Appendix A
UAV configuration

One of the most important parts of the project was to build a state of the art UAV. There were many individual requirements that the configuration should satisfy. The higher level demands were to use commercial off the shelf (COTS) products in order to save time from implementing again successful existing parts and simplifying the replication due to the practical design. Further than that, open hardware products were chosen so that it would be easy to get support from the related communities and it would also be able to choose from different manufacturers with lower prices. In general, COTS components tend to be inexpensive, upgradable and reconfigurable. Moreover, it is easy to gain experience even before starting to experiment, since many researchers have already used them and published relevant papers. Aside from the general requirements, specific research has been conducted for each individual part in order to use the most appropriate component and how this item can be combined with the others in the most efficient way.

A.1 Chassis, brushless motors and Electronic Speed Controllers (ESC)

A.1.1 General description

The most basic and influencing component in a UAV is its chassis. There is a great range of available options according to the number of motors and their topology. For the current project, a quad copter has been chosen. Some of the advantages of selecting quad copters are the low price, the great manoeuvrability and the enough available power to add accessories since they have only four motors. The option of using a tri-copter has been discarded due to its limited trust and power capabilities. On the other hand, hex or octo-copters can fly in higher heights and greater flight speeds, are safer if one motor dies, since the rest can pick up the slack and also can handle higher overall payloads. These are considerable advantages but for the specific project these do not affect the objectives and add only unnecessary complexity.

Regarding the motors of the UAV, the most popular type is the brushless motors. Brushless motors are much more efficient than the conventional brushed ones. They have a greater lifetime and they do not require maintenance due to the absence of brushes and commutators. In addition to that, the absence of brushes eliminates the friction and thus they have very high power density (in terms of size and weight), which means longer battery life. In general, brushless motors are very easy to control their speed accurately and adjust it quickly. Nowadays, the prices of the brushless motors are similar to brushed so they are not expensive as they were in the past. Finally, it generates less noise that causes weaker electrical magnetic interference (EMI), which is very important for the interference of the GPS.

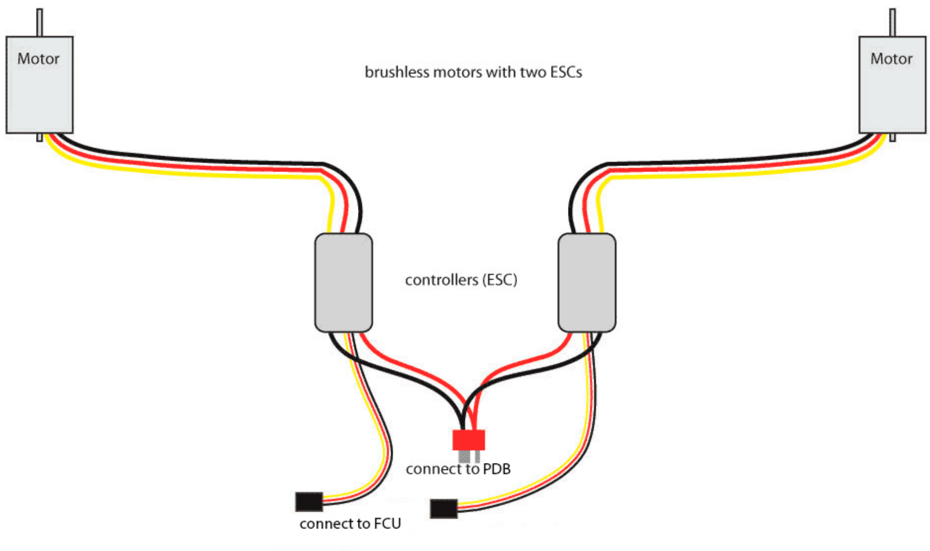

Fig.A.1 Brushless motors and Electronic Speed Controllers (ESCs) connection to flight management unit and the power distribution board (image modified from one in www.pteroworks.com)

The use of brushless motors requires the presence of Electronic Speed controllers (ESC). Electronic speed controllers are responsible for spinning the motors at the speed requested by the flight controller unit (FMU). Each brushless motor is connected with three wires (fig.A.1) to the corresponding ESC. This is because brushless motors are three phase motors having three coils inside. Consequently ESCs activate the coils in sequence and depending on the synchronization they can accelerate or decelerate the motors to the desired speed. The ESCS comprises of the following parts:

- Microcontrollers that activate or deactivate the coils and calculate timing by measuring the feedback in the coils caused by the movement of the magnets.
- 5V voltage regulators to produce a stable supply and a low battery cut-off feature to stop spinning the motor when the lithium polymer battery is drained. This feature protects the battery from suffering permanent damages that occur if it drained below a threshold.

A general schematic of a UAV wiring is shown in the (fig.A.2)

The Interface Analysis Centre (IAC) has a fleet of UAS platforms for radiation mapping such as quad-copters, hex-copters and octo-copters. For the specific project, it provided the chassis of a quad copter having the following components installed:

- Four brushless motors
- Four Electronic Speed Controllers ESCs

A.1.2 Vibration damping

The UAV's flight management unit (FMU) sits in the upper part of the central hub. It is equipped with accelerometers in the inertial measurement unit (IMU), which are sensitive to vibrations. In general, in most of the flight modes it is crucial to have a correct position estimate. The calculation of the position estimate is carried out using data from the IMU in combination with the barometer and GPS. It is clear that vibrations can interfere the operation of these units and lead to unacceptable performance. Generally speaking, the motors and propellers produce a high frequency and low amplitude vibration. The vibration needs to be less that 0.3 g in the X and Y axis and less that 0.5G in the Z axis (Copter.ardupilot.com, 2015).

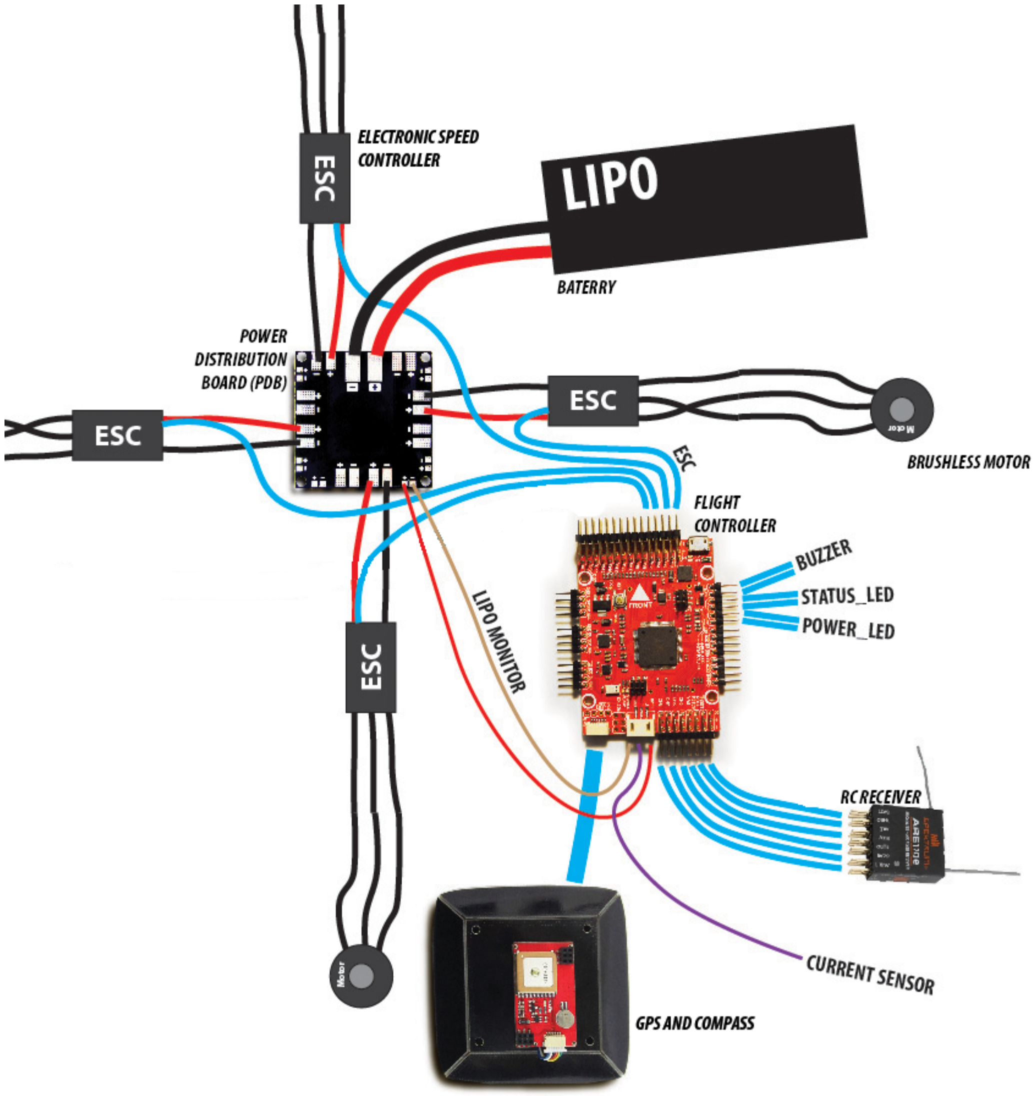

Fig.A.2 A general schematic of a UAV wiring (image modified from one in www.diymulticopter.org)

The most important factor that affects the vibration is the frame. Frame arms should be as rigid as possible. Carbon fiber armed copters and copters with injection-molded exoskeletons perform much better than cheaper frames, which tend to be flex. It is also very important to assemble secure and flex-free all the conjunctions like motors to frame arms, frame arms to central hub and accessories to frame. Another factor that plays a role in the vibration is the propellers. They should be fully balanced. The size and the slope are important. Large slow propellers will induce more vibration than small fast ones. In addition, the material from which they are made of affects the vibrations. Carbon fiber-made have the best performance.

Since the UAV has been assembled following the guides for minimizing the sources of vibration, a further optimization step can be implemented. More precisely, the flight controller mounting plate can be installed on the central hub using anti-vibration absorber rubber balls. Inserting inside the rubber balls squeezed PVC foam earplugs can enhance this technique. The earplugs provide an additional damping medium with a different frequency damping range. The earplugs also stiffen the bulb mounts up a bit, preventing excessive free motion from being caused by normal flight maneuvers.

A.1.3 Magnetic interference

An additional factor that should be minimized since it degrades the performance and can cause serious problems in various flight modes is the magnetic interference. The DC currents of the UAV cause this interference. The places where DC current exists is in the power distribution board (PDB) and the wires between the ESC and PDB. To combat this effect the following techniques can be adapted:

- Keeping the length of DC current wires as short as possible.
- Placing the external GPS and compass module above the FMU and the PDB in the lowest part of the central hub to ensure the greatest distance between them.
- In cases where it is feasible, twisting the wires between the PDB, ESC and battery and using grounded shielding.
- Finally, using 4-in-1 PDB and ESCs instead of 4 separate ESCS and a PDB, which is the case in our project, so as to produce less

interference since all the circuitry is enclosed in an aluminium case without any free wires running along (fig.A.3).

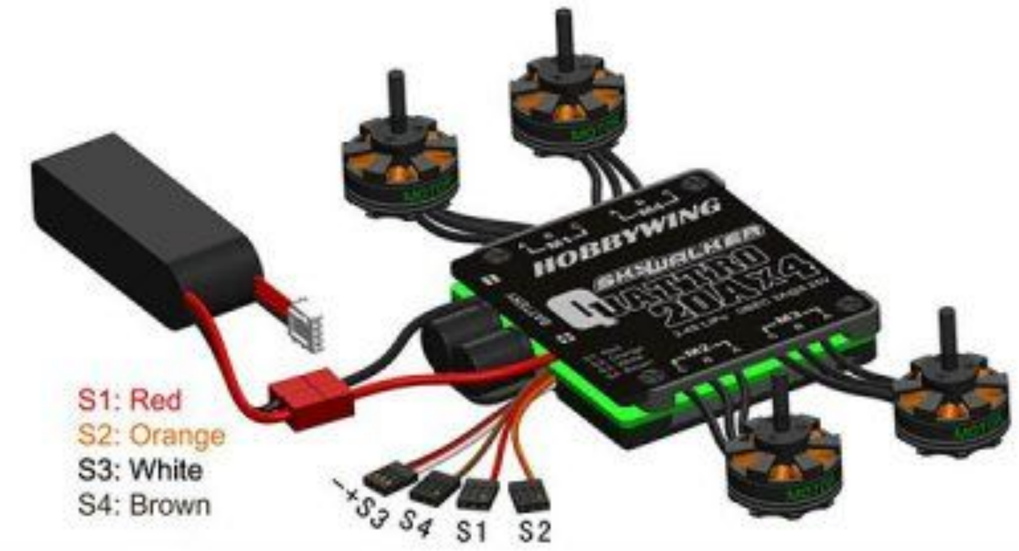

Fig.A.3 4-in 1 ESC and PDB module for less magnetic interference (image from copter.ardupilot.com)

A.1.4 Power module

The project's UAV is powered by Lithium – Polymer (LiPo) batteries. This type of batteries is the preferred power source for the most electric models. The advantages of employing them are the high discharge rates and the high-energy storage/weight ratio. However, they require special handling and charging. The most important matter to consider is the safety. Specific chargers should be used specifically designed to charge LiPo cells with the correct parameter set such as correct voltage and cell count.

In addition to the batteries, in order to provide filtered clean power to the FMU without glitches, a power module has been installed (fig.A.4). Through the 6P cable, it provides stable 5.3V voltage as well as current consumption and battery voltage measurements to the FMU. This module does not provide power to the

ESCs, which are fed directly from the LiPo batteries through the power distribution board (PDB).

Fig.A.4 Flight control board power module T plug (image from www.littleblupigs.com)

A.2 Flight controller

The flight controller or flight management unit (FMU) is the nerve center of the UAV. This component is a microcontroller and gathers all the connections from the various accessories. It sends the appropriate commands to the ESC and receives data from the sensors, the GPS and the compass as well as the telemetry link. The flight controller provides a built-in inertial measurement unit (IMU) and a barometer. The IMU, in general, is a component that integrates accelerometers and gyroscopes. It receives data from both and using sensor fusion algorithms it can estimate the current position and attitude of the UAV. The main usage of the barometer is to inform an estimation of height for altitudes above 10m.

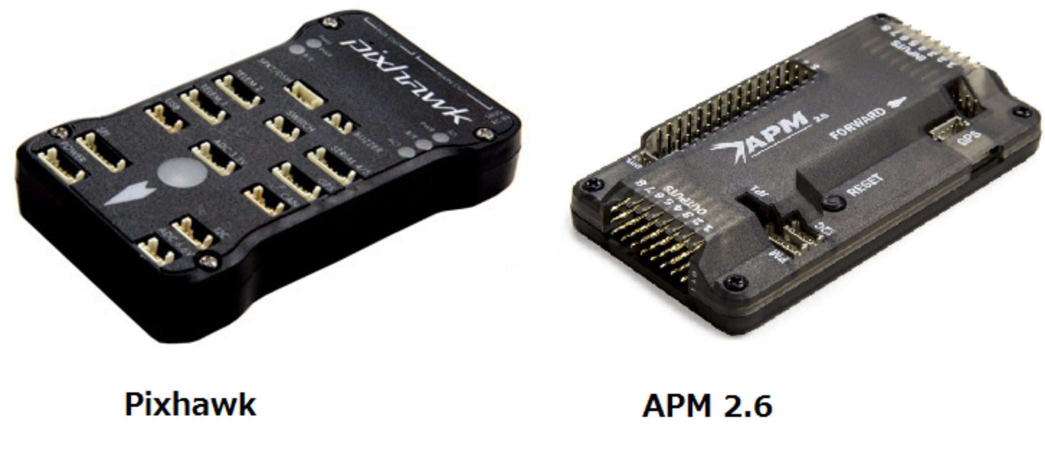

Fig.A.5 The most popular flight controllers: Pixhawk and APM 2.6 (image from copter.ardupilot.com)

There are two dominant flight controllers in the market (fig.A.5), the AMP 2.6 and the Pixhawk. The APM 2.6 is a complete open source autopilot system. It is based on the mega microcontroller based on the Atmel's 8bit-ATMEGA2560 chip. It includes a 3-axis gyro and accelerometer (6-DOF MPU-6000) and a barometer (MS5611-01BA03). It is compatible up to the APM:Copter 3.2 version firmware. Generally speaking, it is the most popular and bestselling flight controller with a large supporting community and plenty of online tutorials ranging from simple use to code developing.

On the other hand, the descendant of the APM is the Pixhawk board. The need of having a board that can offer more processing power and more available memory lead the ETH's PX4 team to design it. Pixhawk is an advanced autopilot system designed by the PX4 open-hardware project. A 32-bit ARM Cortex M4 processor running NuttX real time operating system (RTOS) powers it. It provides abundant connectivity options for additional peripherals (UART, I2C, CAN). It also has a MicroSD card slot for data logs.

Essentially, the difference between the two flight controllers is that the APM is old, well tested, and fully featured, but at the end of it's development cycle. The Pixhawk board is new, is more powerful, but it has not been as fully tested, and it has a lot of promise for the future. For the current project although the time frame of developing an application was very restricted, the need of flight controller that can support various advanced sensors and provide capabilities to implement obstacle avoidance techniques restrict the available choices. APM has been satisfying the need for a tried and tested configuration, with a large support and availability of many tutorials since there was no prior experience, yet the Pixhawk has been chosen in order to accommodate the project's enhanced requirements. The Pixhawk is more complex with a restricted knowledge base and a single point of support. It is a new project and quite immature compared to APM but it is the only tool if one wants to carry out professional projects.

A.3 Telemetry

Telemetry is a popular accessory added in UAVs that provides an air-to-ground data link between the autopilot and your ground station laptop or tablet. Although it is possible to control the UAV via the telemetry stream, it is safe to use an additional remote control (RC) for that, due to the superior reliability of that dedicated radio link and controller.

The telemetry equipment supports two transmission frequencies bands, the 433MHz and 915MHz radio links. The former is selected (fig.A.6) for the current project, mainly for the following reasons:

- The 433MHz is legal in Europe
- The 915MHz interference with the GSM bands, so in regions where mobile antennas exist (more in urban areas) it is more likely to have worse communication.

Fig.A.6 433MHz radio telemetry kit (image from www.rctimer.com)

The project's quad copter is equipped with an open source implementation of the Xbee replacement radio set. It is fully compatible with the 3DR radio system which is the market standard yet significantly cheaper. It has a range of approximately 1 mile using transmit power up to 20dBm. It uses the MAVLink communication protocol (Micro Air Vehicle), which is a very lightweight, header-only message marshaling library. It supports both frequency hopping spread spectrum (FHSS) and adaptive time division multiplexing (TDM).

A.4 GPS and compass module

This component includes a GPS and a compass (fig.A.7). The GPS component is the u-blox 6-position engine, a low power consumption high performance GPS adapted to the miniature form factor (NEO-6 series, 2011). It uses the NMEA protocol with baud rate equal to 9600 and 5Hz update rate. The other component is the HMC5883L compass. It is a popular magnetometer with 1-

2 degree compass heading accuracy. It is considerably fast reaching 160Hz maximum output rate (3-Axis Digital Compass IC HMC5883L, 2010).

Fig.A.7 Neo 6M GPS and MAG v1.2 module (image from www.rctimer.com)

A.5 On-board computer

On-board or companion computers, are single board computers that add the real intelligence to the UAV or generally in a robotic system. Admittedly, the addition of on-board computer adds to the restricted payload of a UAV but there is no other way to develop a sense of autonomy to the vehicle. It is noteworthy that the flight controllers (APM or Pixhawk) are not capable of executing complex computer vision or SLAM (Simultaneous Localization and Mapping) algorithms.

From a technical point of view, the actual operation of companion computer is that it can be used to interface and communicate with the flight controller using the MAVLink protocol. Aside from the inter-communication of the subsystems of the vehicle, this protocol is also utilized for the communication between the ground control station and unmanned vehicle. In my case, the companion computer gets all the MAVLink data which are produced by the autopilot, GPS and the sensors' readings, and can use them to make intelligent decisions during a flight.

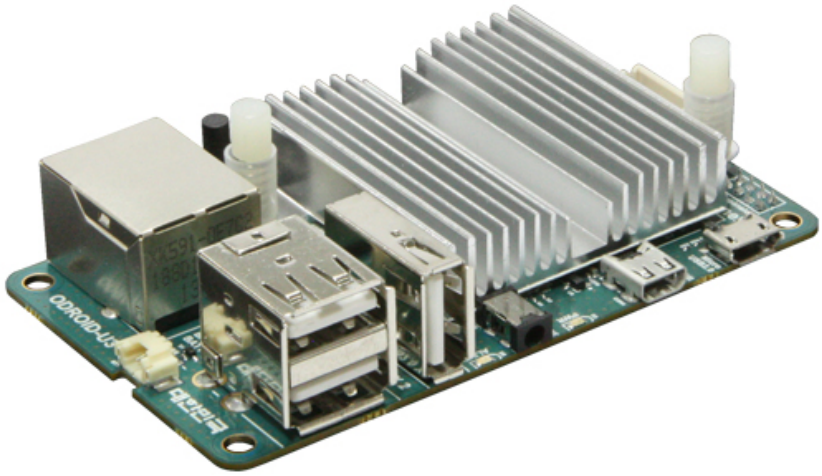

Fig.A.8 Odroid-U3 companion computer for robotics applications (image from www.hardkernel.com)

For the project's UAV, the Odroid U3 mini-computer was employed (fig.A.8). The selection of the specific model was based on the recommendation of the PX4 development community. More precisely, the requirement was to use a mini-computer having the computational power to support a slim Linux version running ROS. Odroid U3 is powered by a 1.7GHz Quad-Core processor and a 2GB RAM. It supports MicroSD and eMMC storage. The latter is 4 times faster than the Micro SD, which allows executing computer vision and robotics algorithms. It hosts 3 high-speed USB2.0 ports and 100Mbps LAN. Odroid U3 on-board computer has also a serial UART port in order to provide system console interface for platform development and debugging. All in all, it is a card-size (83 x 48 mm), light (48g including the heat sink) yet powerful minicomputer, which ideally complies with the robotics control requirements.