THE APPLICABILITY OF GECKO ADHESIVES IN A DOCKING MECHANISM FOR ACTIVE DEBRIS REMOVAL MISSIONS

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ABSTRACT

Biologically inspired synthetic adhesives, or gecko adhesives, outperform in many ways common adhesives. Among other properties, gecko adhesives offer on/off-functionality and reusability, which makes them predestined for use in space flight, e.g. in active debris removal missions (ADR) or as an auxiliary tool for extravehicular activities (EVA). The Institute of Aerospace Systems (ILR) at Braunschweig Technical University investigates the usability of gecko materials for ADR docking missions.

This paper presents a thorough literature research of gecko adhesives, ADR approaches and mechanisms that use gecko adhesives. To analyze the properties of different gecko materials, a test environment is developed. The setup of this test environment is described as well as the according tests that have been performed to assess the adhesives' performance. Preliminary results are presented and an envisaged roadmap is shown to advance the technology readiness level (TRL) of a docking mechanism based on gecko adhesives.

Key words: gecko adhesives, docking mechanism, active debris removal, load tests.

1. INTRODUCTION

Space debris poses a threat to spacecraft, such as the International Space Station. The collision of Iridium 33 and Cosmos 2251 has revealed the consequences space debris can have on the space environment [22]. Research has shown that especially in Low Earth Orbit (LEO) the space debris environment has to be stabilized and the collision risk has to be reduced to maintain an acceptable collision probability for future space missions. Simulations show that active debris removal (ADR) missions or post mission disposal (PMD) strategies have to be implemented to slow down the increase of new fragments [15]. It is commonly believed that at least five objects have to be removed from orbit every year to avoid the Kessler syndrome [14] [23].

The Institute of Aerospace Systems (ILR) at Braunschweig Technical University provides outstanding expertise in modeling, simulating, and analyzing the space debris environment. ILR has derived a priority list for high-risk debris objects based on their environmental criticality and estimated the cost of an active removal of those priority objects [13]. Priority objects include e.g. Envisat or Zenit 2 and Ariane 4 upper stages. Currently, ILR focuses on research which addresses the implementation of a docking mechanism for ADR missions and thus completes the research chain from analyzing debris to mitigating the objects with the highest priority.

Docking to priority objects is difficult and potentially hazardous as those objects are generally non-cooperative and expected to be tumbling due to perturbations caused by e.g. Earth's gravity gradient or magnetic field [4]. Most debris objects do not possess a docking/berthing interface. Former approaches have tried to address these issues by using nets or harpoons to catch debris for a deorbit maneuver [19]. These techniques, however, exhibit the risk of creating even more debris and cannot be repeatedly used if the capture process was imprecise. Also robotic arms have been used for berthing procedures. This method though is not suitable for the numerous debris objects without a special berthing interface. ILR develops a new docking mechanism based on gecko adhesives. Those materials imitate the feet of a gecko, which has the natural ability to climb vertical walls as well as ceilings, even if the surface is perfectly flat. As the gecko materials have not been primarily designed for space use, the applicability of the adhesives to space use has yet to be proven. This includes long-term functionality in vacuum, robustness to high and low temperatures, durability to radiation, and adhesion to different materials commonly used in space. Further, space debris objects will undergo degradation while being in space, which could reduce the adhesive forces of the docking mechanism.

In the process of developing the new docking mechanism, ILR has developed a test environment to analyze different kinds of gecko adhesives with respect to maximum normal and shear forces. The results of those analyzes are the base of the development of a docking mechanism prototype.

2. STATE-OF-THE-ART

Supporting the tests conducted at ILR, a comprehensive literature research was conducted. A comparison of current ADR approaches was performed as well as an analysis of current mechanisms using gecko adhesives.

2.1. Gecko Materials

Geckos can naturally adhere to surfaces independent of its orientation. This adhesion is not influenced by factors like roughness or humidity [2]. Although high adhesive forces must be present to do this, geckos can still remove their feet from a surface with ease. This is possible only because of the gecko's skin, which is composed of millions of so called setae that get in contact with a surface. The resulting van der Waals forces can hold the gecko independent of its orientation and the surface. Nevertheless, the gecko can remove its feet easily and fast. Gecko adhesives are synthetic materials that imitate the properties of a gecko's foot.

There are different types of gecko adhesives, most of which feature either mushroom-shaped fibers or anisotropic wedges. Fig. 1 (left) depicts a schematic diagram of a gecko adhesive composed of mushroom-shaped fibers. Those adhesives need a preload in normal direction to activate the adhesion. After the application of a preload, the material adheres to a surface until a higher load is applied, which deactivates the adhesion. A schematic drawing of a wedge type gecko adhesive is shown in Fig. 1 (right). Unless a shear force is applied to those gecko materials, their adhesion is "turned off". Once under a shear load, the adhesives can bear normal loads. The material can be released by reducing the shear force to zero or by strongly increasing it.

When producing synthetic gecko adhesives, many design parameters need to be balanced, as for instance the material properties, contact shapes, means of contact splitting and the material's hierarchy [9] [21]. The **material properties** of a gecko adhesive need to be balanced so that the material is soft enough to guarantee close-fitting contact with the surface, but at the same time sufficiently stiff so that the mushroom fibers or the wedges do not entangle each other, cluster, or store to much elastic energy which counteracts the van der Waals forces [9]. The influence of the **contact shape**, e.g. mushroom-tips, wedges, flat or spherical tips, has been found to have a great impact on adhesive performance, but also depends strongly on the surface [6] [21]. For example, flat tips show very good performances on perfectly smooth surfaces, but even with only a slight roughness, their performance decreases. Mushroom-shaped tips are well suited for long-term attachment, as they stay attached without the need of a continuous force, but are not easily removable because they require a force or a peel movement for release. On the contrary, wedge-shaped materials need a continuous shear force to keep adhesion activated, but can easily be released by reducing the shear force. This makes wedge-shaped adhesives better suited for dynamic applications. **Contact splitting** describes the division of a macroscopic contact, e.g. between a gecko adhesive and a surface, into many smaller subcontacts. It has been studied in many research projects [9] [12]. Contact splitting is a basic principle of gecko adhesives, as thousands of fibers each get in contact with a part of the surface. This is an advantage in comparison with an overall smooth adhesive, as the gecko adhesive can better adjust to rough surfaces and the propagation of cracks is prohibited. The structural **hierarchy** levels of a gecko adhesive are mimicked from nature. Geckos own several levels of hierarchy in their feet [2]. Fig. 2 schematically depicts the hierarchy levels from a macroscale view of a gecko's foot over microscale views of lamellae and an array of setae to a nanoscale view of spatulae tips. The hierarchy allows bringing the spatulae into close contact with rough surfaces. It has been shown that more levels of hierarchy improve an adhesive's performance [16].

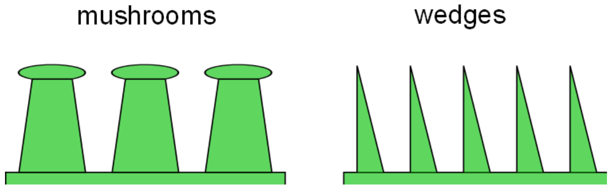

Figure 1. Two kinds of GSAs; Mushroom shaped fibers and anisotropic wedges

Most important for the application of gecko adhesives in a docking mechanism for ADR missions is their on/off functionality and their reusability. But gecko adhesives offer a lot more properties that make them eligibile for use in an attachment mechanism for space use. The following properties of gecko materials are commonly believed to be advantageous [1]:

- anisotropic attachment
- high adhesion coefficient
- low detachment force
- material independence
- self-cleaning
- anti-self-stickiness
- non-sticky default state

Anisotropic attachment describes the fact that normal preloads can generate shear adhesive loads and vice versa. A **high adhesion coefficient** implies that only low preloads are needed to generate high adhesive forces. These facts can be employed for a docking mechanism. As already described above, the **detachment forces** of gecko adhesives are very low. This makes gecko adhesives well suited for space applications, as the appliance of high detachment forces has to be seen critical in a zero gravity environment. The **material independence** needs to be shown for specific space materials. However, van der Waals forces are material independent as long as two

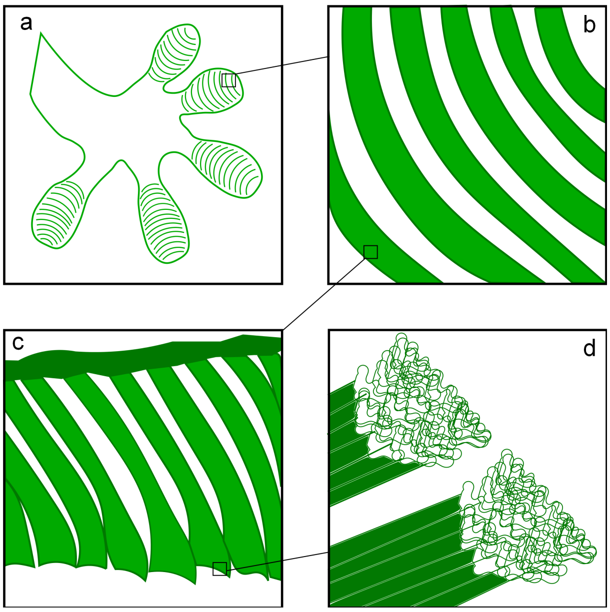

Figure 2. Different hierarchy levels of a gecko: a foot (a), several lamellae (b), numerous setae on one lamella (c) and spatulae on one seta (d)

materials get in close enough contact. Thus, it only has to be guaranteed that the gecko adhesives come in sufficiently close contact to the target surface. The last three properties, **self-cleaning**, **anti-self-stickiness** and **non-sticky default state**, make gecko adhesives easily manageable and reduce the risk of them becoming attached to parts they must not attach to. Those properties make gecko adhesives eligible for a variety of applications.

Important for space applications is the functionality of gecko adhesives under space conditions. Radiation, a wide temperature range or vacuum are only some of the aspects which need to be kept in mind when planning to use gecko adhesives for space applications. It has been shown for a selection of gecko adhesives that adhesion is not or only negligibly influenced by radiation, vacuum or temperature variations [10] [18]. However, space functionality also needs to be proven for the respective gecko adhesives that will be used in an ILR docking mechanism.

2.2. Active debris removal concepts

As there are various approaches to active debris removal, the advantages and disadvantages of ADR concepts in comparison to gecko-based concepts are of interest. Table 1 shows the most important aspects of the comparison for a selection of ADR concepts. The different concepts are only ranked relative to each other. Therefore, a technology which has been ranked less suitable is just seen less suitable than the other technologies and might still be eligible for ADR missions. Furthermore, the comparison has been done to the best of knowledge without the conduction of experiments to proof the assessment.

The **reusability** criterion addresses the advantages of a mechanism concept which can be used repeatedly, either in the case of missing the target object or in the case of removing multiple target objects during one mission. In the first case, a complete failure of the ADR mission is averted, in the second case, the ADR mission has a greater impact and is more economic. The **complexity** criterion covers the assumption that a more complex system is prone to errors more often. Thus, a less complex ADR concept is desirable. Although a **detumbling possibility** is not mandatory for a successful removal of a target debris object, it nevertheless increases the potential use spectrum of a mechanism. Possible applications of a mechanism beyond ADR include but are not limited to servicing missions or EVA support. Therefore, a higher detumbling possibility is desirable. The **adaptability to different surfaces and shapes** is one of the key requirements, as the potential targets of an ADR mission are of various type [13]. A mechanism that can catch curved objects or dock both to flat and smooth solar panels as well as MLI foil is better than a mechanism that is restricted to only a few surfaces and shapes. Keeping in mind the space debris mitigation policies that are being introduced as well as the already critical state of the LEO environment concerning debris saturation, minimizing the **risk of creating new debris** while using ADR mechanisms is of utmost importance. An ADR concept is thus ranked "good" in Tab. 1 when it imposes a low risk of creating new debris, e.g. by crashing into the target object or by ejecting new debris on contact. The **multi-purpose** criterion is not directly connected to ADR missions but takes into account potential applications beyond ADR. Gecko materials can, for example, be used for EVA support or to attach new devices (e.g. deployable sails) to spacecraft and are thus ranked "very good". In the following, the assessment of two concepts is exemplary described as well as the assessment of a gecko-based concept.

The use of harpoons for ADR has been studied by Astrium UK [19]. A prototype harpoon was built and tested against materials commonly used in satellites. Although those tests did not show a critical output of new debris, the harpoon concept is considered less suitable with respect to the risk of creating new debris in comparison to the other technologies shown in Tab. 1. The reusability criterion is seen critical as it is expected to be complicated to pull in a tether in space after the harpoon has missed a target and as furthermore only a limited number of harpoons can be incorporated into a mission. On the other hand, the harpoon concept seems advantageous concerning the adaptability to different surfaces and shapes, as it has been shown that a harpoon can penetrate for example real satellite panels, solid aluminum plates or lightweight objects [19].

The ion beam shepherd is one of the no-contact concepts in Tab. 1. Naturally, its adaptability to different surfaces and shapes is perfect and its risk of creating new debris is very low. Also the reusability criterion is fulfilled, as the ion beam system can be reused several times. However, the concept does not acquit itself well concerning detumbling possibilities and multipurpose, as it does not offer

Table 1. Overview of different ADR concepts

	reusability	complexity (low complexity is desirable)	detumbling possibility	adaptability to different surfaces/shapes	risk of creating new debris	multi-purpose
Gecko	++	+	+	+	+	++
Robotic arm	+	--	++	o	--	++
Harpoons	-	o	--	+	--	-
Nets	--	o	--	+	-	--
Ion beam shepherd	++	o	--	++	++	-
Clamping mechanism	+	--	++	o	-	o
Magnetic	++	+	o	o	+	-

++ very good, + good, o medium, - less suitable, -- unsuitable (usability with respect to individual criterion)

any means of attachment and thus can not be used for any other purposes.

As can be seen in Tab. 1, the gecko-based concept outranges the other concepts. Reusability is expected to be ”very good”, as has been shown for some gecko materials [3] [17]. Still, it needs to be shown that the gecko adhesives which will be used at ILR also show high repeatability. The complexity of an ADR mechanism based on gecko adhesives is considered the best of all analyzed concepts, as it is expected that such a mechanism contains only a small number of moving parts and ideally attaches itself to a target once in contact without the need of human supervision. The detumbling possibility depends on the maximum loads the gecko mechanism can handle. As the maximum load can be increased by increasing the number of gecko pads, detumbling possibility is seen as ”good”. The adaptibility to different surfaces and shapes needs to be proven. Gecko materials themselves can adapt to non-flat surfaces on a micro-scale by means of contact splitting [9] [12]. A macroscopic adaption needs to be enabled by a good design of the mechanism, i.e. placing the gecko pads in a way that each of the pads gets full surface contact [18]. In this regard it has been found that the adhesive pads that are being used in a mechanism have to be small in comparison with the radius of a surface curvature [8]. The risk of creating new debris using a gecko mechanism is considered ”good” in comparison with the other concepts. Naturally, a no-contact concept like the ion beam shepherd has an even lower risk of creating new debris, but in comparison with other concepts that need to establish a contact to the debris object, a gecko concept has a comparably small risk due to low possible approach velocities and few moving parts. As a gecko mechanism can be used for several tasks, as described above, its multipurpose usability is considered ”very good”.

2.3. Mechanisms

The use of gecko adhesives in capture mechanisms has been addressed by different researchers. In [18] a proof-of-concept grappling mechanism for flat surfaces has been developed that uses two directional gecko adhesives. Using the gecko pads in opposition allows the application of an omnidirectional load away from the surface. The gecko pads are loaded by an extension spring. After the load is removed, the mechanism can be removed without the need of applying a force, which is important considering a potential use in a zero gravity environment. By increasing the number of pads and suspending them on a foam-like suspension layer, it could be shown that also curved objcts like cylinders can be grabbed with such a mechanism. This is important considering that a large number of potential docking targets are upper stage rocket bodies [13]. By shearing the gecko pads to the outside and not to the inside, the gripper could even be attached to non-stiff surfaces. This shows that a gripper based on gecko adhesives can also dock to materials like MLI foil.

In [7] a mechanism is presented that is also based on opposing gecko pads. This mechanism does not rely on preinstalled fixtures, in contrast to former mechanisms like the robotic arms of the Space Shuttle or International Space Station. It is stated that the presented mechanism can dock not only to solar panels but also to e.g. fuel tanks. The grasper is supposed to be mounted on a robotic arm. Shear forces for adhesive loading can be applied on impact or by turning a leadscrew in the center of the mechanism. Tests showed a maximum successful capture for an object moving with 2 m/s relative velocity and a spin rate of $>$75 deg/s.

An improvement of the previously described mechanism, in which two gecko pads are placed in opposition and loaded by a spring, is given in [11]. The mechanism is advanced by a small linear actuator which puts the spring in the exact position that is needed for generating an optimal preload force. This is done initially before contact. Once the gecko pads get in contact with a surface, the linear actuator retracts, the springs are loaded and the adhesives are ”turned on”.

3. GECKO ADHESIVE TESTING

Tests are being performed at ILR in order to understand and measure the adhesive performance of gecko materials with respect to maximum loads, adaptability to surfaces or repeatability. The gecko materials that have been analyzed vary according to the scale of their structures (e.g. micro- vs. nanostructures), the materials of which they were cast (e.g. PDMS vs. PU 77-50) and the type of structures of which they are composed (e.g. mushroom-type vs. anisotropic wedges). Surface samples resemble a variety of materials commonly used in spaceflight.

3.1. Tested gecko materials

Six types of gecko adhesives are currently analyzed at ILR. The following paragraph gives an overview of those materials.

Types 1- 4
From the Leibniz Institute of New Materials (INM) gecko materials with mushroom-shaped fibers are analyzed. Types 1 and 2 are composed of polydimethylsiloxane (PDMS), Types 3 and 4 are cast from polyurethane (PU 77-50). Types 1 and 3 consist of fibers with a length of 0.8 mm and Types 2 and 4 have fibers that are 2.0 mm long. Fig. 3 shows two different types of those adhesives.

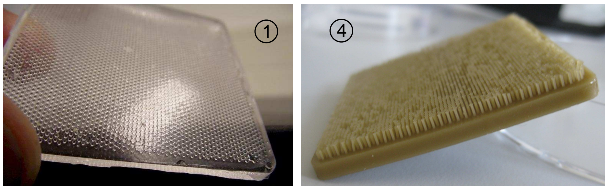

Figure 3. Gecko materials produced by the Leibniz Institute of New Materials; The left side shows type 1, the right side shows type 4

Type 5
Gecko® Nanoplast® is a silicone based gecko adhesive with a thickness of 0.34 mm. It is composed of nano-scale mushroom-type fibers with approximately 29.000 elements/cm^2 [5]. Fig. 4 shows a microscope image of the Gecko® Nanoplast®.

Type 6
In cooperation with the Institute for Microtechnology (IMT) of Braunschweig Technical University, a gecko adhesive composed of anisotropic wedges is being produced, following Parness's "microfabrication recipes" [16]. The adhesives are cast by a twofold photolithographic process. A master of SU-8 is created on a waver before the gecko pads are cast from a PDMS mold. The adhesives feature wedges of four different forms. This allows analyzing the influence of the form of the wedges as well as the influence of the base area and the filling factor. Fig. 5 shows how the adhesives are cast on a waver. It

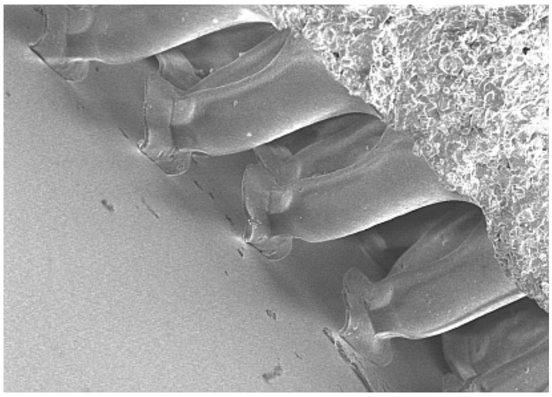

Figure 4. Gecko® Nanoplast®: The base layer as well as the mushroom tips can be clearly identified; Image Copyright: Gottlieb Binder GmbH [5].

also depicts the different base areas of the material. Two square base areas are analyzed as well as two rectangular base areas. The width and height of larger base areas are multiples of the smaller ones. This allows an easy analysis of the dependance of the adhesive forces on the base area. By alternating the base areas, also the filling factor is varied. The filling factor $f = \frac{A_w}{A}$, where A_w is the sum of all wedge base areas and A is the total area of the gecko pad. The adhesives of Type 6 are still under development and can thus not be included in the tests.

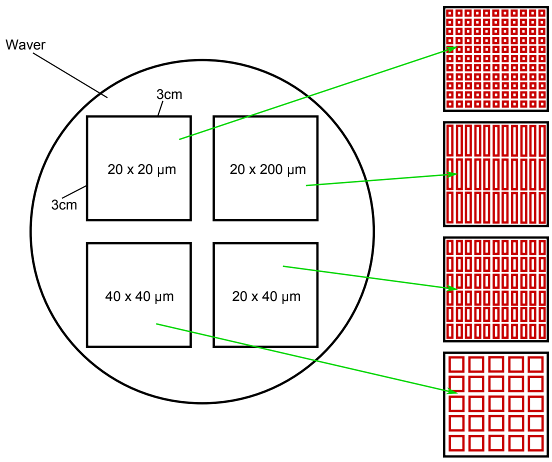

Figure 5. Production of different adhesives on a waver

3.2. The test environment

The test environment enables push-pull tests of gecko adhesives. A one dimensional manual linear drive is used for the tests. Attached to the linear drive is a 10 N force sensor for one-dimensional measurements of the adhesive loads. Surface samples are mounted onto a tiltable platform, while the gecko adhesives are mounted onto a carrier plate (with a two-component adhesive) that is attached to the force sensor. The carrier plates can handle gecko pads of up to 5 cm x 5 cm. However, during the tests described here, all the gecko pads had a size of 2 cm x 2 cm each. This allowed for a direct comparison of the test results. Fig. 6 shows the test environment (for demonstration purposes, without an attached carrier plate). The force sensor measures push and pull loads with an internal frequency of 2000 Hz and a precision of 0.005 N. Data is sent to a computer via an RS-232-interface. So far, the tilt of the platform has to be adjusted manually as well as the linear drive. In future work, this shall be automated.

A typical test procedure starts with choosing the surface sample and the gecko adhesive. Both are then mounted to the tiltable platform or the force sensor respectively. The tilt of the platform is afterwards adjusted and the force sensor is zeroed. The actual measurement procedure then starts with lowering the gecko adhesive onto the surface until a certain preload is measured by the force sensor, followed by lifting the gecko adhesive and, by that, applying a pull load. This is done until the gecko adhesive loses contact to the surface, which is indicated by a measured force of 0 N.

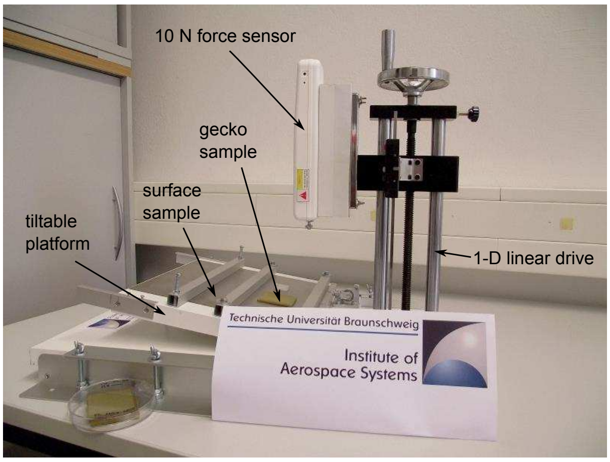

Figure 6. Test environment for the measurement of maximum adhesive loads

3.3. Test procedures and results

As the test environment is currently being set up, not all of the materials described above could already be tested. Thus, this work presents only the preliminary results for two materials (Type 3 and type 5), tested against the glass surface of a solar cell. Samples of 2 cm x 2 cm were used. The test procedure started with a load phase, during which a preload was applied to the sample. Different preloads were tested, ranging from 0.5 N to 8.0 N, depending on the respective gecko adhesive. The time for which the preload was applied was also varied, with a maximum duration of 8 s. Afterwards, the adhesive sample was pulled off the surface in a quasi static way until loss of contact. Table 2 and table 3 show the test parameters which were used for the two tested gecko adhesives. Note the higher preloads that were required for loading the type 5 adhesive.

Table 2. Test parameters for type 5 (Gecko Nanoplast)

Preload	0.5 N	1.0 N	2.0 N	4.0 N
Preload duration	2 s	4 s	8 s	

Table 3. Test parameters for type 3 (INM adhesive, PU 77-50, 0.8 mm)

Preload	5.0 N	6.0 N	8.0 N
Preload duration	2 s	4 s	8 s

In addition to the variations of preload and preload duration, the influence of a constant load, the number of use cycles and the influence of the pull-off angle are of interest. Those are not included in the preliminary results and will be discussed in the future.

Although only preliminary test results are currently available, some insights could be gained. Those are classified and described in the following.

<u>Preload variation</u>
It could be shown that a higher preload leads to higher adhesion (compare Fig. 7). Further studies need to address the question if a threshold exists, i.e. if at a certain point a higher preload does no longer lead to higher maximum loads.

<u>Preload duration variation</u>
Fig. 8 suggests a connection between preload duration and maximum load. It seems that longer preload leads to higher adhesion. As this trend is very small, future research needs to verify this assumption. It can furthermore be seen that a high variance exists between measurements under equal conditions. It is expected that this behavior is caused by alignment errors.

<u>General insights</u>
The type 5 adhesive delivered much higher maximum loads than the type 3 adhesive. Type 5 is composed of nanostructures, whereas type 3 is composed of microstructures. This suggests that finer structures allow higher adhesive forces, probably due to better surface contact.

Bringing the gecko adhesive in full contact with the surface is highly important and not trivial. Although the type 5 adhesive was pivoted on foam rubber and the type 3 adhesive has a suspension layer which is composed of the same material as its microstructures (PU 77-50), the alignment of the adhesives with the surface required special attention and must be seen critical for the development of a docking mechanism.

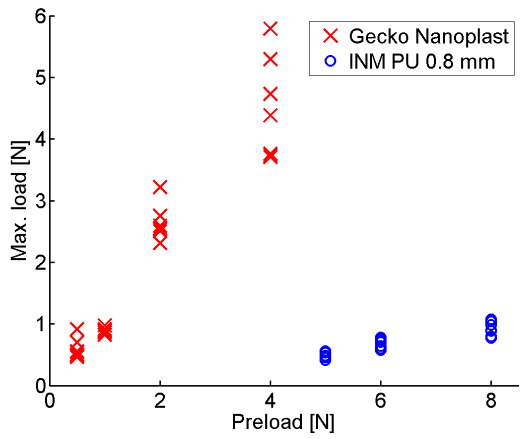

Figure 7. Influence of preload on maximum load

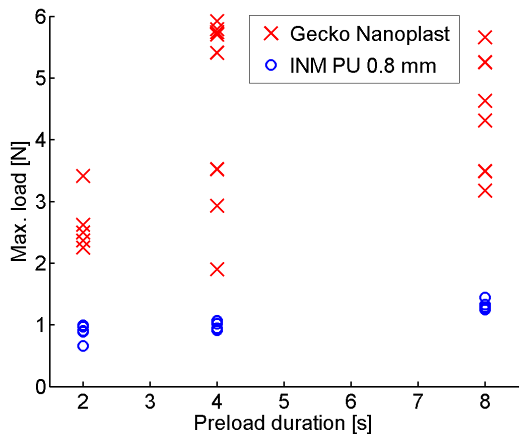

Figure 8. Influence of preload duration on maximum load

4. CONCLUSION & OUTLOOK

The literature research on gecko adhesives has shown very promising results concerning the loads that can be applied to those adhesives as well as their robustness to the space environment. Particularly the on/off-functionality and the repeatability are seen as critical functionality. A comparison of a gecko based docking mechanism with other ADR concepts has shown that this mechanism may outperform other ADR concepts, especially concerning multi-purpose use.

It was shown that several research groups are developing or have already developed climbing robots that are based on gecko adhesives. Some of those mechanisms might be functional in space, but for none of them has space functionality been proven. In general, wedge-shaped adhesives are used in those robots, as these adhesives are better suited for dynamic attaching and detaching. Nevertheless, both wedge- and mushroom-shaped adhesives shall be considered for a docking mechanism, as long term attachment might be needed (e.g. for drag sails). The results presented in this work only include mushroom-shaped adhesives. In the future, tests will be conducted with the wedge-shaped adhesives produced in cooperation with the IMT.

In preliminary tests at ILR, a nanostructure and a microstructure gecko adhesive were tested against a glass surface. The results suggest that higher preloads lead to higher maximum adhesive forces and thus confirm results of other works. A slight upwards trend of the maximum adhesion was observed when increasing the preload duration.

In future tests, also the influence of a constant load, the maximum number of use cycles and the influence of the pull-off angle shall be investigated. It is expected that higher loads lead to earlier loss of contact, a larger angle leads to lower maximum loads and that an adhesive's performance decreases after a high number of use cycles.

Furthermore, surface samples will be chosen from a variety of materials commonly used in spaceflight. The selection will be done to represent both satellites and upper stages and will include but is not limited to solar cells, MLI foil, anodized aluminum or paints. As ADR missions require docking to materials that possibly have been in space for decades and thus have undergone degradation, methods will be studied how to artificially degrade materials. Those will afterwards be used in the test environment. Additionally, it will be analyzed how surfaces which are not ideally flat influence adhesion. A comparison of the maximum loads on ideal and non-ideal surfaces will give a more realistic perception of the applicability of gecko materials to space use.

The tests will help to identify a gecko adhesive which is best suited for use in a docking mechanism. Requirements will then be identified for a docking mechanism and with the knowledge of the adhesive's maximum load, a mechanism prototype will be developed. This mechanism prototype will undergo various tests to proof its functionality and space-readiness.

For this purpose a dynamic ADR-testbed will be used, which is currently under construction at ILR. The testbed allows tests and verification of guidance, navigation, and control (GNC) algorithms as well as mechanisms and robotic operations in connection with cubesats. The test environment will feature an air-bearing system for small satellite models. The satellites can move in two translational degrees of freedom (DOF) and one rotational DOF. In the context of the development of the docking mechanism, the mechanism as well as surface samples will be mounted onto the satellites and docking procedures will be modeled and analyzed. So-called high priority objects, like Envisat, Zenit 2 or Ariane 4 upper stages, as identified in [13], will be built to scale of the satellites to model realistic ADR scenarios. Variations of e.g. approach and contact velocities or approach angles can easily be adjusted and, thus, results can be generated for lots of docking scenarios. This facilitates the in-house verification process of the general functionality of the docking mechanism in comparison to a simulation-only approach.

The next step in the preparation of the docking mechanism for space flight will be the verification of the mechanism in a zero-g environment, for example in parabolic flights, sounding rockets or onboard the International Space Station (ISS). ISS experiments will be the top of the verification process. By this point of time it is expected that the docking mechanism has reached Technology Readiness Level 6.

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