MASSEY UNIVERSITY

SCHOOL OF ENGINEERING AND
ADVANCED TECHNOLOGY

Engineering Project
Submitted as part requirement for B.Eng (Hons).

Development of an aerial vehicle test bed

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Contents

1.0 Summary

A quadrotor helicopter has been developed intended for future use as an aerial vehicle test bed.

The developed vehicle is able to perform all the basic functions needed for future development and has been constructed in such a manner that is easy for others to develop and change the existing design.

This report documents the research and development of this platform and also gives guidance in regards to its future development and possible projects that could be based off of the platform.

2.0 Introduction

The development of small autonomous aerial vehicles is an area of interest that many researches wish to explore. There is currently a large range of projects and research topics emerging in this field .Thus it was decided to construct and develop an aerial vehicle that would be a base for future projects in this field of research.

Autonomous aerial vehicles are true mechatronic systems that combine elements of mechanical, electrical, software and control engineering.

The amount of time needed to be spent constructing an entire vehicle to undertake research on a small facet of autonomous aerial vehicles is too time consuming, thus the ability to use an already constructed platform to build the desired experiments on will greatly speed up research in the future.

Preliminary research has shown that the most versatile and mechanically easy to construct autonomous aerial vehicle is a quadrotor helicopter. This is due to the fact that quadrotors can be fully controlled solely by varying the speed of the four rotors and no mechanical linkages are required to vary the rotor blade pitch angles as with a conventional helicopter.

This report will cover research into previously published papers on quadrotors in order to understand how they are commonly built and controlled as well as researching an already existing quadrotor control board that is available for purchase.

The report will also document research, design and construction of our own quadrotor helicopter that is planned to be used as a test bed for future projects at Massey University.

Conclusions will then be made on the current state of the project and suggestions and recommendations for future research projects and ways the current design can be improved will be given.

3.0 Background

3.1 General Theory

A quadrotor, also called a quadrotor helicopter or quadrocopter, is an aircraft that is lifted and propelled by four rotors attached to the end of four equal length rods [11].

The first recorded construction of a quadrotor was in the 1920's by Etienne Oehmichen. His design was a success and exhibited a considerable degree of stability and controllability for its time. However due to performance issues large scale quadrotor designs never entered into large scale production [11].

Recently interest in quadrotors has resurfaced in the form of small scale unmanned aerial vehicles (UAVs). The new generation of quadrotors have proven to be very capable in providing an agile, stable platform capable of indoor and outdoor flight [11].

Quadrotors are robust and simple helicopters to construct as they do not have the complicated swashplates and linkages found in conventional rotorcraft [12].

Flight control is achieved simply by manipulating the speeds of the four rotors. Each rotor in the system produces thrust, as well as a torque around its centre of rotation. To stop the vehicle from rotating about the yaw axis rotors one and three must rotate clockwise while rotors two and four rotate anticlockwise. When all the rotors are rotating at the same angular velocity the net aerodynamic torque on the system will be zero, stopping unwanted rotation. Because of the different directions of rotor rotation, counter rotating propellers must be used so thrust is all in the positive direction.

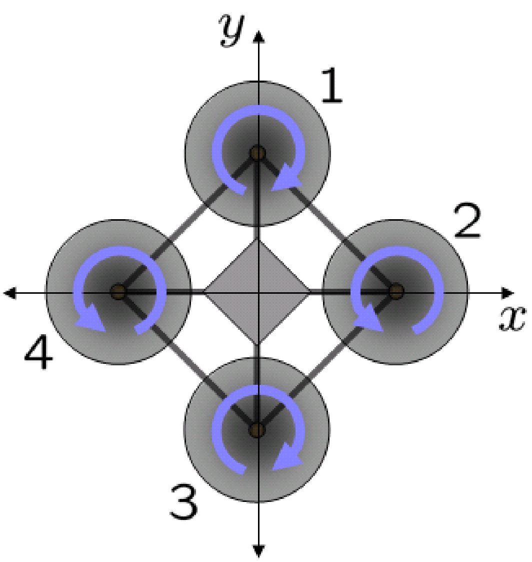

Figure 1 - Quadrotor net torque diagram [11]

By manipulating each individual rotors angular acceleration and hence the torque it is possible to move the vehicle in six dimensional space as demonstrated in figure 2.

Due to the use of four smaller blades instead of a single large blade as in conventional helicopters there is less rotational kinetic energy stored in the propellers, making the quadrotor a safer platform to work with. As well as reducing the chance of catastrophic damage in a collision.

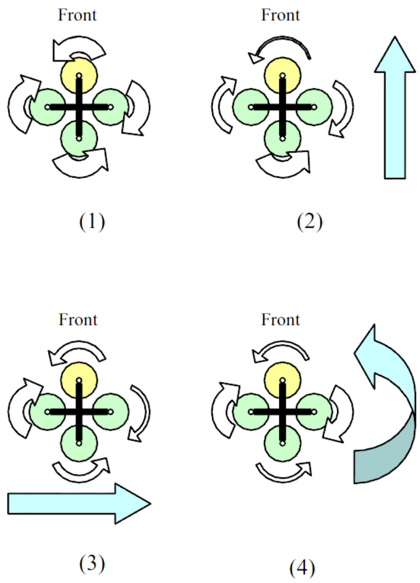

Figure 2 The concept of controlling the direction of a quadrotor. The arrow's size is proportional to the corresponding rotor's speed. (1) Ascending, (2) Move forward, (3) Move to right, (4) Rotate counter-clockwise [13].

3.2 Literature Review

Before beginning this project a search was undertook to find research that had already been done in the areas of controlling and building quadcopters. Several relevant papers were obtained. Important findings are detailed below.

Previously researched quadrotors commonly utilise Proportional, integral, derivative (PID) control[10, 12, 13, 16], machine vision systems [14, 17, 19] and in some cases fuzzy logic [15].

Currently the most advanced quadrotor belongs to the General Robotics, Automation, Sensing and Perception (GRASP) Laboratory at the University of Pennsylvania, it uses a machine vision system for control, however as multiple off platform cameras are used and all control calculations are performed at a high processing power base station it is consider not to be a true autonomous system.

Most fully autonomous quadrotors are currently using PID control schemes. This is often used in conjunction with various filters and statistical models to obtain the best possible control.

Various tactics are utilised to get the most accurate control scheme with PID control including the use of Kalman filters and Complementary filtering to reduce noise and errors introduced into the system [18].

Research has shown that aerodynamic effects on quadcopters such as blade flapping and aerodynamic effects relating to the motion of the vehicle relative to the free stream can be ignored at low velocities [17]. Aerodynamic effects introduced by the frame construction can be reduced by making modifications to the design and a minimal distance between rotor tips of 2.54cm must be maintained to avoid rotor wake interference [10].

It is possible to develop a quadcopter for low speed indoor flight without taking aerodynamic effects into account, however outdoor platforms moving at higher speeds in the presence of wind disturbances need to be able to compensate for these effects or control over the system will be poor.

3.3 Hardware Review

As well as researching current literature, a pre built quadrotor control system was purchased for the purpose of gaining firsthand knowledge in currently available systems.

The system purchased is the Universal Aerial Video Platform (UAVP) developed by Wolfgang Mahringer of Germany.

The principle behind the UAVP project is the creation of one controller board that can be easily used on any user made platform.

The UAVP board uses the PIC16F876 Microcontroller and has pins for attaching various sensors, including:

- Gyroscopes
- Accelerometer
- Compass
- Barometric sensor
- GPS module

To gain a broad understanding of the sensors used in this project, one UAVP motherboard was purchased along with three Gyroscopes, one accelerometer and a compass from www.quadroufo.com.

The UAVP platform is semi autonomous as it still needs human input from a radio transmitter to be controlled. The microcontroller however takes care of mixing the signals to control the rotors individually, as well as helping the vehicle stabilise.

No successful flight tests were made using the UAVP board as the microcontroller could not read the outputted signal from the transmitter correctly; this is a common problem with the UAVP board.

The cheaper radios available do not often output pulse pulse modulated (PPM) signals or provide them accurately enough for the UAVP board. The transmitter that was trialled used a pulse code modulated (PCM) output so the board would not be initialised.

An attempt was made to use a PCM to PPM converter to fix this issue, but attempts were unsuccessful.

Although flight was not possible, much about quadrotor circuit design and general operating principles were learned from this board.

It is recommended that in the future in-depth research is undertaken into isolating the problem with the radio transmitter and perhaps trailing a different model of transmitter.

4.0 Development and Exposition

4.1 Sensor Selection

In order to control the quadrotor we must use sensors that are able to communicate to our control system the current state of the quadrotor. So that calculations can be performed to work out what outputs are required to move the vehicle to the desired position as well as maintaining stability.

The system that we will be developing is known as an inertial navigation system (INS). An INS is defined as “a navigation aid that uses a computer, motion sensors (accelerometers) and rotation sensors (gyroscopes) to continuously calculate via dead reckoning the position, orientation, and velocity of a moving object without the need for external references.” [1]

As a quad rotor is a six degree of freedom system, at a minimum it will need to be able to measure rotation and motion in three axes. Our INS will be developed around three single-axis gyroscopes, one three–axis accelerometer and a two-axis compass.

The sensors that we will be using are the same used on the UAVP board.

4.1.1 Gyroscopes

The gyroscopes used in this project are the Analog Devices, ADXRS300 ±300°/s Single Chip Yaw Rate Gyro with Signal Conditioning.

This analogue device outputs a voltage proportional to the angular rate about the axis normal to the top surface of the package [2]. The device also provides a 2.5V reference and a temperature output to be used for compensation techniques.

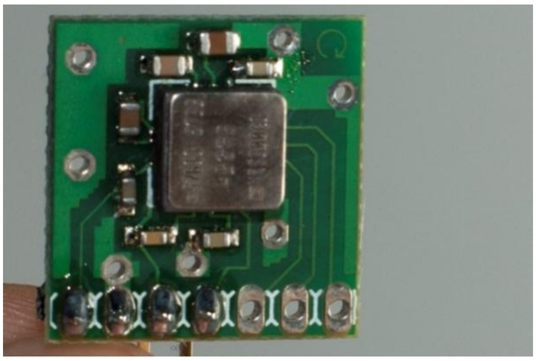

Figure 3 – ADXRS300 Gyroscope

The sensor is interfaced to the microcontroller by using the microcontroller’s onboard 12 bit successive approximation Analogue to Digital Converter (ADC0) set up in differential input mode; we then use ADC0 to measure the difference between the rate signal and the 2.5V regulated signal from the chip. This is done to reduce errors that can be introduced from temperature changes and other noise introduced to the system.

We will arrange the three gyroscopes in the same manner seen on the UAVP control board in order to obtain rotational measurements of the three axes, pitch yaw and roll.

4.1.2 Accelerometer

The Accelerometer used is ST's LIS3LV02DQ 3-Axis ±2g/±6g Digital Output Low Voltage Linear Accelerometer.

The LIS3LV02DQ is a three axes digital output linear accelerometer that includes a sensing element and an IC interface able to take the information from the sensing element and to provide the measured acceleration signals to the external world through an I2C/SPI serial interface [3].

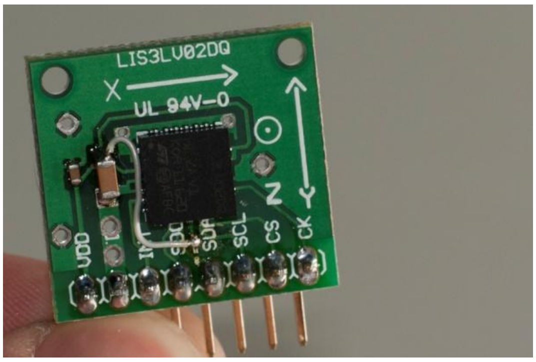

Figure 4 - LIS3LV02DQ Accelerometer

The package has three analog-to-digital converters on board that convert the acceleration readings from the Microelectromechanical systems (MEMS) sensor into high resolution data words. The output data rate is user selectable based on the selected Decimation Factor which spans from 40 Hz to 2560 Hz. Acceleration data is accessed through either I2C/SPI interface.

This sensor is interfaced to the microcontroller using the SPI bus.

4.1.3 Compass

The Compass used is the Honeywell HMC6352 2-axis Compass with Algorithms.

The HMC6352 is a fully integrated compass module that combines 2-axis magneto-resistive sensors with the required analogue and digital support circuits, microprocessor and algorithms for heading computation [4].

The sensor is interfaced to the microcontroller using the I2C bus system. The microcontroller sends a byte command to the address of the compass and the compass in turn sends back two response bytes containing the heading output data in tenths of degrees from zero to 3599. It is also possible to set up the compass to automatically transmit data to the microcontroller at selectable rates of 1Hz, 5Hz, 10Hz or 20Hz.

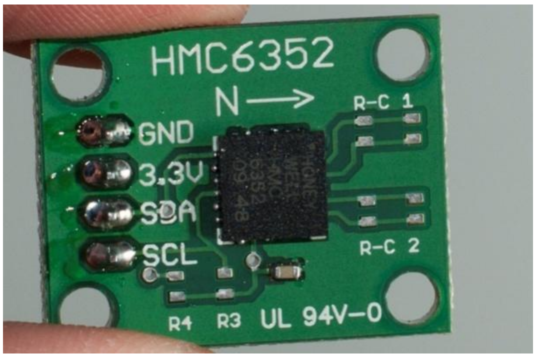

Figure 5 - HMC6352 Compass

4.2 Motor, Propeller, Electronic Speed Controller and Battery Selection

A mechanical actuation system is required to generate the appropriate downward force to lift and manoeuvre the quad rotor. Our system consists of Brushless Electronic Speed Controllers (ESC), Brushless DC Motors and propellers. The components chosen will be off the shelf remote control aircraft items that are readily available from hobby stores.

4.2.1 Brushless DC Motors

Brushless motors are chosen for this project as they offer several advantages over DC motors, including more torque per weight, efficiency, reliability, reduced noise, longer lifetime (no brush and commutator erosion), elimination of ionizing sparks from the commutator, more power, and overall reduction of electromagnetic interference [5].

The brushless motors that we have chosen to use for this project are the HexTronic DT750's. These motors are rated highly among the quad rotor community and perform very well compared to other brushless motors while still remaining at a very cheap price (Table A).

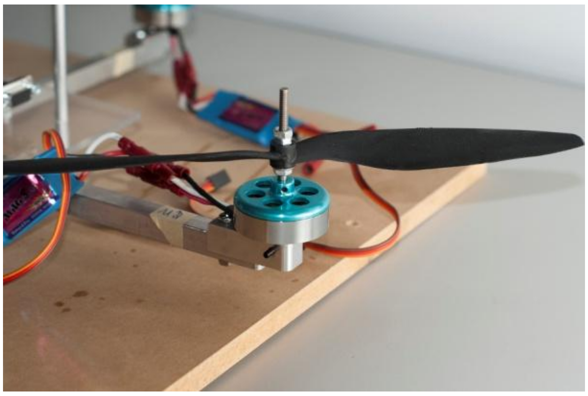

Figure 6 – HexTronic DT750 motor with EPP1045

The DT750 draws a maximum of 18 Amps and is capable of producing a thrust of approximately 1000 grams. This makes it ideal for use in a medium sized quad rotor. With four DT750’s operating at ideal conditions we are able to achieve a theoretical maximum thrust of 4Kg.

4.2.2 Propellers

Propellers convert rotary motion into aerodynamic lift force. As discussed in the background, two pairs of counter rotating propellers are needed in a quadrotor helicopter so that the net aerodynamic torque is zero.

The availability of counter rotating propellers is limited with only a few outlets stocking them and with only a small selection of sizes on offer.

The propellers we will use in our project are the EPP1045’s; they have a blade length of 10 inches with a pitch of 4.5 inches/revolution. Their large size will help produce the required lift we need and we already know that they perform well when paired with the DT750 brushless motors (Table A).

4.2.3 Electronic Speed Controller

Brushless Electronic Speed Controllers (ESC) are used to control the brushless motors. An ESC controls the brushless motor by converting the supplied DC from the battery into three phased AC. It does this by varying the switching rate of a network of field effect transistors [6].

The ESC we will be using is the TowerPro w18A Brushless Speed Controller, it is able to supply 18A (20A burst) which satisfies the requirements of the brushless motors. It also provides us with a regulated 5V / 1.5A supply, this eliminates the need to design our own regulator circuits to power our sensors and other peripheries required. It is also one of the cheapest available ESC on the market.

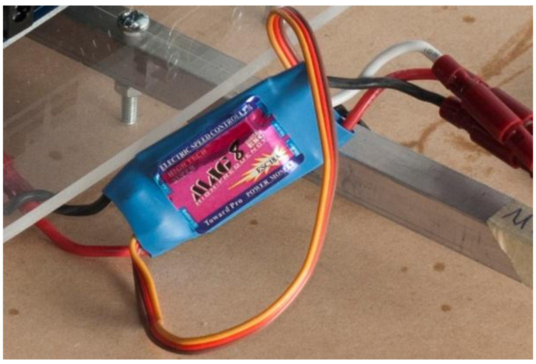

Figure 7 – TowerPro w18A Brushless Speed Controller

In a standard radio control setup, the TowerPro w18A Brushless Speed Controller is expected to be plugged into a receiver module where it receives a 42 Hz PWM signal with pulse widths varying between 1ms (no throttle) and 2ms (full throttle).

4.2.4 Battery

We require a battery to provide us with the electrical energy needed to run the system.

Lithium polymer batteries (LiPO) are becoming increasingly popular for powering remote control aircraft; this is because of their light weight, energy density, longer run times and the ability to be recharged [7]. Their major disadvantage is their comparatively high price to other battery technologies.

The battery we will be using is the BatteryHobby 11.1V 15C 2200maH Li-Poly. It is able to supply the required voltage to run the motors, ESC, microcontroller and sensors.

Figure 8 - BatteryHobby 11.1V 15C 2200maH Li-Poly

4.3 Microcontroller Selection

In order to gather information from the sensors, interpret the data and send the appropriate control signals to the actuators a microcontroller is needed.

The microcontroller that we will be using is the Silicon Laboratories C8051F020. It is important that we use this microcontroller as it is the microcontroller all engineering students learn throughout their degree at Massey University. Development boards and the Silicon Labs IDE are readily available and the teaching

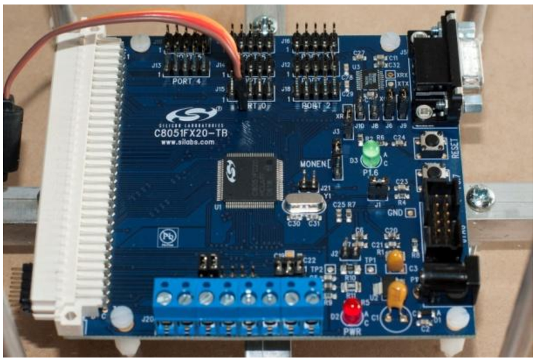

Figure 9 - Labs Micro-Controller Development Board C8051F020-TB

staff have a great deal of knowledge and experience with using this microcontroller.

The Silicon Labs Micro-Controller Development Board C8051F020-TB provides us with the microcontroller chip and other rudimentary peripherals such as an oscillator, power supply, RS-232 serial communication connector as well as easily accessible header pins for digital outputs and screw terminal blocks for analogue inputs [8].

The microcontroller is programmed and debugged through a JTAG interface.

4.4 Frame Design and Construction

In order to bring all the components of our quad rotor together a frame needs to be built. The main design consideration for the frame, as for most aircraft is minimising weight. Because this is a multi-rotor vehicle a separation gap of 2.54 cm must be maintained between propeller tips to avoid wake interference [10]. Additional considerations specifically for this project are robustness and the ability to easily adjust and mount new devices.

Research into currently built quad rotor frames was undertaken to be the basis for our initial design. This design was then improved through an iterative process.

The three most common materials used in construction of quad rotor frames are carbon fibre, plastics and aluminium. These materials are all lightweight while still providing adequate strength in demanding applications. As the machining of carbon fibre is difficult and specialised cutters are needed we will be limiting the materials that we will use in our design to aluminium and plastics.

All designs were first drawn in SolidWorks so it was easy to visualise what the final design would look like as well as allowing the easy production of technical drawings and for the use of SolidWorks measurement tools such as being able to accurately measure the mass of a design.

The original design was inspired by the Wyvern Quadrotor Helicopter [9]. This frame is comprised of:

- A central node - containing all the control equipment and components.
- Motor nodes – which the brushless motors and propellers are attached to.
- Three hollow aluminium support tubes to connect the motor nodes to the central node.

Figure 10 – Wyvern Quadrotor Helicopter [9]

4.4.1 Design One

Our original frame follows the Wyvern in its use of multiple aluminium supports; it has two interlocking beams made of extruded square tube aluminium purchased from Ulrich Aluminium, die number: UA1206.

This specific aluminium was chosen as it was the smallest hollow tubing readily available in the workshop. It is 12 x 12 mm with a wall thickness of 1.6 mm.

Figure 11 – Welded aluminium interlocking joints

Cuts are milled into the length of the aluminium tubing so we can connect the four pieces together with an interlocking joint which is then sealed by welding the pieces together. This allows us to avoid extra weight from using other fastening methods.

We will not need to create a central node to hold our electronics as we can mount them directly to the flat surface of the aluminium tubes.

Motor mounts must be constructed so the brushless motors can be attached to the aluminium frame. Our motor mounts are made from Nylon that has been machined on the CNC mill. These mounts are designed to clip onto the end of the supports and have the same mounting pattern specific to our brushless motors so we are able to bolt on the motors.

SolidWorks estimates the total mass of the design to be 400 grams, excluding other components and fasteners.

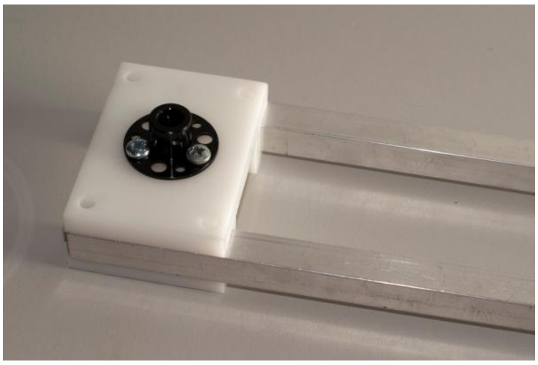

Figure 12 – Motor Mount

Although the weight of the design is within our limits of total theoretical thrust produced by our motors, it was found that this design would not be sufficient.

When thrust tests were carried out in the lab it was observed that although lift was being produced the motors had to be running in the upper limits of their throttle range. This will limit the payload weight of the Quadrotor and also creates difficulty for controlling the vehicle. The control issues arise from there being too little throttle range available to help in stabilisation.

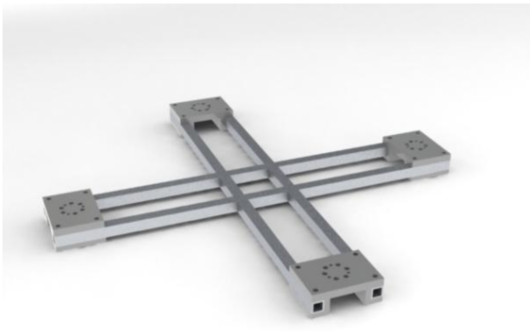

Figure 13 – Full assembly in SolidWorks

It is hypothesised that the causes for this lack of thrust are due to large amounts of material (from the mounting blocks and double frame structure) blocking the flow of air from the propellers.

4.4.2 Design Two

The second frame was designed with two major goals in mind; to make weight savings by minimizing the material used and to reduce the area of material directly beneath the rotors.

The aluminium frame was redesigned to be only a single bar crosspiece, it is still joined with a welded interlocking joint. The length of the frame was also minimized as much as the propellers would allow. In this design there is a minimum distance of 5.4 cm between propellers which is approximately double that of the wake interaction point of 2.54 cm.

The second change that was made was changing the motor mount. This new mount was designed to have the bare minimum material in contact with the mounting pattern of the brushless motor so that there would be no extra material blocking the air flow of the rotors.

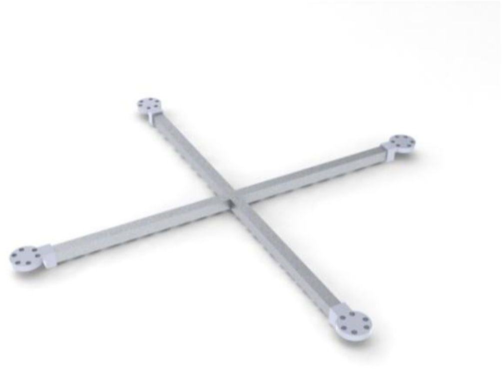

Figure 14 – Second Frame Design

SolidWorks estimates the new designs weight to be 75 grams, 18.75% of Design Ones weight.

Design Two was never fully constructed as it was not possible to create the desired motor mount on the Massey CNC machine as the part had hard corners.

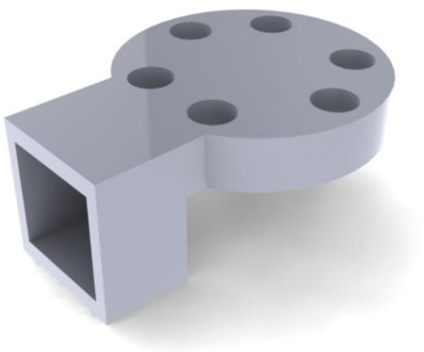

Figure 15 – Second Motor Mount

4.4.3 Design Three

The third design follows on from the second, utilising the same aluminium crosspiece built for the second design but the motor mounts have been designed so they are able to be machined in the Massey CNC machine.

The new motor mount is very different to the previous two designs as it does not attach to the motor using the mounting pattern present. The original motor is disassembled and the motor shaft is directly inserted into the mount and secured with grub screws.

Because of the grub screws the mount will be made from aluminium as it will be more resilient to the shear forces present on the thread.

Figure 16 – Third Moto Mount

This design is estimated to weigh 75 grams, the same as Design Two.

A piece of Perspex is added into the centre of the frame to mount the microcontroller board and other required PCB's as well as acting as the guide plate for the testing station.

4.5 Printed Circuit Boards

Two basic printed circuit boards (PCB) were designed and made for this project; a power distribution board and a sensor board. These boards are sized to be 10x10cm so that they will mount in line with the microcontroller board.

4.5.1 Power Distribution Board

A PCB is needed to effectively distribute power to all required parts of the system. The design process is simplified as the ESC's provide their own 5v / 1.5A regulated supply.

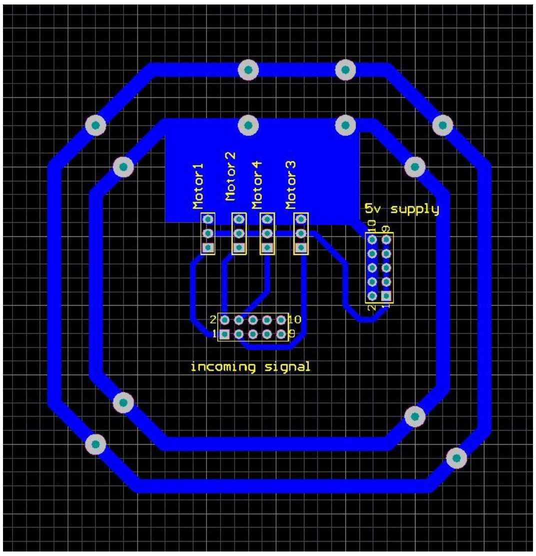

Figure 17 – Power Distribution Board PCB

We directly connect the 11.1v LiPo battery to the PCB where it is allowed to run around the outside of the board. Wires soldered into pads around this main track provide power to the ESC's and the micro controller.

The signal lines to the ESC's are also connected to this board. This is done for two reasons; the signal lines are 3 pin connecters and will not directly interface with the PCA output pins on the micro. Also, the ESC's provide a 5v regulated supply, this is fed onto the power distribution board and a 5 pin header is provided for extra peripherals to plug into if they require a 5v supply.

4.5.2 Sensor Board

To provide accurate angle information the gyroscope sensors need to be mounted as close to the centre of mass of the vehicle as possible, we are unable to fix them permanently however as our design needs to be modular for future research projects.

The PCB designed fits onto the screw mounts that the micro controller board uses and is comprised of 3 correctly orientated female headers for the gyroscopes to fit into as well as a 5x2 male header for signal and power lines to be attached.

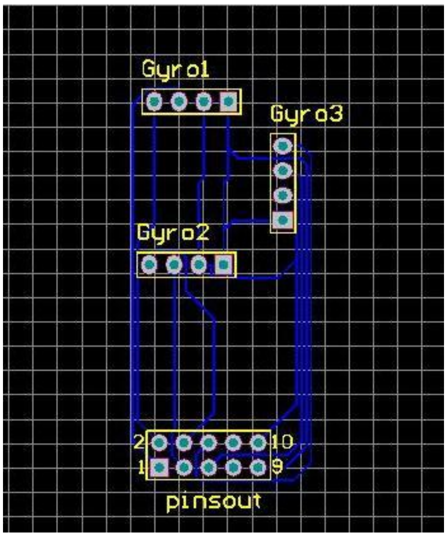

Figure 18 – Sensor Board PCB

4.6 Full Assembly

As this project is intended to be a test bed for future projects an emphasis was placed on keeping the final product as modular and simple as possible. Allowing people new to the project to easily understand how the system works as well as allowing for easy modifications, maintenance and disassembly.

The central node of the quadcopter is a multi tiered structure comprised of:

- Power Distribution Grid Board
- Micro-Controller Development Board C8051F020-TB
- Sensor Board

Screw mounting blocks are used to mount the boards on top of each other.

Bullet plugs are used to connect the motors to the ESC's and power distribution grid. This makes it easy to disconnect and replace faulty parts or to trial new

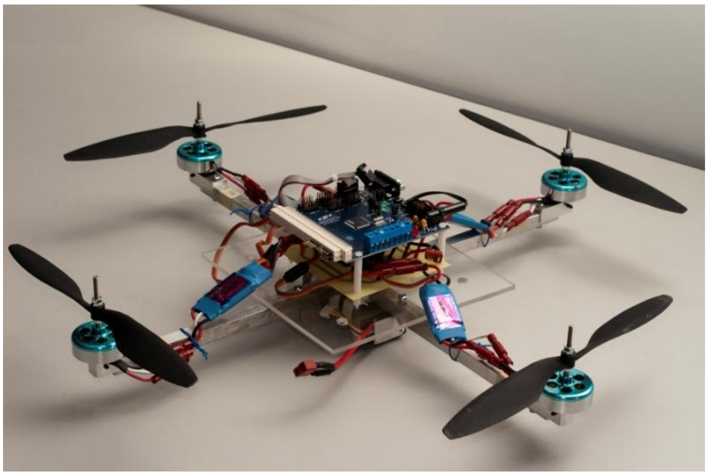

Figure 19 – The full Assembly

motors or ESC's

The Perspex mounting block and motor mounts are bolted onto the frame.

The power distribution grid provides extra pins to the 5V supply for additional peripherals to be added in the future. There is also ample room to add extra devices to the 11.1V supply.

The Sensor board has female headers for the appropriate sensors to be plugged into; this enables users to remove sensors easily for further experiments or replacement.

The final assembly weighs 1200 grams.

4.7 Testing Station

In order to complete accurate thrust testing and tune the control system while maintaining operator safety and protecting expensive equipment from damage a test rig needs to be constructed.

The constructed test rig is a block of wood with four cylindrical aluminium shafts protruding vertically out of the surface these shafts are placed so that they line up with the holes in the Perspex mounting sheet on the quadrotor.

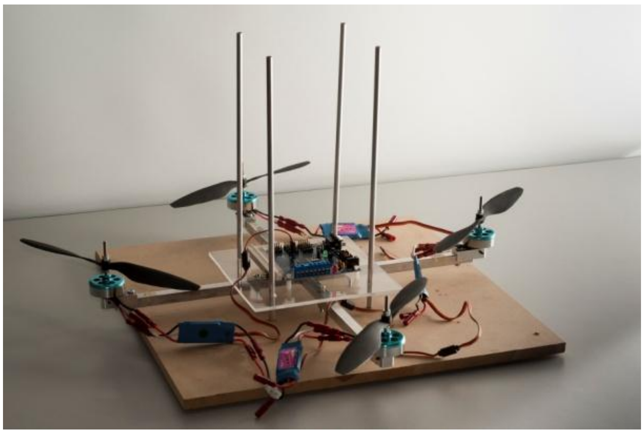

Figure 20 – Testing Station

Wooden stop blocks are screwed into the top of the shafts to stop the quadrotor from escaping the testing station.

Initially the holes are very small only allowing for vertical movements along the shaft, but as the control software improves these holes can be embiggened to introduce more dynamic movements into the system, emulating free flight conditions.

When using the testing station it is important to place it behind an object, such as a plastic screen so if anything does go wrong unexpectedly the user is safe. The wooden board needs to be clamped or weighted down sufficiently to prevent unexpected movements.

4.7 Control Software

The microcontroller is programmed using the Silicon Laboratories IDE in the C programming language. To satisfy the requirements of the project it is important that the software is capable of several major functions:

- Serial communication to a base station
- Gathering Sensor Data
- Performing mathematical operations for the purpose of control
- Updating motor speeds

The microcontroller code can be viewed in its entirety in the appendix.

4.7.1 Pin Assignments

The digital crossbar (XBR0) is set to 0x27, which corresponds to the following pin configuration:

Pin	Connection	Description
P 0.0	TX0	Transmit RS232 Data to quadcopter
P 0.1	RX0	Receive RS232 Data from quadcopter
P 0.2	SCK	Serial Clock (SPI Bus)
P 0.3	MISO	Master Input, Slave Output (SPI Bus)
P 0.4	MOSI	Master Output, Slave Input (SPI Bus)
P 0.5	NSS	Slave Select (SPI Bus)
P 0.6	SDA	Serial Data Line (I2C Bus)
P 0.7	SCL	Serial Clock (I2C Bus)
P 1.0	CEX0	PCA PWM output for controlling ESC1
P 1.1	CEX1	PCA PWM output for controlling ESC2
P 1.2	CEX2	PCA PWM output for controlling ESC3
P 1.3	CEX3	PCA PWM output for controlling ESC4

The SPI bus and I2C bus are set up for future interfacing of sensors.

4.7.2 Serial Communication

Serial communication to the quadcopter is necessary so that we are able to send instructions to start subroutines and test programs after safely initializing the system as well as to receive data back for analysis and debugging purposes. Currently this is done using UART0 and a 3 wire RS232 connection; it is planned that this will be upgraded to a wireless communication so that un-tethered flights may be performed.

On the microcontroller Timer 1 is set up to generate a baud rate of 115200 bps to set the serial ports frequency of operation.

Using a serial-to-usb connector and software such as ‘termite’ it is possible to connect to the microcontroller and send and receive data.

4.7.3 Motor Control

To control the motors we must emulate the standard radio control signal that the ESCs expect to receive. To do this we will use the microcontrollers Programmable Counter Array (PCA) set up in 16-bit PWM mode.

The timebase of the PCA is set to be Timer 0 overflow; we then set up Timer 0 to overflow every 0.024ms giving our PWM signal a frequency of 42Hz.

We must set up four PCA’s in the same configuration so we are able to control each individual motor.

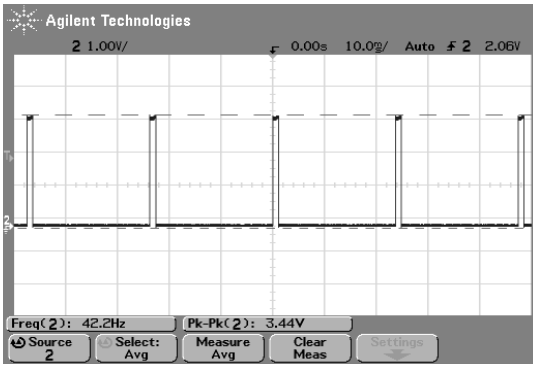

Figure 21 – Oscilloscope reading of outputted motor control signal.

Manipulation of the duty cycle is achieved by changing the values in the respective PCA’s capture compare register. This can be done in real time on the microcontroller as needed. However the pulse widths must be kept at 1ms until the start up initialization has been completed.

4.7.3 Interpreting sensor data

In order to make use of the analogue data that the gyroscopes output we must utilise the analogue to digital converter on the microcontroller.

As detailed in the research section, the gyroscope outputs a signal of 2.5V when it is not moving and this increases or decreases based on the direction and speed of rotation.

ADC0 is set up to run a conversion every time timer 3 overflows.

The ADC is set up in differential input mode, with the rate signal going to the positive terminal and the regulated 2.5V signal going to the negative terminal, this helps us avoid the problems of calibrating the software to find the midpoint as by default the ADC will now read zero when the gyroscope is not moving.

After the timer 3 overflow has triggered an ADC conversion the ADC will use the successive approximation technique until it has converged to a solution. Once the conversion is complete the ADCO interrupt flag is raised calling our interrupt routine.

As we have three analogue sensors that we wish to measure we must include a simple ‘select’ variable in our ADC0 interrupt routine. This allows us to measure from one differential input on the first overflow of timer3, complete a conversion and then change our selected input for the next conversion.

Inside the ADC0 interrupt routine a simple smoothing filter is run to reduce erroneous noisy signals, this is a very simple if statement that checks that the signal has changed by more than 25 ADC values. If the signal is deemed to be unchanging the measured value is discarded.

4.7.4 Performing control calculations

Once we have got the rate data for one axis we must integrate this data to find the change in angle (Δθ) between ADC measurements.

Once The ADC has performed two consecutive rate measurements on each axes, a function is called to perform the calculations. Inside this function ADC interrupts are turned off, so that the calculations will run as fast as possible. After the current angle is performed a PID function is called, that calculates new motor speeds in relation to the angle error in relation to the reference frame [0 0 0].

The Δθ is continuously added inside the software, this enables us to know the quadrotors current position in relation to its starting reference frame. Integration is performed using Simpson’s rule:

Where represents the rate at time 1, and represents the rate at time 2.

Variables used in calculating this angle must be declared as floats due to the high precision required.

As noise present in the measured signals is also integrated the current position of the quadrotor is only accurate over small time periods.

It is also important to note that control can only be performed as fast as the update rate of the ESCs, which in our case is 42Hz.

4.7.5 Code Initialisation

The microcontroller is initialised with the following functions:

```
EA = 0;             // disable global interrupts
WDTCN = 0xDE;       // Disable watch dog timer
WDTCN = 0xAD;       // Disable watch dog timer

Init_clock();       //Initialise clock at 22.11 Mhz
Init_ports();       //Initialise crossbar and configure ports
Init_Timer();       //Initialise timers
Init_ADC0();        //Initialise ADC0
Init_UART0();       //Initialise UART0
Init_PCA0();        //Initialise PWMs
pulsesizeH = 0xF4; //Set startup initialisation values for ESCs
pulsesizeL = 0x00; //Set startup initialisation values for ESCs
position = 0;       //Define reference frame as 0

EA = 1;             //Enable global interrupts
```

All the initialisation methods called can be seen in full in the appendix.
The pulsesizeH and pulsesizeL variables are used by the PCA's to produce a PWM of 1ms, this is so that the ESC's pass their safety check at start-up and initialise properly.

4.7.6 Main Loop

Inside the main loop different sections of code are run based on what instruction has been sent by the base station. Series of 'if statements' are used to separate the programs, as the main 'while (1)' loop runs it checks to see what the last received character was. If there is a match it runs the corresponding section of code.

This allows us to have several different test programs loaded onto the micro at any one time.

For example:

```
if(finalChar == 'b')
{
        pulsesizeH = 241;
        pulsesizeL = 0;
        PCA0CPL0 = pulsesizeL;
        PCA0CPH0 = pulsesizeH;
        PCA0CPL1 =  pulsesizeL;
        PCA0CPH1 =  pulsesizeH;
        PCA0CPL2 =  pulsesizeL;
        PCA0CPH2 =  pulsesizeH;
        PCA0CPL3 =  pulsesizeL;
        PCA0CPH3 =  pulsesizeH;

}
```

This code starts spinning all motors at minimum speed as a start up test if the microcontroller receives the character 'b' through RS232.

4.8 Research

4.8.1 Motor control

In order to write the code on the microcontroller necessary to control the motors we must first learn how they work under normal circumstances.

On a standard model aircraft a brushless motor is connected to an ESC this ESC is connected to the battery, it also has a 3 pin connecter which is connected to the radio receiver that controls the aircraft.

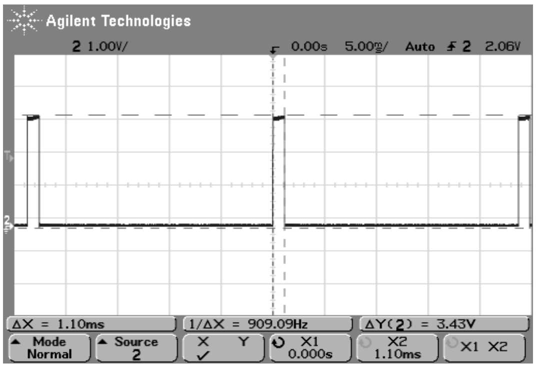

Figure 22 – oscilloscope reading showing pulse size of motor control signal

The radio receiver is powered by 5 volts that it receives from the ESC's regulator. The ESC then receives a modulated control signal from the radio receiver and outputs a 3.3V PWM signal at a frequency of approximately 42Hz with a duty cycle between 1ms and 2ms.
A duty cycle of 1ms corresponds to zero throttle, and 2ms full throttle respectively.

Upon start-up throttle must be held to zero, otherwise the ESC will not initialise as a safety precaution.

4.8.2 Gyroscopes

Using an oscilloscope, the 'rate' output from the ADXRS300 gyroscope was measured, having a good understanding of how this output behaves gives us a good insight into the best way to read this data for the purpose of performing control calculations.

From the oscilloscope readings we can see that the angular rate signal sits at a voltage of 2.5V when the device is not moving about the axis normal to the top surface of the package. When the package is rotated the rate voltage increases or decreases, according to the rate and direction of rotation. Voltage levels below 2.5 volts represent clockwise rotation and voltage levels higher than 2.5 volts represent anti-clockwise rotation. Voltage levels of 0.5V and 4.5V represent the maximum measurable rate of rotation in their respective directions.

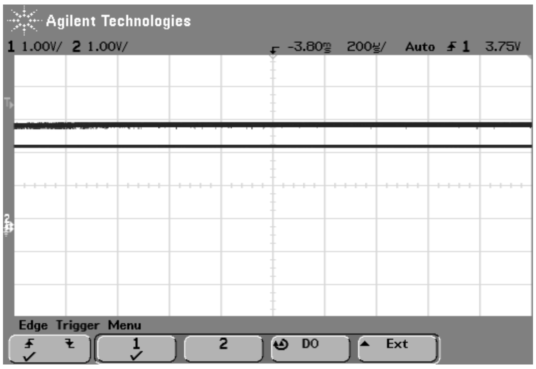

Figure 23 – Oscilloscope reading, showing an anti clockwise rotation against the 2.5V reference.

As you can see in figure 24 even when the gyroscope is stationary a small amount of noise is present. This noise can trick our software into thinking the craft is moving when it is in fact stationary.

The ADXRS300 package also outputs a 2.5V reference, this can be used to create a differential input for analogue to digital

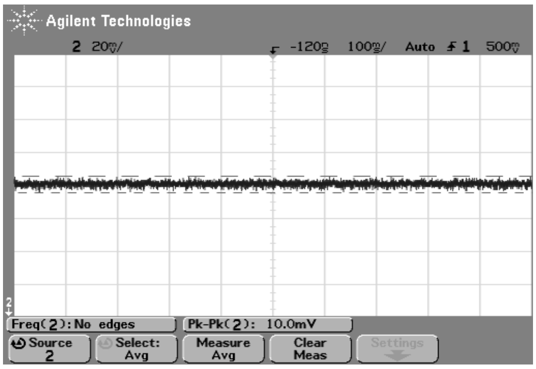

Figure 24 – Oscilloscope reading showing noise present in the rate signal.

conversions. This is beneficial for two reasons:

- Code is now simplified as the ADC will see a positive value for anti-clockwise rotations and negative values for clockwise rotations.
- Noise common to both lines will be removed.

4.8.3 Thrust tests

It was necessary to perform thrust tests specific to each frame so that we can find the throttle point that results in hover, this will be the set point that will be used for beginning PID control.

Initially thrust testing was carried out with only the bare minimum components attached to the frame. The frame was clamped to a wooden shaft and thrust was increased until it felt like the thrust had reached the hover point. From this we can determine a reasonable range to start with our experiments on the testing station.

Once the quadcopter has been set up in its fully equipped configuration it is placed onto the testing station and accurate thrust testing can be carried out. Thrust can be increased until the copter is able to fly up the guide poles on its own accord, in our future control calculations we want set the motor speed to a little bit less than this so that it hovers.

4.8.4 I2C and SPI interfacing for compass and accelerometers

In order to receive data from the compass, the I2C bus must be used. The C8051F020 supports use of the I2C bus.

Code was obtained from the cygnal laboratories website as well as a simple ‘bit-bashing’ routine developed.

These programs both demonstrate the ability to send information to the device but at the current time of writing this report, reading data back has been unsuccessful.

Both I2C programs developed can be found in the appendix.

Due to time constraints no attempts were made at developing code to implement the SPI bus.

5.0 Bill of Materials

As the majority of parts have been ordered from overseas, prices will be listed in New Zealand Dollars based on the exchange rate at the time of writing. Shipping will not be included, it should be noted however that there is a major cost associated with shipping parts from overseas, and buying nationally is recommended where possible.

Consumables like solder and other small items such as wire and bullet plugs are disregarded.

5.1 Items Purchased

Quantity	Item	Cost
1	UAVP Flight Controller w/o Sensors	$ 110
6	ADXRS300	$ 269
2	HMC6352	$ 138
2	LIS3LV02DQ	$ 95
4	EPP1045 Counter rotating pair	$ 37
4	DT750 Brushless out runners	$ 48
4	18A ESC	$ 53
1	Tx/Rx	$ 80
1	QuadroPPM	$ 46
1	Battery	$ 30
	Total Cost	$ 906

Twice the amount of sensors and propellers were purchased. This was because of the high probability of sustaining propeller damage in tests and also so spare equipment was available for future projects and in case of damage.

5.2 Cost of Developed Quadcopter

Quantity	Item	Cost
1	Silicon Labs Micro-Controller Development Board C8051F020-TB	$ 150
3	ADXRS300	$ 135
1	HMC6352	$ 69
1	LIS3LV02DQ	$ 48
2	EPP1045 Counter rotating pair	$ 19
4	DT750 Brushless out runners	$ 48
4	18A ESC	$ 53
1	Battery	$ 30
	Total Cost	$ 552

6.0 Conclusions

A quadrotor helicopter was developed for the purpose of creating an aerial vehicle test bed.

Major work has been undertaken in the designing and constructing of the physical vehicle and basic software has been implemented for communication with a computer via RS232, motor speed control as well as the beginnings of an inertial navigation system.

A testing station has been constructed so that future developments in control strategies can easily be tested without introducing unnecessary risks to hardware and operators.

7.0 Recommendations

There are still ample opportunities for the development of this test bed, these include but are not limited to:

- Completing work done on the I2C bus and get communication between the compass and microcontroller working.
- Implement code to use the SPI bus to read data from the accelerometer.
- Further develop the inertial navigation system to produce accurate position data.
- Develop the PID control to produce accurate stabilisation and fully autonomous flight.
- Implement more sensors onto the platform such as GPS and altitude sensors.
- Develop an intuitive human machine interface for the purpose of controlling the platform.
- Implement wireless communication between platform and base station.
- Implement a wireless video feed from the platform to the base station.

Once the test bed has been proven to be a reliable stable platform research projects can be developed around it, some examples include:

- Several quadcopters working autonomously for search and rescue, incorporating thermographic cameras.
- Collection of air samples.
- Viewing large structures from the outside for damage inspection (oil rigs, windmills)
- Military applications, such as reconnaissance and sound triangulation for locating snipers.
- Security and border patrol.
- Video recording platforms.

8.0 References

[1] Inertial Navigation System. Retrieved from http://en.wikipedia.org/wiki/Inertial_navigation_system

[2] ADXRS300 Datasheet

[3] LIS3lV02DQ Datasheet

[4] HMC6352 Datasheet

[5] Brushless DC electric motor. Retrieved from http://en.wikipedia.org/wiki/Brushless_DC_electric_motor

[6] Electronic speed control. Retrieved from http://en.wikipedia.org/wiki/Electronic_speed_control

[7] Lithium-ion polymer battery. Retrieved from http://en.wikipedia.org/wiki/Lithium-ion_polymer_battery

[8] Chew, M. T., & Sen Gupta, G. (2005). Embedded Programming with Field-Programmable Mixed-Signal uControllers.

[9] Mechanical Design. (2010). Retrieved from http://wyvernupenn.blogspot.com/2010/04/mechanical-design.html

[10] DiCesare, A., Gustafson, K., & Lindenfelzer, P. (2009). Design Optimization of a Quad-Rotor Capable of Autonomous Flight.

[11] Quadrotor. Retrieved from http://en.wikipedia.org/wiki/Quadrotor

[12] Pounds, P., Mahony, R., and Corke, P., "Modelling and Control of a Quad-Rotor Robot," In Proceedings of the Australasian Conference on Robotics and Automation, 2006.

[13] K. W. Weng, Abidin M.S.B, "Design and Control of a Quad-Rotor Flying Robot For Aerial Surveillance," 4th Student Conference on Research and Development. Malaysia, pp.173-177, June 2006.

[14] Stowers, J., Hayes, M., & Bainbridge-Smith, A. Quadrotor Helicopters for Visual Flight Control.

[15] D.M.W. Abeywardena, L.A.K. Amaratunga, S.A.A. Shakoor, S.R. Munasinghe(2009, December). A Velocity Feedback Fuzzy Logic Controller for Stable Hovering of a Quad Rotor VAV. Fourth Intemational Conference on Industrial and Information Systems, Sri Lanka.

[16] Mian, A., Daobo, W. Modeling and Backstepping-based Nonlinear Control Strategy for a 6 DOF Quadrotor Helicopter. Chinese Journal of Aeronautics. 2008, 21(3):261-268

[17] G. M. Hoffmann, H. Huang, S. L. Waslander, and C. J. Tomlin, "Quadrotor helicopter flight dynamics and control: Theory and experiment," in Proc. AIAA Guid., Navig., Control Conf., Hilton Head, SC, Aug. 2007

[18] Colton, S. (2007, June 25). The Balance Filter A Simple Solution for Integrating Accelerometer and Gyroscope Measurements for a Balancing Platform. Massachusetts Institute of Technology, America

[19] GRASP Laboratory. Retrieved from http://www.grasp.upenn.edu/

9.0 Appendix

Table A

	EPP1045 Prop	Kv	Source	Price	Wt	Max T	Watts/oz	Watts/oz	WQF	Vib-O	Vib-R
Rank				$	(oz)	(oz)	@maxT	@16 oz - Wt		(Low Freq)	(Hi Freq)
1	KDA20-22L	924	Hobby City	17	2.5	32	5.0	4.0	62%	1.9%	2.6%
2	DT-750	750	Hobby City	11	3.3	31	4.4	4.3	70%	3.1%	2.7%
3	Turnigy 2213/22	924	Hobby City	19	2.6	30	4.7	4.2	60%	2.9%	
4	Turnigy 2217/20	860	Hobby City	20	3.0	31	4.7	4.5	58%	3.3%	2.7%
5	DT-700	700	Hobby City	11	3.3	29	4.3	4.5	70%		4.8%
6	KA20-20L	1050	Planeinsanerc	25	2.7	36	5.4	4.3	57%	2.8%	
7	HC2812-0650	650	Maxx Products	52	2.7	20	3.5	3.9	62%	2.3%	4.3%
8	2210N	1000	Hobby City	6	1.9	32	5.2	4.3	61%	4.8%	
9	2410-09 Red Base	840	QuadroUFO	10	2.6	23	4.0	4.0	57%	4.6%	
10	2410-09 Gold Base	840	Nitro Planes	10	2.6	23	4.3	4.2	56%	3.8%	7.9%
11	2410-09 Open Base	840	Hobby City	6	2.5	23	4.4	4.2	54%	8.5%	6.3%
12	2410-09Y Blue Base	1100	RobotBirds	7	2.6	20	4.8	4.8	45%	3.8%	6.0%
13	2409-18 Open Base	1000	Hobby City	10	2.5	29	5.5	5.5	37%	4.3%	
14	C2409-1200	1200	Hobby City	6	2.4	32	6.4	5.1	56%		6.5%
15	FC2822	1200	Hobby City	6	1.9	28	6.8	5.8	55%		4.1%
16	D2730-1300	1300	Hobby City	8	1.3	17.6	6.5	6.1	45%		5.1%