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Design and Implementation of Electronic Sub-systems for the STAJe- Phase 1 Payload

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Abstract

STAJe- Phase 1 is a University of Queensland flight program that implements cost effective commercially off-the-shelf (COTS) hardware component which aims to demonstrate high speed (Mach 3-5) electric propulsions. This paper concentrates on the design and manufacturing of customable printed circuit boards which are required to integrate with the mechanical design. It is an example of interdisciplinary collaboration made simple by using modern design and manufacturing approaches. These approaches also allow for rapid manufacturing and ground testing of the system. The functionality and challenges with the mechanical interfaces of each electronic sub-system for STAJe- Phase 1 payload is discussed within a framework of predefined scientific requirements.

Keywords: *Electric Propulsion, PCB Design, Rapid Manufacturing, COTS Hardware*

Nomenclature

A0 – Primary (Master) Arduino DUE

A1-A5 – Secondary (Slave) Arduino DUEs

COTS – Commercial-off-the-shelf

1. Introduction

1.1. Overview

Australia has a long history in hypersonic design, testing and flight trials. Unlike in most countries where hypersonics RDT&E was a Defence-driven effort, Australia's Defence hypersonic program commenced due to the success of university-based hypersonic fight testing through the HyShot [1], HyCAUSE [2]and HIFiRE [3] programs. This resulted in developing very cost-effective processes and procedures to undertake hypersonics RDT&E using sub-scale vehicles.

The Australian experience demonstrated that "university" and "small" does not equate to "unsophisticated". Many aspects of materials, guidance and control, aerodynamic database validation, hypersonic system integration etc can all be validated and de-risked by low-cost, sub-scale RDT&E.

STAJe-, a supersonic flight program consolidated into three phases, is one such novel approach which aims to explore the application of electric propulsion using affordable (COTS hardware) and rapid manufacturing techniques for the space and defense industry [4].

The STAJe- Phase 1 flight vehicle (Fig 1) is to be boosted to Mach 3.2 and 18km altitude where the

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Flight Module (to the left of the white dashed line) is separated from the Ejection Module [4].

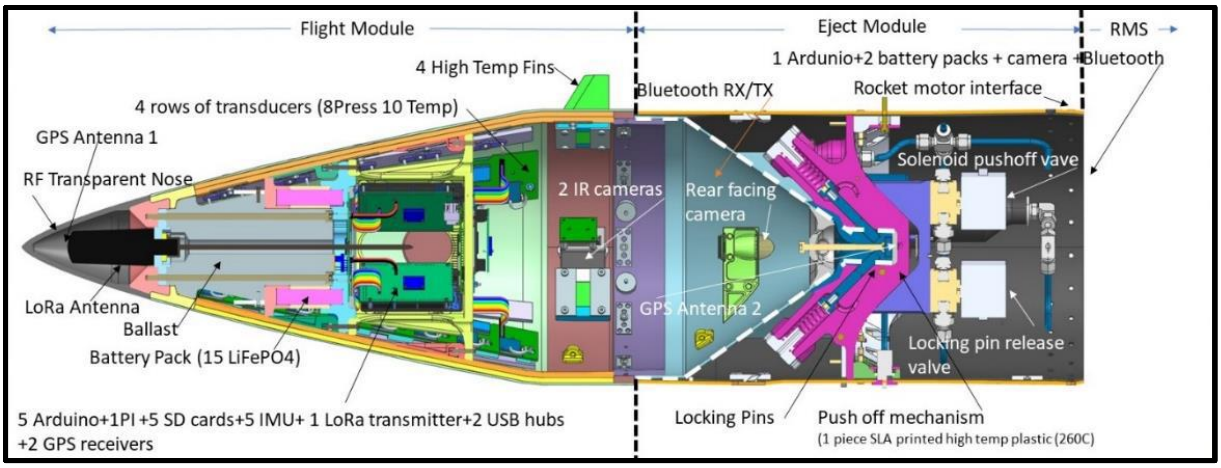


Fig 1. Technical drawing of the STAJe- (Phase 1) payload **[4]**.

This payload will demonstrate:

- new RF transparent high temperature materials that can be mass produced [4];
- bespoke shell design that will withstand the temperature of the flight and the loads during accelerations (that can be wound, or pressure molded) [4];
- the application of additive manufacturing with infill for all internal parts [4];
- COTS hardware and software [4];
- IR cameras and IR transparent materials that are transparent at various wavelengths for distributed temperature measurements, rather than point measurements;
- CSiC fins that implement manufacturing processes that are also applicable to mass manufacturing [4];
- Long Range WIFI [4] and Bluetooth for communications external and internal to the payload, respectively; and
- new attitude and guidance software.

By using light-weight materials and infills in the additive manufactured bulkheads, the total weight of the Flight Module has been reduced to 16kg, of which 8 kg is ballast required for aerodynamic stability.

1.2. Aim

The aim of this paper is to outline our electrical designs and their implementation for STAJe- Phase 1 payload.

The scientific requirements and success criteria for the flight program were enclosed within a scientific requirements document initially developed to provide direction to the program. It details the electrical requirements for the Flight Module and the Ejection Module (Fig 1).

The major electrical requirements for Phase 1 were to:

- read and store the pressure and temperature data from the payload skin during flight; and
- recover the Flight Module in what amounted to a GPS denied environment.

In order to satisfy the first requirement, a range of custom PCBs housing different COTS components were designed and implemented as electronic sub-systems for the payload. This process involved designing a schematic as per the electrical requirement, acquiring the relevant hardware, ground testing of the circuit assembly and then manufacturing it for the launch. All the custom electronic printed circuit boards were designed to fit the mechanical structures within the payload. This requires interdisciplinary collaboration and design of complex hardware structures. This type of integration is pivotal for the success of any flight program.

For the payload recovery in a GPS denied environment, telemetry tower stations ranging from 5m to 13m in height, have been designed and will be installed at multiple locations at the launch range. A long-range Wi-Fi transceiver (LORA technology) module is used to track the payload by implementing time of arrival (TOA) of a simple sentence, received signal strength which is correlated with experimental measurements of distance (RSSI) as well as measurements of the Doppler Shift in the arriving signals [4].

2. Flight Module

Multiple Arduino DUEs have been used in a primary-secondary (Master-Slave) configuration for STAJe-phase 1, such that a primary microprocessor, A0, controls all the secondary microprocessors, A1-A5. Communication between the primary and secondary microcontrollers is via I2C protocol. All except A5 (located in the Ejection Module) have shields (custom made PCBs) which house a micro-SD card reader, current and voltage sensors and an a 6DOF IMU. High fidelity data is stored on the SD card of each secondary microcontroller.

Furthermore, A0, being the controller, has two additional shields (Fig 2):

- A LORA shield (COTS transceiver module) which is responsible for transmitting limited flight data down to the ground control stations. The LORA shield also has a GPS module which is connected to a patch antenna; and
- A GPS shield (custom made PCB with COTS components) houses a second GPS module, the patch antenna for which is placed in the plunger (rear section of the payload). This approach increases the probability of GPS data being received throughout the flight trajectory (Fig 1).

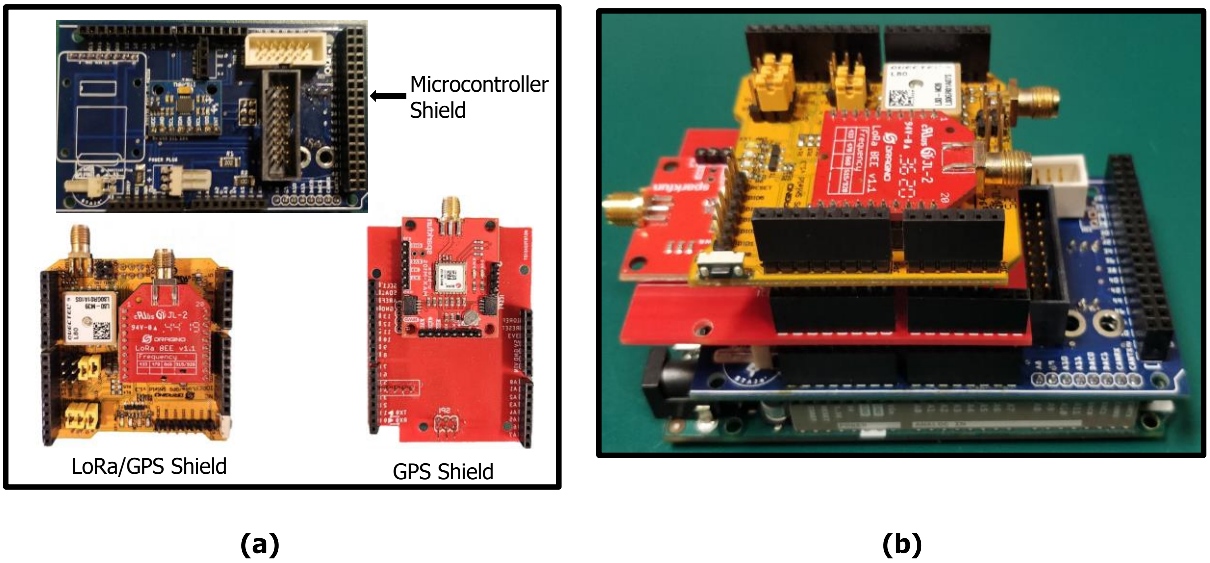


Fig 2. Three shields used on A0 (a). Microcontroller and GPS shields are developed in-house which incorporates COTS hardware. The Lora/GPS is a COTS component **[5]**. A0 as an integrated stack (b).

The secondary microcontrollers (A1-A4) sit inside a 3D printed structure designed to protect them during impact with the ground. It is a 3D printed structure made from plastic and referred to as the Cage as shown in Fig 3. Each of these secondary microcontrollers are connected to their own Collection Board (custom made PCB) which collects data from eight pressure transducers and ten RTDs (Resistance Temperature Detector). These measurements are made along the forebody of the payload in every quadrant. The pressure transducers communicate with their respective microcontroller (A1-A4) via a multiplexer and I2C protocol while the RTDs, use the SPI protocol.

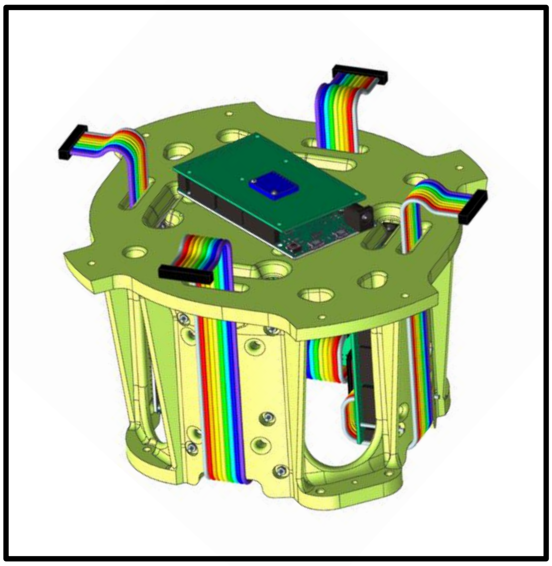
The Cage also houses A0 and a Raspberry Pi 4B which is connected to three IR cameras.

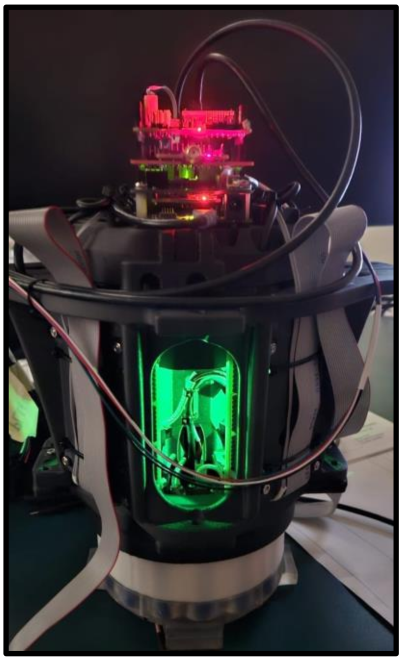
The programming ports of all the microcontrollers are connected to a USB-C hub which is accessed via the umbilical hatch (Fig 1). This enables:

- pre-flight monitoring of all the electronic components via umbilical to the ground station, ensuring proper functionality; and
- reprogramming of the microcontrollers as required.

Finally, the power for the payload is provided by a bank of Lithium-ion polymer batteries. These are located in front of the Cage. This location for the batteries was chosen to assist with making the vehicle aerodynamically stable. Again, this type of integration between the mechanical and electrical systems is not uncommon in any system, however, flight vehicles have their own unique requirements.

It should also be noted that the Cage is located aft of the ballast weight. This is strategical, so that the momentum of the payload is biased to the front of the cage. This maximizes the probability of successfully recovering the SD cards on each of the microcontrollers.





(a) **(b)**

Fig 3. CAD model of the Cage (a) and 3D printed mechanical structure with electronic systems (b).

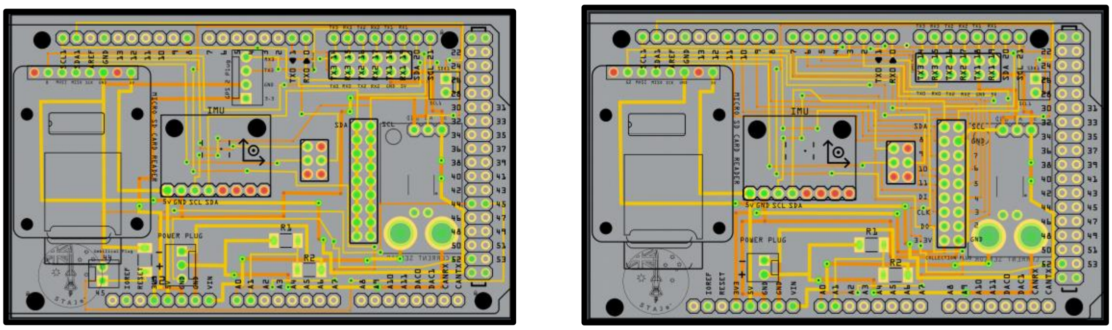
2.1. Microcontroller Shield

The concept of using a shield was introduced to reduce the wiring. It is argued that this approach reduces the complexity and the potential for failures during flight. Two shields were designed using Fritzing software, one for A0 and the other for A1-A4 (Fig 4). Both the shields have slightly different functionalities:

- A0 Shield

  The aims of this shield are to:

  - provide flightworthy access for control all the secondary Arduinos A1-A4 (in the Flight module), A5 (in the Ejection module) and the Raspberry Pi via I2C (WIRE) and Serial connections, respectively;
  - simple routing of the digital ports required for internal communications;
  - record inertial measurements along the centerline of the vehicle [4];
  - store data collected by A0 on an SD card;
  - measure the voltage supplied to A0 from the batteries via an analog port;
  - measure the current being supplied to A0 via an analog port; and
  - detect the launch through detachment of the umbilical.



(a) **(b)**

Fig 4. A0 shield (a) and A1-A4 shield (b). The orange lines indicate the copper traces on the bottom layer of the PCB while the yellow lines indicate the copper traces on top layer of the PCB.

- A1-A4 Shield

In addition to the capabilities listed for A0, the A1-A4 shields also have a multipin plug used to communicate over SPI and I2C (WIRE) to their respective Collection boards. It should be noted that the I2C communication from A0 to A1-A5 is via the WIRE port on A0, but the WIRE 1 port on A1-A5. The communication of A1-A4 with their respective Collection Board is via WIRE. This ensures that additional pullup resisters are not required.

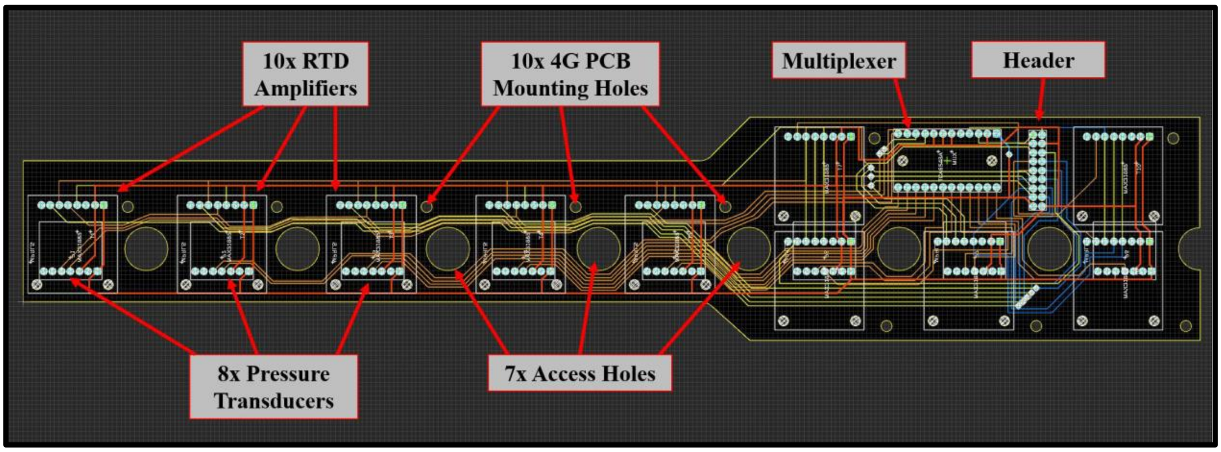
All COTS components were initially individually tested to ensure component compatibility with Arduino DUE, after which the PCB was designed.

2.2. Collection Boards

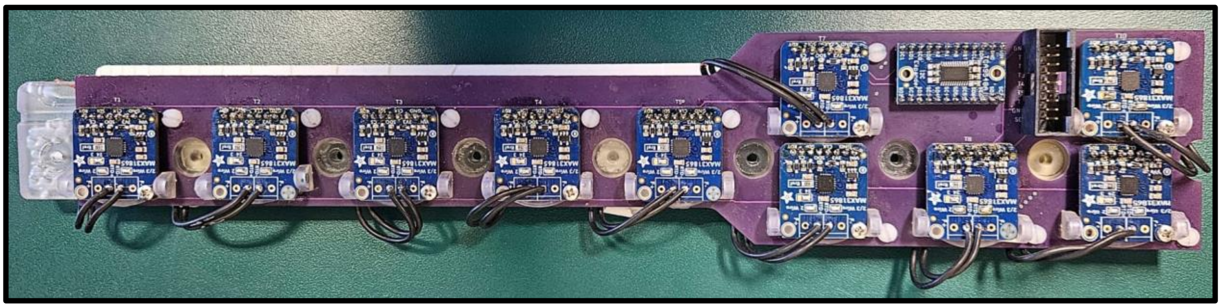
The first flight of the STAJe- program is required to have four separate rows of temperature and pressure measurements along the length of the payload, as per the scientific requirements. Each row will be measured by a single transducer assembly. Each assembly consists of the transducer mount, the assembly mount, and the Collection Board (custom PCB) which is populated with the components [4]. Similar to Power PCB, the designing of Collection Boards also required a mechanical and an electrical interface for bolt hole alignment. The transducer mount and Collection Board work together to secure the transducers in place, ensuring the location of measurement is accurate.

As seen in Fig 5, the Collection Board is a four-layer PCB which is used to mount all the electrical components of each sensor module which was designed using Autodesk Fusion 360 software. Each sensor module contains ten RTD amplifiers (MAX31865), eight pressure transducers (MPRLS), a multiplexer (TCA9548A), and a multipin header [4]. All sensors are ultimately routed to this header, either directly in the case of the RTD amplifiers, or via the multiplexer in the case of the pressure transducers. This is so that the secondary microcontroller which the Collection Board feeds to, can access all transducers via the header.

The transducer assemblies are mounted to the inside wall of the vehicle [4]. As such, considerable effort was required to ensure the transducers and mounting structures could withstand the rigors of the flight. The RTD amplifiers are assembled on the top layer facing the inside of the Flight Module. While the RTDs and pressure sensors are positioned on the bottom layer closer to the payload skin as shown in Fig 5.



(a)



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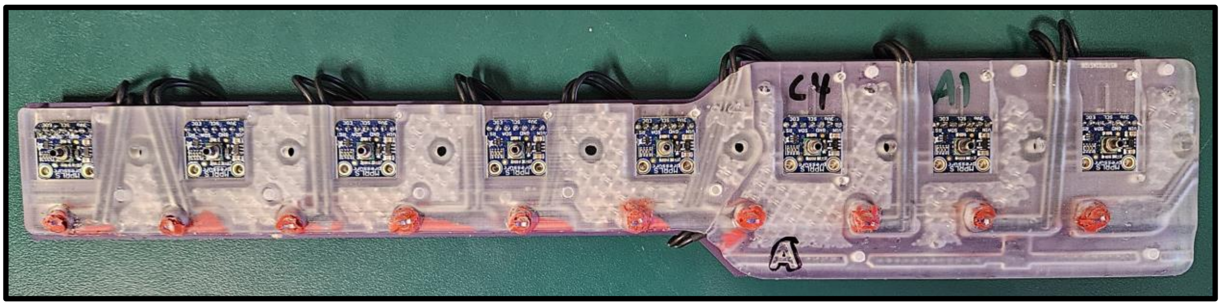


(c)

Fig 5. PCB view of Collection Board (a). Front view which has the RTD amplifier and Multiplexer (b), whereas the back view of the assembly has RTDs and Pressure sensors (c).

2.3. Power PCB

The Power PCB provides power to the entire payload. It is a two-layer custom designed PCB which sits on top of the battery pack as depicted in Fig 6. The electrical design of this board was relatively simple, however, integration into the mechanical design was not. The need to develop designs which meet the electrical and mechanical requirements can be time consuming. This was largely overcome by using a step file provided from the mechanical designers to define the PCB shape along with the bolt hole orientation. The design of the board was then possible using Fritzing software for board development.

The board consists of:

- an optically coupled relay which enables switch from external power supply to internal battery power. This is controlled by A0 and is initiated 120s prior to the expected launch time; (The payload boots up on external power supplied through the umbilical)
- a regulator which converts the power supply voltage to 5V necessary for the PI;
- circuitry for battery charging. This PCB is directly connected to the battery cells which have a specific arrangement. Three battery cells connected in series to make up one bank, and five such banks are connected in parallel to provide a maximum voltage of 9.6V.

It is interesting to note that there is no battery management system on board. Instead, a parallel charging approach controlled externally has been implemented.

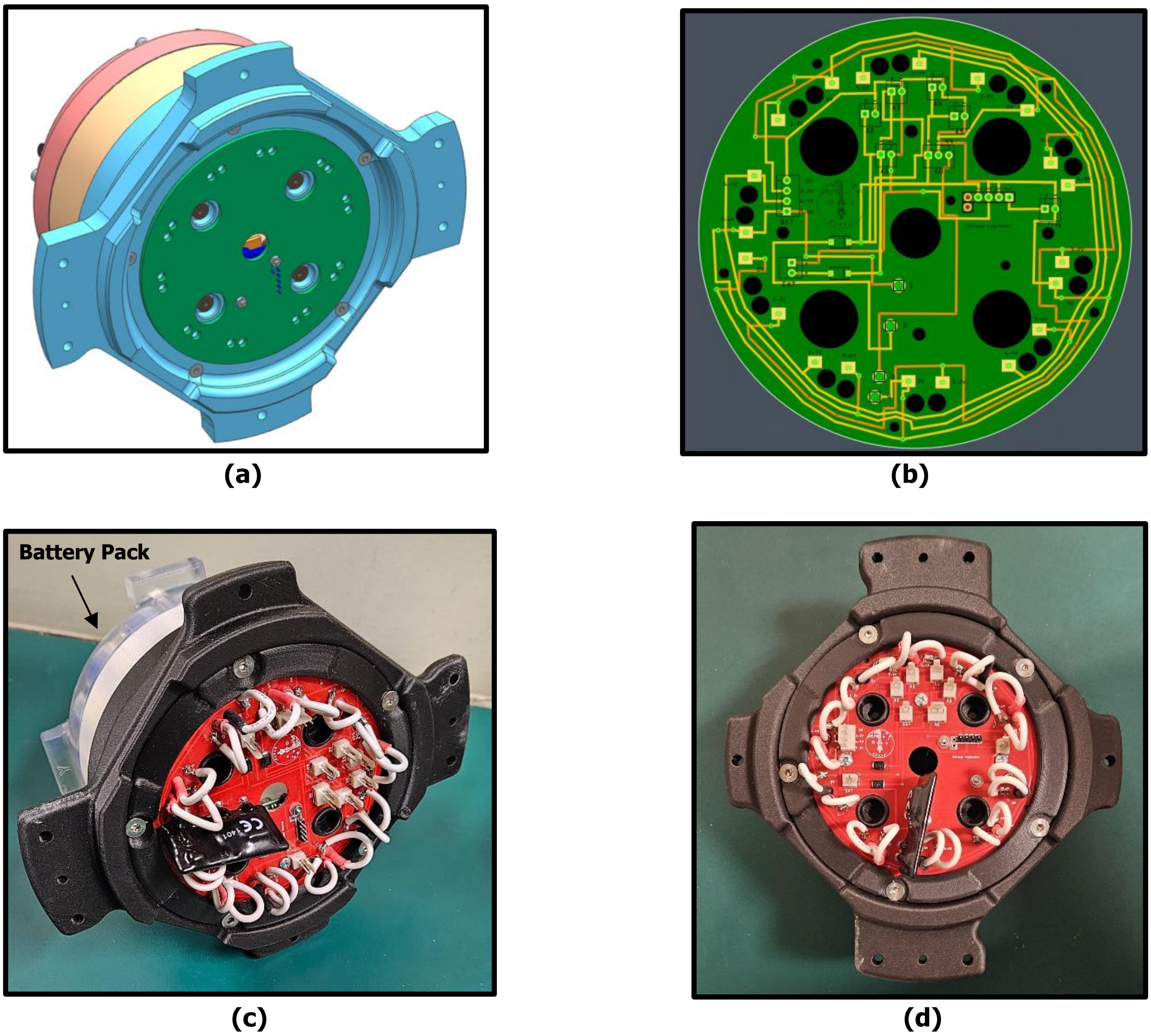


Fig 6. Power PCB on the ballast (a). PCB view of Power PCB (b). (c) and (d) show the assembled Power PCB on a 3D printed mechanical ballast connected to the battery pack.

3. Ejection Module

The Ejection Module has only one secondary microcontroller A5 which is controlled by A0 via USB-C cable through the plunger (Fig 1). A5 enables separation from the Flight Module using two solenoid valves placed inside the Ejection Module [4]. An additional battery pack is used to power the valves which are connected to air cylinders responsible for Ejection (Fig 1) [4].

Being the only secondary microcontroller in the Ejection Module, A5, has two custom made PCBs as listed below (Fig 7):

- A5 shield

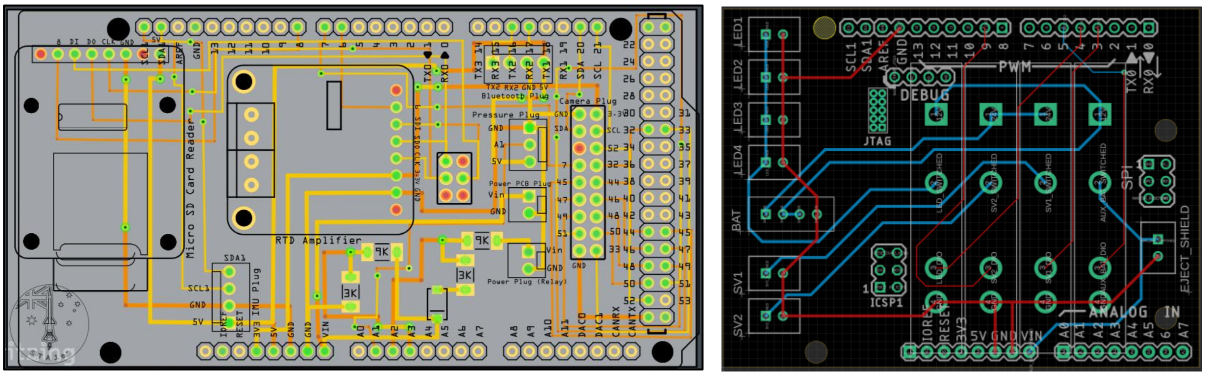
  This shield is connected to:

  - a camera (OV-7670) for taking images of the payload module as it is ejected;
  - a Bluetooth module (HC-05) which will transmit images from the Eject module camera to the Flight Module;
  - LED lights which will be used by the Flight Module camera to measure its speed;
  - an RTD amplifier to measure the air cylinder temperature via SPI protocol;
  - a pressure transducer for measuring the air cylinder pressure via analog pins;
  - an SD card reader to store the temperature and pressure data;
  - additional battery pack with means of measuring their voltage states via analog pins using a resistor divider.

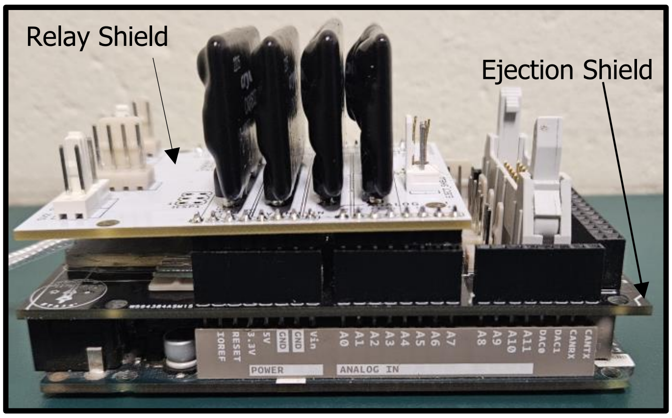
- Relay Shield

  The relay shield is another custom PCB designed to accommodate four optically coupled relays. The function of each is to:

  - enable switching from Flight Module battery power to the Ejection battery power which is used to power all the electronic components in the Ejection Module via A5;
  - provide battery power to the solenoid valves;
  - provide battery power to the LED lights.



(a) **(b)**



(c)

Fig 7. PCB view of the Ejection shield (a) and the Relay shield (b). A5 assembled (c).

4. Conclusion

The design of all the electronic subsystems and their integration with the mechanical structures has been presented. This paper also details the functionality of each electronic custom designed part and discusses measures taken to mitigate certain integration challenges. It was demonstrated that a sophisticated system could be manufactured using cost-effective COTS hardware. All the electronic sub-systems have been successfully tested to satisfy the scientific requirements for STAJe- Phase 1 flight program.

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6. Acknowledgements

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7. References

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