Martlet II Avionics Postmortem

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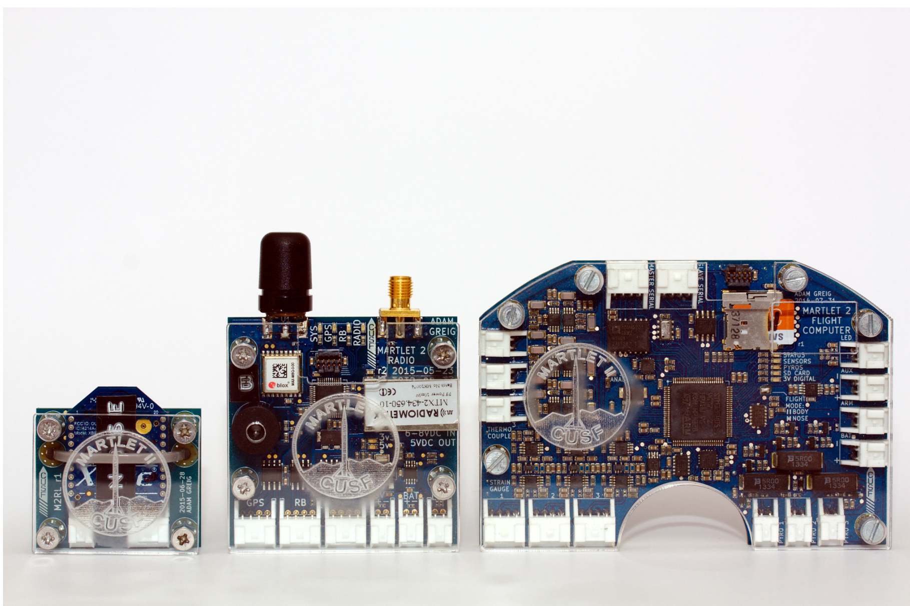

Summary

Overview

Successes

Problems

Takeaways

Contents

Introduction

Martlet II Overview

Martlet 2 was an amateur rocket designed, built, and launched by Cambridge University Spaceflight in 2013-2015. It was intended to reach a speed of around 1km/s and an altitude of around 15km, establishing a new UK amateur altitude record.

After a scrubbed launch due to weather in October 2014, Martlet 2 was launched in October 2015 from Black Rock Desert, Nevada, USA. An anomaly occurred three seconds into the flight, resulting in the rapid and thorough destruction of the rocket including the avionics.

Figure 1: Martlet 2 in Black Rock Desert, Nevada, in October 2014

Report Scope and Goals

A custom set of avionics was designed for Martlet 2. After the scrubbed launch, some were updated to address issues in the original designs. This document is a postmortem and a retrospective of those avionics, reviewing the original design and evaluating the choices made and lessons learnt for future avionics programmes.

This postmortem is concerned with the avionics and their integration with the larger rocket system, but will not discuss matters solely related to the rocket or other components, nor will it detail the flight anomaly except insofar as it relates to the avionics design and possibility for future improvements.

Project Objectives

The original objectives for the avionics were, in priority order:

1. Control the recovery system deployment
2. Downlink rocket position information for recovery purposes
3. Record vital rocket parameters (altitude, velocity, acceleration, location)
4. Downlink additional information
5. Record additional sensors, including inertial, strain, and temperature

Think carefully about precise objectives and priority. Lots of time was wasted on things that were not mission critical to the detriment of those that were.

Avionics Overview

This section presents the hardware as-flown to give context to the rest of the analysis.

Custom Hardware

M2FC

`M2FC` is the main flight computer. Onboard is an `STM32F405VGT6` microcontroller, a 32-bit, high performance ARM device. There is a MicroSD card; an inertial measurement unit (IMU) consisting of a low-G accelerometer (`ADXL345`), high-G accelerometer (`ADXL375`), gyroscope (`L3G4200D`), magnetometer (`HMC5883L`), and barometer (`MS5611`); three pyrotechnic channels; three strain gauge analogue inputs; three thermocouple analogue inputs; and two isolated serial ports. Additionally there are connectors for the main power supply battery, an arming switch (which is simply placed inline with the battery before power is provided to the board), an auxiliary power output, and a bicolour status LED.

There are two `M2FC` boards on Martlet 2: one in the nosecone with the main avionics stack, responsible for firing the Metron protractors which separate the nosecone from the body of the rocket and for communicating with `M2R`; another in the body of the rocket responsible for firing the Metron protractor which releases the main parachute and for recording the strain gauges and thermocouples in the rocket fins.

The early design called for a pyrotechnic board `M2P` to control the recovery system and a datalogging board `M2D` to record flight data. The decision was made early on to combine the pyrotechnic board and the datalogging board into the flight computer `M2FC`, as they required some very similar sensors and software. In retrospect, it seems likely that keeping these separate would have been beneficial: the recovery system could be simpler and thus more reliable, and the datalogger could be worked in isolation allowing better development collaboration with less risk of compromising the main objectives.

Consider maintaining modularity even when integration is tempting; it preserves isolation and separation of concerns.

M2R

`M2R` is the radio board. Onboard is an `STM32F303CBT7` microcontroller, a uBlox `MAX-M8Q` GPS receiver, a Radiometrix `MTX2` FM radio transmitter, and a buzzer. There are connectors for power input, a status LED, two isolated serial ports (which attach to `M2FC` and the RockBLOCK satellite modem), and isolated access to the GPSs' serial port.

There is one `M2R`, in the nosecone of the rocket.

M2RL

`M2RL` is a radio link between the two `M2FCs`. It consists of a series 2 Xbee modem and serial isolating hardware.

M2PA

`M2PA` is a radio power amplifier, boosting the 10mW from `M2R` to around 500mW for transmission.

JOEY

As a backup locating device, a Joey tracker was installed in Martlet 2 as well. It had its own independent power supply, GPS, and radio. While this was not required in the event, its presence was reassuring and there is no reason to believe it would not have worked (had it not been torn to pieces during flight).

Use a totally separate and independent tracker for backup.

Other Electronics

Additionally there are two small cameras, a RockBLOCK satellite modem, two arming switches, three battery boxes, and four Metron protractors.

Installed in the fin are three strain gauges in a half-bridge configuration, with an unloaded set of strain gauges to provide temperature compensation, and a thermocouple to measure the fin root temperature.

RockBLOCK

PerfectFlite

Cameras

Other Components

Metrons

Strain Gauges

Thermocouples

Battery Cases

Arming Switches

Status LEDs

Antenna

Interconnections

In the body of Martlet 2 is one `M2FC` connected to: the fin strain gauges and thermocouples, the body `M2RL`, the Metron to release the main parachute, a single battery box, an arming switch, a status LED, and providing power via the auxiliary connector to one camera (and `M2RL`).

Most of the avionics are in the nosecone, where `M2FC` is connected to `M2R`, the nosecone `M2RL`, three Metrons for separating the nosecone and two battery boxes in parallel (each 4xAA Lithium primary cells). Its auxiliary power connector provides power to two cameras, `M2RL` and `M2R`.

See the wiring diagram for a more detailed representation.

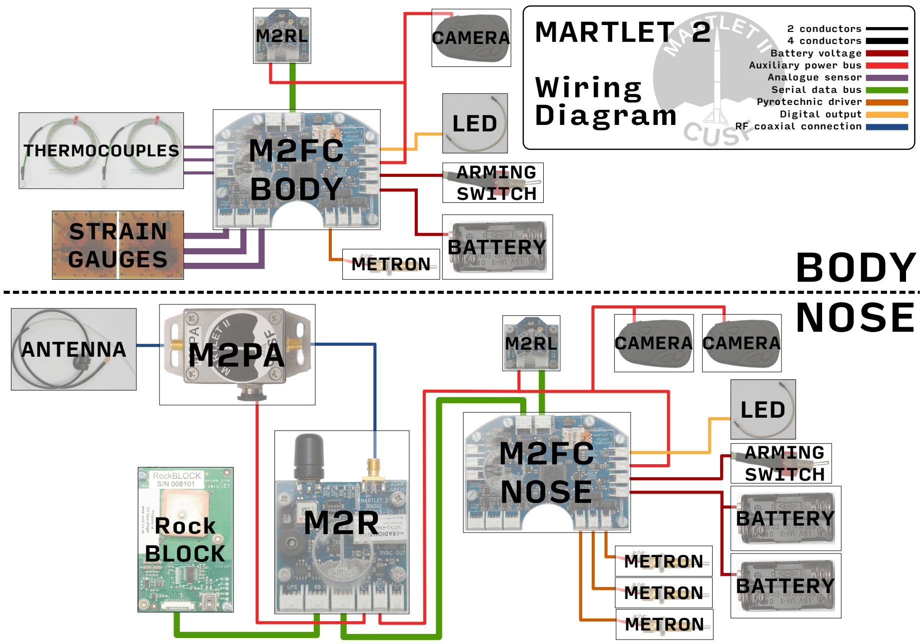

Figure 2: System Overview

Project Management

Time Management

Collaboration

Prioritisation and Feature Freeze

System Review

Little thought was put into the whole system design early on, such as interlinking the avionics and regulating and distributing the power supply. Much of this had to be designed once the rest of the avionics were finalised, which led to a suboptimal solution.

Consider how individual components will form the complete system before finalising their design.

Hardware Review

This section will address the design, manufacture, and testing of the avionics.

Technology Choices

All PCB design was performed in KiCAD. While a few issues were encountered due to version upgrades during the development programme, in general this software worked well.

Setting up a common library of component symbols and footprints from the beginning would probably have saved time over copying symbols separately for each each project.

Establish a common library for symbols and footprints which all projects can share.

Design Procedure

The current procedure for carefully checking schematic and board layout led to only a single mistake in production: the powered isolator `ADuM5201` was given a normal-width `SOIC16` footprint where the datasheet called for a wide variant. Luckily the chip was easily modified be folding the legs around so this did not present a serious issue in production.

Careful and thorough checking of the PCB designs, including against the CUSF checklist, resulted in very few issues on a complicated design.

Manufacture was by reflow soldering and had no issues beyond a few small solder bridges which were readily reworked. Again standard procedures seem to have worked very well here.

M2FC

Analogue Section

`M2FC`'s analogue section is responsible for converting the small electrical signals from the thermocouples and strain gauges into useful levels at the ADC. The design used specialised amplifiers as a frontend followed by a dual active antialiasing filter. These parts ended up being a substantial fraction of the total avionics cost, but were high specification and performed as required during testing and during flight. Additional testing and characterisation would have been useful and more time could have been allocated to this. In future less potent antialiasing filters might be sufficient but this design appears to have worked well.

Pyrotechnic Drivers

The pyrotechnic channels consisted of a small N-channel MOSFET driving the gate of a higher current P-channel MOSFET which controlled high side power to the Metron protractors. Each channel additionally had a high power 5Ω resistor in series to limit total current, and a continuity measurement circuit. The high power resistors are physically large devices and it unclear how crucial they are; additional testing or characterisation may be useful in future.

The channels were not tested with the actual Metron devices until it was far too late to remedy any defects, instead only being tested with other pyrotechnic devices. This was a serious testing defect. In the event, the DC current provided through the pyrotechnic channel was insufficient to fire a Metron, but luckily using 10ms duration pulses instead proved reliable. The datasheet for the Metron devices claims a lower all-fire current with such pulses, so this is to be expected. This lucky escape meant no hardware alterations had to be performed.

Test pyrotechnic drivers with the flight pyrotechnic devices.

The continuity testing worked as designed. In future resistance measurement would provide more information and may be able to indicate faulty connections.

Inertial Measurement Unit

The IMU consisted of a number of low-cost individual MEMS sensors. On the whole this design worked to within acceptable limits, with some issues.

The two accelerometers worked well and having the two acceleration ranges covered was helpful. The barometer worked very well but did not appear to indicate when a conversion was complete despite datasheet claims, so had to be polled instead, though this only caused a slightly lower data rate.

The gyroscope appeared somewhat unreliable and additionally is a more obtuse sensor than the accelerometer. Some fault likely lies in the additional complexity of I2C instead of SPI. In future attempting to stick to SPI devices would probably simplify matters.

The magnetometer had similar issues to the gyroscope. Neither were required for flight computer operation however, so this did not present issues in this flight. For flights requiring a higher degree of state estimation, it may be prudent to select alternative gyroscopes and magnetometers.

Fully and partially integrated IMU sensors are available which would reduce alignment errors and simplify communication and drivers.

Consider using a more integrated IMU solution, or at least keep everything on an SPI bus and choose a different magnetometer and gyroscope.

SD Card

Both `M2FC`s had an SD card to store flight logs. SD cards have the serious advantages of high storage density, high write speeds, low cost, ready availability, high survivability, and ease of connection to a computer. Interfacing to them was straightforward and allowed high rate data to be stored without concern for filling up the storage space.

Mechanically they presented some issues. Connectors tend to emphasise ease of insertion/removal which is undesirable in this application. There were concerns that high vibrations and accelerations would cause the SD cards to bounce on their contact pins or even eject from the holder. The only obvious remedy was to use adhesive to secure the SD card, which complicates reading data off them after the flight.

Alternatives were considered such as onboard flash memory or eMMC. Onboard flash can be soldered down, but tends to either come in very low storage space, or large packages with high pin count parallel interfaces. eMMC is even worse in this regard, with most packages difficult to solder and requiring more complicated interface circuitry.

In the event some issues were encountered with SD card retention; see below for details.

On balance the SD card seems the best solution for high rate data, but perhaps lower rate flash storage could be useful as a backup for critical data.

Off-Board Integrations

M2R

Radio

GPS

RockBLOCK

Buzzer

M2RL

The original design to interconnect the two `M2FC` boards, in the nosecone and in the body tube, was to use pogo pins on an interface board mounted near the nosecone separation point. This design proved very fiddly and delicate, with the pogo pins repeatedly breaking off during assembly. A more robust connector would be required for this sort of interface.

After the 2014 scrub, `M2RL` was designed to provide a radio link between the boards instead. This was much easier to integrate with the rocket design. Unfortunately time constraints meant this was not active during the flight, so its potential performance is unknown.

In future such radio links could be integrated onto the flight computers or possibly just downlinked to the ground station directly.

M2PA

Originally a power amplifier based on the `ADL5324` device was installed on `M2R` but being integrated made it difficult to test and tune. After the scrubbed launch the amplifier was moved to its own board, `M2PA`. This made testing easier but took substantially more payload space.

The amplifier design was fairly successful, meeting specification. In future this design could probably be used integrated. Alternative amplifiers have become available which require substantially fewer external tuning components and offer higher powers which might be superior, such as the Skyworks `SKY65116`.

After the 2014 scrub, the power amplifier was moved off `M2R` and into its own box. This design worked well and the amplifier survived the flight. It's possible that in future returning to an integrated amplifier once the design is proven would have worked well too, simplifying avionics wiring.

Arming Concept

The design for arming the avionics system was essentially a power switch on the body of the rocket, which controlled all power to the avionics. Obviously with the switch off, no pyrotechnic devices could fire, ensuring the rocket was safe. Two power switches were required, on the nosecone and on the body tube.

The connection to the power switch was provided on `M2FC`, which connected directly to the battery pack and then placed the arming switch in series before drawing any power.

This design was fairly simple but several issues were encountered

Power Management

The power distribution design was not considered until after the majority of the avionics were finalised. Each piece of avionics had been designed with the assumption that somehow around 6-7V of battery power would be available, as an appropriate voltage to regulate down to 5V and 3.3V for electronics systems while also providing enough margin to reliably fire the Metron protractors used in the recovery system. The design was therefore to use 4xAA lithium primary cells in a battery, connected to `M2FC`, which would then power the rest of the system once armed through the `AUX` connector.

In the original design, `M2R` had its own separate battery supply and thus arming/power switch. In the 2014 scrub update, `M2R` is instead powered on the `AUX` bus from `M2FC`, which uses both battery packs in parallel to give maximum capacity for the combined system. This new design allowed for a single power switch which reduced complexity.

Don't use separate batteries for otherwise interdependent and connected systems, it just increases complexity. Central power switching is nice.

Using lithium primary cells had some advantages for mass, power density, availability, and transport. CU Spaceflight have successfully used these cells for many varied missions so they were an obvious choice here. Being able to install a known-fresh set of batteries immediately prior to flight was reassuring, and being able to purchase these batteries at most large shops worldwide was likewise useful.

However, they necessitate battery holders which were all either difficult to mount securely, awkwardly shaped, or both. Reliable connections to the cells under the high acceleration conditions expected in flight was a pressing concern. In the original design, large Bulgin holders were used, but they were very awkward to fit in the mounting design. Post-scrub, smaller regular holders were used, but they did not provide any mounting points and were essentially friction fitted into a smaller compartment. Neither design was ideal, although it appears that the eventual design did provide power during acceleration.

In future it would be well worth considering a lithium ion rechargable main system battery with a dedicated power distribution board that can monitor and provide power to system components individually. Voltages could be regulated to some extent centrally, and supply currents could be measured, providing useful debugging information. Recharging allows for shore power to be used via an umbilical, which means the rocket may be powered up and on the pad for long durations, reducing urgency once padded up.

Give more thought to power supply design and distribution, including the option of rechargable batteries and an umbilical providing shore power.

Other Electronics

Beyond `M2FC` and `M2R` there were several other electronics systems on Martlet 2, some integrated with the main avionics.

RockBLOCK

`M2R` connected to a RockBLOCK Iridium satellite modem, which could relay position information from anywhere in the world. While a nice backup, this was probably not necessary at the launch site (a complete flat) and added complication to the avionics design and mounting. In the event the satellite modem did not have a chance to send any messages. In theory it is quite functional and would be useful on a future project where this level of backup communication is required.

Satellite modems can work well but consider if it is really required for a given flight, compared to the mass, power, and complexity cost.

PerfectFlite

To ensure the altitude reached would be recognised for record keeping purposes, a commercial altimeter (a PerfectFlite model) was fitted. No issues were found with this totally isolated system, although again clearer design on mounting and integration would have simplified launch operations.

Cameras

We originally fitted a GoPro Hero camera and a Mobius ActionCam, both activated manually (the GoPro over the radio) before launch. After the 2014 scrub, the camera plan was updated to use only “808 #16” cameras, configured to begin recording when power is applied. They were then connected to `M2FC`’s auxiliary power output, so they began recording when the rocket was armed. This system worked very well and made final arming easier. Unfortunately during the flight anomaly the cameras were broken up and the SD cards were lost.

Small 808 cameras worked well. Activating them via the main avionics was a good idea. In future, secure the SD cards as well as possible, perhaps by gluing.

Other Components

Metrons

Strain Gauges

- Assembly issues
- Potential to short out excitation, putting whole flight computer at risk

Thermocouples

Battery Cases

Arming Switches

Status LEDs

Antenna

Interconnects

- Spec55 is wonderful
- JST PA did a good job
- External connectors in future
- Connector in the airframe?
- Umbilical to shore?

Manufacture

Issues Encountered

Testing

Software Review

Technology Choices

Reliability Management

Watchdogs

Hardware Error Handling

Calibration

- Accels calibrate offset obviously, need to rotate for scale

Drivers

Flight State Machine

Safety Timeout

Ignition Detection

Status Collection and Reporting

Telemetry Collection, Forwarding and Storage

Software Interfaces

Testing

Ground Station Software

Release Management

Integration Review

Mounting

- Don't glue things
  - Really Really Really
  - LED broke off
  - Arming switch broke off
  - Other arming switch broke off
  - Arming key broke off
  - Both cameras broke off eventually
  - Don't glue things

Enclosures

- More enclosed
- Easier to assemble
- No need to open to reprogram etc

Switches and LEDs

Cameras

Antennas

Cabling

Sensors

Launch Retrospective

Missing Features

Assembly

Performance

Radio

Datalogging

Sensors

State Estimation

Pyrotechnics

Flight State

Issues Encountered

No RockBLOCK Signal In Enclosure

Accidental Metron Firing During Assembly

Arming Switch Location

- Too high up
- Behind launch rail

Radio Not Enabled

- Required reprogramming

Arming Key Broke

Arming Switch Detached

Status LED Detachedo

Upright Requirement

Ignition Detection Sensitivity

Lack of Safety Timeout

Early Body Metron Firing

SD Cards Lost

Conclusions and Recommendations