ELECTRONICS AND SENSOR SUBSYSTEM DESIGN FOR DAEDALUS 2 ON REXUS 29: AN AUTOROTATION PROBE FOR SUB-ORBITAL RE-ENTRY

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ABSTRACT

The Daedalus 2 mission aboard REXUS 29 is a technology demonstrator for an alternative descent mechanism for very high altitude drops based on auto-rotation. It consists of two probes that are ejected from a sounding rocket at an altitude of about 80 km and decelerate to a soft landing using only a passive rotor with pitch control.

This type of autonomous, scientific experiment poses great challenges upon the electronics subsystem, which include mechanical stress, power system reliability, sensor redundancy, subsystem communication, and development procedures.

Based on the data gathered in Daedalus 1 [1] multiple new approaches were developed to fulfill these requirements, such as redundant communication links, mechanical decoupling of PCBs and fault-tolerant power source selection.

Key words: Robust Electronics, Re-Entry, Autorotation, REXUS 29.

1. INTRODUCTION

The experiment will fly as a payload on an Improved Orion sounding rocket as part of the REXUS/BEXUS program and will test a novel form of re-entry and descent control without parachutes, adding to the knowledge base of rotors in space applications, especially regarding the descent of interplanetary probes.

The use of autorotation has already been conceptually demonstrated by the predecessor project Daedalus 1, which operated completely passively. In contrast, Daedalus 2 decouples the rotor from the main body and uses an active control system for sink rate and rotor rotation speed by changing the pitch of the rotor blades, which poses great challenges for the electronics and software implementation.

2. SYSTEM TOPOLOGY

The Daedalus 2 experiment consists, as most space missions do, of a space, a ground and a user segment. The user segment covers post-flight data analysis and will not be covered here in detail. It receives the recorded and recovered data after the flight from the ground segment. A schematic overview of the space and ground segment is presented in Fig. 2.

The rocket board computer (RBC) and the Spaceseeds with their Seed Board Computers (SBC) and CoProcessors (COP) form the space segment. The RBC remains on the REXUS rocket for the whole duration of the flight. Its main tasks are power control for the Spaceseeds (see Sec. 3.4) as well as telecommand and telemetry forwarding between the REXUS rocket uplink provided by the REXUS service module and the Spaceseeds (further discussed in Sec. 4.2).
The two Spaceseeds are the free-falling units (FFU) that will be ejected at trajectory apex of roughly 80 km, autonomously control their descent and landing and will then later be recovered to extract the detailed protocol stored on the redundant on-board flash storage. (The ejection is timed by the REXUS service module and is therefore not a task of either of our systems.) A Spaceseed has two CPUs, the SBC and the COP. The SBC is the main computing unit responsible for data acquisition, communication, the flight controller and data logging; the COP is responsible for interfacing with additional periphery, such as power and thermal management. This split allowed software development to be more focused on their respective sub-task and made it possible to develop two separate electronic boards which can undergo development revisions independently, thus a multi-board design for the board computer allowed for much faster design iterations while also helping to work around space constraints.

The ground segment consists of our ground station which interfaces with the uplink to the REXUS service module, the Iridium network for receiving direct downlinks from the Seeds and a recovery device which helps locate the landed seeds, which interfaces via LoRa. It collects and displays the received data and allows commanding the system before ejection. Displaying live data is important as the FFU’s GPS position is required for successful recovery.

3. ELECTRONICS

3.1. Mechanical Challenges

As a rough outline for maximum accelerations we build on the experience from Daedalus 1, where one of the three probes experienced forces in excess of 115 g over 20 s. This occurred because the Spaceseed entered flat spin, a flight configuration where the main body is not oriented vertical as planned but horizontal, while rapidly spinning around the z-axis.

And although the new flight controller should prevent another flat spin, the system should still be robust against such situations. Together with the accelerations and vibrations on board the rocket and later during atmospheric entry, this results in extreme mechanical stresses for all components and especially connectors are at a high risk of loose contacts or complete failure.
For mechanical robustness it was chosen to use a special construction technique with mechanically decoupled connectors to build a robust multi-board flight computer. Specifically Hirose FX23L connectors have the ability to float, i.e. to still make shock- and vibration-proof connections, even if misaligned by as much as ± 0.6 mm (see Fig. 4).

Additionally, each solder connection of wires to PCBs uses two solder holes and a mechanical hole to provide stress relief.

### 3.2. Redundant Sensor Configuration

The maximum acceleration during the Daedalus 1 flat spin could not be determined as the measurement surpassed the maximum value of 115 g that the accelerometer could measure. That is why Daedalus 2 carries two accelerometers per Spaceseed, where the first is quite precise and used as input for the flight controller while a second high-load accelerometer provides measurements up to 400 g and could also be useful as a second reference during result analysis.

A second critical sensor is the barometer because it is the main reference for determining both height and vertical speed, as GPS won’t be available in high altitudes. Again two sensors are used, where the first obtains a precise accuracy of 2.5 mbar over the range from 10 mbar to 1200 mbar while the second has lower accuracy but can reach down to 0 mbar, which is useful because much of the flight is performed in very low atmosphere.

### 3.3. Battery Choice

The battery chemistry chosen for the experiment is Li/\text{SO}_2\text{O}_3, specifically SAFT primary cells of type LO 35 SX, because of their non-flammability, big temperature range, high peak current and the excellent energy density.

| Table 1. Li/\text{SO}_2\text{O}_3-cell characteristics [4] |
|---------------------------------------------------------------|
| **Characteristics**                                       | **Value**            |
| Self-Discharge                                               | >3 %/year            |
| Storage Temperature                                          | −60 °C to 85 °C      |
| Operating Temperature                                        | −60 °C to 70 °C      |
| Capacity                                                     | 2.2 A h              |
| Voltage (at 250 mA and 20 °C)                                | 2.8 V                |
| Current (cont)                                               | 2 A                  |
| Current (peak)                                               | 5 A                  |
| Weight                                                       | 30 g                 |
| => Energy Density                                            | 0.74 MJ kg\(^{-1}\)  |

The cells are employed in a 3S2P configuration, leading to a nominal voltage of 8.4 V at a capacity of 4.4 A h. For redundancy purposes each individual battery strings should suffice for a successful mission. In the case of failure of a single string it will be automatically disconnected using the circuit described in Sec. 3.4.

### 3.4. Power Topology

The Spaceseeds can be powered from 6 V to 40 V via three inputs. Two inputs are used for the batteries, while the third is supplied by the Rocket Board Computer which relays the 28 V supply from the REXUS Service Module (RXSM).

Upon Spaceseed ejection the RXSM connection is severed and the experiment shall seamlessly switch from the external power supply to the internal batteries. In its simplest form this can be achieved with diode OR-ing, where each supply has a Schottky diode, such that the highest supply voltage will always power experiment.

\[ P = V_{\text{DROP}} I_{\text{LOAD}} \]

\[ P = 2 I_{\text{LOAD}}^2 R_{\text{DS(ON)}} \]

*Figure 6. Comparison of Power Loss for Traditional Schottky Diode vs Ideal MOSFET Diode*

This has the downside of a voltage drop of roughly 400 mV across the diode which causes additional power dissipation. Instead, an ideal diode circuit was implemented that uses two back-to-back MOSFETs. This way the power dissipation is only dependent on the drain-source resistance \( R_{\text{DS(ON)}} \), which can be as low as 5 mΩ. Two FETs are needed to both switch the supply current and block any return charging currents.

To switch the MOSFETs, an ideal diode controller is employed which compares the voltages across the ideal diode and switches the gates if needed. By using a small hysteresis of 20 mV for the comparator both batteries can...
Figure 7. Schematic of the Power Switch Circuit

supply the experiment at the same time if their voltages are close enough.

An additional advantage is that the controller can be used by the COP to completely switch off a power supply if desired. This is required by REXUS guidelines for the phase of “radio silence”, in which any currents inside the experiment are strictly forbidden. For example during the critical stage of the rocket motor integration “radio silence” is employed, as ground currents across the rocket hull may trigger accidental ignition.

For this we use two D flip-flops as seen in Fig. 7, which can be set by the SBC using DIS_BAT1, DIS_BAT2 and a rising edge on FF_CLK. The flip-flops are always powered by their respective battery, so to enter radio silence the following procedure takes place:

- Experiment is supplied by V_BAT1, V_BAT2 and the rocket supply V_RXSM.
- Radio silence is requested, the COP sets both flip-flops.
- The ideal diode controllers for the batteries switch off, the experiment is only supplied via V_RXSM.
- The RBC cuts the V_RXSM supply, the Spaceseeds completely switch off while the flip-flops prevent the circuit from waking up via battery power.
- Power to the RBC is cut and the experiment is completely switched off.
- When reapplying external power the RBC boots, power is applied to the Spaceseed and the COP reactivates both batteries. Now the system is again armed for ejection.

3.5. Recovery Strategy

The recovery of the fallen Spaceseeds is a secondary objective, since for the performance evaluation of the autorotation system as parachute alternative the wireless data may be sufficient. Still, successful recovery has a high priority so redundant systems were devised.

3.5.1. GPS Positions

Each Spaceseed has a u-blox ZED-F9P GNSS module to determine descent speed and position with an accuracy of 0.01 m + 1 ppm CEP at an update rate of 20 Hz. The position estimate is used as flight controller input, but also transmitted over the Iridium network to the ground station backend server which can display a landing prediction on a ground station frontend.

Although successfully used on Daedalus 1 this setup relies on the availability of two satellite networks, GPS and Iridium, as well as a working power system.

3.5.2. LoRa

If only a coarse location of the unit is known, possibly through GPS positions transmitted some time before the landing via Iridium or trajectory extrapolation, the recovery crew needs assistance in location the FFU, which may be hidden in the snow or a forest.

This recovery mechanism works by having the landed units repeatedly broadcast their GPS position if available - or dummy data otherwise - over a long range (LoRa) radio module, which provides multiple kilometers of range albeit at low data-rates.
A purpose-built recovery device will receive these messages transmitted by the Spaceseeds if they are in range and display the received data but also the received signal power. By connecting a directional antenna to the device and turning on the spot, the direction of the transmitter on-board the Spaceseed can be determined. Repeatedly perform this maneuver and moving in the indicated direction should lead the crew to the FFU.

3.5.3. RECCO Reflectors

Additionally, a passive recovery system is deployed which was originally devised for avalanche search and rescue (SAR) operations. It uses a passive reflector that is usually built into the garments worn by users and which is lightweight (4 g) and small, such that multiple reflectors can be attached to a single Spaceseed. The active detector is either a hand-held device or attached to a SAR helicopter and has a range of 200 m through air and 30 m through snow.

This system has the advantage that it does not rely on being powered or having a working communication downlink, but due to its limited range should only be considered as fallback.

4. COMMUNICATION CHANNELS

The Daedalus 2 experiment consists of multiple components that need to communicate with very different network requirements in concern to reliability, latency and bandwidth.

- During testing we need to transmit all data at full bandwidth if a wired connection is available, but also support streaming a subset of the data wirelessly if the testses required it. An uplink must also be supported.

- The COP and SBC need high bandwidth and reliable communication to exchange telemetry and control actuators.

- The communication between the RBC and SBC must be reliable and correctly handle the disconnect during ejection.

- Communication between the RBC and the ground station is low-bandwidth but must be reliable for commanding and telemetry reporting before lift-off.

- Communication between the Seeds and the ground station must be reliable for reporting the GPS positions and ideally as much data as possible in case recovery is not possible.

- We need a way to help the recovery crew find the FFUs.

We addressed these challenges with the following design, which will be discussed in more detail in the rest of this section.

- Use a publish/subscribe messaging system between the space components.

- Use MAVLink for communication via the REXUS service module and for recovery.

- Use Iridium for the direct downlink from the Spaceseeds.

4.1. Publish/Subscribe Messaging

Our software uses the real-time operating system and middleware RODOS\(^1\) [5] which was originally designed for use in satellites. It includes a publish/subscribe message passing system. This allows us to exchange product types (C structs) between different software components, independent of whether they are located on the same or a different computing node. Decoupling components this way increases flexibility and reusability but necessarily increases complexity.

This is used extensively in our space segment to communicate between software components on the same and different nodes. To facilitate communication between different nodes, multiple transport protocols (LinkInterface in RODOS terms) may be used. Between the SBC and COP we use a simple UART connection because of its simplicity and reliability. The RBC and the two Spaceseeds communicate with a CAN bus. It was chosen because of its ability to connect more than two nodes and the availability of an ACK system. We learned however that our design here resulted in increased complexity during ejection as bus arbitration is no longer possible for participants without a termination afterwards.

4.2. Up- and Downlink

As mentioned above, two protocols are used for the communication between the space and the ground segment to balance the different constraints and needs on each channel. They shall be discussed here in more detail.

4.2.1. MAVLink

MAVLink\(^2\) (Micro Air Vehicle Link) is the protocol we choose for the down- and uplink during testing and via the REXUS service module. It was originally designed

\(^1\)Current development happens at https://gitlab.com/rodos/rodos

\(^2\)MAVLink’s project website is at the time of writing available at https://mavlink.io/en/
for use with drones over wireless channels and therefore already provides message framing, routing information (sender and destination), error detection, message authentication and replay protection.

It is implemented as a code generator which reads a message definition and is able to emit package generation and parsing code in multiple languages, including C++ (used for embedded development) and Java (used for the ground station, see Sec. 4.3 for more info). This reduces development time and increases reliability, as no parsing code has to be written manually, which eliminates a large field of possible errors.

The error detection and message authentication are not strictly required for the wired testing connection. To reduce the number of different software systems and thereby keep complexity limited, we decided to use MAVLink here anyway.

4.2.2. LoRa

Both Spaceseeds carry a LoRa transceiver, which is used to provide a wireless testing connection and an additional recovery mechanism. LoRa is a proprietary IoT modulation scheme and protocol optimized for a long range by use of Chirped Spread Spectrum (CSS) modulation, but only offering a low data rate as a trade-off. It is currently developed by Semtech.

4.2.3. Seed Downlink: Iridium

Because of our experiences with Daedalus 1 we choose to again use the Iridium network as our Spaceseed downlink. Due to the high cost of satellite data transmissions however we do not use MAVLink as it would introduce overhead like including routing information twice per packet. Instead, we transmit raw C structs which increases complexity as for example endianness and message versioning needs to be considered manually instead of letting the software automatically handle it. This choice allows us to maximize transmission of science and position data. The latter is crucial, as it is required for recovery of the Spaceseeds with their flash memories, which hold full-rate science data.

The Iridium satellite constellation consists of 66 cross-linked low earth orbit satellites at an altitude of 780 km. This provides global network (including polar coverage) that guarantees a low possibility of signal loss and highly reliable communication. By using the Iridium Short Burst Data (SBD) service each Spaceseed will stream their position and some key telemetry over a passive quadrifilar helix antenna to the network. This data is then transmitted over TCP to a backend server that is part of the Daedalus 2 ground station infrastructure to enable successful recovery.

4.3. Ground Station

The data arrives at ground station via different channels in different formats (MAVLink and C structs from Iridium). Its main job is receiving, storing and presenting this data to the user. To achieve this, the data is unpacked and transformed into a common, self-describing format (JSON) for storage and further processing. It must also be able to command the system during testing and while it is on the launch pad.

This is achieved by the highly modular and reusable ground station framework Telesion\(^3\). It separates the backend, where incoming and outgoing data is processed and stored for future analysis and review, from the frontend which displays received telemetry and also provides the telecommand interface.

This separation allows multiple operators to command and inspect the system from multiple computers. Additionally, it also increases reliability as the amount of code in the critical processes (the backend) is reduced, and the components responsible for communication between frontend and backend as well as storage are well tested, as they can be and have successfully been used for other projects as well.

5. PRE-FLIGHT EVALUATION

To verify the system design before the actual flight on the REXUS rocket multiple evaluation tests were performed:

- Bench tests to verify the whole communication chain end-to-end
- Location tests using the LoRa Recovery Device
- Wind tunnel tests to simulate flight conditions

\(^3\)The software is open source and available online at [https://github.com/wuespace](https://github.com/wuespace) in the telestion-\* repositories, the project specific code is available at [https://github.com/wuespace/telestion-project-daedalus2](https://github.com/wuespace/telestion-project-daedalus2)
The wind tunnel tests in particular provided valuable insights as it forced all subteams (in particular the mechanical, embedded software, electronics and simulation team) to work together and synchronize their progress.

5.1. Power System Verification

In a standard test environment the tunnel produces constant wind speeds of roughly 15 m s$^{-1}$ while the flight controller adjusts the blade pitch of the rotor to reach a target rotor rotation speed. After a pre-programmed time interval a new target speed is chosen to observe the step response of the control algorithm. All sensor readings as well as various internal states would be saved to the flash storage for later detailed analysis with a rate of 250 Hz, just like in a real flight.

One such analysis can be seen in Fig. 9, where the power system was evaluated with special focus on the current draw of the three servos that control the blade pitch. This showed that even under maximum rotor speeds the current was well within design limits, both battery strings were utilized equally, and no critical voltage drops occurred during pitch changes.

5.2. Tachometer Verification

Another critical test involved the verification of the tachometer that measures the rotor rotation rate. This sensor was built from scratch using dedicated logic gates and low-level microcontroller periphery, as well as compensation factors in software. Naturally, the measurements needed to be independently verified before the sensor output could be trusted.

For this the accelerometer and gyroscope readings were used, as the rotor will also induce vibrations corresponding to the rotation rate. These frequencies can be determined by doing a Fourier analysis on the measurements as seen in Fig. 10. Indeed, three distinct waveforms can be seen that correspond exactly to the readings from the tachometer as well as the second and fourth harmonics. The fourth harmonic is the most dominant, which makes sense as the rotor consists of four blades, so most of the vibrations will have a frequency four times higher than the full rotor rotation.
6. CONCLUSION

This proposed structure, from electronics over communication to system topology, proved valuable and delivered good performance in pre-flight tests such as mechanical shaker tests and flight simulations in a wind-tunnel. Of course, it is impossible to predict all aspects of a real flight, but the system appears robust and will be used as flight hardware in March 2023.

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