SMARD-REXUS-18: DEVELOPMENT AND VERIFICATION OF AN SMA BASED CUBESAT SOLAR PANEL DEPLOYMENT MECHANISM

Maria Grulich¹, Artur Koop¹, Philipp Ludewig¹, Johannes Gutsmedl¹, Johannes Kugele¹, Thomas Ruck¹, Ingo Mayer¹, Alexander Schmidt¹, and Karl Dietmann²

¹Technische Universität München, Boltzmannstr. 15, 85748 Garching, Germany, list@smard-rexus.de
²Hochschule München, Lothstraße 34, 80335 München, Germany, list@smard-rexus.de

ABSTRACT

SMARD (Shape Memory Alloy Reusable Deployment Mechanism) is an experiment for a sounding rocket developed by students at Technische Universität München (TUM). It was launched in March 2015 on REXUS 18 (Rocket Experiments for University Students). The goal of SMARD was to develop a solar panel hold-down and release mechanism (HDRM) for a CubeSat using shape memory alloys (SMA) for repeatable actuation and the ability to be quickly resettable. This paper describes the technical approach as well as the technological development and design of the experiment platform, which is capable of proving the functionality of the deployment mechanism. Furthermore, the realization of the experiment as well as the results of the flight campaign are presented. Finally, the future applications of the developed HDRM and its possible further developments are discussed.

Key words: SMARD; REXUS; TUM; CubeSat; MOVE-II; SMA; HDRM.

1. INTRODUCTION

Since 2011 the Institute of Astronautics (LRT) and the scientific student group WARR (Scientific Workgroup for Rocketry and Space Flight) have been developing a CubeSat called Munich Orbital Verification Experiment-II (MOVE-II). Because the payload requires at least 20 W of power, the satellite will be equipped with four 210x80 mm solar panels. These panels will be in a stored configuration during launch and will be deployed in orbit, which makes an HDRM necessary. Usually a single-shot system is used for such a mechanism. MOVE-II’s predecessor CubeSat First-MOVE used a mechanism based on melting wires, which was a single-shot system. This HDRM was launched and tested on REXUS 4 by the student team VERTICAL from TUM.[1] The testing and qualification of First-MOVE showed that the ability to easily reset the HDRM should be an important design consideration. The reusability simplifies testing and reduces the time between tests and the possibility of a potential failure during the assembly procedure. For this reason it was decided not to use the flight-proven First-MOVE mechanism, but to instead develop a new system using a NiTi-based SMA spring. To ensure a successful operation of the mechanism during MOVE-II’s mission, thorough testing of the mechanism in all relevant environments is necessary. With high vibrational stresses and g-loads during launch, as well as the vacuum and milli-gravity environment during the coast phase, a sounding rocket is ideal for this purpose. The milli-gravity phase should be used to measure the oscillations of the solar panel. Therefore an accelerometer and a magnetic rotary decoder are installed. A thermistor measures the temperature near the SMA spring. A camera (GoPro HERO3+ Black) documents the progression of the experiment, especially the deployment and movements of the solar panel in milli-gravity.

2. EXPERIMENT OVERVIEW & DESIGN

The SMARD experiment is installed inside a standard 300 mm REXUS module. It consists of three structural components mounted on a bulkhead as can be seen in Fig. 1: the camera housing, the ERIS housing and the frame carrying the experiment assembly. The camera housing is made of aluminum with a glass fiber reinforced polymer (GFRP) back plate. The onboard computer, ERIS, consisting of three printed circuit boards (PCBs) is mounted inside an aluminum housing
which provides stability and shielding. The experiment itself consists of the mechanism under test and a generic two-unit CubeSat solar panel dummy loosely based on preliminary requirements from the MOVE-II mission.

After launch, the HDRM is activated and the panel is opened by the spring hinges.

2.1. HDRM

The heart of the HDRM is the SMA spring. SMAs are able to "remember" their original shape. This effect is due to a solid-state phase transformation between two crystalline structures in the metal. In the cold state, the crystalline structure is detwinned martensite. In this phase the SMA can be deformed as needed. When the alloy is heated up the crystalline structure transforms to austenite, which means it returns to its pre-deformed shape.[3] SMAs can have a reversible stretching of 4-6% and can be used for at least 1,000 cycles. They exist in a lot of different forms, for example: tubings, wires, sheets, foils and springs.[3] The temperature at which the transformation from martensite to austenite starts is called activation or transformation temperature and can be adjusted by slight changes in alloy composition and through heat treatment.
In the NiTi alloys, for instance, it can be changed from above 100° C to below -100° C.[4]
The activation temperature of the SMA spring used for SMARD is about 85° C. When the SMA cools down it transforms into a twinned martensite phase, until it is deformed again mechanically, which resets the metal of the used spring to its starting configuration, as illustrated in Fig. 4.

![Figure 4. Solid-State Phase Transformation of Shape Memory Alloys [3]](image)

The SMA spring used for the HDRM has a force of 6 N and a stroke of 6 mm. The outer diameter is 4.47 mm and the used wire diameter is 0.735 mm.
The HDRM consists of five parts: a housing, an aluminum slider, an insulation plate, a mechanical spring, as well as an SMA spring.
The slider is placed in the housing, while both springs are attached to the slider on one end and to the housing on the other end, as can be seen in Fig. 5. Both springs operate as tension springs. The whole HDRM is then mounted onto the experiment frame with an insulation plate made of glass fiber between the HDRM and the aluminum (Fig. 6 insulation plate not shown).
The HDRM’s main task is to either lock the solar panel hook in position or release it.

This is done by the slider, which can move between two positions: closed (during launch) and open.
Closed is the default position, when the HDRM is not activated (Fig. 7).
In order to contract the SMA spring, the activation temperature of about 85°C has to be reached. By applying an electrical current of 1.9 A at a voltage of 3.3 V for 10 s the SMA spring heats up to the activation temperature due to the ohmic resistance of the spring wire itself.
With a contraction force of about 6 N the SMA spring overcomes the opposing mechanical spring force and therefore moves the slider into the open position (Fig. 8).

![Figure 6. Positioning of the HDRM](image)

![Figure 5. HDRM](image)

2.2. Electronics Segment Overview

The electronics segment mainly consists of a measurement and control system called ERIS, sensors to measure
experiment data and the activation of the HDRM. ERIS is based on CERESS.[2] ERIS uses the newest sbRIO board (sbRIO-9626), by National Instruments for data storage and experiment control, using its integrated SD-card and RS-485 interface. It has smaller dimensions and lower mass than the one used in CERESS.[5] The experiment is controlled by ERIS which acquires data from all sensors and stores the data on an on-board SD-card. Additionally, important parts of the data are sent down to the ground station using the CERESS telemetry protocol and the REXUS SM data link.

2.2.1. Data Acquisition System

The sbRIO-9626 provides a powerful field-programmable gate array (FPGA) with two million gates as well as a 400 MHz real-time central processing unit (CPU). Furthermore 110 digital I/Os and 32 analogue channels are integrated.[5] The acquired data are partially sent down to the ground station with the RS-485 interface while the rocket is in flight. The sbRIO is connected to two Power and Sensor Interface Boards (PSIBs). These boards provide connections to all sensors and the REXUS SM. The REXUS Service Module (SM) supplies all experiments with power. [6] Since its 28 V are unregulated and too high for the components used in the experiment a voltage converter is needed that is also located on the PSIBs. They provide regulated power for all systems including the sbRIO. Furthermore they include a voltage converter for the HDRM. They provide regulated power for all systems including the sbRIO. Furthermore they include a voltage converter for the HDRM.

This voltage converter has an output voltage of 3.3 V and can deliver up to 5 A of current which is approximately the range of power, which a CubeSat can provide for the HDRM.

2.2.2. Sensors

Several sensors are used to measure the deployment of the solar panel and to monitor the temperatures of the electrical components. The magnetic rotary encoder chip tracks the opening angle of the solar panel at a sample rate of 10 kHz with a resolution of 12 bit over a full revolution of 360°. Two accelerometers (type LIS331H) with a range of ±24 g and the same 10 kHz sample rate are used to track panel oscillations while opening. Additionally two NTC-thermistors are used to measure the heating of the SMA spring and the surrounding components.

2.3. Software Design

The software for SMARD is part of the ERIS system and was programmed, based on the CERESS software, using LabVIEW 2013. The main functions of ERIS can be described as follows:

Timeline Execution of Events: Although the REXUS SM provides the experiments with three user definable signals, ERIS utilizes an internal timeline in order to trigger more events (e.g. restarting the camera). The three signals are: Start Of Experiment (SOE), Start Of Data Storage (SODS) and Lift-Off (LO).[6] The timeline is executed on the real-time (RT) CPU of the sbRIO. When a certain event should occur, the timestamp of the FPGA sends an interrupt.[2]

Timestamping: Using the FPGA of the sbRIO-9626, ERIS utilizes two timers: one which is started during the booting sequence of the system and the other that is started after LO in order to be able to commence the timeline at exactly defined times. Both timers have an accuracy of up to 1 ms.

Telemetry Generation: Telemetry packages, which are generated on the FPGA and sent by the RT CPU, are used to send data to the ground station as a backup. The message format used in ERIS, like CERESS, includes a 40 bit header, the relevant data, and for verification of the sent data a checksum and cyclic redundancy checksum.

Event Logging: After an event a log file is generated and stored on board on the internal non-volatile storage of the sbRIO-9626. It contains all state changes, signal changes and file information, which prevents unwanted data loss due to file overwriting.

Signal Detection and Handling: The signals provided by the REXUS SM (SOE, SODS and LO) are detected by ERIS and observed in case of a change of the signals. Since the LO signal is hardware driven, a debouncing of the signal is necessary. For this purpose, if the signal is true, the software checks the signal for a time span of 200 ms. Every 10 ms a sample is taken and only when all samples are true, the signal will be accepted as received by the OBDDH.

Data Acquisition: There are two types of data acquisition implemented in ERIS: the digital data acquisition and the analogue data acquisition. The temperature and maintenance data, such as voltage and current of the supply lines, are analogue signals, which do not need a certain protocol. The accelerometers are connected via serial peripheral interface (SPI) bus. Voltage and current of the SMA spring power supply and the voltage across the SMA spring while it is being activated is measured using an analogue-to-digital converter (ADC) chip connected via SPI to the sbRIO. The current running through the SMA spring while it is being activated is measured using a Hall effect based current sensor, which is connected to an analogue channel of the sbRIO.

Data Storage: The data generated by the data acquisition system are stored on the on-board 2 GB SD-card.
with a possible maximum rate of 2 MBps. ERIS uses the File Allocation Table (FAT) file system provided by the SD-Card Module.

The binary data are stored in one file on the SD-card, since different acquisition rates are used (10 kHz for the magnetic rotary encoder, 1 kHz for the acceleration sensors and 1 Hz for the remaining analogue sensors).

Camera and Mechanism Control: A digital signal on a pin of the GoPro connector activates the camera and a signal on another pin initializes the recording and storage of the images. The camera is deactivated after the experiment has ended in order to ensure a safe storage of the video file. The mechanism on the other hand is also controlled by a digital signal to the interface boards. These then apply power to the mechanism, thereby activating it.

2.4. Ground Segment

The ground station (GS) is implemented in LabVIEW 2013 and SQL.

Since the main purpose of the ground segment is to receive real-time data from ERIS, it has only been slightly modified from the original CERESS GS software.\[2\] The SMARD ground segment consists of the ground station, including a server and clients, which interface with the ESRANGE ground segment. The SMARD ground segment is connected to ERIS via the RS-232 TM/TC connection provided by the ESRANGE ground segment system. The main functions of the ground station are:

- Provide status information of the experiment (acceleration, temperature, voltage, errors, etc.)
- Verify experiment success
- Data backup in the unlikely event of recovery failure

The heart of the ground station is a MySQL database that handles the distribution of telemetry (TM) packages and provides access for multiple clients, such as the scientific display, which shows the acceleration values of the sensors, by using the Open Database Connectivity-Protocol (ODBC) over LAN. Therefore further clients can easily be added without the need of a time-consuming system reconfiguration.

The database is fed by a LabVIEW program (TM receiver) running on a Windows PC, where the RS-232 connection is located. This TM receiver handles the low-level RS-232 serial communication functions such as byte-wise reading from the serial port buffer.

In order to handle the incoming serial data, a TM decoder program checks the packages for errors and reads the report ID of the package to identify the data type. Based on this, the appropriate decoder program splits the data stream according to the decoding definition.

These separated data packages (binary format) are then forwarded to an SQL-handler which sends them to the MySQL database via LAN. Multiple clients can now connect to the database and asks for data, which is returned to the client via SQL. These data are then parsed by the client and the results are shown on the displays.

3. FLIGHT RESULTS

The EuroLaunch RX-18 housekeeping data show that REXUS 18 lifted off at 13:29 UTC on the 18th of March 2015 from ESRANGE, reaching its apogee of 81.7 km at 140 s into the flight.

During the launch SMARD was exposed to a maximum of 16.8 g. A yo-yo de-spin to initiate the milli-gravity phase was unsuccessful, resulting in a continued roll rate of 2.7 Hz and thus, due to the centrifugal acceleration of this rotation, preventing the rocket from entering a state of weightlessness. Upon reentry, a flat-spin phase around all three axes of the rocket, exerted strong and quickly alternating forces on the experiment for roughly 150 s.

3.1. HDRM and Panel Movements

Fig. 9 shows the rotation of the panel around its axis. Instead of swinging open, the solar panel remained closed due to the centrifugal forces, which were caused by the continued spinning of the rocket. However, a small orientation change of the panel occurred as the HDRM was activated shortly after the 600 s mark. This is due to the fact that the HDRM performed nominally and the panel was released from the mechanism. This thesis is also supported by accelerometer data in Fig. 10, where a peak upon HDRM activation shows that the panel slightly moved. Finally, in the GoPro footage the release can be clearly seen.

Strong movements (Fig. 9) and accelerations (Fig. 10) can be observed from 720 s onward. Here the panel is opened and closed rapidly by alternating centrifugal forces due to the rocket being in flat spin during reentry. This behavior prevents evaluation of the opening movement of the solar panel as it would have been in milli-gravity.

Since the panel did swing open and closed, when the direction of forces changed, and the hook as well as the HDRM itself were undamaged after the flight, it can be said that the SMARD mechanism itself performed as planned and released the panel upon activation.

3.1.1. SMA Spring

As soon as the liftoff occurred the SMA spring started to heat up as can be seen in Fig. 11 (page 7), resulting from the heating of the rocket itself. However, one can still clearly see a change in temperature gradient at the time the spring actuation occurred. Concerning the maximum temperature of the SMA spring, a precise statement
Figure 9. Magnetic Rotary Decoder Data of the Solar Panel Movements

Figure 10. Acceleration of Panel Z-Axis in Bulkhead Coordinates (Differential)
cannot be made due to the lack of direct contact between the sensor and the SMA spring. The maximum temperature of a component was the bulkhead with about 65°C, which is less than the activation temperature of 85°C for the SMA spring.

In Fig. 12 you can see the voltage across the HDRM. The used SMA spring driver section is set to a voltage of 3.3 V. The spring driver section should regulate the voltage to this fixed level, but it is normal that due to errors in the feedback loop the voltage can vary a little bit. Also, the voltage stays below to the nominal 3.3 V due to the voltage drop in the cables of the HDRM. The used SMA spring driver can deliver up to 5 A of current. The maximum current of 1.95 A (Fig. 13) and the maximum power draw of 6.15 W of the SMA were slightly less than expected but within the constraints of the MOVE-II electrical power system, proving the usability of an SMA-based mechanism on CubeSats. Due to the rising temperature and the associated increase of the springs’ ohmic resistance, it can be observed that both the power and current decrease while the mechanism is being activated (Fig. 13).

The MOVE-II CubeSat design currently employs an EPS board from Clyde Space that is capable of delivering a maximum power of 30 W depending on battery loading state. This shows that the developed HDRM could be used without any problems regarding the power consumption.

The decrease in current and power during activation tells us, that the resistance of the HDRM increases. On the one hand this effect results from the rise in temperature of the SMA material and on the other hand the resistance also increases because of an increase of contact resistance between the conductive parts inside the HDRM during movement.

Throughout the flight, SMARD’s electronic boards and sensors all performed nominally and collected data which was stored and, in parts, sent down to the ground station. Fig. 11 shows the temperatures of different components over time. By comparing the curves of the bulkhead temperature and the main DC/DC converter temperature (labeled “Traco” in Fig. 11), one can clearly see how well insulated the electronics boards are from the bulkhead: especially for the Traco, the temperature rise is primarily due to its self-heating since the rate of heating does not increase at liftoff.
3.2. Post Flight Tests

After the experiment was recovered and returned to the SMARD team it turned out the panel itself took no damage from the strong “flapping” movements during reentry. In contrast the hinges took severe damage, including plastic deformation of the lever, making the panel hard to move around its rotation axis. Since the damage results from the harmful conditions of reentry, it does not impair the hinge’s future use for MOVE-II. The HDRM itself including the SMA spring was tested and activated after the launch and still worked nominally, proving the SMARD-mechanism’s durability and suitability for a CubeSat and the multitude of tests preceding its launch.

4. CONCLUSION

In summary the team SMARD developed a fully functional HDRM for CubeSats based on SMA. It was successfully verified on board a sounding rocket. An important goal of the experiment was to measure and observe the oscillations of the solar panel during milli-gravity. Since the REXUS 18 mission unfortunately did not have a milli-gravity phase, these measurements could not be made. The estimated success can be split into three categories based on the experiment objectives. Success values have been assigned to each category with a total of 100 % meaning complete experiment success:

- Functional verification of the mechanism on its first flight: 60 %.
- Visualization of solar panel deployment: 10 %.
- Measurement of solar panel movement in milli-gravity: 30 %.

The mechanism functioned as expected and the camera visualized the panel’s oscillations. The measurement of the solar panel’s movements using the magnetic rotary decoder and the accelerometer worked as expected. Due to the lack of milli-gravity no data related to the behaviour of the solar panel in a reduced gravity environment could be generated. All in all the resulting success of the flight for SMARD is 70 %.

5. OUTLOOK

The heart of the SMARD project was the development of a HDRM for CubeSats. This mechanism will be further developed within the MOVE-II project. Since the SMARD mechanism proved to work successfully during the launch and flight, with even harder conditions than expected for an orbital mission, it has made a big step towards being used on the MOVE-II satellite. The evaluated flight data are already being used at TUM’s Institute of Astronautics to further scale down the HDRM within the scope of a bachelor thesis. The aim of the bachelor thesis is to improve the electrical conductivity as well as the size of the mechanism and to consider a protection against possible resonance effects.

ACKNOWLEDGEMENTS

The authors would like to thank all the institutions and companies that supported the SMARD project, specifically:

- DLR/DLR-MORABA
- ZARM
- SSC
- SNSB
- RYMDTYRELESEN
- ESA
- National Instruments
- Ingpuls
- Gutekunst Federn
- DAAD
- Bund der Freunde der TUM
- WARR
- TUM/LRT

REFERENCES