UNIVERSITY OF SOUTHAMPTON

An Unmanned Aerial Vehicle for Oceanographic Applications

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Abstract

Progress is reported on the development of an Unmanned Aerial Vehicle (UAV) at the National Oceanography Centre, Southampton. Literature on the use of remote sensing in ocean science is examined and a gap identified between the high-resolution, infrequent measurements made by ships and the wide area low-resolution measurements made by satellites. The commercial UAV market is summarised and internal development has been selected as offering lower-cost and more flexibility in a potentially higher performance vehicle. Requirements are identified and a low-cost-robust design philosophy has been adopted for all aspects of the development.

A new revision of the vehicle was designed, manufactured and manually test flown with some success but a lack of engine power means the propulsion system will need to be re-examined. A highly integrated Flight Control System based on Micro Electro Mechanical Systems sensors and an ARM 7 processor has been developed. The prototype Flight Control System was flown in the vehicle and flight data was recorded. This data was used to assess the performance of the vehicle. Future work is identified in developing the launch system, proving software robustness and developing improved actuation for control surfaces.

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List of acronyms

ADS/B	Automatic Dependent Surveillance/Broadcast
CAA	Civil Aviation Authority
CPU	Central Processing Unit
CTAS	Converging Traffic Alert System
DC	Direct Current
DCDC	Direct Current to Direct Current
FCS	Flight Control System
FPU	Floating Point Unit
GPS	Global Positioning System
INS	Inertial Navigation System
NERC	Natural Environment Research Council
NOC	National Oceanography Centre, Southampton
PID	Proportional, Integral, Differential
PDF	Proportional, Derivative, Feedback
RADAR	RAdio Detection and Ranging
RAM	Random Access Memory
ROM	Read Only Memory
RTOS	Real Time Operating System
SGDL	Sensors Group Data Logger
TCAS	Traffic Collision Alert System
UAV	Unmanned Aerial Vehicle

Chapter 1

Introduction

1.1 Research Context

The National Oceanography Centre, Southampton (NOC) is the focus for the UK's oceanographic activity, performing research into chemical, geological and biological processes in the world's oceans. This research involves simulation, sampling and indirect measurement using satellites. Sampling and *in situ* analysis of the deep ocean is usually done onboard the Natural Environment Research Councils (NERC) research ships (Figure 1.1) or using automated buoys, underwater vehicles or floats.

Figure 1.1 - NERC research vessel James Cook berthed outside the NOC

The scientists working at the NOC want to measure the ocean for more parameters, at greater spatial and temporal resolution in the most time efficient manner possible. One of the most expensive aspects of ocean research is the use of research ships. Ship operations can be made more effective by using satellite data to direct the vessel to areas of interest. Although, as will be shown in section 2.2 this is not always ideal. This project aims to characterise an established need for an Unmanned Aerial Vehicle (UAV) to enhance research ship operations (Chapter 2) and then develop an appropriate system.

1.2 Summary

A vehicle has been designed to suit the requirements of ocean research. This design has a range of > 1000 km and a prototype has been manufactured for flight-testing (Chapter 4). Initial flights have shown the design to be underpowered when climbing although otherwise operating well. A new hardware autopilot has been designed and a prototype manufactured (Chapter 5), this has been used to record a large amount of data during flight-testing. A new revision of the Sensors Group Data Logger has been designed to support UAV payload control and improve performance for chemical sensor control (Chapter 7). This will satisfy the requirements of the primary (oceanographic) application and provide a useful platform for wider UAV research currently in progress at the University of Southampton.

Remaining work includes developing the vehicle for ship operations, completing the low-level software for the flight control system and performing robustness proving. It is also hoped to develop a custom smart actuator for the flap system (Chapter 8).

1.3 Novel contributions

This multidisciplinary project is application focused and is concerned primarily with the development and construction of high performance functioning prototypes that together constitute a novel system (no comparable research or commercial UAV system exists (see sections 2.3 and 2.4). System and component-level novel contributions include:

1. The design, construction, and test of a long-range, low-cost, UAV airframe for ship based oceanographic applications (Chapter 4)

2. The design, construction and test of a low-cost, robust and potentially certifiable autopilot with health monitoring functionality and black box recording system (Chapter 5)

3. The design, construction and test of a generic low-cost, high performance logging and control electronics suitable for UAV and *in situ* deep sea operation (i.e. at high (<60MPa) ambient pressure) (Chapter 7)

1.4 Report structure

This report is split into sections relating to the areas of work undertaken. Much of the work was carried out in parallel. Chapter 1 provides an overview of the work completed to date and describes the long-term timeline and the relationship of this project to the others associated with the NOC UAV project.

Chapter 2 is a review of the literature related to the application of a UAV to oceanography, existing vehicles, control systems and the safety aspects of operating unmanned vehicles. Chapter 3 uses the conclusions from the literature review to define the requirements for the whole vehicle. Chapter 4 describes the development of the airframe and propulsion system including aerodynamic and structural work. The development of the Flight Control System (FCS) is described in Chapter 5. Chapter 6 describes instrumented flight tests of the airframe (under manual control) using the FCS as a black box recorder. Chapter 7 describes the modifications made to the Sensors Group Data Logger to make it appropriate for use in the UAV. Chapter 8 draws conclusions on the progress made so far and identifies the direction of the future research.

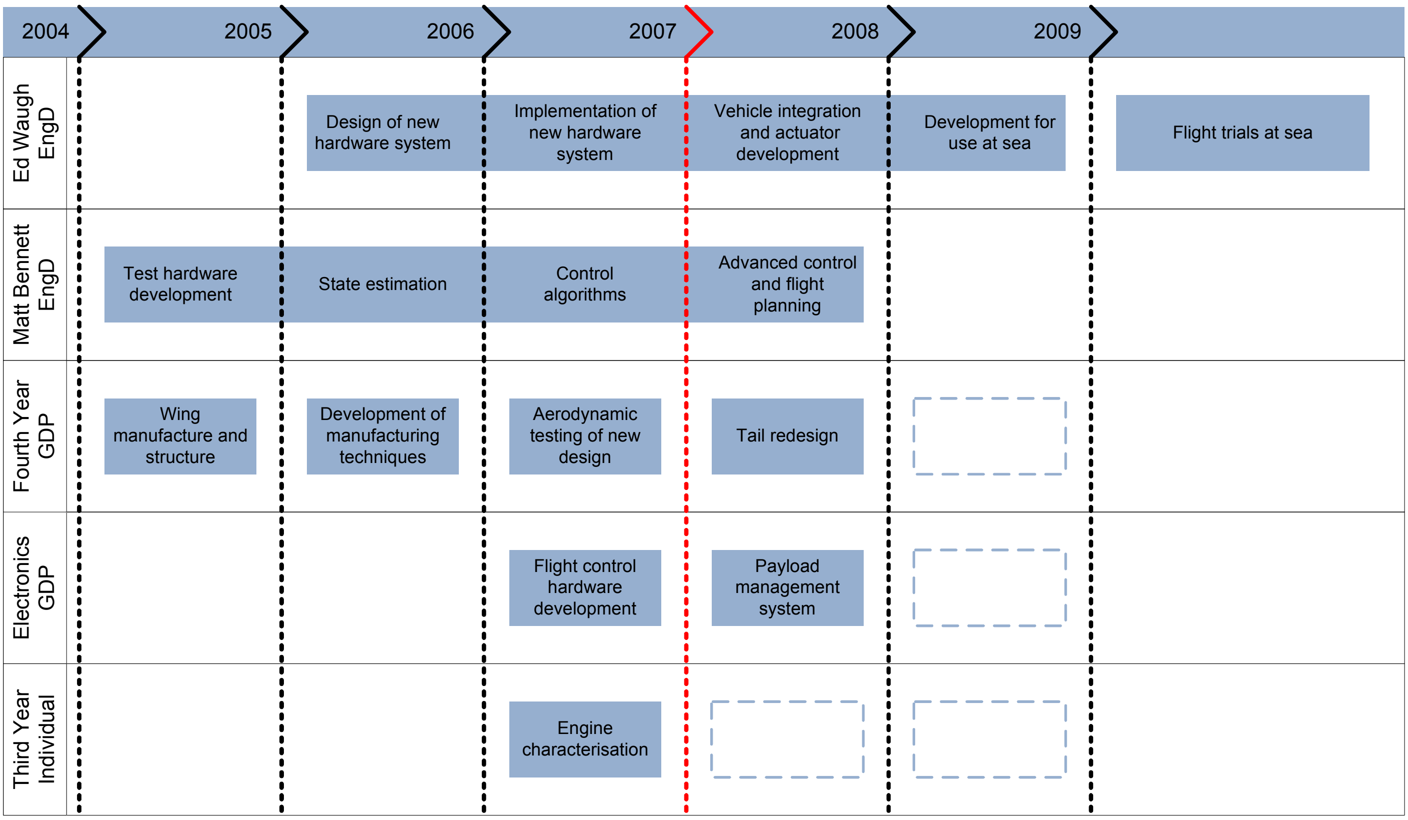
1.5 Project structure

The project has two main streams both led by engineering doctorate students, the hardware development stream including vehicle structure, aerodynamics and electronics and the software development stream including simulation and algorithm optimisation. These are supplemented by undergraduate projects in aerospace, materials and electronics. The undergraduate projects are targeted at work not in the critical path for the project, these independent units allow the students to pursue their own ideas and develop their own solutions. This work is then evaluated by the doctorate students and the supervisory team for inclusion in the project. The distribution of work between streams is shown in Figure 1.2.

The long-term aim of the project is to begin flight trials from a research vessel in the autumn of 2009. The timeline for the project is shown in Figure 1.3.

	Ed Waugh EngD Development of a UAV for oceanographic applications	Matt Bennett EngD Development of software algorithms for a low-cost UAV	Fourth year GDP Aerospace, mechanical and electronics undergraduate students
Hardware	Flight Control System - Requirements definition - Component selection - Physical board design Payload Management - As flight control system	Flight Control System - Modification and repair of ONavi autopilot - Integration of camera Payload Management - Supervision of GDP group	Payload Management - Integrate with sensors and vehicle
Software	Flight Control System - Structural design - Low-level code Payload Management - Library development	Flight Control System - State estimation - Control - Navigation	Payload Management - Develop preliminary code
Aerodynamics	- Requirements definition - Supervision of fourth year students - Experiment design	- Modelling for simulation	- Computational fluid dynamics - Aerodynamic optimisation - Operation of wind tunnel
Structures	- Requirements definition - Fuselage and non-aerodynamic design - Supervision of fourth year students - CAD modelling - Design tracking - Mould design and manufacture		- Strength modelling (FEA) - Manufacture of components - Integration of tail surfaces
Propulsion	- Requirements definition - Supervision of fourth and third year students - Characterisation experiment design and setup - Fuel system design	- Modelling for simulation	- Engine characterisation experiments
Project planning	- Long term, whole project planning - Planning own work - Assisting in proposal writing - Creating project specifications for student groups	- Planning own work	- Developing a schedule based on the project specification
Flight Testing	- Scheduling - Preparation of all aspects - Experimental design - Aircraft setup - Organisation on site	- Flying test vehicle	

Figure 1.2 - Project responsibilities and relationships



Note: Year boundaries are academic years starting October 1st

Figure 1.3 - Overview of project timeline

Chapter 2

Literature review

2.1 Introduction

Literature is examined to inform design decisions and generate the requirements for the project. The current application of Unmanned Aerial Vehicles (UAVs) to ocean sensing is investigated and new areas are identified. This information is used to generate an outline specification for the vehicle and then a market survey is performed to find a suitable commercial system.

2.2 Application

As part of the continuing programme to enhance measurement techniques, the National Oceanography Centre, Southampton (NOC), commissioned a of study into the use of UAVs in oceanography [1]. There have also been studies by Lomax [2] and Peterson [3]. These indicate a gap between high-resolution direct measurements at sea and wide-area but low-resolution satellite measurements. They suggest this gap could best be filled with an airborne platform.

The most common ocean parameters measured by satellites are; surface temperature, using infrared and microwave radiometers [4, 5] and colour using panchromatic cameras [6]. It is also possible to measure wind speed and surface roughness by adding a scatterometer [2]. Imaging resolution from new satellites has improved to 3metres resolution for colour images; however, the sensing equipment available to oceanographic research is more normally around 15-90 metre resolution. Using an airborne vehicle allows much higher resolutions (0.2 m and less [2]) due to the proximity of the sensor to the ocean. There is also a great deal more flexibility, the sensor can be upgraded or filters applied to improve performance, which is not possible with a satellite [3].

The most useful satellite systems for oceanographic sensing are in a low polar orbit as this allows the whole surface of the earth to be scanned as it rotates under the satellites path [3]. These satellites pass over the same area approximately four times each day allowing the tracking of changing systems. However, the onboard infrared radiometers and panchromatic cameras are unable to penetrate cloud, leading to very poor performance in conditions other than clear skies. New microwave radiometry techniques can measure sea surface temperature in all weather conditions except rain [7]. An airborne vehicle is able to fly under the cloud base and stay on station in the area of interest to take frequently repeated measurements. This offers significant advantages when monitoring a rapidly changing system.

Manned aircraft have a number of serious limitations for oceanographic applications. They are too large to launch from a research ship and would have to fly from a land-base close to the area of interest. This would reduce time on station and would create significant cost and logistics issues. There would also be a long start-up time for each mission. In addition, mission length is determined by the crew who can only work for eight-hour periods, operation in shifts is at the penalty of reduced range or payload, or increased mission cost. Lomax and Pluck *et al* both conclude that UAVs offer the best solution due to their flexibility, potentially smaller size and lower cost [1, 2].

Several medium-scale applications such as plankton bloom monitoring where the area of interest is hundreds to thousands of kilometres in size, could be enhanced by the improved temporal and spatial resolution offered by a UAV. Features this large would require an aircraft with a range in excess of 1000 km and the ability to travel fast enough to view large areas.

In some cases, existing sensor technology can be directly applied to oceanographic UAV operations without modification. Sea colour could be measured with panchromatic cameras (e.g. Nikon D200 [8] (£800)) with a suitable vibration-reducing mount. A gimballed mounting may offer advantages. Alternatively recording the aircraft's orientation would allow the image location data to be corrected with post-processing.

Infrared imaging packages suitable for small UAVs are commercially available. The Photon from Indigo Systems [9] measures less than 10 cm in its longest dimension and weighs under 300 grams. Fitted with a 14.5 mm lens it has a pixel size of one square metre from a 200-metre altitude. The camera captures 7 to 13.5 μm wavelengths and translates them to an analogue video signal that would require calibration before using to measure absolute temperature.

White capping and wave height data is of interest when investigating the chemical exchange of the ocean and the atmosphere. Measuring white capping could be done with the panchromatic imagery and wave height data could be measured using a miniaturised RADAR system or by deploying small buoys [10, 11]. The micro-sized wave buoy from Planning Systems Inc [11] can be deployed at altitude and at only 5 cm long could easily be carried by a small UAV. The system has been test deployed by a manned aircraft [10] and the average wave period measured showed a good correlation with the baseline system used.

Even with a relatively small set of parameters that can be measured with commercially available sensors; a suitably equipped UAV would provide useful data on a range of oceanographic variables. As well as providing data in its own right, one of the most useful modes of operation of a UAV could be in supplementing the work of a research vessel. This would involve tracking ahead of the vessel to allow its research to be more accurately directed to areas of interest.

Such a UAV could also be applied to disaster monitoring as well as research. Tracking of oil spills, harmful algae blooms [12] or other contaminant would allow protective measures to be applied more effectively and swiftly by recovery crews. The ability to deploy the vehicles rapidly would allow imagery to be taken in advance of the contaminant reaching coastal areas. This could then be used after the incident to direct clean-up crew activities.

To be most effective an oceanographic UAV would need to be launched and recoverable from a typical ocean research vessel. This limits the size of the vehicle to something that could be dismantled to fit inside a standard shipping container (6.5 m x 2.5 m x 2.5 m). To be considered cost effective any vehicle would need to be of a value equivalent to the research it is able to perform. A NERC research vessel costs around £15,000 to run per day, a UAV operating to enhance this research would need to cost less than this taking into account the potential for losing the vehicle during recovery.

The application of a UAV to oceanographic research can supplement and enhance existing programs of ocean research as well as providing support to disaster recovery operations. Such a UAV would need to be able to carry a scientific payload of small instruments that could be varied depending on the mission to be flown. To carry the infrared and panchromatic cameras described would require a volume of 3 litres and a mass of 500 g.

It would also need to be operated from a typical research vessel. This will involve handling the vehicle on deck and transporting it to and from the ship as well as launch and recovery. To be cost effective such a UAV would need to be under £15,000 per vehicle and per day including staff costs and the possibility of loss during recovery. This means the capital cost of each UAV should be no more than £5,000.

2.3 Existing Unmanned Aerial Vehicles

2.3.1 Military

The most well known UAV is arguably General Atomics Predator B [13], which has been used (and filmed in operation) extensively in military applications for reconnaissance and weapons deployment [14]. A 20m wingspan and one and a half tonnes of payload make this one of the largest UAVs available and therefore too large to operate from research vessels. However, the long endurance of 30+ hours, high level of autonomy and robustness would otherwise make this a good choice for a research vehicle, allowing the largest instruments to be carried, along with possibly hundreds of deployable buoys. The Predator is available in an unarmed version called Altair; estimates of cost are around £4,000,000 per vehicle.

The Pioneer UAV has been used extensively by both the US army and navy for reconnaissance. It is a relatively short-range vehicle (180 km) with an endurance of just 5 hours although it does carry a large payload of moveable cameras. The vehicle can be ship launched using rocket or catapult but it is very large (205 kg) with a wingspan of 5 metres making it difficult to accommodate on a small vessel. There have also been some problems reported with pioneer [15], its inability to operate in rain would severely limit its use as a research vehicle and the lack of automated take-off and recovery has led to a high accident rate.

The Insitu group ScanEagle [16] is the military variant of the SeaScan described in detail section 2.3.2.

One of the smallest UAVs in regular use by the US military is the AeroVironment Raven [17]. This is a hand launched, electric powered UAV weighing just 2 kg. Its small size would make launch and recovery at sea relatively easy as the whole vehicle can be handled by one person. However, it is limited to a range of just 10 km and cannot carry a payload beyond the fitted cameras. The cost per vehicle is around £17,000.

Military UAVs are designed to perform a specific task regardless of cost. This generally makes them unsuitable for use in a commercial environment. Some make the transition from commercial to military, like the SeaScan (described in section 2.3.2); however, most will never be a viable proposition. The Predator and Pioneer are both to large and expensive to be suitable, the Raven is too small and limited in range. The small seaplanes that have been demonstrated [18] are unable to operate in the heavy conditions anticipated.

2.3.2 Commercial

There are several UAVs now for sale aimed at a variety of markets from advanced hobby aircraft pilots through to off the shelf systems including crew to perform specific missions. The Micropilot MP-UAV [19] is based on a trainer aircraft for hobby pilots and includes a basic flight control system. It is a very low-cost system at £6,000 including a ground station and radio link. However, its flight endurance is only 20 minutes and due to its balsa construction, would be unlikely to survive in adverse weather conditions, it would also be very difficult to make waterproof.

The most well known commercial UAV is the Aerosonde; it is a 3-metre wingspan, 14 kg pusher configuration designed primarily for the barometric measurement. It has been successful in operations in the Arctic as well as flying across the Atlantic and has an endurance of over 50 hours. If required it is possible to purchase operational time rather than your own aircraft. This includes all the personnel and equipment necessary at £300 -> £600 per flight hour for a four-week mission. To purchase a complete system including four aircraft is £410,000.

The Insitu group SeaScan is a UAV designed specifically for operation at sea [16]. It includes a catapult launch and a wire recovery system (Figure 2.1). The vehicle has very long endurance at over 22 hours and only a 3-metre wingspan. It can carry payloads of up to 6 kg and includes an inertial stabilised camera turret. Three vehicles, a control centre, launcher, capture system and training is around £650,000.

Figure 2.1 - Seascan UAV being recovered (left) and ready for launch (right)

Launching a UAV from a ship, as in the case of the SeaScan, is usually done with a catapult or other system that allows it to be accelerated quickly to flight speed. However, the ability to launch from the sea could offer big advantages to oceanographic study. Launch and recovery are simplified along with gaining the ability to land at a distant point, collect a sample and then launch and return to the ship. NASA have conducted experiments with a seaplane [20] intended for use as an unmanned cargo carrier. The vehicle operated successfully but only in very calm conditions. The Gull UAV from Centaur Systems [21] has also demonstrated launching from the sea surface, also in calm conditions. It is likely that a research vessel operating in the open ocean would rarely encounter the sea states in which these vehicles can operate.

Advanced Ceramics Research in the US have developed the Manta B UAV [22], this is a pusher configuration with an all-up-mass of 23 kg and 6-hour endurance at 30 ms^{-1} giving a range of approximately 600 km. The package includes three vehicles with autonomous operation, a pneumatic launcher, spares and training for £200,000.

The MLB Bat UAV [23] features 6-hour endurance, 180-mile range, with a 2 Kg payload and only a 2-metre wingspan. The avionics package also includes the ability to track and follow road convoys as well as autonomous bungee powered launch. At only £25,000 for the basic package including launcher, ground station and training this would make a suitable platform from which to develop a waterproof version capable of the water landings required.

Commercial UAVs are now of a quality that makes them appropriate for adaptation to suit the specific requirements of oceanographic missions. However, many are still far from economically viable for operation from a research vessel (see section 2.1). Despite its relatively short range, the closest is the MLB Bat UAV. If the advanced package was selected (£50,000) and a couple of vehicles were included, it would be necessary for each vehicle to survive five flights with only minor repairs. It is unlikely that the engines would survive landing in seawater although spares could be sourced independently. The main disadvantages of a bought in system is the high replacement cost and the lack of configurability. This could become limiting as more complex and unusual missions are required.

2.3.3 Academic

Many academic institutions are now running UAV projects. Most of these are focussed on the development of advanced flight control algorithms including cooperative flight [24] and distributed control [25]. The majority of the vehicles used are off-the-shelf hobby aircraft that serve only as a taxi for the electronics payload. This type of vehicle is unsuitable for use in oceanographic research as they are usually too small, too flimsy and have short flight durations. No academic institutions are currently attempting to develop what is essentially a commercial vehicle targeted to a specific application and as such, are not a good model for this project.

2.3.4 Conclusions

The high cost of military grade vehicles makes them inappropriate for oceanographic research due to the low vehicle cost necessary (see section 2.1). Academic vehicles are usually too simple and perform too poorly to be useful at sea and for the long duration missions that will be required. Of the commercial vehicles, the Bat UAV is the closest fit with the requirements especially if several vehicles were supplied for the £50,000 initial cost, although, it would still require a large amount of customisation to suit the environment.

Developing the vehicle internally not only allows tight control of our vehicle (our primary objective) but also allows the design to be tailored to the application from the start. Access to wind tunnel and computer cluster facilities allow a highly optimised design to be developed that can compete on range and endurance with the best commercially available vehicles. The experience gained while developing the vehicle will also be invaluable when it comes to deployment and predicting performance in challenging weather conditions.

2.4 Flight Control Systems

2.4.1 Commercial Systems

Flight Control Systems (FCSs) are supplied with all of the commercial UAVs described in section 2.3. These all offer the basic functions required to stabilise a fixed wing UAV and perform waypoint based navigation using GPS waypoints. They can be purchased separately so if a custom airframe were developed it would still be possible to make use of an off-the-shelf control system, substantially reducing development time.

The most common FCS amongst the commercial UAVs is Cloud Caps Piccolo range, now at version 2 (shown in Figure 2.2). The system includes high frequency (4 Hz) GPS, an Inertial Measurement System (IMS) with external magnetometer option, autonomous launch and landing, a wide range of interfaces and weighs only 233 grams. The Piccolo FCSs have flown many hours in the Aerosonde UAV and there are links between the companies as the two systems were originally developed together[26]. It has also been used by a number of university projects, successfully piloting a range of different airframes [24, 27] and in cooperative flying [28]. The Piccolo is reported to be reliable and easy to configure in all cases. A single Piccolo II is £4,000 with an additional £4,700 for the ground station and £500 for the developer kit. The cost of each Piccolo is very high when compared to the required total vehicle cost of £5,000 established in section 2.1, there would need to be a high confidence of safe recovery if a system this expensive was used.

Blue Bear Systems [29] have recently developed a miniaturised FCS that includes stabilisation functions and has considerable processing power available to the end user. It is designed to fit into very small UAVs and has an open architecture allowing access to the software. It is likely that this system would require some additional development to make it appropriate for use in oceanographic research, as it is not supplied in any enclosure. The system is supplied at £1000 per unit where the base station is an additional cost. It is difficult to rate the performance of this system as the only examples of its use are from Blue Bear, this is probably because it is relatively new. The design of hardware, with a large processor fed with sensor data by a microcontroller, requires the use of a Real Time Operating System (RTOS). This makes the system more difficult and expensive to develop (see section 5.2).

The Micropilot MP2028 is widely used by academic projects due to its low-cost. The technical specification is similar to the other products described here but some users report problems configuring it and in its flight performance [30]. The MP2028 is £2,700 for the basic board including no radio link or compass. The age of this product and its reported poor performance, make it a risky choice for a project aiming for a high level of reliability.

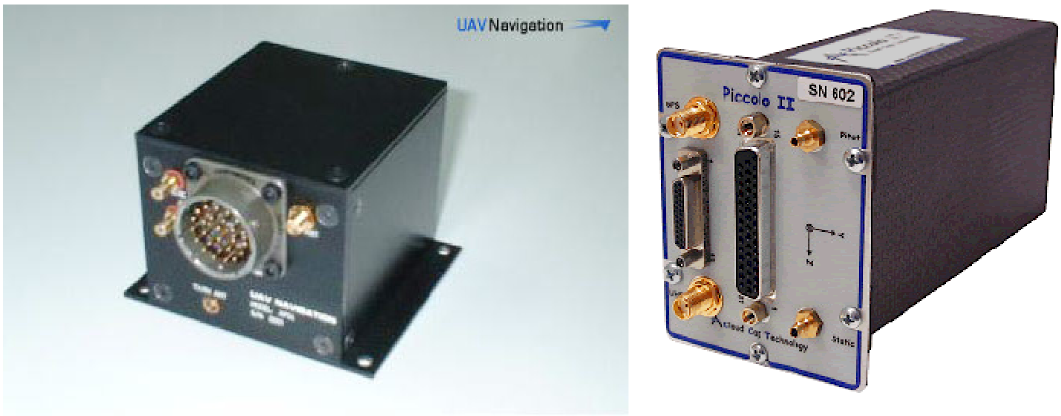


Figure 2.2 - UAV Navigation AP04 (left) Cloud Cap Piccolo II (right)

The AP04 flight control system shown in Figure 2.2 has been developed by UAV Navigation [31]. In addition to flight control and navigation, the AP04 features dual processors and software algorithms that allow (in some cases) for multiple sensor failures and single failure of any sensor. This combined with a waterproof and shockproof housing makes it a suitable choice for operation in hostile environments. It has not been possible to obtain a quote for the AP04 although one has been requested. It is expect that it would be similar in price to the Piccolo II.

Crossbow Inertial Systems [32] supplement their range of inertial measurement units with an autopilot family that uses their sensors. The most appropriate system from this family is the NAV420 that incorporates sensing and inertial algorithms to provide a system that outputs inertial data. This can then be custom programmed although the inertial algorithms are not retained and would need to be rewritten. An open source project does exist although this is far from complete. At £4,500, the NAV420 is the majority of the budget for the whole UAV and does not include any flight control software.

Using an off-the-shelf FCS would significantly reduce the development time of the UAV. The Crossbow and UAV Navigation systems are designed to survive in harsh environments and the Cloud Cap systems have extensive flight time. The cost of these systems, however, is prohibitive when compared to the £5,000 vehicle cost required, especially when the hardware they contain is itself quite low-cost. They are also inflexible compared to a fully custom system as no hardware changes could be made to accommodate new features. These considerations combined with the electronics experience in the group make it advantageous to develop a system internally.

2.4.2 Hardware Component

All the FCSs examined use the same type of measurements to control the aircraft. They sense rotation with gyroscopes and acceleration with accelerometers each in three axes. This is supplemented by dynamic pressure for airspeed, static pressure for altitude and a GPS to provide positional drift correction. In some systems, magnetic sensing is also included, which can give redundancy for speed and heading measurement (if there is no wind) or provides true heading (as opposed to ground track) and allows the estimation of wind speed and direction if winds are present. Figure 2.3 shows the main components of a FCS.

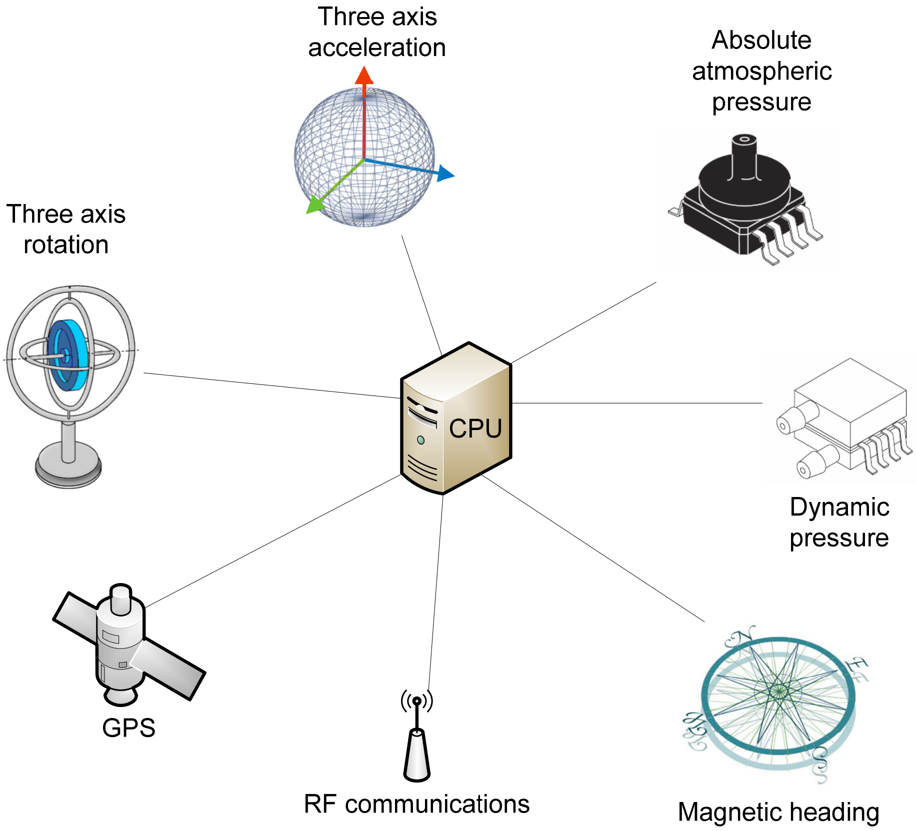


Figure 2.3 - Diagram of FCS main components

The development of low-cost Micro-Electro-Mechanical Systems (MEMS) inertial sensors has been the enabling technology for small UAV systems. Traditional Fibre Optic Gyroscope (FOG) based IMUs offer exceptional performance. The KVH TG6000 IMU [33] has an angular rate range of 750 °/s and a resolution of 3×10^{-2} °/s. It is also very low drift (±1 °/hr), has low non-linearity (1000 ppm) and is highly insensitive to off axis rotations. It can also measure accelerations of ±70 g with a resolution of 3×10^{-4} g. This military grade system costs around £20,000.

MEMS inertial sensors do not provide the raw performance of conventional devices with typical gyroscopes [34] limited to ±300 °/s at a resolution of 2.4×10^{-2} °/s and accelerometers with a range of ±2 g and a resolution of 1.2×10-3 g. The problem when comparing these values is that the MEMS sensors can exhibit worse characteristics in areas like drift, which are not presented by the manufacturer. However, these sensors are several orders of magnitude cheaper than their conventional counterparts at around £50 for the six required. Due to their relatively low-cost nature, all the FCSs examined in section 2.4.1 use almost identical sensor suites based on MEMS sensors.

An advantage of MEMS sensors is better robustness over traditional sensors. The KVH TG6000 is rated to a maximum non-operating shock of 200 g while MEMS sensors are typically rated at 2000 g while operating [34]. This has led to their use in munitions applications [35].

The main difference between commercial FCSs is the amount and type of processing power used to execute the inertial and control algorithms. The Piccolo system uses a Motorola MPC555 processor running at 40 MHz that can achieve 50 Million Instructions per Second (MIPS) and has a hardware Floating Point Unit (FPU). The addition of the FPU is significant as it makes processing large matrices of floating point numbers possible in real time. This can be important for some algorithms as described in section 2.4.3. The disadvantage of a fast CPU is an increase in power consumption; this can be significant over a long duration mission. Cloud Cap do not run an Operating System (OS) on the Piccolo and program directly for the processor, there is no indication of any software quality-assurance method, which may be critical in gaining aviation authority approval to operate (section 2.5).

Blue Bear take a different direction with their system and have a high-speed integer processor, a 400 MHz XScale that can do 480 MIPS. This does not include a FPU but due to its high clock speed, can perform these calculations very effectively in software. Blue Bear run a Linux based operating system that allows very easy code development and porting directly from Matlab routines. This combination of software makes it very difficult to prove reliable operation but is very convenient for rapid prototyping. Despite its high clock speed, the XScale draws very little power in operation.

The Micropilot and AP04 both use low-cost microcontrollers (the AP04 uses two) to perform data collection and all calculations. This makes them simple to program and cheap to build but does mean they have limited processing ability. They are programmed directly and do not use an OS. Micropilot uses a 33 MHz Motorola M-Core that can do around 40 MIPS but has no FPU; this processor also lacks any additional hardware to reduce the burden of data collection, further reducing the available processing time. Both these systems have demonstrated successful flights including the use of Kalman filters (described in section 2.4.3) for inertial positioning which, suggests it is feasible with this amount of processing.

In addition to the fully integrated systems, it is possible to purchase an inertial measurement system that could then be interfaced to a processing board to create a complete system. These include polished algorithms for state estimation that would significantly reduce development time. High performance systems from Crossbow [32] cost from £2,500 and can easily exceed the cost of the NAV420 at £4,500 (see section 2.4.2). Other systems like the Sparkfun 6DOF IMU [36] are essentially just the same inertial sensors as the FCSs offer but pre-mounted and easy to use. The Crossbow systems are too expensive for the same reason as the FCSs (see section 2.4.1), the other systems like those from Sparkfun do not offer the advantages of a real IMU, as they include no processing, just raw data outputs.

There is no consensus on the optimum processing solution amongst the FCSs available on the market today. Different systems take completely different approaches, often to tailor themselves to a specific market. Low-cost inertial sensing is performed in the same way by all the systems examined. MEMS sensors (usually from the same manufacturer) are used and their outputs filtered to give an acceptable estimate of aircraft state. The hardware used in all these systems is in itself, quite cheap. The cost of the systems usually comes from the integration and software. A custom-built FCS should offer the same features as the best available commercial systems but provide the reduction in cost of having been developed internally.

2.4.3 Software Component

The commercial FCSs examined in section 2.4.1 all use very similar software schemes. The Kalman filter is preferred for state estimation due to its ability to compensate for the strengths and weaknesses of the low-cost MEMS inertial sensors [37]. The filter can also incorporate data from GPS [38] and provide estimates of unmeasured parameters like gyroscope bias [39]. Gyroscope bias is especially important as the low-cost MEMS sensors can drift dramatically within a matter of minutes. An extended Kalman filter is typically used in UAV applications due to the non-linear nature of aircraft dynamics.

Most UAV control systems use Proportional-Integral-Differential (PID) controllers as these are well understood and methods exist for tuning the gains. Some more sophisticated systems use state-space or adaptive models but these are generally only found in large and military UAVs. An alternative to the PID controller is the Pseudo Derivative Feedback (PDF) controller. This differs from the PID because the proportional and derivative terms are in the feedback rather than forward stage [40].

This offers a performance improvement over PID but they are more difficult to tune and there are less examples in the literature [41].

The computational requirements of the software will determine the processing requirements of the system. The computational requirements of an Extended Kalman Filter can be very high especially when done in floating point on an integer only processor. An example of this is the floating point Kalman filter implemented on the test hardware by Bennett [41]. The filter requires approximately 260,000 instructions per execution when GPS data is updated in addition to inertial data. This is 58% of the instructions available on a 50 MHz ARM core every 100 Hz. Some developers have used processors with a hardware FPU to get round this problem, although it is possible to write a Kalman filter that uses fixed point [42]. Integer calculations require 20 -> 35 instructions less than emulated floating-point instructions (very mixture dependent). This allows a smaller processor to be used, resulting in power savings or a more sophisticated algorithm to be executed.

Another major factor in determining the processing requirements is the rate at which the aircraft surfaces need updating. The Crossbow [32] inertial measurement and autopilot systems operate at a rate of 100 Hz. It is difficult to find information on the rates used by commercial systems but due to the maximum 100 Hz bandwidth limitations of the MEMS gyroscopes (values are similar for the other devices) there is no benefit going faster.

The FCS software component will necessarily include Kalman filtering for state estimation and either PID or PDF controllers for stabilisation. It should also be considered that more advanced controllers might be used in the future. These would likely be the same order of processing as the Kalman filter so the ability to process up to 500,000 instructions at 100 Hz would be desirable if everything was implemented in floating point. In addition, there may be several higher layers of control to provide advanced functions including navigation. The software in commercial FCSs is the expensive part of the system. It is mathematically sophisticated and requires a high level of reliability making it difficult and time consuming to develop.

2.4.4 Payload Management

Any UAV for oceanographic research will need to carry a mixture of scientific equipment as payload. This will require data from the FCS about position and will need data storage and possibly transmission to the research vessel. Some commercial FCSs like the Piccolo [43] include some of this functionality (2 serial interfaces and 4 analogue inputs). Although convenient, this places an extra load on the FCS as well as potentially requiring rewriting of the FCS software for different payload combinations.

Separating the payload management from the flight control reduces the complexity of the FCS making it more reliable and leaving more processing time for advanced algorithms. Commercial data logging systems like the DT50 [44] have flexible inputs and can record 16-bit analogue data at rates up to 100 kHz. One of the disadvantages of this kind of system is the inability to transmit selected data on demand to the research vessel, which may be in only intermittent contact with the UAV. It is also unable to perform even basic analysis on the data; perhaps to flag an important change that the scientists might want to examine in more detail.

Separating the data logging from the FCS creates a far more flexible and maintainable system. The level of sophistication required in such a system is such that an off-the-shelf data logger would not have the flexibility required. The NOC have already developed a low-power data logger that should fulfil the immediate requirements of the project [45] and provide the processing power to perform more advanced operations as these become necessary.

2.4.5 Conclusions

The use of MEMS sensors has become the standard method of measuring inertial variables in all the commercial FCSs examined. This hardware is relatively cheap to develop and manufacture compared to the cost of the final product. The value in the commercial systems is in the software algorithms for state estimation and flight control. Purchasing a commercial system would mean that the both the software and hardware are paid for each time. An internally developed system would only face the cost of replacement hardware as the software could be programmed into the new board. As the requirements are for the lowest possible vehicle cost, it makes sense to develop the system internally. This allows the maximum amount of flexibility as well as making the vehicle a development platform for more advanced control techniques and flight system research.

Kalman filtering is essential for accurate state estimation and the requirements of implementing an Extended Kalman Filter (possibly a fixed-point version) must be considered when determining hardware requirements. The processing requirements for PID and PDF controllers are very similar although it would be worth ensuring that more advanced controllers could run on any hardware to future-proof the design.

2.5 Safety

The most important issue when considering the operation or certification of any unmanned vehicle is the safety of the operators and those who may be affected by the operation. In the case of UAVs, this includes any people or property flown over by the aircraft. Papers are examined that discuss safety issues relating both to UAVs and to full size aircraft due to the small body of working directly related to UAVs. The implications for a low-cost UAV and the practicality of implementing the recommendations, is considered.

Presently there is only limited documentation available on the future certification requirements for UAVs. The governing body for the UK, the Civil Aviation Authority (CAA), is involved in a continuing process of refining its position and released the second edition of its UAV guidelines [46] at the end of 2004. These guidelines will form the basis of any future legislation that is considered necessary.

The fundamental principle laid down in the CAA guidelines is that any UAV must meet or exceed the safety standards for manned vehicles if it is to operate in controlled airspace. This creates a significant problem for small UAV projects that wish to fly over land or around the coast of the UK. To meet these requirements the aircraft must be able to sense other aircraft with the same (or better) ability as a human pilot and take avoiding action. They must also have all the communication systems to be “seen” from air traffic control as if they are a conventional vehicle.

Casarosa [47] evaluates the impact of safety requirements on UAVs by considering all the components required to achieve manned aircraft levels of safety (10^{-9} failures per flight hour). They identify the fundamental aircraft components and additional equipment to provide the required safety level such as, a visual flight reckoning system, a transponder and a traffic collision-avoidance system (RADAR). Summing the masses of these gives an overall minimum weight of 150 kg for the onboard systems and a take-off weight of 450 kg. This leads Casarosa to conclude that a fully certifiable UAV must have a wingspan of around 7.7 metres. The size and complexity of a vehicle with these kinds of features makes it unlikely that it could fit into the low-cost gap identified in section 2.1.

In assessing methods of certification for civil UAVs, Haddon and Whittaker [48] compare the operation of UAVs in the military environment with potential operations undertaken by civil UAVs. They conclude that it would not be possible to operate civil UAVs simply with a code of requirements. This is because the CAA would have no direct control or even information about the kinds of missions being flown. Their solution is that a set of airworthiness standards should be derived from the existing set for manned aircraft. This also retains the scope for individual criteria that are dependent on mission type. So for example, a mission in an environment where there is little risk may incur a more relaxed approach.

Haddon and Whittaker then examine both unpremeditated descent and loss of control scenarios. An unpremeditated descent is a failure that results in the inability to maintain a safe altitude above the surface. This is dominated by the reliability of the propulsion system. A loss of control scenario uses the terminal velocity of the aircraft to calculate kinetic energy and it is dominated by control system reliability. Their conclusion is that aircraft, which on failure simply ditch at the location of the failure, are far less likely to gain approval than those that can maintain some control and return to a known safe area for recovery. To achieve this level of performance on failure it may be necessary to include multiple independent control systems or a system that can detect and adapt to failures if they occur.

When UAVs are operating in the same airspace as regular air traffic there is potentially a danger to other aircraft. UAVs are often small, fast and hard to see so they need to be able to identify themselves to other aircraft and air traffic control in the same way as a conventional aircraft. It is also generally agreed that they should operate under the same Visual Flight Rules (VFR) as light manned aircraft. Le Tallec [49] examines how this may be possible. Light aircraft usually rely on the “see and avoid” principle although this can fail when there is a high closing speed or through lack of pilot vigilance. In UAV terms, this would need to be translated to “sense and avoid”. This has traditionally meant active systems like RADAR however; even modern man-transportable systems are much too heavy, delicate and expensive to be carried on a small UAV.

Le Tallec then goes on to examine the use of a Converging Traffic Alert System (CTAS) developed and tested in France. This system includes the ability to measure the aircrafts position, transmit this data to other aircraft and to inform the pilot of danger. A system of this kind would be more suitable for small UAVs than existing Automatic Dependent Surveillance-Broadcast (ADS/B) systems as they are designed for wide-body aircraft and are consequently much too large and heavy. It would also be compatible with the Traffic Collision Alert System (TCAS) used by ground control although the CTAS messages are much simpler. Le Tallec concludes that this system would be highly popular with airspace authorities, and could be made available for less than $1000. This system could allow small UAVs to operate in controlled airspace but it relies on all air traffic carrying it as well as support from ground stations. It is expected that it will be more than a decade before such a system is viable option.

The findings of the presented publications have serious implications for this project. To fly in any airspace some kind of approval will be necessary from the relevant authority. By considering the potential requirements they will have at any early stage it is possible to improve the chances of gaining such approval. The main advantage the project has is the type of operations undertaken (section 2.1). These will initially be over unpopulated areas (offshore), with no air traffic under the UAV flight ceiling of 200metres.

Ensuring that a single point failure of the control system does not cause the whole aircraft to fail will also be critical. Redundant surfaces and actuators, identified by Casarosa [47] as the most vulnerable point, will be critical in improving robustness. Quantifying the potential failure rates of many components including actuators will be important through identification of the most common failure modes and testing to destruction.

As soon as flights to investigate coastal features or in more areas of greater air traffic are required, some method of deconfliction will be necessary. In the case of CTAS, this could possibly be carried by the UAV itself or it could be carried onboard ship and relay UAV information to other aircraft. Avoidance should be straightforward as the UAV will be relatively manoeuvrable and able to change altitude rapidly without danger.

There is little information on UAV safety that can be applied directly to the project. However, extrapolations can be drawn from the publications presented. By following these outlines, it should be possible to develop a low-cost aircraft that performs in a manner acceptable to certifying authorities within the scope of its operation. Full certification can never be expected for a civil UAV of this type because of the extremely high costs. The CAA also requires the manufacturer to be authorised in advance for this type of development.

2.6 Conclusions

A gap in oceanographic sensing techniques has been identified and this gap could be filled by a UAV. This UAV would need the ability to be launched and recovered by a NERC research vessel. It should carry standard equipment like the cameras [8, 9] described in section 2.1 (500 grams and 3 litres without batteries) and have room for additional sensors. This gives a total payload requirement of at least 1.0 kg and 10 litres. To examine the features of interest it must be able to cover distances > 1000 km within a working day (8 hours) which gives a cruise speed of around 35 ms^{-1}. The combination of these requirements points to a vehicle that is high performance and very specialised.

The commercial UAV market has several solutions that nearly meet the requirements set out in section 2.1. All of them, however, have a cost of ownership that is higher than the £5,000 per vehicle necessary. The absence of an appropriate commercial system indicates the need to develop one internally. The use of a commercial FCS within a custom airframe was rejected, as this would also increase individual vehicle cost beyond the £5,000 constraint.

Little formal consideration is given to safety and reliability issues in non-military UAV systems. While it is not possible for a UAV developed on this scale to meet the requirements of the CAA's certification programme, there are steps that can be taken to move in that direction, in airframe (Chapter 4) and control system (section 5.2) development. Improvements in technology and new legislation may make it reasonable for UAVs to operate using ADS/B or similar system in the future. Any new vehicle design should consider the impact this would have on payload and power supply should it become necessary.

Chapter 3

System Design

3.1 Introduction

The requirements established in section 2.6 were used to develop an approach to the design process for the vehicle. This approach (section 3.2), coordinates all aspects of the work. The original project in 2003 [1] performed a preliminary design for the vehicle based on similar requirements and some of the elements are retained, including approximate dimensions for the aircraft. The refinements made to these are discussed in Chapter 4.

3.2 Approach

The design approach for the complete system is that certification level reliability should be aimed for where possible whilst keeping development and unit cost as low as possible. One of the key ideas is to use low-cost components but to monitor them closely for signs of failure and to offset poor performance by using sophisticated software. The application of this approach is described in more detail as it relates to each stream in the project (Chapter 4, Chapter 5).

3.3 Modes of operation

The CAA is not only concerned with the robustness of the vehicle but also the types of operation it will perform and in what airspace. It is hoped that the operations planned for the NOC UAV will allow for some relaxation of the other requirements. The reason for this is that they will not take place in controlled airspace or above any populated areas. Three modes of operation have been defined with increasing levels of reliability necessary in the vehicle and will be implemented sequentially and in discussion with the CAA, as the project develops.

3.3.1 Mode 1 – Short range

Mode 1 is suitable for directing ship operations to areas of interest. The UAV flies a box pattern ahead of the vessel to detect fronts and upwelling.

Restrictions

- Always within line of sight
- Flight area is monitored visually and by ships RADAR
- Altitude between 100 and 200 metres
- Constant radio communications between ship and UAV for course correction and status monitoring
- On loss of communications link vehicle holds position by circling until contact re-established or auxiliary engine cut off activated

3.3.2 Mode 2 – Deep Sea

Mode 2 is for operations in the deep ocean, well away from other shipping and low flying aircraft. This can be used for mapping large features or searching for areas of interest.

Restrictions

- Altitude between 100 and 200 metres
- Constant communication between ship and UAV by either radio or satellite for course correction and status monitoring
- Course planned to avoid shipping areas and heavy weather
- Loss of communication causes UAV to return to last known ship position

3.3.3 Mode 3 – Traffic

Mode 3 is operationally the same as mode 2 except that it takes place in areas where other traffic may be present. These may be coastal but still unpopulated. The restrictions are the same as mode 2 but with the addition of those listed below.

Restrictions

- Sensing of other aircraft using ADS/B
- Transmission of position and intentions using ADS/B
- Ability to automatically take avoiding action in case of potential collision

3.4 Flight conditions

The design of the vehicles structure, propulsion and control systems need to be based on a set of common performance parameters. These parameters are not the final values for the finished system but a set of interim targets. They should represent the most common case (cruise) as well as the extreme conditions encountered at launch and landing.

3.4.1 Cruise condition

Cruise condition is defined by the need to achieve optimum range and endurance.

- Lift/ drag performance > 10
- Speed of approximately 30 ms^{-1} (to cover required distance in one work day)
- Fuel consumption < 300 g/hr (to get required endurance from fuel load)
- Ability to perform well over the weight change due to fuel load

3.4.2 Landing condition

Landing requires the slowest possible approach to reduce the impact with the water.

- Speed of < 17 ms^{-1}
- Good rudder authority to allow cross wind landing
- Waterproof payload bay

3.4.3 Launch condition

Launch requires that the aircraft can be accelerated rapidly.

- 6 G loading in forward direction

3.4.4 Climb condition

Climb condition is important not only after launch but also to define the performance required in heavy weather conditions.

- Climb rate of > 1:10 when fully loaded

3.5 Conclusions

The design approach, modes of operation and flight conditions combine to give a complete definition of the system. Using this, the detailed design process can begin. The airframe and propulsion development are described in Chapter 4 and FCS development in Chapter 5.

Chapter 4

Airframe

4.1 Introduction

The requirements for the vehicle described in sections 2.6 and 3.4, demand an airframe that is resilient and aerodynamic. These requirements are summarised below:

- Range in excess of 1000 km
- Endurance longer than 8 hours
- Payload mass of up to 2 Kg
- Payload volume of up to 10 litres
- Capable of launch from a ship
- Recoverable after landing and immersion in sea water
- Structural cost of less than £1,500 to meet total cost requirement of £5,000

4.2 Aerodynamic development

The first prototype vehicle developed in 2003 was designed entirely using classical aerodynamic methods (Figure 4.1). This vehicle was successfully test flown using landing gear for recovery (not shown in figure). Despite the success of the test flight, the vehicle did not meet the requirements due to its poor aerodynamic performance, over powered engine and weak wing construction. The next few years of undergraduate projects focussed on attempting to improve these areas.

The sizing and configuration of the vehicle was determined in the first year of the project. A pusher configuration, where the engine is at the back of the fuselage was selected so that sensor payloads would be able to sample clean air ahead of the engine. The size was determined by the payload volume and mass followed by the volume of petrol required to run the engine for the required endurance.

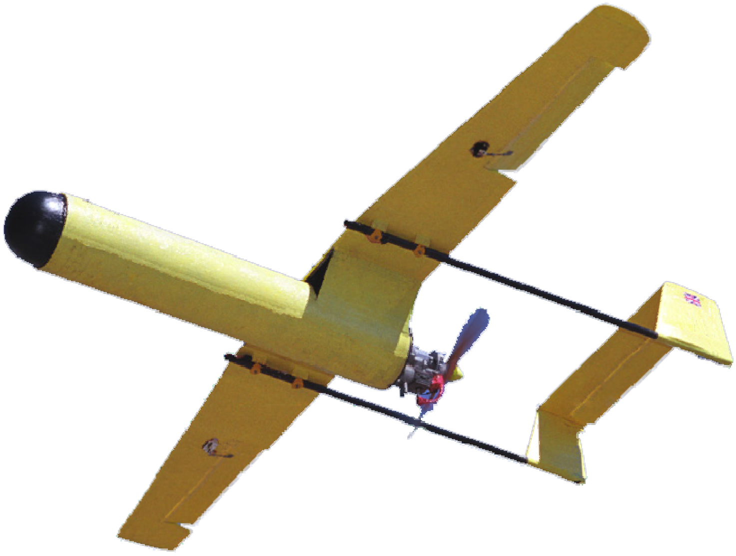


Figure 4.1 - NOC UAV mark 1

At the start of this project, more advanced composite construction methods had been developed for the fuselage and wing by a series of undergraduate groups (see section 4.5). However, only limited progress had been made in aerodynamic performance with different designs from each year of the project and little evidence to support any of them. The undergraduate GDP group starting in summer 2005 were given the task of redeveloping the wing as they had particular skills in Computational Fluid Dynamics (CFD). This resulted in summer placement for one of the students and a report into the design [50].

The recommendations made by Endicott were:

- Use of the Selig 9037 wing section
- Wing cross section; at root 204.21 mm, at tip 122.55 mm
- 3.2 metre wing span
- Use of a straight sided fuselage to eliminate acceleration of flow under the wing
- Sink wing into fuselage body
- Use of split flaps as oppose to simple flaps to improve performance

- Design for a more pointed nose

These recommendations were refined and the fuselage redesigned to provide the minimum cross section to accommodate the engine, fuel and expected payload. Its length was set by the need to counter balance the tail and engine against the payload and avionics around the centre of lift of the wing. The result of this design work is shown in Figure 4.2.

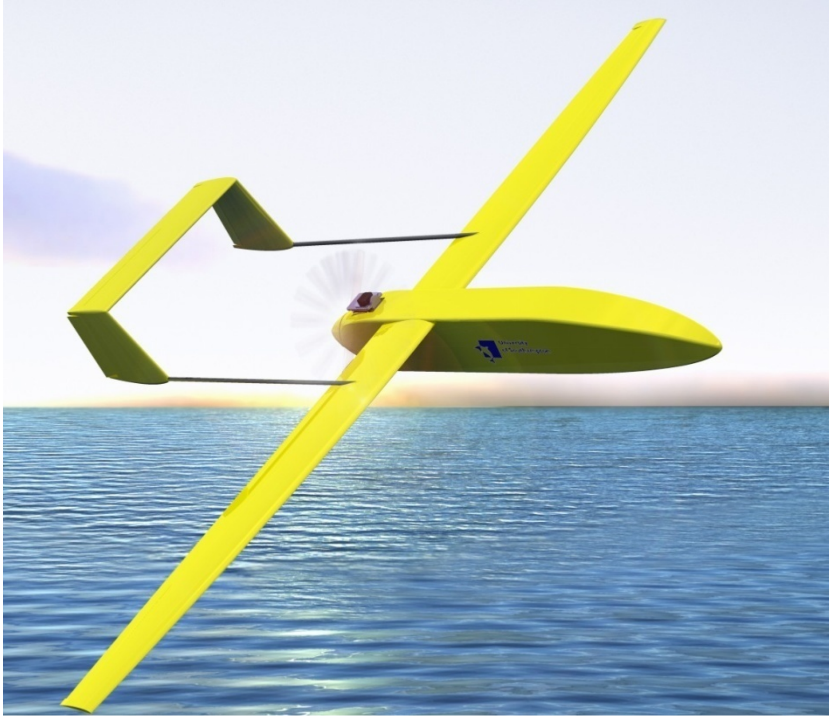


Figure 4.2 - Artists rendering of NOC UAV mark 2 design

The main differences between the two designs are summarised in Figure 4.3. The volume of the fuselage has been substantially reduced although still meets the requirements set out in section 2.6. However, the CFD calculated lift to drag ratio at cruise is substantially improved doubling the effective range of the aircraft.

	Mark 1	**Mark 2**
Wing span	2600 mm	3160 mm
Flaps	None	Split flaps, 30%, 1000 mm
Overall length	2450 mm	2055 mm
Predicted Lift/Drag	4	10
Payload volume	20 litres	10 litres

Fuel tank volume	7 litres	5.8 litres
Engine	2-stroke, 28 cc	4-stroke, 25 cc
All Up Mass (AUM)	15 kg	15 kg

Figure 4.3 - Design differences between mark 1 and mark 2

4.3 Wind tunnel work

To confirm the data calculated by CFD a half scale model of the mark 2 design was manufactured to test in the wind tunnel. The objective was to demonstrate the improved L/D performance (validating the CFD results) and to test a selection of flap designs, as it was not possible to model them successfully using CFD.

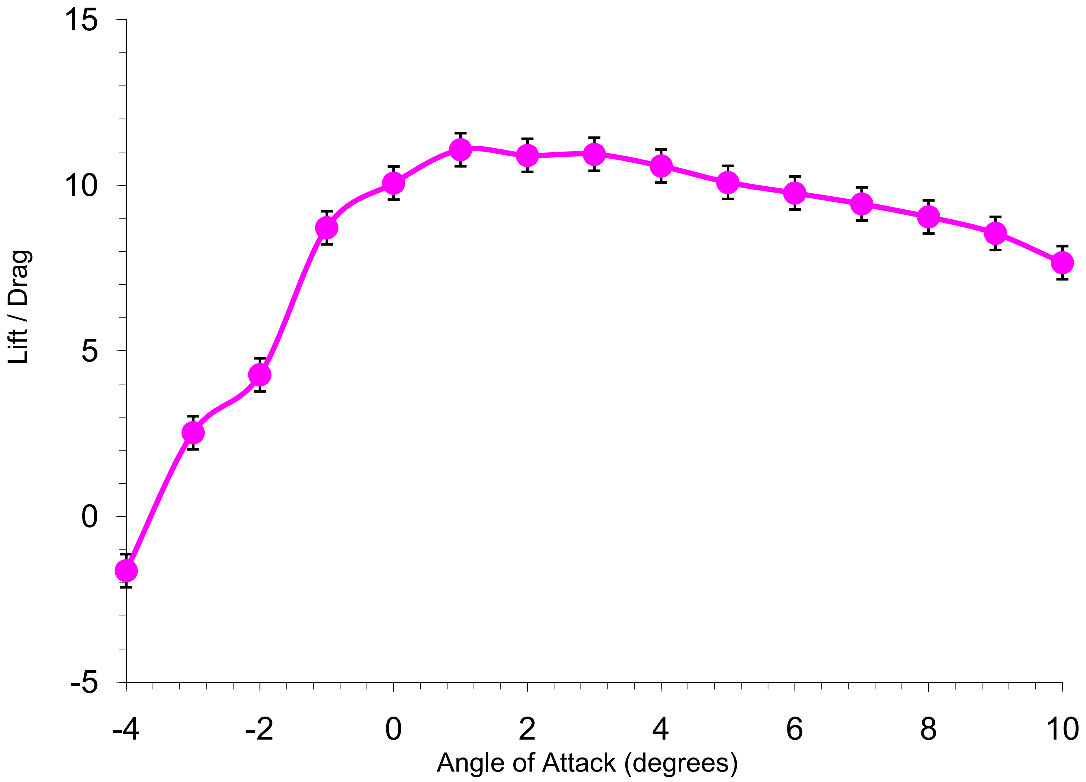


Figure 4.4 - Wind tunnel results L/D

Figure 4.4 shows the results of the L/D testing. At an angle of attack of 1°, the L/D ratio hits a peak of 11, slightly better than the CFD result. This difference may be because CFD tends to overestimate drag.

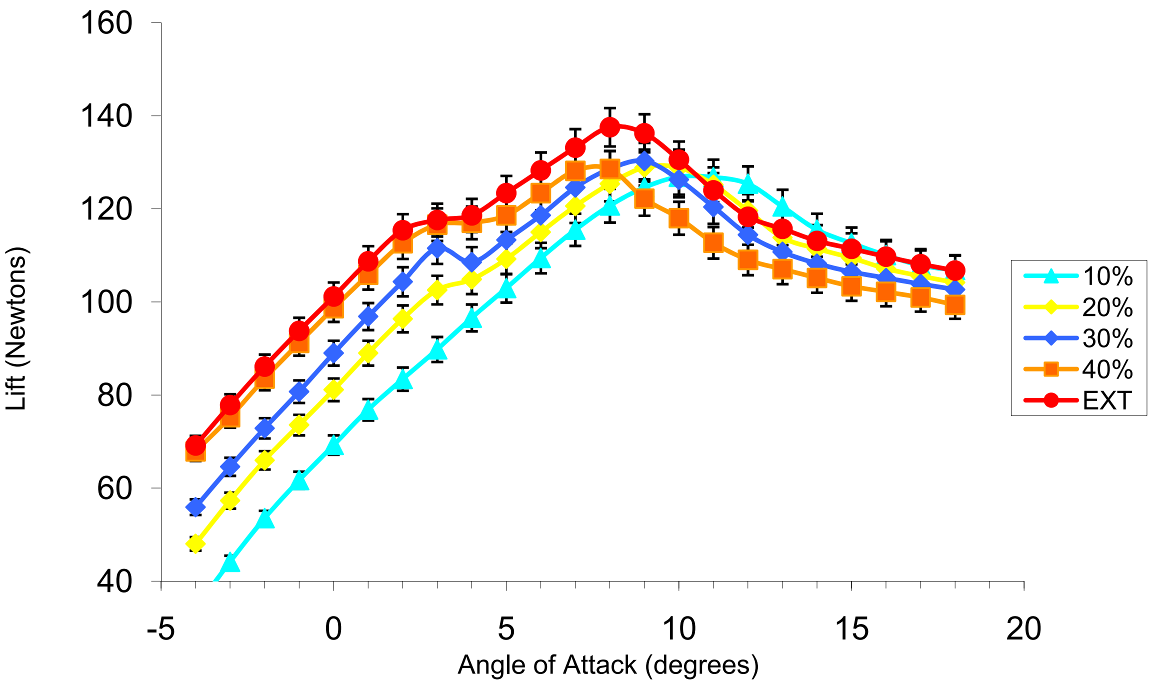


Figure 4.5 - Wind tunnel results, flaps

The target landing speed for the aircraft is <17 ms^{-1} and so flap data was calculated just below this at 15 ms^{-1}. Figure 4.5 shows the results for different flap designs set to 30° deployment. The flap designs are measured as a percentage of the wing chord and all designs run the entire length of the wing before the ailerons (1 metre each side). As shown in the figure, increasing the flap size increases not just the maximum lift of the wing but also the lift for a given angle of attack.

The most effective design is the plot marked EXT. This design is an extending flap that not only deploys to 30° but also extends the chord of the wing by 20%. This is better performing but more mechanically complex and therefore was not selected for the vehicle at this time.

The maximum mass of the aircraft is 15 kg so to remain in the air ≈150 N of lift must be generated by the wing. As shown in the figure none of the designs could reach the design point of 150 N at 15 ms^{-1}, in fact they only reach this amount of lift at 17 ms^{-1}. This is acceptable as the flaps are only to be deployed during landing where speed will be reduced gradually to make the aircraft lose lift so it descends while being pitched nose up. In addition, at landing the fuel weight will be approaching a minimum giving an aircraft mass of approximately 12 kg. This is accomplished with a small safety margin at 15 ms^{-1} with the extended and 30% flap designs.

The flap selected for the vehicle was a 30% flap deployed to 30°. This was the best compromise between lift performance at lower speeds and the drag created that would need to be overcome by the engine.

4.4 Engine development

To meet the range performance requirements set out in section 2.6 an extremely efficient engine is required. Commercial UAV engines like those developed by RCV [51] perform extremely well and use heavy fuel but are very expensive. At the time of writing all RCV's engines are also too large to be suitable for the project but collaboration is being discussed that may fund the development of smaller, lower cost versions.

The mark 1 vehicle used a 28cc, 2-stroke petrol engine that generated 1.3 kW peak power. The 2-stroke cycle is inherently inefficient due to the unburned fuel passing through the system and the engine was more powerful than required for the more aerodynamically efficient mark 2 vehicle. At cruise condition (see section 3.4.1), the wind tunnel data indicates that 14.6 N of thrust will be required which is 503 W (given an 85% efficient propeller).

Moving to a 4-stroke engine would offer an immediate improvement in performance, the Honda GX25 was identified as the smallest 4-stroke petrol engine available and its specifications are shown in Figure 4.6.

Parameter	Value	Units
Capacity	25	cc
Cycle	4-stroke	
Maximum power	810	watts
Speed at maximum power	7000	rpm
Maximum torque	1.25	Nm
Speed at maximum torque	5000	rpm
Fuel consumption	340	g/kWh
Fuel	Unleaded petrol	
Carburettor	Diaphragm type	

Ignition	Transistorised magneto

Figure 4.6 - Honda GX25 specifications

As the engine would have to operate in very different conditions to those it was designed for, it was decided to perform a characterisation. This work was performed with the assistance of a third year engineering student who operated the test system, took the measurements and produced an analysis of the data.

The test system was rebuilt based on a previously used design and improved and maintained as part of this project. The system was set up in an open-ended cargo container to allow air to flow through and exhaust gases to be vented. The engine was mounted on a rig measuring reaction torque, RPM, temperature and fuel flow. This data was captured using LabView and the throttle was controlled with the same system that operates in the UAV. A set of differently pitched propellers were run at a range of RPMs and fuel flow recorded for each.

The work on the system included:

- Improvements to the fuel flow measurement to isolate vibration, wind noise and improve resolution
- Addition of connectors to allow the electronics to be moved indoors for storage
- Control of throttle using a linear actuator and hobby transmitter
- Signal conditioning enhancements
- The LabView system for data acquisition and display
- Site risk assessment
- Training of undergraduate student in equipment use and safety precautions
- Procurement of all equipment including selection of propellers
- Day-to-day setup and oversight of work

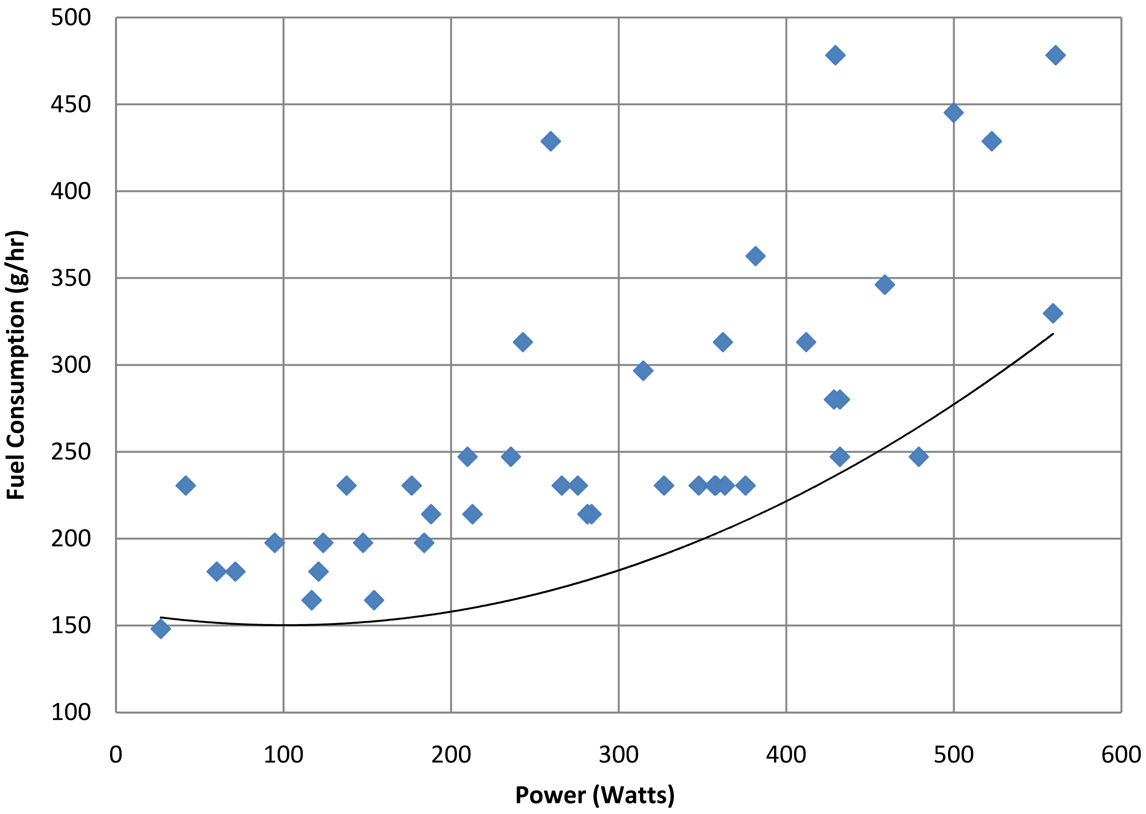


Figure 4.7 - Honda GX25, power v.s. fuel consumption

The results of the testing (Figure 4.7) show that the GX25 met the fuel consumption figures quoted for it. When generating the 500 W required for cruise it consumes around 275 g/hr (using a least means squared polynomial fitting on the data boundary). The mark 2 design can carry up to 5.8 litres (4.2 kg) giving an endurance of 15.3 hours and a range of 1600 km at 30 ms^{-1}.

4.5 Manufacture

The structural design of a full size aircraft requires a very careful balance of weight and strength. These structures are certified using simulation and testing to demonstrate that they have a safety factor of at least 1.3 over the expected maximum strength required. It is expected that the CAA will require at least the same factor for UAVs.

The loads experienced during handling and transportation are far greater than the flight loads for a small UAV. As such, these will determine the minimum strength of the structure, resulting in an in-flight safety factor that is relatively high. In addition, the NOC UAV has two unusual phases of flight that require additional strength, the high G loading during launch and a potential impact during landing. These will also be important in determining the required strength. The minimum strength / weight achievable with the material available is very high so the numerical structural analysis of the vehicle is left to the undergraduate student groups, see section 1.5 for more information on the distribution of tasks.

As part of undergraduate projects over the last four years many composite construction techniques have been attempted. The requirements for the technique are:

- Good external surface finish
- Light weight part with minimum resin
- Strong, low velocity impact resistant parts
- Manufacture by students / personnel with limited practical skills
- Resulting parts are easily assembled
- Process can be repeated reliably
- Moulds can be modified to experiment with different designs

After much experimentation the current recommended technique is:

- Always female moulding
- CAM cut mould or former to make mould
- Use sandwich structures with Rohacell foam or Balsa cores
- Wet layup
- Cold cure (not autoclave)
- Vacuum pressure using bag
- Use of joggles to help assembly
- Moulds to form all joints so complex joins are not required during assembly

4.6 Systems integration

Integration of the propulsion, structural and electrical systems was performed as part of this project.

4.6.1 Electrical system

The design philosophy established in Chapter 3 was to make the best use of low-cost actuators and sensors. The actuators selected for the control surfaces of the UAV are low-cost hobby aircraft servos. These are cheap, flexible and fast, however, they are not very robust and have no protection if they become stuck, causing them to be destroyed from overheating. To mitigate these factors it is planned to monitor their performance very closely by measuring position and current draw. To allow this to be done centrally each servo requires four wires. This is discussed in more detail in section 8.5.

Wiring was selected by designing for the worst-case loading caused by each servo. As power consumption is critical, it is important that losses in the wiring be reduced as far as possible. For the first vehicle, a 7/32 AWG core size was selected so that power loss to the most distant servos was 0.23 W at 1 A peak load. This gave a total wiring weight of 441 grams for the whole vehicle. Future work to characterise the servos may indicate a lower current draw allowing a smaller core size to be used. Moving to 7/34 AWG, would reduce wiring weight by half to 222 grams.

4.6.2 Battery specification

To provide the current necessary to run all the actuators for a possible endurance of over 12 hours requires a high-performance battery technology. The best energy-to-weight ratio technology available is Lithium-Ion. However, these packs require careful monitoring and charging to get best performance and prevent explosions. Nickel-Metal-Hydride (NiMH) was selected as this is a robust technology, is easy to charge and has good capacity. A 6 volt, 4.5 Amp hour pack weighs 300 grams.

Chapter 5

Flight Control System

5.1 Introduction

To meet the low-cost requirement identified in section 2.1 it was determined that the Flight Control System (FCS) must be developed internally, as the commercially available solutions were too expensive or performed poorly. Figure 5.1 shows the position and connectivity of a bespoke FCS within the aircraft system.

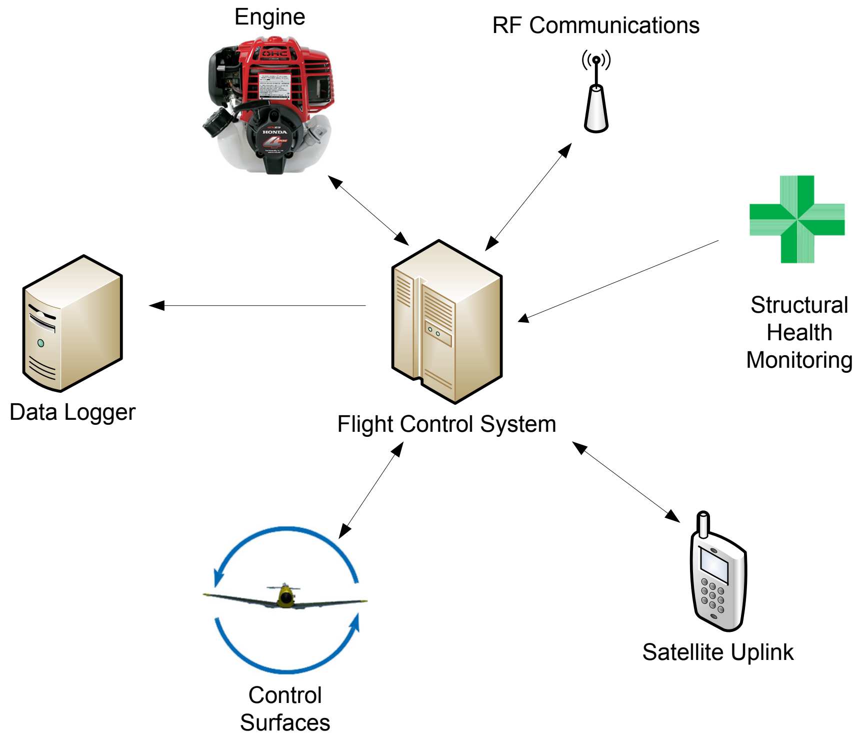


Figure 5.1 - FCS interfaces to the UAV and ground station

The FCS needs to be evaluated as part of the complete aircraft system and must achieve equivalent or better levels of robustness. It will be critical in monitoring the health of the airframe, control surfaces and engine. The functions required of the system are:

- Measurement of inertial parameters making best use of low-cost sensors
- GPS reception
- Processing of sensor data to find the state of the aircraft
- Processing of current state and required state to produce inputs to the system
- Control of all surfaces
- Monitoring of control surfaces, engine and eventually airframe
- Communications with the ground station
- Power supply monitoring and control
- Ability to continue navigating in the absence of some sensor data
- Black-box data recording for post-flight analysis

5.2 Approach

In section 2.4 the requirements for a suitable FCS were established, these are:

- A unit cost of under £1,000 for the hardware in order to be part of a complete system at under £5,000
- The hardware must be robust to survive handling in a wet environment, in-flight vibration and possible impacts during vehicle assembly
- Software must be robust to deal with sensor and actuator failures
- Hardware and software must be developed to be potentially certifiable (see section 2.5)
- The system must support health monitoring of the structure and control surfaces
- There should be enough headroom to allow the use of sophisticated flight control algorithms (section 2.4.3)

To achieve the low hardware cost required the design should make use of widely available components, particularly MEMS inertial sensors. These are used by all the commercial autopilots available for small UAVs, they are more noisy and prone to drift than traditional transducers but they are also more robust (section 2.4.2).

By combining all the systems required into a single package it should be possible to substantially improve hardware robustness simply by reducing the risk of connector failure and operator error. It will also be easier to protect components from water and handling damage. The tight integration of vehicle structural and control surface monitoring will help to combat one of the weakest areas in current small UAVs, the use of actuators design for hobby aircraft.

A UAV developed to be so low-cost and by an organisation other than the main aerospace manufacturers is very unlikely to be CAA certifiable (see section 2.5) due to the expense of meeting the documentation and formal proof requirements. These are not just incurred during the main development but also when any software, hardware, structural or aerodynamic change is made to the vehicle during its life. The CAA is continuing to evolve its requirements in order to support the new commercial UAVs and their roles, some of which will be in controlled airspace. It is likely this will result in a set of graduated requirements that depend on the size of vehicle, the type of work undertaken and the airspace in which the operation takes place.

The initial operations envisaged for the NOC UAV take place in the deep ocean (section 2.1). If the UAV is to be used to identify interesting features it needs to perform search patterns which can take place within the line-of-sight of the ship, keeping a visual and RADAR check of the area over flown. Constant communication with the research vessel allows changes to be made at any time. Even with this very low risk activity, it is important to consider how to make the vehicle as certifiable as is reasonable. This will not only ensure its correct and safe operation but that in the future it may be possible to fly coastal or over-land missions.

Meeting robustness requirements for the vehicle structure is more possible for a small UAV than with a large vehicle (discussed in section 4.5). However, for the control system it is substantially harder. Pre-certified components (like a standalone IMU) are too expensive, as is self-certification, and any software needs to conform to stringent quality guidelines.

Given that the requirements described could not be met, a study was performed to examine how easily they could be approximated and what this would offer to the project. The electronic hardware, particularly in inertial measurement, is largely determined by the need to meet the budget requirements. These components are not available in a certified form as this only applies to complete devices, normally including software and an interface either to another device or to the pilot.

Some standards do exist for these kinds of components, including some for the reliability conscious automotive industry [52]. However, they are not universally supported, making it difficult to choose all components to conform to a single standard. Many manufacturers do offer components targeted specifically at automotive use and these will be considered acceptable unless they are found to perform poorly on an individual basis (section 5.3).

Software is even more important in a UAV than in a manned aircraft. It is in complete, independent control of the vehicle and the ground station crew have only a limited ability to put control into the hands of a human pilot. The software standard used in developing avionics for the manned aircraft industry is DO178-B. The level of compliance required is varied according to the impact a software failure would have on the flight. In the case of a UAV control system, this is considered ‘catastrophic’. To develop for DO178-B from scratch would require a team of developers, skilled not just in coding but also in generating the necessary documentation.

To reduce the cost of implementing software to this standard it is possible to buy Real-Time Operating Systems (RTOSs) that have been previously certified in other applications. This then provides a base of code that will not need to be examined so closely during certification. *Integrity* from GHS [53] can be used in this way although at £10,000 for a single, non-commercial license it is still extremely expensive. There would also be a steep learning curve and any new code written for it would still need to be to DO178-B for the system to be certifiable.

Running any kind of Operating System requires additional processing overhead as in addition to the algorithmic code to control the aircraft it must perform frequent status checking on different processes. More processing requires a more sophisticated and faster processor that will draw more current, increasing the power consumption of the system.

It is possible to develop certifiable software without doing all the work from scratch and without using a RTOS by using a modelling and code synthesis suite, like SCADE from Esterel Technologies [54]. This allows control algorithms to be modelled in a graphical environment and tested to ensure they perform correctly. The code generator then creates DO178-B certifiable code. This does not certify the entire system as this must include the hardware certification; however, it does go a long way to create confidence in the most critical and difficult to test part of the software.

There are also tools available to help with the development of software for use in automotive applications. These generally ensure that the software conforms to the MISRA standard [55]. This is a less sophisticated standard than DO178-B and there is no formal certification process so software tools tend to implement a variety of levels of functionality.

It is possible to achieve the combination of low-cost and some software and hardware reliability in a number of ways. However, two distinct options can be drawn out and these are shown in Figure 5.2. The first is use of a third party RTOS built around a large processor, probably supported by an additional smaller processor to perform data collection. The second is the use of a smaller processor that is programmed directly and a system such as SCADE is used to generate the algorithmic code with a MISRA code checker used to analyse the lower level functions.

	RTOS	No RTOS
Hardware complexity	More	Less
Hardware development time	More	Less
Software complexity	More	Less
Software development time	Equal	Equal
Processing requirements	More	Less
Partly certifiable	Yes	Yes
Cost of Development tools	Equal	Equal
Cost per unit	More	Less

Figure 5.2 - Comparison of FCS options

From Figure 5.2 it is clear that avoiding the use of a RTOS reduces many of the system requirements while still allowing a high-level reliability to be achieved. This choice affects not just software development but also the hardware design described in section 5.3.

5.3 Design

Figure 5.3 shows the major components selected for use in the FCS. Each component was chosen by examining the market for the type of device required and evaluating it on the following criteria:

- Performance
- Robustness
- Cost in small quantities
- Availability in small quantities

In addition to those listed, numerous other supporting components were chosen in areas like analogue to digital conversion and power regulation.

Component	Device Selected	Notes
CPU	Freescale, MAC7116	Automotive grade CPU High performance ARM7 core Low power consumption Multiple serial interfaces
GPS	Fastrax, iTrax130	Up to 4 Hz operation WAAS and EGNOS support
Gyroscope (Z axis)	Analog Devices, ADRXS300	Low-cost, easily available
Gyroscope (XY axes)	InvenSense, IDG-300	Two axes in a single device Simplifies mounting requirements
Accelerometer	Freescale, MMA7260Q	Three axes in single device Low cost and easily available
Compass	PNI, MicroMag3	Three axes in single device Simple interfacing requirements
Absolute pressure	Freescale, MPX4115A	Fully integrated sensor Low cost due to mass production Automotive grade
Dynamic pressure	Freescale, MPXV5004	Fully integrated sensor Low cost due to mass production Automotive grade
Radio modem	Aerocomm, AC4868	Low operating frequency gives large range
Black box	Multimedia card	High speed data recording Simple interfacing requirements

		Previous experience with these devices
Enclosure	ModICE	Automotive grade Waterproof and robust

Figure 5.3 - Component selections for FCS

It is beyond the scope of this report to detail the design methodology and specification of the complete autopilot including all components and subsystems. Section 5.3.1 gives an example of the method used for the pressure-sensing element of the design.

5.3.1 Pressure sensing

One of the critical areas for the control system that was identified by the algorithm development EngD project was for accurate pressure sensing (Bennett [41]). Absolute pressure is used to estimate altitude and dynamic pressure to estimate airspeed; these supplement the inertial sensors and the GPS providing high-rate data. The original sensors on the hardware for this project were interfaced using a 10-bit analogue to digital converter across their entire pressure range, giving an altitude resolution of several metres. Bennett improved on this design by using a 16-bit analogue to digital converter and limiting the range to a 200-metre ceiling. This gave a theoretical maximum resolution of 3.5 cm.

Bennett [41] considers this enough resolution, and that the resolution is limited by the fundamental sensor noise, however, the range of 200 metres may be too small for some applications where imagery of large areas is required. The design also used voltage dividers to create the voltage references. These are at best around 1% accurate and output voltage will shift with the temperature difference between the two resistors. Standard resistors can have a temperature coefficient as much as 5000 ppm/°C.

To improve on this design a 24-bit sigma-delta analogue to digital converter was used, not to improve resolution (as Bennett has already shown this to be limited by the fundamental sensor noise) but to increase range. By keeping the Least Significant Bit (LSB) size the same, the greater number of bits allows a larger voltage range to be measured at the same resolution.

This greater flexibility in range allowed the use of off-the-shelf precision voltage sources that have much greater accuracy (0.05%), low noise (41 μV_{RMS}) and lower temperature drift (10 ppm/°C) than voltage dividers. Although the fundamental device noise in a voltage source is higher than in a resistor, they reject noise from the power supply, which would propagate through a voltage divider circuit. The laboratory test results of the design for the absolute pressure sensor converter are shown in Figure 5.4.

Parameter	Value	Units
Effective number of bits	21.3	bits
Effective resolution	1.7	mm
Noise free bits	18.6	bits
Noise free resolution	11.3	mm
Range	4494	metres
Voltage offset	3.3	volts
Voltage reference	2.048	volts
Converter gain	2	n/a

Figure 5.4 - Absolute pressure sensing converter design

The dynamic pressure sensor and other systems were designed using the same method. Existing systems were analysed and then the latest components were used to improve performance. All are sampled at a much higher precision than necessary so, when combined with careful layout and the use of clean power supplies this should make the most of the low-cost sensors used. The results of this work are shown in section 5.4.

5.3.2 Layout

The components were brought together in a single circuit schematic shown in Appendix 1 and the analogue sections were simulated. The final layout of the FCS is shown in Figure 5.5. The layout required careful consideration to ensure that the analogue performance requirements were met and that the board fit securely in the enclosure. The board is four layers, with power and ground planes split to isolate analogue and digital sections. The power supplies are individually selected for each section to provide either very low noise for analogue or very high efficiency for digital sections.

The PCB was manufactured and the majority of components placed by Newbury Electronics Ltd [56].

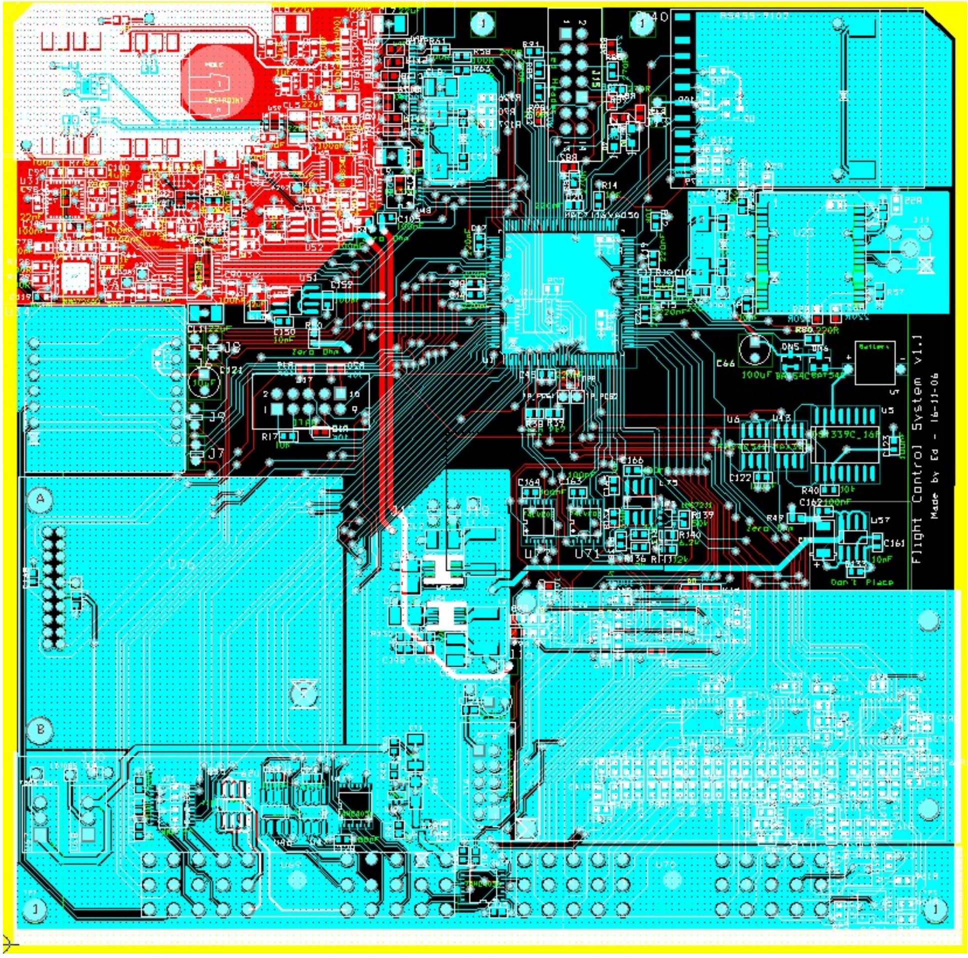


Figure 5.5 - FCS layout

5.4 Results

The completed system is shown in Figure 5.6. A few minor errata were corrected and the software was developed to read the sensors and perform other low-level tasks. This has not yet undergone any robustness analysis or testing so is not suitable to control the UAV. However, it is possible to measure parameters on the bench and to assess the performance of some devices statically.

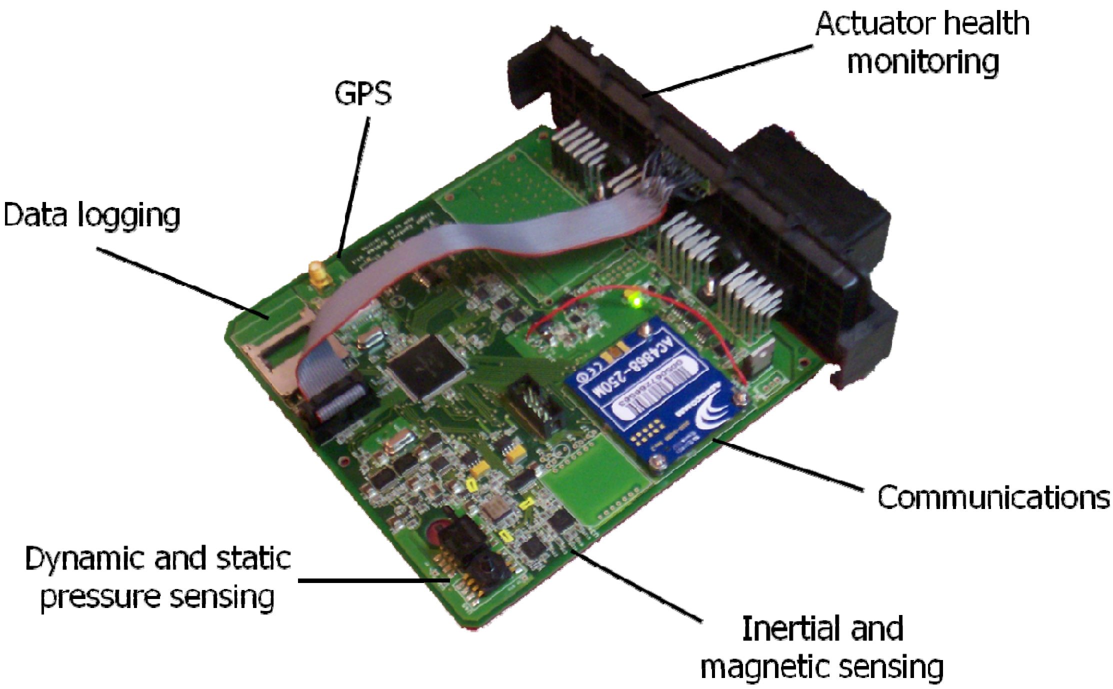


Figure 5.6 - Flight Control System

To assess the performance of the sensor measurement techniques used the absolute pressure sensor, gyroscopes and accelerometers were sampled for 10 seconds (1000 samples). This data was then processed to find the standard deviation and then converted into the real number of bits being measured. Figure 5.7 shows the results of this analysis.

Sensor	Sample precision	Measured precision	Units
Absolute pressure	24.0	15.6	bits
Absolute pressure	1.7	56.0	mm
Gyroscope X axis	16.0	13.2	bits
Gyroscope Y axis	16.0	15.0	bits
Accelerometer X axis	16.0	10.8	bits

Figure 5.7 - Results of FCS sensor testing

The pressure sensor noise-floor is above the resolution of a 16-bit converter and so it would appear that using the 24-bit converter is unnecessary. However, as described in section 5.3.1, this has allowed a much wider dynamic range to be measured. The gyroscope shows excellent performance with a maximum of 15-bit resolution on the Y-axis channel making this well worth converting the signal at 16-bit. The accelerometer performs relatively poorly offering little advantage over using a 10-bit converter. It is possible that an alternative part could be found to replace this in the future.

One of the key requirements established in section 2.6 was for a range of > 1000 km. To help achieve this, as few battery packs should be carried as possible, so the electronics should consume as little power as possible. The board consumes around 2 watts when reading all sensors, processing the data and transmitting over the RF link. Due to an error in the power supply layout it is currently only around 55% efficient where it should be 90%. This is easily corrected in future revisions of the board. Using the 4.5 Ampere-hour battery packs described in section 4.6.1, the current board could operate for 13 hours.

5.5 Conclusions

The FCS developed for the NOC UAV project has a rich feature set tailored to the specific needs of the project. All sensors are operational and more than 300,000 integer operations are available after data collection and filtering for every loop of the control algorithms. This is enough to execute the floating point Kalman filter and PDF controller used by Bennett. Using a more sophisticated algorithm for control would require converting some or all of the algorithms to fixed point. The final specification is shown in Figure 5.8. The power consumption of <1.8 watts compares very well to that of the Cloud Cap Piccolo [43] that draws 4.8 watts. Data collected by the FCS during flight is presented in Chapter 6.

Feature	Quantity
Processing	> 40 MIPS integer
IMU	3 axis acceleration 3 axis rotation 3 axis magnetic
GPS	WAAS/EGNOS enhanced at 4 Hz
Barometric altitude	0 -> 1000 metres
Dynamic pressure	0 -> 45 ms^{-1}
RF communications	Range > 10 miles
Black box	4 GB at 200 kBps
Actuator control	8 channels

Actuator monitoring	8 channels
Pilot override	Integrated and independent (all channels)
Power consumption	< 1.8 watts (operating)

Figure 5.8 - FCS feature list

The FCS hardware is now ready for integration with the rest of the vehicle. While this is taking place, the control algorithms developed by Bennett will be adapted to operate on the new hardware with the aim of flying the trainer aircraft automatically.

Chapter 6

Instrumented Flight Test

6.1 Introduction

Flight test 4 on the 11th of September 2007 was unsuccessful in that the vehicle seemed underpowered. The vehicle was accelerated to approximately 50 mph before release from a car-mounted cradle, the aircraft then climbed for around 5 seconds before stalling and falling. However, the Flight Control System (FCS) was onboard the aircraft and successfully recorded all parameters, allowing the vehicle's performance to be examined in detail.

6.2 Performance analysis

The engine performs as expected given that it should reach 5500 RPM at 30 ms^{-1} and there seems to be no reason to think that a fuel/air flow or throttle problem caused unusual performance.

Figure 6.1 shows the speed of the vehicle in ms^{-1} (red) and the engine RPM (blue) against time. Speed has been scaled by a factor of 1.5, as the sensor had not been calibrated at the time of the test. The vertical green line indicates the point of release from the launch cradle, to the left of the line the speed can be seen increasing as the car accelerates. Initially the RPM drops as the car starts accelerating as when stationary a large part of the propeller is stalled, reducing the torque required. After this, the RPM increases with speed. At 11 seconds, the car has reached 50 mph and then holds this speed and this is shortly followed by the release.

At release, the UAV is travelling at 22 ms^{-1}. According to the wind tunnel measurements for an all-up-mass of 11 kg, this forward speed is enough to support the aircraft at an angle of attack of 3 degrees. After release the speed reduces as it is exchanged for altitude and the engine RPM drops as it becomes more heavily loaded.

The engine performs as expected given that it should reach 5500 RPM at 30 ms^{-1} and there seems to be no reason to think that a fuel/air flow or throttle problem caused unusual performance.

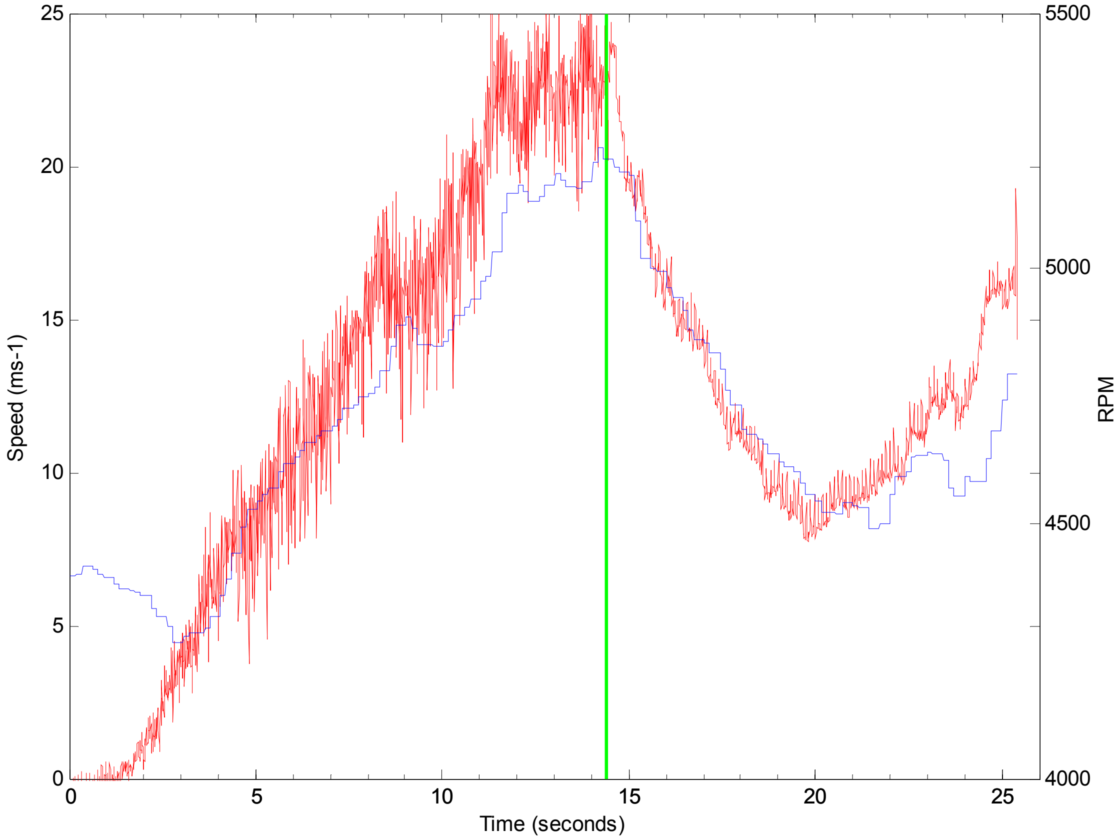


Figure 6.1 - Speed (red) and RPM (blue)

Figure 6.2 shows speed (red) and altitude (blue) against time. The vertical green line indicates the point of release from the cradle. After release, the vehicle exchanges airspeed for altitude climbing to a peak of 25 m. The two vertical cyan lines mark the period that the vehicle was climbing. In this period, the average airspeed was 13.5 ms^{-1} and the climb rate was 5.95 ms^{-1} giving a ratio of 1 in 2.2. The expected maximum climb rate that maintains constant airspeed is 1 in 20. After altitude peaks at 25 m, the aircraft is fully stalled and out of control. Some speed is regained during the descent but never enough to resume controlled flight.

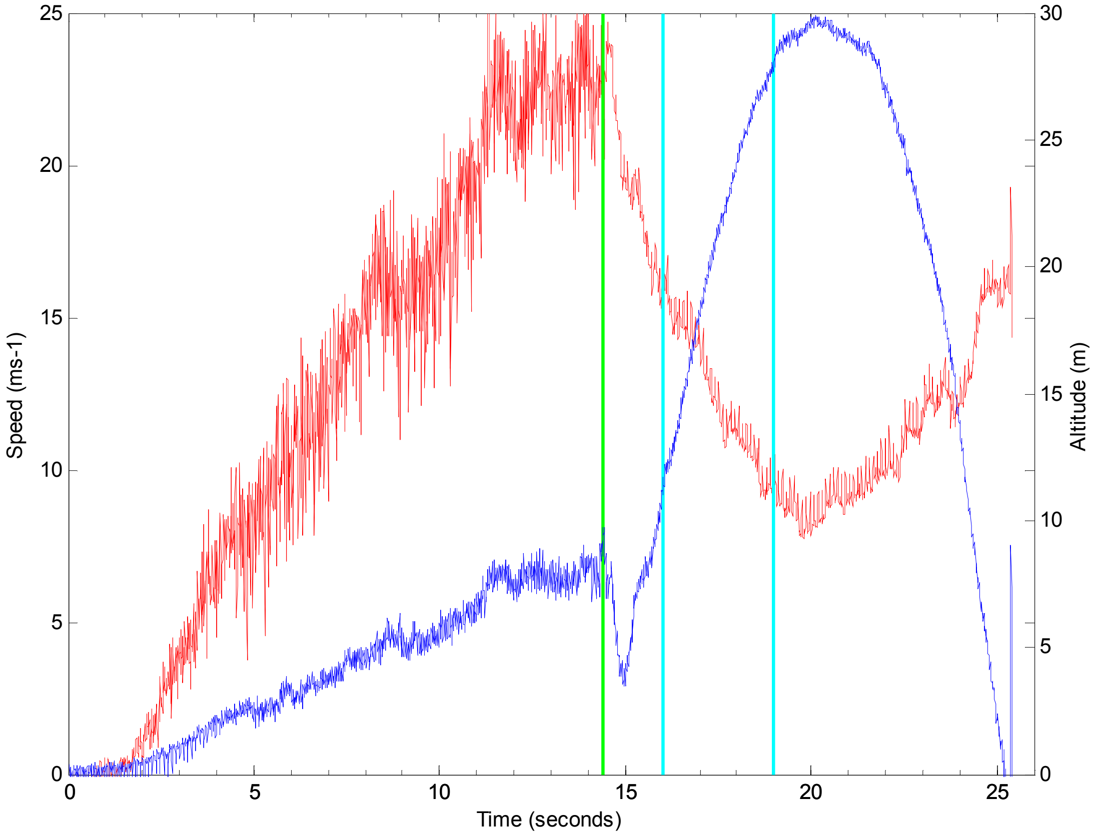


Figure 6.2 - Speed (red) and Altitude (blue)

6.3 Conclusions

The test flight demonstrated the value of data logging with the high performance FCS and validated this unit's performance. This data reveals how and why the vehicle performed as it did which could not be assessed visually on the day or with video footage. It also demonstrated that the vehicle was performing as expected but also that in its current state it will prove difficult to fly manually. It does not perform like a hobby aircraft but more like a glider, requiring very gentle climbs and good conditions. Watching the flight video (FlightTest4.avi on accompanying CD) it is impossible to tell that there is a problem until it is too late. The direction of flight, directly away from the pilot, means that the loss of airspeed cannot be seen and it appears to be climbing well until it stalls. It may have been possible to recover at this time by putting the nose down and gaining speed but lack of authority in the control surfaces may have made this impossible.

In the short term, it will be necessary to use a more powerful engine to allow manual piloting for the assessment of the airframes performance. It may also be necessary to have more power available to cope with poor weather conditions.

Chapter 7

Payload Management

7.1 Introduction

Although this project is focussed on developing a UAV, the most important part of any mission will be the collection of the oceanographic data. Following the review of existing data logging systems 2.4.4 it was determined that a custom data recording and relaying system would be required. This is due to the requirement that the system must not only accurately record data during the flight but also relay data to the research vessel when requested. It may also be beneficial to perform some simple analysis on the data to identify features that may alter the flight plan.

To provide the sophisticated features and flexibility required, it was decided to use an existing data logger design developed at the NOC for use in chemical and biological sensing [45]. This design would need to be adapted to suit the specific needs of the project.

7.2 Detailed requirements definition

Version 1.1 of the Sensors Group Data Logger (SGDL) was designed for use in the Wave Buoy project where high precision analogue data was time-stamped and recorded for deployments of several days at a time. The specifications for the logger are shown in Figure 7.1.

Parameter	Value	Units
Processor frequency	40	MHz
Average processing rate	10	MIPS
Storage capacity (maximum)	4	GB
Storage data rate (maximum)	100	kBps
File systems supported	FAT32	-
Analogue to digital resolution (see section 7.3.3)	16	bit
Analogue to digital voltage input swing	0 -> 5	V
Analogue to digital resolution	0.76	µV
Analogue to digital sample rate (maximum)	30	kSps
Sensor reference	5	V
Time–stamp resolution	1	second
Time-stamp drift	≈ 5	min/year
External serial interfaces		
RS232	2	-
USB	0	-
SPI	1	-
I^{2}C	0	-
Supply voltage	8 -> 11	V
Power consumption (operating)	1	W
Power consumption (sleeping)	10	mW

Figure 7.1 - Sensors Group Data Logger v1.1 specificatons

The new revision of the SGDL will not only need to support operations as part of the UAV payload but also the next generation of chemical sensors. This will add additional requirements to those of the UAV, these are:

- Smaller physical size
- More flexible voltage support (5 V -> 40 V)
- Ultra low power consumptions sleep mode
- Low power solenoid valve drivers
- Stepper and DC motor drivers
- Temperature monitoring
- Constant current sources (temperature independent)
- Ability to survive crushing forces

During UAV operation, the SGDL will sit at the centre of a mixture of sensor types, distributing information, relaying data and recording information. Figure 7.2 shows an example of expected sensors and their interconnections.

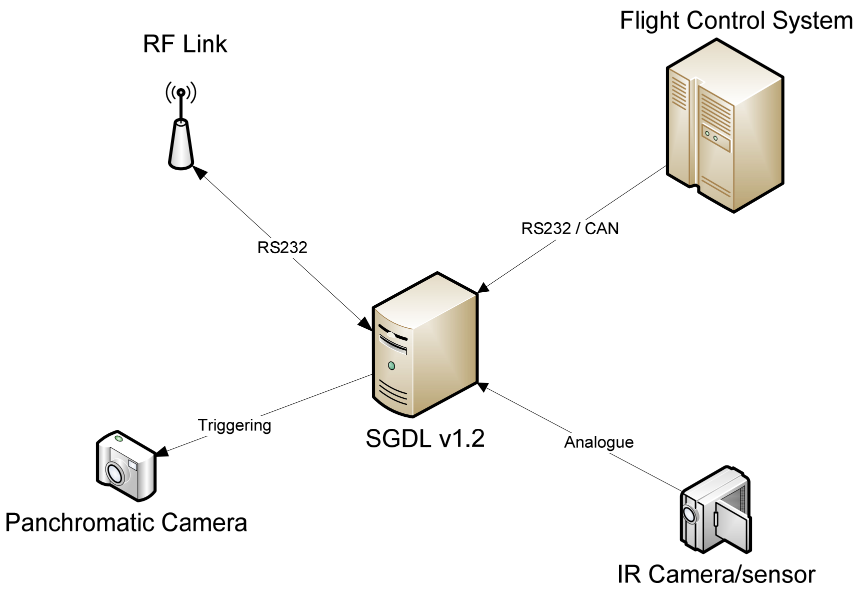


Figure 7.2 - UAV sensors and interconnections

7.3 Design

For discussion purposes, the requirements have been grouped into sections of related issues. Each of these sections led to specific design decisions that shaped the final system.

7.3.1 Physical size

Version 1.1 of the SGDL was a single PCB with a footprint of 60 × 70 mm and a maximum height of 20 mm. The new generation of chemical sensors require the board and all connections to fit roughly within the area of a credit card 80 × 50 mm. This means that board itself will need to be even smaller than that, whilst accommodating the new functionality required. To achieve this small footprint a two-board system was designed, a primary processing board with general-purpose connections and daughterboard with components and connections specific for each application.

As the high-power systems and high input voltage support (section 7.3.5) would only be required by the chemical sensing applications, these systems were placed on the daughterboard. Stacking the boards means that height was a more important dimension than in v1.1. Due to this and the increased number of connections to the boards new miniature headers were selected reducing the maximum height of the boards to 12 mm. When stacked with 15 mm spacers this gives a total height of 40 mm. Figure 7.3 -

Technical drawing of SGDL v1.2Figure 7.3 shows a drawing of the stacked system, a more detailed drawing is in Appendix 3.

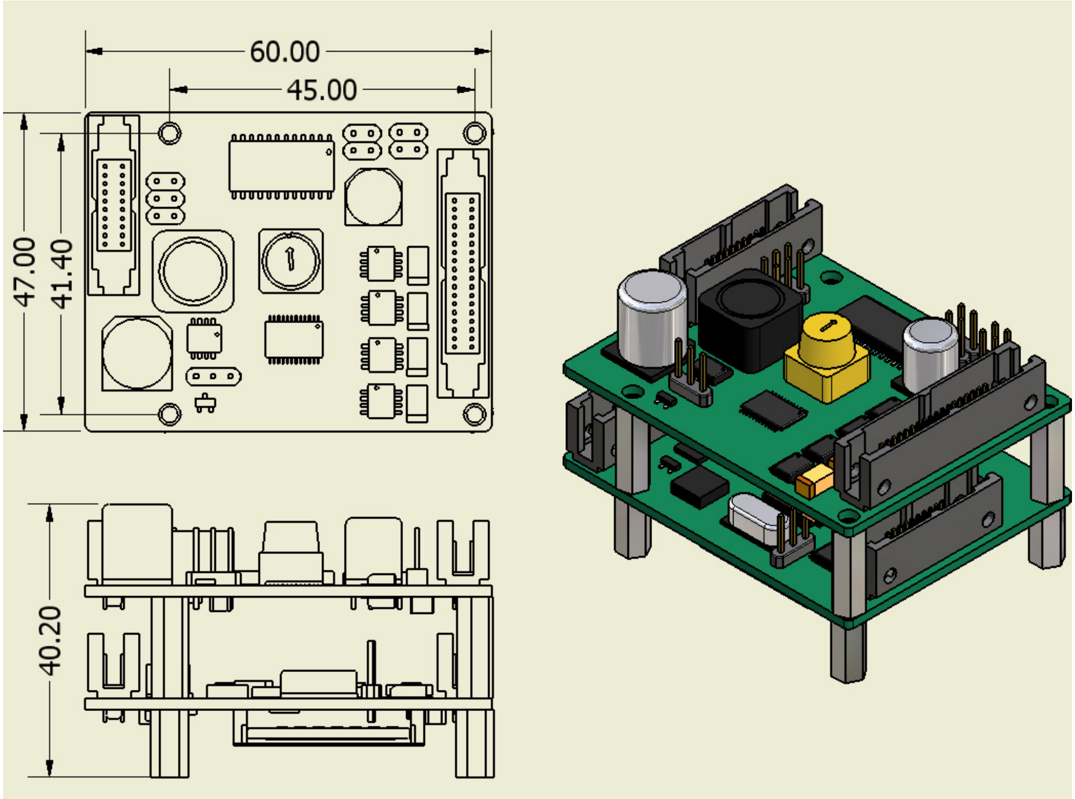


Figure 7.3 - Technical drawing of SGDL v1.2

7.3.2 Voltage support and low power consumption

In some of the seaborne sensor applications proposed, only very high DC voltages are available. To use these to power the small actuators, valves and the data logger, it is necessary to reduce them to a more useful level. This reduction is achieved in three stages; first, the conversion of the high-voltage input to 12 volts is done using a high efficiency, switching DCDC converter. This is located on the daughterboard, as it will only be needed in chemical sensing applications. The remaining steps are both performed by the processing board, a high efficiency switching DCDC step down to 6V followed by a low noise linear regulator to supply the electronic components. This cascading approach allows maximum input voltage flexibility (5 volts -> 36 volts) whilst retaining high efficiency (≈ 90% per stage) and good noise performance in the analogue sections.

To provide a low power consumption mode, the regulators and most onboard devices can be shut down by the processor. The processor then enters sleep mode, reducing its own power consumption considerably. There is a further mode where supply is taken from a supplementary battery. This allows all regulation to be switched off, removing the energy losses from this process. The results of these efforts are described in section 7.4.2.

7.3.3 Analogue measurement

Analogue measurement with the SGDL v1.1 was very successful, giving low noise data (≈15 bits) very reliably. It was decided to stay with the same analogue to digital converter family but to use a different version (ADS8345EB) that accepts a 2.5-volt reference rather than 5 volt, which simplified the supply requirements as well as allowing a more advanced reference (LT1790A) to be used. The analogue to digital system's performance is characterised in section 7.4.1.

7.3.4 Serial interfaces

To increase the flexibility of the SGDL additional serial interfaces have been added including I^2C and USB2.0 interfaces. The USB2.0 interface allows rapid download of information stored on the MMC card at around 2.0 Mbps compared to 0.2 Mbps when using RS232. This will be important in applications where the card cannot be retrieved (perhaps from inside a pressure housing). The I^2C interface is used for communication between stacked boards due to its flexible addressing technique.

7.3.5 Driving high power devices

A typical chemical sensor would include several valves and pumps to control fluid flow and occasionally a DC or stepper motor. Optimal control of all these devices is achieved by controlling the current flowing in their windings. In the case of the motors, a sense resistor is used to detect peak current and this is controlled by pulse width modulating the output signal. To reduce the standing current of the valves and pumps they are actuated using their full rated voltage for only a very short period (≈20 ms). This can then be reduced to half the rated voltage to hold position.

7.3.6 High pressure survivability

A common failure of electronic devices under pressure is the electrolytic capacitors crushing, so where possible, these were replaced with ceramic or tantalum capacitors. A footprint for a cylindrical crystal was included along with the surface mount, as these are reported to survive better.

7.4 Results

7.4.1 Analogue performance

The majority of chemical sensors have an analogue output so making the best possible measurement of this signal is crucial to getting good performance from the system. The output signals are typically not very dynamic but require a very precise DC measurement. Using a Successive-Approximation-Register (SAR) type converter allows the most flexibility in conversion rate and is simple to multiplex so eight channels are available on a single device.

Figure 7.4 shows a histogram of 50,000 samples of the voltage reference taken at 4.6 kHz. Each bin represents a step of 7.6×10^{-7} volts so the signal peak is 0.2 mV away from ideal. This offset could be due to a number of factors in the design but is small enough that the error is likely to be dominated by any filtering stage ahead of it. The combined system error could be removed by calibration. The maximum device performance quoted by the data sheet is for 96.3% codes occurring within one bin of the peak signal. The noise performance of the board is measured as 97.7% of codes. This improvement is probably due to the use of a very high-performance voltage reference both for referencing the converter and supplying the voltage to be measured.

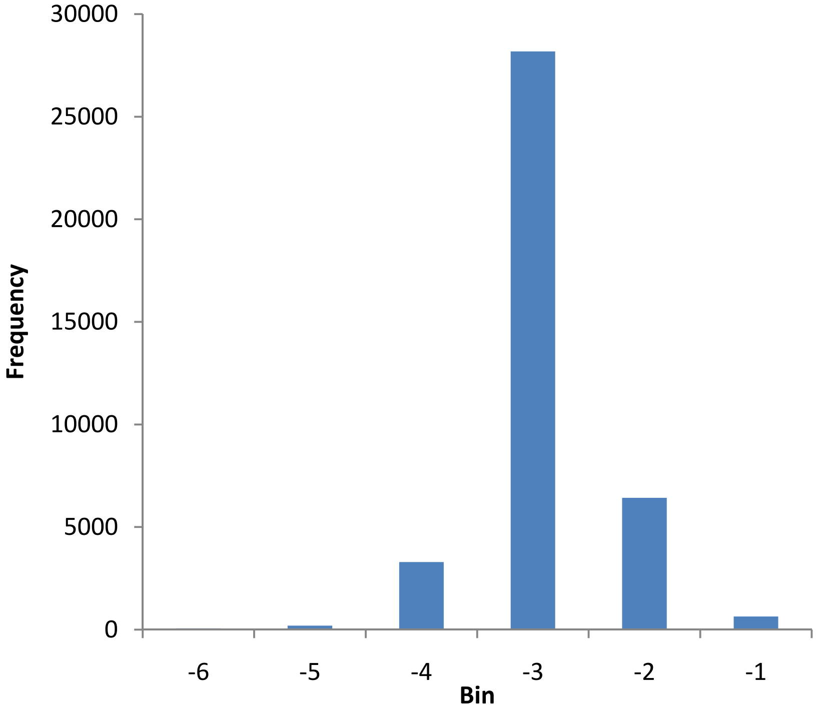


Figure 7.4 - Voltage reference measurement at 4.6 kHz

A disadvantage of a multiplexed SAR converter is cross talk between channels. The voltage reference was measured again along with a ground connection on the second channel. This was performed at a lower sample rate of 1.7 kHz due to communication limitations. The results of this experiment are shown in Figure 7.5 and the offset in the converter has increased by 0.15 mV towards ground. The noise performance is still very good at 92.9% of codes within one code of the peak. This change in performance could be reduced by ensuring that the analogue input is driven by a low impedance source and by increasing the acquisition time available to the converter.

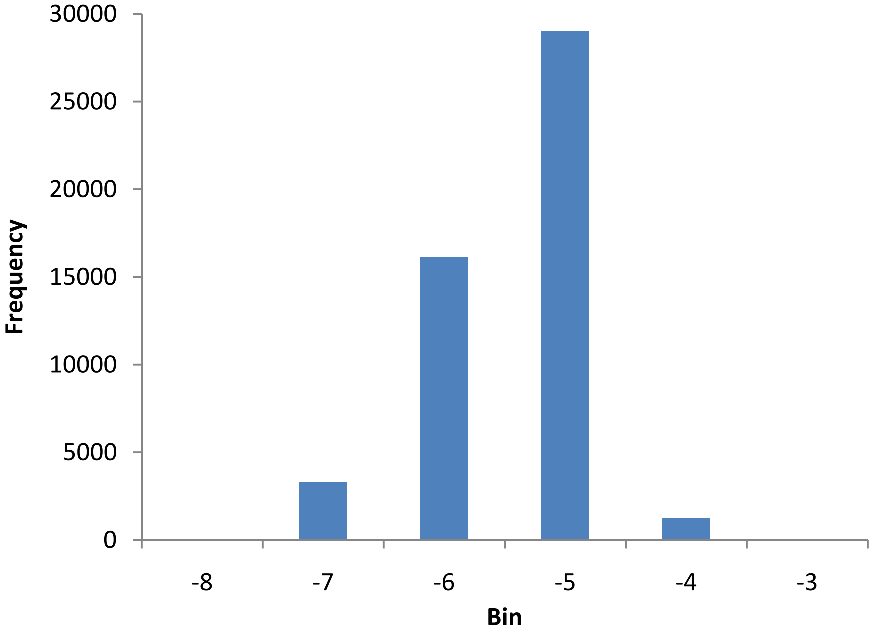


Figure 7.5 - Voltage reference measurement at 1.7 kHz

7.4.2 Power consumption

In low power sleep mode the SGDL version 1.2 is currently drawing 42 mA (290 mW). This is low enough for operation as a UAV data logger however not enough for the chemical sensing application. The previous data logger could be reduced to less than 0.5 mW.

7.4.3 High pressure survival

At the time of writing, it has not been possible to pressure test the new SGDL however, it has been successfully operated in oil.

7.5 Conclusions

The SGDL version 1.2 has the capability to control complex systems over long periods and record large quantities of high-resolution data. Its use in the UAV project can now continue with an undergraduate project to source, purchase and install suitable sensors in the fuselage. These will then be integrated with the SGDL to provide control, reporting and possibly data recording. The system that is developed will then be evaluated by the doctorate students on the project and some or all of it incorporated into the final design.

To improve the power consumption of the new data logger a new board will be manufactured with some modifications to the USB interface.

Chapter 8

Conclusions and Future work

8.1 Introduction

In the first two years of this project, a great deal of progress has been made. The vehicle has been almost entirely redesigned and aerodynamic performance has been improved leading to greater range and endurance. The vehicle meets the criteria set out in section 2.2 and now needs to be further developed for use at sea. Future work will focus on improving the robustness of the vehicle.

8.2 Conclusions

After four test flights, the mark 2 vehicle design has still spent only a short amount of time in the air. The final flight included the recording of flight parameters and allowed analysis of its performance (section 6.2). The data indicates that even though human pilots have struggled, the vehicle would fly with the current propulsion system. However, as many initial flights will be performed in some part by a human pilot, it is necessary to ensure that they can fly it easily and safely. As such, a more powerful engine will be sourced for testing. In the short flights, the vehicle appeared well balanced and has good control authority on all surfaces.

The Flight Control System (FCS) performed well on its first test flight and recorded detailed data for the entire flight. It also survived the impact of the crash without any damage. This system is now ready for further software development and the addition of the control algorithms as part of the doctorate project by Bennett. The novel use of over-sampled, low-cost sensors has paid off by providing data of a resolution not available with commercial autopilots.

8.3 Vehicle

The development of the vehicle for use at sea will mostly be focussed around launch and recovery. A launcher based on an existing system used by ATS [57], one of the companies involved as part of a commercial steering group for the project (see section 8.6). Recovery preparation will focus on ensuring the payload bay is waterproof and designing a system to make grappling for the vehicle simple.

Undergraduate students will design a new tail for the vehicle that can then be evaluated by the doctorate and supervisor team. More information on this project can be found in the project specification in Appendix 4.

The method for characterising and assessing the performance of the propulsion system has been very successful; however, it now appears that criteria used for the design were not correct. An attempt will be made to analyse the requirements particularly regarding performance in poor weather conditions. This should lead to a more detailed specification that can then be compared with commercial engines and discussed with RCV [51] (see section 8.6).

Manufacturing improvements will continue with the development of new tail moulds and once the design has more flight time, moving the wing manufacture to a sandwich construction with a support spar.

8.4 Flight Control System

Development of the existing flight control hardware will continue to ensure that all the functionality is working as expected and the hardware is robust to vibration, water and impact. It is possible that the system could fit inside a smaller enclosure and this possibility will be investigated if time allows.

The critical aspects in FCS development are the addition of robust control algorithms for the full size aircraft. These will be derived from the work by Bennett on the algorithm development project. Demonstrating the reliability of the software will be essential. This will be done using MISRA for low-level code and SCADE for the algorithmic code as described in section 5.2. Robustness for control surfaces is described in section 8.5.

The new FCS can record detailed flight data and this can be fed back into the simulation for use in system identification and improvement of control algorithms. This work will be in collaboration with Bennett. Additional algorithmic development will continue as part of this project to include the monitoring of actuators and increasing robustness.

8.5 Robustness and redundancy in surfaces

In section 2.5, the most common area of failure in all UAVs is the control surfaces. As these are so critical, there will be a special focus on making them as robust as possible. Following the approach determined in Chapter 3, low-cost actuators will be used but monitored very carefully to predict failure. Initially this work will involve the testing of hobby actuators. Figure 8.1 shows the expected paths of failure of the servos and the predicted method of detection.

It may be possible to apply Failure Mode, Effects and Criticality Analysis (FMECA) to evaluate the actuator performance and software tools to aide with this will be investigated.

In addition to the work on the existing actuators, a new type of actuator using a linear stepper motor has been designed. It is not clear if this will be appropriate for all the surfaces on the aircraft due to slow operation. However, it should be; more robust, use less power, be self-monitoring, report performance data and cost less than £100.

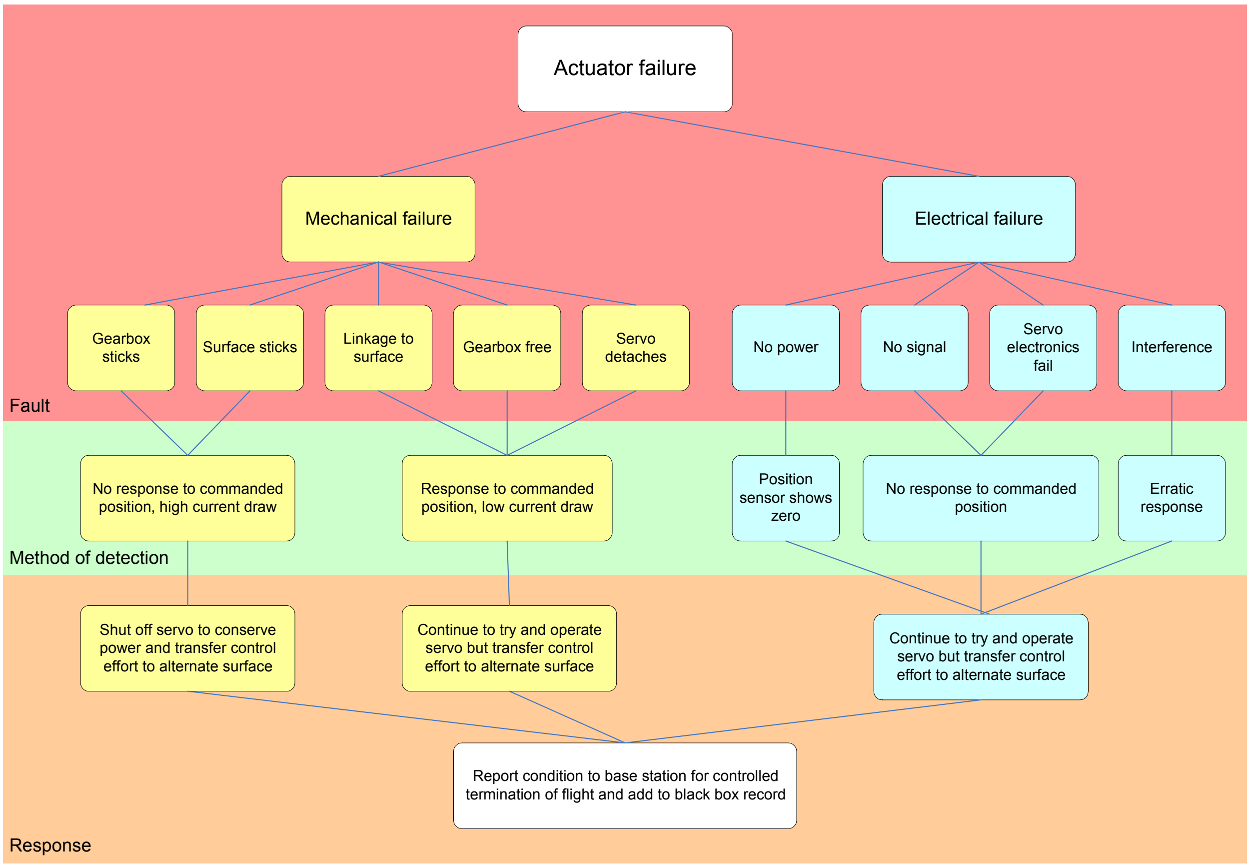


Figure 8.1 - Actuator failure diagram

8.6 Planning

The work planned for the next two years of the project will be funded by a proposal currently under submission to EPSRC. This includes money for launcher development and time onboard the University research ship Callista to perform testing at sea. If successful, the funding should be available from the start of 2008.

As part of the proposal, a steering group of commercial companies has been assembled to assist with identifying and pursuing any commercial technologies that may be developed. The group members are listed in Figure 8.2. The group will meet twice annually to discuss progress and help establish new goals.

Company	**Expertise**
QinetiQ	Developing and operating military UAVs
Vosper-Thorneycroft	Interested in using UAVs in civilian applications

ATS Group	Experts in UAV operation and piloting
RCV Engines	Developers of rotating sleeve engines for UAVs

Figure 8.2 - Steering group members

In addition to the existing proposal, it is hoped that a bid for funding may be made in collaboration with RCV engines to develop their technology to make it more suitable for small fixed-wing applications.

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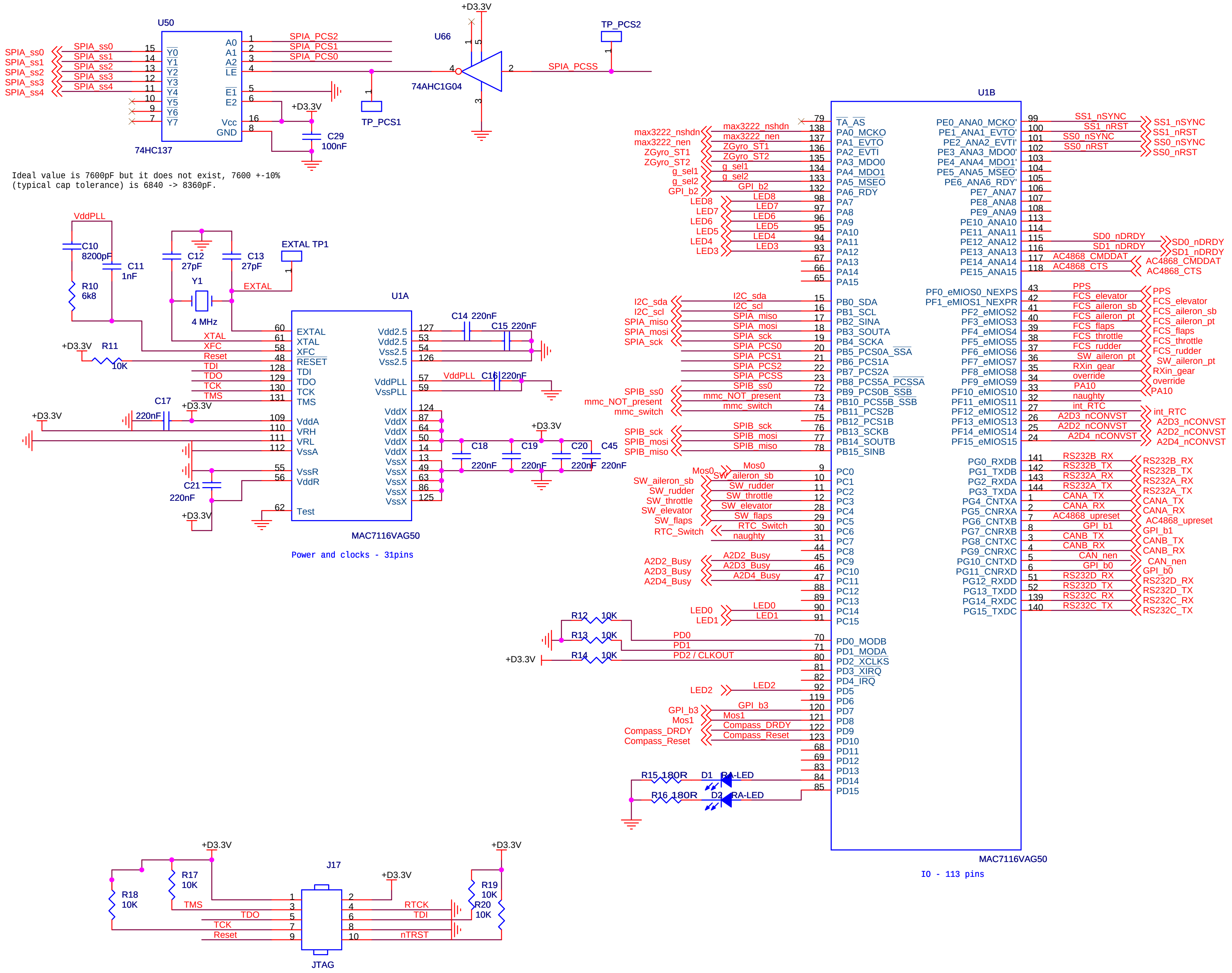
Appendix 1

Flight Control System schematic



Ideal value is 7600pF but it does not exist, 7600 +-10%
(typical cap tolerance) is 6840 -> 8360pF.

Power and clocks - 31pins

IO - 113 pins

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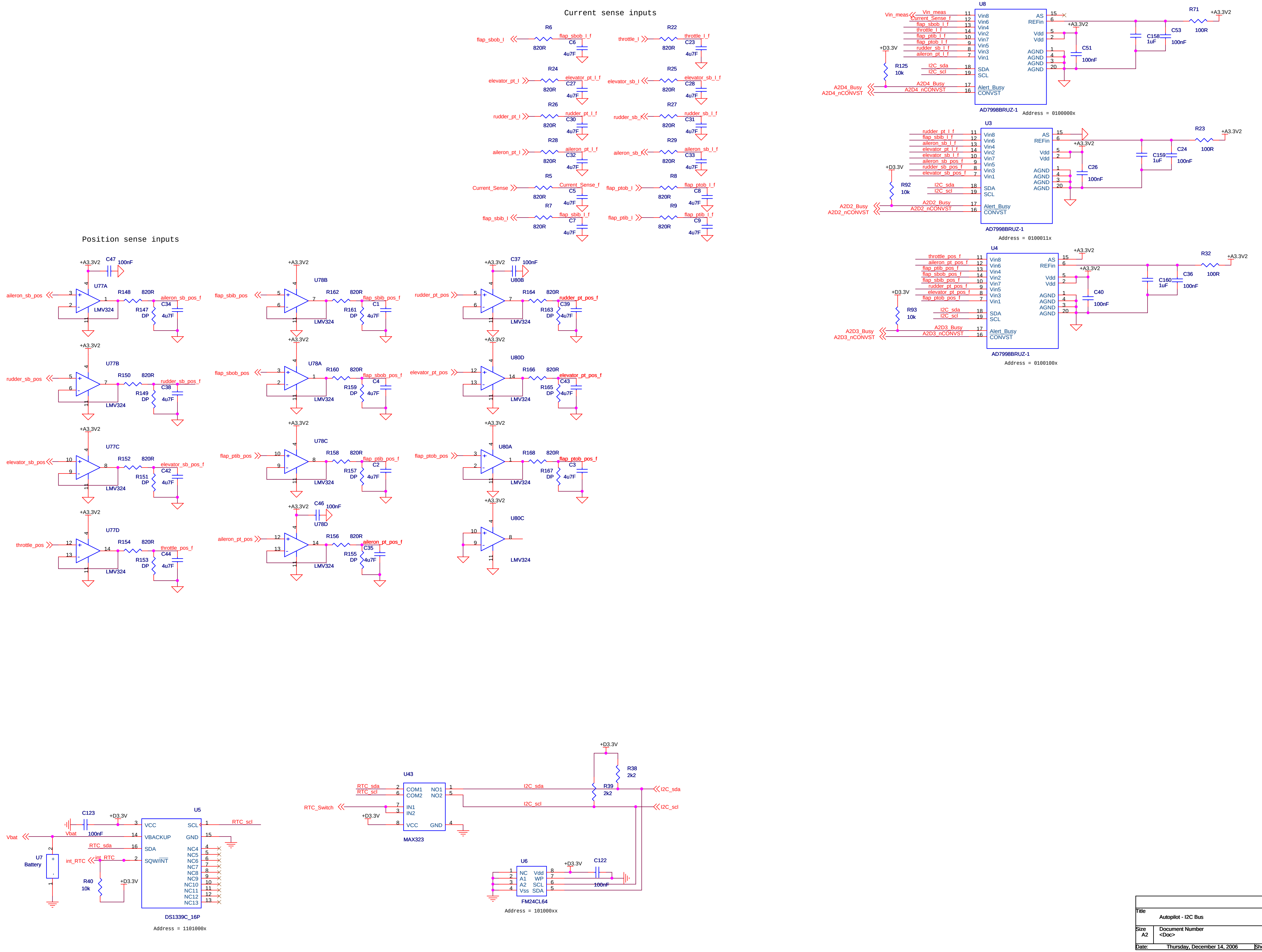

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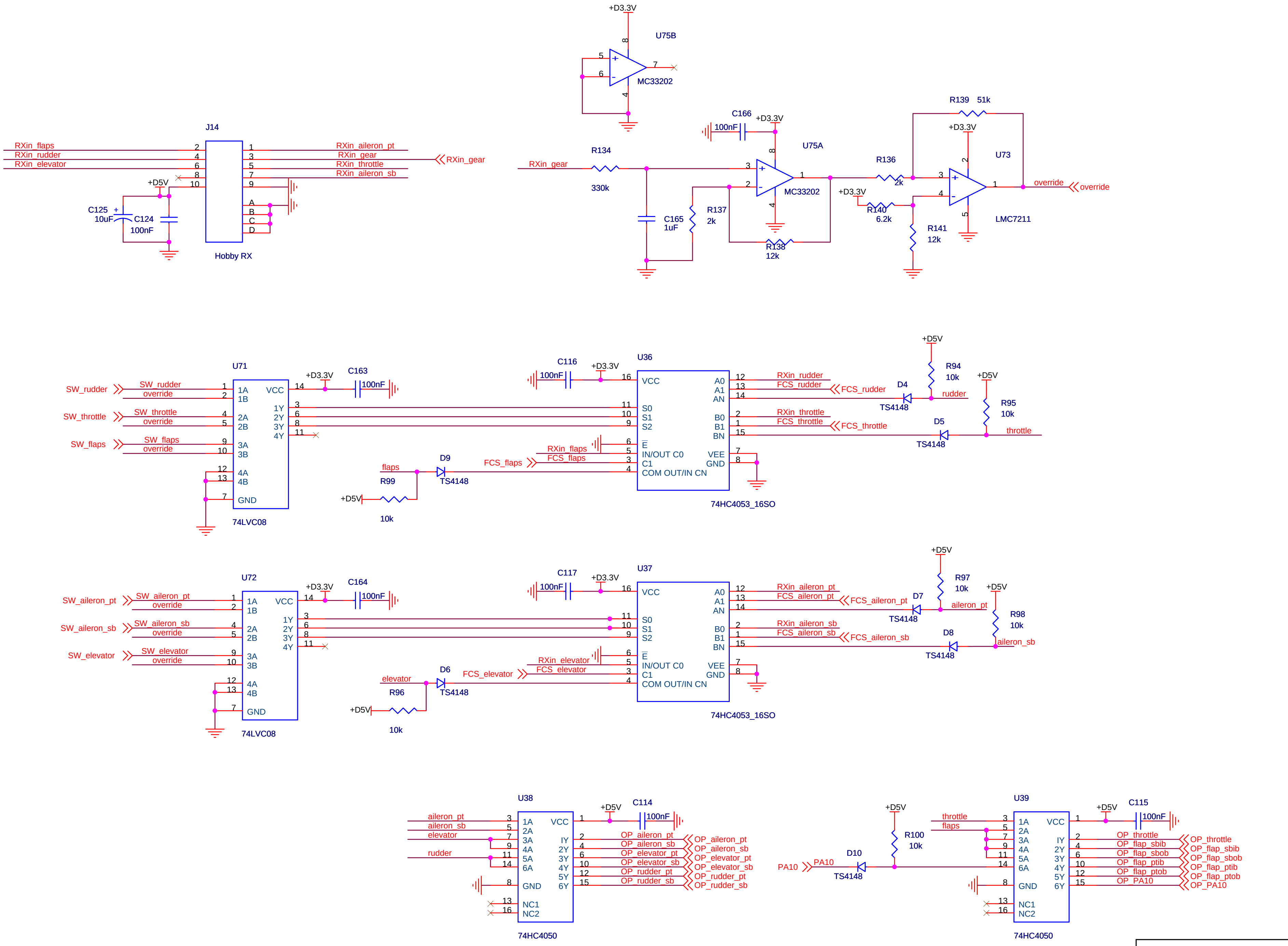

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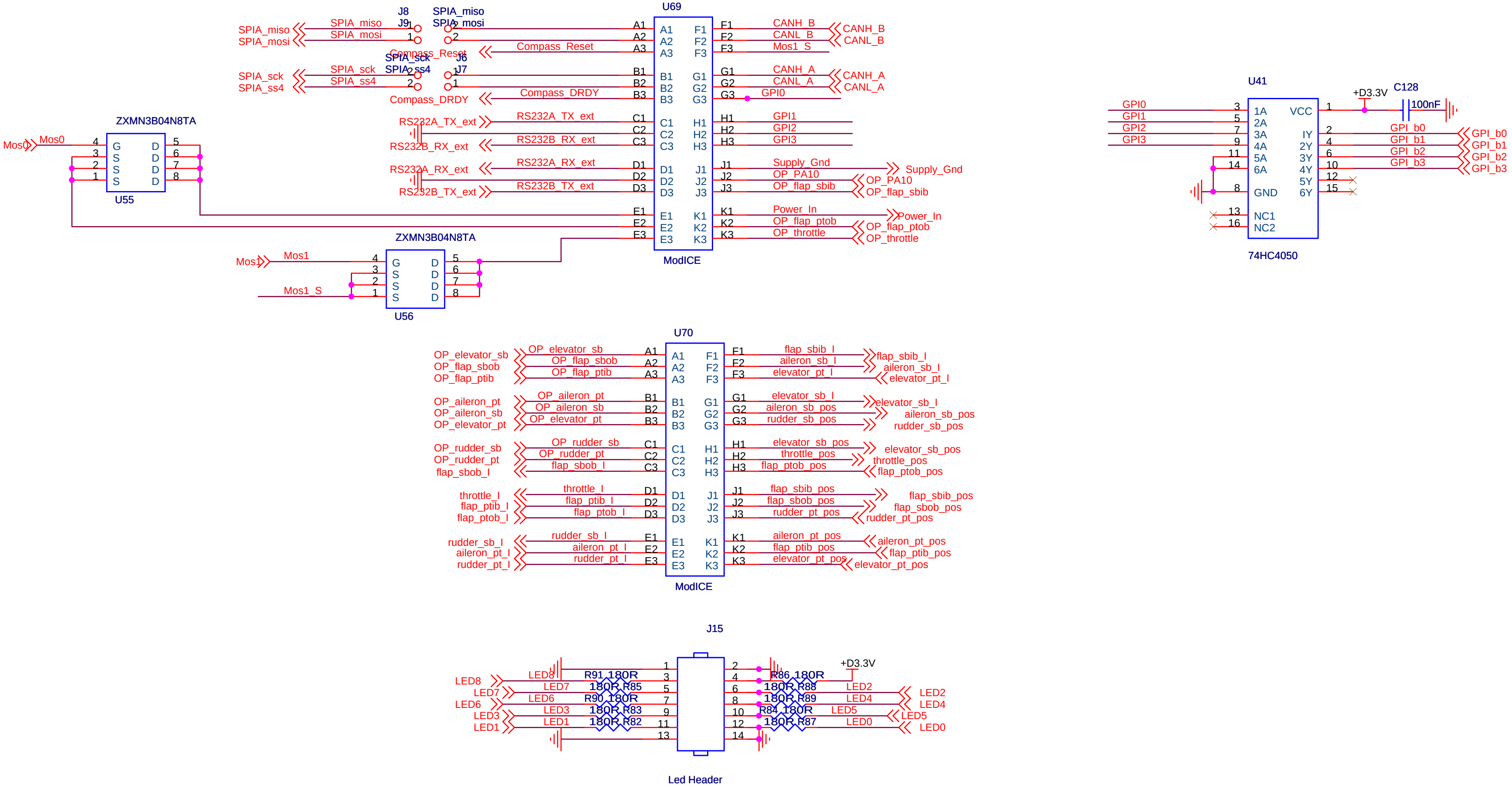

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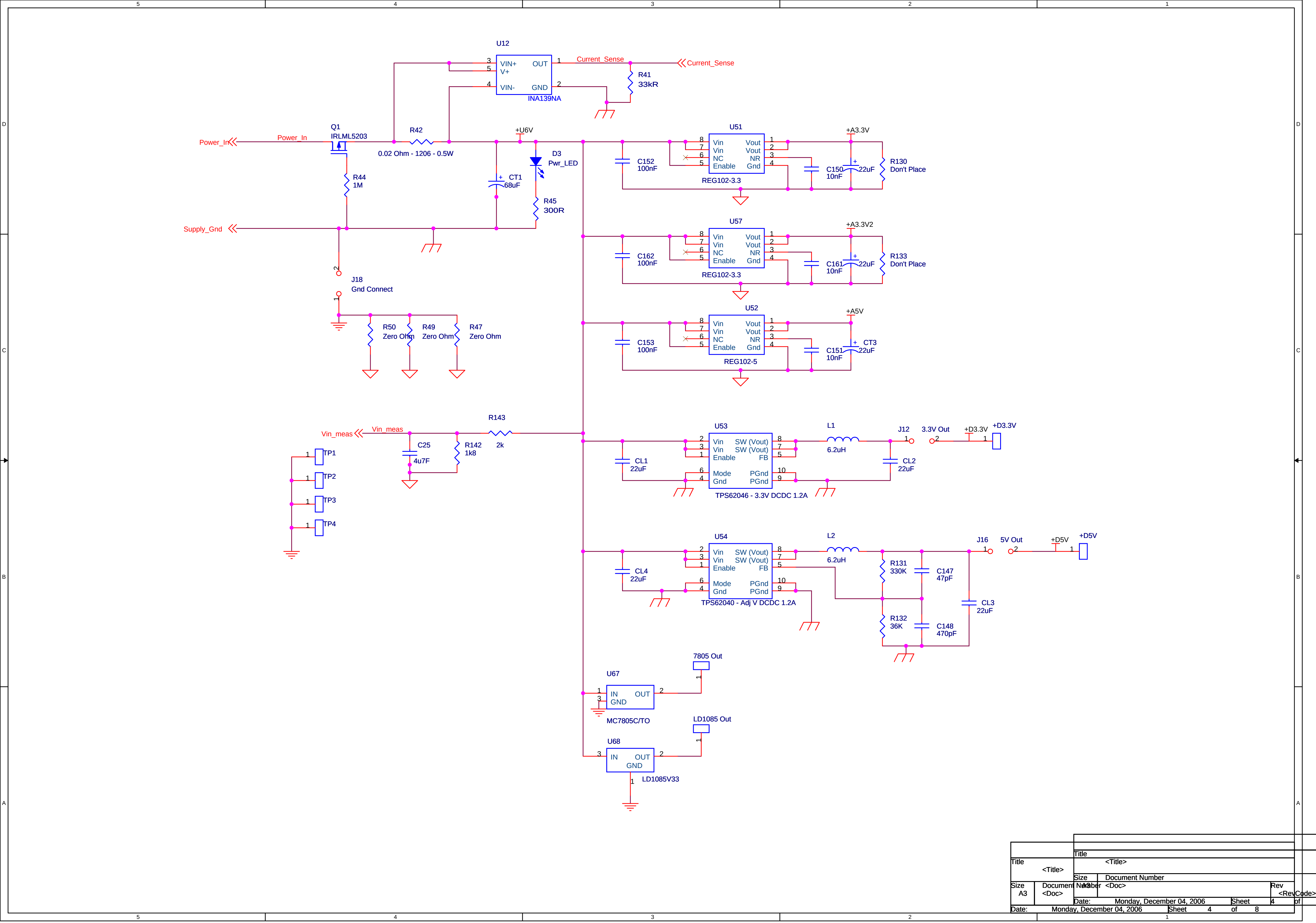
U12
VIN+
V+
VIN-
OUT
GND
INA139NA
Current_Sense
Current_Sense
R41
33kR
Power_In
Power_In
Q1
IRLML5203
R42
0.02 Ohm - 1206 - 0.5W
+U6V
D3
Pwr_LED
R44
1M
CT1
68uF
R45
300R
Supply_Gnd
J18
Gnd Connect
R50
Zero Ohm
R49
Zero Ohm
R47
Zero Ohm
U51
Vin
Vin
NC
Enable
Vout
Vout
NR
Gnd
REG102-3.3
C152
100nF
+A3.3V
C150
10nF
22uF
R130
Don't Place
U57
REG102-3.3
C162
100nF
+A3.3V2
C161
10nF
22uF
R133
Don't Place
U52
REG102-5
C153
100nF
+A5V
C151
10nF
CT3
22uF
R143
2k
Vin_meas
Vin_meas
C25
4u7F
R142
1k8
TP1
TP2
TP3
TP4
U53
Vin
Vin
Enable
Mode
Gnd
SW (Vout)
SW (Vout)
FB
PGnd
PGnd
TPS62046 - 3.3V DCDC 1.2A
CL1
22uF
L1
6.2uH
CL2
22uF
J12
3.3V Out
+D3.3V
+D3.3V
U54
TPS62040 - Adj V DCDC 1.2A
CL4
22uF
L2
6.2uH
R131
330K
R132
36K
C147
47pF
C148
470pF
CL3
22uF
J16
5V Out
+D5V
+D5V
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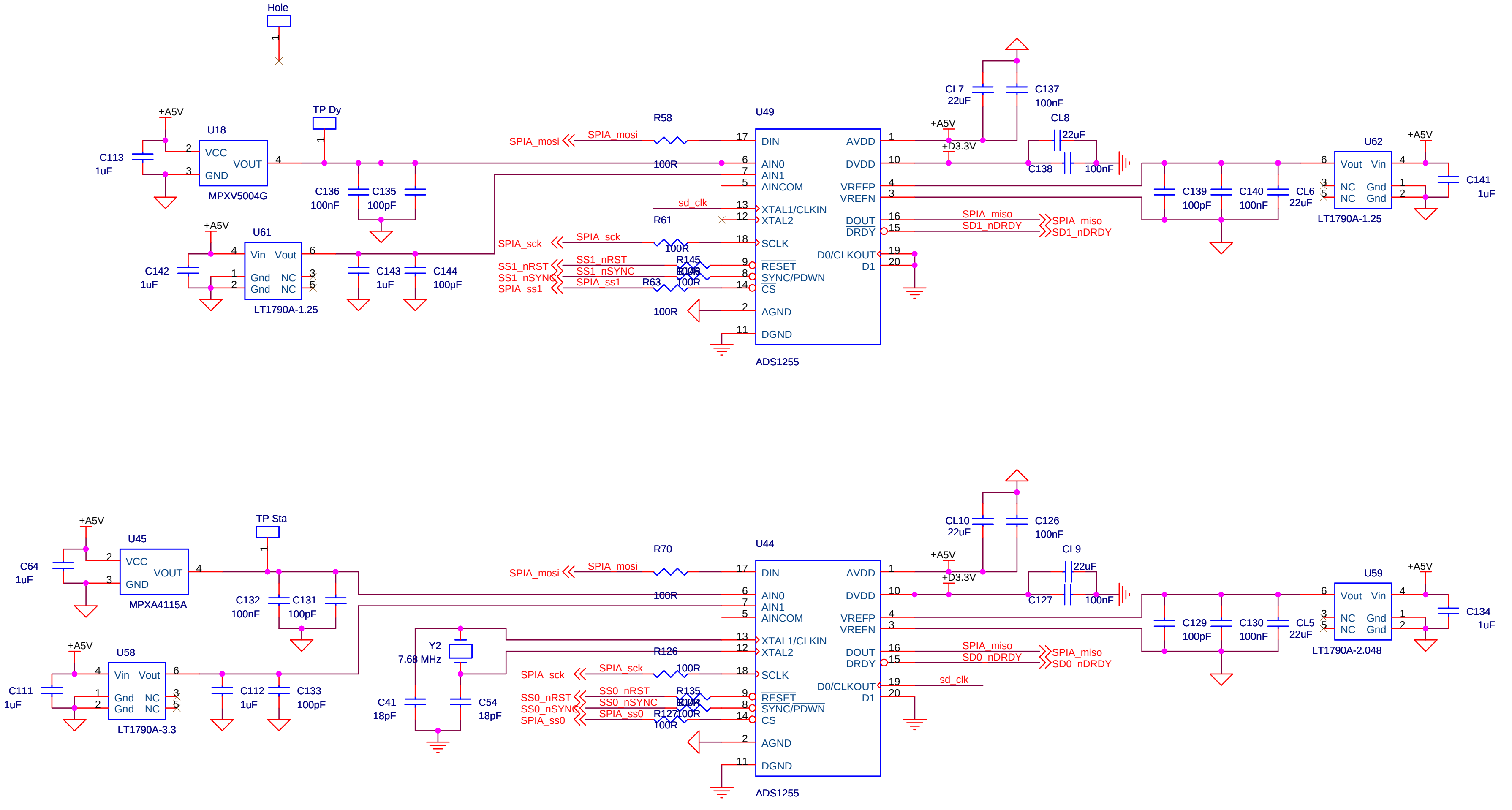

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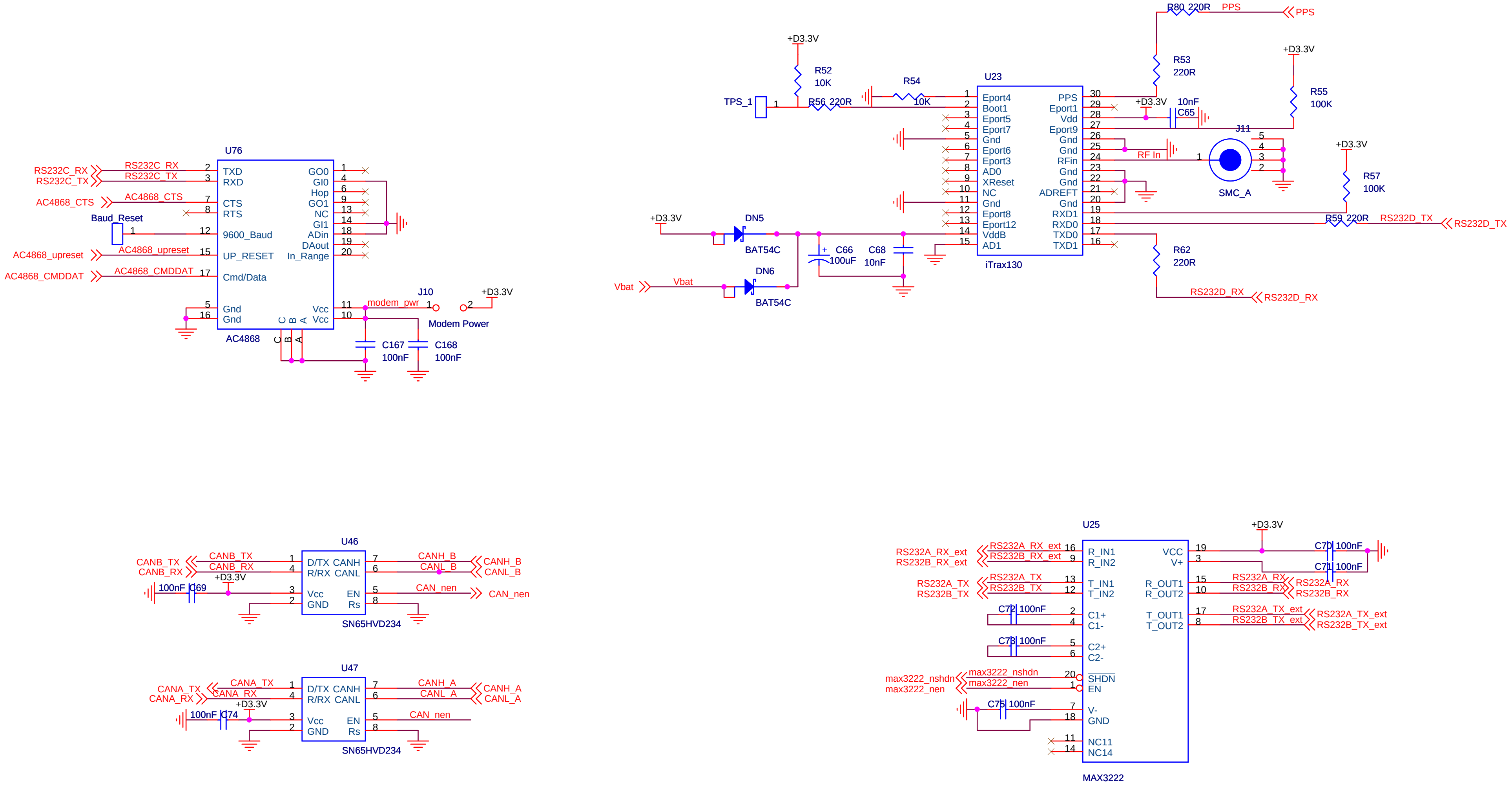

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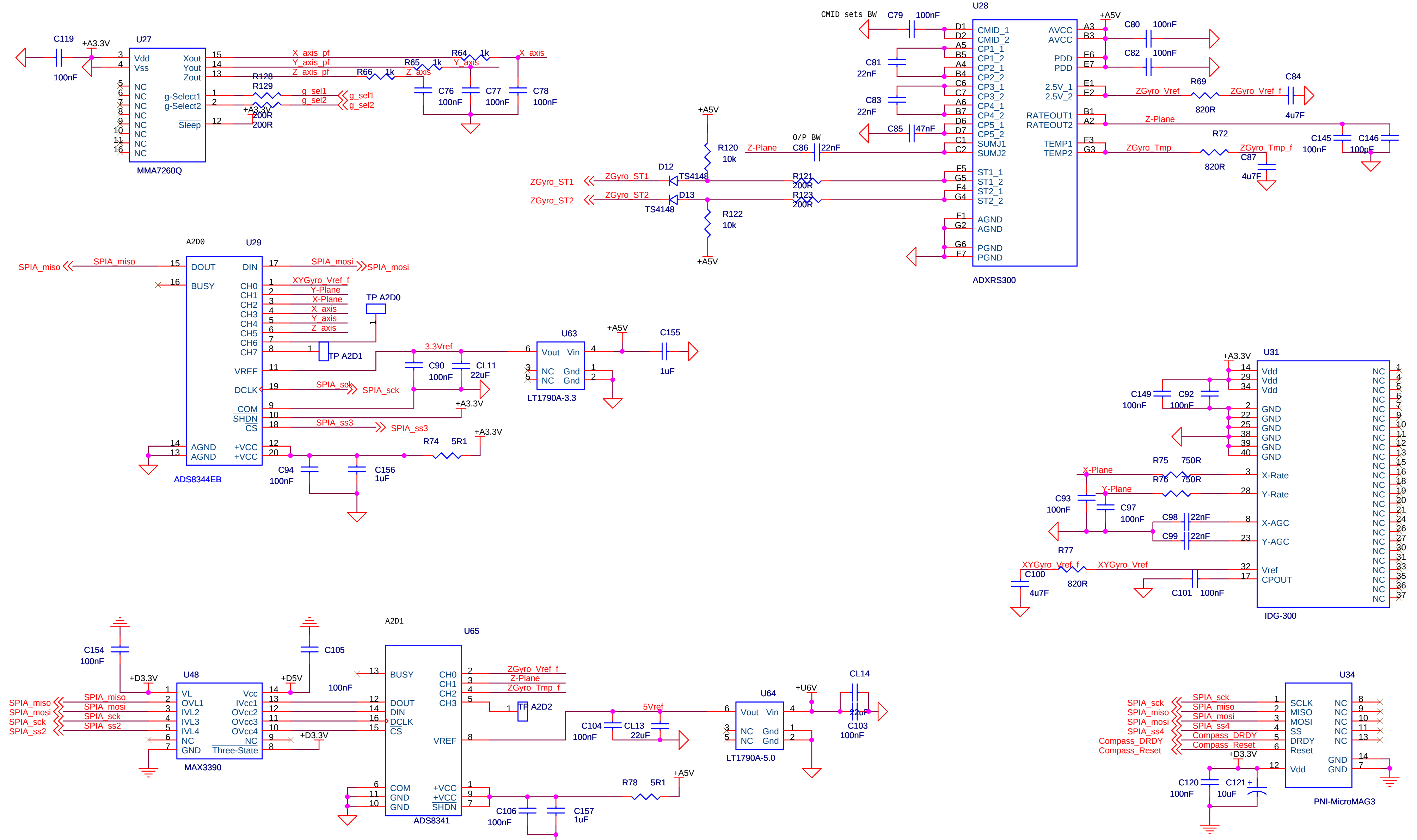

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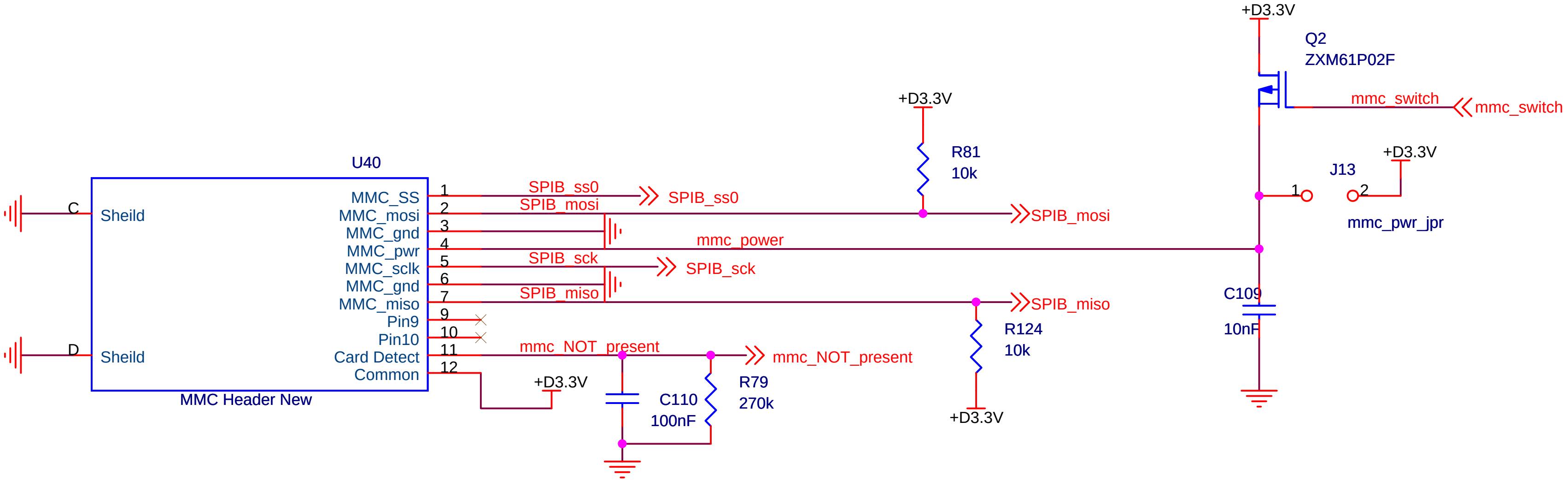

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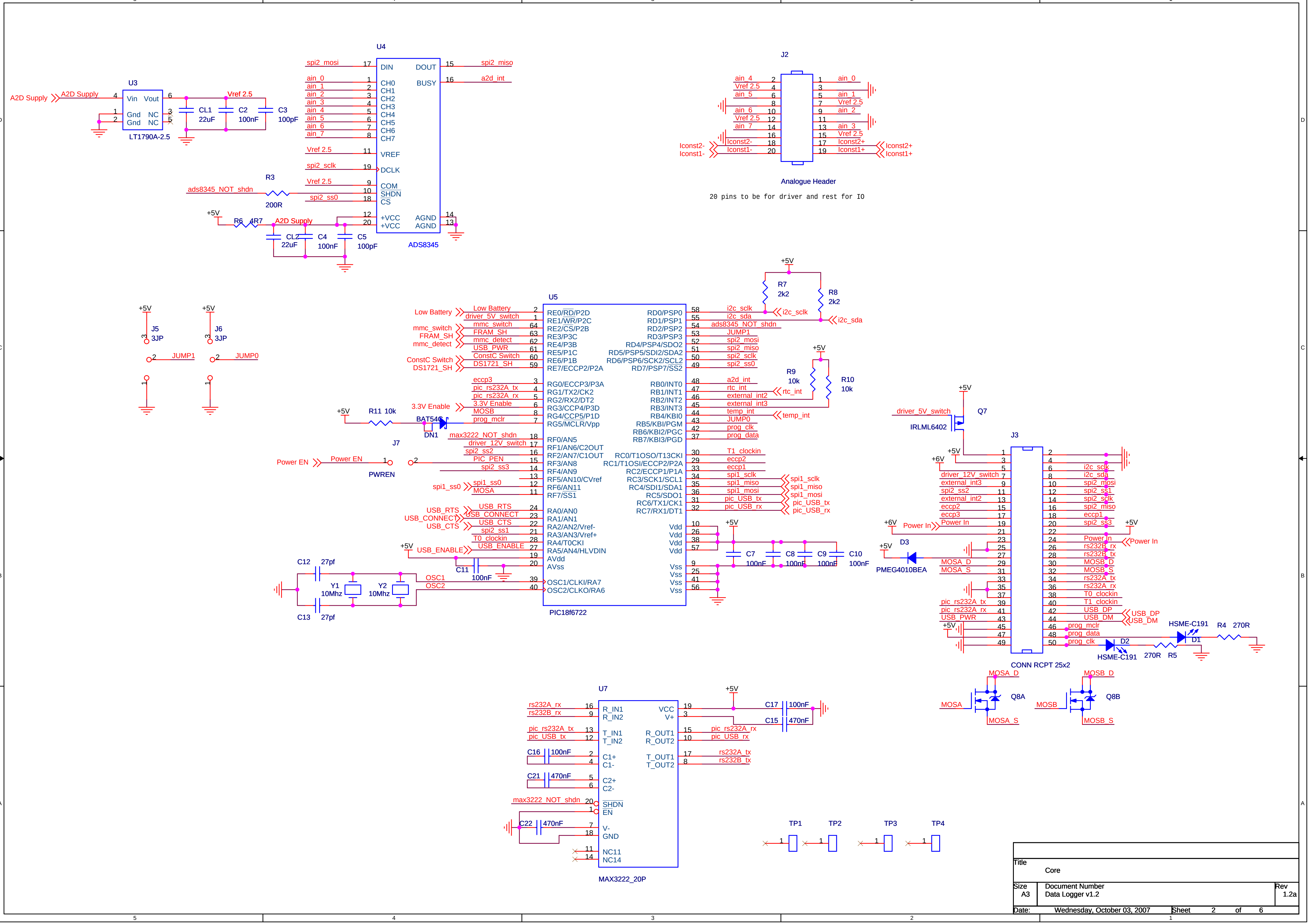
Appendix 2

Payload Management System schematic

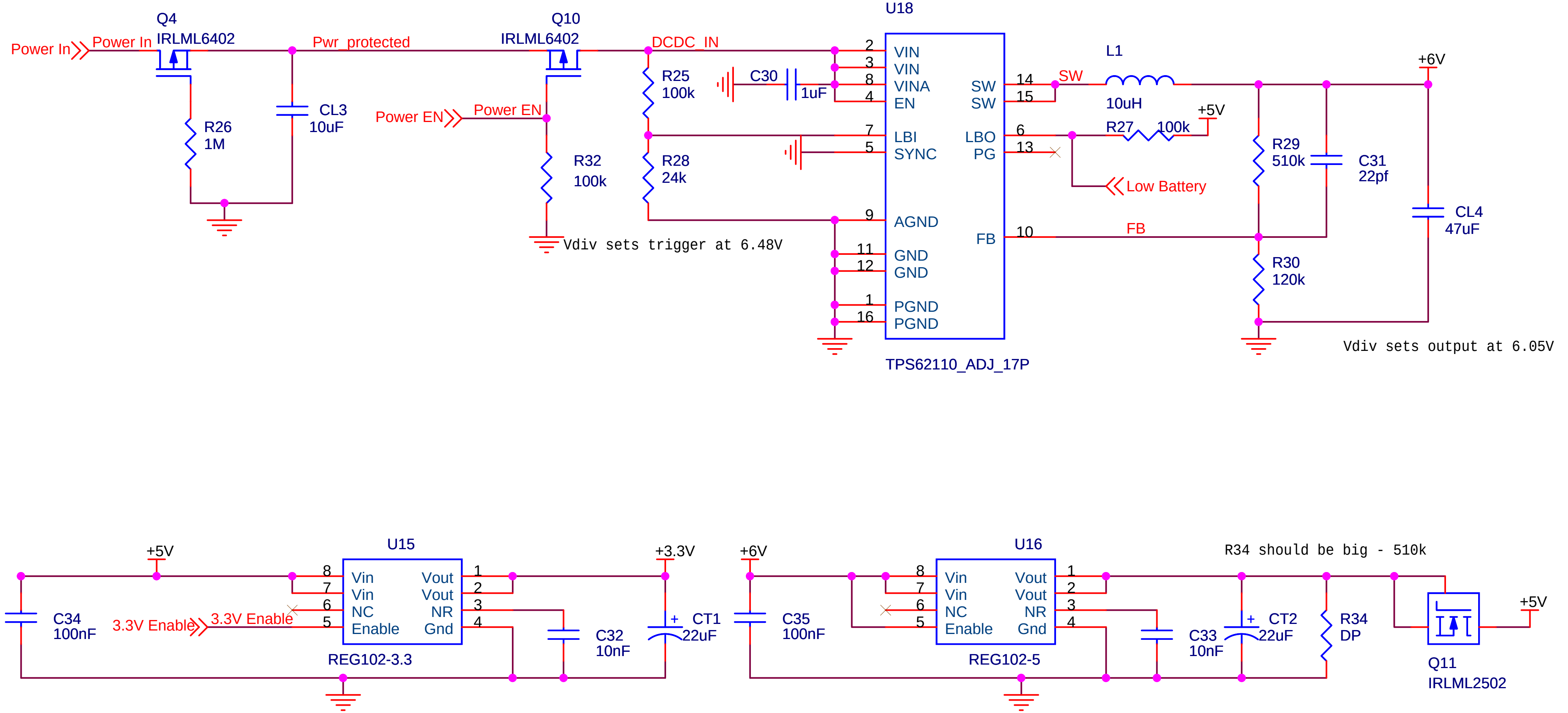


Title
Core

Size A3
Document Number
Data Logger v1.2

Rev
1.2a

Date: Wednesday, October 03, 2007
Sheet 2 of 6



Vdiv sets trigger at 6.48V

Vdiv sets output at 6.05V

R34 should be big - 510k

Mosfet to stop current return

By powering the 3.3V regulator from the 5V line the board can accept a 5V supply without modification.

- 5V and 6V regulators are automatically disabled
- There is no reverse polarity protection in this case
- There is little loss of efficiency

Tants are used on linear regs as Cout as the ESR helps with stability at low currents.

Title	Power Supply		
Size A	Document Number Data Logger		Rev 1.2a
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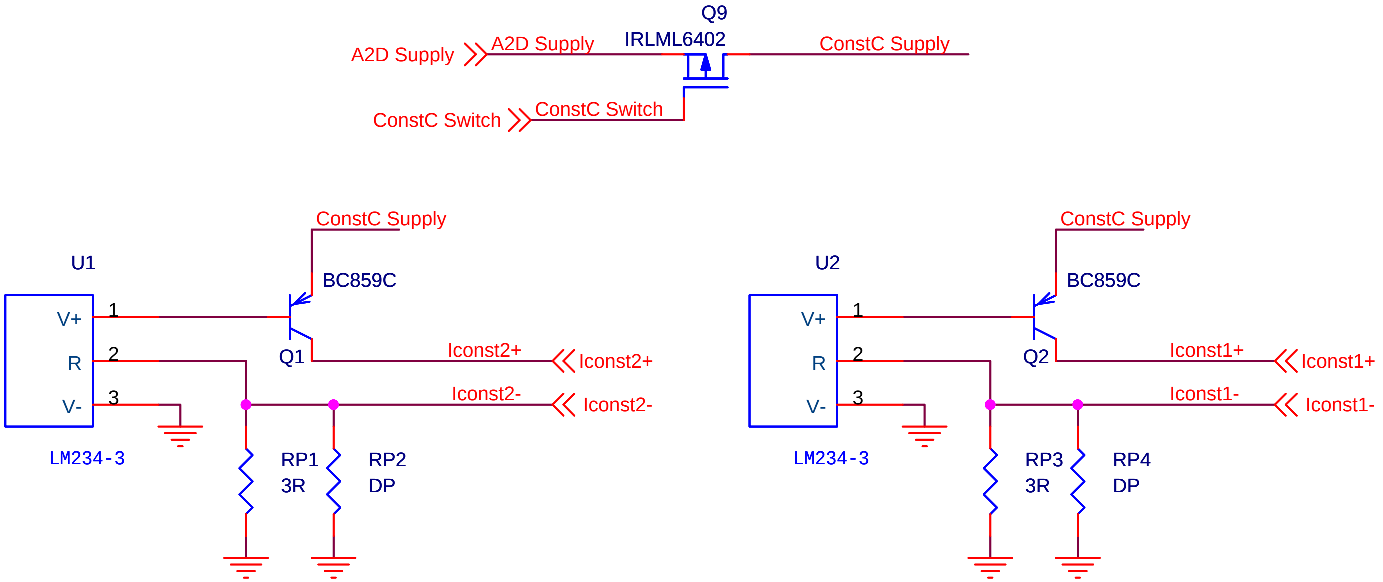


Current = 0.065 * (1/Rp1 + 1/Rp2)

Current = 0.065/Rp

As long as the equation for the current in the LED contains a resistive term it will have temperature dependence.

Title
LED Constant current circuit

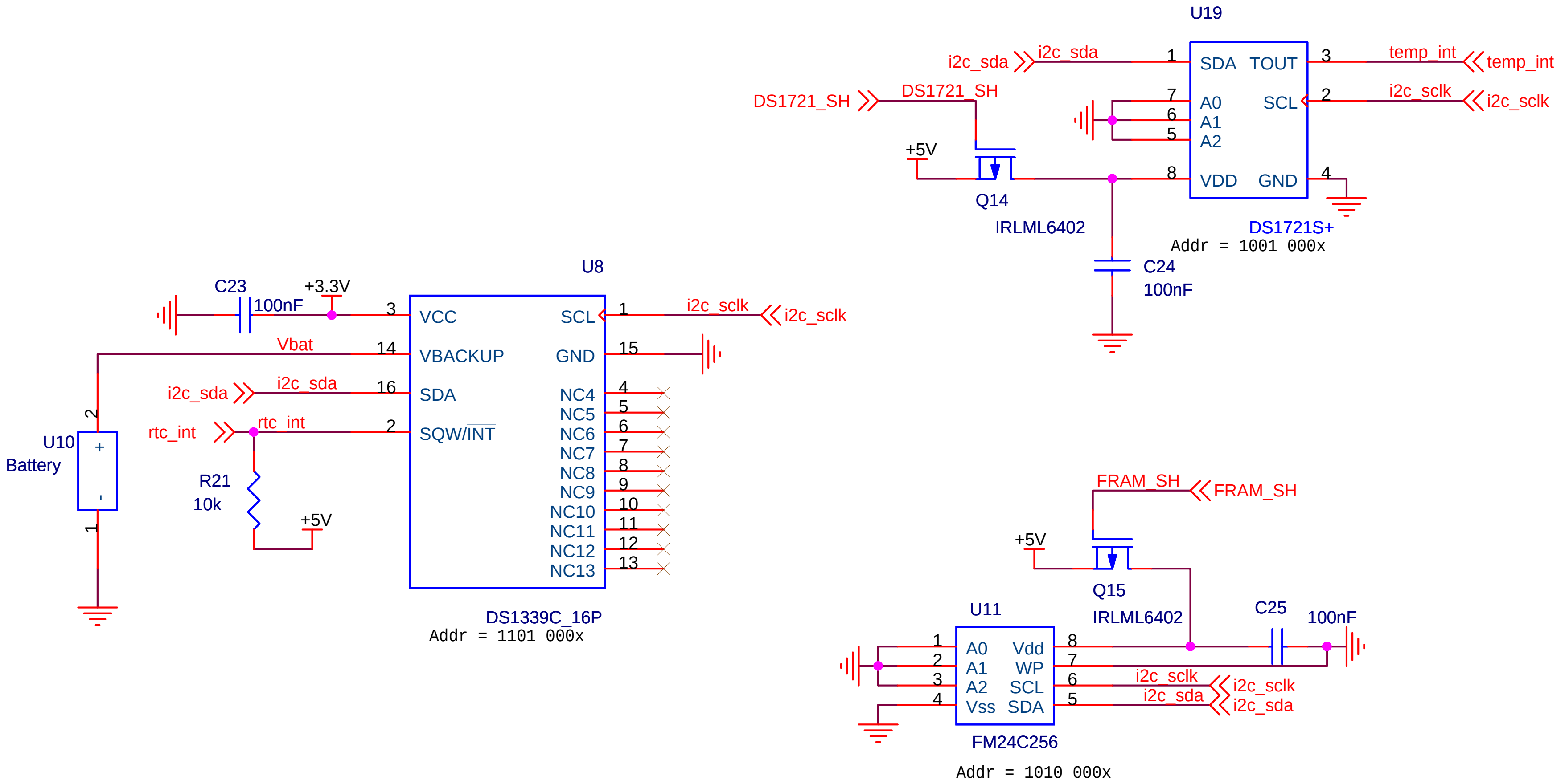
Size
A

Document Number
Data Logger v1.2

Rev
1.2a

Date: Monday, October 01, 2007

Sheet 1 of 6

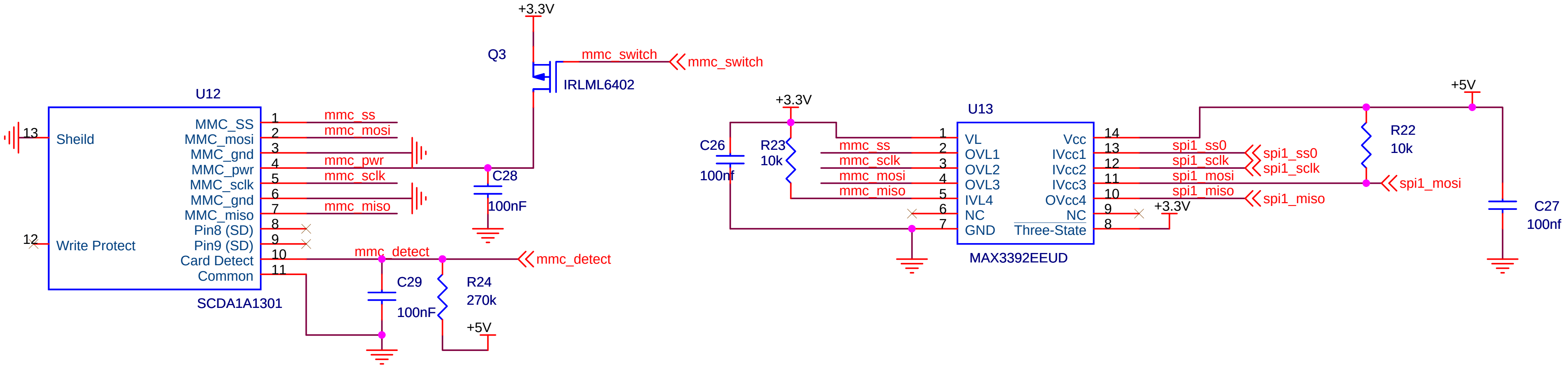


For the FM24C512 the A0 bit is used the address MSB.
This means it is worth also leaving the alternate address
unused: Addr = 1010 001x.

Title
I2C Bus

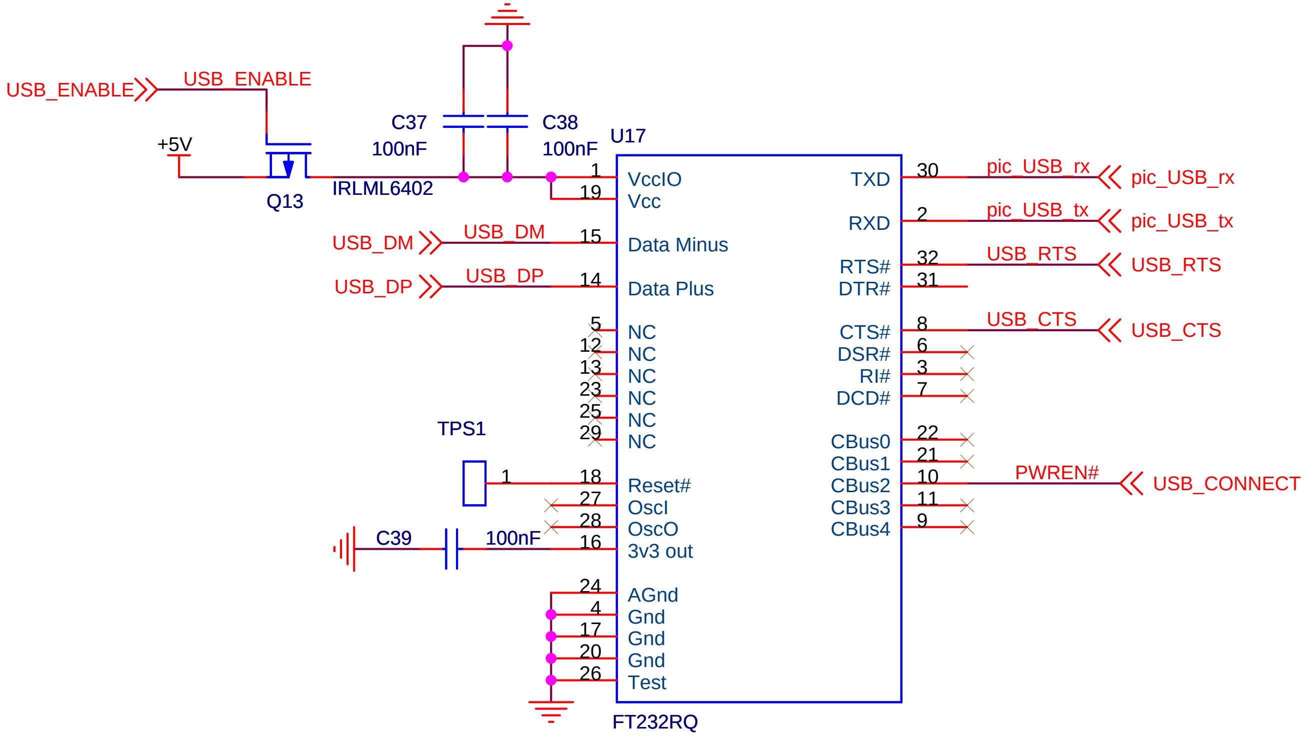
Size A
Document Number
Data Logger v1.2
Rev 1.2a

Date: Monday, October 01, 2007
Sheet 3 of 6



New MMC socket with standoff
 - Common not connected to case
 - Detect goes low on card present
 - Case connected to ground
 - Write prtoect ignored
 - Pins 8&9 are for SD mode

Title MMC Interface		
Size A4	Document Number Data Logger v1.2	Rev 1.2a
Date: Monday, October 01, 2007	Sheet 4 of 6	



USB power is detected by the PIC and then the FT232RQ
is enabled

Sheild unconnected as
cable will be sheilded
from PC end.

Title	USB2.0 Interface			
Size A	Document Number Data Logger v1.2			Rev 1.2a
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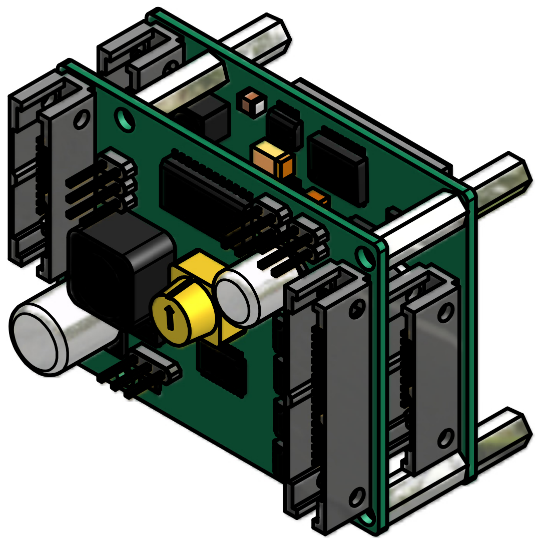
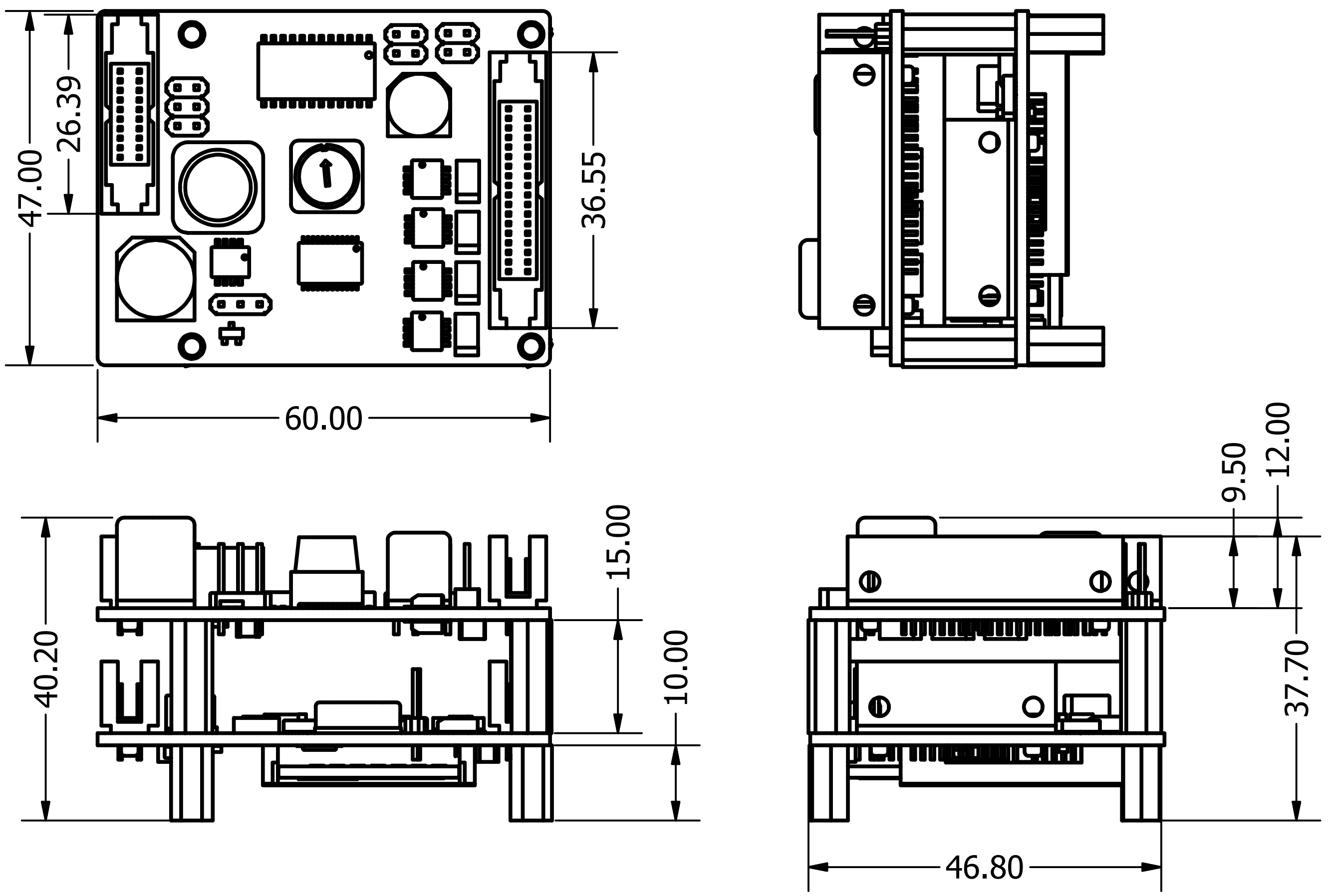
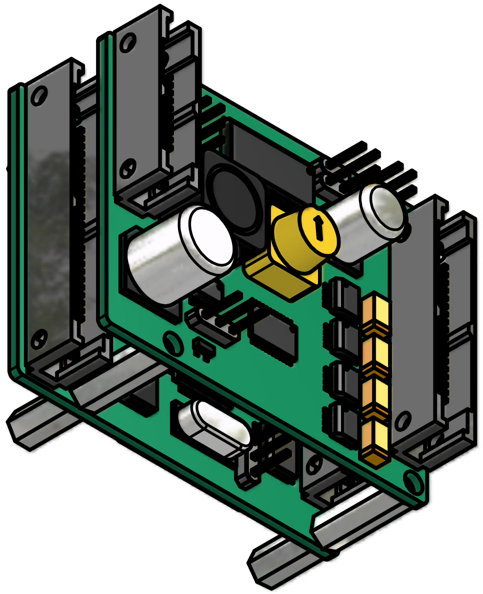
Appendix 3

Payload Management System technical drawing







SCALE 1 : 1

DRAWN
Ed Waugh
01/11/2007
CHECKED
QA
MFG
APPROVED

Sensors Group, NOC, UK

TITLE
Stacked SGDL v1.2

SIZE
A4
DWG NO
SGDL Stacked together assembly
REV
SCALE
SHEET 1 OF 1

Appendix 4

Project specifications for student groups

ECS Group Project Specification

Previous Unmanned Aerial Vehicle (UAV) research and student projects at the National Oceanography Centre (NOC) have focussed on developing and demonstrating a flying vehicle. With these goals now achieved, the next phase of research must develop the payload that the vehicle will carry. Many of the components in the payload will be off the shelf and these must be integrated with data logging to create a complete system that is independent from the rest of the UAV.

Areas of work

- Consultation with oceanographic scientists to determine a useful and achievable payload
- Selection and acquisition of appropriate sensors
- Use of the NOC sensors group data logger to synchronise and record data
- Integration of sensors with data logging and power supply within the 1.5Kg weight limit
- Development of data processing software for windows in C# or Matlab
- Testing of sensor package
- Flight test of sensor package

Possible sensors

- Visible light imaging
- Infra-red and/or ultra-violet measurement or imaging
- Atmospheric sensors
- Ambient light measurement (for calibration of images)

Deliverables

- Project report detailing design process and justification of decisions
- An integrated sensor payload ready for deployment on the UAV
- An instruction manual detailing the setup and operation of the payload
- Details of all equipment used allowing easy replacement or the manufacture of additional payloads

- Easy to use software for processing the returned data and creating files that are useful to the oceanographic scientists and that integrate with packages they currently use

SES GDP Specification 2007

The Unmanned Aerial Vehicle (UAV) project at the National Oceanography Centre (NOC) is now in its fifth year of development. The fundamental design decisions for the vehicle have been taken and the focus is now shifting to refining the aerodynamic performance. This includes improvements to the lift over drag (L/D) as well as characterising and improving the dynamic performance of the aircraft during manoeuvres. The characterisation of the vehicle should also result in a model suitable for use in flight control system modelling.

Areas of work

- Make a redesign of the tail to an inverted V design for improved aerodynamic performance and have this manufactured to fit the existing wind tunnel model
- Enhance the existing wind tunnel model to include adjustable ailerons, elevators and rudders
- Measure the performance of the model in the wind tunnel in a variety of conditions to determine the control authority available and the effectiveness of the redundant systems
- Develop a model of the vehicle with both types of tail in Aerosim and compare this to the model generated by AVL

Deliverables

- Project report detailing design process and the decisions made
- New more efficient tail design
- Half scale model of both designs of tail with adjustable surfaces
- Conclusions about the effectiveness of the current tail, suggestions for improvement and comparison with the new design
- An Aerosim model of the vehicle based on tunnel data that can be compared with one generated by AVL

Appendix 5

Contents of accompanying CD

Name	Description
Transfer Report.pdf	A copy of this report
Flight Test Videos	Video footage of flight tests, requires XVid codec (supplied)
- Flight Test 1	Launch failure due to lack of speed
- Flight Test 2	Launch failure due to release mechanism
- Flight Test 3	Longest flight
- Flight Test 4	Climb too steep (discussed in Chapter 6)