µAV - Design and Implementation of an Open Source Micro Quadrotor

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Abstract

This paper presents the design of µAV, a palm size open source micro quadrotor constructed on a single Printed Circuit Board. The aim of the micro quadrotor is to provide a lightweight (approximately 86g) and cheap robotic research platform that can be used for a range of robotic applications. One possible application could be a cheap test bed for robotic swarm research. The goal of this paper is to give an overview of the design and capabilities of the micro quadrotor. The micro quadrotor is complete with a 9 Degree of Freedom Inertial Measurement Unit, a Gumstix Overo® Computer-On-Module which can run the widely used Robot Operating System (ROS) for use with other research algorithms.

1 Introduction

There has been a rapid increase in interest for the development of micro aerial robots for use in a range of applications, such as operating in a swarm formation. By scaling down the size of the platform it gains the ability to operate in tightly constrained environments and closer swarm formations. This enables the platform to perform tasks that other larger aerial vehicles can't, such as search and rescue operations in constrained environments.

In order to test and improve the state of the art in these robotic fields it is important to test and experiment on a real robotic research platform. However, to test swarm applications the cost increases dramatically when using larger more expensive quadrotor platforms.

This paper proposes the micro Unmanned Aerial Vehicle (µAV) as an open-source low-cost and easy to manufacture robotic research platform as a solution. The µAV is a quadrotor platform constructed from a single Printed Circuit Board (PCB) simplifying the design and fabrication while also making it easy to share and improve the design as an open-source project.

The micro quadrotor is shown in Figure 1 illustrating its palm size nature. In this paper we firstly describe other established research and commercial micro quadrotor platforms. We then present the design of the µAV system, outlining its main subsystems and how they are integrated onto a single PCB. The electrical design is presented, illustrating the layout of the PCB, design considerations and selection of components. The software design up to the current time is then presented. A dynamic model and controller is simulated to validate the system's ability to produce stable flight. We conclude with a discussion of the system and results to date, and outline the future directions of this open source project.

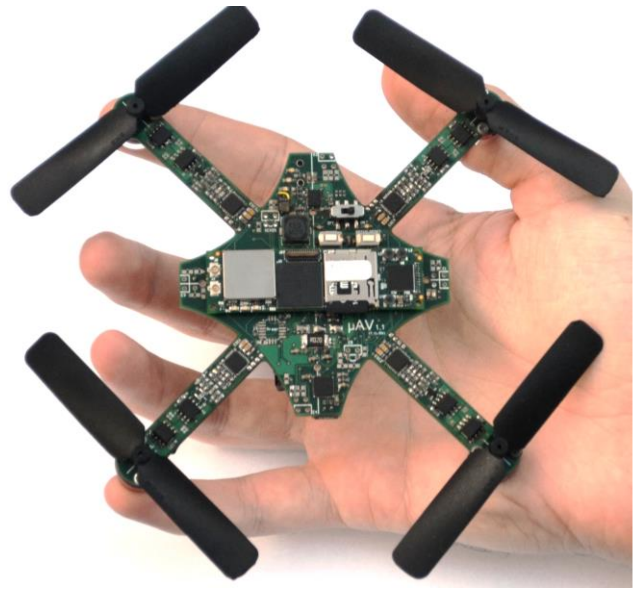


Figure 1 – Image of the constructed µAV quadrotor platform.

2 Background

This section outlines other micro scale quadrotor platforms that have been previously designed for both research and commercial applications. Other open source quadrotor projects and resources are also outlined.

2.1 Research Platforms

There have been a limited number of palm-sized quadrotors developed for research. Of note are two small-scale quadrotor platforms developed in the Grasp Laboratory at the University of Pennsylvania. They are not explicitly open sourced and being sold by the company KMel robotics. Relatively few details are available. The NanoQuad weighs approximately 75g and can support a payload of 20g, whereas the Nano+ weighs 150g and can have a payload of 70g. Both platforms support dual communication radios but the Nano+ also has an optional GPS, Gumstix and camera add on. Both platforms from KMel robotics are shown in Figure 2.

The NanoQuad, shown in Figure 2a, is agile enough to fly in a small-scale swarm formation, with the aid of an external localisation system [Kushleyev, *et al.*, 2012]. This work shows how agile the NanoQuad can be, demonstrating a lateral step response with a 1 second rise time and capable of manoeuvres up to 32rad/s in roll and pitch.

Another novel palm-sized research quadrotor [Konomura and Hori, 2013] includes a dedicated FPGA for onboard image processing. It can perform onboard visual feature detection of the ground at 5Hz using the FPGA. The platform weighs a total of 128g and is 260mm×260mm in size.

2.1 Commercial Platforms

There have been a few commercial Remote Control (RC) level micro scale quadrotors. These platforms do not explicitly have the capability of being fully autonomous for robotic research platforms but have the potential to be adapted for different applications. One downside to these commercial platforms is that they use brushed DC motors which are, in most cases, less efficient then brushless motors of the same size.

The Crazyflie Nano Quadcopter developed by Bitcraze is shown in Figure 3a. It has many features including a 10 Degree of Freedom (DoF) Inertial Measurement Unit (IMU) and a 32bit Cortex-M3 MCU running at 72MHz. The Crazyflie weighs approximately 19g with a payload of 10g. An important feature of the Crazyflie project is that the design is released under a creative commons license allowing it to be altered for non-commercial use. The design can be found online at http://www.bitcraze.se/.

Another small RC based quadrotor, the QR Ladybird has been fabricated by Walkera, and is shown in Figure 3b. The QR Ladybird is 125mm×125mm×38mm in size and weighs approximately 25g and features a 6 DOF IMU.

2.2 Open Source projects

There are many online resources for open-source quadrotors. This includes a variety of autopilot software. A good review of open-source platforms and software for larger scale quadrotors can be found in [Lim, *et al.*, 2012]. Some of the established online resources include an Arduino based autopilot entitled Arducopter developed by the DIYdrones community (http://diydrones.com/). Another established project is Openpilot (http://www.openpilot.org) an open source project led by RC hobbyists. A similar RC hobbyist project is the Multiwii (http://www.multiwii.com/) an autopilot software package based off the IMU implemented within a Nintendo® Wii™ remote.

Another well-established open source quadrotor project, PIXHAWK [Meier, *et al.*, 2011], has been developed by the Computer Vision and Geometry Lab at ETH Zürich. The project has developed an open source PX4 Autopilot and a ground control software package, QgroundControl (http://qgroundcontrol.org/) which uses the MAVLINK communication protocol developed by the PIXHAWK project. Both the ground control software and communication protocol have also been used within the Arducopter project.

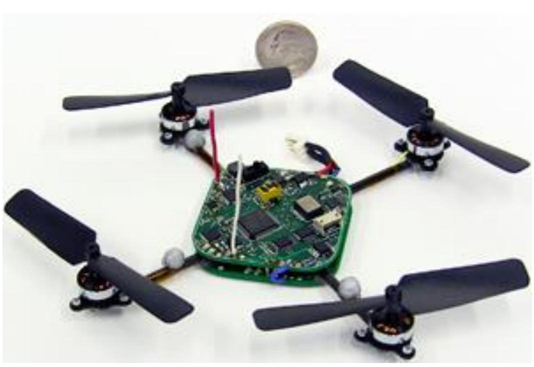
(a) (b)

(c)

Figure 3 – Remote control commercial micro quadrotors. (a) Crazyflie Nano Quadcopter designed by Bitcraze. (b) QR Ladybird quadrotor developed by Walkera. (c) Pocket Quad v1.1 designed by HobbyKing

3 System Design

The µAV was designed to feature all of the necessary components to achieve stable and dynamic flight while also including as many features as possible to enable full autonomy. These features include a 9 DOF IMU, altitude sensor, four sensorless brushless motor controllers, battery management unit, Infrared (IR) obstacle detection sensors and a Gumstix Overo® computer module with support for a Gumstix Camera. This section gives an overview of how all the features are integrated together on a single PCB. A block diagram of how the subsystems are connected is illustrated in Figure 4.



(a)

(b)

Figure 2 – Research level closed source micro quadrotors from KMel Robotics, images from http://kmelrobotics.com. (a) NanoQuad platform weighing 75 grams with a payload of 20 grams. (b) Nano+ platform weighing 150 grams with a payload of 70 grams and featuring optional GPS, Gumstix and camera module.

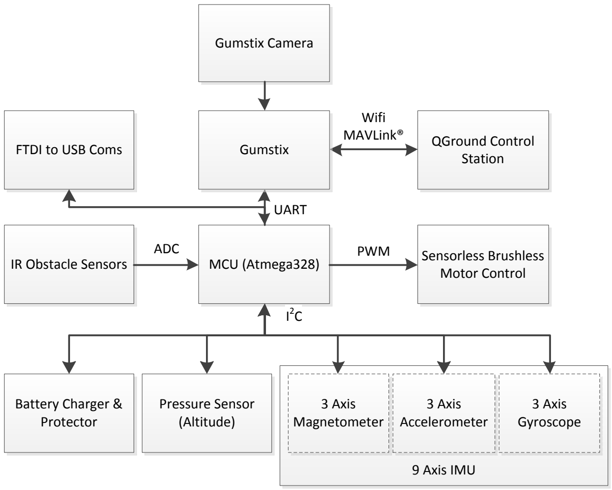


Figure 4 – Block diagram illustrating the components of the system at there respective communication protocols between each subsystem. The central MCU unit provides a communication hub between all the peripheral sensors and devices and the Gumstix module while also acting as the low level controller for achieving stabilised flight.

3.1 Microcontroller Unit (MCU)

The central hub to the micro quadrotor is an 8 bit microcontroller which was selected to interface to all of the components and act as the low level controller and communication pathway to the Gumstix module. The microcontroller that was chosen for this task is an Atmega328 which is a Atmel® 8-bit AVR RISC-based microcontroller containing 32KB of flash memory and 2KB of Static Random-Access Memory (RAM).

This microcontroller was chosen since it has low power consumption, is low cost and supports all the interfaces for the quadrotor's subsystems. This includes a 6 channel Analog to Digital Converter (ADC) to read the analog signals from the IR obstacle sensors; an I^{2}C interface to communicate with the IMU, altitude sensor and Battery management unit; a Universal Asynchronous Receiver/Transmitter (UART) for serial communication to the Gumstix module; and lastly six Pulse Width Modulation (PWM) channels to provide inputs to the brushless motor controllers.

Figure 5 –3D model generated by Solid Edge.

3.1 Gumstix Overo® Computer Module

In order for the quadrotor to be used as a research platform for other robotic applications it was important to have an onboard computer that could support common robotic algorithms. There is a growing body of robotic research that supports the use of the Robot Operating System (ROS) [Quigley, *et al.*, 2009] which includes a large set of libraries and tools for a range of robotic applications. The Gumstix Overo® COM was selected because of its ability to run a Linux based operating system and to run ROS, therefore allowing easy integration with other robotic research.

The Gumstix modules are small scale computers with a size of approximately 58mm×17mm, around the size of a packet of gum, and is shown in Figure 6a. The computer can be fitted directly on the PCB of the micro scale quadrotor.

The Gumstix Overo® is a low power (approximately 1Watt at full load) member of this family that contains an ARM® Cortex™-A8 Core processor that can run up to speeds of 1GHz. The Gumstix Overo module also contains a fixed point C64x+ digital signal processor that supports OpenGL POWER SGX™ graphics acceleration. This allows the Gumstix to run onboard robotic vision algorithms and support the use of camera modules shown in Figure 6b and Figure 6c. The Gumstix Overo® also includes Bluetooth and 802.11b/g Wi-Fi communication, which is important for communication with a ground-control station.

(a) (b)

(c)

Figure 6 – Image of Gumstix Overo® and Compatible Cameras modules (a) Gumstix Overo® Fire computer-on-module. (b) Caspa™ camera module compatible with Gumstix Overo COM's. (c) Gumstix camera module from e-con Systems.

3.2 Motor and Propeller Selection

In order to have the ability to fly, the brushless motors and propellers have to be selected to produce enough thrust to not only counter the weight of the vehicle but must also produce additional thrust in order to perform dynamic movements. Ideally the smaller the size and lighter the vehicle the easier it is to generate lift.

The largest component to account for with regards to size was the Gumstix module measuring 58mm×17mm×4.2mm. Therefore the total PCB board size needed to account for the size of the Gumstix. This defined the initial starting point for the size of the PCB. The overall size of the PCB for the µAV is 107mm×107mm illustrated in Figure 7.

Propeller Selection

The propellers of a quadrotor comprise two counter rotating pairs. Counter rotating propellers are driven in opposite directions to produce the same thrust direction whilst producing opposite reaction torques about the rotation axis. This means that the reaction torques due to the angular velocities of the propellers are ideally cancelled.

At design time there was limited choice of counter-rotating propellers for a quadrotor at this scale. The propeller that best suited the size and scale of this quadrotor was found to be a 3"×2" (diameter×pitch) counter rotating propeller designed by Grand Wing Servo (GWS). These propellers are illustrated in Figure 1 and are also found on the NanoQuad and Nano+ platforms.

The total weight of the µAV is approximately 86g, as outlined in Table 1. Therefore the minimum thrust that is required for one motor and propeller combination is approximately 0.21N (21.5 grams) of thrust. Using the coefficient of thrust for the selected propeller (see Table 5) the minimum angular velocity of the propeller to produce positive lift is approximately 1.59×10^3 rad/s (15,100 rpm).

Subsystem	Weight
Gumstix	5g
Battery 2S 470mAh	33g
Blank PCB	15g
PCB components	9g
4×Propeller	8g
4×Motor	16g
Total	86g

Table 1 – weights of quadrotor components and total weight.

Motor Selection

One of the important parameters when selecting a brushless motor is to choose the appropriate velocity coefficient, K_v, specified in rpm/V. The velocity coefficient defines the no load speed of the motor for a given input voltage. With the minimum angular velocity for the selected propellers at 15,100 rpm, K_v for the motors needs to produce sufficient propeller speed for a given input voltage. Ideally a higher the K_v rating would raise the no-load speed and therefore develop higher thrust.

Table 6 shows the DC gain determined from a step response of the selected motor, with load, is approximately 4,000rpm/V, which is actually less than half of the no-load rating. A comparison of brushless motors at the appropriate scale, and with K_v higher than the minimum, are shown in Table 2, and the selected motor highlighted.

Motor Name	Weight	K_v (rpm/V)	Max Current
Turnigy A1309	2.8g	7500	3A
Aero Electronics C05M	4.0g	11000	6A
Aero Electronics ADH30S	2.6g	6100	2A
Hobby King AP03	3.1g	7000	3A

Table 2 – Comparison of outrunner brushless DC motors with selected motor highlighted in grey.

4 Electrical Design

The novelty of the µAV quadrotor is the simplicity of its construction and fabrication. This simplicity is a consequence of the integrated electrical design which incorporates all the components required for an autonomous micro quadrotor. The advantage of designing a quadrotor in this fashion is the ease of replication and manufacturing. This section outlines the design and selection of the electrical components of the µAV quadrotor implemented on the PCB. The specifications of most of the electrical components are shown below in Table 3.

Component	Product	Specifications
Power Supply	Texas Instruments TPS54356	3.3V, max 3A
Gyroscope	Invensense IMU-3000	3 Axis, 16 bit resolution at ±250, 500, 1000, and 2000˚/sec
Accelerometer	Analog Devices ADXL345	3 Axis, 10 bit resolution at ±2, 4, 8, and 16 g
Magnetometer	Honeywell HMC5843	3 Axis, 12 bit resolution at ±4G
Pressure Sensor	VTI SCP1000-D11	30kPa -120kPa range at 19 bit resolution
Gumstix	Overo® Fire	ARM Cortex-A8, weight 5.6 grams, ≈400mA@Full load
Motor Control MCU	Atmega8L	8MHz at 3.3V, 8KB flash, 1KB SRAM
Motor Driver MOSFETs	Fairchild Semiconductor® FDS8858CZ	Dual N&P channel, Max ±30V@7.3A, ≈20mΩ Resistance drain to source

Table 3 – Selected electrical components and specifications on the µAV PCB.

4.1 Power Supply and Battery Selection

The power supply of the micro quadrotor provides 3.3V to all the peripheral devices and the Gumstix module. It provides approximately 400mA for the Gumstix and less then 100mA for all the other peripherals. A switch mode power supply from Texas Instruments was selected that can provide a maximum of 3A, enough to handle the transients required to power all onboard devices.

The Turnigy nano-tech 2-cell lithium polymer battery was selected for the micro quadrotor. This battery balances both weight and energy having an energy density of approximately 103Wh/kg. The nano-tech battery is a small, lightweight and high-discharge battery designed specifically for flying vehicles. The battery can supply a continuous current of 25×C Amps where C is the battery's capacity and has a maximum supply of 40×C Amps. A 2-cell battery was selected, which enables higher propeller speeds and thus more thrust, however at the cost of increased power consumption. The two-cell configuration provides a good trade-off between maximum propeller speed and power efficiency.

The Turnigy nano-tech range offer a selection of battery capacities that have an appropriate package size to fit on the µAV platform. The capacities include 330mAh, 460mAh and 850mAh. The batteries come in the same length and width packages but increase in height proportional to capacity as outlined in Table 4.

Battery	Size	Weight
Turnigy nano-tech 330mAh	63x32x9mm	27g
Turnigy nano-tech 460mAh	63x32x11mm	33g
Turnigy nano-tech 850mAh	63x32x16mm	49g

Table 4 – Range of Turnigy nano-tech batteries and there corresponding size and weights. Ideal battery selected is highlighted in grey.

4.2 Attitude and Altitude Sensors

A 3-axis rate gyroscope, 3-axis accelerometer and 3-axis magnetometer were chosen to provide a 9 DoF IMU for attitude estimation. The specifications of the gyroscope, accelerometer and magnetometer are outlined in Table 3. The gyroscope and accelerometers are positioned at the centre of mass of the platform, illustrated in Figure 7. This simplifies the attitude estimation for the platform. We originally selected a barometer to measure local atmospheric pressure and thus estimate the platform's altitude. Unfortunately our selected pressure sensor was discontinued and the current prototype does not have an altitude sensor.

4.1 Electronic Speed Controller (ESC)

The motors used on the µAV quadrotor are brushless DC motors with 3 phase windings wound in a wye (Y-shaped) configuration. These require a 3 phase motor driver. One of the cheapest methods of achieving speed control of a brushless motor is to use a sensorless configuration that utilises measurement of the back Electromotive Force (EMF) generated by the motor as it turns.

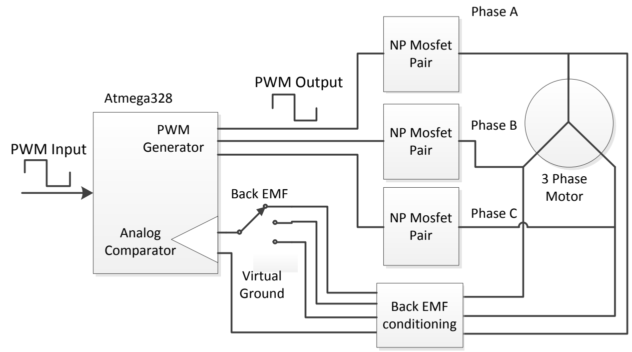


Figure 8 – Simplified schematic diagram of a single electronic speed controller. The controller uses the back EMF of a floating phase and detects a zero crossing with respect to a virtual ground in order to measure the current speed of the motor.

A sensorless brushless speed controller contains three main subsystems: the microcontroller, motor driver and back EMF signal conditioning systems. More details of the theory of sensorless brushless control can be found in [Yedamale, 2003] and the application note [Atmel, 2005].

First, a microcontroller is used to power the motor windings (referred to as commutation) and to measure the speed of the motor using the back EMF signals. Second, the motor driver stage routes the power through the 3 phases of the motor using PWM and logic signals generated by the microcontroller. The motor driver is configured in a 3-phase H-bridge configuration.

Third, the back EMF conditioning stage transforms the motor's back EMF signal into an analog voltage which is fed to an analog comparator in order to measure motor speed. The input to the ESC defines the desired voltage or speed to be controlled. For the ESC implemented on the µAV platform the input is the desired voltage across the motor as defined by the pulse width. An

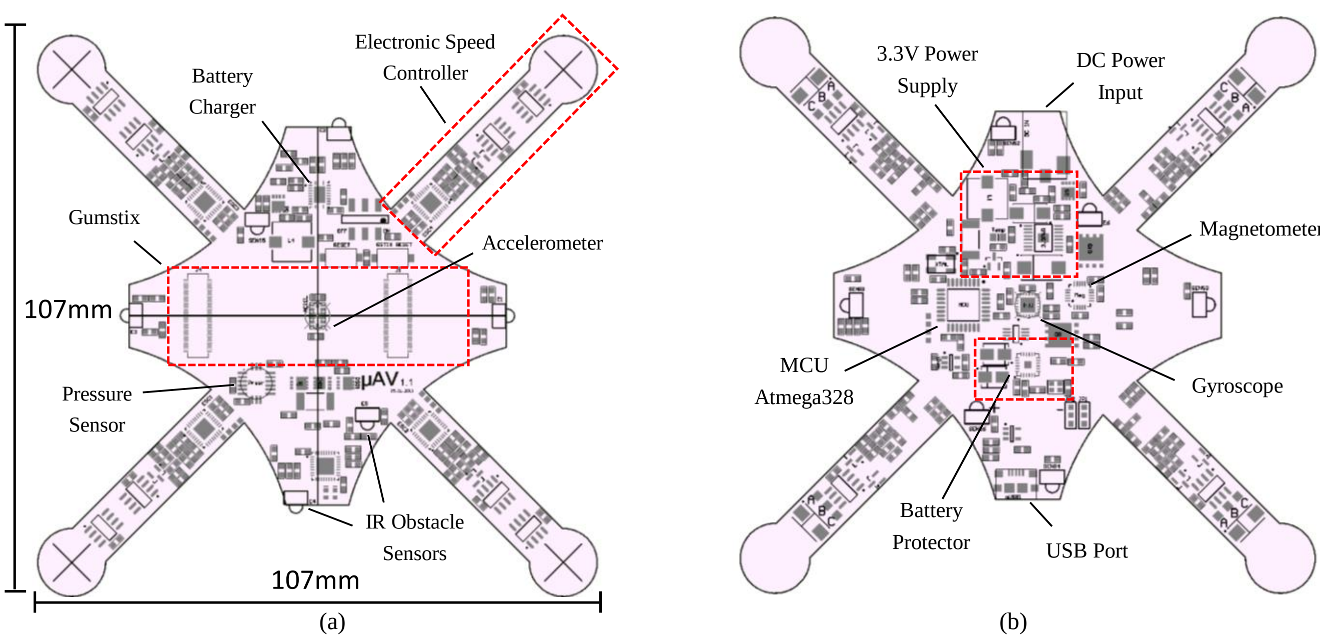


Figure 7 – Layout of PCB for the µAV quadrotor (a) Top layer layout highlighting the Electronic speed controllers on each arm; the position of the Gumstix and connectors; the IR obstacle sensor positions; the pressure altitude sensor; and the battery charging unit. (b) Bottom layer layout indicating the MCU position; gyroscope and magnetometer locations; power supply area; battery protection layout; USB communication port and DC power input plug.

outline of how the subsystems are connected to complete the ESC is shown in Figure 8.

The ESC for the quadrotor requires the ability to handle large transient currents, while also switching efficiently to modulate the battery voltage to the required value. These requirements are tied to the selection of the switching MOSFETs. For the selected motor given in Table 2 the max rated current is 6A and therefore the ESC should be able to handle the current. The MOSFETs selected can handle up to 7.3A continuous current.

5 Software Design

This section describes the software developed to date for interfacing and controlling the µAV quadrotor. The open source ground control station and communication protocol is also outlined.

5.1 Ground Station

The ground station for the µAV platform allows the user to monitor, test and command the robot to perform different tasks. An open-source ground control station, QGroundControl from PIXHAWK was chosen as it supports the use of the efficient wireless MAVLINK communication protocol. Some of the features of QGroundControl includes on-board parameter tuning, a plotting window for on-board sensor data and manual piloting through joystick inputs.

An RC transmitter can also be integrated for manual piloting through the use of a USB transmitter to joystick device. Figure 9 shows a screenshot of the QGroundControl software used with the micro quadrotor. Currently the ground control station communicates with the µAV platform via a point to point Xbee® Wi-Fi link.

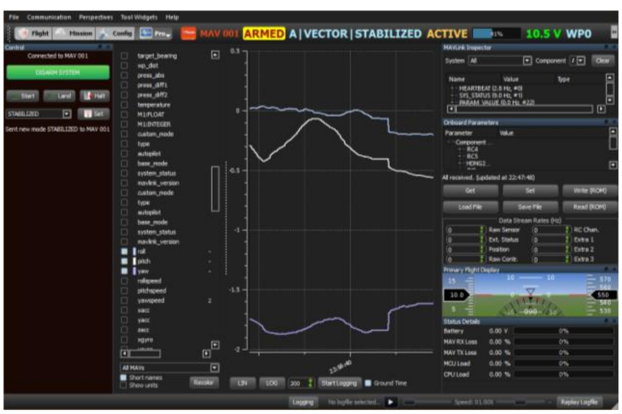


Figure 9 – Screenshot of QGroundControl open source software developed by PIXHAWK.

5.2 MAVLINK Communication Protocol

In order to send commands, onboard images or manually pilot the µAV platform an efficient open source communication protocol was used. MAVLINK is a communication protocol that can efficiently pack C-structs and send them to the ground control software. The protocol supports a many packet types allowing the µAV to accept mission commands, navigation waypoints and manual pilot commands.

5.3 Attitude Estimation

A complimentary filter was implemented on the MCU to estimate roll, pitch and yaw. The complimentary filter was chosen as it is simple and efficient for implementation on an 8-bit microcontroller [Baerveldt and Klang, 1997].

5.4 Brushless Motor Control

The software implemented on the sensorless brushless motor controllers is an open source project developed by Simon Kirby (https://github.com/sim-/tgy) for upgrading the firmware on commercial ESC products. The software was easily modified to run on the Atmega8 microcontroller of the ESC as implemented on the µAV.

6 Modelling and Control

In order to validate the design and control of the quadrotor, before physical implementation, a dynamic model, simulation and controller was developed. This section outlines the derived dynamic model, the implemented simulation including the model specific parameters for the quadrotor and lastly presents the results from an implemented feedback controller for stabilising the roll and pitch angles during simulated flight.

6.1 Dynamic model

The µAV quadrotor platform was modelled using the dynamic equations presented in [Pounds, *et al.*, 2002]. Let $\xi = (x, y, z)$ denote the position of the centre of mass of the quadrotor with respect to a fixed inertial frame, $\mathrm{A} = \{E_x \quad E_y \quad E_z\}$. The orientation of the quadrotor can then be expressed using an orthogonal rotation matrix R that transforms the positions from the body fixed frame $\mathrm{B} = \{E_1^b \quad E_2^b \quad E_3^b\}$ to the inertial frame.

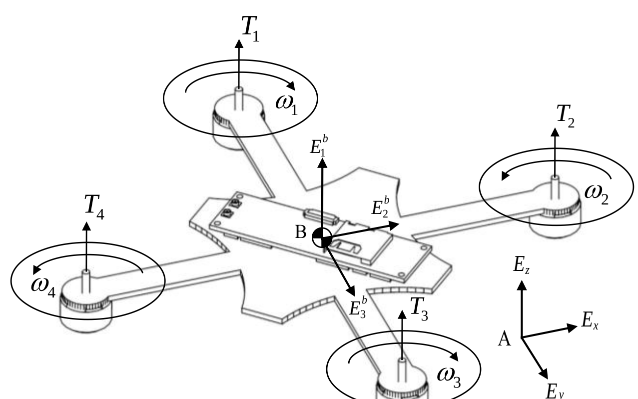


Figure 10 – Diagram of the µAV quadrotor illustrating the reference frames, thrust and angular velocities.

Let V and Ω represent the linear and angular velocities, respectively. The mass of the quadrotor is represented by m and the inertia mass matrix is denoted by $\mathbf{I} \in \mathbb{R}^{3\times3}$. Let T_H and Γ denote the total thrust and torque generated by the propellers respectively. The dynamics of the quadrotor can then be modelled using the following equations

$$\dot{\xi} = RV \tag{1}$$

$$m\dot{V} = -m\Omega \times V + mgR^T e_3 - T_H e_3 \tag{2}$$

$$\mathbf{I}\dot{\Omega} = -\Omega \times \mathbf{I}\Omega + \Gamma \tag{3}$$

A thrust acting along the axis of the motor shaft and drag Q_i, acting around the motor shaft is generated by the angular velocities of the rotors. The thrust and drag can be modelled as proportional to the square of the angular velocity of the rotors in the form

$$T_i = \alpha\omega_i^2 \qquad Q_i = \kappa\omega_i^2 .$$

Where α is the coefficient of thrust for a specific propeller type, κ is the coefficient of drag, ω is the angular velocity of the propeller and $i \in \{1,2,3,4\}$ denotes the motor and propeller number. For this platform the constants α and κ are empirically derived. Figure 10 illustrates the orientation of the reference frames, thrust vectors and angular velocities.

6.1 Simulation

A simulation of the micro quadrotor was developed using the Robotics Toolbox [Corke, 2011] with contributions from [Pounds, 2007]. The parameters of the model where estimated using a Solid Edge CAD file shown in Figure 5. Table 5 gives the parameter values of the dynamic model for the µAV quadrotor.

Parameter	Value
m (Mass)	86 g
I_{xx} (Inertia)	7.1×10^{-5} kg·m^2
I_{yy} (Inertia)	8×10^{-5} kg·m^2
I_{zz} (Inertia)	14×10^{-5} kg·m^2
d (length of arms)	66×10^{-3} m
r (rotor radius)	41×10^{-3} m
p (propeller pitch)	51×10^{-3} m (3”)
α (Thrust coefficient)	8.304×10^{-8}

Table 5 – Parameter values for the dynamic model of the micro quadrotor.

The dynamics of the motor from input to propeller speed was empirically derived by measuring a step response of each brushless motor and propeller combination. Figure 11 shows the results from the step response on all four brushless motors.

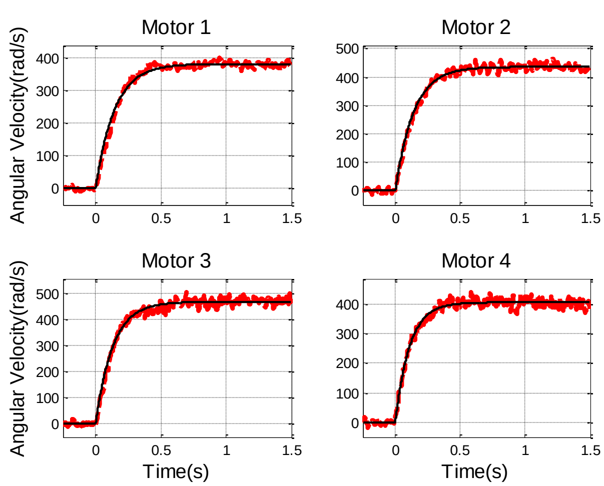


Figure 11 – Plot of measured step response versus modelled step response of four motor combinations.

From the measured step response of the motor and propellers a first order model was fitted using the MATLAB System Identification Toolbox. Table 6 gives the model parameters for the motors obtained from the system identification.

Step Info	Motor 1	Motor 2	Motor 3	Motor 4
Rise Time (sec)	0.321	0.309	0.291	0.246
DC gain (rad/s/V)	382	435	469	405
Time constant (τ)	0.146	0.140	0.133	0.110

Table 6 – Motor and propeller voltage to angular velocity transient characteristics.

In order to stabilise the roll and pitch axis of the simulated µAV platform a PD feedback controller was implemented and empirically tuned. Figure 12 shows the result from the closed loop response simulated controller starting from pitch and roll angles of 10 degrees.

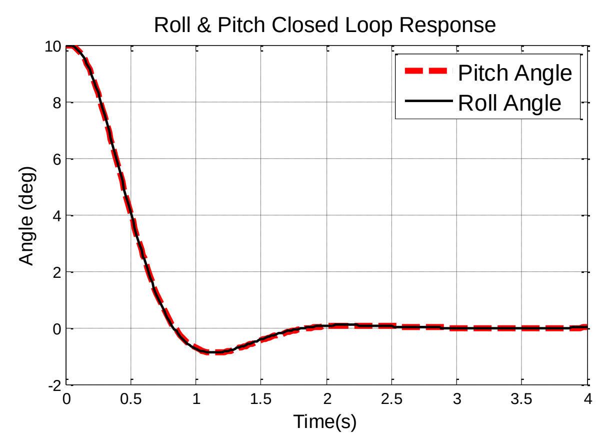


Figure 12 – Plot of the controlled response for pitch and roll angles during simulated flight.

7 Discussion and Conclusion

This paper has described the design process and the implementation of a micro quadrotor robotic platform. We have shown that the platform has the capability of being a low-cost and versatile micro unmanned aerial vehicle for use as a robotic research platform.

The development is ongoing and more details and current progress of the project can be found at http://tinyurl.com/qut-mUAV. This is an open source project and if you like to contribute or collaborate please contact the authors.

8 Future Work

There is still some work left before we achieve our goal of a highly functional robotic research platform. Future work will look at integrating ROS on the Gumstix allowing useful packages to give the platform more capabilities. The choice of brushless motors and propellers could also be optimised for better efficiency.

At this point in time we require the ground control station in order to provide manual piloting. In future designs we would consider incorporating an RC receiver to enable manual piloting directly from an RC handset.

The open-source ESC firmware implemented on the quadrotor only performs open-loop speed control, with rise time dominated by the mechanical dynamics of the motor and propeller. Future work would modify the firmware for closed-loop motor speed control which would improve the agility of the vehicle.

Finally, many improved components have become commercially available over the duration of our project. The next design iteration would incorporate these as appropriate, whilst maintaining the simple but high-integrated mechatronic design principles of this vehicle.

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