Technical Report
AVES

Team 02 Technical Report to the 2021 EuRoC

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Abstract

AVES, Latin for *bird*, is the name of the first rocket designed and built by the Aerospace Team Graz (ASTG) to be launched at a competition, namely the EuRoC 2021 taking place in Portugal. In fact, AVES will be the first rocket ever to be launched by the team. Its main mission goals are to reach the exact target height of 3 km in the solid SRAD (S3) category as well as to land and to be recovered safely. The single-stage launch vehicle consists of an outer structure made of glass- and carbon fiber along with nose- and tailcone and fins. Starting from the top, the payload is located within the nosecone, followed by the recovery subsystem, the flight computer, the air-brake and the propulsion subsystem. The payload is made up of CanSats, which are outsourced to projects by students of two different secondary technical schools. These projects involve atmospheric measurements and a flight computer. Beneath the payload lies the two-parachute recovery system that can be triggered redundantly. It is followed by the self-designed and built flight computer, which runs an operating system that was also developed by the team. Another highlight of our mission, located below the flight computer is the 360 degree camera system as well as the air-brake, which can be used to increase aerodynamic drag in the cruise phase to reach the target height as accurately as possible. The lower part of the rocket houses the propulsion subsystem, that consists of an insulated aluminum tube and a nozzle made of graphite. A mixture of potassium nitrate and sorbitol (Rocket Candy) is used as propellant in the form of spaced fuel grains. RADAX joints with integrated mounting for the avionics and recovery subsystem enable to separate the rocket at two points to make all the subsystems accessible. In addition to the rocket itself, a self-built groundstation that allows live data downlink shall be tested during flight. All in all, AVES has been an ambitious (first) rocket for the team to design, build and test in the last couple of months. Especially the many Student Researched And Developed (SRAD) components have made the project as demanding as is has been. Last but not least, this mission and the competition itself will help the team members to gain experience, to expand their knowledge and to make new friends and colleagues from all over Europe.

Godspeed to all the teams!

Contents

1 Introduction 1

2 System Architecture 4
2.1 Overview 4
2.2 Avionics Subsystem 5
2.2.1 SRAD Flight Computer 6
2.2.2 Telemetry 8
2.2.3 Power Supply 9
2.2.4 Avionics Mounting Structure 10
2.2.5 Cameras 11
2.3 Ground-Station Subsystem 12
2.3.1 Open MCT 12
2.4 Propulsion Subsystem 13
2.4.1 Engine Design 13
2.4.2 Propellant 14
2.4.3 Ignition 16
2.4.4 Overview of Propulsion Tests 17
2.4.5 Motor Performance 18
2.5 Aerodynamics Subsystem 19
2.5.1 Air-brake System 19
2.5.2 Nosecone 20
2.5.3 Fins 22
2.5.4 Computational Fluid Dynamics analysis of the rocket surface 24
2.6 Structure Subsystem 26
2.6.1 Expected Loads 26
2.6.2 Shell 27
2.6.3 RADAX 28
2.6.4 Thrust structure and motor retention 30
2.6.5 Tailcone 30
2.6.6 Fins and fin mount 31
2.7 Recovery Subsystem 32
2.7.1 Introduction 32
2.7.2 Opening System 33
2.7.3 Ejection System 35
2.7.4 Parachute and lines 37
2.8 Payload Subsystem 38
2.8.1 Introduction 38
2.8.2 Payload enclosure 38
2.8.3 Flight computer HTL Neufelden & Flight computer HTL Pinkafeld 39
2.8.4 Weight compartments 39

3 Mission Concept of Operations Overview **40**
3.1 Flight Phases 40
3.2 Flight Simulation: Open Rocket 42
3.3 Simulation Motor Performance 46

4 Conclusions and Outlook **47**

5 Appendices **49**
5.1 Acronyms 49
5.2 System Data 50
5.3 Payloads 51
5.4 Detailed Test Reports 55
5.4.1 Ground Test Demonstration of Recovery System 55
5.4.2 Parachute Extraction Test 63
5.4.3 Parachute Flight Test 64
5.4.4 Static Hot-Fire Test 65
5.4.5 Hybrid/Liquid Propellant loading and off-loading 80
5.4.6 Combustion chamber pressure 81
5.4.7 Proof Pressure Testing Pressure Vessels 82
5.4.8 Burst Pressure Testing Pressure Vessels 83
5.4.9 Test of SRAD flight computers with capability of actuating the recovery systems . . . . 5.4.10 Test of SRAD 84
flight computers with capability of actuating the air-brake systems 85
5.4.11 All-on Vertical Hot-Fire Test 86
5.4.12 Tensile and Compression Test of glass-fibre-reinforced-polymer (GFRP) composite 90
5.5 Calculations 91
5.5.1 Calculation of optimal air-brake area 91
5.5.2 Calculation of the parachute and the expected forces 92
5.5.3 Bolted Joint Analysis 94
5.5.4 Adhesive Joint Analysis 96
5.5.5 Opening System: calculation gas pressure 98
5.5.6 Opening System: calculation shear bolt 101
5.6 Hazard Analysis Report 102
5.7 Risk Assessment 103
5.8 Checklists 107
5.9 Engineering Drawings 120
5.9.1 Avionics system 120
5.9.2 Propulsion system 129
5.9.3 Aerodynamics system 136
5.9.4 Recovery system 147
5.9.5 Structure system 157
5.10 Data Sheet of the Pyro Bolt 164

5.11 Data Sheet of the capsule 175
5.12 Data Sheet of Glycerol 176
5.13 Data Sheet of KNO_3 184
5.14 Data Sheet of Sorbitol 194

1 Introduction

We, the Aerospace Team Graz (ASTG), are a student team with about 65 members from different universities in Graz, Austria. We are a purely non-profit organization founded in 2019 with the common vision of building a completely self-designed rocket.
We started this project with the experience of first self-built prototype rocket, which was meant to reach an apogee of 1 km. Therefore our main technical challenge was to use the basic ideas of our prototype and further develop and adapt them to the rules and requirements of European Rocketry Challenge (EuRoC).
Thanks to our partners and suppliers we can make our visions reality and are able to test and construct our rocket-parts. To our main sponsors, partners and suppliers we can count the Technical University (TU) Graz, European Space Agency Business incubation center Graz (ESA BIC Graz), Institute of manufacturing engineering (IFT), Schaffler, Zirkonzahn, Siemens, Robotunits, Austria Technologie & Systemtechnik (AT&S), host-tech, Swagelock and many more.
As can be seen in Figure 1 the majority of the team is currently studying at the TU Graz. Nevertheless, there is still a number of students enrolled in other universities in Graz.

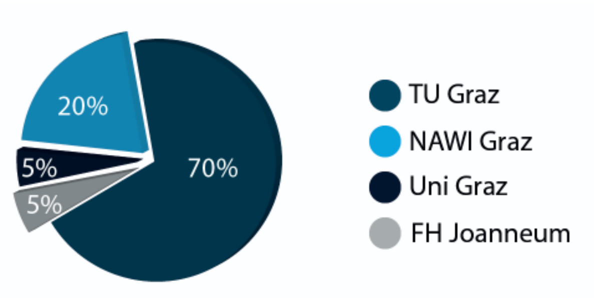


Figure 1: Universities of ASTG members

The majority of our team is currently enrolled in technical studies. Nevertheless, there are several students registered in the humanities, sciences, and other programs. Mechanical and industrial engineering are the two courses that hold the most students of the ASTG. In the following list you find all the programs which are represented at ASTG.

- Mechanical/Industrial engineering
- Electrical engineering
- Information and Computer engineering
- Software engineering and Management
- Physics
- Aviation
- Space Science and Earth from Space
- Biomedical engineering
- Chemistry
- Mathematics
- Geodesy
- English and American studies
- Business administration
- Psychology

Our team, as seen in Figure 2, is structured mainly into two teams namely the Rocket Team and the Business Team. These are further split into modules.

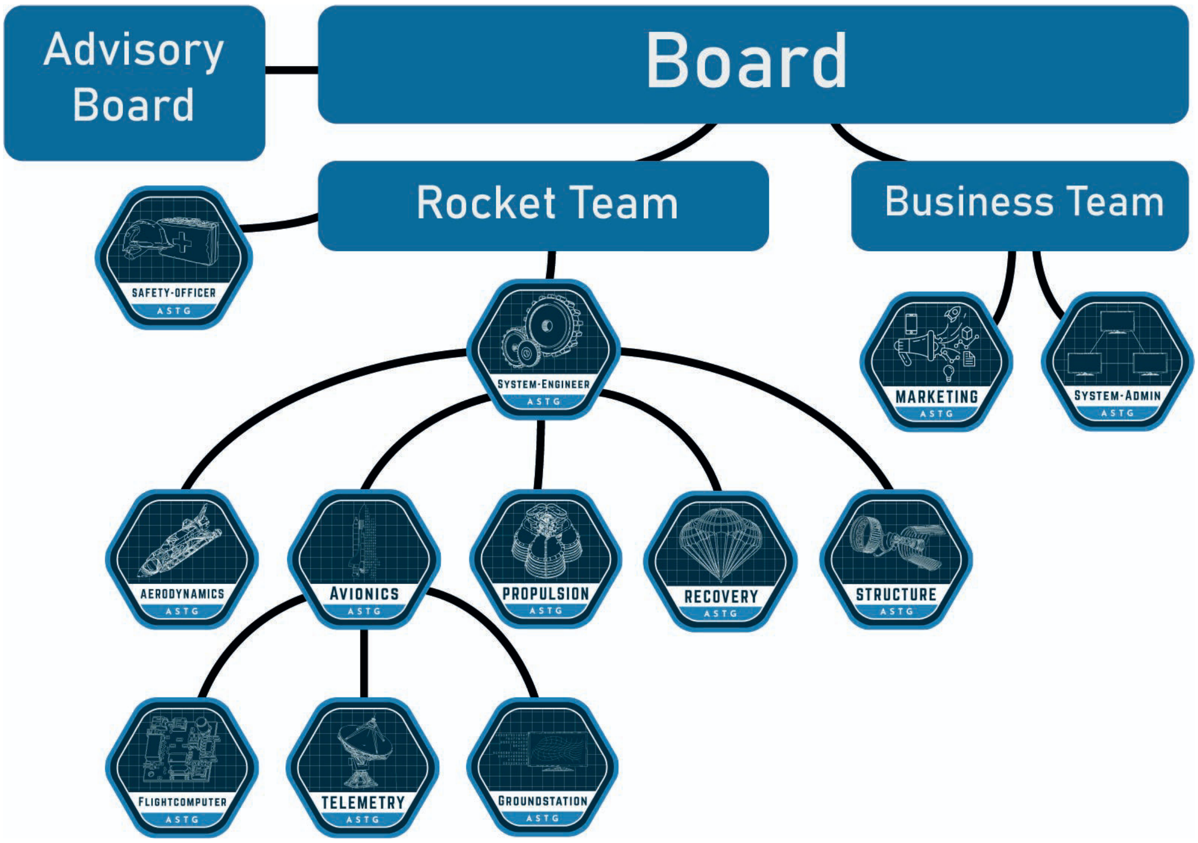


Figure 2: Team Structure

Aerodynamics is responsible for the basic flight stability of the rocket and the aerodynamic design from the nose cone to the fins at the tail. Once the design is finished, the construction of the prototypes as well as tests in the wind tunnel and field experiments follows. In Avionics, everything revolves around the electronic hardware and software of the rocket, working on sensors and the main computer as well as dealing with the control of the rocket, data transmission and visualization. In Propulsion, the rocket engine is conceived, designed, and manufactured. The team deals with additive manufacturing processes, fluid mechanics and materials, among many other things. Parachutes and their anchoring and ejection system are being developed in Recovery so that the rocket can safely return to the ground. All manufactured components must be integrated into the outer skin and basic structure of the rocket, which is done by our Structure team. This team also focuses on the reduction of weight and the balancing of the center of gravity of the rocket. The System Engineers coordinate and optimize the overall process ranging from project-, risk-, time-, to resource management. Finally, our Safety Officers ensure the safety of the entire team while testing and handling hazardous substances.
The Business Team is divided into Marketing and System Administration. The Marketing module ensures that the ASTG is well represented on various social media platforms. They also deal with the organization of our conferences and focus on team building and launch events.

2 System Architecture

2.1 Overview

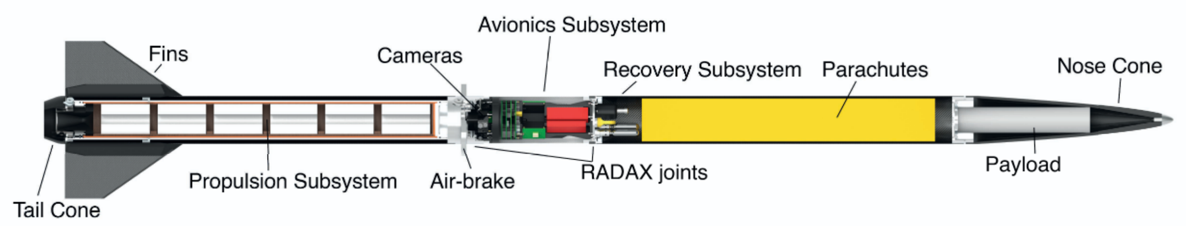


Figure 3: AVES Cross-Section

The Propulsion System is placed in the back of the rocket. The booster is fixed with the Tailcone and centered with the fin mounts on the bottom and with the bottom plate of the airbrake on the top. It contains 6 grains of casted rocket-candy to reach the required thrust. A carbon tube covers the whole propulsion system and works as the structural component. The fins are mounted with screws through the carbon tube to the fin mounts which are glued inside the carbon tube. The bottom plate of the air-brake is glued to the carbon tube too. To reach the exact apogee the regulation system of the flight computer increases the aerodynamic drag by actuating the air-brake. Above the air-brakes you can find the 3 cameras which are responsible for delivering a 360° video recording. In the following tube the avionics bay is built in. A SRAD and a Commercial Off The Shelf (COTS) flight computer ensure redundant control of all critical systems. The installed telemetry communicates with the ground station and sends all recorded data for visualization and evaluation. The Avionics bay is encapsulated with a glass-fibre tube so that the RF-signals are not disturbed. The upper RADAX joint connects the upper carbon tube to the glass fiber tube. In the upper carbon tube sits the recovery system including the drogue parachute and the main parachute. It is mounted to the upper RADAX joint. Last but not least there is the nosecone on the top of the rocket. The tip is made of aluminium to withstand the aerodynamic pressure during the flight. The nosecone contains the Payload which has the size of 3 CanSats in a row. The Payload has 2 build-in flight computers designed in cooperation with teams of two different schools, the HTL Neufelden and the HTL Pinkafeld.

2.2 Avionics Subsystem

The avionics of our system consist of multiple subsystems. The requirements of these systems are:

- Logging sensor data
- Triggering recovery events
- Controlling the air-brake
- Recording and storing camera footage

} Flight-computer

- Sending sensor data to the ground-station

} Telemetry system

In order to fulfill these requirements, we have designed multiple systems that are implemented on custom Printed Circuit Boards (PCBs). We divide these systems into our SRAD Flight-computer and the Telemetry system. The SRAD flight-computer handles all tasks except for the data transmission to the ground-station, which is done by the Telemetry system. For redundancy we chose to use the Eggtimer TRS from Eggtimer Rocketry as this is also the official altitude logging and tracking device. This COTS flight-computer ensures a redundant recovery deployment, in case our SRAD flight-computer fails and provides data for the official height logging.

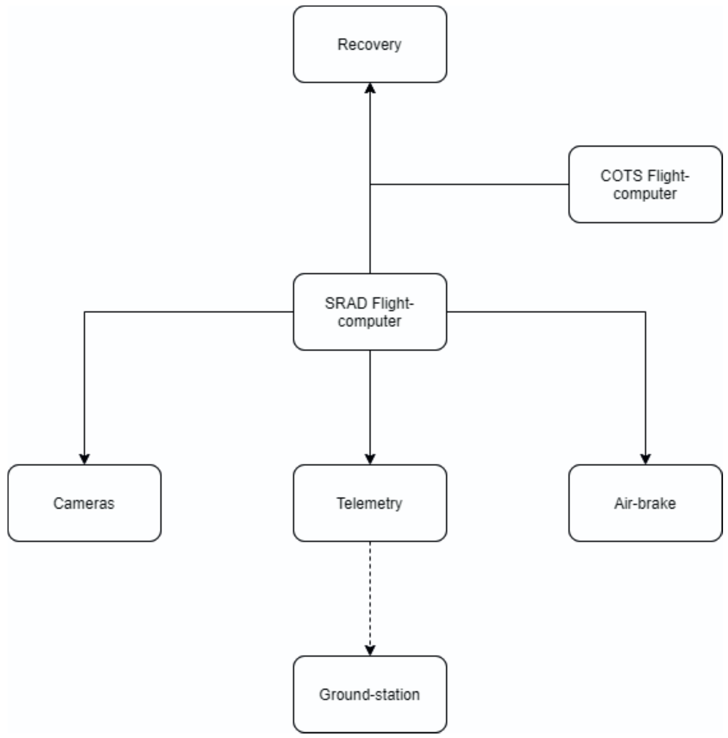
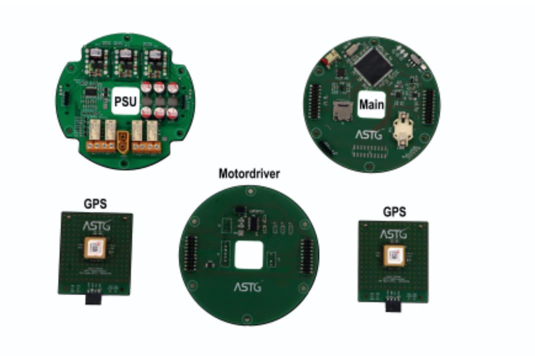


Figure 4: Avionics Subsystem Overview

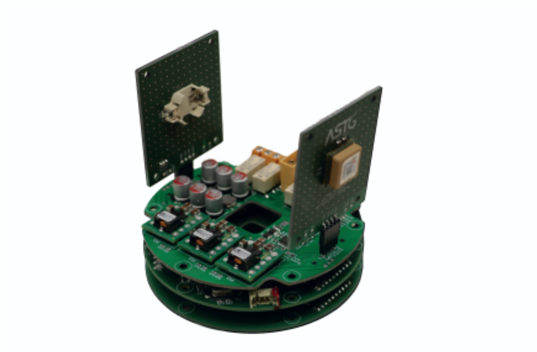
2.2.1 SRAD Flight Computer

2.2.1.1 Hardware

For the main Micro Controller Unit (MCU), a dual core ARM processor was chosen to create a platform that can be used as a basis for this rocket and future projects. The PCBs used for AVES were all custom designed and consist of a Main PCB, a Power Supply Unit (PSU) PCB, a Motordriver PCB and two Global Navigation Satellite System (GNSS) PCBs.



(a) Assembled Printed Circuit Boards



(b) Assembled PCB Stack

Figure 5: SRAD Flight Computer PCBs and Stack

Sensors
The SRAD flight-computer uses 5 sensors. An Inertial Measurement Unit (IMU) with 6 degrees of freedom (dof) (3 axis accelerometer and 3 axis gyroscope), a 3 axis high-g accelerometer, a barometer and two GNSS chips. The sensors were placed on the Main PCB with the exception of the two GNSS chips, which are placed on a separate PCB each.

Storage
For storage, an SD-Card with 2 GB of memory and a FLASH chip with 8 MB of memory are used in addition to one FLASH bank of the MCU. Both external storage devices are placed on the Main PCB.

2.2.1.2 Operating System

An in-house Real Time Operating System (RTOS) called RavenOS was written for the MCU. Being based on SmartOS, RavenOS carries over the general philosophy of the RTOS, which focuses mainly on compositional software design through sophisticated time and resource management. An application is organized as a system of concurrently running tasks with individual stacks that can communicate using events and can use resources for the protection of critical code sequences. The time management is done using a local system time which provides tasks with the ability to sleep for an arbitrary time, as well as the possibility to specify a deadline when waiting for events. The scheduling is done using the Highest Locker Protocol (HLP), which utilizes dynamic task priorities depending on the resources currently held by the individual tasks.

2.2.1.3 Software

The brain of AVES is responsible for data processing and controlling. The SRAD operating system RavenOS is specifically designed to run all calculations in real time. Starting just before takeoff all data will be logged throughout the flight. Before takeoff the final calibration of the sensors is performed. After booster burnout, the air-brakes deploy and are controlled by the flight computer. Finally, the most important task is sending signals to deploy the parachutes.

Data Processing

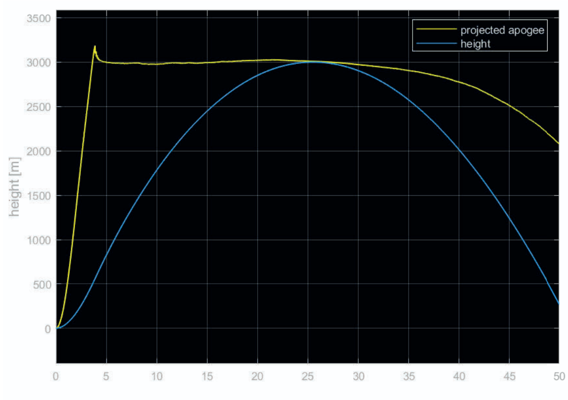
After acquiring all sensor data, a strapdown algorithm is used to perform relative positioning. Using Tustin approximation, it integrates the sensor data (specific force and angular velocity) to get the required velocity and position values in a local-level coordinate system.

In order to increase the reliability of the control system, a Kalman Filter was implemented to aid in height determination using the barometer. Simulations show that this drastically improves the performance of the algorithm.

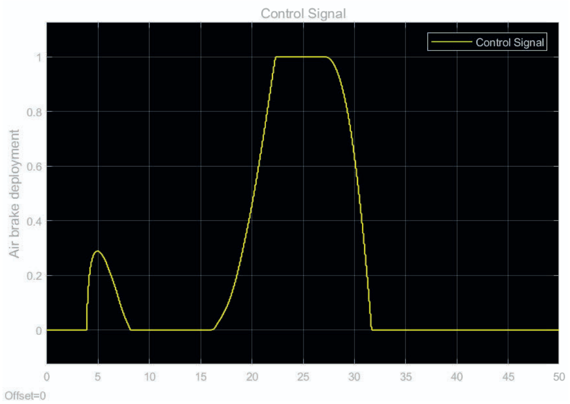
One of the more challenging hurdles of designing the code for sensor fusion was the fact that AVES will approach the speed of sound. At velocities near Mach 1, there are certain effects that cause an inconsistency in the measured air pressure, which results in false height data. As a countermeasure, it was decided not to include barometer data at high velocities. Since the rocket will only be flying at such speeds for a short amount of time, the Kalman Filter will be able to cover the outage by using IMU data.

Controller

Following the calculation of the current position and velocity, the controller creates an estimate on how high the apogee will be. This is shown in Figure 6a: the blue line shows the actual height of the rocket and the yellow curve represents the apogee calculation over time. Based on that value, the air-brakes will deploy a certain amount, which is depicted in Figure 6b. Since there is no way to have direct feedback from the system, the Apogee Estimator also takes the air-brake position into account when ascertaining the maximum height AVES will reach. The simulation model can be seen in Figure 95.



(a) Apogee estimate versus actual height over time



(b) Control signal plot over time

Figure 6: Simulink Results of Controller

State Detection

Chute deployment relies on State Detection, which is why this is the most critical part of the software to assure that AVES comes back down safely.
All events of the flight are represented by a state defined in software: Liftoff, Booster Burnout, Apogee, Drogue chute deploy, Main chute deploy, Landing. As the name of this task suggests, its job is to detect these events and set actions according to the flight plan.
At liftoff, all sensors will have been initialized and the data processing and logging will have started. After booster burnout, the controller takes action by controlling the air-brakes. At apogee, the flight computer deploys the drogue chute and the main parachute. The state diagram can be seen in Figure 94.

2.2.2 Telemetry

The Telemetry-Subsystem consists of two parts: one as part of the rocket and one on the ground as part of the groundstation. They share the same PCB design but differ in the antenna type used for transmitting and receiving data. As a way of communication we use two wireless links on 433 MHz, which can be utilized in either direction. One link uses the Long Range (LoRa)-, and the other uses the Automatic Packet Reporting System (APRS)-Protocol. For this we utilize a single core ARM-MCU to process and buffer data and two transceiver chips to send these.

(a) Top Side (b) Bottom Side

Figure 7: Assembled Telemetry PCB

2.2.2.1 Rocket - Antenna Package

Due to the available space inside the rocket being very limited we opted for a compact microstrip antenna. Our MCU communicates with the MCU of the Main PCB, to get data from the myriad of sensors built into the rocket.

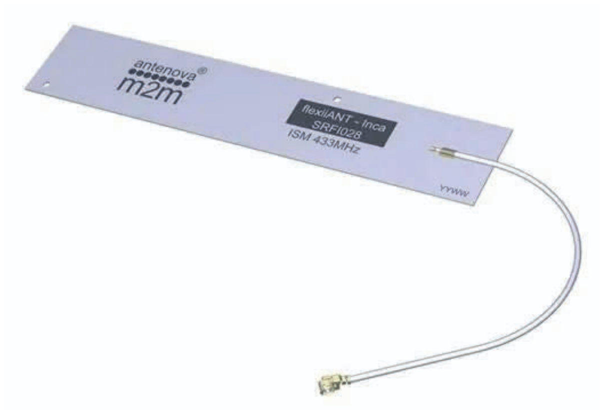


Figure 8: Microstrip Antenna for the Rocket

2.2.2.2 Ground Station

On the ground we opted for another antenna with a strong directional propagation, two self-built Yagi antennas. A Yagi antenna is a special type of directional antenna. After receiving the sensor data we send it over a serial link to the ground station to save and visualize it.

2.2.3 Power Supply

Electrical power is supplied by two Lithium-Polymer (LiPo) batteries, one with 14.8 V and 2400 mA·h for our SRAD flighcomputer (main battery), and one with 7.8 V and

1300 mA·h for the COTS flightcomputer (redundancy battery). Additionally we can provide external power over our pad connector to keep the main battery fully charged for as long as possible during pre-flight checks. The main LiPo is designed to keep all systems running for at least 2 hours, while the redundancy LiPo has an expected run time of over 24 hours, and is still able to activate the recovery system. The PSU converts the main battery voltage to the levels (12 V, 5 V, and 3.3 V) needed for our electrical systems, and also balances the 4 battery cells. The electrical system can be disconnected by inserting an arming pin that has to be removed before flight.

2.2.4 Avionics Mounting Structure

(a) Avionics Bay in flight orientation

(b) Avionics Bay close up (upside down)

Figure 9: Mounted Avionics Bay

All the PCBs, batteries, and antennas are attached to the avionics mounting. It is 3D printed from Polyethylene Terephthalate Glycol (PETG) with heat-set threaded inserts for the screws. Inside the rocket the bay attaches to the recovery plate at the top and is braced against the 3D printed camera structure. The batteries each have a separate compartment. Below the batteries two GNSS antennas as well as four telemetry antennas are mounted with a space in the center for the battery wiring. Below the antennas is the PCB-stack, in the order of PSU, telemetry, main, and motordriver boards. The PCB-stack is held together with 3D printed spacers and long screws that go all the way to the top PETG parts. At the bottom there is a conical ring that serves to protect the PCBs and also to align radially and brace axially against its counterpart.

2.2.5 Cameras

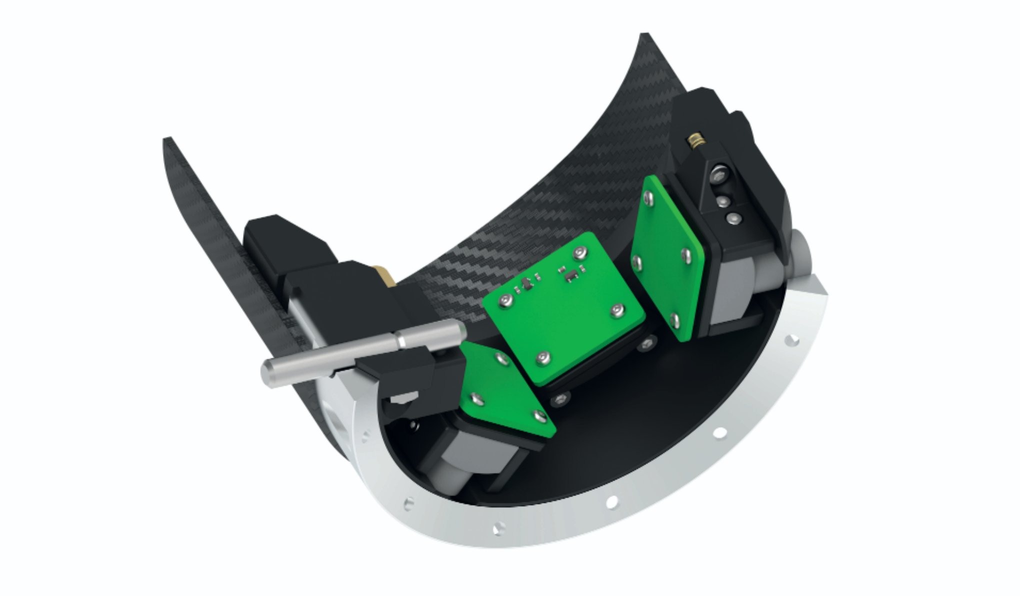


Figure 10: Camera Mounting Structure & Arming Pin

We use three 4K RunCam Hybrid 2 cameras to capture a 360 degree recording of the flight. They are built into the lower RADAX joint and held into place by a 3D printed camera structure. This mounting structure can be seen in figure 10. They are connected to a custom-made PCB (Figure 11) that is also mounted inside the 3D printed housing. This PCB has the purpose of individually controlling and monitoring all three runcams. They are controlled by a serial interface. The state of the cameras is monitored by the current.

(a) Top

(b) Bottom

Figure 11: Assembled Runcam Printed Circuit Board

2.3 Ground-Station Subsystem

The Goal of our Ground-Station Subsystem is to be a flexible and easily applicable system which enables us to dynamically operate, visualize and diagnose all aspects of our rocket. This should be implemented in a way that the system can easily be expanded or tailored to future capabilities of our rocket or other missions.
We settled for a software application which receives the incoming data from the telemetry system, stores it in real-time in our database and from there visualizes it through a tool called Open Mission Control Technologies (OpenMCT).

2.3.1 Open MCT

OpenMCT is an open source and web-based mission control framework for visualization of data on desktop and mobile devices developed through NASA. OpenMCT is designed for analysis, visualization, operation and support of spacecraft missions. OpenMCT provides an extensible plugin system allowing it to be integrated with existing ground systems and adapted to support multiple missions as well as non-space applications. Through this approach, multiple participants can watch different custom layouts tailored to their need on the launch-site. In Figure 12 a Simulation of Mission Operator Layout can be seen.

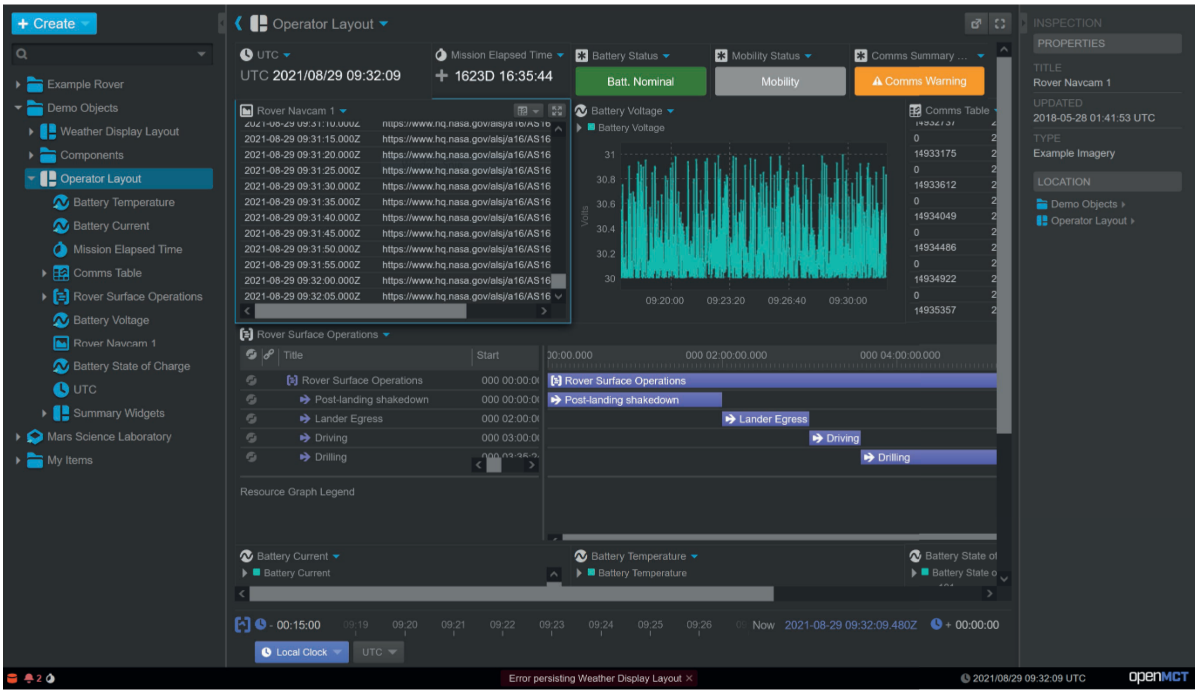


Figure 12: Symbolic Picture of Open MCT Application

2.4 Propulsion Subsystem

The general goal of the design was to create a reusable platform that can be further developed due to its simple structure. Commercial systems were used as a source of inspiration for the basic design decisions. After their analysis, our system was designed and developed completely independently.

2.4.1 Engine Design

The basic structure of the propulsion system consists of a aluminum tube with an outer diameter of 100 mm and an inner diameter of 92 mm. This guarantees that the system can be easily expanded. Due to the availability as a semi-finished product in standard dimensions we were able to reduce the required machining operations. The main task of the tube is to absorb the pressure forces generated during combustion. At each end, there is a snug fit for the O-ring turned out internally and an internal thread which closes the combustion chamber and absorbs the axial forces. Axial securing is achieved via the threads into which a retainer ring is screwed. Two axial M4 threaded holes make it possible to insert two screws and thus tighten the large thread. In addition, one of the two tapped holes has a radial borehole in which a plastic part is inserted. This is pressed outwards by the M4 screw into the main thread thus securing it. The two retainer rings press on the bulkhead on the one hand and on the nozzle holder on the other. An O-ring is inserted in the grooves of the two components, which seals the combustion chamber and thus prevents gases from escaping. The nozzle holder has another O-ring, which also seals the combustion chamber.

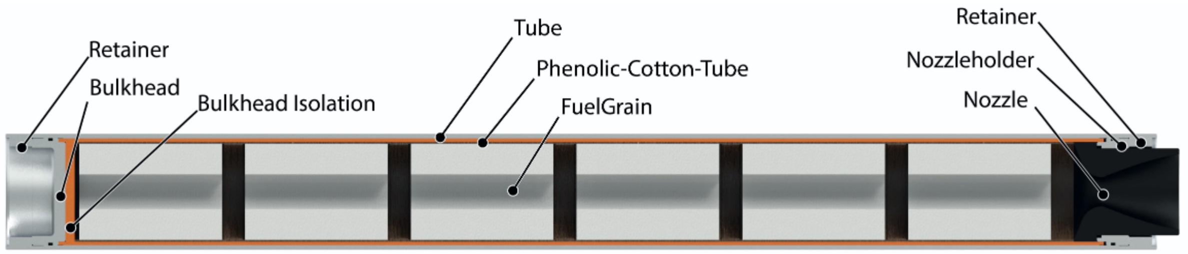
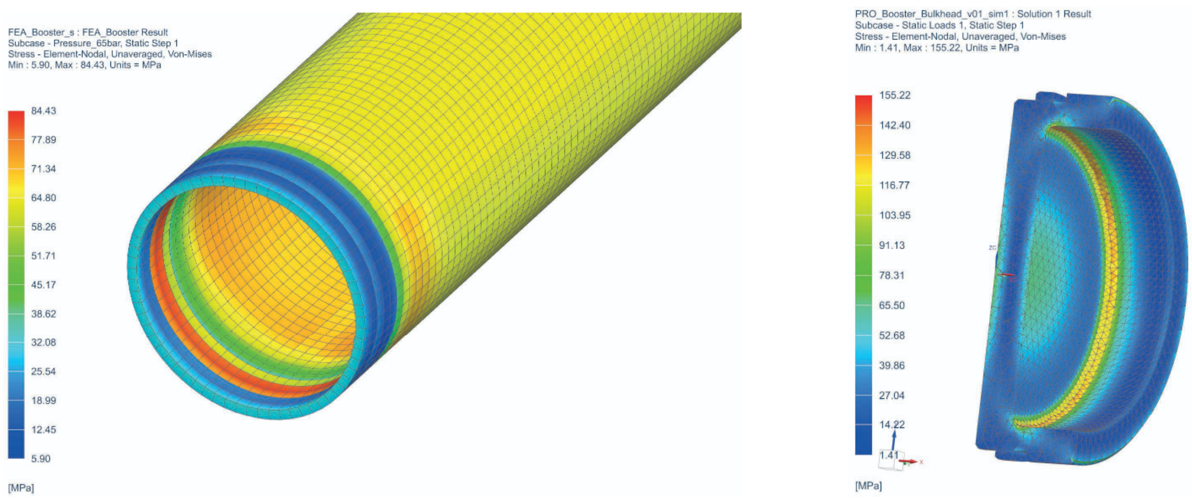


Figure 13: Propulsion System

Without complete insulation, the aluminum would not withstand the thermal stresses released from the combustion gases. Therefore, a continuous layer of insulation is very important to protect the integrity of the combustion chamber. The main insulation consists of a cotton phenolic resin tube with 3 mm wall thickness. This protects the aluminum from the hot combustion gases. The axial insulation on the bulkhead side consists of a cotton phenolic resin disc, which is glued into the insulation tube with high temperature silicone adhesive. The nozzle is inserted directly into the insulation with the same silicone adhesive. To withstand the thermal and abrasive stresses, the nozzle was made of graphite. Theoretically, other materials would also be possible, but this

material was selected in order to gain experience for future projects with graphite.
After an initial preliminary design with the Barlow's formulas, the tube made of EN AW 6060 T66 was checked for its pressure resistance by the use of an Finite Element Analysis (FEA). The FEA was conducted with twice the expected chamber pressure, i.e. 65 bar. The ends in particular were examined more closely, whereby the thread was not calculated in detail, but an "adhesive connection" was assumed. The highest von Mises stress was thus found to be 84.43 MPa in this connection. Within the homogeneous structure, the maximum stress is 73 MPa. The strain in radial direction was 0.047 mm, which should not be a problem especially for the O-rings.
In summary, the yield strength of 160 MPa is not exceeded even at double load, which means that the tube meets the requirements. Our Bulkhead design was also verified by a FEA. The maximum occuring Von-Mises stresses were 155 MPa, well below the maximum yield strength 220 MPa of the material EN AW 2007. The maximum load occurred on the outer side of the Bulkhead as seen in Figure 14.



(a) FEA Boostertube

(b) FEA Bulkhead

Figure 14: FEA Bulkhead and Boostertube

2.4.2 Propellant

For the propellant we decided to use Rocket Candy, because it is easy to prepare, there is a lot of literature about it and the components are easy to obtain. This propellant consists of potassium nitrate, which acts as an oxidizer, and sorbitol, as the fuel. Sorbitol is non-toxic and is mainly used as a sweetener. It exists as a white crystalline powder and has its melting point at around 100 °C. Potassium nitrate is also non-toxic, is also present as a white powder and has a melting point of 334 °C.
Before processing, the grain size and moisture content of the potassium nitrate needs to be taken into account. If clumps form, the potassium nitrate should be dried in a drying chamber or at an elevated temperature for several hours. If clumps are still present,