Reusable high-power rocketry with atmospheric data collection

Abstract—**High-power rocketry allows conducting atmospheric measurements and introduces individuals to the challenges of rocket launches. The team of undergraduate students built a high-power reusable rocket and a custom-made PCB flight computer with the goal of creating an open-source educational resource. After simulations in OpenRocket, the final design was manufactured with workshop machinery and 3D printers. The flight computer, which incorporated sensors and LoRa radio, was designed in KiCAD and its components were soldered by a reflow oven. On the initial launch, the rocket reached an altitude of 721 m and enabled by stable telemetry transmission, was successfully recovered.**

Index Terms—**Rocket, PCB, Microcontroller, Embedded systems**

I. Introduction

One of the aims of this project was to build an open-source platform consisting of a flight computer and a rocket for the high-power rocketry community. High-power rocketry is a hobby that involves the design, manufacturing, launch, and recovery of a model rocket. Upon ignition, the solid rocket fuel propels the rocket upwards. At burnout a few moments later, the rocket continues travelling until it reaches its apogee, the highest point of the flight path, then begins descending. A parachute is ejected on the descent to ensure the rocket is recovered safely with minimal damage [1].

A compartment near the top of the rocket holds the avionics – a flight computer with various electronic devices for measurement, transmission and tracking purposes. Usually, due to the size and weight constraints, there is a need to design a custom Printed Circuit Board (PCB).

This paper describes the development of the whole rocket and a flight computer. The main specifications for both the rocket and the flight computer are established, the design decisions are justified and the manufacturing process is described. A high-level overview of the software is provided together with a description of communications with the components. Lastly, the flight data and its analysis are presented. The design files and the code were open-sourced. Individuals interested in high-power rocketry can use this publication together with the open-sourced resources as a guide for their own rocketry projects.

II. Specifications

The goal of the project was to build a high-power rocket that reaches the maximum altitude possible while transmitting its position and atmospheric measurements.

A. Rocket Specifications

To ensure that the rocket satisfies all of the goals of the project, specifications were prepared. Table I shows the quantitative specifications for the physical rocket. The minimum total impulse was set to 80 Ns due to the chosen engine category which allowed us to classify the rocket to be a high-power rocket [2]. The minimum payload mass was set to be 100 g and the maximum landing speed was set to 15 ms^{-1} to follow the guidelines of the National Rocketry Competition (NRC) [3]. The stability constraint between 1.5 and 2.5 was determined as a requirement to launch at Midland Rocketry Club (MRC).

TABLE I: Rocket specifications

Specification description	**Value**
Minimum Total Impulse (Ns)	80
Minimum Payload Mass (g)	100
Stability	1.5 to 2.5
Maximum Landing Speed (ms^{-1})	15

B. Flight Computer Specifications

Similarly to the rocket, a list of specifications was prepared for the flight computer as well. Table II shows the specifications for the flight computer ordered by the priority. The highest priority was the recovery of the rocket. This is realized by obtaining GPS coordinates and transmitting them to a ground station via radio. Another high-priority specification was measuring the atmospheric parameters, namely temperature, pressure and humidity. The pressure can be used to estimate the altitude reached. To better track the position of the rocket and the maximum altitude reached, an Inertial Measurement Unit (IMU) is used. Since the rocket's landing site can be visually obscured by vegetation, a buzzer is useful for recovery. In case of unreliable radio transmission, a flash chip storing the telemetry data in non-volatile storage is used as a backup. The magnetometer is a low priority although the purpose of this sensor is to combine readings with the IMU sensor using a sensor fusion algorithm to determine the orientation of the rocket more accurately.

TABLE II: Flight Computer Specifications

Specification description	**Priority**
Obtain GPS coordinates	Critical
Transmit telemetry to ground station	Critical
Minimum battery life of 1 hour	High
Measure temperature and pressure	High
Determine the movement of the rocket using the IMU	High
Emit sound using buzzer after landing	Medium
Store the telemetry in non-volatile storage	Medium
Measure magnetic orientation	Low

The minimum battery life was set to 1 hour. The rocket setup, launch, flight and landing were estimated to be 20 minutes. Upon landing, the flight computer would transmit GPS coordinates to the ground station for recovery. However, to account for GPS failure an additional 40-minute buffer was added to use the buzzer and the radio link signal strength for locating. The worst-case total current was calculated as shown in Table III. When the worst-case total current was multiplied by the minimum battery life, this corresponds to a minimum battery capacity of 256 mAh. In the final design, an 800 mAh battery was used which can provide more than 3 hours of battery life.

TABLE III: Current consumption per component

Component	Current (mA)
IMU (BMI088)	5.15
Magnetometer (LIS3MDL)	0.27
Temperature, pressure and humidity sensor (BME280)	0.71
GPS module (Quectel L80-M39)	25.00
Radio transmitter (LAMBDA-9P +17 dBm PA Boost)	90.00
Flash chip (W25Q64JV)	5.00
Magnetic buzzer (TDK SDR08540M3 88dB(A)/10 cm)	85.00
Microcontroller (STM32F446RE [90 MHz @ 25°C])	45.32
Total	**256.45**

III. Design process and manufacturing

The work on the project was split into two teams – one team working purely on the rocket and the second team working on the flight computer. Each team had their own meetings and meetings between the different teams were scheduled if necessary.

A. Rocket

The rocket was initially designed in a program called OpenRocket [4]. It allows users to select components and modify their parameters to build up a rocket. The design can then be simulated to determine the flight behaviour and observe the expected changes in variables such as velocity, stability, and mass over time. From this information, modifications can be made to optimise the rocket. Each component of the rocket was assigned to a member. Through research, simulation, and mathematical work, the individual parts were optimised and then integrated together. Fig. 1 shows the final design in OpenRocket with the labelled components. The location of the Centre of Gravity (CG) is shown as a blue and white circle. The location of the Centre of Pressure (CP) is shown as a red circle. The stability margin of the rocket is defined as the distance between the CP and CG. It is measured in calibres, with one calibre being the body diameter of the rocket [5]. The flight computer is located in the top part of the rocket which is ejected during the parachute deployment. To prevent the loss of the top part, it is connected to the rest of the rocket with a shock cord. The launch lugs are required to hold the rocket upright on the launch pad. The fire-resistant blanket protects the parachute and the shock cord from the ejection charge gasses. The engine block and centring rings ensure the engine stays firmly in place. The fins are used to ensure a stable flight and their aerofoil cross-section was optimised to reduce drag.

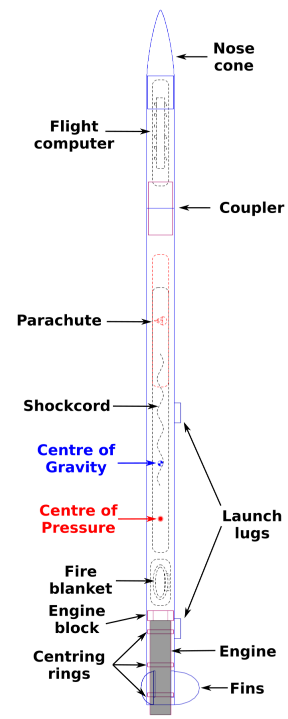
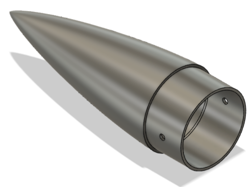
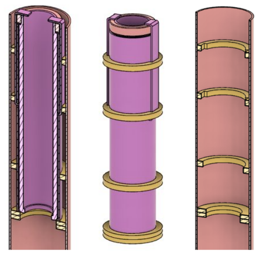


Fig. 1: Final rocket design

The final design was then manufactured at the university workshop. The body tube was made from phenolic tubing. A 3-axis pillar drill was used to carve slots for the fins. Phenolic tubing was chosen due to its low weight but high strength [6]. The tube was cut into two compartments, one to house the avionics, and the other to house the recovery system. Separate components and the final manufactured rocket are shown in Fig. 2. The nose cone was 3D printed using Acrylonitrile Butadiene Styrene (ABS), a material chosen for its impact resistance [7]. The nose cone had holes at the bottom, which lined up with holes drilled into the body tube. This allowed for a pair of screws to pass through the whole assembly and fasten the nose cone to the body tube (Fig. 2a). A mount to hold the engine was created from a smaller diameter phenolic tube. Plywood rings were laser cut to hold this smaller tube securely within the large one (Fig. 2b). A pair of engine hooks were manufactured from steel. These clamp the engine in place, preventing it from falling out when the ejection charge is triggered. The recovery system consisted of a 1.5 m long Kevlar shock chord attached to the engine mount using an eye bolt. This shock chord then had a Nomex fire blanket attached to the other end. A 60 cm diameter nylon parachute was secured to the shock cord to ensure the safe recovery of the rocket (Fig. 2c). A set of three fins was then 3D printed and evenly spaced at the end of the tube (Fig. 2d). The 3D render of the flight computer enclosure is shown in Fig. 2e and the fully manufactured rocket is shown in Fig. 2f.

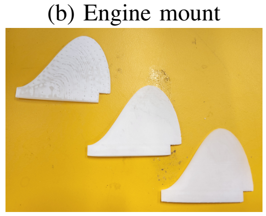


(a) Nose cone

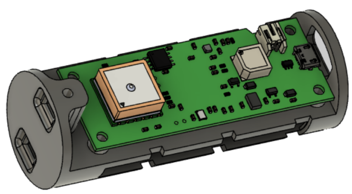


(b) Engine mount

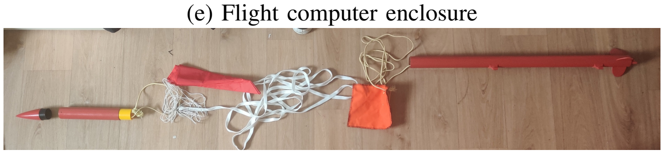
(c) Recovery system



(d) Fins



(e) Flight computer enclosure



(f) Final manufactured rocket

Fig. 2: Individual Rocket Components

B. Flight computer

The team has been iterating on its custom flight computers over generations of rockets. The previous rocket was not recovered after launch since the flight computer radio range was insufficient. Therefore, the new design prioritised a reliable and sufficiently long-distance radio link. Fig. 3 shows the high-level diagram of the flight computer that was designed. The heart of the whole system is the STM32 microcontroller that connects all the other subsystems. Serial Peripheral Interface (SPI) connects the radio transmitter and Quad Serial Peripheral Interface (QSPI) connects the flash chip. Inter-Integrated Circuit (I^2C) protocol was used to connect the temperature, pressure and humidity sensor, magnetometer and IMU. The GPS module was connected to the microcontroller via a Universal Asynchronous Receiver-Transmitter (UART). The electromagnetic buzzer was connected to a Bipolar Junction Transistor (BJT) which was controlled by a 2.4 kHz square wave signal generated by the microcontroller. The computer is powered by the power subsystem with regulated 3.3 V voltage.

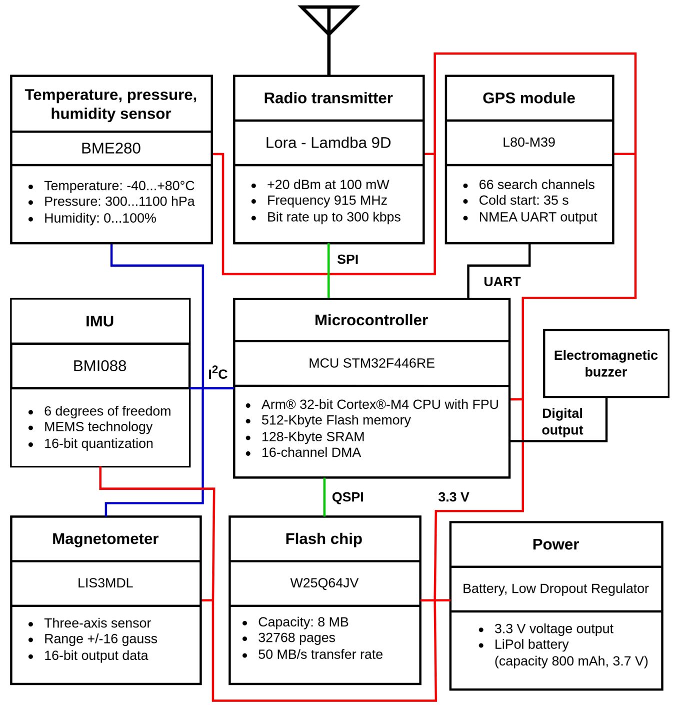


Fig. 3: Flight computer – diagram

The GPS chosen was the Quectel L80 module. This module has an integrated patch antenna which negates the need for an external antenna. There are 66 search channels and 22 simultaneous tracking channels which allow for a cold start of less than 35 s. [8].

The radio used was a LAMDA 9D Transceiver based on the Semtech SX1272. It uses the Long Range (LoRa) RF modulation scheme which is ideally suitable for long-range ($\approx$12 km), low bit rate (up to 300 kbps) links [9]. In addition, the radio has very low power consumption. The TX mode current with +17 dBm gain of the power amplifier is 90 mA from the 3.3 V power supply. The frequency utilised is 915 MHz which is allocated for the use of industrial, scientific and medical (ISM) applications [10]. The space constraint of less than 18 cm in the upper rocket compartment presented a challenge in selecting an antenna. Finally, it was decided to use a 5/8 wavelength helical antenna. Due to the lack of space, no radiators or ground plane was fitted for the antenna. This decreases the antenna gain. Future designs could use a larger upper rocket compartment to fit a dipole antenna.

One of the reasons to choose the environment sensor BME280 is that a single sensor measures temperature, pressure and humidity [11] and the current consumption is low. The sensor has an official library for the STM32 platform which reduced software development time.

The IMU BMI088 was designed for harsh vibration environments. It has high 16-bit precision and an extended measurement range of up to $\pm 24g$. This made it suitable for measuring both accelerations just after launch and after parachute deployment using the same sensor [12].

The magnetometer LIS3MDL is a three-axis sensor which is suitable for sensor fusion. Its 16-bit resolution allows for high precision measurements and has very low current consumption [13].

The flash chip W25Q64JV was chosen for its 8 MB capacity, which was more than sufficient for storing the telemetry, and because of its high data transfer rate of 50 MB/s [14].

The dimension of the PCB was 76 mm by 28 mm with a thickness of 1.6 mm. The width was constrained by the inner diameter of the rocket tube which was 34 mm. The PCB chosen was a 4-layer stack up with the inner 2 layers used for ground and VCC and the outer layers used for signal and components (Fig. 4). The sensors, GPS and power circuitry were separated into sections and the STM32 microcontroller was placed at the centre of the design. The components on the board were powered using a 3.3 V Low Dropout Regulator (LDO) which were powered by either a 5 V USB supply for debugging and reading values from the flash chip or a 3.7 V Lithium Polymer battery during the flight. To prevent current from flowing from the 5 V supply into the battery, a diode was used. This diode forward voltage [15] was chosen to be small (≈43 mV) so that the input voltage into the LDO was at least 150 mV greater than the output voltage [16].

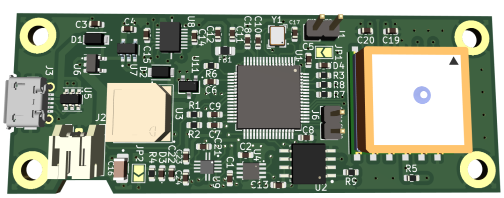


Fig. 4: Flight computer PCB render

The software was written in a modular way as suggested by [17], thus allowing for easier diagnosis of the bugs meaning that the code for each component was developed and thoroughly tested. One of the biggest challenges when developing the software for the flight computer was the lack of libraries available for the STM32 platform.

Firstly there was a need to develop a custom library for the GPS module L80-M39. This module, when turned on, continuously sends the GPS messages via UART. The final code for the computer uses Direct Memory Access (DMA) to read the data from the GPS module. This allows running other code while reading GPS information. When the GPS messages are read fully, the DMA controller triggers a callback function which starts to parse the GPS messages and stores the relevant information to the struct.

The temperature, pressure and humidity were measured using BME280. The official library [18] was used to handle the communication with the sensor using I^2C.

Due to the lack of an official library for STM32, a custom library for the chosen radio module was developed. The library uses SPI register operations to communicate with the radio module. Firstly, the library configures the module and then periodically sends data streams to be transmitted to the ground station.

The electromagnetic buzzer was timed to sound 15 minutes after launch. A square wave signal is generated on the base of the BJT in series with the buzzer to induce the sound. The frequency of 2.4 kHz was chosen since it coincides with a peak frequency response.

The whole process of the flight computer development and manufacturing involved thorough testing. Before connecting the PCB with soldered components to the battery, a detailed inspection including the use of a continuity tester was conducted. Due to minor errors in the first PCB version, a second iteration was designed and manufactured. For redundancy reasons, multiple PCBs of the same iteration were manufactured and mounted with components. During the development of the custom GPS library, the module was tested multiple times. The same procedure applied to the radio module. After each iteration of the radio library was done, a range test in an outdoor space was conducted.

IV. Flight data analysis

The launch took place at an open field in Twycross, Leicestershire on 9th July 2023. Infrastructure was provided by the Midlands Rocketry Club, with one of their range safety officers also present. The rocket was mounted onto a launch rail – a 30 mm x 30 mm aluminium extrusion. Launch lugs attached to the outer surface of the rocket fit into the slots on the extrusion to keep the rocket aligned during the first few moments of the launch. An electrical igniter was inserted into the engine, allowing it to be detonated at a distance. The flight of the rocket was stable and the deployment of the parachute was successful. Due to the reliable transmission link, the recovery process of the launched rocket was smooth.

Following the collection of pressure data, the International Standard Atmosphere model [19] was used to calculate the height of the rocket. For an atmosphere in hydrostatic equilibrium [20], the air pressure as a function of height and density is given by

$$\frac{dp}{dz} = -g\rho \,, \tag{1}$$

where p is pressure in Pa, z is height in m, g is gravitational acceleration in $\mathrm{ms^{-2}}$ and ρ is air density in kg $\mathrm{m^{-3}}$. Since air density is difficult to measure directly, the gas equation [20] is used to express air density as a function of pressure and air temperature as given by

$$\rho = \frac{p}{R_d T} \,, \tag{2}$$

where R_d = 287.059 J $\mathrm{kg^{-1}K^{-1}}$ is the gas constant of dry air and T is the air temperature in K. Both air temperature and gravitational acceleration are dependent on height. For temperature, there is a mean negative temperature gradient with respect to the height of -0.0065 K $\mathrm{m^{-1}}$ within the troposphere [21]. The corrected temperature formula is given by

$$T = T_0 - 0.0065z \tag{3}$$

where T_0 is the reference point temperature and z is vertical distance from the reference point.

Gravitational acceleration can be taken into account using geopotential height which is the integral of the gravitational acceleration from ground to height of measurement normalised by the mean gravitational acceleration [20]. However, since the maximum height of the rocket is less than 1500 m, the difference between geopotential height and geometric height is less than 1 m [20]. Therefore gravitational acceleration is assumed to be constant for the operational height.

After substituting (2) and (3) into (1) the temperature model in differential form is shown in (4).

$$\frac{dp}{dz} = -\frac{gp}{R_d(T_0 - 0.0065z)} \tag{4}$$

(4) is integrated to obtain (5).

$$z_1 = \frac{T_0}{0.0065}\left(1 - \exp\left(\frac{0.0065R_d}{g}\ln\left(\frac{p_1}{p_0}\right)\right)\right) \tag{5}$$

The limits for pressure are from p_0 which is the air pressure measured on the ground to p_1 which is the air pressure measured in flight. The limits for height are from 0 m at the ground to z_1 in flight. The ground temperature T_0 = 295.8 K was taken from the INORTONJ2 airfield weather station [22] located approximately 300 m from the launch site.

(5) was applied to the raw pressure values to produce the graph in Fig. 5. The maximum height of 721 m was achieved 11.4 s after launch. However, there are sources of uncertainty in the calculation. Treating gravitational acceleration as constant and using the gas constant for dry air will have caused an overestimate of the height reached. For the BME280 pressure sensor, there is an RMS noise of 0.2 Pa and there is an offset of 1.5 Pa/K [12]. This offset would cause an overestimation in height. The uncertainty of temperature measurement from the weather station is unknown.

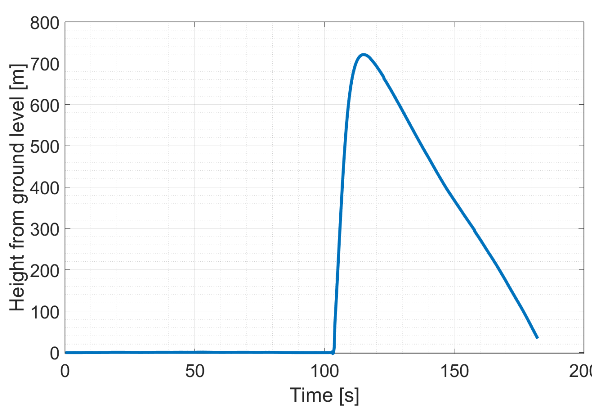


Fig. 5: Graph of rocket altitude

The GPS data collected was overlaid on a map in Fig. 6. For approximately 3 seconds immediately after launch, the GPS location coordinates appear to be fixed to a constant value. This was because the acceleration of the rocket exceeded the maximum rating of $4g$ [8] for this period leading to inaccurate readings.

The total flight duration of the rocket was 78.81 s. The straight line distance from start to end location calculated using the World Geodetic System of 1984 (WGS84) Reference Ellipsoid [23] was 896 m.

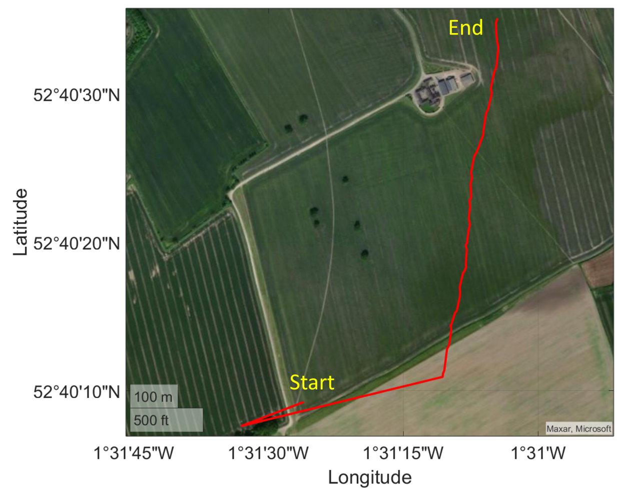


Fig. 6: Map of flight path

V. Future Work

Although the rocket was safely recovered, the nose cone had shattered on impact with the ground. This could be prevented by increasing the wall thickness of the hollow nose cone, improving its durability.

At the launch, the flight computer software was not fully completed due to lack of time. The magnetometer, flash chip and IMU were not used. In a future version, the IMU data could be used to determine the orientation of the rocket during flight which will be useful in analysing the flight characteristics of the rocket and aid in future development.

VI. Conclusion

This paper details the design, manufacture and integration of a high-power rocket and its flight computer. The rocket was launched and successfully recovered. The telemetry was transmitted during the stable flight which allowed a fast localisation of the landing site and a smooth recovery. The maximum altitude reached by the rocket was 721 m and it landed 896 m from the launch site. Unfortunately, the software for the less critical sensors was not finished and integrated in time. This was mainly due to the longer duration of the work on the physical PCB. However, since the rocket and flight computer were fully recovered, the flight computer with the updated software can be launched on the next occasion. Rocketry projects similar to ours are a great opportunity for interested individuals to improve their engineering skills such as manufacturing in the workshop, 3D printing, PCB design or programming. Coming into this project with limited skills, our team members developed the skills to complete the project. We believe that this paper together with the open-sourced resources [24] are valuable guides for people interested in rocketry and can help them gain the skills that we mentioned.

VII. Acknowledgements

This project was part of the student society. Contributors include: *REDACTED*.

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