Department of Mechanical Engineering

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ENME 480: Rocket Systems Engineering

Literature Review and Work Performed

by

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1. Introduction

The purpose of this document is firstly to record the findings of a literature review performed on the following areas in rocketry or related topics:

- Rocket characteristics influencing sensor selection (such as roll rates).
- Rocket Inertial Measurement Units (IMU) requirements.
- IMU design – sensor requirements and selection, noise removal.
- Other sensor systems used in a controlled rocket.

Following the literature review will be an outline of the work I performed.

2. Research

A lot of electronic systems are utilised in the guidance of rockets. A key component of any such guidance system is its inertial measurement unit (IMU). This component is responsible for determining the spatial location and orientation of the rocket throughout its flight. Data derived from the IMU is also responsible for the control algorithms used to keep the rocket on its desired trajectory, also in real-time. This research concentrates on the inertial measurement systems used in a guided rocket. It also aims to investigate the key components and implementation of an IMU, and also other supporting avionics used in a guided rocket.

2.1. Rocket rotation

To increase the accuracy of unguided missiles, the airframe is designed in such a way to induce rotations throughout its flight [1]. Rotating the missile improves flight performance as it balances out eccentric imbalances in rocket, such as uneven placement of internal components and imperfections in its aerodynamic body. It also balances out miss-aligned thrust from the rocket's propulsion system. Control systems in guided missiles also have the ability to control the roll rate throughout their flight [2]. Roll rate is also often changed in flight depending on conditions such as the rocket's current speed and angle of attack.

Rolling the rocket to achieve better stability can come at a price. Intuitively high speed rolling has detrimental effects, where the rolling of a rocket increases aerodynamic drag [3]. Another issue with rolling the rocket about its principle axis, particularly while transitioning from one rate to another is that of inertial roll coupling [4]. If the difference in angle between the geometry axis (pitch axis) and the principle axis is sufficiently large, rolling will introduce a coning motion due to generation of centrifugal forces. If left this will lead to catastrophic flight, thus the variation of roll rates should be minimised throughout the rocket's flight.

2.2. Rocket IMU sensor requirements

Most literature relating to controlled rockets inevitably focuses on guided missiles, used for military applications. Missiles vary greatly in size, but like a model rocket they too require precise inertial measurements and tightly controlled control algorithms.

A study [5] using spin-stabilized sounding rockets (rockets used for research and collect scientific data throughout their sub-orbital flight) indicates that roll rates of around 4 to 6 Hz (1440 to 2160°/s) are induced. Not all rockets are spin-stabilized; in fact many controlled rockets aim to eliminate spin to simplify the required control algorithms. Never the less, this gives an indication to a sensible angular rate range for the roll rate detecting gyro. Although a typical MEMS based gyro such as an ADXRS300 [6] has a dynamic range of ±300°/s this can be extended easily to ±1200°/s, ±11000°/s, or a maximum ±50,000°/s by some external passive components [7]. Note that extending the range of the gyro not only results in lower sensitivity, but also introduces more drift as much as 2°/s over the temperature range [7].

In the paper by A. Gamble and P. Jenkins [8] the IMU components in a GMLRS ATD missile are mentioned. IMU systems utilised are typically a Litton LN-200 or a Honeywell HG1700, both of which feature state of the art fibre optic / laser ring gyros and silicon machined accelerometers. These ultra-high performance IMUs contain sensors that are highly linear and have a very low drift / bias. The gyros have a dynamic range in excess of ±1000°/s and can measure accelerations greater than ±50g.

Not all controlled rocket applications can afford such expensive IMUs, and can get away quite adequately with much cheaper commercial grade IMUs. The highly successful rocket in last year's NASA Student Launch Initiative [9], 'Pike' developed by the 'Chimaera Hybrid Rocketry' group [10] used the Microstrain 3DM-GX2 [11]. The 3DM-GX2 appears to be customizable when bought straight from Microstrain, and contains three gyros, three accelerometers, and a three axis magnetometer.

2.3. IMU Design

With the advancements of modern digital electronics and micro-electromechanical system (MEMS) sensors, there are a lot of readily available solid state inertial measurement units (IMU). The price range varies based on the quality of the sensors used, and the intended application. For instance, IMUs aimed towards hobbyists can be bought from Sparkfun [12] which has a price range around $125USD to $450USD. Commercial grade units such as the 3DM-GX2 [11] can also be purchased for around $1700USD. However considering the designated budget of $2000NZD for the project, neither option presents a viable solution in the cost-performance metric.

The essential components of an IMU are gyros and accelerometers. Studies [13] have been performed which attempts to design an IMU from accelerometers only, by carefully positioning six accelerometers on a cube-shaped mount. However considering the current technology, the cost of MEMS based gyros are no longer an issue, and the cost in accurately machining of the mount would not likely offset the benefits of using an all accelerometer IMU. Further it is found [14] that such a configuration leads to output errors that grow significantly faster than conventional gyro-accelerometer based IMUs.

Another type of sensor often used in IMUs is magnetometers. These sensors measure Earth's magnetic field, and are typically used along with accelerometers to track static orientation. Magnetometers are thus used to correct for drift in the other sensors readings, particularly when GPS information is not available [15]. However the bandwidth of magnetometers is typically around 30Hz, which will not be of great use in the relatively short flight of the rocket. Furthermore magnetometers are affected by the presence of large ferrous objects; it is likely that the rocket's motor will corrupt the magnetometer's readings.

Accelerometers measure acceleration and are used to track static orientation, while gyros measure angular rate and are used to track dynamic orientation. Neither sensor is without its flaws: accelerometers are affected by impulses of motion, while MEMS based gyros drift. Two digital filters are often implemented to fuse both sets of data, and also remove bias from the sensor readings. The two such filters are the Wiener filter, and the Kalman filter.

The Wiener filter [16] can be implemented as a finite impulse response (FIR) filter, which therefore will always be stable (impulse response will converge to zero). The Kalman filter [17] on the other hand is a recursive filter, which in practise is often harder to implement and tune. Without the correct posterior estimate, covariance matrix, or suitable initial conditions the Kalman filter easily becomes unstable. Both filters provide a solution to fuse the sensor data, remove noise and bias from the sensors outputs. The Kalman filter is typical more efficient as it requires only the last previous sensor readings, whereas the Wiener filter will typically require knowledge of more previous readings.

2.4. Other sensor and electronic systems used in a controlled rocket

In addition to the IMU, there are typically other electronics and sensors in a guided rocket. The 'Pike' [10] for instance, comprises of the following key electronics:

- 600MHz Gumstix Verdex XL6P [18] single board computer.
- A data logging device.
- A 3DM-GX2 [11] IMU.
- A 20Mile range communications / telemetry radio.
- Onboard video camera.
- PerfectFlite altimeter [19].

3. Work Performed

A fundamental part of a controlled rocket is its avionics. This is the electronic and control systems used to provide the following functionality in real-time:

- Determine the spatial position and rotation of the rocket.
- Current altitude.
- Data logging, GPS, and wireless communication.
- Control of actuation surfaces to change the rocket's path.
- Trajectory correction and height prediction.

I was in charge of designing and building the hardware for the avionics for the controlled model rocket. This required attention to detail, as the reliable and failsafe operation of the avionics is critical for the rocket.

3.1. Avionics System Architecture

Before detailed design could commence on the electronics, we needed to design the high level system architecture. I proposed a modular approach, where each sub-module was controlled via a dedicated microcontroller. These sub-modules would then communicate to a main controller (Gumstix, see *www.gumstix.com*) through a serial bus such as I2C, UART, or for high speed transfers SPI, using a standardised communications protocol. The proposed system is as shown in Fig. 3.1.1.

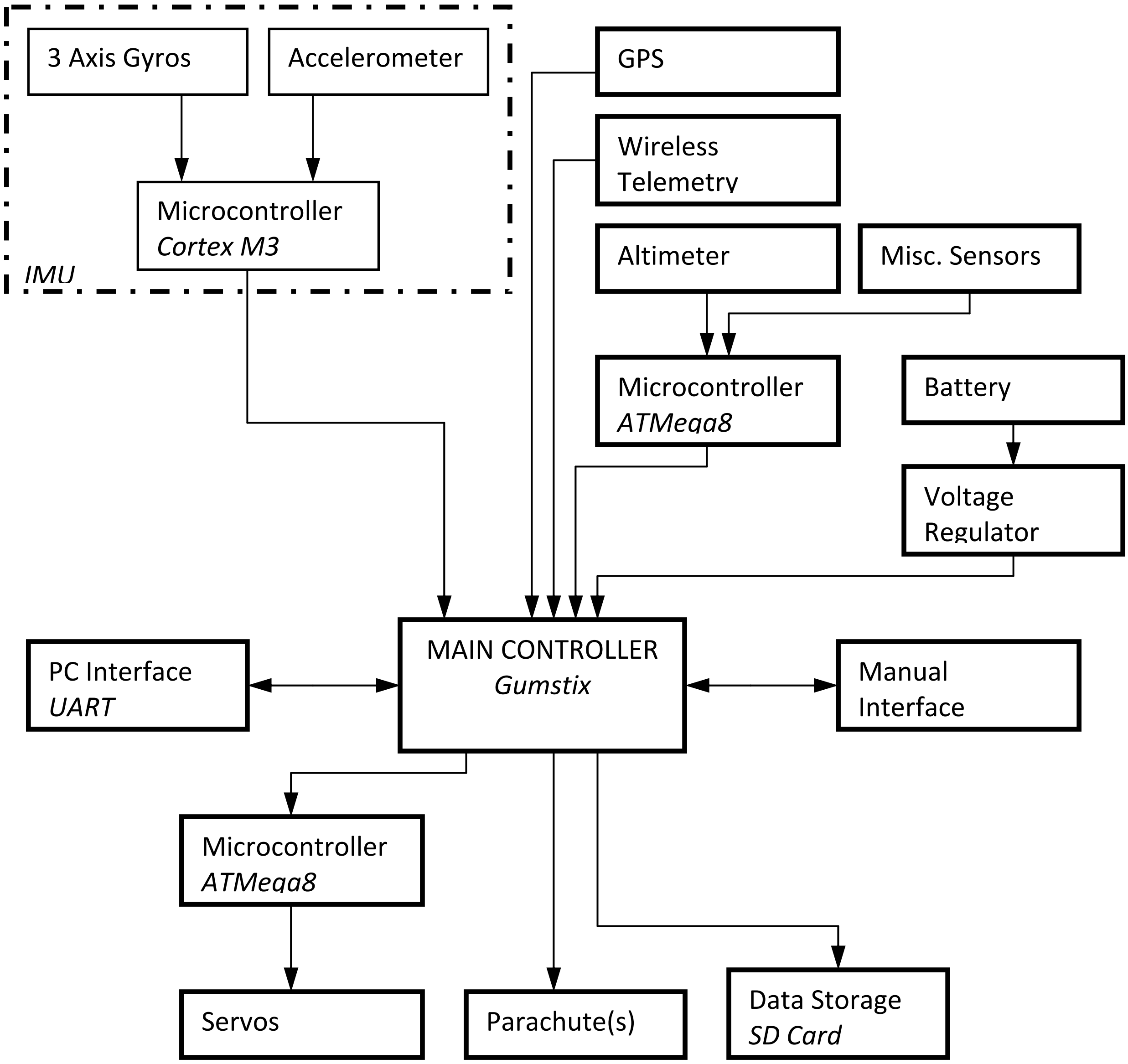

Figure 3.1.1: Initial system architecture.

Having an entirely modular approach would be the only solution had we bought a Gumstix single board computer (as they are quite expensive). However after discussions with John Stowers (developer of the quadcopter from GRC), it was discovered that this approach would not be possible given the short time frame of the project. From what John had discovered from his quadcopter, control algorithms can be written in a manner than a 600MHz processor running a real-time operating system is not required. A 32 bit microcontroller such as an ARM7 running at 50MHz would be adequate, provided that control was written in mostly fixed point arithmetic.

John was also kind enough to share his hardware design as used in the quadcopter. I chose to take this information on-board. Although it drastically changed the architecture of the system, John had already designed a working IMU and had extensive software we were allowed to have and develop for our own purposes. A revised system architecture diagram is shown later on in Fig. 3.4.3.

3.2. IMU sensor selection

Prior to adopting the hardware used in GRC's quadcopter, I was in charge of developing a suitable IMU for the rocket. Its key parameters were:

- Low cost
- Simple – use only the sensors required
- Easy to fabricate
- Sufficient for the task

As discussed in section 2.3 most IMUs contain the following sensors:

- Accelerometers – measure acceleration.
- Gyros – measure angular rate.
- Magnetometers – measure Earth's magnetic field, and use to enhance accuracy of readings.

Magnetometers were ruled out as their readings are influenced by metallic objects (such as the rocket motor) and they have slow update rates (in the order of 30Hz), making them not particularly useful for guidance of a 10 or so second rocket flight.

In order to make the IMU easy to fabricate, I firstly designed a system using sensors that could achieve the 6 D.O.F requirements while all being mounted in the same plane. This lead to the following sensors:

- Gyro roll axis: IXZ650 – ±2000 °/s and ±440 °/s dual outputs, $20USD, 100Hz bandwidth.
- Gyro pitch and yaw axes: IDG500 – ±500 °/s and ±110 °/s dual outputs, $20USD, 100Hz bandwidth.
- Accelerometer roll plane: ADXL345 – ±16g, $15USD, 3200Hz bandwidth.
- Accelerometer pitch and yaw planes: ADXL320 – ±5g, $8USD, 2500Hz bandwidth.

The total cost of sensors for this IMU is $63USD. However what made this design unviable was the low bandwidths of most of the components, limited by an internal low pass filter embedded inside most of the sensors chip.

A few more revisions on IMU sensor selection were carried out, eventually arriving to the conclusion that one could not attain a combination of suitable sensors that could be laid out on the same plane. PCBs mounted orthogonally as typically done in commercial IMUs would be required. The revised sensors were as follows:

- Gyro roll, pitch, and yaw axes: ADXRS610 – ±300 °/s (with ability to increase its dynamic range through external components), $35 to $52USD, 2500Hz bandwidth.
- Accelerometer roll plane: ADXL321 – ±18g, $8USD, 2500Hz bandwidth.
- Accelerometer pitch and yaw planes: ADXL320 – ±5g, $8USD, 2500Hz bandwidth.

The revised sensors had ample bandwidth, and alone would cost a total of $121 to $172USD (depending on where the gyros were purchased from Digikey or Sparkfun). It was also planned to have each analogue sensor output to be fed into an external low pass filter before being sampled by an ADC, preventing excessive noise and aliasing effects entering the measured reading.

Shortly afterwards, I was introduced to John and his hardware used in his quadcopter. John kindly offered his expertise and support, which he even allowed us to have spare circuit boards he had developed. This offer could not be refused, especially since a lot of John's hardware could be adapted to be used in the rocket. Without knowing any details of the quadcopters electronics, I was also pleasantly surprised that my final sensor selection had converged to what John actually uses in his quadcopter.

3.3. Fabrication of GRC IMU

After adopting the GRC quadcopter electrical hardware design, I was in charge of ordering all the parts and soldering components onto the IMU. Despite having a bill of materials, ordering the components was not as easy as it sounds.

Several crucial components such as the ADXRS610 gyros and MAX1168 ADC were quite difficult to get hold of. The gyros John had ordered were from Digikey, however these high specification components are on an export restriction list, with New Zealand being one of the 'blacklisted' countries. Several alternatives sources were tried, and eventually these components were ordered from Sparkfun (http://www.sparkfun.com) who apparently do not pay much attention to the export restriction policies.

The ADC also proved to be tricky to get, as all sources I had looked at either did not stock this item or had a minimum order quantity of 50 (which is restrictive at $15USD each). This component also held up the IMU construction, and was only recently obtained (21-Oct-09), after John (who is currently on a university exchange) was kind enough to send back a spare ADC from Switzerland.

Once most of the components had arrived, most of the IMU boards were kindly soldered up by our industry mentor K. Adams shop (ELF – Electronics Layout Fabrication). This company specialises in populating PCBs, but had not dealt with ball grid array (BGA) parts often. Dean from ELF attempted to solder a BGA part (a gyro), but after I tested the functionality of the sensor it was found to be not soldered on correctly. I reasoned that an incorrect temperature profile had been applied, where upon inspection some solder pads had not been reflowed.

Since I had successfully dealt with such difficult to solder parts, I proceed to reflow solder all the BGA parts myself. After doing so, a functionality test of the parts showed that this time they were properly soldered. I was able to solder the parts using solder paste, flux, and a hot air rework station. I also removed the lead-free solder that came balled on the BGA part with a de-soldering wick, to keep the content of the solder consistent. Figure 3.3.1 shows the amount of solder paste used in a successful soldering of a BGA part.

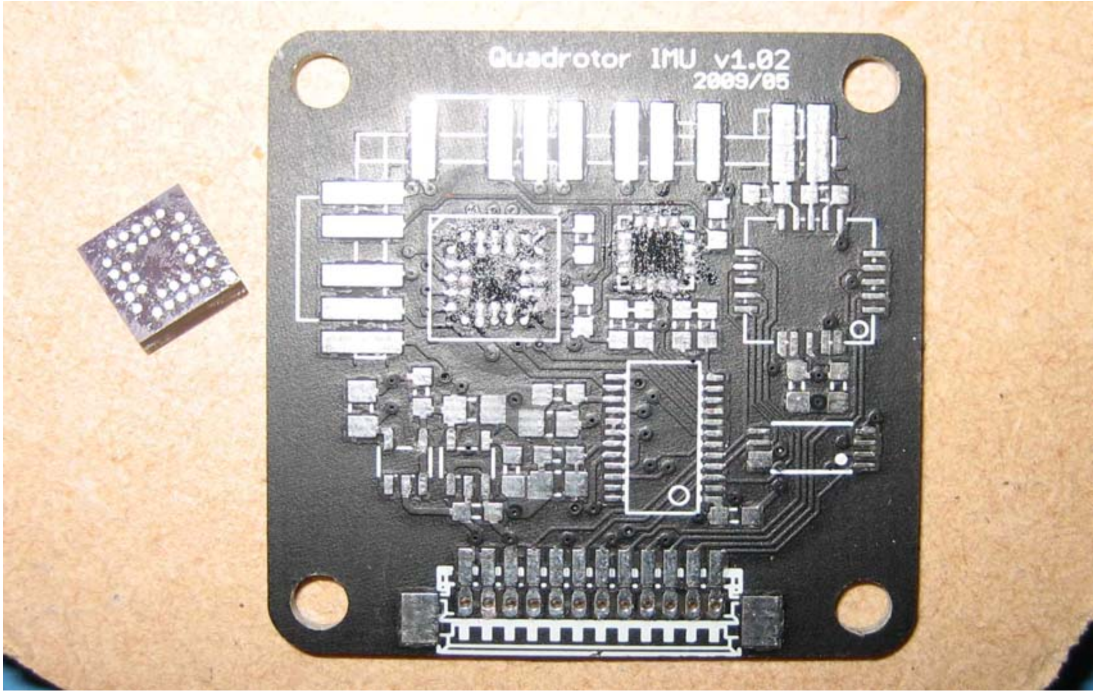

Figure 3.3.1: Amount of solder paste used in a successful reflow solder of a BGA part.

I proceeded to populate all the other components on the three IMU boards, while Dean from ELF was able to populate the main board. Figure 3.3.2 shows the completed IMU and main boards. The current status of the IMU and main board is as follows:

- Main board has been tested, and basic functionality is working. We are able to program simple input-output test programs onto the microcontroller.
- All IMU sensors have been individually tested. The reading of these sensors through the ADC has yet to be tested.

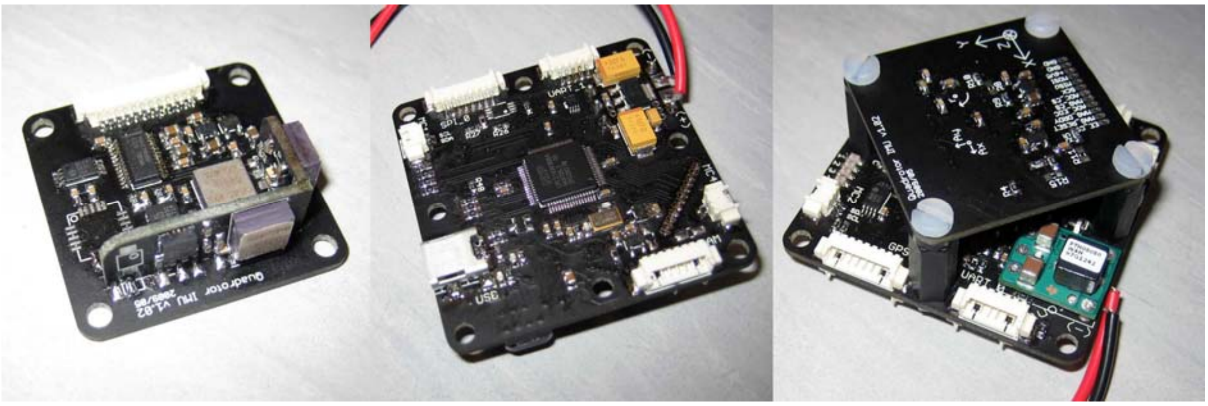

Figure 3.3.2: Assembled boards from left to right – IMU, main, IMU and main.

3.4. Design and Fabrication of Supporting Electronics

The quadcopter hardware took care of most of the avionics required in the rocket. In addition to the quadcopter boards, the rocket required the following functionality:

- Parachute deployment ignition circuits.
- Wireless telemetry.
- Data logging.
- Servo connections and power regulation.

The above required functionalities were achieved in two circuit boards. I was responsible for their design, layout and fabrication. A complete system of electrical circuit boards is shown in Fig. 3.4.1, while Fig. 3.4.2 shows the circuit boards assembled in a stack:

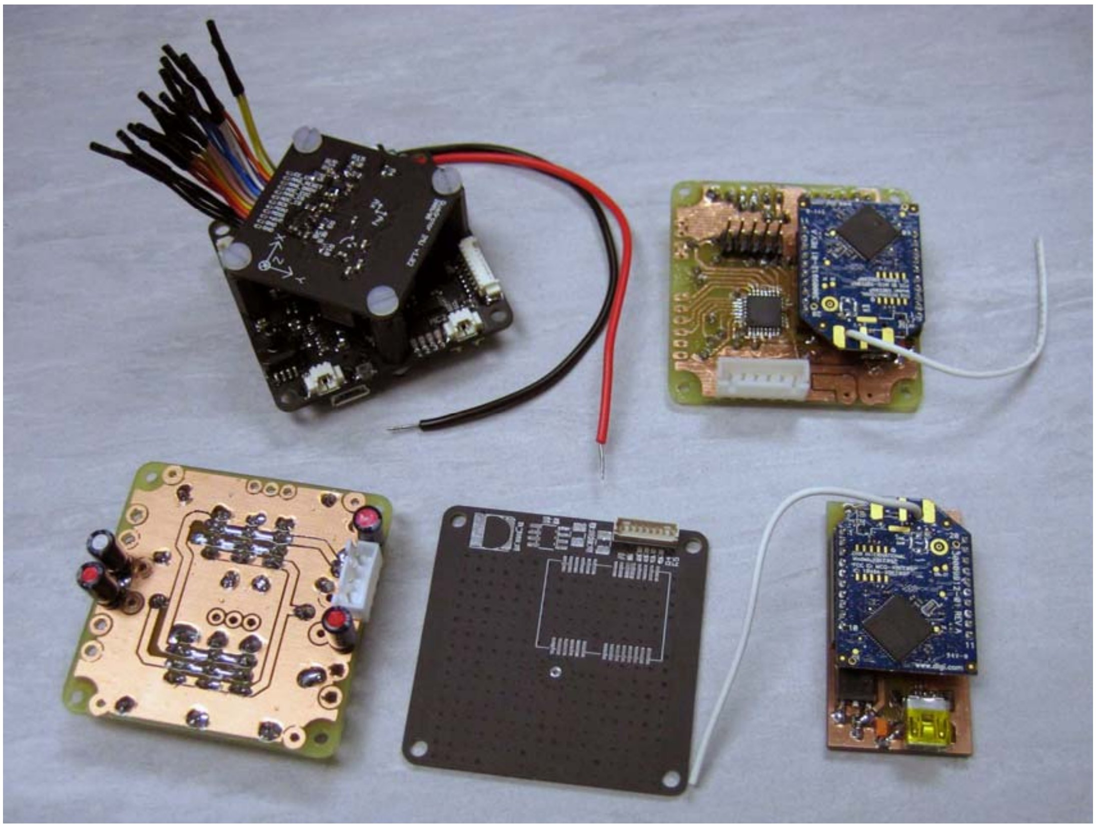

Figure 3.4.1: Avionic boards from left to right, top to bottom – IMU and main, Wireless with data logging and igniters, Servo and power regulation (shown without power regulator modules), Unpopulated GPS, and PC wireless adapter.

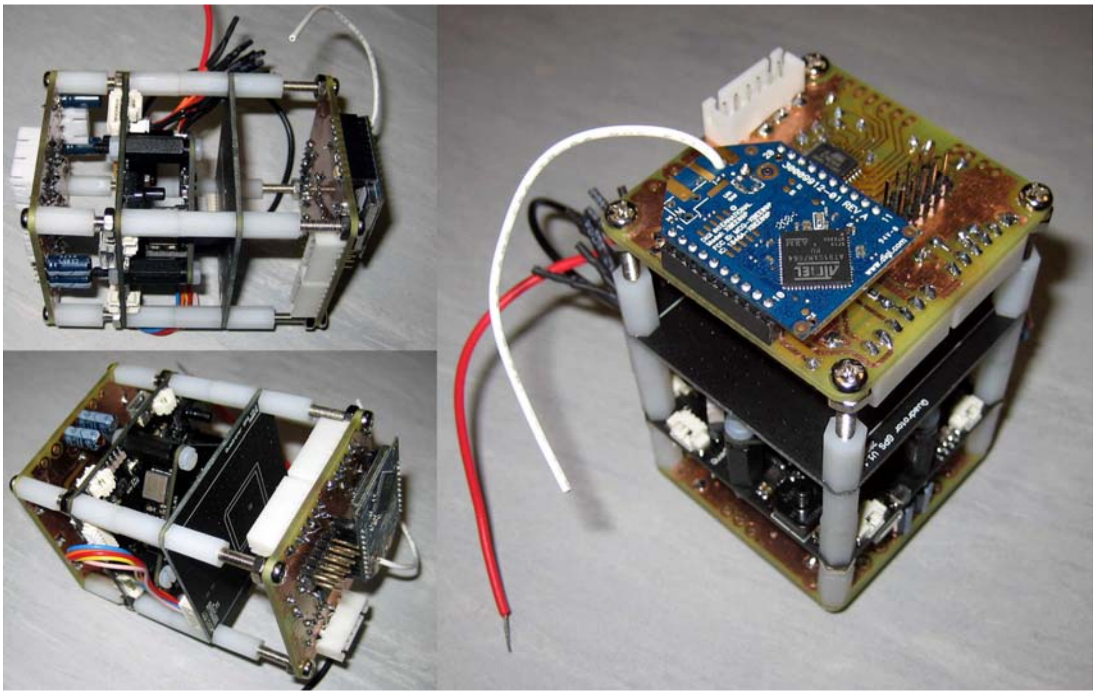

Figure 3.4.2: Avionic stack of boards.

Figure 3.4.3 below shows a block diagram of the finalised avionic components:

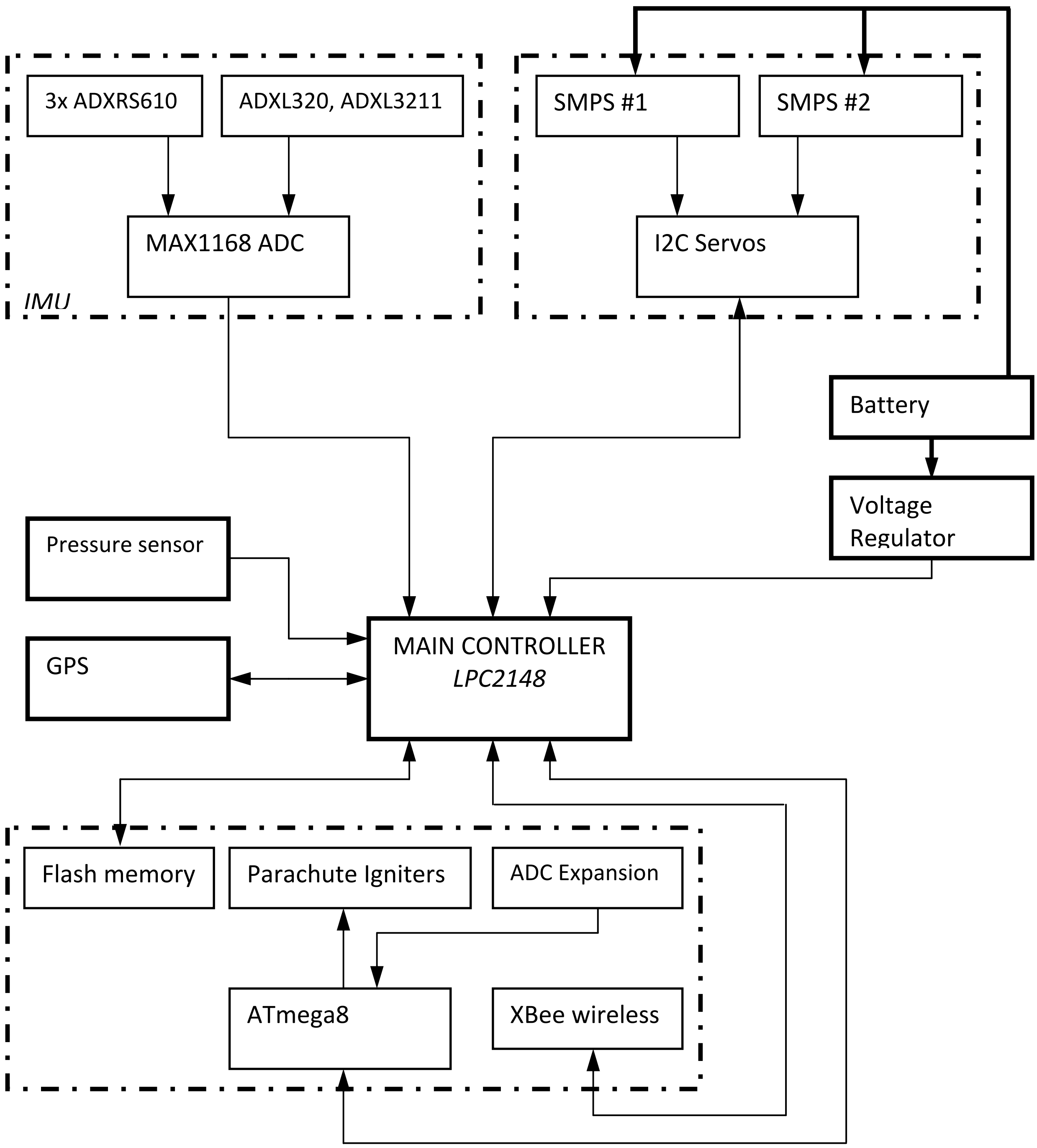

Figure 3.4.3: Avionic block diagram of the electrical rocket system.

The following sections highlight implementation and design decisions/features in the circuit boards I personally designed for the rocket:

3.4.1. PC wireless telemetry adapter

A simple circuit that contained a USB to UART bridge, debug LEDs, and an XBee wireless module. Refer to Appendix 6.1 for detailed schematic.

3.4.2. Servo and power regulation

Simple digital servos with an I2C interface (OpenServo) will be used to control the actuation surfaces. These could be powered straight off a two cell lithium polymer (LiPo) battery, however the characteristics of the servos such as their holding torque and angular speed will change depending on the battery's charge level. To remove the dependence of on supply voltage, the power to the servos was regulated through a buck switch mode power supply (SMPS). The power modules PTN78020W from TI are used, which have the ability to change their output regulation voltage by changing the value of one resistor, and can efficiently deliver up to 6A.

The servo and power regulation board was designed to accept two SMPS units, giving up to 12A of voltage regulated supply. Currently the output is set to 7.2V, thus since the converters are of the buck topology the supply battery will need to be at least a three cell LiPo battery.

I2C is a serial bus, so multiple servos can be connected to the same bus and share the same control wires. The design has six sockets for proper power delivery, rather than limiting it to drive six servos. For high current servos (<2A max) it is recommended not to exceed two servos per socket. Refer to Appendix 6.2 for a detailed schematic.

Also note that the connectors used (JST-XH) have a self locking mechanism, and are also used throughout my custom boards. Having connectors that do not come loose during flight are just as critical as the operating of the electronics.

3.4.3. Wireless telemetry with data logging and parachute igniters

Wireless functionality is simply added by provided a breakout board to an XBee module. A UART port from the main board connects straight to the XBee.

Data logging functionality is provided by means of a 32Megabit flash chip with SPI interface. Again, there is a straight connection from the main board to the flash chip.

The parachute igniters are simply controlled electronic switches. When activated, these basically provide power to its output load, which in this case is a fuse filament embedded inside a pocket of gunpowder. When deployed, electrical current heats up the fuse which in turn ignites the gunpowder, thus deploying the parachute. I have designed in measures to protect this circuit from shorting out the battery. Firstly, a 3.5A positive temperature coefficient (PTC) resistor is installed between the battery and all of the igniters. In the event that this limit is exceeded, the resistance will automatically increase thus limiting the current draw. The successful deployment of the parachute is also important, so two PTC resistors are connected in parallel for a higher tripping current and redundancy protection. Refer to Appendix 6.3 for schematic.

Also note that I have designed in up to six additional ADC ports, in the event of expansion of the system. These ports will also be managed in a similar as the igniters, through I2C communication with the onboard microprocessor.

3.5. Design of Avionics Enclosure

I have designed a SolidWorks model which captures the essential details of the avionics, and also shows how they should be arranged in a stack. Figure 3.5.1 below shows this:

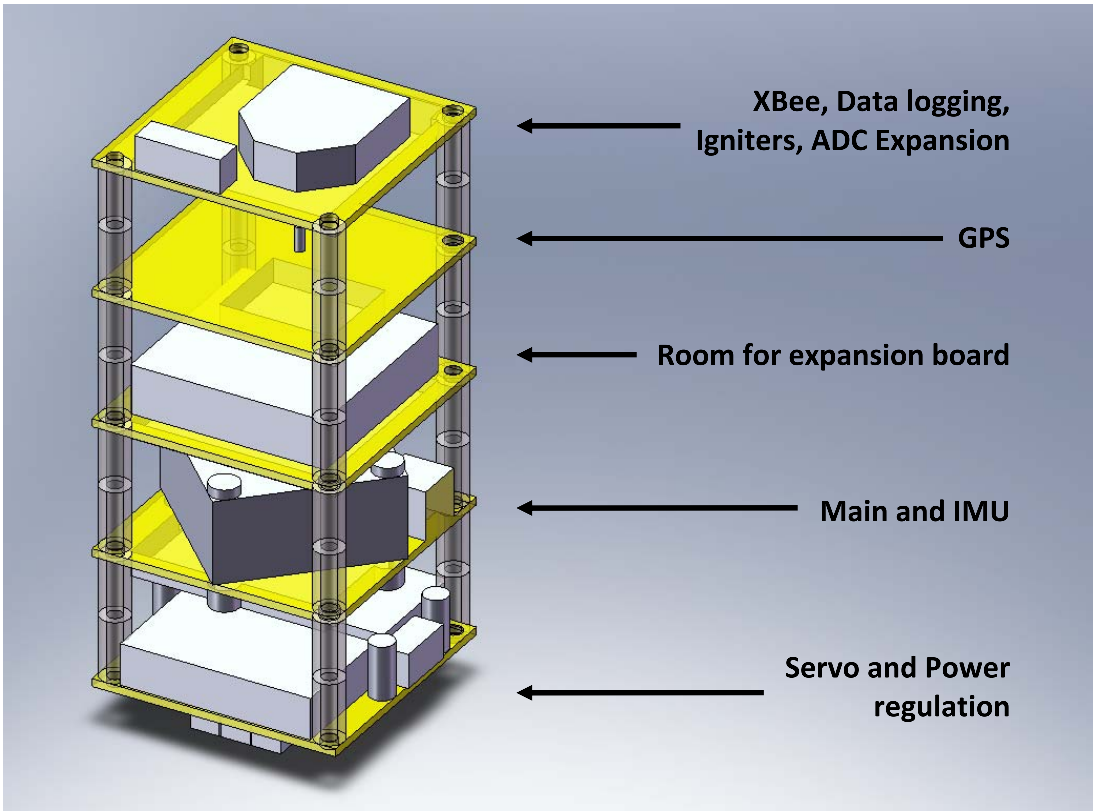

Figure 3.5.1: SolidWorks model of the avionic stack of boards.

Due to the late arrival of electrical components, detailed design work on a suitable enclosure has yet to be made, however possible ideas are as follows:

- Cylindrical PVC pipe with caps.
- Custom made fibreglass enclosure, with rubber supports to protect the unit to some extent from unintended impacts.

3.6. Other tasks

I was in charge of setting up the subversion repository (SVN) as well as managing it. This has proven to be a useful tool throughout the development of the project, as it allowed easy sharing of current designs, software, and documentation. It also stores all the previous revisions which are particularly useful when large changes are made in design while developing.

I was also in charge of ordering and maintaining a budget of the electrical equipment used in the rocket, particularly towards the avionics. Figure 3.6.1 below shows the executive summary of the expenditure of the electronics. Note that even although the expenditure of the electronics alone exceeds the project’s entire budget, the cost of good quality sensors such as the ones used in the rocket cost a lot anyway. Also a lot of the parts had to be bought in from overseas, which meant that around $250NZD was spent on shipping.

Date	Location	Item and description	Cost (NZD)
28-Aug-09	SICOM	Miscellaneous - plastic spacers and header and sockets	$19.60
9-Aug-09	Ebay	STM32 Dev board	$83.20
20-Aug-09	Digikey	Most components to populate a single IMU and main board, excludes gyros	$541.80
28-Aug-09	Sparkfun	Gyros, OpenServo, Xbee units. Builds two units with spares	$1,100.93
30-Sep-09	Maxim	5x ADC for IMU (MAX1168)	$260.55
11-Oct-09	Farnell	Miscellaneous components for one IMU and main board	$157.47
27-Oct-09	Farnell	Estimate - yet to order. Power module and miscellaneous	$50.00
		Total	$2,213.55

Figure 3.6.1: Executive summary of the expenditure of the rocket's avionics.

4. Conclusion

I have carried out my role in the rocket project team with competency. I have been in charge of the design, sourcing of parts, fabrication and testing of the rocket's avionics. Due to setbacks such as export restrictions of gyros and hard to find parts, the avionics of the rocket has just been finished but has yet to undergo extensive testing and software development.

The avionics developed consist of high quality sensor components, which are likely to exceed the instrumentation requirements of the rocket. Future revisions should therefore be able to benefit from hindsight, and utilise more cost-efficient sensors and systems.

As mentioned the developed system has most of its hardware completed. The hardware that has been developed has been designed to be robust using connectors that should not come loose in flight and provide some flexibility in future expansion.

5. References

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6. Appendix

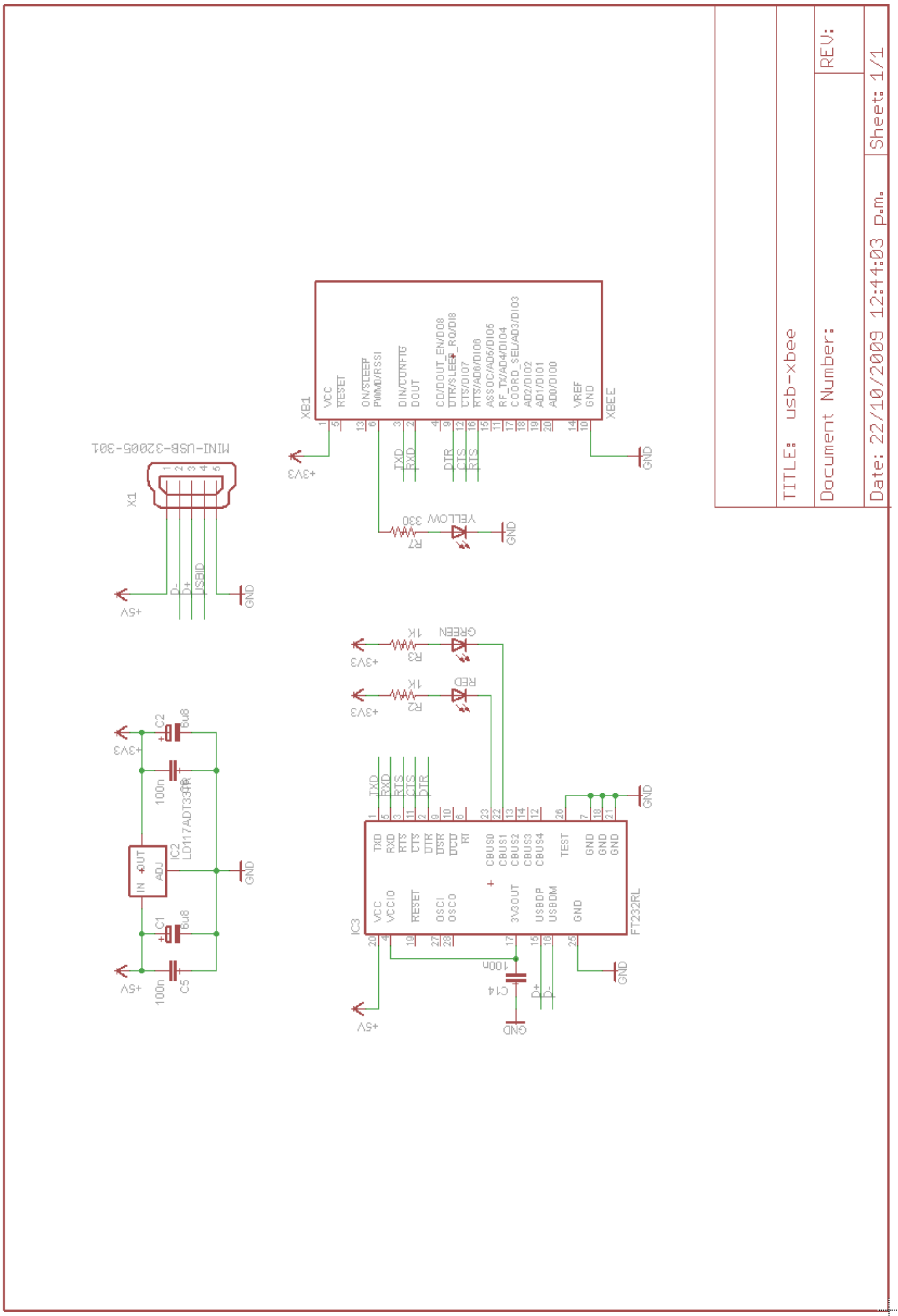

Figure 6.1: PC wireless telemetry schematic.

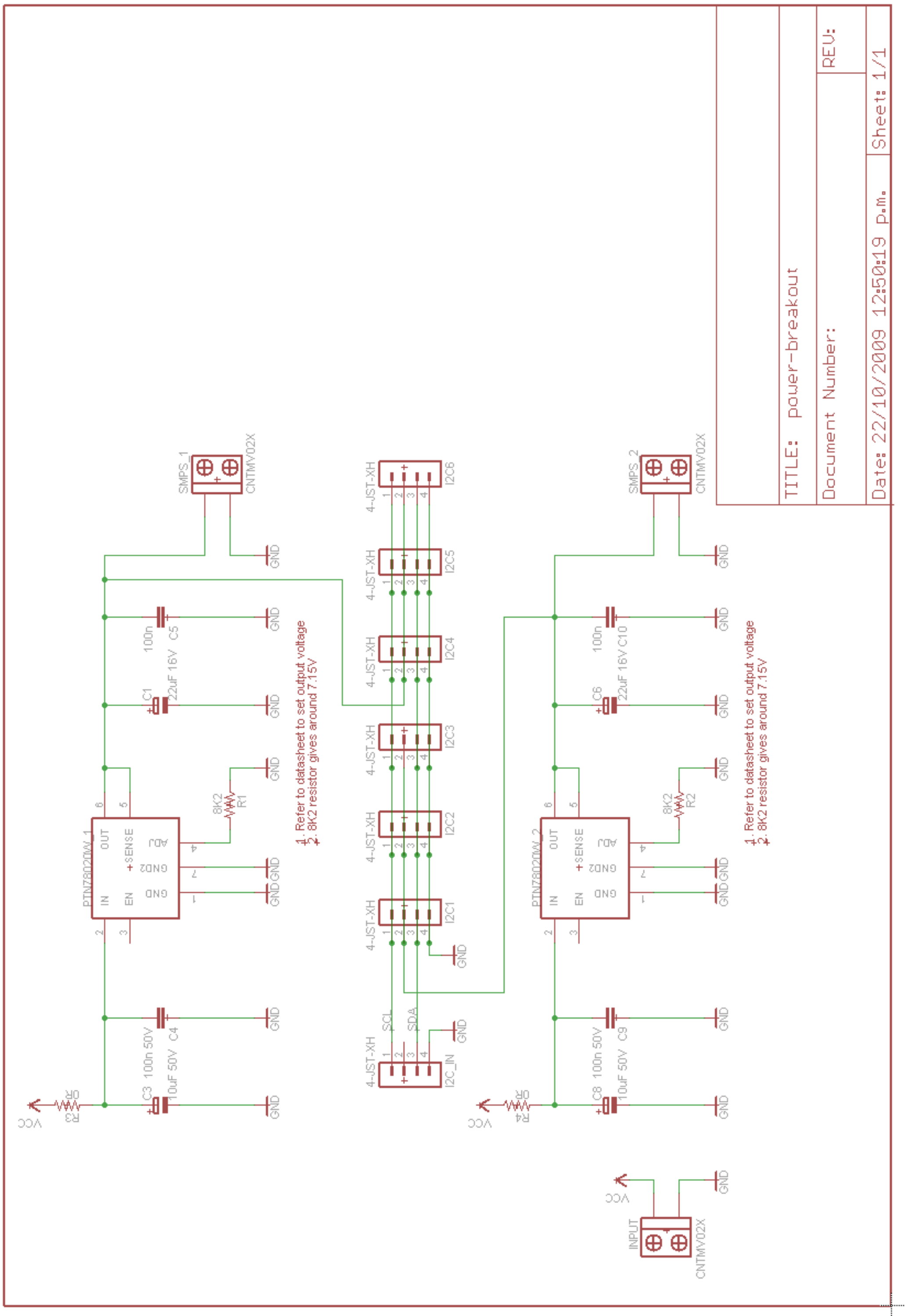

Figure 6.2: Servo and power regulation schematic.

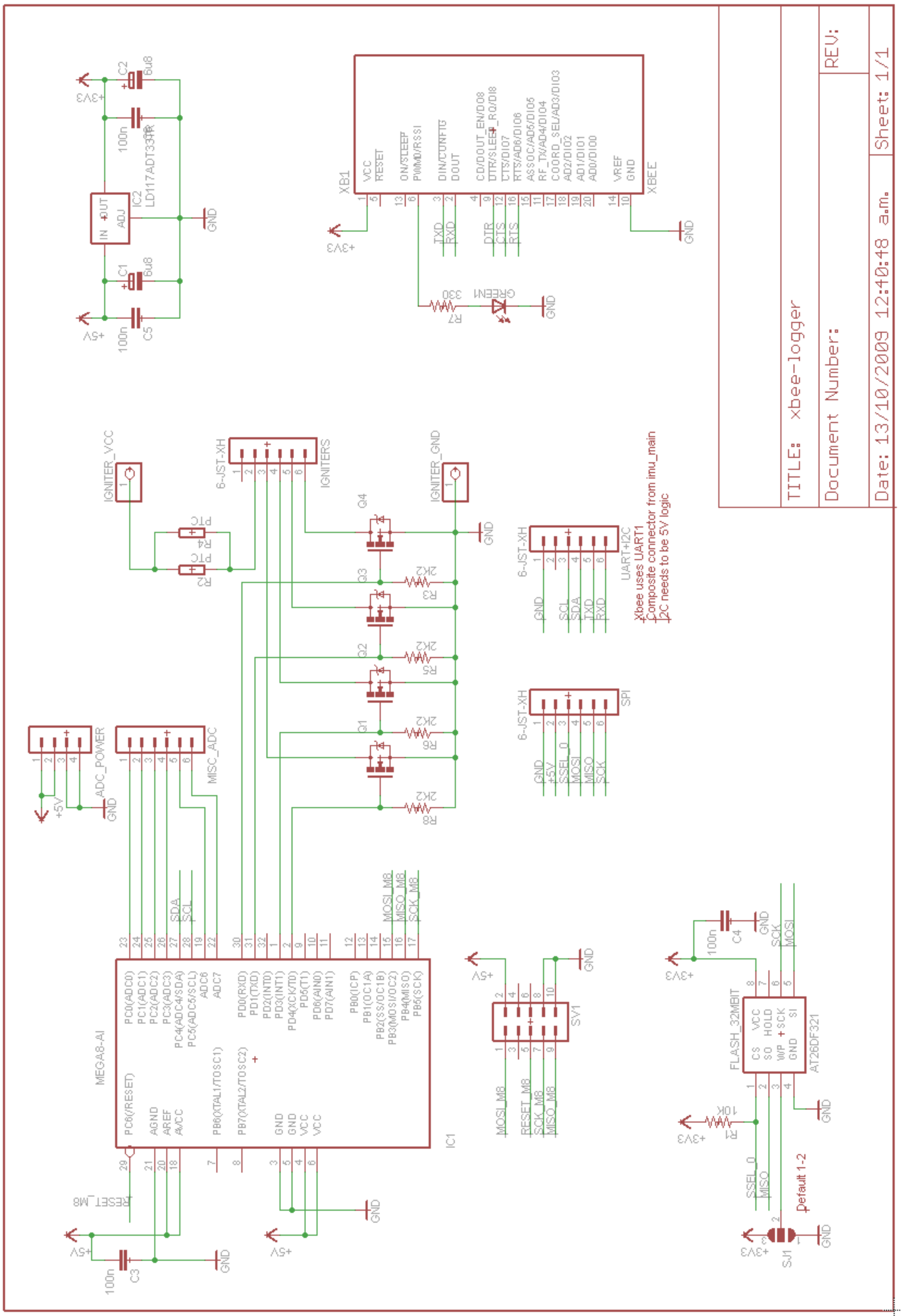

Figure 6.3: XBee, data logging, and parachute deployment igniters schematic.