Suborbital Autorotation Landing Demonstrator on REXUS 29

Johanna Mehringer[1], *Lennart Werner*[2], *Clemens Riegler*[3] *and Frederik Dunschen*[4]

Abstract

Current developments in the aerospace industry point towards more frequent interplanetary travel in the future. However, the main focus of developments is on launcher technology, yet the descent of interplanetary probes is of high importance for the success of future missions. Additionally, to the present landing approaches using either a powered descent requiring fuel or a combination of different parachutes, a third method is investigated in this project. The chosen approach is called autorotation and is commonly used in helicopters. When a helicopter suffers a loss of power, it can still land and even choose its landing site without the utilization of an engine. Similar to parachutes, the presented technology can be applied to various atmospheric conditions by modification of rotor and control parameters. Moreover, a rotor in autorotation can provide directional control and thus the choice of a landing site, which is not feasible using a parachute. All these factors make autorotation an interesting option as an entry descent and landing (EDL) technology for interplanetary missions. Our project, Daedalus 2 implements the autorotation landing strategy as part of the REXUS student project campaign under DLR / ESA / SNSA supervision. Since 2018 we are developing the SpaceSeed Mk.2, a technology demonstrator that incorporates a rotor and all necessary technological means to perform an autorotation EDL maneuver from an apogee of 80 km. The mission concept is laid out within the presented paper. This includes the main challenges like miniaturization of the SpaceSeed v2 due to the size constraints of the REXUS rocket or the used sensors for height and position determination. The importance of a technology demonstrator tested on a sounding rocket to prove the feasibility of our presented system is laid out in our publication. Furthermore, the custom development of electrical, mechanical and software sub systems is discussed. Additionally, the planned mission profile will be explained, including flight phases and different activities conducted by the SpaceSeeds during flight. Moreover, the main differences and improvements to Daedalus 1 are being discussed.

Keywords

Reentry, Landing, Autorotation, Parachutes, Rotors

[1] Corresponding author: University of Wuerzburg, Wuespace e.V., Germany, johanna.mehringer@wuespace.de
[2] University of Wuerzburg, Germany
[3] University of Wuerzburg, Germany
[4] University of Wuerzburg, Germany

1. Introduction

Daedalus 2 is a student project that investigates alternatives to parachutes. Since 2018 roughly 40 students are working on the mission. In contrast to telescopic or inflatable rotors we decided to use a tiltable rotor system. This adds to the scientific knowledge base about rotor systems in space applications. The main focus of this paper is the mechanical setup of the implemented system. It will shine light onto the general layout as well as significant implantation details. Special attention will be payed to the tilting mechanism of the rotor as it is the most complex mechanical subsystem.

2. State of the art

The Technology Readiness Level (TRL) of autorotation in the context of space flight is comparably low. However, the idea is not novel. Multiple studies have investigated the topic. The most prominent examples shall be introduced in the following sections.

2.1. KRC-6

The KRC-6 represents one of the earliest developments for autorotation vehicles. In the 1960s Karman Aerospace and the US Airforce tried to build cargo deployment vehicles based on autorotation. They quickly realised that this technology could be used for space. This was followed by the campaign that built and improved the KRC-6. A total of 12 vehicles were built and tested. Good results were achieved, however, the campaign was discontinued due to unknown reasons. It could be due to the idea being way ahead of its time. The KRC-6 was remote controlled and used mechanical gyros due to the lack of advanced micro electronics which are available now. [1]

2.2. Auto-Rotation in Martian Descent and Landing (AMDL)

In 2009 EADS (now Airbus) performed a study for autorotation landers geared towards Martian missions. The prevalent problem on Mars is the low atmospheric density. This implies that a comparably high rotor radius is needed. AMDL chose to investigate the solution that employs inflatable rotors. They found that it is possible to deploy such a rotor and save a lot of weight and space. However, the low rigidity of the rotor was a problem that could not be overcome in the initial study. A further study to investigate this problem was suggested but seems to have never been implemented. [2]

2.3. ARMADA

ARMADA represents another study that investigated the use of rotors for EDL on Mars. In 2009 they studied a similar issue to AMDL but decided to use a telescopic rotor. Compared to AMDL the rigidity of a telescopic rotor blade is clearly superior to an inflatable rotor. The study showed significantly better results. They stated that other celestial bodies might be more suited for a near term mission, due to the higher atmospheric density. [3]

2.4. SpaceSeed

The predecessor SpaceSeed Mk.1 in the Project Daedalus 1 is also an important element of the state of the art. Launched in 2019 the vehicle built a foundation for the next mission. It was a technologically simple prototype for evaluating the concept design space. There was no controllability and the rotor was locked to the vehicle. During the flight it only showed moderate stability and in some flight zones it even showed significant instabilities. The learning of Daedalus 1 were very important for the development of Daedalus 2. An image of the SpaceSeed Mk.1 can be seen in Figure 1. [4]

Figure 1. Flight hardware SpaceSeed Mk.1 for Daedalus 1 [4].

3. Approach

This section describes the general setup of the Daedalus 2 mission. Daedalus 2 is a project carried out in the framework of the DLR / ESA / SSA joint venture program REXUS/BEXUS. Here, European students are given the opportunity to design, build and operate their own experiment on a sounding rocket. Daedalus 2, which is participating in the current cycle on REXUS rocket No. 29, comes from the student spaceflight association WueSpace.

3.1. Daedalus 2

The primary goal of the Daedalus 2 experiment is to demonstrate full re-entry and landing based on rotor pitch actuation only. As is common in conventional helicopter emergency landings, a maneuver known as an autorotation landing can be performed to achieve a safe and smooth landing without any type of propulsion. The concept will be tested from a drop altitude of 70 km to evaluate the system at reasonably high re-entry speeds.

Mechanically, the experiment consists of an ejection mechanism mounted on the launch vehicle, and two ejectable re-entry capsules, the so-called "space seeds". Beginning with ejection at apogee of flight, the two SpaceSeeds operate autonomously on their way back to the surface. During descent, rotor speed, ambient pressure, GNSS position and lidar distance to the ground are continuously measured and used to control the angle of attack of the main rotor. Key information is transmitted at a low rate to the ground station via the IRIDIUM satellite network. The transmitted data includes the GNSS position and the current estimated altitude, to provide an approximate estimate of the landing zone for subsequent recovery. To prove the feasibility of autorotation-based re-entry from space and have a record of mission success, high frequency data will be stored on the spacecraft's internal memory.

4. Implementation

Figure 2. SpaceSeed with fully tilted rotor blades.

Besides the basic structure, three fundamental mechanical decisions were the implementation of the swashplate mechanism, the accommodation of the rotor inside the REXUS rocket and how to avoid instabilities during the descent. This section describes the mechanical setup of the SpaceSeeds with a focus on the elements that address these problems. A cut through the whole SpaceSeed can be seen in Figure 3.

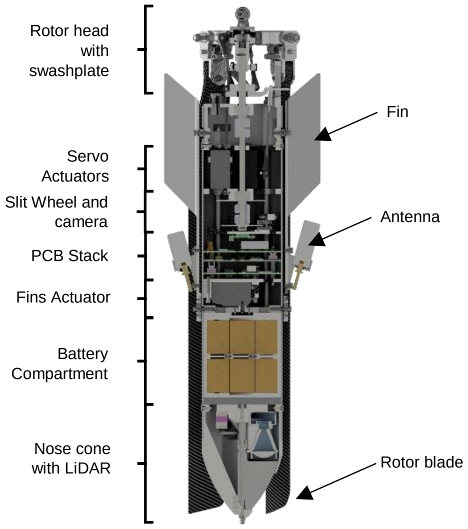

Figure 3. Cut view of the SpaceSeed.

4.1. Inner Structure

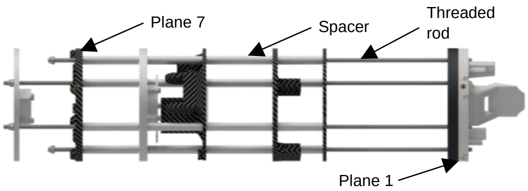

Figure 4. Skeletal Structure of the SpaceSeed.

The skeletal structure of the SpaceSeed, pictured in Figure 4, is composed of four threaded rods and seven planes, that are separated with spacers.

4.1.1. LiDAR

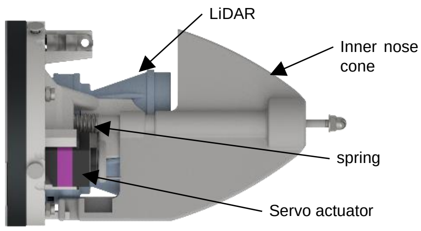

Figure 5. Opening mechanism of the nose cone.

Starting at the nose cone, the first plane accommodates the LIDAR that is used for height measurement during the landing phase. To protect it until the final phase of the flight and to retain the aerodynamic profile during re-entry, the LIDAR is covered by an inner nose cone. Just before measurement begins, a servo actuator releases a spring mechanism that rotates the inner nose cone out of the field of view of the LIDAR. The servo actuator, the spring and all other parts of the mechanism are also mounted on this plane.

4.1.2. Battery Compartment

Between the first and the second plane the battery compartment is fixated (Figure 6). The six batteries that power the SpaceSeed are put into cartridges, connecting them to two plugs. These cartridges can be slid into the compartment, where the plugs connect to the corresponding jacks. This allows for battery replacement without the need to disassemble the SpaceSeed.

4.1.3. Fins Actuators and PCB Stack

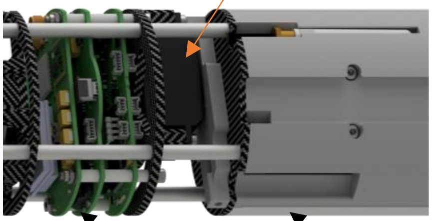

Figure 6. PCB Stack, Fins Actuator and Battery Compartment.

Between the second and third plane the servo actuator for the fins is placed. The fins mechanism will be discussed further in chapter 4.3.

On the third plane the PCB stack is mounted, consisting of three boards stacked upon each other.

4.1.4. Slit Wheel, Camera and Ball Bearings

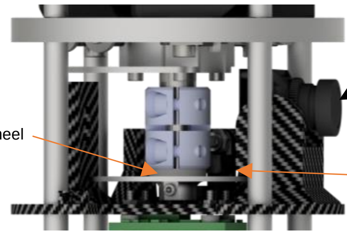

Figure 7. Camera, slit wheel and optical switches.

A camera for gathering in flight footage of the descent is placed on the fourth structural plane. A hole within the outer shell allows for a sideways look.

The plane also contains two optical switches. In combination with the slit wheel fixated on the rotor shaft, that ends in this area, they enable the measurement of the rotational speed of the rotor.

The next plane contains one of the two ball bearings that support the rotor shaft. The second ball bearing is placed in the last plane. While all other planes are 3D printed, these two planes are made out of aluminium, as they are expected to experience larger strain

4.1.5. Servo Actuators

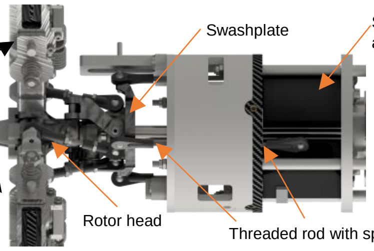

Figure 8. Rotor head with swashplate connected to servo actuators.

The three servo actuators, that control the swashplate and thereby the pitch of the rotor blades are fixated between the fifth and sixth plane.

The area between the servo actuators and the seventh and last plane serves as space between the swashplate and the servos. Additionally the seventh plane holds a USB-C socket to connect the Seed to the Rocket Board Computer before ejection.

4.2. Rotor System

As main part of the rotor system a standard RC helicopter rotor head with its corresponding swash plate is used, which is connected to the three servo actuators by threaded rods and spherical heads (Figure 8). This setup would be suitable for cyclic pitch, but only collective pitch is used in the Daedalus 2 project. The rotor blades, with a length of 470mm, are standard RC helicopter parts as well. They are made out of carbon fibre.

4.2.1. Tilt Mechanism

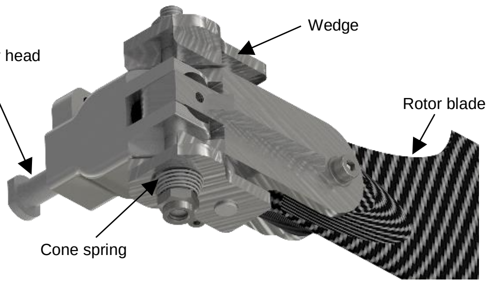

Figure 9. Rotor joint topside in tilted position.

As the SpaceSeed has to fit into the REXUS rocket no standard blade mounts come into consideration. Instead a specially designed tilt mechanism is used. The mechanism can be seen in the tilted position in Figure 9 and in the opened position in Figure 10.

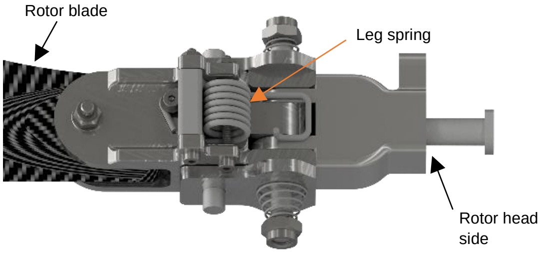

Figure 10. Rotor joint bottom in opened position.

During the ascent of the REXUS rocket, the rotor blades are kept in the fully tilted position by a tube mounted on the rocket. As soon as the SpaceSeed is ejected, the wings are free and a leg spring forces the mounts into the open position. To ensure, that the joint stays open, even if sudden shocks occur, a wedge is placed on both side. When the joint is fully extended, both are pushed into the matching cut-outs in the mount by a cone spring, which arrests the tilt mechanism.

4.3. Fins

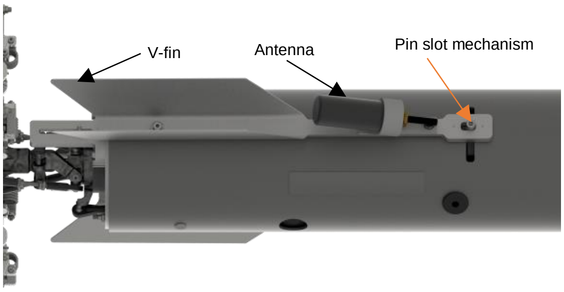

Figure 11. V-fin in middle position.

On the outside of the SpaceSeed two V-shaped aluminium fins are attached. They are pivoted between the sixth and seventh plane. Between the second and the third plane they are connected to one servo actuator via a pin slot mechanism. For this on both sides a ballhead is connected to the servo, that can slide through a low friction 3D printed part inside the fins and thereby enables the fins to tilt in both directions. On the one hand the fins contribute to the overall stability of the SpaceSeed and on the other hand the mechanism enables the minimization of the body rotation.

5. Outlook and future work

The two SpaceSeeds used as flight hardware for the REXUS rocket launch and two additional spare instances are already assembled as described in this paper. Wind tunnel tests indicate, that the structure withstands the high rotational speeds of the rotor, the SpaceSeeds will experience during the flight. The actual rocket launch and thereby the prove of concept of the project is scheduled for April 2023. After this the results will be analysed to understand the existing future challenges.

A first possibility would be to test the concept for different scales. This would be needed to use it as landing mechanism for payloads, as the free space in the Daedalus 2 Space Seed is very limited. With these results a comparison to other rotational landing mechanisms, like the concepts with the inflatable or the telescopic rotor blades mentioned in chapters 2.2 and 2.3 would be feasible. In a future revision another technological enhancement of the SpaceSeed could be to use the cyclic pitch to control the flight direction and thereby influence the landing position.

Acknowledgements

There are a lot of people and institutions that helped us in various ways throughout the project and who deserve our gratitude and a mentioning here. Regarding institutions, we begin with thanking the German Aerospace Centre DLR [5], the Swedish National Space Agency SNSA [6] and the European Space Agency ESA [7] as the main organizers of the REXUS/BEXUS programme. In addition, the campaign would not be possible without the Swedish Space Corporation SSC [8]. The Centre of Applied Space Technology and Microgravity ZARM [9] also deserves special thanks for constantly helping the team to improve and successfully conclude the project cycle.

Further we want to thank the Julius-Maximilians-University Wuerzburg, especially the Chair for Aerospace Information Technology [10], represented by Prof. Hakan Kayal.

The Daedalus 2 team is grateful to all the sponsors who made the project possible: Atomstreet, Mouser Electronics, Carbonteam Shop, Hacker Brushless Motors, MathWorks, Siemens, ublox, VDI, Breunig Aerospace, Airbus, Ansys, Hirsch KG, PCB Arts, Vogel Stiftung, MÄDLER, WÜRTH ELEKRTONIK, PartsBox, molex, LRT Automotive, ZFT, Iridium, TELESPAZIO and ARCTIC. An overview of all helpers and sponsors can be found in [11]

References

[1] D. Robinson and others, “Investigation of Stored Energy Rotors for Recovery,” *Kaman Aircraft Corporation, Aeronautical Systems Division TDR-63-745,* 1963.

[2] R. A. Diaz-Silva, D. Arellano, M. Sarigulklijn and Sarigul-Klijn, “Rotary decelerators for spacecraft: historical review and simulation results,” in *AIAA SPACE 2013 Conference and Exposition*, 2013.

[3] T. V. Peters, R. Cadenas, P. Tortora, A. Talamelli, F. Giulietti, B. Pulvirenti, G. Saggiani, A. Rossetti, A. Corbelli and E. Kervendal, “ARMADA: Auto-rotation in Martian Descend and landing,” *NEBULA,* 2009.

[4] C. Riegler, I. Angelov, F. Kohmann, T. Neumann, A. Bilican, K. Hofmann, J. Pielucha, A. Böhm, B. Fischbach, T. Appelt, L. Willand, O. Wizemann, S. Menninger, J. von Pichowski, J. Staus, E. Hemmelmann, S. Seisl, C. Fröhlich, C. Plausonig and R. Rath, “PROJECT DAEDALUS, ROTOR CONTROLLED DESCENT AND LANDING ON REXUS23,” 2019.

[5] Website of the German Aerospae Centre, [Online]. Available: dlr.de. [Accessed 21 March 2022].

[6] Website of the Swedish National Space Agency, [Online]. Available: www.rymdstyrelsen.se. [Accessed 21 March 2022].

[7] Website of the European Space Agency, [Online]. Available: esa.int. [Accessed 21 March 2022].

[8] Website of the Swedish Space Corporation, [Online]. Available: sscspace.com. [Accessed 21 March 2022].

[9] Website of ZARM, [Online]. Available: zarm.uni-bremen.de. [Accessed 21 March 2022].

[10] Website of the Chair of Aerospace Infromation Technology, Julius-Maximilians-University Wuerzburg, [Online]. Available: www8.informatik.uni-wuerzburg.de. [Accessed 21 March 2022].

[11] Website of Wuespace, [Online]. Available: www.wuespace.de. [Accessed 21 March 2022].