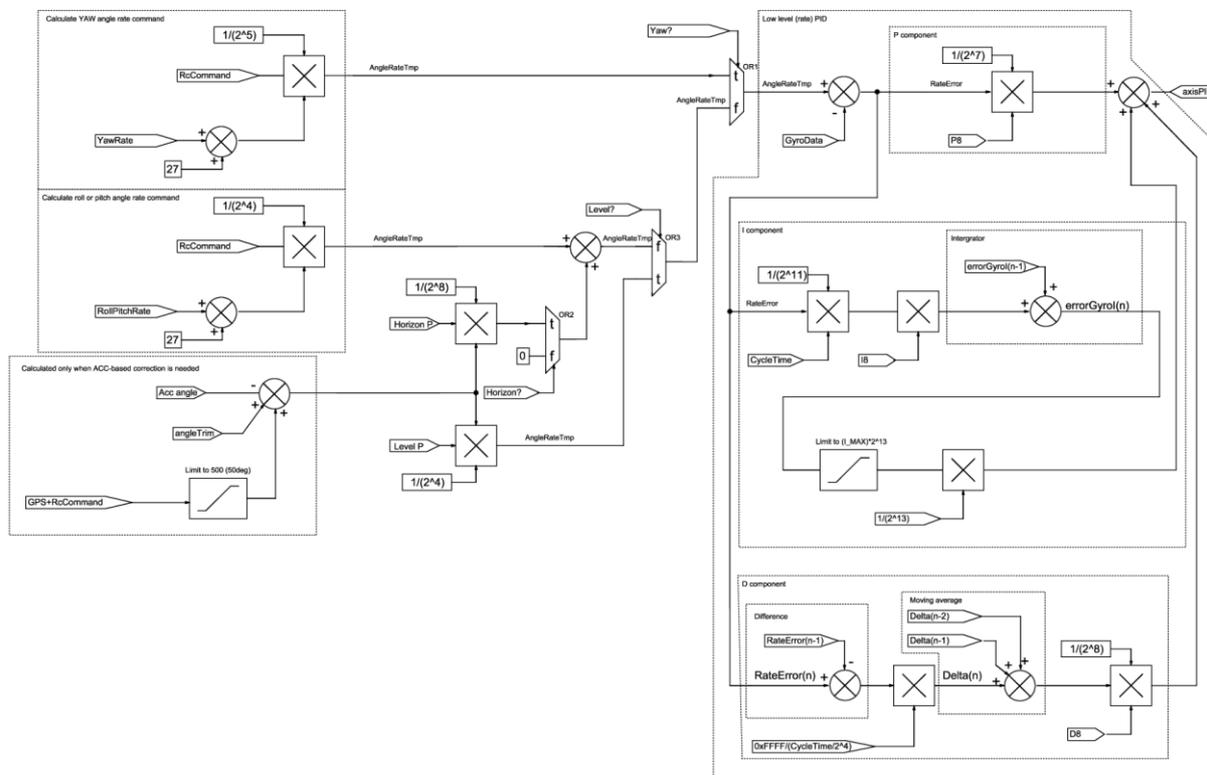


Figure 26. Implementation of PID controller in the quadrotor. (Khoroshko, 2013)

## APPENDIX C: COMPLETE CIRCUIT

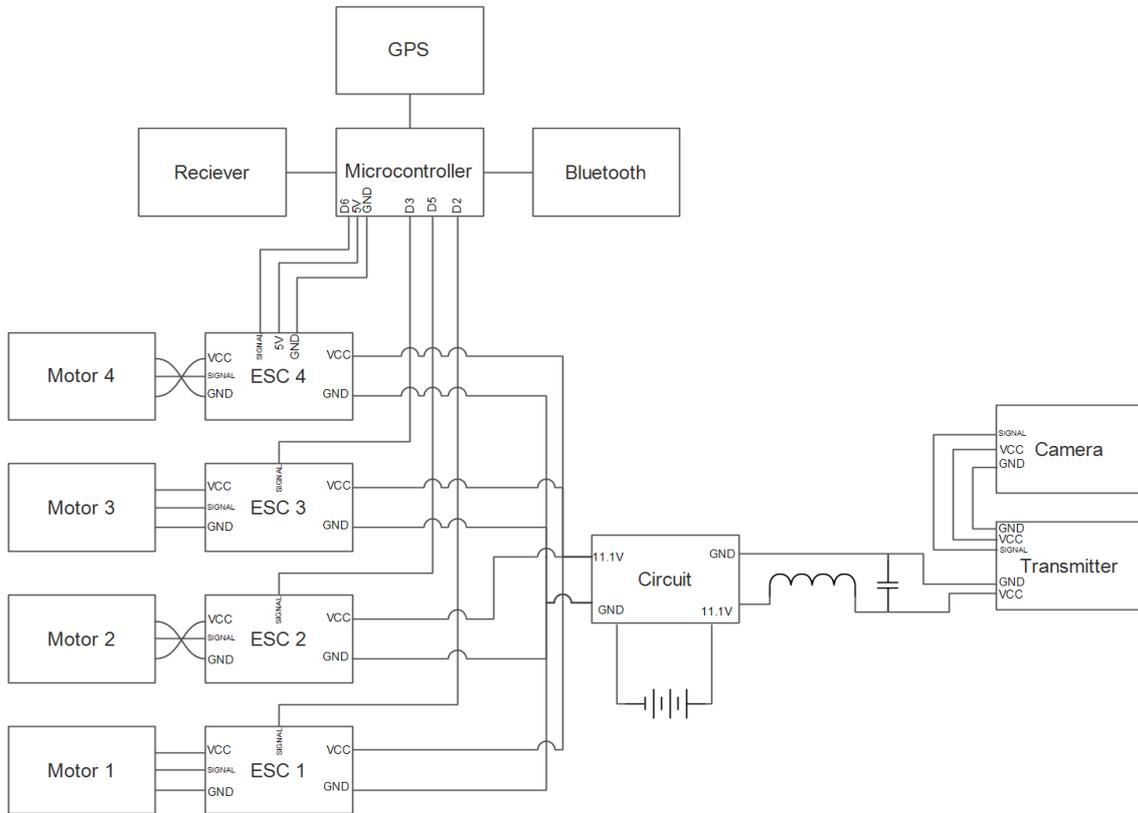


Figure 27. Complete circuit for the quadrotor.

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