

Saimaa University of Applied Sciences
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**The Design, Construction and Implementation of
an Autonomous Outdoor Quadcopter using an
RPi microcomputer and a MultiWii flight controller**

Thesis 2017

Abstract

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Instructor: Lecturer Timo Eloranta, Saimaa University of Applied Sciences

The purpose of the present study was to design and construct an outdoor aerial vehicle, called a quadcopter, with autonomous flight functions, and to install within the vehicle a video streaming system. The thesis also includes a research study on a number of practical applications of such a working model. Throughout the project, the principal method of study relied upon has been independent research.

Pertinent data were collected in the Lappeenranta Academic Library and from sources on the Internet. The study was carried out at the Saimaa University of Applied Sciences in the Department of Mechanical Engineering and Production Technology. Additional practical data for the thesis were gathered from technical literature and Internet sources, with advice and recommendations from Saimaa University lecturers.

The construction phase of the study resulted in the creation of an operational quadcopter which achieved autonomous flight. Further research led to an examination of some of the ways in which such a low-budget quadcopter could be put to use.

An additional study will be required to increase the quadcopter's flying time and range. Eventually, such a model-sized, working aerial vehicle could be utilized by individuals, organisations and governmental agencies.

Keywords: quadcopter, quadrotor, UAV (Unmanned Aerial Vehicle), drone, MAV (Micro Air Vehicle), autonomous flight, RPi (Raspberry Pi) microcomputer, MultiWii flight controller.

Table of contents

| | |
|--|----|
| TERMINOLOGY | 4 |
| 1 INTRODUCTION | 5 |
| 1.1 Research Motivation | 5 |
| 1.2 Research Objective..... | 8 |
| 1.3 Research Scope and Approach | 8 |
| 2 BACKGROUND..... | 9 |
| 2.1 Available Quadcopter Technology | 9 |
| 2.2 Current Advances in Quadcopter Performance | 9 |
| 3 MECHANICAL DESIGN AND COMPONENTS..... | 10 |
| 3.1 Initial Concepts and Design Process | 13 |
| 3.2 Frame Design..... | 14 |
| 3.3 Motor Designs | 16 |
| 3.3.1 Theoretical Performance | 17 |
| 3.4 ESC..... | 18 |
| 3.5 Battery..... | 19 |
| 3.6 The Propellers..... | 21 |
| 4 SYSTEM ARCHITECTURE | 24 |
| 4.1 Multiwii | 24 |
| 4.1.1 Sensors..... | 25 |
| 4.1.2 Camera Gimbal..... | 27 |
| 4.2 Raspberry Pi | 29 |
| 4.2.1 Camera Server and Camera Software | 29 |
| 5 CONTROL..... | 32 |
| 5.1 Radio RX..... | 33 |
| 5.2 3DR Telemetry | 34 |
| 5.3 MultiWii PID..... | 35 |
| 5.4 MultiWii Conf..... | 37 |
| 6 EVALUATION..... | 38 |
| 6.1 Mechanical Performance | 38 |
| 6.2 Control Performance | 40 |
| 7 CONCLUSION | 41 |
| 8 Appendices | 45 |
| 9 References | 48 |

TERMINOLOGY

| | | |
|----------|---|------------------------------------|
| 1. ABS | - | Acrylonitrile Butadiene Styrene |
| 2. AC | - | Alternating Current |
| 3. BLDC | - | Brushless DC Motor |
| 4. CCW | - | Counterclockwise |
| 5. CPU | - | Central Processing Unit |
| 6. CW | - | Clockwise |
| 7. DC | - | Direct Current |
| 8. ESC | - | Electronic Speed Controller |
| 9. FC | - | Flight Controller |
| 10. FEM | - | Finite Element Method |
| 11. GPS | - | Global Positioning System |
| 12. GUI | - | Graphical User Interface |
| 13. HTML | - | Hyper Text Transfer Protocol |
| 14. IDE | - | Integrated Development Environment |
| 15. IMU | - | Inertial Measuring Unit |
| 16. LiPo | - | Lithium Polymer |
| 17. MAV | - | Micro Air Vehicle |
| 18. PID | - | Proportional Integral Derivative |
| 19. PWM | - | Pulse Width Modulation |
| 20. RC | - | Radio Controlled |
| 21. PRI | - | Raspberry Pi |
| 22. RPM | - | Revolution Per Minute |
| 23. RTMP | - | Real-Time Messaging Protocol |
| 24. Rx | - | Receiver |
| 25. SIG | - | Signal |
| 26. SF | - | Slow Flyer |
| 27. Tx | - | Transmitter |
| 28. UAV | - | Unmanned Air Vehicle |
| 29. VTOL | - | Vertical Takeoff and Landing |

1 INTRODUCTION

1.1 Research Motivation

Quadcopters of the hand-held size used for this study are currently available on the market and their use has piqued the interest of the general public. Continual advances in miniaturization and the rapid development of the electronics have allowed drones of every type and size to evolve at an accelerated pace. Interest in the field of UAVs is increasing, as their current relevance has now become a subject of significant research by governments and much speculation in the media.

In department stores and specialised shops, the average consumer can now purchase a quadcopter of the approximate size used in the present study. The prices for such aerial craft range from twenty dollars US (Eachine E010 Mini) up to five thousand dollars US and higher (DJI INSPIRE 2). The least expensive quadcopters are growing in popularity for family entertainment in parks and open fields. The medium-priced ones can be of satisfactory quality and may come with a stable camera module intended for taking aerial photos and for filming videos. The highest-priced quadcopters tend to be preferred by commercial organisations for capturing sport events in high quality video, performing surveillance and exploring vast territories. In agriculture quadcopters can help farmers to survey distant croplands and predict harvests (Anderson, 2014).



Figure 1. Quadcopter in flight

<https://www.technologyreview.com/s/526491/agricultural-drones/>

In short, quadcopters can find wide application in a range of activities, mainly those associated with aerial photography. In recent years, commercial use has extended to such enterprises as Amazon for the delivery of goods in mountainous regions.

Currently, an especially relevant topic is the utilization of quadcopters in viewing and photographing forestlands and observing wildlife in their natural habitat. This topic is a subject of research for the present study and is discussed further.

Both Finland and Russia are heavily wooded and are among the world leaders in timber exports. In fact, approximately 80% of the territory of Finland is covered by forestland. Looking after such vast expanses of forested territory is a challenging task, both for the foresters who look after the wooded forests and the rangers who are charged with caring for the resident animal populations.



Figure 2. A forest ranger visually surveying an expanse of forestland
<http://www.dfiles.me/forest-ranger-at-work.html>

Both Russia and Finland allocate significant financial sums in their annual budgets in an effort to control such vast forested territories. In addition, statistics show that the forestry budgets of both countries are, as a rule, inflated by the need to pay extra compensation to foresters and rangers who are often compelled to work in long overtime shifts.

Rangers are assigned multiple duties. These include observing and controlling wildlife populations, providing extra animal feed in winter, making arrangements for hunting parties during the hunting season, ensuring that hunters and fishermen have the appropriate licences, and engaging in the endless battle with poachers. The job becomes far more difficult in winter when severe weather conditions and deep snow can prove frustrating as the rangers attempt to carry out their responsibilities. No matter what the weather, scores of animal feeding locations must be inspected regularly, animal migrations must be monitored and, occasionally, herbivore populations need protection from predators, chief among which are wolf packs that may have grown to unnatural proportions.



Figure 3. A Russian ranger with his modest equipment
<http://afisha.68.ru/text/freetime/892910.html>

Due to the constraints of limited forestry budgets, foresters and rangers must perform their tasks with little more than a snowmobile and a navigator, through far too often their scant equipment may be limited to no more than a compass and a pair of skis. (Polyakov, 2015.)

1.2 Research Objective

The present thesis focuses on creating a quadcopter based on an RPi (RaspberryPi) microcomputer and MultiWii microcontrollers. The chief objective of the project is to design, construct and demonstrate the viability of a quadcopter-drone that could perform a variety of tasks in the fields of forestry and wildlife conservation.

Introducing a drone for the purposes described could dramatically increase the efficiency of foresters and rangers. Provided that the quadcopter is capable of performing autonomous monitoring of forested regions and wildlife, the use of such an aerial vehicle could also prove economical.

1.3 Research Scope and Approach

The present research proposes two main goals and a third potential goal:

1. Identifying principal targets and objectives
2. Design and fabricate a full-sized quadcopter prototype
3. Drafting plans for developing the quadcopter and initiating full-scale production

The first two goals have been achieved, the thesis now focuses on the result of their completion. While the third goal extends beyond the scope of the present study, it offers a pathway to proceed with future work.

2 BACKGROUND

2.1 Available Quadcopter Technology

The quadcopter (or quadrotor) represents one example of an emerging class of vehicles called MAVs (Micro Air Vehicles), which are a subclass of the vehicles called UAVs (Unmanned Aerial Vehicles). Like other MAVs, the quadcopter has already demonstrated myriad applications. First designed a century ago, modern quadcopters have evolved into small, easily maneuverable vehicles. Having proved their usefulness in aerial photography, current experimentation is allowing quadcopters to communicate intelligently with other intelligent machines, to investigate unexplored environments, and to maneuver in dense surroundings with speed and precision. These recent advances will allow quadcopters to be adapted to long-term surveillance and serve invaluable in search-and-rescue missions. Furthermore, if innovative developing technologies are combined into the quadcopter, it will be capable of advanced autonomous missions that are not currently possible with any other vehicle. (Johnson, 1994.)

Any type of UAV is popularly called a drone, though the term actually refers to any type of robot-controlled vehicle – in the case of a UAV, one that flies, but drones may also refer to other types of robot-controlled vehicles which operate on land or under water.

The quadcopter is a subclass of UAVs, which are divided according to their type of flight. In the copter-type vehicles, the propellers are arranged vertically and thus flight is due to the thrust of the propellers, whereas fixed-wing UAVs fly like a conventional airplane with the lifting force caused by the shape of the wing. The quadcopter has four motors mounted on the four arms of the frame, with each arm positioned at a 90-degree angle to the others. There are two sets of CW and CCW propellers mounted on the motors to create opposite force and thus avoid unwanted rotation during horizontal flight.

2.2 Current Advances in Quadcopter Performance

According to the author's research, the quadcopter's control elements had to be altered for autonomous flight to be achieved.

Among the most positive features of the proposed quadcopter are the low cost of its components and the relative ease of fabrication, factors which do not in any way detract from the quadcopter's performance.

A major improvement in the quadcopter for this study is the implementation of autonomous flight combined with a built-in RPi video unit. The program for video transmission and changes to the flight controller represent the author's original work.

These low-cost additions and alterations make the finished product unique among quadcopters.

3 MECHANICAL DESIGN AND COMPONENTS

The quadcopter's most visible component is its frame, which must be strong enough to withstand the varying degrees of stress exerted on it during flight. At the same time, the frame must be lightweight in order to reduce the load on the motors and to increase flight time.

There are three main axes of movement, for which the standard aerodynamic terms are pitch, roll and yaw. The following figure illustrates these axes as they apply to a fixed-wing airplane.

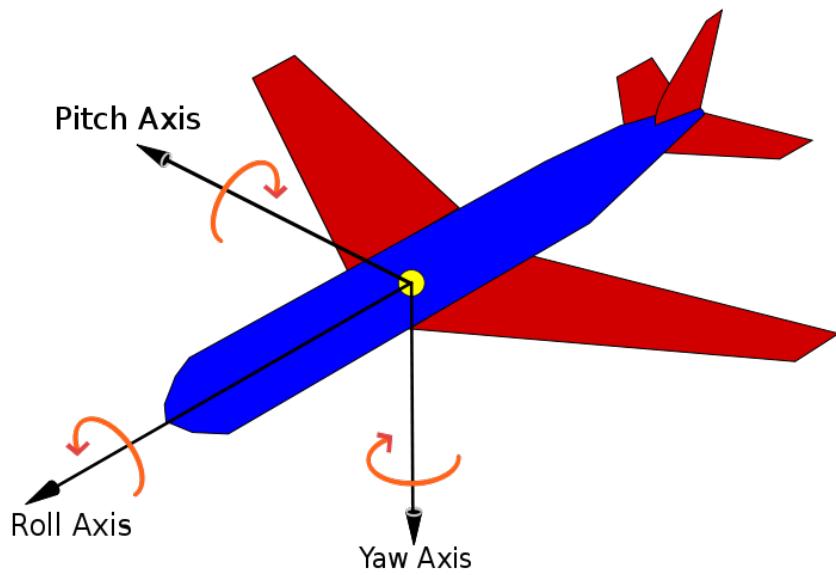


Figure 4. Pitch, roll and yaw
<https://i.stack.imgur.com/65EKz.png>

A quadcopter differs from other aircraft designed for vertical takeoff and landing in that the pitch, yaw and roll axes are controlled by the pilot applying varying degrees of thrust between the four motors. As quadcopter uses four motors with four propellers to create thrust and give lift, two of the motors must rotate clockwise and the other two anti-clockwise. Thus, with two pairs of motors, this configuration results in the torque from one motor being equal to that of the corresponding motor rotating in the opposite direction. (Pri, 2015.)

To make a motor rotate clockwise or anti-clockwise on the yaw axis, the corresponding pair of motors must increase their rotation speed. If the pilot-controller directs the craft to tilt to the right or to the left, the corresponding pair of motors must start to spin faster. Throttle control is carried out by increasing or decreasing the rotation speed of each set of the motors.

Figure 5 demonstrates the various quadcopter movements that result from changing motor speeds.

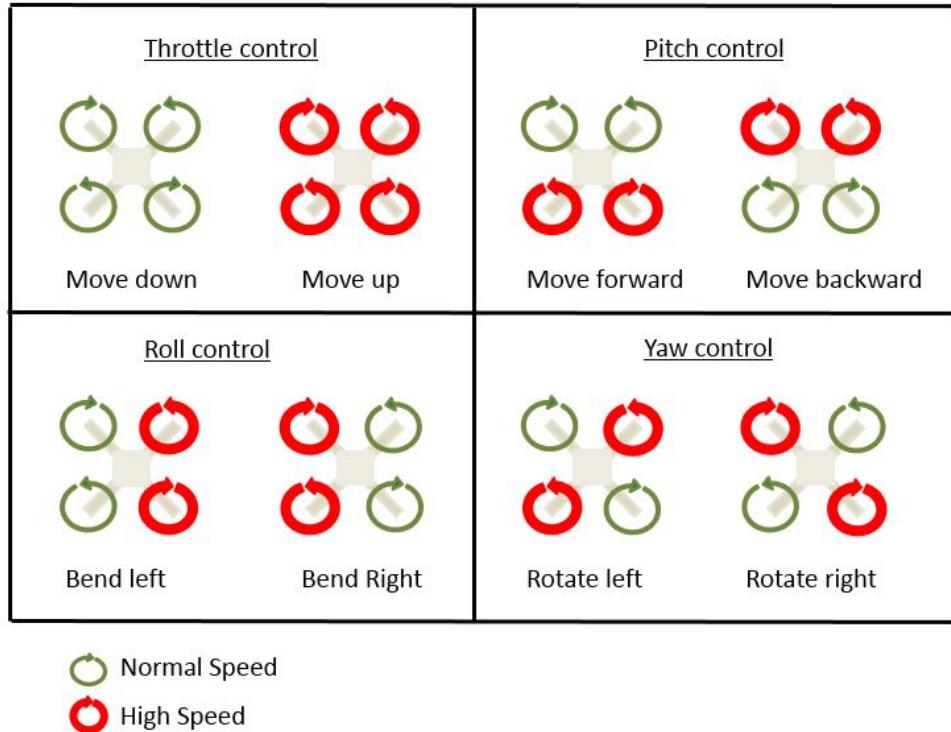


Figure 5. Quadcopter movements

<http://dronenodes.com/wp-content/uploads/2016/02/quadcopter-motion.jpg>

Direct-current brushless motors are usually chosen to power model-sized quadcopters because they produce minimal friction as compared to brushed DC motors. They are also more effective due to their high-speed range and high power output.

With this type of motor, a special controller, called Electronic Speed Controller, is mandatory. The ESC is used in DC brushless motors to control the rotation speed by changing the PWM signal coming from the transmitter and converting it into tri-phase AC power output. The subsequent chapters will present detailed descriptions of the motors and ESCs.

3.1 Initial Concepts and Design Process

Upon initiating the study, the author used a DJI Phantom 4 quadcopter as the project model. The overall concept of the workings and theoretical performance of the craft in the present study was gathered from the model described. After testing, the frame size and motor capacities proved to be in satisfactory proportion, as the vehicle chosen had a stable control system and adequately long flying time. (Phantom 4, 2016.)



Figure 6. DJI Phantom 4
<https://www.dji.com/phantom-4>

The design process began with the frame, which is 420 mm in length, indicating the distance between the paired motors. To make the appropriate calculations, the various stresses exerted on the frame had to be taken into account. The four motors propel the vehicle upwards, while the force of gravity is sufficient to allow the vehicle to move downwards. Its theoretical performance was tested by SolidWorks FEM Analysis and on an ANSYS Workbench. The figure below illustrates the static model of the assembly and the safety factor for the whole structure.

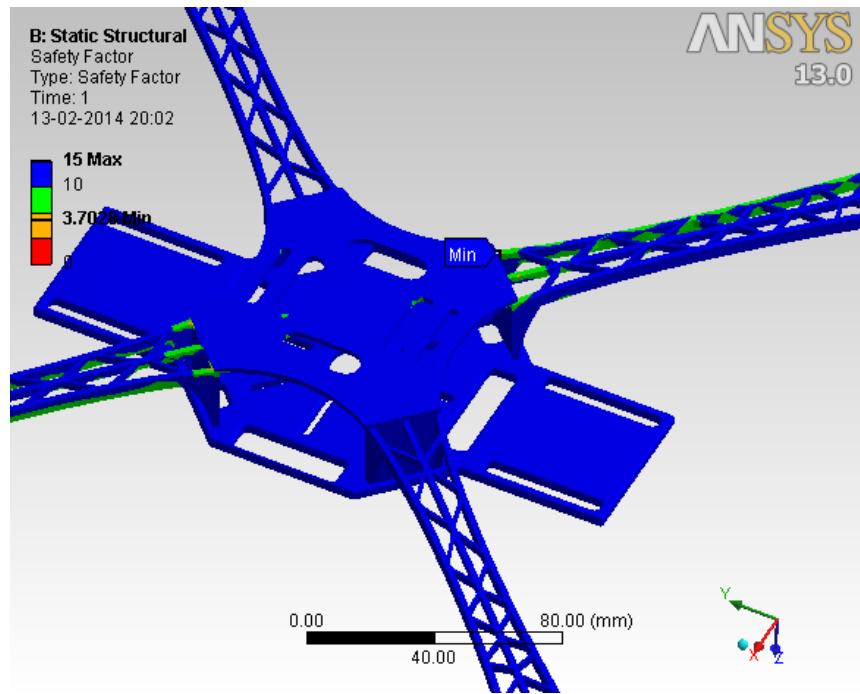


Figure 7. Safety factor of the assembled frame base

As evident in Figure 7, the stress distribution is greater on the bolted joints. The safety factor for the whole structure is rated at 3.7, which is above average for the purposes of the study.

3.2 Frame Design

As previously stated, the quadcopter frame is a critical element, as it must be strong enough to carry small loads and rigid enough to respond instantaneously to control signals. For the project, ABS plastic was selected as the main frame material. Drawing 1 (Appendix 1) details the frame dimensions. Because of budgetary constraints, the frame itself was ordered online instead of being entirely self-built. The potential does exist, however, to construct a frame by using 3D printing or laser cutting.

The stress calculations for each arm of the frame are depicted in Figure 8.

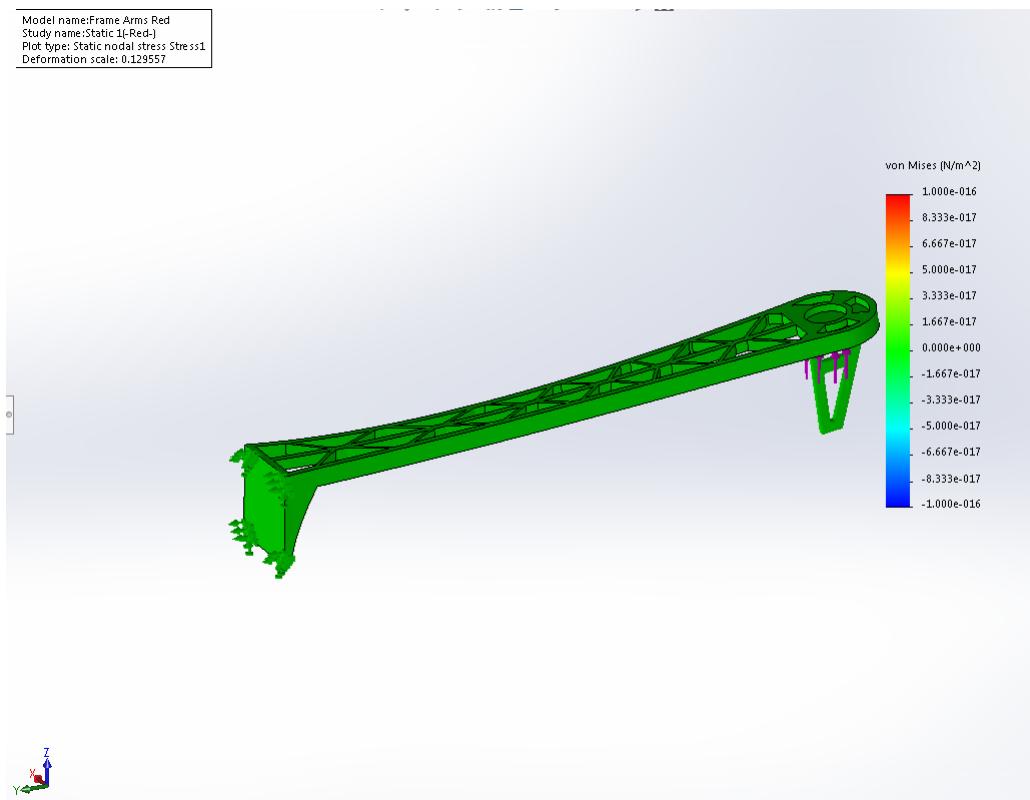


Figure 8. Static nodal stress

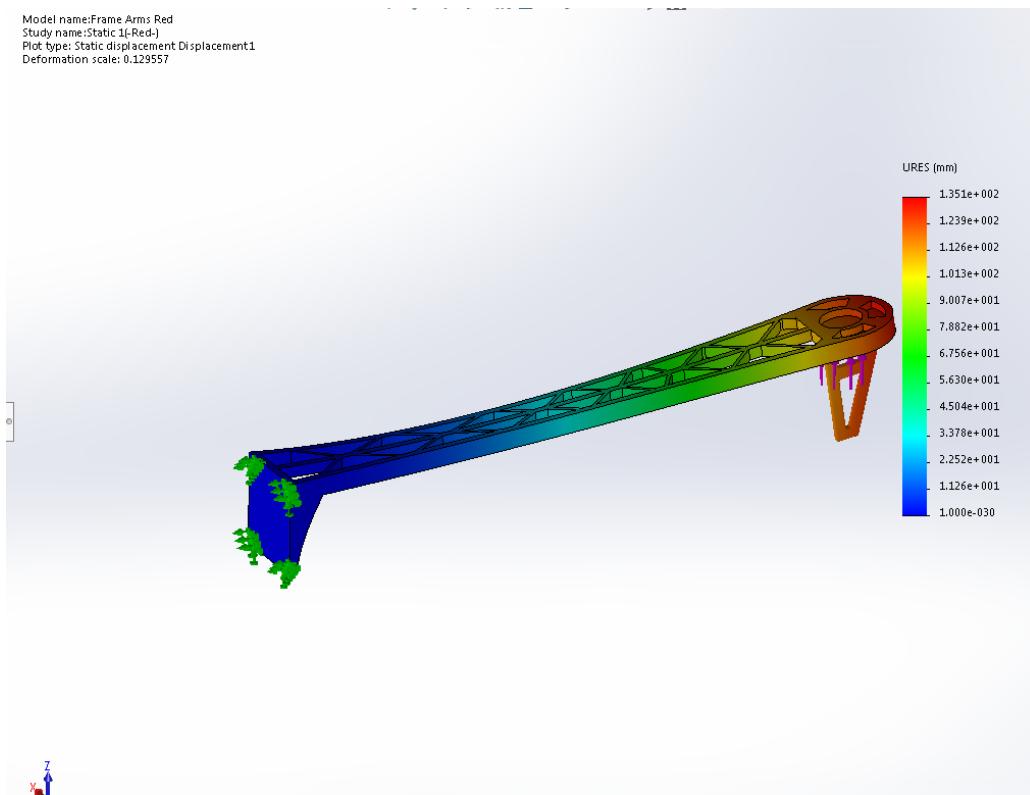


Figure 9. Static displacement

Figure 8 shows that the average stress of an arm is 1.7 N/mm^2 , which is sufficient for a total load of approximately 10.0 N, and demonstrates that the load on each arm is 2.5 N.

Figure 9 illustrates the static displacement of an arm. The result of the displacement is only slightly above the satisfactory level, as the load on each arm is 2.5 N.

However, the overall estimation of static stresses with FEM demonstrates that the frame will be adequate strength for the load and will thus prove to be sufficiently reliable for the purposes of the present study.

3.3 Motor Designs

The motors chosen are Brushless DC motors. BLDC motors are often used in quadcopters of the size required for the project. This type of a motor is easy to control and is suitable for mounting on the frame.

Each motor consists of a permanent magnet which rotates around a fixed armature. BLDC motors offer several advantages over brushed DC motors. Among the advantages are more torque per weight, reduced noise, greater reliability, longer lifetime and increased efficiency. (Prof. A. V. Javir, 2015.)



Figure 10. Turnigy Aerodrive SK3 2826-1240kv

The motors used in the project are Turnigy Aerodrive SK3 2826-1240kv brushless out-runner motors. They provide ideal power, which is 150 watts, and a

medium K_v , rate of 1240 rpm/volts. Such a degree of K_v is appropriate, as it provides the required rotational speed as well as high torque.

3.3.1 Theoretical Performance

The performance of a brushless DC-motor is nearly identical to a brushed DC-motor. The major difference lies in the BLDC's commutator being integrated into the speed controller, while a brushed DC motor's commutators are located directly inside the motor. K_v rating is the relationship between the RPM and the voltage.

For the motor chosen in the present project:

$$Kv = 1280 \left[\frac{\text{rpm}}{\text{volts}} \right]$$

By measuring the electro-mechanical relationship, the torque constant K_t can be determined as follows:

$$\text{Electrical power} * \text{efficiency} = \text{Mechanical power}$$

$$E * I * \sqrt{(3)} = N * \frac{2\pi}{60} * T$$

$$\frac{E}{N} = 0.0604599788 * \frac{T}{I}$$

where

- E = motor voltage rms [V]
- I = motor current [A]
- N = angular velocity of the motor [rpm]
- T = motor torque [Nm]

$$\frac{E}{N} = \frac{1}{K_v}$$

$$\frac{T}{I} = K_t$$

thus, the constant relationship between K_t and K_v is obtained.

$$K_t = \frac{1}{0.06046} * \frac{1}{K_v}$$

$$K_t = 0.01794 * K_v$$

The torque can be calculated as

$$T = I * K_t$$

The next step is to measure the current with ammeter and write down the values of T to the table.

3.4 ESC

An Electronic Speed Controller (ESC) is used for controlling a brushless motor.

The ESC operates at 100Hz frequency with a standard RC-signal which yields a high pulse of 1-2 milliseconds. The ESC has an internal regulator that controls the speed of the motor.



Figure 11. TURNIGY Plush 18amp Speed Controller

The ESC chosen for the project is TURNIGY Plush 18amp Speed Controller. Since the maximum current load of the motor is 16A, this type of ESC is suitable.

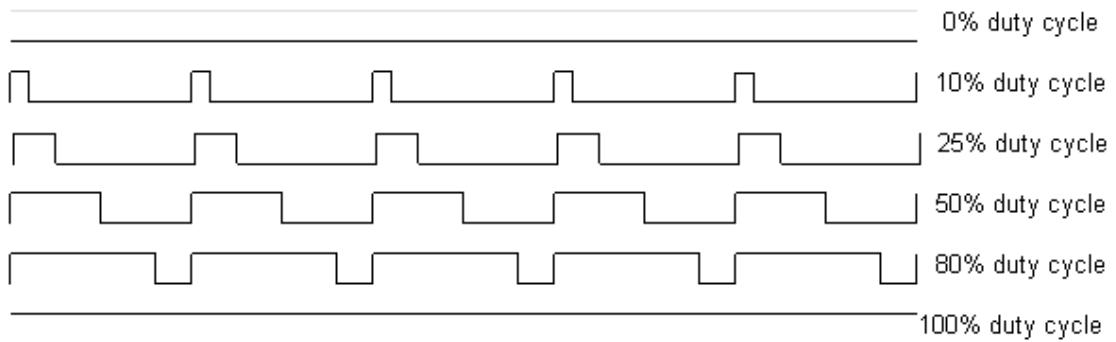


Figure 12. Example of a PWM signal

<https://www.arduino.cc/en/uploads/Tutorial/pwm1.gif>

As mentioned above, the ESC drives a brushless motor by providing the appropriate level of electrical power. The pulse signal is generated inside the flight controller and is then transmitted to the ESC. The optimal rotational speed of the motor is achieved by changing the PWM signal.

3.5 Battery

The battery is also a major component in the project, for only the battery's power supply determines the length of time that the quadcopter can remain airborne. Also of consequence is the weight factor as the battery is the heaviest component mounted in the frame. A lithium polymer (LiPo) battery was selected for the project due to its advantageous power-to-weight ratio and its ability to deliver sufficient power output (Cuong, 2011).



Figure 13. Battery used, 3000mAh

The battery that powers the motor is a three-cell LiPo battery from Turnigy. The battery yields 11.1 volts and 3000 mAh to drive the motors. It can feed 75 am-

peres continually and peak at 125 amperes. It has three LiPo cells in serial connection. Each cell is 3.7 volts, producing a total of 11.1 volts. This particular battery discharges with a 25C rating, which designates the amount of continuous current that can be drawn: $3000\text{mAh} * 25\text{C} = 75\text{A}$. For the present study, there is a 15A average current draw, by means of which the quadcopter's approximate flying time can be calculated as

$$3.0 \text{ Ah} \div 15.0 \text{ A} = 0.2 \text{ h}$$

An approximate estimation of flying time is 12 minutes at medium power consumption. In such a period of time and at an average speed of 40 km/h, the quadcopter can fly a distance of 5.0 km and then return to its launch site. (Flying Tech, 2014)

A power-distribution board is an equally important part of the project, as the RPi and MultiWii also need power. They both require 4.5 - 5.5 volts, which is well within the capacity of a regular three-cell LiPo battery. To achieve the lower voltage, a customized battery pack of four alkaline 1.2-volts (AA) batteries was assembled.



Figure 14. 4.8 V Battery pack

Figure 14 is a photograph of the 4.8-volts battery pack. It has a Mini-USB plug for connecting to the RPi microcomputer which also redirects power to the MultiWii flight controller. The battery pack is light enough to be carried by the quadcopter and yet can provide sufficient power for both the RPi and the flight controller.

3.6 The Propellers

Choosing the correct type of propeller was based on two factors: the power output of the motors and the battery capacity. According to calculations, the optimal choice would be an 8045 SF propeller, which is fabricated from durable, lightweight plastic, measures 8 inches in length and is designed with a 4.5-inch pitch. The pitch indicates that with each rotation the propeller moves 6 inches in a translative direction. (Warren, 2004)

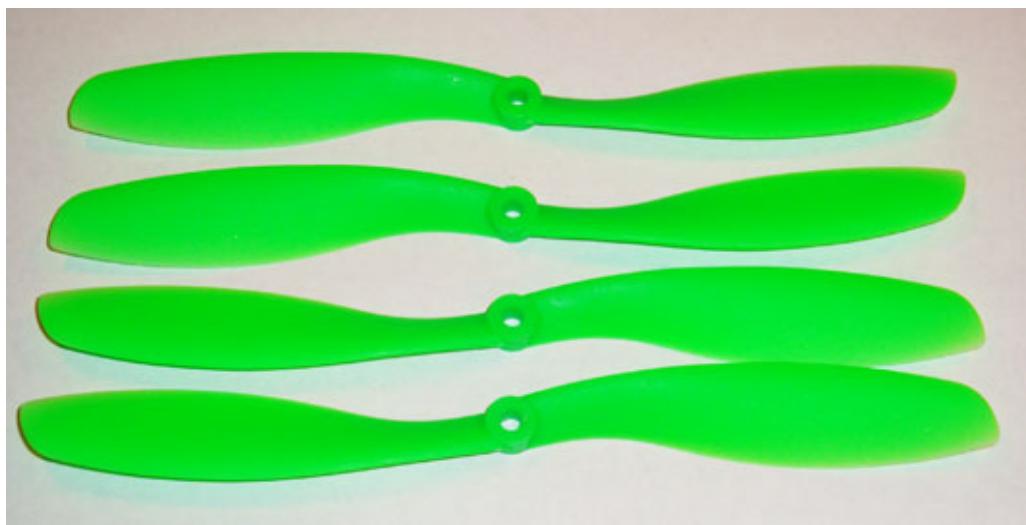


Figure 15. Four SF 8045 propellers, two CW and two CCW

The chosen propellers are sturdy enough to lift a loaded quadcopter, and as they are relatively inexpensive, several extras can find a place in the project's budget. These extras are an important addition, as the propellers represent the most brittle and overworked elements of the quadcopter's movable parts. In addition, the type of propellers used in the project are sufficiently well balanced and of low vibration, thus eliminating the need to balance them prior to the quadcopter's first flight.

The aerodynamic features of the propellers are of keen importance and are relevant to the design and construction of any aircraft. There are three main forces acting on the quadcopter while in flight. These are thrust, centrifugal force and torsion. Thrust is the force acting on the quadcopter's vertical movement, which is a direct result of the propellers' rotation. Centrifugal force is also a result of

propeller rotation, but tends to spin the blades out of and away from the centre. In the case of the present study, the centrifugal force involved in the operation of the propellers can be disregarded, as its effect on the quadcopter is virtually negligible. The torsion, or twisting force, is a feature of the blade design and is caused by the resultant air forces which tend to twist the blades towards a lower blade angle.

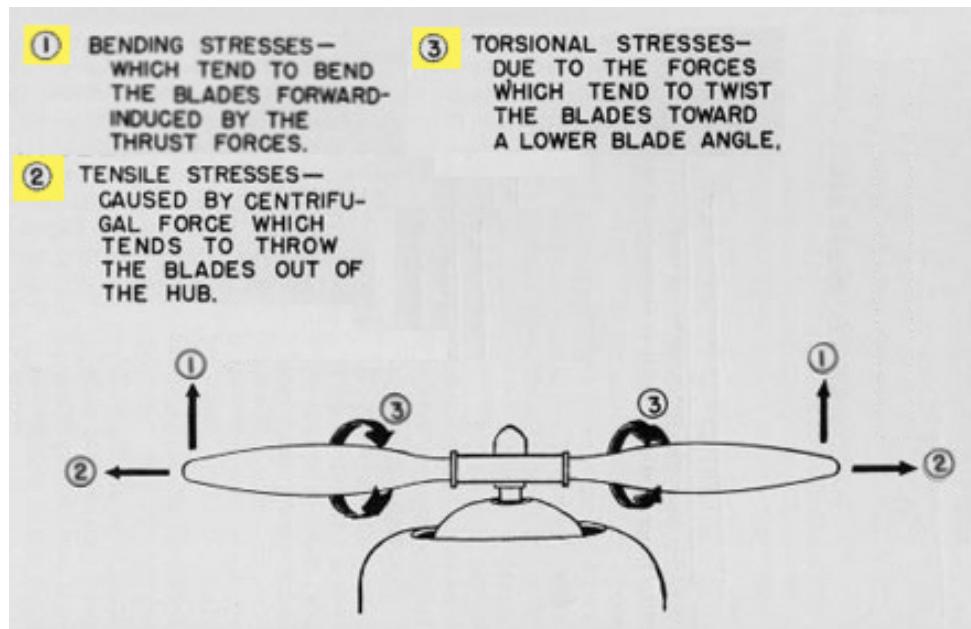


Figure 16. Propeller aerodynamics

Three main stresses act upon the propellers while the quadcopter is in flight. These are bending stress, tensile stress and torsion stress. Bending stress is caused by the thrust force, which tends to bend the blade forward as the quadcopter moves through the air. Tensile stress is caused by centrifugal force, which for the purposes of the present study is insignificant. Torsion stress is produced in the rotating blades by their dual twisting motions, one of which is the stress resulting from the action of the blade and is referred to as the aerodynamic twisting moment. (Thai Technics, 2002.).

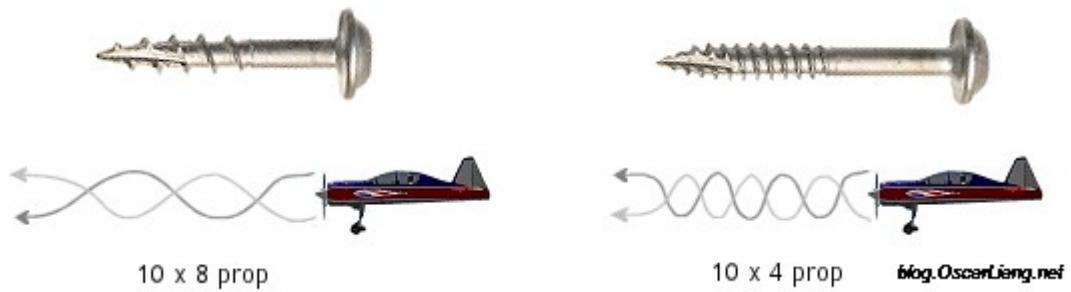


Figure 17. An illustration of propeller pitch

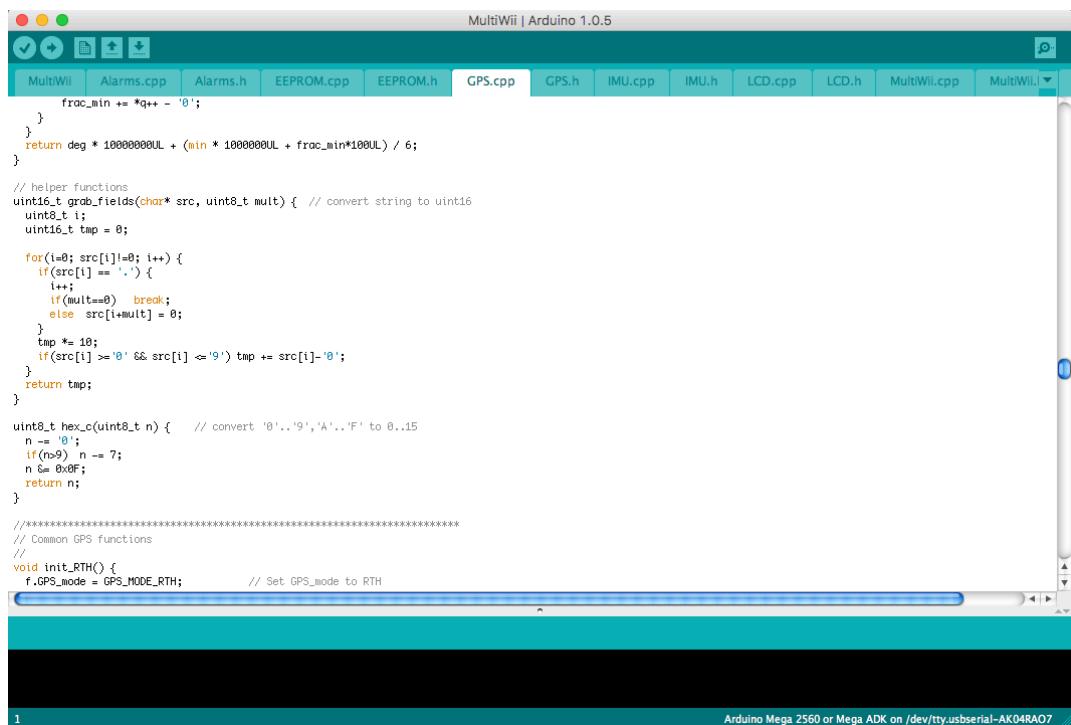
Each propeller is defined by its rotational direction, length and degree of pitch. An 8045 value means that the propeller has an 8-inch diameter and a 4.5-inch pitch. Different values of pitch affect the quadcopter's performance while in flight. A higher pitch value leads to a greater draw of air current, but as more air is drawn, a greater load is placed on the blade as it spins. As a rule, a larger propeller or one with a higher pitch will increase the vehicle's speed but will also require more power. (Liang, 2013.)

4 SYSTEM ARCHITECTURE

As designed and constructed, the author's quadcopter is based on a MultiWii flight controller and an RPi microcomputer, the second of which is used for onboard video reception and transmission. In future quadcopter designs, it may be more expedient to eliminate the MultiWii flight controller altogether and utilise only the RPi microcomputer, as the craft also has different sensors, a radio receiver, 3DR telemetry and a gimbal-system camera.

4.1 Multiwii

The flight controller (FC) is the controlling brain centre of any UAV. Inside the FC there are numerous essential components, such as an IMU, a PID controller, the PWM signal output, a processor and many others. The present study uses a MultiWii flight controller because it operates reliably, does not present a major expenditure and supports all of the required features, including GPS navigation. (MultiWii, 2015.)



The screenshot shows the Arduino IDE interface with the title bar "MultiWii | Arduino 1.0.5". The menu bar includes File, Edit, Tools, Sketch, Help, and a Language dropdown set to English. The toolbar contains icons for Open, Save, Print, and other functions. The main window displays the "GPS.cpp" file from the MultiWii library. The code includes helper functions like `grab_fields` for parsing strings and `hex_c` for converting hex characters to integers. It also contains comments for common GPS functions and an `init_RTH()` function. The status bar at the bottom right indicates "Arduino Mega 2560 or Mega ADK on /dev/tty.usbserial-AK04RAO7".

```
MultiWii | Arduino 1.0.5
File Edit Tools Sketch Help Language: English
GPS.cpp
MultiWii Alarms.cpp Alarms.h EEPROM.cpp EEPROM.h GPS.h GPS.cpp IMU.cpp IMU.h LCD.cpp LCD.h MultiWii.cpp MultiWii.h

// helper functions
uint16_t grab_fields(char* src, uint8_t mult) { // convert string to uint16
    uint8_t i;
    uint16_t tmp = 0;

    for(i=0; src[i]>=0; i++) {
        if(src[i] == '.') {
            i++;
            if(mult==0) break;
            else src[i+mult] = 0;
        }
        tmp *= 10;
        if(src[i] >='0' && src[i] <='9') tmp += src[i]-'0';
    }
    return tmp;
}

uint8_t hex_c(uint8_t n) { // convert '0'..'9','A'..'F' to 0..15
    n -= '0';
    if(n>9) n -= 7;
    n <= 0x0F;
    return n;
}

//*****
// Common GPS functions
//
void init_RTH() {
    f_GPS_mode = GPS_MODE_RTH;
}
```

Figure 18. Arduino IDE: GPS implementation code

The programming aspect of the project was done in Arduino IDE, as depicted in Figure 18. Open-source Arduino software makes modifying the code and up-

loading it to the flight controller simple procedures. This software works exceptionally well with a MultiWii boards as both are based on Arduino open-source software.

MultiWii software contains an important file, which is called Config.h. Both basic and advanced setups can be accomplished in this file. Tuning, calibrating and using optional features must be done in advance of the quadcopter's initial flight.

4.1.1 Sensors

The sensors in a quadcopter also play a vital role, as they gather all of the pertinent information and send it to the flight controller for further processing. Without having this information, the quadcopter cannot function effectively.

There is a number of different types of sensors in a quadcopter. These are a gyroscope, an accelerometer, a magnetometer, a barometer, a GPS, a ultrasonic distance sensor and others. The gyroscope, accelerometer, magnetometer and barometer are usually built into a single component called the Inertial Measuring Unit (IMU). A GPS and ultrasonic sensor are optional features, though they significantly improve a quadcopter's orientation while in flight.



Figure 19. IMU board

For this project, the sensor board is an internal feature of the flight controller. The board helps to translate information directly from the IMU to the processor, which significantly increases processing speed.

With the help of an IMU, the quadcopter can instantly obtain information on its flight orientation. The gyroscope helps the quadcopter to maintain an absolute angular reference, while the accelerometer measures the degree of the vehicle's rotation in space. These various sensors are most often combined with the GPS system through a digital filtering system. The accelerometer and gyro provide short-term data, while the GPS corrects any of the accumulated errors of the IMU. Also, a barometer sensor is used outdoors to maintain a particular altitude. (Benriplay, 2014.)



Figure 20. Ultrasonic distance sensor

Figure 20 depicts an ultrasonic distance sensor. Such a sensor is chiefly used within an enclosed space. It can measure the distance from the quadcopter to a surface below it, so that the vehicle can instantly climb in altitude. This type of sensor is an analog, whereby a single input/output pin (SIG) triggers an ultrasonic burst and then acts upon the echo's return impulse. The unit measures the time that elapses for the echo's return, and then transmits the information to the MultiWii as a pulse signal via the same input/output pin.

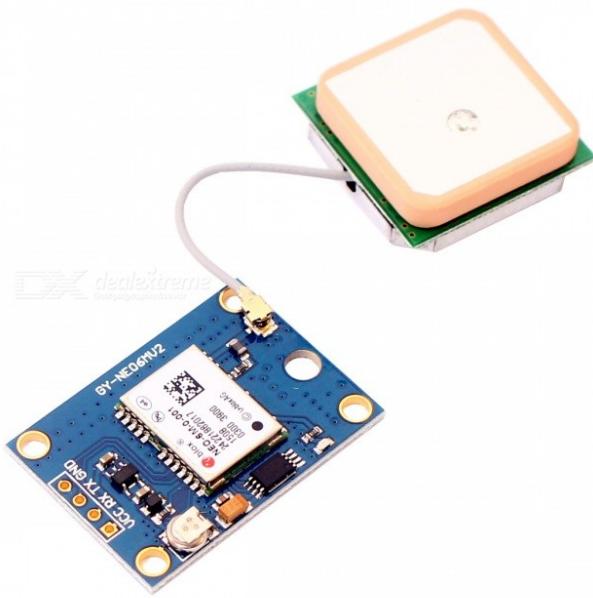


Figure 21. GPS unit with antenna

In Figure 21, a GPS unit is shown with its connected antenna. During outdoor flight, the GPS plays an important role. Constantly assisted by this unit, the quadcopter can achieve autonomous flight, as well as perform other movements such as holding its position, maintaining altitude and returning to its launch site. These functions are built into MultiWii firmware, which, like Arduino, is open-source software.

There are also many other different types of sensors, such as voltage and temperature monitors. Though they can improve quadcopter performance, they were not employed in the present project.

4.1.2 Camera Gimbal

To obtain a stable video recording, it became obvious that a special device was needed. For this project, the author built a camera gimbal with servo motors in order to stabilize the video recording.



Figure 22. Camera Gimbal mounted on the frame

When the camera is mounted to the quadcopter and is then launched into flight, the video picture can be negatively affected by the shaking motion of the vehicle's constant changes in pitch, roll and yaw. The motors also cause significant vibration which, in turn, vibrates the camera. Such shaking movements and vibrations cannot be eliminated by even the best flight controller, which stabilises only the quadcopter's basic movements while in flight. However, there will always be disturbances of one sort or another which the flight controller cannot lessen. Therefore, a reliable camera gimbal is an essential addition. For this purpose, the author customized a pan-tilt bracket with two servo motors, which were then connected to MultiWii to control them. (Corrigan, 2016.)

The resulting effect of these additions was excellent control over the pitch and roll axes. The computer program for stabilizing the quadcopter was partially created by the author. Along with stabilization, the program provided the additional benefits of high quality video transmitting and remote control of the camera gimbal.

4.2 Raspberry Pi

Possibly the greatest innovation of the work done on the quadcopter for the present study is the use of an RPi microcomputer. Its use proved to be an ideal asset for video streaming, video processing and ease of programming, which are its basic functions.

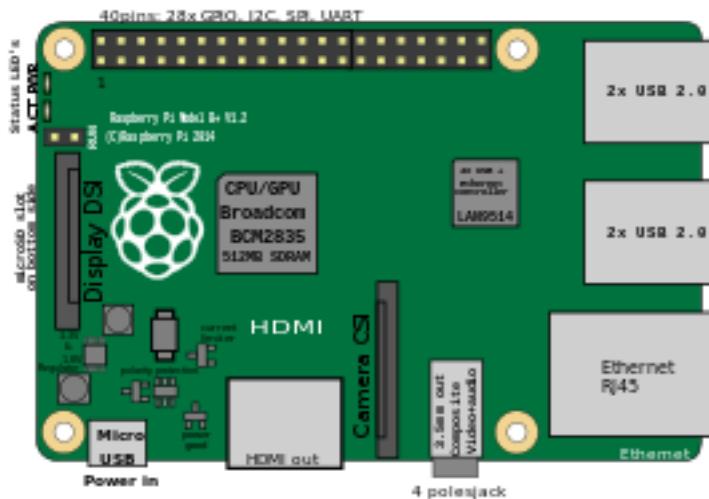


Figure 23. RPi 2

The first-person view option is achieved with the help of an RPi Camera module to process the video data and then transmit it to the microcomputer, where the video streaming process is done by Wi-Fi. Transmission can be performed up to a radius of 300 metres. The RPi addition makes this particular quadcopter unique because of the use of two microcontrollers which can be piloted with either of two different devices, a remote control or a Smartphone.

During future development, a more powerful vision system can be designed and implemented. Such functions as pattern, face recognition and close-up surveillance can all be performed with the help of an RPi.

4.2.1 Camera Server and Camera Software

For successful video transmission, the camera module and RPi must be used in conjunction with a camera server and the appropriate software. The author created most of the programming and installed the server, aspects of the project which add to the quadcopter's uniqueness.

The camera server is based on NGINX, which is a lightweight web server application that can be installed in the RPi. Following the same principles that apply to an Apache server, NGINX can serve HTML (Hypertext Markup language) files over HTTP (Hypertext Transfer Protocol). Within the NGINX server the author installed a private RTMP (Real-Time Messaging Protocol) server inside the NGINX component. The RTMP server was originally created to allow the parallel streaming of audio, video and data messages over the Internet between a flash player and a server (Parmar & Thornburgh, 2012.).

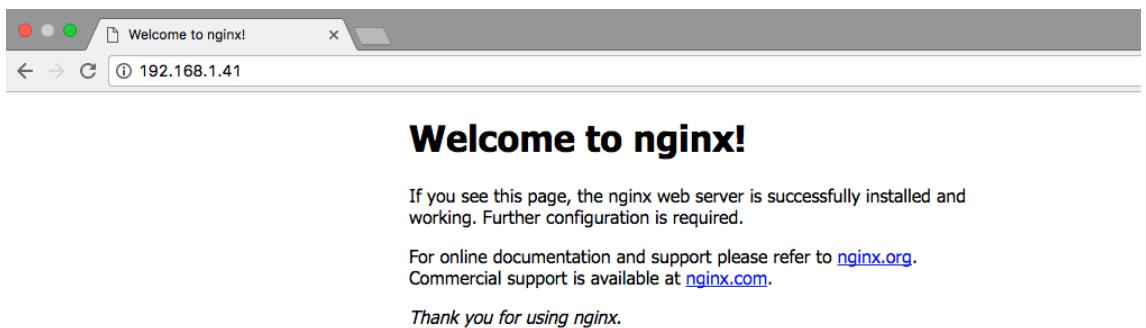
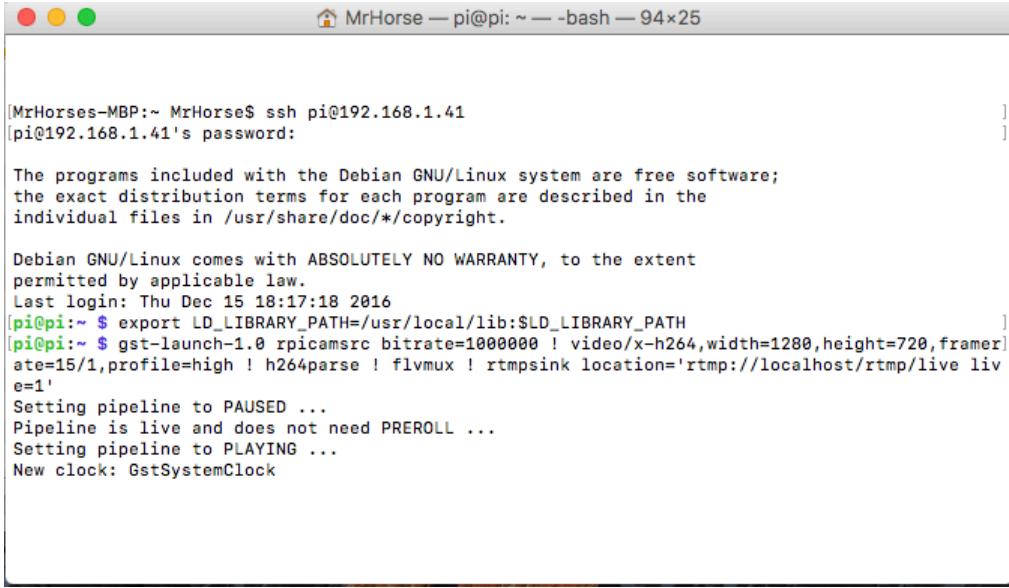


Figure 24. Operating the NGINX RTMP server

The author installed the server and completed the necessary compilation. Accomplishing these tasks require more than five hours, chiefly because of the increased CPU use of the RPi.

Reliable camera software is essential for achieving high-quality video processing. Therefore, GStreamer camera software was chosen for the project as its use allows passing the video stream through a local network to a streaming media server. GStreamer 1.10.2 provides a library for constructing graphs of the components involved in producing media. The application supports a range extending from simple playback and audio-video streaming to complex audio-video processing. In addition, different codices and improved filtration technology can be applied with the help of a simple, generic interface. (GStreamer OSMF, 2016.)



```

MrHorse-MBP:~ MrHorse$ ssh pi@192.168.1.41
[pi@192.168.1.41's password:

The programs included with the Debian GNU/Linux system are free software;
the exact distribution terms for each program are described in the
individual files in /usr/share/doc/*copyright.

Debian GNU/Linux comes with ABSOLUTELY NO WARRANTY, to the extent
permitted by applicable law.
Last login: Thu Dec 15 18:17:18 2016
[pi@pi:~ $ export LD_LIBRARY_PATH=/usr/local/lib:$LD_LIBRARY_PATH
[pi@pi:~ $ gst-launch-1.0 rpicamsrc bitrate=1000000 ! video/x-h264,width=1280,height=720,framerate=15/1,profile=high ! h264parse ! flvmux ! rtmpsink location='rtmp://localhost/rtmp/live live=1'
Setting pipeline to PAUSED ...
Pipeline is live and does not need PREROLL ...
Setting pipeline to PLAYING ...
New clock: GstSystemClock

```

Figure 25. GStreamer screenshot

A critical element of GStreamer application is `gst-rpicamsrc`, which can be implemented in the RPi to increase its functionality and thus make it possible to capture the GStreamer source element from the RPi camera module. The installation procedure was achieved immediately following the NGINX implementation, which made it possible to test the whole program. Previewing the broadcast video is possible on any device that supports network streaming, including laptop computer, or a Smartphone with a video player installed. (Nginx: Linux Packages, 2013.)

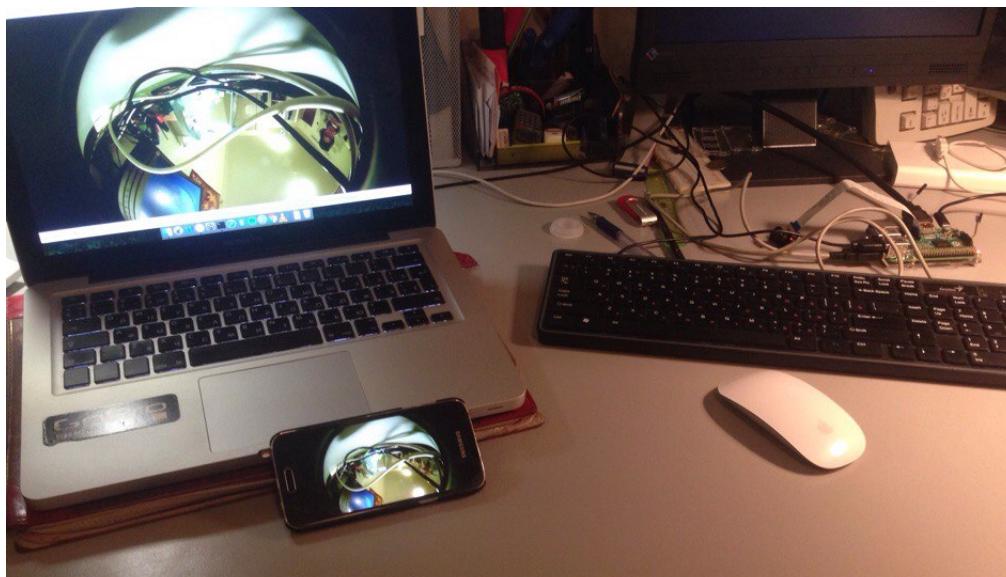


Figure 26. Video broadcast in action

During the testing period, it became apparent that many video players add one to two seconds of lag because of buffering. The solution for bypassing the buffering was to open the RTMP streaming on the MXPlayer of an Android Smartphone, to shut off the RPi's streaming and to wait for approximately five seconds before restarting the streaming. In the end, the buffering time was reduced to an insignificant 300 ms.

The overall results of the video streaming were as follows:

- Good quality for a first-person video view
- 720p quality with 1 m bitrate and 15 fraps per second
- CPU usage of the RPi at 18 - 21 %

5 CONTROL

An active control system is a necessity for dealing with so many hardware and software components. It is also essential to maintain stable control if the quadcopter is to perform well and reliably. The control process is divided into three parts: the radio system, 3DR telemetry and PID controller. The radio system is used during testing and for establishing flight procedures within a site area. The 3DR telemetry is capable of sending and receiving information on longer distances and during autonomous flight mode. The PID controller is located within the MultiWii microcontroller and is used for minimizing errors by adjusting the control inputs.

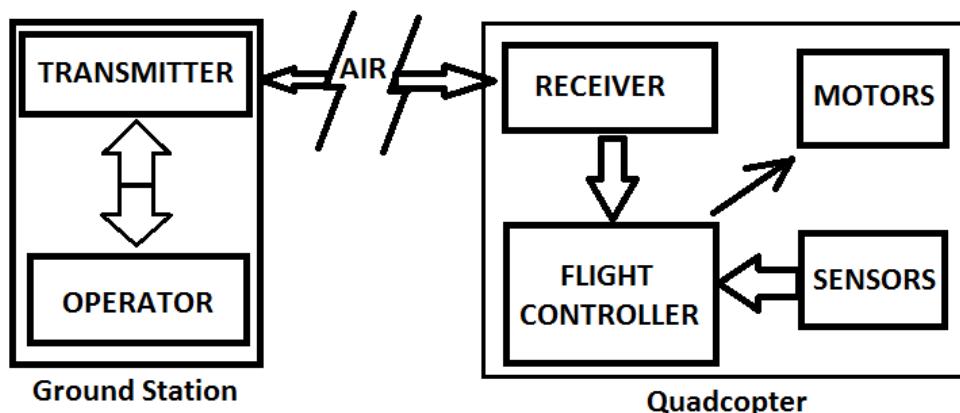


Figure 27. 3DR Radio Modules

5.1 Radio RX

Radio control consists of two major components, the transmitter (Tx) and receiver (Rx). The receiver is of the PWM type, indicating that it uses separate servo wires for each channel. Since there are a total of six channels in this control system, the receiver has six separate input wires. The minimum number of channels for controlling the quadcopter is four, as only pitch, roll, yaw and throttle need to be controlled to maintain flight. The first three primary flight control channels are designated as Elevator, Aileron and Rudder.

By adding more channels it is possible to control such auxiliary features as flight mode, camera trigger, camera gimbal control, landing gear and some others.

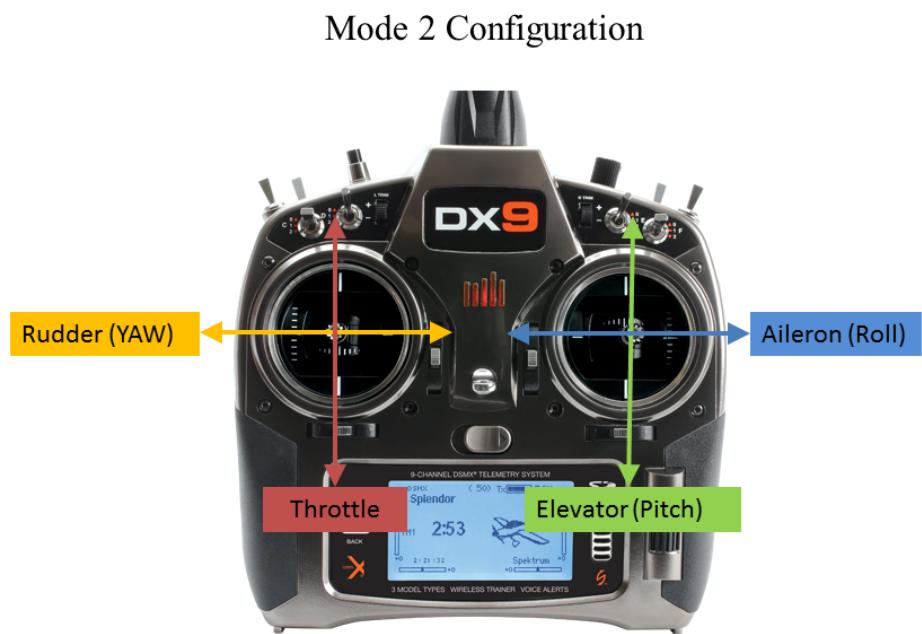


Figure 28. Transmitter channels

<http://norunway.com/wp/wp-content/uploads/2014/07/Mode-2.png>

For a quadcopter, as for any UAV, its radio-operated remote control system constitutes the single means of directing the vehicle's movements. A radio transmitter sends various signals, which are then modulated into the proper channels. The electronic receptors in the quadcopter receive these radio signals and demodulate them so that each signal controls a different task. For example, one such signal from the radio transmitter directs the movement of the throttle

analog stick. The more pressure applied to this lever, the greater is the value of throttle being modulated and transmitted directly to the quadcopter. When the vehicle receives the signal, all values are demodulated and the channels governing the throttle increase the motor speed to an appropriated degree. (Gulzaar, 2016.)



Figure 29. FlySky 2.6 GHz transmitter

For the present project, the transmitter frequency is 2.6 GHz, which is the most common frequency used for small, remoted-controlled ground and air vehicles. The antenna is small enough to be easily portable. However, the corresponding range is shorter than that possible with the 27/72 MHz frequencies. For this particular transmitter the maximum range is approximately 500 metres. Such a range is adequate for the purpose since the quadcopter will be used mainly in autonomous flight mode.

5.2 3DR Telemetry

Besides requiring a radio control system, the present project also requires 3DR telemetry. According to the principles of telemetry, the receiver not only receives data but also sends various data back to the transmitter, meaning that the receiver operates like a modem. With the aid of telemetry, valuable information is received from the quadcopter while in flight. Such data may include battery voltage to indicate signal strength.



Figure 30. Air and Ground Modules of 3DR Telemetry

The author programmed the 3DR radio, after which the air and ground 3DR telemetry modules were configured and paired before being installed in the quadcopter. The final step was setting the baud rate, which is the speed of communication between the air and ground modules. In telemetry the usual speed is 57600 bits per second. After setting the baud rate, the air and ground stations were ready for firmware uploaded.

5.3 MultiWii PID

The PID (proportional-integral-derivative) controller is a closed-loop control system in the MultiWii firmware to calculate the difference between a measured variable and a desired set-point. The PID controller then attempts to minimise any errors by adjusting the control inputs. The controller interprets the data measured by the sensors, such as the gyroscope and accelerometer, by comparing that information with expected values in order to alter speed, move in a certain direction or maintain stable hovering. (Liang, 2016.)

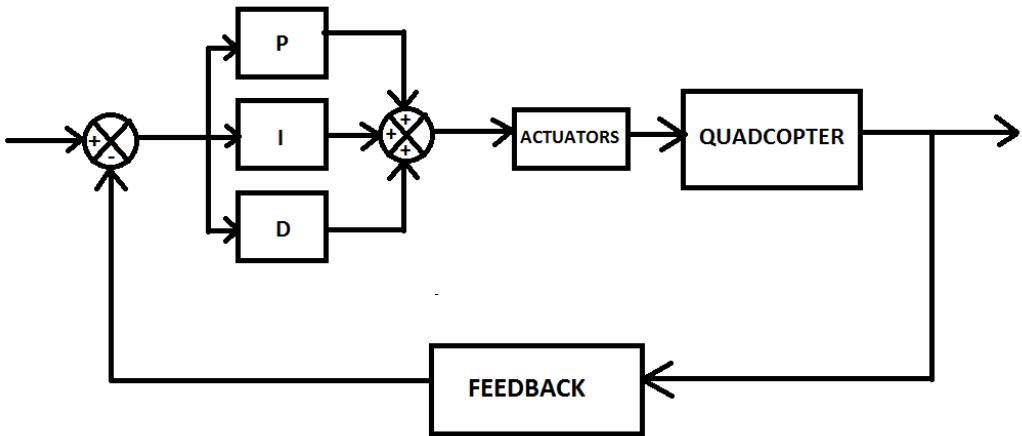


Figure 31. PID controller working principle

The PID controller's calculation algorithm includes three separate parameters: the proportional, integral and derivative values. These values can also be interpreted in terms of time, where P represents a present error, I represents accumulated past errors and D is a prediction of future errors.

Within the tri-faceted PID control system, the P value is the most critical, as its job is to return the quadcopter to a stable position. For example, when the right stick on the transmitter is pushed forward, the quadcopter will begin to fly and then automatically stabilize itself to a horizontal position. The higher the P value, the greater is the job to achieve stability. On the other hand, if the P value is set too high, the quadcopter will experience high-frequency oscillation and the whole system will become unstable.

Within a period of time, the I value integrates the error, so the longer the error persists, the greater is the force applied. An increase in the I value is used to smooth the movements of the quadcopter caused by fluctuation in the P value.

The D value represents the opposite of the P value. In general, the D value changes the force applied when it senses a decrease or increase in position error.

The project author tuned all the PID values before the quadcopter could be launched on its first flight. The configuration was carried out in MultiWii Conf.

Although the PID settings profoundly affect the quadcopter's performance, eliminating the vibration of the propellers and motors must be done even before configuring the PID. Similarly, the weight distribution on the frame plays a vital role in the quadcopter's stability.

5.4 MultiWii Conf

A MultiWii Conf open-source program was used for the ground control station because it combines most appropriately with the MultiWii flight controller firmware. This particular program comes with an option that accommodates the PID parameters and an attitude indicator. It also provides data on the speed of the motors and the radio signal, shows the sensors graph, and gives other relevant information.



Figure 32. MultiWii Config program

As the MultiWii Config platform is open source, the configuration of the GUI (Graphical User Interface) can be easily changed and tuning the PID settings is a simple matter. As shown in Figure 32, there are also input graphs and a transmitter signal. The sensors diagram depicted at the bottom of the GUI helps to debug and adjust the accelerometer, gyroscope and barometer.

On the right side of the GUI, a visualization menu displays the quadcopter's current position and location. The GPS navigation system allows the MultiWii to navigate autonomously through multiple Way Points. (EOSBandi, 2013.)

Another significant advantage of the MultiWii Cong is the program's capacity to switch between flight modes. This particular GUI supports ACRO, ANGLE and HORIZON flight modes:

- ACRO stands for Acrobatic Flight Mode for maneuverability and fast control. Only the gyroscope is used in this mode.
- The ANGLE mode provides stability and shows whether the Pitch, Roll, Yaw and PID level values have been set correctly. This flight mode is regulated by the gyroscope and accelerometer.
- HORIZON is a combination of the ACRO and ANGLE modes. This mode ideally pairs the 'Calm' and 'Aerobatic' RC sticks.

6 EVALUATION

The performance of the quadcopter prototype was tested manually more than fifty times under both outdoor and indoor conditions. The frame's strength and durability were tested with FEM simulations. The balance of the propellers was tested using the reflected laser beam method. The Vibration Sensor was used to balance the motors.

The performance of the quadcopter's onboard sensors was achieved in the MultiWii Config by comparing the results with the values considered most highly desirable.

6.1 Mechanical Performance

The result of the frame's overall performance was judged by the author to be 'very good'. The bolt connections between the components are so stable that the frame can be depended on for many years of use. The motor mountings have also proved to be reliably durable.

Even before the project started, it was assumed that some of the quadcopter's working parts would heat up while operating. The components which emit varying degree of heat are the motors, ESCs and battery. After just a few tests, however, it became apparent that their location relative to the craft's exterior frame allowed them to be cooled by the air rushing past them. The possibility of the working and moving parts being negatively affected by overheating thus became a minor concern.

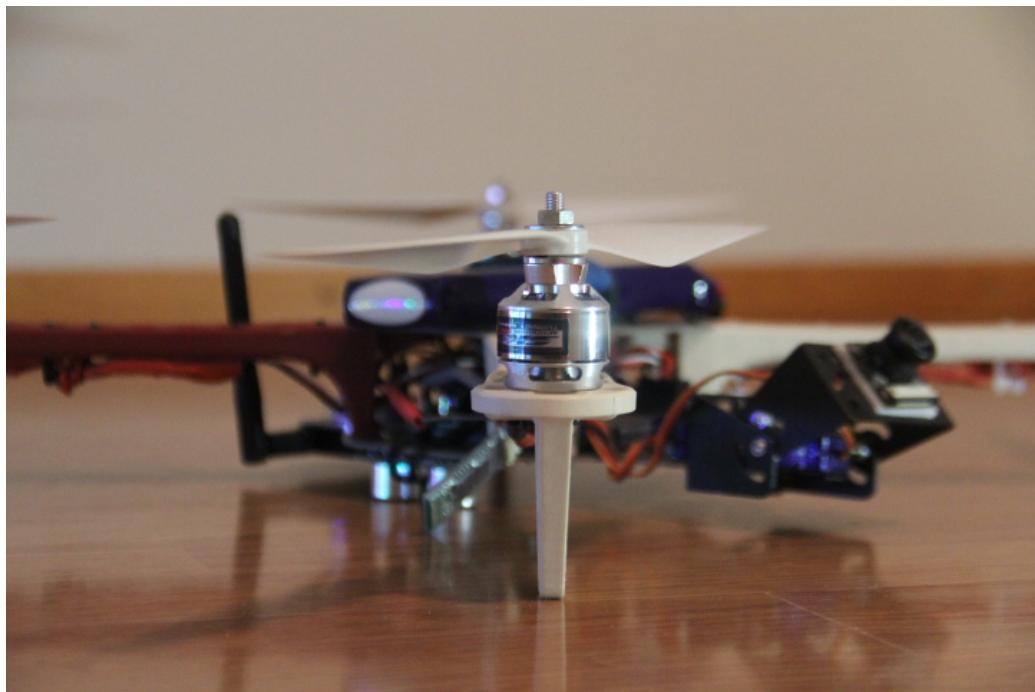


Figure 33. Motor's mount

During numerous test flights the quadcopter's frame proved to be ruggedly durable and its connections stable. When it was noted that some of the sensors were not mounted securely enough for the load, they had to be reinforced with extra clamps and strong elastic tape.

The main flight controller is attached to the frame by four bolts. There is also a length of 3 mm compressed foam tape stretched underneath the controller to help eliminate vibration which might otherwise negatively affect the sensor data.

The propellers also cause strong vibration if not properly balanced with a special calibration tool. Such a procedure is mandatory whenever the propellers need to be replaced.

6.2 Control Performance

One of the essential setup procedures for the whole system is the precise calibration of the Electronic Speed Controllers. These ESCs are basically responsible for the motors rotating at the rate of speed determined by the flight controller. The correct calibration procedure ensures that the ESCs exhibit the minimum and maximum pulse-width modulation (PWM) values received from the flight controller. For the quadcopter, the minimum PWM value is set at 1150, a value which is so low that the motors do not turn at all. When a value of 50 is added to the PWM variable, the motors start turning at minimum speed. The maximum PWM value is 1800, at which setting the motors rotate at their highest speed.

The PID settings are similarly relevant to maintain stable flight. The setup process was done in the MultiWii configuration program. A PID loop setup was thus chosen as the most appropriate tuning method. The first step was positioning the quadcopter's main load in the very middle of the craft in order to create a balanced centre of gravity. The P value was set at 0.0060, which is in the middle of the P range for this particular system and results in the drone's movements being smooth and stable.

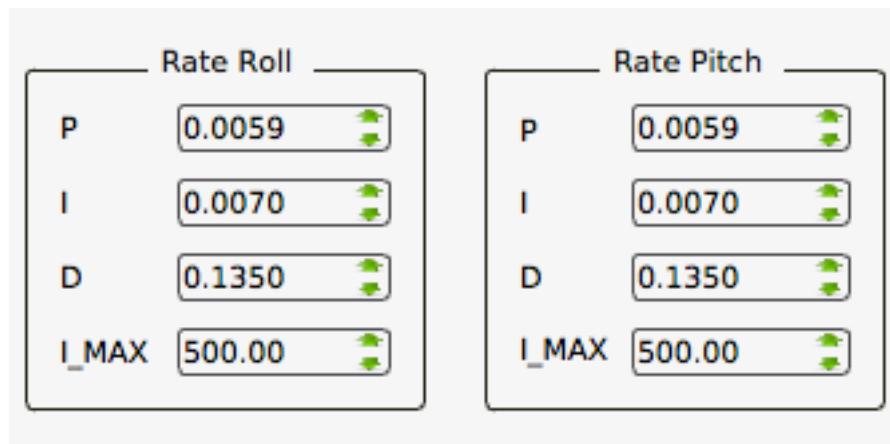


Figure 34. PID settings

During testing it was determined that the drone's maximum range was approximately 4.5 kilometres, which is considered sufficient for such a craft. This overall performance is in complete accord with the quadcopter's maximum theoretical distance of 5.0 km.

Taking everything into account, the option of autonomous flight was achieved: the quadcopter demonstrated that it was able to fly between multiple waypoints, to hover when so instructed and to perform reliably in making video recordings. During these various testing periods, the RPi server also proved to be more than adequately stable.

During the final test flight, the main controller experienced a failure, which led to the temporary collapse of the whole system and resulted in the quadcopter falling to earth. The vehicle's most important components were not damaged and only one propeller had to be replaced. Accordingly, a post-crash forensic analysis was conducted. The analysis showed that one element of the flight controller was defective and had caused the accident. Before resuming future flights, the flight controller will be completely replaced and the quadcopter's electronic system will again become stable.

7 CONCLUSION

On the whole, the quadcopter prototype of the present study has demonstrated its merits. In particular, the MultiWii flight controller, despite its small size, has proved to be unexpectedly powerful in controlling the quadcopter's complicated system. The RPi microcontroller has also confirmed that it is an essential factor in video processing and broadcasting. Both the MultiWii and the RPi worked harmoniously in tandem, a successful interdependence which has demonstrated that their implementation in the project was the correct choice.



Figure 35. Final Prototype

The overall performance of the sensors was also positive, even though at the start of the project the magnetometer displayed a number of obvious errors. Afterwards, it was discovered that the problem was one of magnetic interference due to the magnetometer's close proximity to the power wires. When the magnetometer was repositioned, it began functioning correctly and the errors ceased to appear.

The control system generally displayed stability and reliability. In the early stages of the project, the control system's periodic instability was found to be the result of inexact calibration. Following the first outdoor tests, mistakes in the control system were discovered and resolved.

Figures

Figure 1. Quadcopter in the sky, p. 6.

Figure 2. Forest ranger at work, p. 7.

Figure 3. Russian ranger's equipment, p. 8.

Figure 4. Pitch, Roll and Yaw axes, p. 11.

Figure 5. Quadcopter motions, p. 12.

Figure 6. DJI Phantom 4, p. 13.

Figure 7. Factor of safety of the assembly, p. 14.

Figure 8. Static nodal stress, p. 15.

Figure 9. Static displacement, p. 15.

Figure 10. Turnigy Aerodrive SK3 2826-1240kv, p. 16.

Figure 11. Turnigy Plush 18amp Speed Controller, p. 18.

Figure 12. Example of PWM signal, p. 19.

Figure 13. LiPo Battery, p. 19.

Figure 14. 4.8 V Battery pack, p. 20.

Figure 15. SF 8045 propeller, p. 22.

Figure 16. Dynamics of propeller, p. 22.

Figure 17. Propeller's pitch illustration, p. 23.

Figure 18. Arduino IDE. GPS implementation code, p. 25.

Figure 19. IMU board, p. 26.

Figure 20. Ultrasonic distance sensor, p. 27.

Figure 21. GPS unit with antenna, p. 27.

Figure 22. Camera Gimbal mounted on the frame, p. 28.

Figure 23. Raspberry Pi 2, p. 29.

Figure 24. Running NGINX RTMP server, p. 30.

Figure 25. Gstreamer screenshot, p. 31.

Figure 26. Live video broadcast, p. 31.

Figure 27. 3DR Radio Modules, p. 32.

Figure 28. Transmitter channels, p. 33.

Figure 29. FlySky 2.6 GHz transmitter, p. 34.

Figure 30. Air and Ground Modules of 3DR Telemetry

Figure 31. PID controller working principle, p. 36.

Figure 32. MultiWii Config program, p. 37.

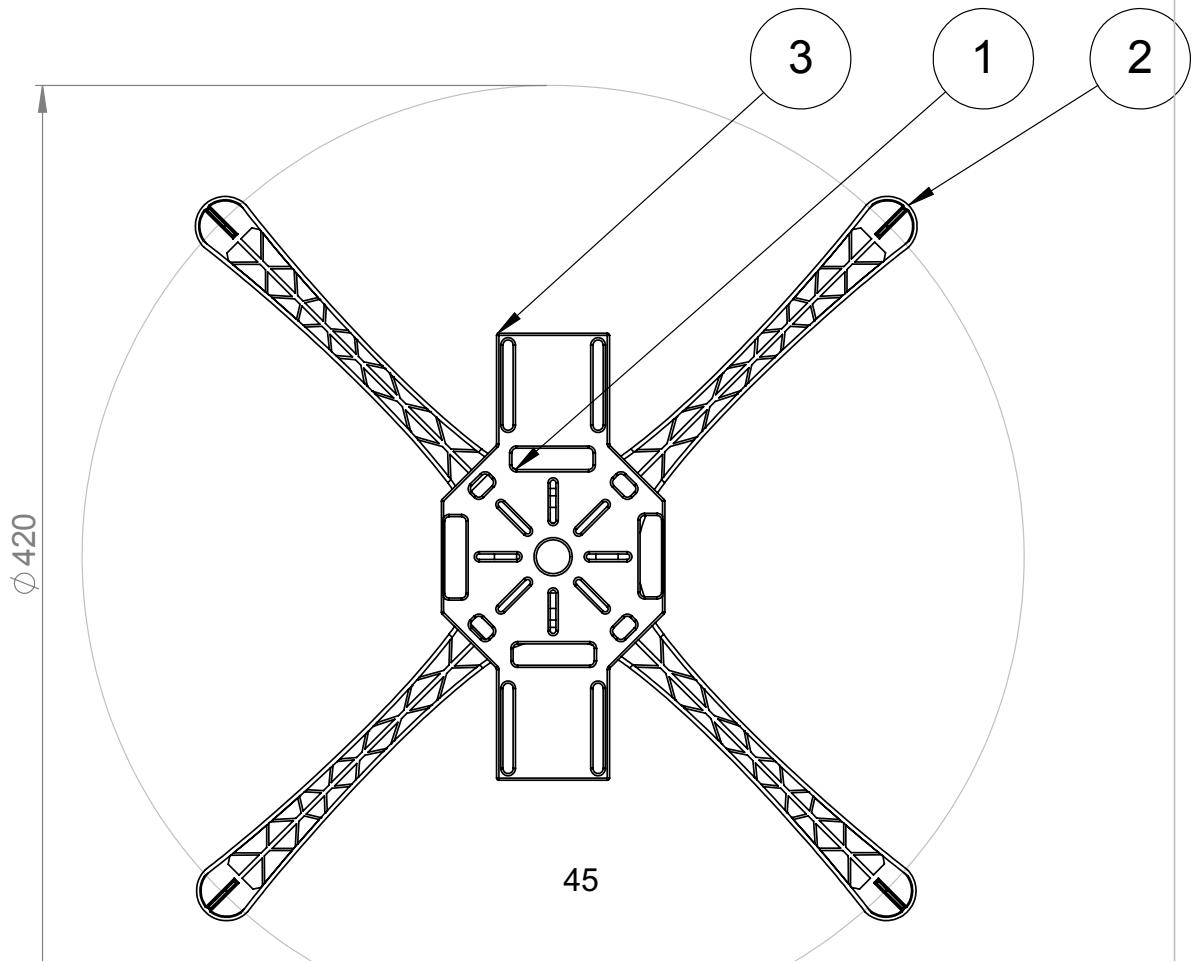
Figure 33. Motor's mount, p. 39.

Figure 34. PID settings, p. 40.

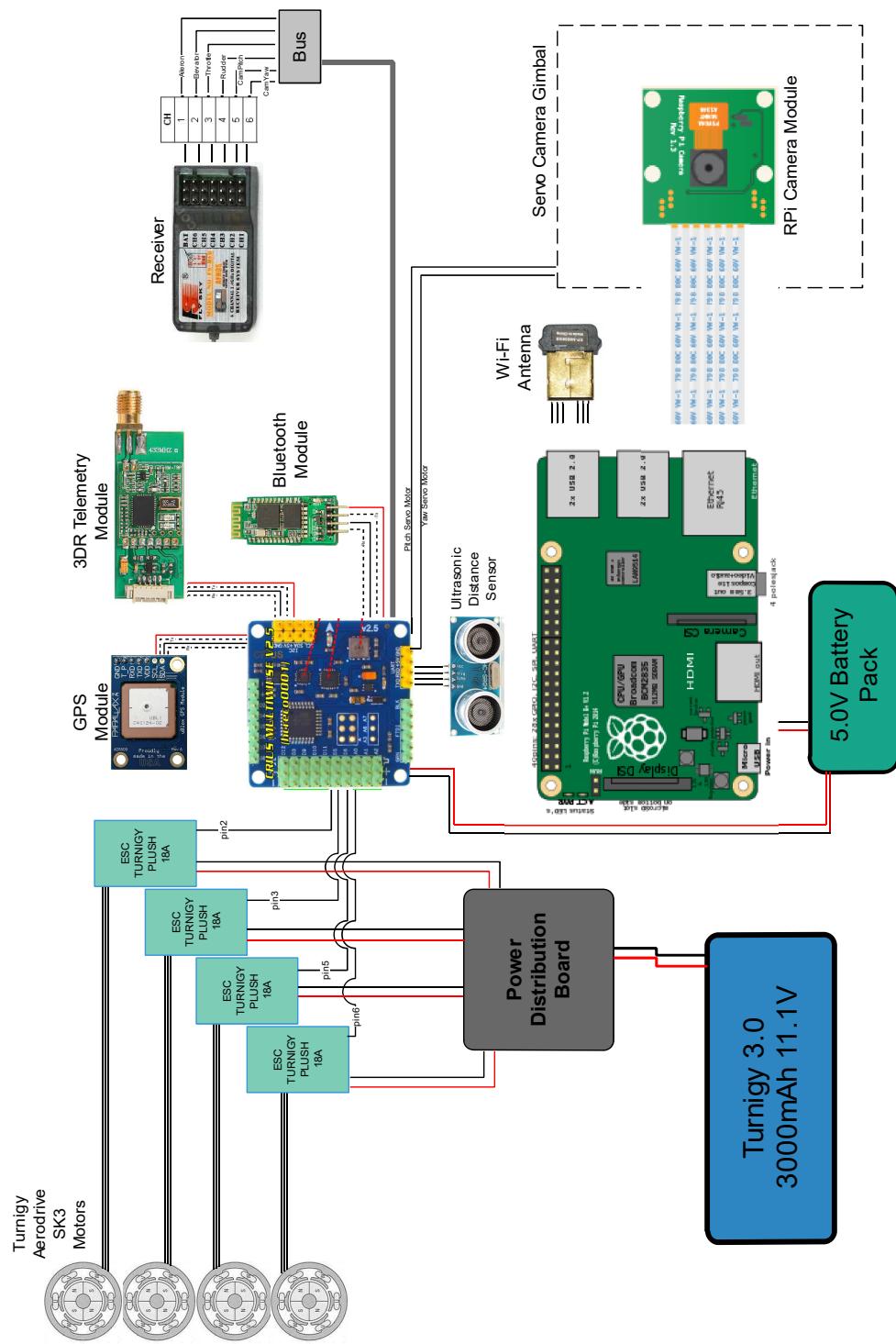
Figure 35. Final Prototype, p 41.

8 Appendices

| Rev | Appendix 1 | Muutos / Change | Pvm / Date | Suunnittelija / Designer |
|----------|--------------|-----------------|------------|--------------------------|
| ITEM NO. | PART NUMBER | Material | | |
| 1 | Upper Plate | | | FiberGlass |
| 2 | Frame Arm | | | ABS-plastic |
| 3 | Bottom Plate | | | FiberGlass |



Appendix 2



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