Improving an Active Stability System of a Sounding Rocket via Data Monitoring and Interpretation Methodologies

MECH5080M **Team** Project Report
Team number: 101
Supervisor: *Dr Jongrae Kim*
Title: *Improving an Active Stability System of a Sounding Rocket via Data Monitoring and Interpretation Methodologies*
Date: *30/04/2024*

IMPROVING AN ACTIVE STABILITY SYSTEM OF A SOUNDING ROCKET VIA DATA MONITORING AND INTERPRETATION METHODOLOGIES

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ABSTRACT

A common barrier to maximising the altitude of a rocket is the angle induced by wind, known as weathercocking. To overcome this issue, active stabilisation is often implemented, with the intent of keeping the rocket's flight path as vertical as possible.

The project described in this report encompasses the improvement of a previously designed actively controlled canard system for a sounding rocket, through the design of a brand-new flight computer board running an STM-32 chip with bare metal firmware, a sturdier and better characterised mechanical system, refined control logic, and the addition of a custom telemetry setup with extended data monitoring and interpretation.

Full simulation and physical tests including a successful launch with the control system activated were conducted to evaluate the performance of the components and ensure a safe and reliable system that could be implemented within future rocket designs.

Keywords *— active control system, sounding rocket, canard module*

1. INTRODUCTION

Sounding rockets, tools used for suborbital testing and atmospheric studies, often encounter trajectory deviations due to wind and other external turbulences. These disturbances can lead to unwanted dispersion and diminished peak altitudes (apogees). By incorporating active vertical controllers, the trajectory of the rocket can be corrected, thus generate a safer and more reliable flight. This project was conducted to improve an existing active control system by making significant changes and integrating further data methodologies.

Whilst Aptos, a module that enables active stabilisation, had been previously built and field tested in the Pathfinder rocket, it had never been activated during flight [1]. The current group refined the previous design by remodelling the canard transmission mechanism and reimplementing the entire hardware-software architecture. The update included a new bare-metal C firmware, custom electronics, and further features such as a database storage system, visualisation tools and telemetry capabilities.

Testing was conducted to verify the system's integrity. Upon completion of the design phase, readings from the new hardware and firmware were benchmarked against those from commercial mobile applications. Visual testing procedures were implemented to confirm the accurate orientation of the canard module. The hardware was placed in a vacuum chamber to mimic the atmospheric pressure differences experienced during flight. Ultimately, the module was successfully launched with the active controller engaged. Despite not maintaining a fully vertical trajectory, corrective oscillations were observed that are later discussed in the report.

After a brief theoretical background, this report begins by introducing the mechanical system and canards (sections 3.1 & 3.2), followed by the active control improvements (section 3.3). The next sections introduce the implementation of the new custom flight computer board and firmware (sections 3.4 & 3.5). The final design sections highlight the addition of a database, visualisation tool, and telemetry system (sections 3.6-3.8). The report is concluded with a discussion of results and future work (chapters 4-6).

2. THEORETICAL BACKGROUND

2.1. Rocket Active Stability

Whilst the flight angle of a rocket can be controlled to some degree through passive stability, a common obstacle to vertical flight is the tilting of a rocket by the wind, an effect known as weathercocking [2]. To counteract weathercocking and allow more vertical trajectories, different active stability systems have been developed through the years. The most common ones being a gimbaled engine exhausts which permit thrust vectoring [3]. A second method is using aerodynamic surfaces on the passive fins, which work in very similar ways as the ones on aircraft [4]. However, both those systems are mounted at the aft of the rocket and require a lot of internal space to store the different systems next to the rocket motor.

The third option, which has been chosen for the Aptos module [1], involves aerodynamic control by using aerofoils called canards. These fins positioned midsection of the rocket adjust their attack angles in response to changes in orientation, altering the airflow to generate torque for directional control.

2.2. Data Pipelines

A data pipeline was designed to support the improvement of the active vertical control of rockets. A data pipeline sequentially processes units where the output of one serve as the input for the next [5]. This automated system moves data from storage units to higher level applications, reducing manual handling. After a test flight, data from the onboard computer is uploaded to a centralised database for visualisation and analysis. For further refinement, the data is formatted for compatibility with MATLAB/Simulink simulations, enhancing control adjustments.

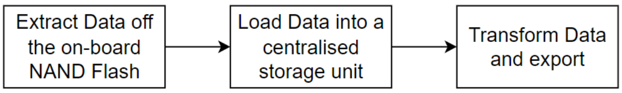

Figure 2.2 Data Pipeline overview [6]

2.3. Literature Review

In rocketry applications, there are a variety of technologies employed to support the active stabilisation systems of controlled rocket designs.

From a flight hardware perspective, various processing units (flight computers) were used by other groups: Commercial-Off-The-Shelf (COTS), Arduinos, Teensy and custom designs. These options are seen frequently, due to their ease of prototyping. Although simple to use, they have limitations in flexibility due to predefined libraries. For more complex applications, other rocketry teams have adopted more powerful microcontrollers, which required more advanced C programming. For example, the launch vehicle TEXUS/MAXUS [7] integrated five on-board experiments that had a custom data collection system.

NASA's sounding rocket program contains several large rockets capable of reaching altitudes between 100km to 1400km. To maintain the launch trajectory, a system called the "Boost Guidance System (BGS)" was developed for rockets launched from smaller ranges. This system uses four canards, operated by two electronic servos with pneumatic support, guided by an LN-200 Inertial Measurement Unit (IMU). As the system contains only two degrees of freedom, it only corrects pitch and yaw, while the rocket is expected to roll at ~4Hz. Eighteen seconds into flight, the canards disconnect from the motors via pyrotechnics, leaving the rest of the flight unguided [8]. The size and cost of this hybrid electrical-pneumatic actuation system with an LN-200 IMU make it impractical for amateur rocketry.

Attempts to integrate canard control systems into rockets have been explored by university groups, although comprehensive documentation is often scarce, with findings only briefly discussed on rocketry-specific forums. A notable attempt was by a team from TU Delft [9], who developed a rocket with canard controls effective in the roll axis alone. This modification reportedly mitigated weathercocking and increased the rocket's apogee, though it also introduced a downwash effect on the passive fins. This observation influenced the integration of a spin-can design in the Pathfinder project. Additionally, the University of Canterbury [10] stands out as the only team to have launched a rocket equipped with a three-axis active control system, yet they have withheld specific outcomes of their project.

2.4 Previous Work

The active control module, officially named Aptos, utilises four independently actuated servos situated in the midsection of the sounding rocket. This year's development builds upon foundational work done previously [1], during which two launches were conducted without the control activated. This happened due to insufficient testing and hardware reliability concerns.

The control design for the Aptos module is centred around a Linear Quadratic Regulator (LQR) controller. This controller optimises a linear dynamic system by minimizing a quadratic cost function, assuming the system, or plant, is linear [11]. Although the canard system itself is nonlinear, linearisation is achieved using first-order Taylor series techniques and small-angle approximations.

The system processes inputs from the onboard gyroscope and accelerometer—components of the Inertial Measurement Unit (IMU)—along with the barometer. These sensors provide critical data on the rocket's orientation, altitude, and vertical velocity. The primary goal of the system is to achieve a vertical orientation, such that the pitch (θ) and yaw (ψ) angles equal zero. Any deviation from this desired state is detected by the controller, which calculates the discrepancy as an error signal. This error is then used to adjust canard actuation angles, minimising the deviation and stabilising the rocket. Through closed loop feedback, the IMU provides the controller with updates on the orientation to continually adjust its output. This output is generically represented in Appendix A Formula 1-5.

The canard deflection angle (δ_i where i denotes the canard number) is derived using Formula 6-9 in Appendix A. This calculation involves the desired moment (M_i) required by each canard to achieve the targeted orientation, the canard's moment coefficient (C_{m_i}), its surface area (A_i), the air density (ρ) and the velocity of the rocket (V).

3. SYSTEM DESIGN

This section presents an overview of the design. The final architecture is illustrated in Figure 3.1, which demonstrates the data flow, starting from collection and storage, followed by its conversion in various formats. Improvements have been carried out on the mechanical design, firmware flow, data transmission and software interpretation, with the overarching goal to enable a faster development of the active controller.

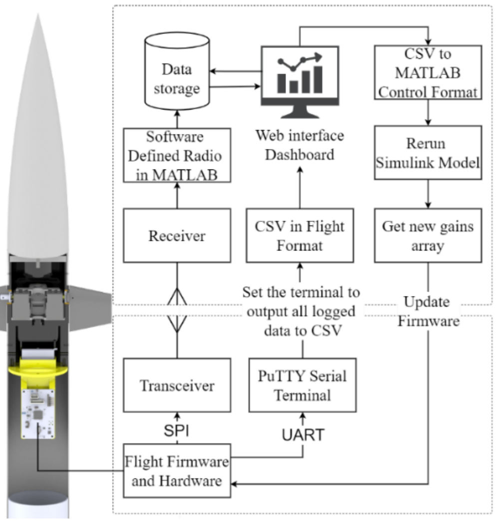

Figure 3.1 Full system integration [6]

3.1. Module Mechanical Improvement

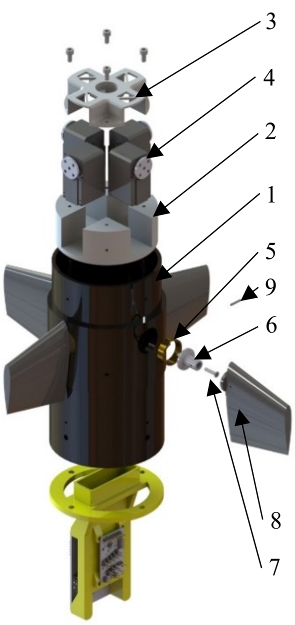

Figure 3.2. Exploded View of the Aptos Module

The Aptos module is positioned below the nosecone, at the fore of the rocket. It contains the flight hardware and the mechanisms that enable the canards to modify the rocket's trajectory.

The assembly of the module begins with the installation of four servomotors (4) onto a 3D-printed frame (2). A 3D-printed lid (3) is placed over the servomotors and the entire unit is inserted into a Delrin casing (1) where bushings (5) were pre-glued. Shafts (6) are attached to the servomotors and secured with a bolt (7). Canards (8) are then mounted onto these shafts and fastened using shear pins. The design emphasises symmetry, and all 3D-printed parts, including the frame and lid, were made from Polylactic Acid (PLA), using a five-wall loop and 15% infill. The shear pins were made with anycubic resin.

The design of the Aptos module has improved the robustness and safety of the active control flight system. The previously used servomotors featured plastic gears, which are prone to breaking under high torque. To address this issue, they were replaced with the STS3215 servomotors, which are equipped with more durable metal gears. Additionally, to protect these upgraded servomotors during landing, shear pins that transmit load during flight but break upon impact were integrated.

To further safeguard the servomotors from the axial load of the fins, four brass bushings were embedded in the module. These bushings absorb the axial stress, preventing it from impacting the servomotors. They feature a slotted design coupled with a lip that engages with the canards, allowing a controlled motion range of +/- 15° to avoid exceeding the aerofoils' stall angle of 16.5°.

3.2. Canards

The overall shape of the canards has been determined using the NACA 4-digit aerofoil standards and a Computational Fluids Dynamics (CFD) software, known as XLFR5. The most important parameters to look at is how the coefficient of lift (Cl), changes according to the angle of attack (AoA).

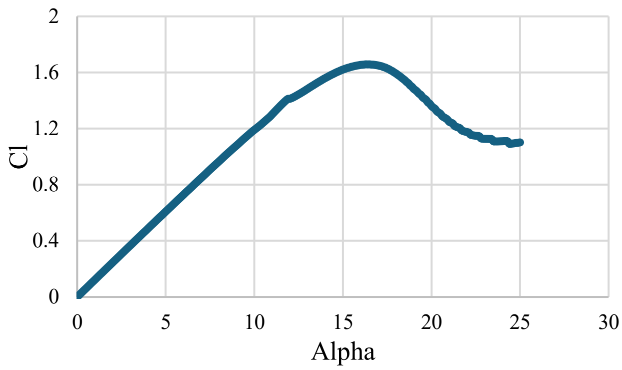

Figure 3.3 CFD Results comparing the Cl to the AoA of the NACA-0016 aerofoil

The aerofoil's shape was decided to be trapezoidal due to its aerodynamic efficiency and ease of manufacture compared to a rectangular or elliptical shape.

The planform of the aerofoil was selected after an empirical study to find the shape that would minimise drag and maximise lift. This was done to reduce the required angle of attack of the aerofoil, which would allow the system to react better to gust winds.

3.3. Avionics Hardware

The flight computer — a processing unit that controls the aerospace vehicles and gather data from onboard sensors — has undergone a complete redesign. The complete system was brought onto a printed circuit board (PCB) with upgraded components [16].

The assembled flight computer, shown in Figure 3.4, is a four-layer PCB measuring 75mm x 45mm. It is mounted to a PLA printed bracket on the bottom of the Aptos module using silicone anti vibration standoffs in the corner mounting holes.

Safety and reliability are critical for aerial systems due to the severe consequences of malfunctions, where human intervention is not possible. Therefore, the electrical schematics were designed to mitigate the impact of any issues that arise from vibration or component fatigue. Arming switches, identified as the components most susceptible to mechanical failures during launch, were a particular focus. The design incorporates debounce circuits and accounts for fail states to ensure vibrations or component fatigue do not trigger sudden power-offs. This precaution helps maintain the canards at safe angles, preventing hazardous situations. Additionally, dual redundancy of components was considered due to the analytical analysis of [17] showing the improvements to reliability, however, was not included due to cost and the short flight duration.

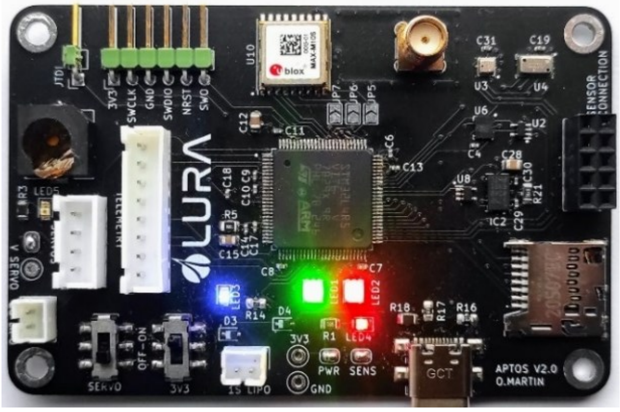

Figure 3.4: New Flight Computer [16]

Components for the flight computer were compared using selection matrixes. Selection matrices are tools that aid the decision-making process by evaluating various attributes of the possible options. The list of key components that were selected for the flight computer is displayed in Table 3.1. The main parts of the system are the microcontroller unit (MCU), responsible for all the flight onboard processing, the inertial measurement unit (IMU), a device which measures angular and linear acceleration in three axes, the NOT-AND (NAND) Flash storage unit, which store data during flight and the barometer, capable of measuring atmospheric pressure in millibars. The latter is used to derive altitude and vertical velocity.

Table 3.1: Flight Computer Components

Type	Component
MCU	STM32L4R5VIT6
Barometer	MS5611-01BA
IMU	LSM6DS3
Accelerometer	ADXL375BCCZ
Temperature & humidity	BME280
Global navigation satellite system (GNSS)	MAX-M10S
Switch Debounce IC	MAX6816EUS+T
3V3 Regulator	TLV76733DGNR
NAND Flash	MT29F8G08ABACAWP

3.4. Firmware

The firmware development went through a series of iterative cycles, each including implementation, debugging, and testing. Each cycle aimed to refine the system's functionality, with a simplified outline of the firmware loop shown in Figure 3.5. During the flight, the firmware adapted its sensor data acquisition rates to match distinct flight stages—launchpad, ascent, apogee, descent, and landing. The sensor readings were used to monitor the launch vehicle's environmental conditions and spatial position.

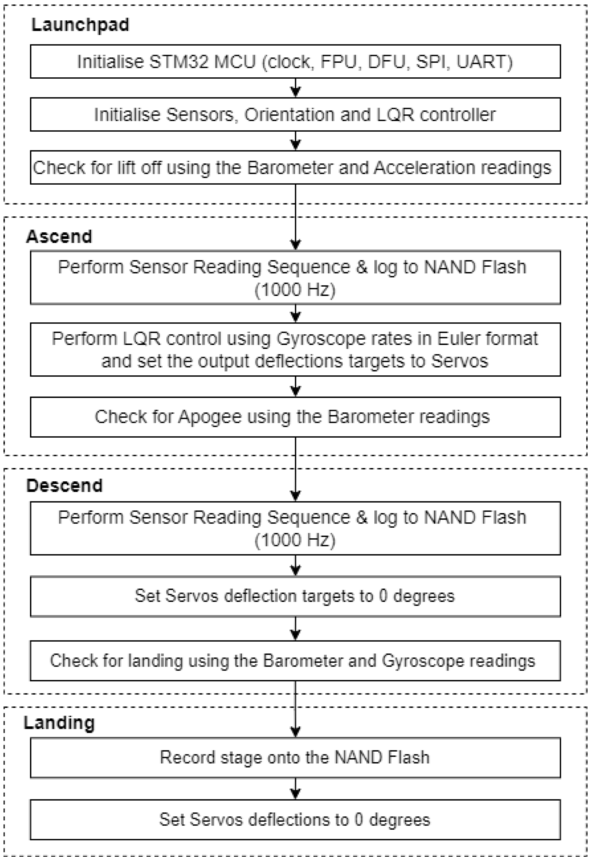

Figure 3.5 Simplified Main Loop Flowchart (a more detailed chart can be seen in Appendix B, Figure B.3)

The STM32 uses a Serial Peripheral Interface (SPI) bus to interface with the sensor hardware on the flight computer. As the firmware was developed in bare metal C, custom drivers had been created to setup and retrieve data from each sensor. These drivers were created to interact with the specific registers required, with no additional bloat which could slow the firmware down. Additionally, the servo motors required a dedicated driver to communicate through single-wire Universal asynchronous receiver-transmitter (UART). UART is used to individually set up each servo's settings such as offset, and software angle limits, and can command the target deflections angles calculated by the controller during flight.

The Linear-Quadratic Regulator (LQR) controller, developed in MATLAB Simulink, was translated into C and embedded onto the firmware. Data from the IMU was used for orientation determination. Additionally, the axes of the gyroscope were not in the same reference frame as the LQR controller. An axis conversion was implemented to align the data correctly with the controller's requirements as shown on Figure 3.6.

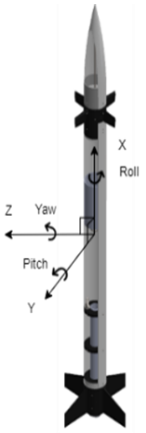

Figure 3.6 Final IMU Axis System [6]

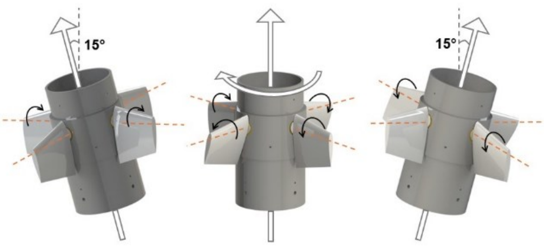

Figure 3.7: Canard Orientation Response [6]

3.5. Storage and display

The subsequent phase was the creation of management tools that support the continuous improvement of the LQR controller. As a result, the flight data was loaded into a centralised storage unit and pulled into a dashboard for visualisation. To improve the controller further, data can be transformed in a format that is compatible with the input to the MATLAB Simulink controller.

For storage purposes, a local MySQL database instance was created [6]. This database acts as a robust platform for data storage, retrieval, and management [18]. The generated MySQL database supports various data types such as numerical, text, and time data types, which are needed to capture the flight profile. The database consists of three tables that store general flight information, sensor readings and controller output. The latter two connect to the general information table through a unique identifier key and include timestamps for each data entry.

Additionally, a web-based application has been developed to facilitate data visualisation. This application retrieves data from the databases and presents it in an intuitive format. Flask was chosen for its RESTful (Representational State Transfer) request handling, built-in development server, and integrated debugger that streamline development.

The dashboard, namely LURA Dash, offers multiple pages that allow users to interact with data in various formats. The main tab can be used to select a flight and display it on the screen. Once visualised and validated, the flight data can be exported in the appropriate format for the input of the controller. The exported file can be integrated in MATLAB to tune the controller gains with real-world data—a significant enhancement from the previous reliance on simulated data alone. This integration promises to simplify and streamline the testing and improvement process of the controller.

3.6. Telemetry

A new telemetry system was developed to increase data redundancy and improve packaging within the rocket. The system comprised of a transmission PCB capable of communication with the flight computer board, in addition to a custom antenna design. Receiver software was also built to demodulate and decode the incoming data on the ground.

A TI CC1200 transceiver was selected for its small form factor and low cost, whilst providing powerful capabilities, including frequency and power programming for ISM and higher-power international operation. The transmission PCB was capable of 2-way communication, future-proofing the design.

The transceiver schematic was based on the TI reference schematic [19] to ensure high reliability. The PCB design was completed to meet a range of guidelines applicable to Rf work [20], most importantly incorporating impedance matched traces, frequent vias for heat dissipation, trace length and curvature tuning, separation of Rf, digital and power circuitry, the inclusion of ground planes wherever possible, and a four layer stack-up to reduce noise.

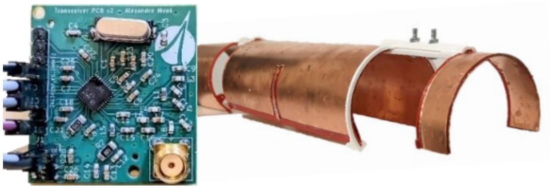
Figure 3.8: Transceiver PCB and Antenna

The ability to acquire low-cost dielectrically characterised 3D printer filament enabled the production of shaped antennas that would otherwise be expensive to acquire or manufacture [21]. A curved patch antenna is developed that moulds to the inner tube of the rocket's body. This design allows for space-efficient integration by accommodating the electronics within the antenna itself, while also maximising its size to house a full-wave patch antenna. Additionally, there is the potential for future external integration on the rocket, which would facilitate telemetry when carbon-fibre is used, as it inherently blocks radio frequencies.

A Polyethylene Terephthalate (PET-G) filament was selected for its ideal dielectric constant of and low cost [21]. Antenna measurements were based on the standard patch design process [22]. To improve the radiation pattern of the antenna, testing was also completed with the addition of Yagi-elements [23].

A Nooelec Software Defined Radio (SDR) module was selected for ground telemetry reception due to its low cost and ubiquity. A custom MATLAB script was developed to filter, frequency-track, and demodulate the incoming radio signals.

4. RESULTS

4.1.1 Vacuum chamber testing

To validate that the flight computer could correctly detect flight stages, the board was placed in a vacuum chamber to simulate the air pressure at higher altitude.

The flight computer and battery were placed in the vacuum chamber and the pressure was reduced to -0.6bar from atmospheric pressure. As illustrated in Figure 4.1, the flight computer interpreted a decrease in pressure as a rocket lift off. After reaching the target pressure, the pump was deactivated and the valve was opened, allowing the pressure to gradually return to ground conditions. From the flight computer perspective, apogee was detected followed by descent. Once at the initial pressure, the landed state was correctly detected. The test data was recorded onto the onboard NAND flash using the standard flight routine and later retrieved in CSV format.

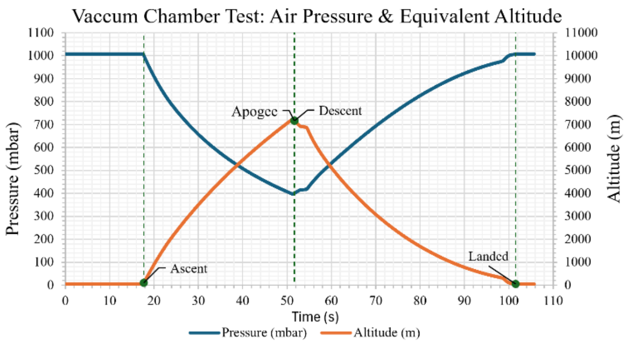

Figure 4.1: Graph showing Pressure and Altitude Results of the Vacuum Chamber Test

Unfortunately, the air pressure profile was not identical to an actual flight profile, which would have had a faster time to apogee and a slow linear descent. This happened because of the limitations of the vacuum chamber with manual valve controls and limited pump speed. However, the results still provided a representative look at the pressure sensing and flight stage detection.

4.1.2 Wind tunnel

The wind tunnel tests were carried out at the ESTACA engineering school in France. A total of four different jigs were created, each representing a set of two canards with different angles of attack ranging from 0 to 15°. The wind tunnel has a maximum windspeed of 40m/s, and each jig was tested three times. To compare data between simulations and experimental wind tunnel results, the Mach number in the CFD software was also set to 0.121.

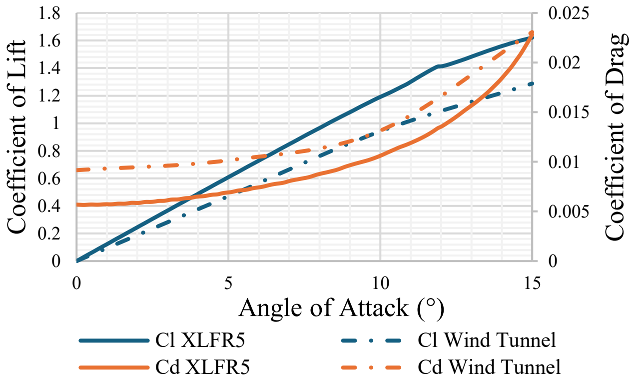

Figure 4.2. Comparison of CFD and Wind Tunnel Aerodynamic Coefficients Results

The CFD coefficients of lift were higher than the experimental data, having a maximum discrepancy of 25.850%. The experimental coefficients of drag were higher than the ones from CFD, with a maximum discrepancy of 37.872%.

These coefficient differences could be caused by the print imperfections of the canards or the jigs that disturbed the airflow by introducing turbulences. Additionally, the wind tunnel rig software might have introduced approximation errors when the coefficients were derived.

4.1.3 Telemetry testing

The telemetry PCB was successfully manufactured and tested, supplying adequately stable voltages, and filtering the output signal at the right frequency without significant reflections.

The custom antenna design was effective, as full characterisation demonstrated similar gains and better directionality than an off-the-shelf helical antenna.

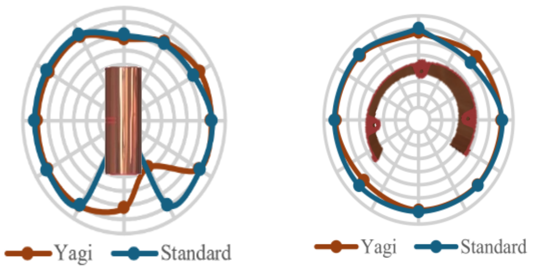

Figure 4.3. Antenna Radiation Patterns

The receiver showed reliable frequency tracking when signal-to-noise ratio was >1.5, however the peak-finding algorithm was very slow (taking up to 0.7s per frame of data), so improvements would be required for live telemetry demodulation.

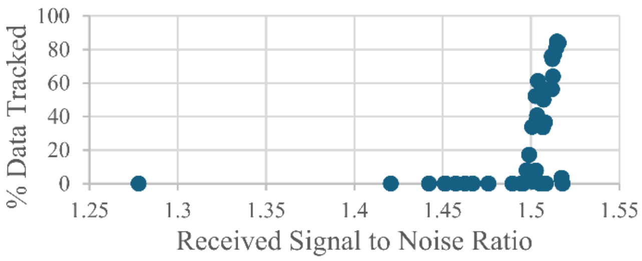

Figure 4.4. Receiver Frequency Tracking

4.1.4 Drone testing

To assess the flight computer's performance, it was mounted on a DJI Phantom 4 Pro drone using a 3D-printed bracket for a series of test flights. The aim was to compare flight computer data against the data gathered from the commercially available drone.

The barometer data sees a large drop in pressure, equivalent to 100m of altitude gain, when the drone takes off. It is suspected that this is the effect of the prop wash caused by the drone impacting the exposed barometer. Additionally, discrepancies in the orientation data were traced back to motor vibrations, which compromised the IMU's accuracy by introducing unfiltered noise into the readings.

4.1.5 Mobile Device Sensor Validation

Tests were conducted in which the flight computer was fixed to a mobile device. Both flight computer and phone axes were aligned and set to record gyroscope, orientation, and accelerometer data. This method circumvented the vibration issues experienced with the drone testing, and the results showed strong correlation in orientation and linear acceleration. Figure 4.5. compares the orientation of the phone and the flight computer in roll, pitch and yaw, while each axis is rotated.

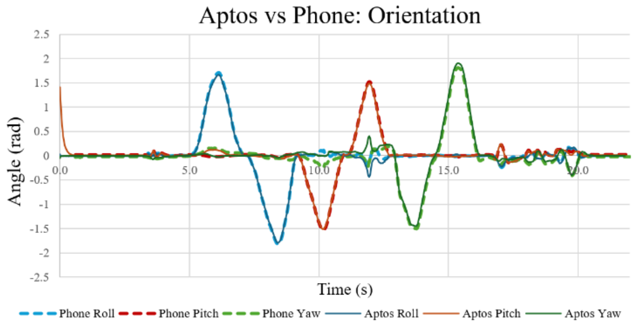

Figure 4.5. Comparison of Aptos vs Smartphone Euler Orientation

4.2. Flight results

The Aptos module was assembled and integrated within the Pathfinder rocket. Using a J570W-14A motor, the rocket was launched with the active control enabled to an apogee of 354m. Readings were collected throughout the course of the flight and the controller was active when the vertical velocity of the rocket was above 30m/s.

The dynamic nature of the rocket's movement, particularly its roll, made it challenging to visualise how this motion affected the pitch and yaw measurements. To simplify interpretation, the rotation rates were converted from the North-East-Down (NED) reference frame to an observer-centric reference frame, to isolate the roll component from the other two axes. This conversion was accomplished using Formulas 23-25 listed in Appendix A. The rocket’s Euler orientation throughout the flight is shown in Figure 4.6.

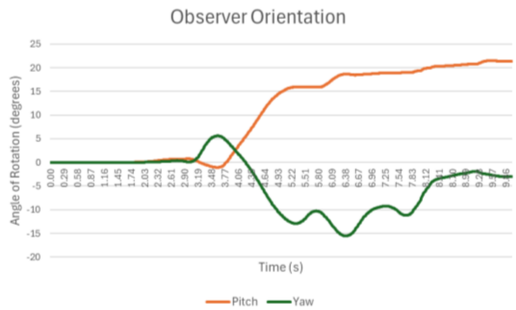

Figure 4.6: Aptos Observer Orientation during the Pathfinder Flight [13]

Figure 4.7 illustrates the response of the canards to the rocket's orientation within the initial five seconds of the ascent. Initially, the deflections are equal to zero, due to the lower velocity during take-off (smaller than 30 m/s). As the rocket separates from the launch pad and increases in velocity, the canards perform correcting movement, reaching the full extent of their operational angle range (± 15 degrees).

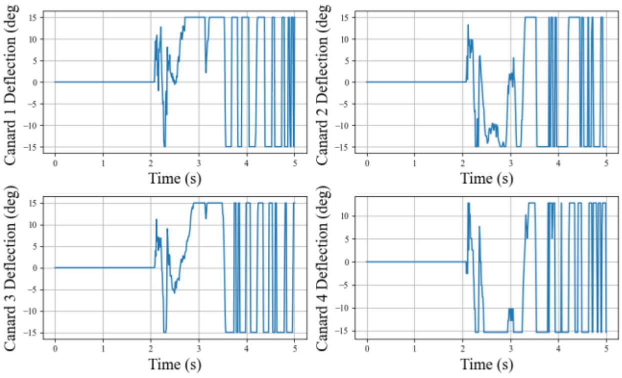

Figure 4.7: Canard Deflection Angles during Flight

5. DISCUSSION

5.1. Flight path analysis

As the Aptos module has never been flown with active control enabled before, it was important to be cautious with the gain values of the LQR controller. These values were reduced to keep the magnitude of the response slower. Contrary to that, Figure 4.7 displays how the canards were at full deflection (±15 °) after three seconds. The response from the controller was too severe, as the deflection angles would have been expected to follow a smooth trend within the window for a controlled response.

The rocket's flight was non-vertical, with deviations in its pitch, despite observable corrective oscillations in the yaw axis. As shown in Figure 4.6, the pitching could be attributed to several factors: the control loop's slow reaction, the servomotors' delayed response, overly conservative gain settings, or the excessive restriction on canard deflection. When facing headwinds, the canards reached their maximum deflection, indicating that their lift coefficient was insufficient to counteract the aerodynamic disturbances. Moreover, during last year's rocket launch, although the canards were locked, the controller was active for data logging purposes. It recorded maximum deflections of 80° [1], a deflection that should be permitted in future flights.

An additional issue arose from the use of OpenRocket simulation data to tune the LQR gains in MATLAB for the Pathfinder rocket. OpenRocket is an open-source software for simulating rocket flights which is useful for basic simulations. However, it lacks features to model more complex dynamics, such as those introduced by the rocket's rotational spin can and the actions of canards. As a result, the controller's tuning was based on an incomplete representation of the flight dynamics. Appendix B, Figures B.3-B.6 compare the servo response of the MATLAB controller versus the actual flight deflections. The MATLAB simulations show a slower servo response, suggesting less need for correction compared to the rapid deflections observed during actual flight, revealing that the simulated controller responsiveness did not adequately match real flight demands.

5.2. Apogee analysis

Post-launch analysis indicated that the predicted flight apogee was not achieved. Figure 5.1 illustrates that while OpenRocket simulated an apogee of 462 meters, the flight reached 354 meters. The difference could be attributed to the OpenRocket limitations, mentioned in the previous sections. Additionally, the rocket's deviation from a straight flight path further resulted in a significant reduction in altitude.

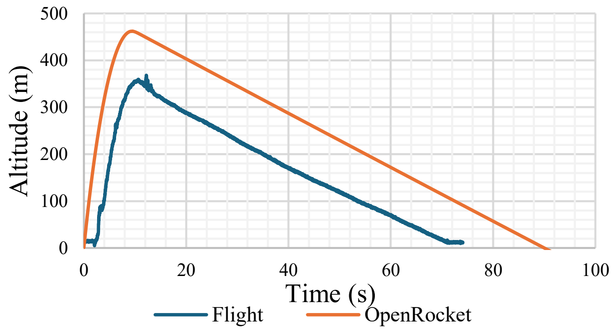

Figure 5.1 Actual Flight versus Predicted Apogees

Some of the altitude loss can be linked to the variable deflection of the canards. However, a similar altitude discrepancy of 76 meters was also noted in the previous year's flights, which were conducted with the canards locked at a 0° angle—a condition replicated in simulations. This suggests that another variable component, the spincan, likely contributed to the losses. The rotational motion introduced by the spincan is not accounted for in the simulations, highlighting a gap in the modelling process.

The ability for the fins to spin freely was important to reduce canard control flow opposition [24], however, may have induced additional drag by generating turbulent airflow or unwanted horizontal forces. An investigative launch should be completed to lock the spin can and measure the effect on apogee.

The ability for the fins to spin freely was important to reduce canard control flow opposition [24], however, may have induced additional drag by generating turbulent airflow or unwanted horizontal forces. An investigative launch should be completed to lock the spin can and measure the effect on apogee.

5.3. Robustness of the canard module

After the Pathfinder rocket landed and was recovered, the canards were confirmed to be in their neutral position, undamaged, and with the shear pins intact. This could be caused by a softer landing than expected. The ground hit velocity was 5.27m/s, softer than the 5.67m/s predicted by OpenRocket, partly because it landed on top of crop fields, which could have absorbed some of the force.

Figure 5.2. Aptos Module after Landing

5.4. Integration Effectiveness of Systems

In the post-flight evaluation, the system pipeline's throughput was quantified at approximately 0.622 MB per minute, which includes the duration of data retrieval from the flight hardware to its eventual ingestion into the database. The primary bottleneck of the system was the NAND Flash's reading speed, which took 92.248% of the entire pipeline duration. In a future firmware version, the data reading procedure would benefit from further improvement.

During the test launch, the data acquisition system used 2416 Kb (approximately 2.359 Mb) of storage. Given the modest storage requirements, it is anticipated that the database can accommodate data from multiple future flights, even with substantial increases in data acquisition rates.

6. CONCLUSIONS AND FUTURE WORK

Project Aptos managed to successfully fly with the active system enabled and has shown promising results in the yaw axis. However, the pitch axis saw little to no correction. This could be caused by the controller's slow reaction time, which did not adapt the angle of the canards in time to effect corrections.

Valuable antenna data was collected, using the MATLAB receiver. Moreover, the transmission system survived the flight without breaking. Unfortunately, the Pathfinder rocket was flown without the complete system due to transmitter issues. However, the telemetry system has undergone extensive ground testing since.

The following objectives were achieved to improve the development of a vertical stabilisation LQR controller. The mechanical transmission system was successfully redesigned and tested using both aerodynamic simulations and physical tests in the wind tunnel. Custom flight computer and Telemetry PCBs were developed, manufactured and programmed using low level coding platforms. A custom antenna has also been developed to transmit data to the ground. To allow data to be fed back into the controller, a data storage solution and visualisation tools were implemented and released.

Areas of the Aptos module which could benefit from further development have been identified. Firstly, a launch with the spincan locked and canards set at 0° could be performed to assess whether the altitude loss can be attributed to the spincan's rotation. This will aid in improving the knowledge of the impact of the spincan between OpenRocket simulations and real launches.

The controller would benefit from further understanding. Implementing hardware in the loop testing would speed up development time and validate future mathematical model. Additionally, real-flight data should be used in the gain tuning process.

From an avionics perspective, additional sensor drivers could be written to enable more data to be collected using the existing on-board sensors, such as GNSS and humidity. Further improvements to the telemetry, such as integrating fast PLLs in the receiver and testing phase array antennas, would improve system reliability. The visualisation tools should display the canard deflections over time to enhance the analysis of the controller's response.

Improvements to the transmission system could include modifications that ensure, should a shear pin break during flight, that the canard remains attached to the rocket. Another improvement could see the use of ball or journal bearings to reduce even further the friction losses due to the canards rotating.

Overall, the project achieved its objectives. This paper serves as guidance for future canards stabilisation systems used in sounding rockets.

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Appendix A Supporting Equations

A.1 LQR Controller

$$J = \int_0^{\infty} (\boldsymbol{x}^T Q x + \boldsymbol{u}^T R u) dt \tag{1}$$

$$where\ \boldsymbol{x} = \begin{bmatrix} \varphi \\ \theta \\ \psi \end{bmatrix}\ and\ \boldsymbol{u} = \begin{bmatrix} u_\varphi \\ u_\theta \\ u_\psi \end{bmatrix} \tag{2}$$

$$u^* = -Kx \tag{3}$$

$$\dot{\boldsymbol{x}} = Ax + Bu \tag{4}$$

$$\begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} a_{\varphi\varphi} & a_{\varphi\theta} & a_{\varphi\psi} \\ a_{\theta\varphi} & a_{\theta\theta} & a_{\theta\psi} \\ a_{\psi\varphi} & a_{\psi\theta} & a_{\psi\psi} \end{bmatrix} \begin{bmatrix} \varphi \\ \theta \\ \psi \end{bmatrix} + \begin{bmatrix} b_\varphi \\ b_\theta \\ b_\psi \end{bmatrix} \begin{bmatrix} u_\varphi \\ u_\theta \\ u_\psi \end{bmatrix} \tag{5}$$

A.2 Canard Deflection Angle

$$\delta_i = \frac{M}{C_{m_i} \cdot A_i \cdot \rho \cdot V^2} \tag{6}$$

$$M_i = I_i \cdot \dot{\omega}_{des_i} \tag{7}$$

$$\dot{\omega}_{des_i} = \frac{\dot{\varphi}_{des}}{I_{\varphi_i}} + \frac{\dot{\theta}_{des}}{I_{\theta_i}} + \frac{\dot{\psi}_{des}}{I_{\psi_i}} \tag{8}$$

$$\therefore\ \delta_i = \frac{\frac{\dot{\varphi}_{des}}{I_{\varphi_i}} + \frac{\dot{\theta}_{des}}{I_{\theta_i}} + \frac{\dot{\psi}_{des}}{I_{\psi_i}}}{C_{m_i} \cdot A_i \cdot \rho \cdot V^2} \tag{9}$$

A.3 Rotation Rate Conversion to Observer Rates:

$$\dot{\theta}_{observer} = \dot{\theta}\cos(\varphi) - \dot{\psi}\sin(\varphi) \tag{10}$$

$$\dot{\psi}_{observer} = \dot{\theta}\sin(\varphi) + \dot{\psi}\cos(\varphi) \tag{11}$$

$$\dot{\varphi}_{observer} = \dot{\varphi} \tag{12}$$

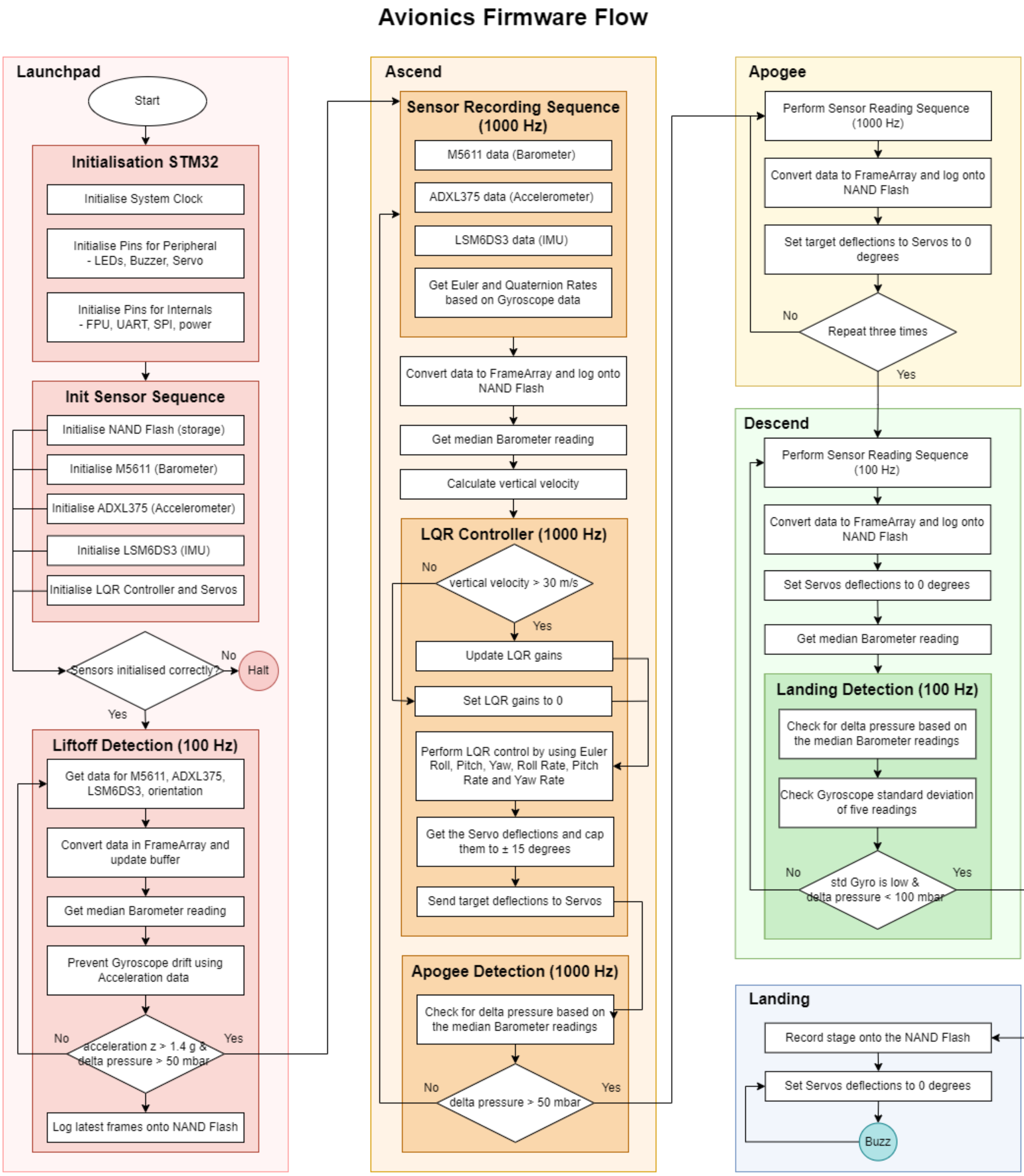

Figure B.2 Detailed Firmware Flow Diagram **[6]**

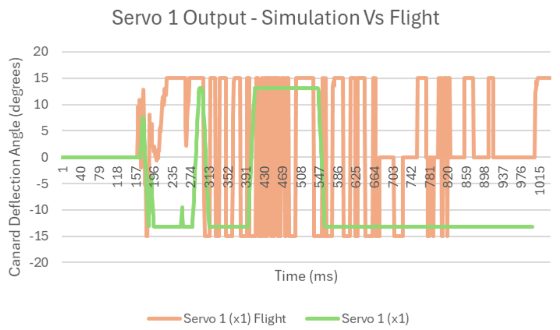

Figure B.3 Servo 1 Deflection Angle during the Pathfinder Launch vs Simulation Canard Deflection.

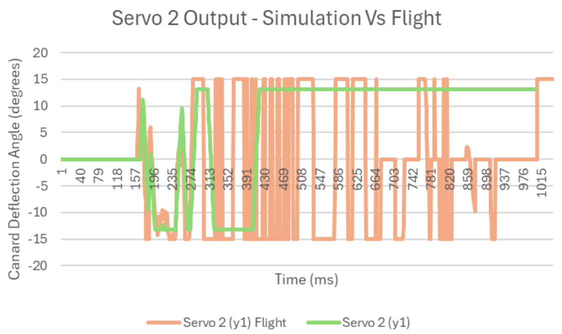

Figure B.4 Servo 2 Deflection Angle during the Pathfinder Launch vs Simulation Canard Deflection

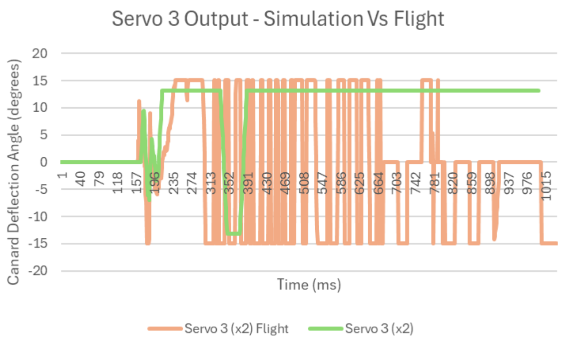

Figure B.5 Servo 3 Deflection Angle during the Pathfinder Launch vs Simulation Canard Deflection

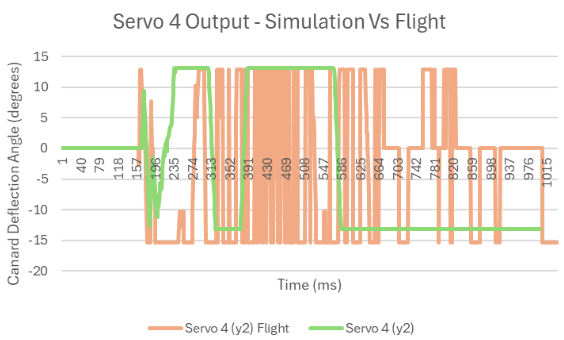

Figure B.6 Servo 4 Deflection Angle during the Pathfinder Launch vs Simulation Canard Deflection.

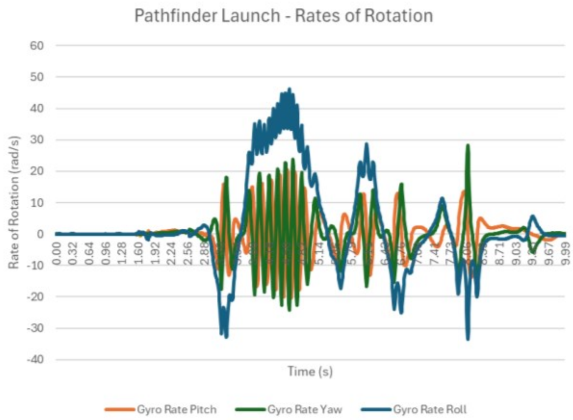

Figure B.7 Rates of Rotation of the Pathfinder Rocket during flight [13]

Appendix C Conduct Performance Plan (CPP)

IMPROVING AN ACTIVE STABILITY SYSTEM OF A SOUNDING ROCKET BY ADDING DATA MONITORING AND INTERPRETATION METHODOLOGIES

MECH5080M Contract Performance Plan

MECH5080M Project Title***: Improving an active stability system of a sounding rocket by adding data monitoring and interpretation methodologies***

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Date: 08/11/2023

Contents

1. Introduction

1.1 Background

The Leeds University Rocketry Association (LURA) is a student rocketry team, founded in 2021. In a short span, LURA has launched multiple rockets and set a new standard for United Kingdom (UK) teams at the Spaceport America Cup. The team is also on track to break the UK amateur altitude record, targeting an ascent to 13 kilometres [1]. All of the team's efforts are pointed towards the overarching long term goal of reaching the Karman line, the boundary between Earth's atmosphere and outer space, which no UK student team has reached. To support this goal, the Aptos Project has been created to develop a working active vertical control system that will allow future LURA rockets to maintain a vertical flight path and reach higher altitudes.

External factors have a significant impact on a rocket's trajectory. Typically, two main systems are employed to mitigate the trajectory. The first is a passive system, that is achieved by controlling the centre of pressure and gravity of the rocket [2]. The rule for stability is that the centre of pressure should be located at least one rocket diameter's length behind the centre of gravity [3]. However, the passive control system is not enough as the rocket will always weather cock due to cross winds, hence the addition of an active control system. [4] The second option is to use control surfaces. These surfaces come in various forms: they can be similar to the elevators on commercial aircraft, which adjust the passive fins' trailing edges, or they can be entire fins that rotate, akin to the rudders on fighter jets known as rolling tails [5]. The previous Aptos group suggested the use of canard fins mounted at the front of the rocket as the active control system. Their design was inspired by other rocketry teams, such as TU Delft, who successfully created a control system module to control roll [6]. The previous group built Pathfinder, a rocket capable of doing active control, and launched it at the Fairlie Moore Rocketry Site in Scotland.

However, the launches done last year lacked active stabilisation due to issues on the electronics and software systems. The current Aptos team plans to refine the existing work by optimising the code, redesigning the telemetry and electronics, as well as conducting at least one launch with the active control system enabled. If successful, this project would then be incorporated into future LURA rockets to reach higher altitudes and potentially set a UK precedent and aid other teams in their own development efforts.

1.2 Aim

The aim is to improve the active vertical stabilisation system of a sounding rocket, by using data monitoring, transmission, and interpretation techniques. This will allow refinement of the control system to correct the rocket's orientation with greater precision, in favour of a higher apogee.

1.3 Objectives

1. Create a control algorithm and simulation using a high-level development tool.
2. Create an electrical system & custom flight computer to provide all the required functionality to enable active control, telemetry, and data monitoring systems.
3. Improve the design of the canards system to achieve a more robust design and the ability to feedback the position to the control algorithm.
4. Establish air to ground telemetry communication with the rocket.
5. To perform data filtering, analysis, and visualisation to further improve the control loops.

1.4 Deliverables

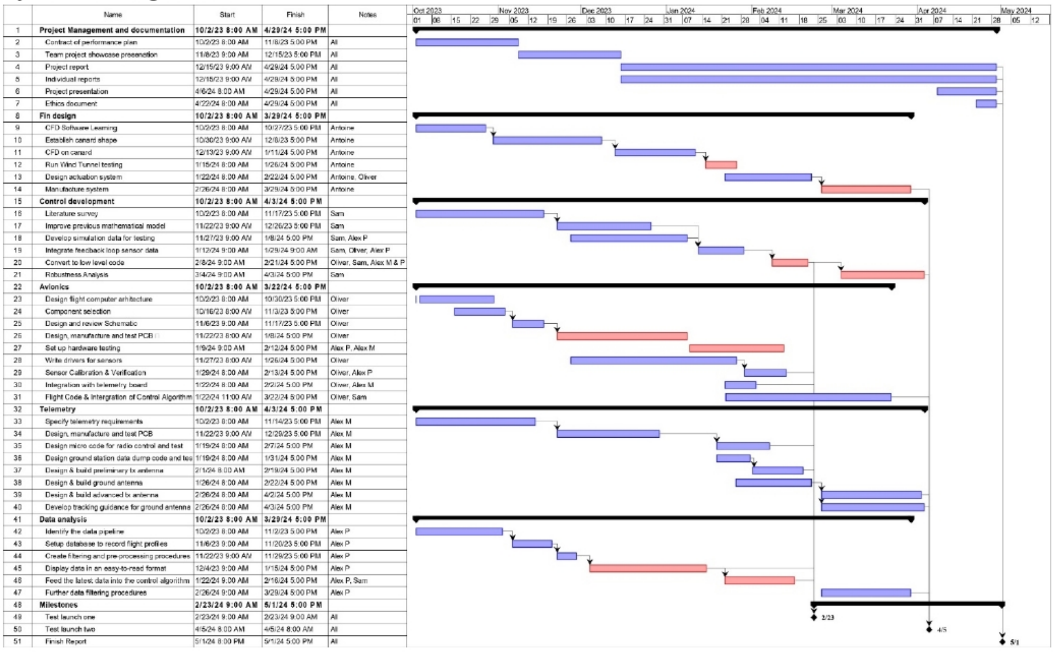
Table 2.1 Deliverables for each objective

1	Control algorithm producing output control data given rocket input sensor data. Simulation of the rocket flight path and canard orientation given random and systematic interference. Storage of all output data produced from the control algorithm for study and use in offline simulations.
2	Schematics of the custom flight computer & electrical wiring. PCB Gerber files for the custom flight computer. Manufactured custom flight computer & electrical system.
3	CFD analysis to determine canards shape. Design an actuation system for the canards. Manufacturing of the canards and actuation system.
4	Radio PCB that can interface with the flight computer to broadcast telemetry data. Onboard and ground antenna designs and hardware capable of reliably transmitting data beyond apogee.
5	An easy to access and manipulatable database that contains flight data. A web-based application to visualise data in dashboard format. A script that feeds data from the database into the control algorithm.
Extra	A group report and five individual reports that outline the work completed. A PowerPoint presentation to present the findings. An ethical report that provides ethical considerations. A GitHub repository that contains the control algorithm, flight computer firmware and data display related software.

2. Project Outline

2.1 Tasks, milestones and timeline

The tasks, milestones, and timeline are laid out in Figure 2.1. While blue is the default colour, red highlights crucial tasks that are essential to the project's development. Although the team aims to finish all tasks within the given timeframe, some may require additional days, as shown by the floating lines.



	Name	Start	Finish	Notes
1	**Project Management and documentation**	**10/2/23 8:00 AM**	**4/29/24 5:00 PM**	
2	Contract of performance plan	10/2/23 8:00 AM	11/8/23 5:00 PM	All
3	Team project showcase presentation	11/8/23 9:00 AM	12/15/23 5:00 PM	All
4	Project report	12/15/23 9:00 AM	4/29/24 5:00 PM	All
5	Individual reports	12/15/23 9:00 AM	4/29/24 5:00 PM	All
6	Project presentation	4/6/24 8:00 AM	4/29/24 5:00 PM	All
7	Ethics document	4/22/24 8:00 AM	4/29/24 5:00 PM	All
8	**Fin design**	**10/2/23 8:00 AM**	**3/29/24 5:00 PM**	
9	CFD Software Learning	10/2/23 8:00 AM	10/27/23 5:00 PM	Antoine
10	Establish canard shape	10/30/23 9:00 AM	12/8/23 5:00 PM	Antoine
11	CFD on canard	12/13/23 9:00 AM	1/11/24 5:00 PM	Antoine
12	Run Wind Tunnel testing	1/15/24 8:00 AM	1/26/24 5:00 PM	Antoine
13	Design actuation system	1/22/24 8:00 AM	2/22/24 5:00 PM	Antoine, Oliver
14	Manufacture system	2/26/24 8:00 AM	3/29/24 5:00 PM	Antoine
15	**Control development**	**10/2/23 8:00 AM**	**4/3/24 5:00 PM**	
16	Literature survey	10/2/23 8:00 AM	11/17/23 5:00 PM	Sam
17	Improve previous mathematical model	11/22/23 9:00 AM	12/26/23 5:00 PM	Sam
18	Develop simulation data for testing	11/27/23 9:00 AM	1/8/24 5:00 PM	Sam, Alex P
19	Integrate feedback loop sensor data	1/12/24 9:00 AM	1/29/24 9:00 AM	Sam, Oliver, Alex P
20	Convert to low level code	2/8/24 9:00 AM	2/21/24 5:00 PM	Oliver, Sam, Alex M & P
21	Robustness Analysis	3/4/24 9:00 AM	4/3/24 5:00 PM	Sam
22	**Avionics**	**10/2/23 8:00 AM**	**3/22/24 5:00 PM**	
23	Design flight computer arhitecture	10/2/23 8:00 AM	10/30/23 5:00 PM	Oliver
24	Component selection	10/16/23 8:00 AM	11/3/23 5:00 PM	Oliver
25	Design and review Schematic	11/6/23 9:00 AM	11/17/23 5:00 PM	Oliver
26	Design, manufacture and test PCB	11/22/23 8:00 AM	1/8/24 5:00 PM	Oliver
27	Set up hardware testing	1/9/24 9:00 AM	2/12/24 5:00 PM	Alex P, Alex M
28	Write drivers for sensors	11/27/23 8:00 AM	1/26/24 5:00 PM	Oliver
29	Sensor Calibration & Verification	1/29/24 8:00 AM	2/13/24 5:00 PM	Oliver, Alex P
30	Integration with telemetry board	1/22/24 8:00 AM	2/2/24 5:00 PM	Oliver, Alex M
31	Flight Code & Intergration of Control Algorithm	1/22/24 11:00 AM	3/22/24 5:00 PM	Oliver, Sam
32	**Telemetry**	**10/2/23 8:00 AM**	**4/3/24 5:00 PM**	
33	Specify telemetry requirements	10/2/23 8:00 AM	11/14/23 5:00 PM	Alex M
34	Design, manufacture and test PCB	11/22/23 9:00 AM	12/29/23 5:00 PM	Alex M
35	Design micro code for radio control and test	1/19/24 8:00 AM	2/7/24 5:00 PM	Alex M
36	Design ground station data dump code and tes	1/19/24 8:00 AM	1/31/24 5:00 PM	Alex M
37	Design & build preliminary tx antenna	2/1/24 8:00 AM	2/19/24 5:00 PM	Alex M
38	Design & build ground antenna	1/26/24 8:00 AM	2/22/24 5:00 PM	Alex M
39	Design & build advanced tx antenna	2/26/24 8:00 AM	4/2/24 5:00 PM	Alex M
40	Develop tracking guidance for ground antenna	2/26/24 8:00 AM	4/3/24 5:00 PM	Alex M
41	**Data analysis**	**10/2/23 8:00 AM**	**3/29/24 5:00 PM**	
42	Identify the data pipeline	10/2/23 8:00 AM	11/2/23 5:00 PM	Alex P
43	Setup database to record flight profiles	11/6/23 9:00 AM	11/20/23 5:00 PM	Alex P
44	Create filtering and pre-processing procedures	11/22/23 9:00 AM	11/29/23 5:00 PM	Alex P
45	Display data in an easy-to-read format	12/4/23 9:00 AM	1/15/24 5:00 PM	Alex P
46	Feed the latest data into the control algorithm	1/22/24 9:00 AM	2/16/24 5:00 PM	Alex P, Sam
47	Further data filtering procedures	2/26/24 9:00 AM	3/29/24 5:00 PM	Alex P
48	**Milestones**	**2/23/24 9:00 AM**	**5/1/24 5:00 PM**	
49	Test launch one	2/23/24 9:00 AM	2/23/24 9:00 AM	All
50	Test launch two	4/5/24 8:00 AM	4/5/24 8:00 AM	All
51	Finish Report	5/1/24 8:00 PM	5/1/24 5:00 PM	All

Figure 2.1 Project Aptos Gantt Chart

Three milestones were identified: the First Launch, the Second Launch and the Project Report deadline, all of which must be met by the 5th of May 2024. The initial milestone, scheduled for February 2024, tests early-stage systems on a lower-altitude launch without canards. In preparation for the launch, the control algorithm will be tested in a simulated environment, hardware-in-the-loop testing will be applied to the custom flight computer and ground telemetry testing will be performed. The second milestone is the launch of Pathfinder with an activated control system. The interim period focuses on refining electronics, software, and integrating mechanical systems. The final milestone corresponds to the deadline of the project report. Approximately one month has been allocated in April for report writing and final data analysis. The last task left for the team is to generate an ethics document related to the project.

2.2 Team structure

2.2.1 Software Engineer - Alexandra Posta

Alexandra is a fifth year Mechatronics & Robotics student with a placement completed at Scuderia AlphaTauri Formula One as a Software Engineer. As a Software engineer, Alexandra has developed data pipelines from the Wind Tunnel sessions, custom web applications for competitor analysis and simulation tools for pre-tunnel pressure testing. This experience makes Alexandra a candidate to filter, store and display flight data. From a rocketry perspective, Alexandra is leading the Avionics pocket from the Leeds University Rocketry Association (LURA), putting her in a good position to lead the group and organise launch days.

2.2.2 Electronics & Telemetry Engineer - Alexandre Monk

Alex is a Mechatronics & Robotics student who has completed a 14-month internship at Renishaw, focusing on FPGA bus design and Flash integration, building good experience in communications. Additional PCB design work completed on the placement will also aid the board design for the onboard telemetry. He also has extensive experience with automated C code generation from MATLAB, which should alleviate workload during this project when transferring the control algorithms developed for simulation onto hardware. Previous work on APRS and amateur radio tracking systems for weather balloons has provided the understanding necessary to design of all parts of the telemetry system. Past Formula Student electronics work and electric powertrain projects have given Alex a good electronics foundation and the practical experience necessary for reliable PCB design in high vibration applications.

2.2.3 Aerodynamics Engineer - Antoine Durollet

Antoine is a mechanical engineering student who has been a part of the Aerostructures team at the Leeds University Rocketry Association for a year. During this year he has gained valued experience in ensuring the integrity of the structure of rockets, as well as using the different flight simulation software to optimize the shape of rockets. All of these skills can be reapplied to design a canard actuation system. He has been learning about Fluids Dynamics for the last 5 years and knows how to use different CFD software, which will help him make decisions based on aerodynamics constraints. All those experiences give him the knowledge to fulfil the role of aerodynamics engineer.

2.2.4 Electronics Engineer - Oliver Martin

Oliver is a Mechatronics & Robotics student who has completed a 13-month internship at Red Bull Advanced Technologies, as an electrical design engineer. While on placement he gained experience defining electrical systems and their requirements, and then taking the appropriate steps to develop the system in an industry environment. He also has experience using microcontrollers, designing circuits, and programming in other projects, including working in the Avionics team at LURA. Therefore, he is well suited to the role of Electronics Engineer leading the development of the Avionics system.

2.2.5 Control Engineer - Sam Bruton

In the role of Control Systems Engineer, Sam is a final year Mechatronics and Robotics student with industry experience designing, prototyping, testing and commissioning factory operations equipment and machinery for Siemens on a 14-month placement. As a Robotics and Automation Engineer, he was responsible for system design and integration and has the ability to communicate and liaise with team members with different backgrounds, to successfully implement a system with exemplary control. He is also a member of the LURA Avionics team working on the control system for their latest rocket and has experience in simulation and modelling. Taking all this into consideration, he is best suited for this role.

2.3 Resources

2.3.1 Software Resources

The Avionics circuit schematics and PCB Gerber files will be produced using KiCAD, an open-source, free-to-use software. In conjunction with KiCAD, Library Loader from SamacSys will be used to add the necessary components into KiCAD, also free to use. For the control system design & simulation, MATLAB/SIMULINK will be used. Any CAD models for physical components will be designed in SolidWorks and CFD analysis will be carried out using Ansys. These three software packages have licences provided by the university.

2.3.2 Monetary Resources

In addition to software, there is a requirement for capital expenditure to purchase components facilitate launching the rocket. As the rocket structure has already been built and is reusable, the Bill of Materials is reduced from that required to build a complete rocket. Only components that are being re-engineered or are single use are included. Table 2.1 outlines the top-level project budget, a more detailed breakdown of costs can be found in Appendix A.

Table 2.1 - Budget Outline

Item	Cost
Wind Tunnel Jig	£15.49
Canards & Actuation	£29.65
Avionics	£297.54
Telemetry	£70
Launch costs	£513
Sub Total	**£933.18**
Contingency 20%	£186.64
Total	**£1,119.82**

3. Project Considerations

3.1 Risk analysis

Several risks were identified that could prevent the completion of the project, and steps were taken accordingly to mitigate the possibility and effects of any obstructing risks. An approach analysing risk probability and severity was taken in order to identify the most influential risks and introduce additional mitigation measures accordingly.

Each table contains risks associated with the project. The overall risk was calculated by multiplying the probability factor by severity and may go up to 25. The overall risk was recalculated after the mitigation factors were applied.

Risk: Underestimation of actual duration to complete the planned functionality.					
Probability	4	**Severity**	3	**Overall Risk**	12
Mitigation:	Increase parallelism and reduce dependencies to allow more flexibility in individual task completion time. Factor of safety added to task time estimates to reduce likelihood of overrunning.				
Probability	3	**Severity**	1	**Overall Risk**	3

Risk: Difficulties obtaining / manufacturing components.					
Probability	2	**Severity**	3	**Overall Risk**	6
Mitigation:	Widely available components with viable alternatives selected. Manufacturing methods that are widely available for low cost are used to mitigate risk of a single suppliers or component types being unavailable.				
Probability	1	**Severity**	2	**Overall Risk**	2

Risk: Budget shortage.					
Probability	3	**Severity**	4	**Overall Risk**	12
Mitigation:	A core implementation budget and additional launch budget are specified. If a certain part of the budget is exceeded, the team can reduce the scope of testing without compromising on the deliverables. If necessary, external companies can be approached for sponsorship in order to bring in sufficient funds to complete the project. A contingency of 20% has been added within the budget estimate to mitigate risk of overspending.				
Probability	3	**Severity**	2	**Overall Risk**	6

Risk: Expertise lacking.					
Probability	3	**Severity**	3	**Overall Risk**	9
Mitigation:	The project is designed to make use of existing knowledge on the team, without significant additional learning. Software packages are used that most members are familiar with. Simulation allows the team to experiment with novel solutions without significant risk to project completion. Academic and industrial supervisors can provide guidance if unexpected problems occur.				
Probability	2	**Severity**	2	**Overall Risk**	4

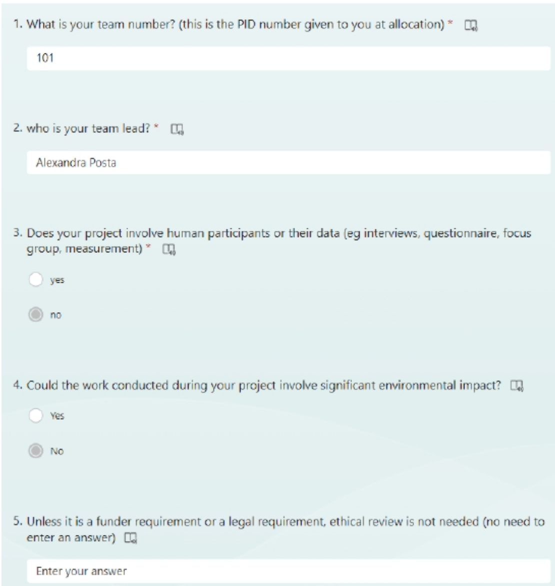
Risk: Unable to launch a sounding rocket.					
Probability	2	**Severity**	4	**Overall Risk**	8
Mitigation:	Some risks associated with launch permissions and logistics are difficult to predict, however any planning or forms required for these will be completed as far ahead of time as possible to enable alternative or revised plans to be implemented. Simulation, and bottle rocket launches that do not require travel or licensing can be completed which would neglect only the physical canard implementation. Multiple launches are also planned to reduce the impact of a single launch cancellation. The possibility of downgrading to a smaller solid propellant rocket that is easier to license also exists.				
Probability	2	**Severity**	2	**Overall Risk**	4

Risk: Catastrophic rocket failure or failure of a project part.					
Probability	1	**Severity**	5	**Overall Risk**	5
Mitigation:	The case of destruction of hardware has been planned for by reducing the value of actual components as much as possible to enable remanufacturing if necessary. An extensively tested and reliable rocket is used to reduce the risk of new problems or catastrophic failure occurring. Parts are individually tested for robustness and take-off forces are considered during the design phase.				
Probability	1	**Severity**	4	**Overall Risk**	4

Risk: Loss of expected man hours.					
Probability	4	**Severity**	2	**Overall Risk**	8
Mitigation:	A margin of error has been added in task time estimates. The project Gantt chart will be routinely updated and regular meetings and schedule revisions ensure the project can continue on track as much as possible.				
Probability	4	**Severity**	1	**Overall Risk**	4

3.2 Ethical considerations

This project includes no human participants or their data and thus considerations to this effect do not have to be made. This has been pointed out in the ethical approval form, on the right. The subject is merely active control and telemetry for a rocket. Whilst these technologies can be implemented on weapons systems, for example in missile design, which can be considered immoral [7], the research conducted here will not intentionally contribute to the defence sector. Its application and scientific value for a student team outweighs any potential use by the defence sector.


1. What is your team number? (this is the PID number given to you at allocation) *

101

2. who is your team lead? *

Alexandra Posta

3. Does your project involve human participants or their data (eg interviews, questionnaire, focus group, measurement) *

yes

no

4. Could the work conducted during your project involve significant environmental impact?

Yes

No

5. Unless it is a funder requirement or a legal requirement, ethical review is not needed (no need to enter an answer)

Enter your answer

Figure 3.1 Ethical Approval Form

A consideration should be made as to the environmental impact of launching a rocket, as the sounding rocket launches planned for the project do emit greenhouse emissions from the black powder and solid propellant burned onboard. However the quantities of these are small and thus have an insignificant impact, meaning ethical approval is not required.

Risk of a rocket rocket failure event is incredibly low. A launch with the control system switched off will be conducted first to enable control system behaviour. This is to be evaluated and deemed safe before any controlled launch occurs. The rocket will also be launched at a designated launch site, clear of people or property, to low altitudes, where even a catastrophic failure or incorrect guidance would not result in destruction or harm to any life or property.

3.3 Project Stakeholders

Three stakeholders are interested in the success of this project. Firstly, the Engineering Department from the University of Leeds would benefit from the project. A vertical control algorithm would not only enhance the university's reputation in rocketry but also draw positive attention as it allows students to undertake innovative projects. Secondly, Theo Gwynn from Airbus is integral to the project, as he can offer vital industrial expertise alongside his Airbus colleagues to push the project forward. Finally, LURA anticipates considerable advantages from a successful outcome, as it would enable the integration of active control stabilization systems in its future rockets — essential for setting new altitude records in the UK.

4. Conclusion

In conclusion, project Aptos aims to integrate a more robust data pipeline into the control algorithm of the vertical active stabilisation system of a sounding rocket. Ultimately, this would enable the greater team, LURA, to launch rockets at higher altitudes. The team working on the project has a diverse range of skills and background knowledge to build upon the system developed in the previous year. This year, the team's primary focus will be on refining the control algorithm. To achieve this, innovative methodologies will be incorporated to improve the way we acquire, transmit, process, and utilize data.

5. References

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[6] DARE n.d. 2014. *Advanced Control Team – Delft Aerospace Rocket Engineering.* [Online]. [Accessed 5th November 2023]. Available from: https://dare.tudelft.nl/projects/act/

[7] Forge J. *The Morality of Weapons Research*. Science and Engineering Ethics, vol. 10, pp. 531-542, 2004.

Appendix A. Budget

Project Aptos Module CPP Budget

Cost Item	Item Name	Quantity		Price per unit	URL	Total Price(inc. VAT)
Wind Tunnel Jig						**£ 15.49**
Aluminium Plate	8mm Aluminium Plate Sheet - Grade 5083 (100mm x 150mm)	1		£ 9.99	https://www.amazon.co.uk/8mm-Alumini	£ 9.99
Rods to fix wing	Aluminium Round Bar/Rod 4mm - 16mm : Grade 6082 T6 (4mm x 100mm)	2		£ 2.75	https://www.amazon.co.uk/Aluminium-Ro	£ 5.50
Canards and Actuation						**£ 29.65**
Axle	M3 Stainless Steel circular rod	1		£ 3.07	https://www.fixandfast.co.uk/stainless-ste	**£ 3.07**
Ball Bearing	ID M3 Ball Bearing	4		£ 2.55	https://www.accu.co.uk/rotary-bearings/6	**£ 10.20**
Canard and Gear Filament	RS PRO 1.75mm Random Colour PLA 3D Printer Filament	3		£ 5.46	https://uk.rs-online.com/web/p/3d-printin	**£ 16.38**
Avionics		Per board	Spare			**£ 297.54**
MCU	STM32L4R5VIT6	1	1	£ 13.37	https://uk.rs-online.com/web/p/arduino/7	£ 26.74
IMU 6 axis	LSM6DS3TR-C	2	1	£ 5.85	https://www.mouser.co.uk/ProductDetail/	£ 17.55
Barometer	MS5611-01BA	2	1	£ 6.06	https://uk.rs-online.com/web/p/pressure-	£ 18.18
High G 3 axis Accelerometer	ADXL375	2	1	£ 12.75	s/ADXL375BCCZ?qs=sGAEpiMZZMuSvlrqIF	£ 38.25
GNSS	MAX-M10S-00B	1	1	£ 16.80	https://www.mouser.co.uk/ProductDetail/	£ 33.60
EEPROM	25LC512	1	1	£ 1.82	https://www.mouser.co.uk/ProductDetail/	£ 3.64
Voltage Regulator	TLV76733DGNR	2	1	£ 0.70	https://www.mouser.co.uk/ProductDetail/	£ 2.10
Current limiter	ST890CDR	1	1	£ 2.37	https://www.mouser.co.uk/ProductDetail/	£ 4.74
RGB LEDs	SMD LEDs	2	2	£ 0.55	https://www.mouser.co.uk/ProductDetail/	£ 2.20
RED LED	SMD LEDs 0805	2	2	£ 0.47	https://www.mouser.co.uk/ProductDetail/	£ 1.88
BLUE LED	SMD LEDs 0805	1	1	£ 0.42	https://www.mouser.co.uk/ProductDetail/	£ 0.84
Buzzer	Piezo SMD Buzzer	1	1	£ 2.33	https://www.mouser.co.uk/ProductDetail/	£ 4.66
Resistors	0805 size SMD resistors	20	20	£ 0.20		£ 8.00
Capacitors	0805 size SMD capacitors	20	20	£ 0.30		£ 12.00
Diodes	Schotky diodes 0805	5	3	£ 0.40		£ 3.20
OR Gates	74AHC1G32GW-Q100,1	5	2	£ 0.20	https://www.mouser.co.uk/ProductDetail/	£ 1.40
Mosfet	N Channel Mosfet	1	1	£ 0.30	https://www.mouser.co.uk/ProductDetail/	£ 0.60
Connectors	Pin headers, Battery connectors, & other PCB mounted connectors	5	3	£ 1.00		£ 8.00
PCBs	Custom PCBs from JLC PCB	2	-	£ 25.00		£ 50.00
Arming Switch		1	0	£ 3.00		£ 3.00
LiPos	850MAH 7.4V 2S 35C SUPERSPORT PRO LIPO BATTERY (With XT30 Connector)	2	2	£ 10.49	https://www.overlander.co.uk/lipo-batteri	£ 41.96
STM32 Nucleo Board	For programming and testing	1		£ 15.00		£ 15.00
Telemetry Electronics						**£ 70.00**
Radio Receiver Transmitter		1		£ 10.00		£ 10.00
PCB		2		£ 10.00		£ 20.00
Rocket Antenna		1		£ 15.00		£ 15.00
RTL-SDR		1		£ 25.00		£ 25.00
Ground Antenna		1		£ 15.00		£ 15.00
Launch Costs						**£ 513.00**
1st launch Motors	H123W-14A 38/240 RMS-PLUS	2		£ 42.50	https://wizardrockets.co.uk/product/h123	£ 85.00
2nd launch Motors	J570W-14A 38/1080 RMS-PLUS Motor	2		£ 114.00	https://wizardrockets.co.uk/?product=j57	£ 228.00
Fuel	Fuel for journey to/from SARA and MRC (based off previous launches)	2		£ 100.00		£ 200.00
Sub-Total						£ 933.18
Contingency		20%				£ 186.64
Total						**£ 1,119.82**