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Launch lock system for reaction wheels

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Abstract

Launch loads are critical forces to the payload. Many structures are not designed to survive these loads, thus, additional systems which absorb them are required. These launch lock mechanisms are available in different varieties. For a future magnetic bearing reaction wheel, two different principles of launch lock mechanism concepts were developed and tested. The first one is based on a spring mechanism, while the second uses electromagnetism to move the locking pins. A first testing with prototypes of both was conducted to evaluate the functionality. Subsequently improvements regarding reducing the mass and construction volume were incorporated in the design. In the course of this, additive manufacturing with PLA filament has been used to study possible applications for these mechanisms. The spring concept resulted to be more reliable than the electromagnetic one, but requires a damping mechanism. A usage of additive manufactured PLA components is a promising possibility for the production.

Keywords Additive manufacturing · Reaction wheels · Launch loads · Launch lock · Shape memory alloy · Bimetal

Abbreviations

PLA	Polylactic acid
AOCS	Attitude and orbit control system
rpm	Revolutions per minute
SMA	Shape memory alloy
AM	Additive manufacturing
ESMATS	European Space Mechanisms and Tribology Symposium
ECSS	European cooperation for space standardization

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1 Introduction and motivation

Satellites use for their attitude and orbit control system (AOCS) reaction wheels as actuators, which exchange angular momentum with the satellite system. These wheels' spin with up to 6000 rpm, smaller ones sometimes even higher. The resulting load on the bearing of the wheels leads to high friction and a limited lifetime of the bearing and therewith of the satellite. An alternative is the use of a magnetic bearing instead of ball bearings. This increases the bearing lifetime compared to mechanical bearings. The most critical parts there are the electronics. But magnetic bearing can only compensate relatively small external loads, so there must be a device to absorb the launch loads until the satellite has reached its final orbit. For this task, a so-called launch lock system is developed. In contrast to standard pyrotechnic devices, this one shall work totally mechanical and use electricity as a trigger.

2 State of the art

During a semester project at the City University of Applied Sciences Bremen students were given the task to develop a launch lock system for magnetic bearing wheel systems [1]. Therefore, three different concepts were developed and analyzed regarding different aspects, as complexity, weight and reliability. The system which satisfied these aspects best was chosen for a simulation in MATLAB/Simulink. The next step is to build a demonstrator, test the system and refine the concept.

Magnetic bearing reaction wheels are a subject of research, due to their advantages as longer lifetime, lower vibrations and higher rotation speeds [2].

Pin puller or launch lock mechanisms can be found mostly on the US market [3, 4], but are also a subject of research in Europe as concepts presented at ESMATS [5–8] show. There is also a shift from pyrotechnical mechanisms to non-pyrotechnical ones, since these generate decreased shock levels and create and no debris. Especially in this context, shape memory alloys (SMA) are getting more and more important. Their advantages over hydraulic or electrical systems are a smaller complexity and therewith higher reliability paired with a more compact integration [9, 10].

Additive manufacturing (AM) is already a big topic in space engineering [11]. It allows to build complex and light parts, especially for longer journeys the printing of spare parts is very helpful. But it has to be considered that these parts require some rework, especially at the functional areas.

3 Requirements

Since the target of this work is to evaluate the basic functionality of the concepts, no quantitative requirements were set in the first place. The most relevant system requirements for the first demonstrator were

- Release the wheel in orbit,
- Low complexity,
- High reliability,
- Low mass,
- Small system volume,
- Reset after release for testing.

These requirements allow a first evaluation of the functionality of the analyzed mechanisms and to find out difficulties, before starting a more extensive test procedure. After the first successful tests, the requirements can get extended in a quantitative form.

To design a product for a flight demonstrator, some additional and very important requirements as the thermal and vacuum environment, real launch loads acting on the mechanism and ECSS standards to help the development and qualification, need to be considered.

For the first approach, it is assumed, that three of the pin pullers are distributed evenly around the reaction wheel, as shown in Fig. 1. Therefore, the load acting on each single one is decreased. The quantity of the pullers is not fixed, yet, and can be adjusted. Furthermore, an off-loading structure to support the wheel around the outer perimeter is an option. The pin pullers would act on it and thus, relieving the wheel.

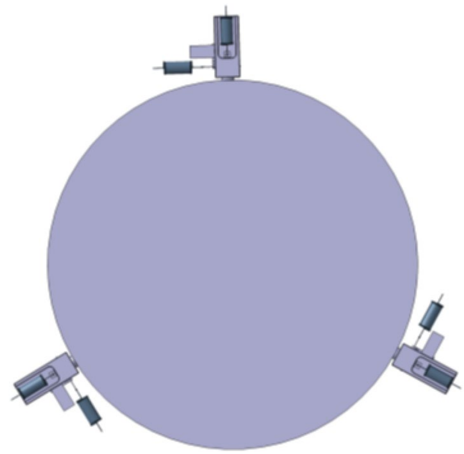

Fig. 1 Arrangement of the three pin pullers around the reaction wheel

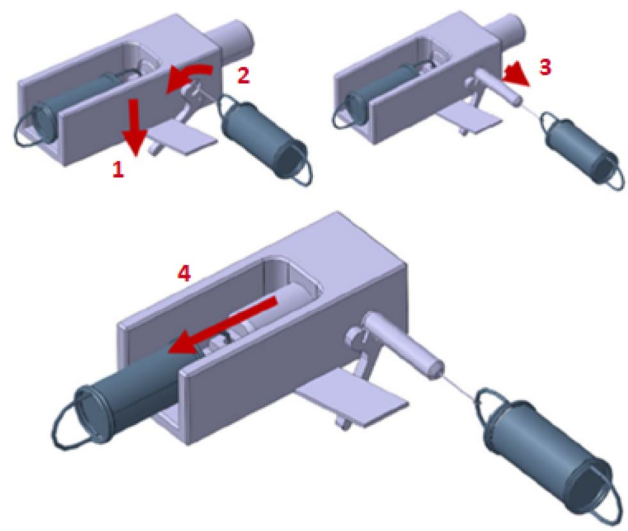

Fig. 2 Sequence of motion of the bimetal-spring concept

4 Bimetal-spring concept

The first concept uses two pull springs and two pins, whereat each spring pulls one pin. To trigger the mechanism a bimetal gets heated. The larger pin, named main pin, is locking the reaction wheel, while the smaller one, named safety pin, is holding the main pin in position until release. The safety pin is kept from moving out of its position by a lever. A thread connects the safety pin with its spring.

Figure 2 illustrates the sequence of motion. To release the wheel the bimetal gets heated, so that it bends and consequently pushes down the lever. This leads to a backward motion of the safety pin, due to its tight spring. Consequently, the main pin can get pulled back by its spring as well and release the wheel.

The distance the main slides backwards is about 20 mm, from which 10 mm will be inside the reaction wheel. 3 mm is the gap between the case of the pin puller and the reaction wheel. This makes sure, that the wheel can spin safely and does not collide with the pin pullers.

4.1 First demonstrator

To test this theoretical principal, a first demonstrator was constructed and the case and two pins were made of aluminum. Due to manufacturing constraints resulting from the geometry of the lever, it was made of plastics. To hold the lever in its position, a screw got screwed in the case. Due to material issues between the steel screw and aluminum case, a thread insert was used. The whole setup was built on profiles to make changes easy, as seen in Fig. 3. It allows an easy possibility to reset the system for multiple tests.

During testing, some major challenges of that design occurred. First, the bimetal could not create enough force to push down the lever. Since the safety pin gets pushed against it, the friction between the lever and the case increases and therewith hindering the required rotation of the lever. Thus, the safety pin cannot move back and the systems functionality cannot be fulfilled.

Furthermore, the system is not resistant against vibrations. These lead to movement of the lever and the bimetal starts to oscillate. Both, but especially the undesired movement of the lever, can lead to an early triggering at an unpredictable time.

Additionally, after triggering, when the pins get pulled back by their springs, they contain a relatively large impulse. To prevent disturbing or damaging other components of the satellite, damping of the impulse is required.

Another aspect is, that the safety pin is floating freely around after moving back. The main pin is still partially inside the case after its backward motion, which prevents a translational motion in two directions. Such a barrier is not available for the safety pin.

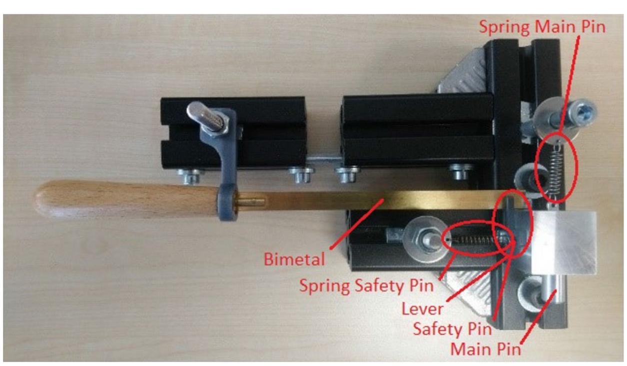

Fig. 3 Setup of the first demonstrator

4.2 Further development

Since this work shall demonstrate only the conceptual functionality of this pin pull mechanism combined with the use of 3D-printing technologies, the focus of further changes is put here.

For the next iteration step, a reduction of weight and system volume is considered, as well as the implementation of solutions for the vibration and free-floating problem. Therefore, PLA-Filament additive manufacturing was used to make the casing smaller and lighter. Figure 4 shows a CAD model of the updated case. In that design, it was also considered to reduce the number of single parts and merge as many as possible to a single one.

The design process was also driven by the possibility to allow the required rework of the functional areas, which are the bores where the pins move along. Another aspect which was considered was the functionality for an easy reset of the system after a release. The possibility to rebuild the mechanism allows multiple tests in shorter time and with less numbers of systems to be manufactured. There was also a change from pull springs to compression springs, which leads to a smaller system volume, since the springs are pulled over the pins and do not have to be located behind them.

On the top of the case, a bore with a third pin can be seen, named blocking pin, which has the purpose to prevent the main pin from sliding back in its initial position after release. Without it, there is a chance, that the main pin will slide back and block the reaction wheel, when it is in operation mode, due to centrifugal or inertial forces.

Figure 5 shows the sequence of motion with all three pins. The bimetal will lie in the slot of the safety pin. When it is

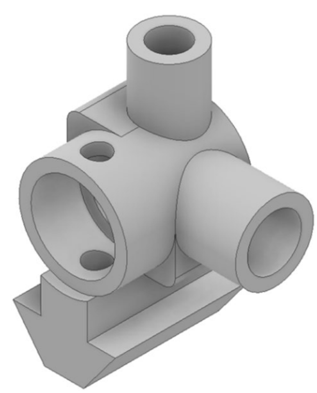

Fig. 4 CAD model of the additive manufactured case. On top the bore of the added blocking pin is located, on the left-hand side the bore for the main pin, and on the right-hand side the bore for the safety pin

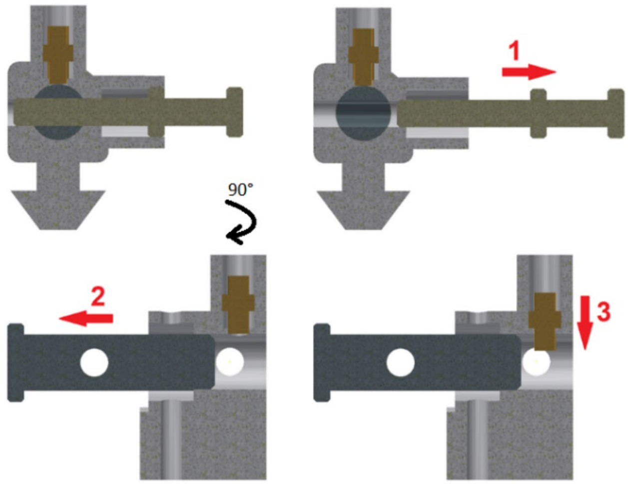

Fig. 5 Sequence of motion of the pins. Top left: initial state. Top right: safety pin moves backwards and releases the main pin. Bottom left (the system gets rotated about 90°, so that the safety pin in out of paper direction): main pin moves backwards, allowing the blocking pin to get pushed down (bottom right)

getting heated, it bends and the pin can get pushed back by its spring. But the used bimetal cannot resist the vibrations as it is supposed to do. Because of the thin thickness, it is very prone to small vibrations, which amplitudes cross the height of the slot of the safety pin. Using higher walls at the slot is helping only partly, since the bending radius of the bimetal when getting heated is also limited. The use of a thicker bimetal would not only be an alternative, but also increase the weight and required heat for bending.

Another kind of bimetal which could be used is a shape memory alloy (SMA) spring. Its concept is shown in Fig. 6.

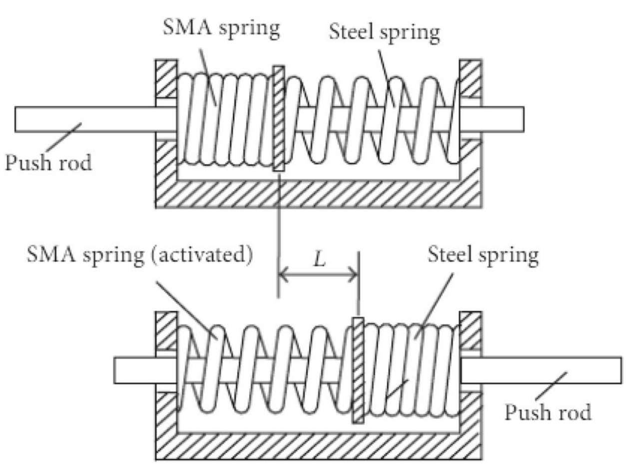

Fig. 6 Concept with a SMA spring [12]. Top: SMA spring is in its initial state and gets compressed by the steel spring. Bottom: when activating (heating) the SMA spring its spring force exceeds the force of the steel spring and compresses it

A reliable use requires an equally reliable thermal control system, to prevent an unwanted activation of the SMA spring. But the safety pin would not be required anymore. Using the SMA spring along the main pin would be sufficient. This decreases the risk of inadvertent release, or failure due to high friction and restraint of the safety pin.

For the use of a SMA spring and to prevent the pins after release from floating, the design was changed again and can be seen in Fig. 7. Guidance tubes got added partly to the case for the safety and main pin. The second half, designed as a lid, can easily get removed for resetting the mechanism after release. The white screw on the top acts as a wall for the spring of the blocking pin, so it gets pushed in the desired direction.

To damp the impulse of the pins in a first step some foam got added at the ends of the guidance tubes, resulting in a smoother impact. However, while this might be sufficient for the plastic components, another damping concept maybe need to be designed when using metal parts.

The arrow design in the tubes is the result of the additive manufacturing process. Due to the printing direction and since it is not possible to print horizontally over an empty space, this design is a good trade-off between mass, functionality and stability. The printing process allows to print

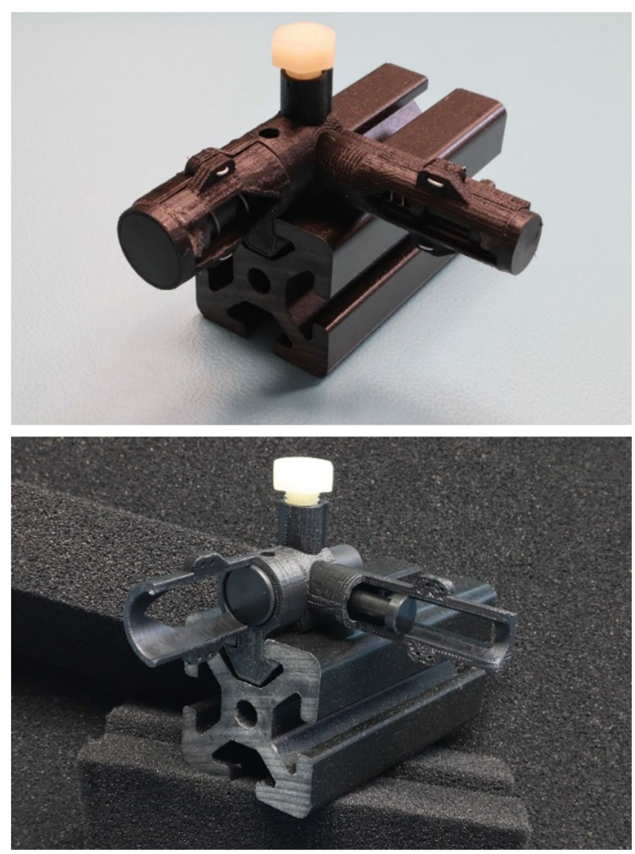

Fig. 7 Latest design for the SMA spring concept

with a maximum angle of 45° above an empty space. In that way, the printer can add another layer on top of the previous one with a small overhang. Bigger angles require a support structure, which increases the printing time and also requires more rework after the printing to remove the support structure.

5 Electromagnetic concept

The second concept uses an electromagnet to move the pins. Figure 8 illustrates the first design. The same case as for the first design of the bimetal-spring concept was used. The head of the pins were changed, so that they can hold a neodymium magnet of 5 mm diameter and 10 mm length. For both pins, a tube out of plastic was made, to guide them in their backwards motion and prevent a free floating after the release. A cap at the end of the tubes has also a magnet and is inserted with the opposite pole than the magnet in the pin. Thus, the magnet in the pin is attracted by the magnet in the cap.

A coil around the tube of the safety pin is the trigger, which creates a magnetic field when a current runs through it. The generated magnetic field interacts with the magnet of the safety pin. Since the coil is fixed, but the pin is able to move in the axial direction, the pins magnet gets attracted by the magnetic field of the coil and moves towards it, along with the pin. The magnet in the cap behind the coil will pull it back completely and hold it in that final position.

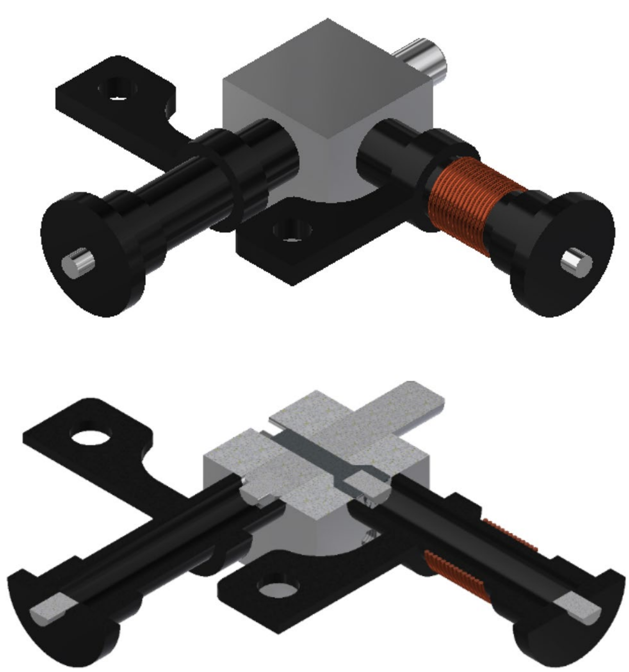

Fig. 8 CAD model of the electromagnetic concept

Therewith the main pin gets pulled back by the magnet of its cap and releases the reaction wheel.

5.1 Test of the first design

To test the functionality, the test-setup shown in Fig. 9 was built up. The current and voltage were varied to find the minimum power required to move the safety pin. Additionally, the temperature of the coil was measured to observe the heat generated by the current running through the coil.

For the coil, a 1.25 mm diameter copper wire was used to create 30 windings distributed over two layers. The mechanism worked with 2 A and 10 V.

One observation of the test was that when the pins connect with the magnet in the cap, they slightly push back the cap, due to their impulse transferred to the cap. This effect is not critical in this phase of the development, but needs to be considered in further investigations of this mechanism.

5.2 Additively manufactured design

After this first test, the general functionality was proved. In another iteration step, the design was changed to a lighter and smaller additive manufactured one, which is shown in Fig. 10.

The case and the tube for the main pin were connected to one part. Since the tube for the safety pin changed slightly, a new coil was built as well. Twenty-five windings on 2 layers mean a total number of 50 windings and a small increase compared to the coil from the first design. The caps and the pins were kept from the first design.

An integration of the cap with its tube to one part is not possible, since the cap needs to get removed to separate the pin from the cap for resetting the mechanism.

This design was tested in the same way as the previous one. During the tests, it occurred, that the safety pin did not

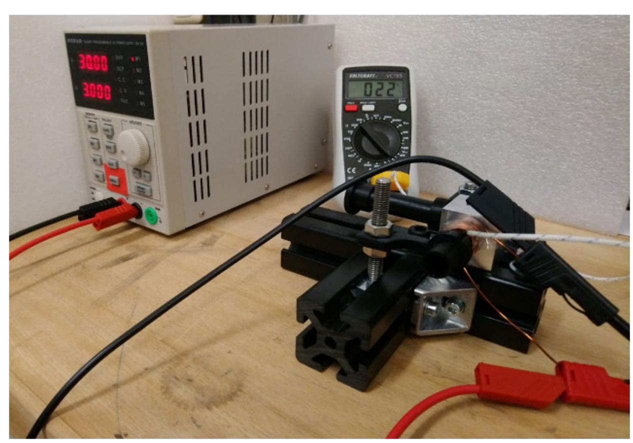

Fig. 9 Test-setup to test the electromagnetic concept

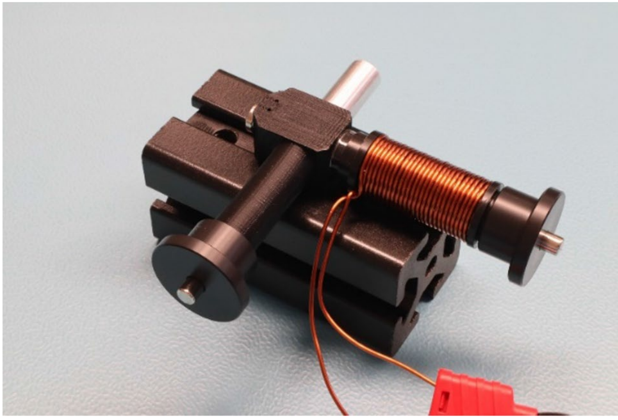

Fig. 10 The second design of the electromagnetic concept

move anymore. Even with higher voltages and currents, the problem remained.

One explanation for this issue might be a higher friction between the surfaces of the pin and the bore. Thus, the bore might need a finer rework or the use of a lubricant can produce relief.

Furthermore, the design of an application specific magnetic actuator is a complex process, which requires a lot of testing and optimization. Within this process, it could be possible to increase the force output, so that the pins move as desired.

6 Conclusions and outlook

Both concepts showed a theoretically functionality under laboratory conditions. A functionality test with simulated loads as they occur during launches has to be done. The possibility to reset both mechanisms was considered during all design processes.

However, a comprehensive and quantitative analysis of all acting forces in possible conditions should be done before further executing the functionality tests.

The electromagnetic concept is difficult to realize since a high current is needed to create the required electromagnetic field and overcome the friction. With increasing loads on the pins, the current also increases due to higher friction, which leads to big batteries and does not make the concept useful. An alternative to test is generating a high current pulse by a small dedicated drive electronics, as discharging a capacitor. Achieving a short electromagnetic peak force could be sufficient to trigger the system.

The bimetal spring concept has a good potential for further improvements and real use. Using springs of different forces, it is easy to adapt the system to the real occurring forces once they are known. A resulting advantage is, that the weight and construction volume would not change much anymore. One main aspect which requires further investigation and will have a big impact on the final design, is the damping. Just using foam as tested is not enough. Either it has to be thicker or more resistant to the appearing forces, or an active damping system is required. Since the system is not tested with a SMA spring, yet, it has to be found out, what amount of heat is necessary to activate such SMA springs for different kinds of materials and the overall performance.

When seeking for further improvements regarding making the system smaller and lighter, it can be considered to not use the safety pin at all. Instead, the SMA spring is put on the main pin itself. This would also decrease the number of used and moving parts and therewith reduce the probability of failure, as it was shown that the transverse located safety pin can reduce the functionality.

The total weight of the additive manufactured bimetal-spring concept is about 25 g, while the hybrid magnet concept weighs about 100 g, but with pins out of aluminum. These weights are below other hold down and release mechanisms for example from [5–8].

Using PLA-Filament additive manufactured parts comes along with time and weight advantages. The printing time was about 4 h. It was just necessary to rework the functional areas, where the pins slide. The additive manufacturing also allows the connection of two parts, e.g. the case and tube, to one single part, which would be challenging with the classical subtractive manufacturing processes. The use of plastics instead of metal comes along with a significant weight advantage. But an investigation regarding the strength, stiffness and thermal resilience of the additive manufactures system is necessary.

Another aspect which has not been examined in detail in this work, is the inadvertent release, due to i.e. vibrations during launch. The concept with the SMA spring could be a solution but requires another study.

An overall feasibility of the concepts could be proven. Therein the electromagnetic concept showed some weak spots, while a solution with a SMA spring seems reasonable.

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