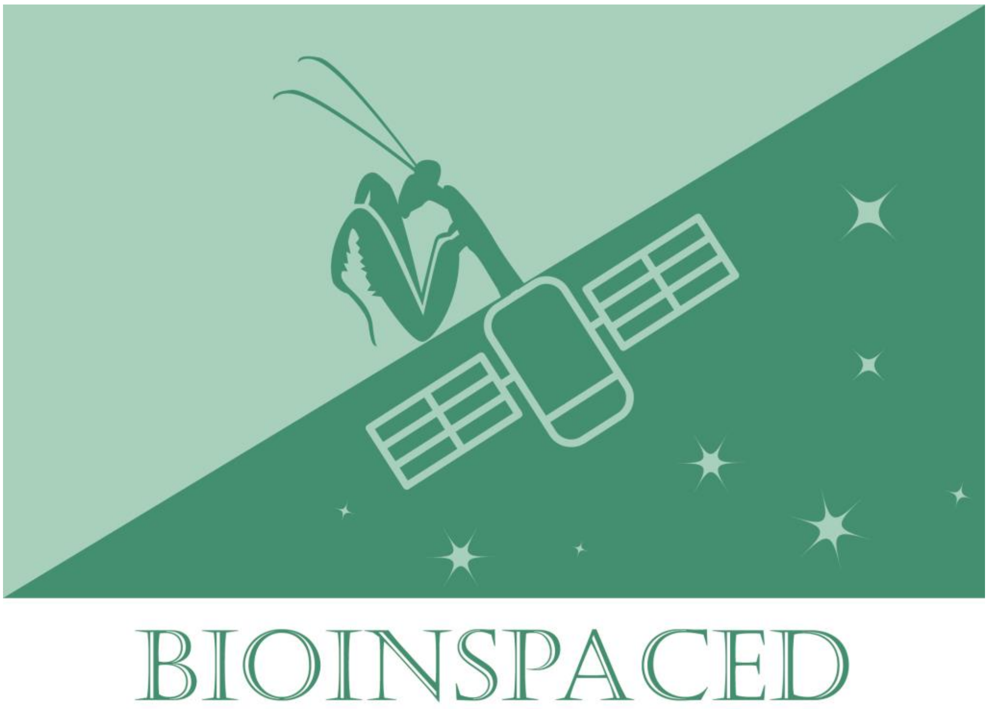
FRAUNHOFER CENTER FOR MARITIME LOGISTICS AND SERVICES CML

» BIOINSPACED | Bioinspired Solutions for Space Debris Removal «



Executive Summary Report

Deliverable Description

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List of abbreviations

ADR	Active debris removal
BIOINSPACED	Bioinspired Solutions for Space Debris Removal
CML	Fraunhofer Center for Maritime Logistics and Services
DRSR	Debris Removal Selection Review
DSR	Design Space Review
ESA	European Space Agency
FSSR	Final Scenario Selection Review
LEO	Low Earth Orbit
MTB	(Team) Maritime Technologies & Biomimetics
TUBS	Technical University Braunschweig (subcontractor in BIOINSPACED)
TN	Technical Note
WP	Work Package

1 INTRODUCTION

The use of space and the generation of technologies for its exploration have yielded a variety of advances and devices even for applications down on Earth. For some time now, biological organisms have served as an inspiration for technical development and can be found throughout many industries including aerospace engineering and space exploration. For example, the wood wasp and its ovipositor drilling into the bark of trees have been used as a model for surgical instruments on earth, and have also been considered as a solution for extraterrestrial drilling and sampling for decades (Gao et al. 2006; Menon et al. 2006; Nakajima and Schwarz 2014). An x-ray telescope with lobster eye optics presents another, more recently developed biomimetic approach to discover remote objects in space outside Earth's atmosphere and was used on the Czech nanosatellite launched in 2017 (Daniel et al. 2019). The increasing utilization of the extraterrestrial environment is respectively associated with an increasing number of satellites, spacecrafts and devices occupying the orbits around earth, which has now led to a major problem: space debris. At the end of 2019, 25,297 objects were orbiting the Earth, consisting of satellite constellations, payloads and rocket mission related objects. However, 67 % of these objects are decommissioned devices, retired satellites, fragments from collisions and a lot of small size space debris (Space Debris Office 2020).

Now, this accumulation has grown to an extent where discarded debris and rocket fragments pose a significant threat of colliding with current mission vehicles and operational satellites. Hence, the concern of the space community has shifted towards a more sustainable management and dealing with devices at their end-of-life stage, while endeavors have been initiated trying to resolve the problem of space debris.

The cataloguing of any object in space and its continuous tracking is done by ground- and space-based systems operated by various space agencies and aerospace companies. Keeping track of all objects orbiting Earth is crucial to prevent collisions and a cascading debris production. It also enables a more secure mission planning, since launches of new spacecrafts and satellites can be timed appropriately without interference of other orbiting objects. Ground-based systems used for space surveillance and monitoring of objects in space can be split into the categories of radar and optical measurements. Optical measurements usually consist of telescopes, which register the optical reflection characteristics of orbiting debris (Gao and Zhao 2019). The debris is naturally illuminated by the sun on its path around the Earth and thus partially reflects some light to an observer telescope on the ground. Ground-based telescopes are often preferred for the observation of objects in GEO (Hampf et al. 2013). For radar measurements, a scattered microwave beam is emitted, which bounces off any object in its path, creating a reflecting wave that is then received by the same (monostatic) or different (bistatic) transmitting antenna. The information extracted from the signal include the time of detection, position and reflected energy, which provides information on the detected object (Morselli et al. 2015). Radar is especially suitable for the detection and tracking of debris in Low Earth Orbit and dominates over optical measurements in their high sensitivity and independence of weather and day/night time conditions (Muntoni et al. 2017).

Space-based systems usually constitute of a collection of satellites like e.g. the U.S. Space-Based Space Surveillance mission, which incorporates many satellites responsible for the detection and tracking of debris (Grassi et al. 2015). This type of tracking allows for the observation of much smaller objects and debris fragments ranging down to between 0.05 to 0.1 meters in LEO and 0.3 to 1.0 meter in GEO (Gao and Zhao 2019). Based on the combination of the mentioned systems and locations distributed all over the globe, debris larger than 10 cm can be detected and tracked (Ansdell 2010).

When talking about space debris and reducing its accumulation in orbit, one must differentiate between active debris removal (ADR) and debris mitigation. While active removal targets already existing non-functioning objects orbiting Earth, debris mitigation describes actions prior to the launch of spacecrafts and attempts to minimize the number of objects that will eventually end up as debris in the future. Both are crucial for future and continuous use of the space environment (Ansdell 2010), since space debris does not only hinder the use of certain orbits in space and displays risk for collisions, but also poses threats to life on Earth as its re-entry can present a significant risk of damages in case components survive the atmospheric burn up. Hence, the mitigation of space debris is of the utmost importance and has caused a shift towards a more sustainable mission design. Additionally, space debris mitigation guidelines were established that include provisions for avoiding the release or break-up of space systems that would create additional debris, releasing all remaining fuel and energy resources on board and disconnect batteries, thereby decreasing the risk of explosions. Further efforts to reduce the accumulation of space debris have been encoding and incorporating deorbiting manoeuvres or removal systems such as drag sails at a spacecraft's end-of-life (United Nations 2010; Stokes et al. 2019). More recent developments concern the reusability of systems such as carrier rocket parts that are landed back on Earth after transporting their designated payload beyond Earth's atmosphere (Sippel et al. 2017; Stappert et al. 2019; Vojtěch and Pleninger 2018). While current mission systems launched into the orbits around earth are often equipped with some kind of provision to prevent it from becoming space debris or designed for post mission disposal strategies, previous campaigns did not include any end-of-life management of satellites and rocket stages. Thus, active debris removal concentrates on removing older technology that has been launched previous to more recent international sustainability efforts that are so-called legacy items. However, ADR for current mission vehicles is still important in case they malfunction or are unexpectedly destroyed through explosions and collisions (Olivieri et al. 2020).

Therefore, research has focused on active space debris removal options, many of which, however, remaining in the developmental stage and require proof-of-concept efforts or real scenario field testing. Some of the proposed active debris removal (ADR) concepts already include biologically inspired ideas such as the prominent example of using the gecko's feet as a model for adhesive materials implemented in a gripper to allow for docking to debris in space without requiring a specific adapter or compliant object (Alba-Padilla et al. 2016). In fact, one biomimetic option, a spider web-like net to catch orbiting debris is the only of two concepts that have ever been successfully tested in the space environment. However, biology's diversity is great and might therefore present even more mechanisms and options that can be applied to or serve as inspiration for the current project BIOINSPACED.

For some time now, biological organisms have served as an inspiration for technical development in aerospace engineering and space exploration as the examples of the wood wasp and its ovipositor drilling into the bark of trees for extra-terrestrial drilling and sampling (Gao et al. 2006; Menon et al. 2006; Nakajima and Schwarz 2014), and the x-ray telescope with lobster eye optics to discover remote objects in space launched in 2017 (Daniel et al. 2019) show. Some proposed ARD concepts already include biologically inspired ideas such as the prominent example of using the gecko's feet as a model for adhesive materials implemented in a gripper to allow for docking to debris in space without requiring a specific adapter or compliant object (Alba-Padilla et al. 2016). In fact, one biomimetic option, a spider web-like net to catch orbiting debris is the only of two concepts that have ever been successfully tested in the space environment. Therefore, looking at biology, its great diversity of mechanisms and its evolved features often presents great transferable concepts and may provide valuable contributions to ADR. Due to the variety of features available in nature, especially those essential for space systems such as response-stimuli adaptability, robustness and lightweight construction, autonomy and intelligence, energy efficiency, and self-repair or healing capabilities (Ayre 2004; Egan et al. 2015), biological mechanisms can be transferred and adapted to improve or even revolutionize traditional engineering approaches.

2 PROJECT OBJECTIVES AND OVERVIEW

The BIOINSPACED study was funded by the ESA and is short for Bioinspired Solutions for Space Debris Removal. It had the overall goal to find biomimetic solutions for novel technologies that can contribute to ESA's CleanSpace initiative by mitigating space debris, especially in low earth orbit (LEO). Analysing existing biomimetic examples and screening nature's idea pool supports the design and development of new bio-inspired solutions to fulfil the technical requirements related to an ADR mission. The elemental mission steps of launch, phasing, far- and close-range rendezvous, as well as capturing and deorbiting of debris, were identified and reviewed during the initial phase of the project.

Afterwards, an extensive literature review and brainstorming activities were carried out in a two-stage approach: Firstly, the transferability of existing biomimetic applications within the fields of robotics, materials science, kinematics, mechanics and space technology among others, into prospective ADR solution was studied. Already well-known biomimetic ADR concepts are for example the micro-patterned dry adhesion mechanisms of spider legs or gecko feet (Seidl 2008; Trentlage et al. 2016; Bylard et al. 2017; Busche et al. 2020). Subsequently, a biomimetic analysis was performed, screening the pool of nature's ideas to propose new solutions, which include those demonstrating great challenges for "traditional engineering".

All collected concepts were summarized in a catalogue and underwent a feasibility analysis, evaluating their potential for implementation into an ADR mission scenario. The best performing and thus most promising concepts were integrated into several holistic mission scenarios. After a collaborative discussion among Fraunhofer CML, TUBS and ESA, three of these most promising scenarios were selected for further investigation and conceptual design. One scenario was chosen at the end of Task 3 and then build into a demonstrator in Task 4. Subsystem were defined and how the biological models could be adapted and trasferred into technical systems. Thus, a demonstrator was created capable of showing how biomimetics can impact space systems. In the last phase of the project, individual subsystems of the demonstrator underwent preliminary experiments to validate their functionality. An overview of the project tasks and included outcomes is shown in Figure 1.

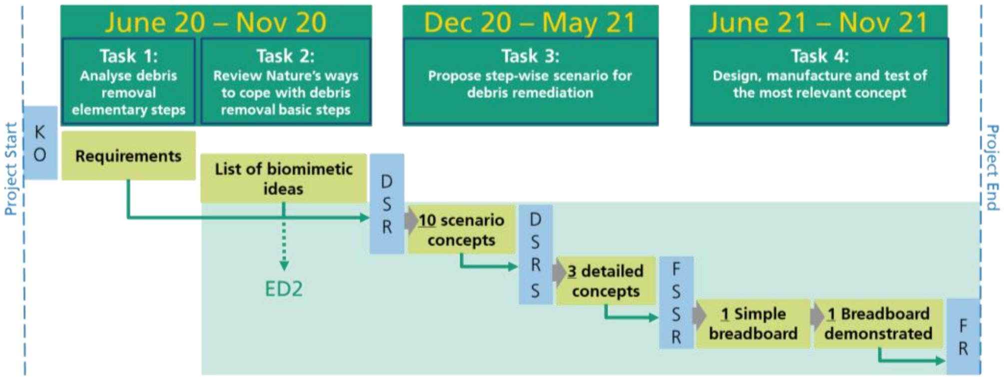


Figure 1: Envisioned timeframe of the individual tasks and their interaction. After the project's kick off (KO), Task 1 and 2 act as preparation for the scenario development and are concluded with the Design Space Review (DSR), where the number of collected ideas will be reduced to 10. In Task 3, those 10 scenarios will be further investigated and present at the Debris Removal Selection Review (DSRS). At this point, the number of concepts will be reduced again to the most promising 3, which will be developed more in detail. Lastly, at the Final Scenario Selection Review (FSSR), the final concept will be chosen that undergoes prototyping and testing in Task 4. The project is concluded with the Final Review (FR) at the end of Task 4, where the outcomes, findings and prototype of the best space debris removal concept will be revised.

3 OVERALL PROJECT OUTCOMES

Besides the required developments and milestones comprised within the individual tasks of the BIOINSPACED project, a variety of additional information and important discoveries were ascertained within its scope. In the following, these outcomes and lessons learned will be summarized with a reference to the corresponding task and how they should be treated in future research.

The BIOINSPACED project was initiated to find bio-inspired solutions for space debris removal because the identification, orbital alignment, capture and removal of uncooperative bodies in space is incredibly complex and no fully functioning method is available to date. Biology and its evolved mechanisms often provide specialized concepts that show great transferability to technical systems. They benefit from millennia of evolution and thus present a great diversity of features available that are often deemed essential for space systems as well, such as response-stimuli adaptability, robustness and lightweight construction, autonomy and intelligence, energy efficiency, and self-repair or healing capabilities (Ayre 2004; Egan et al. 2015). These can be transferred and adapted to improve or even revolutionize traditional engineering approaches.

The most important lesson learned within the scope of this project, however, is the requirement of end-of-life solutions for new spacecrafts currently deployed into the space environment and a solid management plan when they have completed their mission. This would reduce the steep increase of orbiting debris pieces and reduce the cascading effect, which otherwise would generate an infinite number of difficult to track small-scale fragments. First efforts towards this direction have been accomplished and international agreements on debris mitigation have been established by the United Nations (United Nations 2010).

Another important aspect for the utilization of the space environment is the advancement and implementation of on-orbit servicing and maintenance schemes for spacecrafts that demonstrate controllable end-of-life limitations such as low remaining fuel resources, minor damages or electrical malfunctions. If it were possible to extend the lifespan of spacecrafts, in particular for satellites, the number of debris due to additional rocket launches (Fairings, upper stages) would decrease significantly and have a beneficial economic side effect as well.

Lastly, the analysis and investigations conducted within the BIOINSPACED project have stressed the need for debris removal. Uncooperative and uncontrolled bodies and fragments circling various orbits around Earth do not only endanger communication, observation and surveillance on Earth, but also threaten and complicate human space flight and habitation on the ISS. Within BIOINSPACED, it was possible to increase the public's awareness regarding the problem of space debris and disseminate the advantageous role biomimetics can play when developing removal concepts as shown in the generated publications (Banken et al. 2021a; Banken et al. In press) and social media materials.

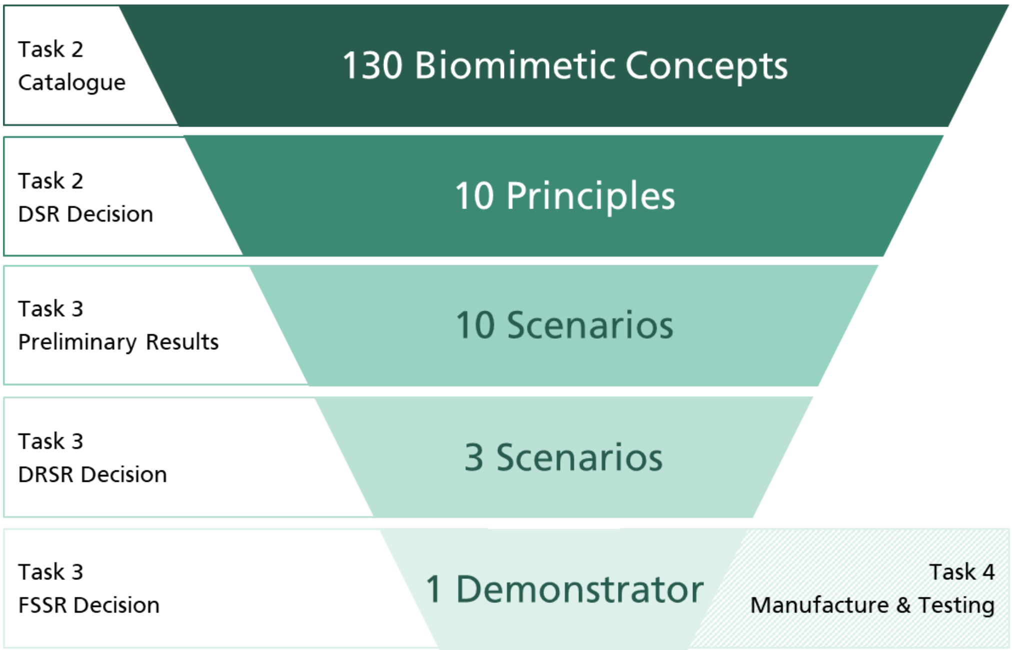


Figure 2: Conversion Flow of biological mechanisms and organisms transferred onto technical systems for ADR throughout Task 2 and Task 3. Starting with the catalogue of biomimetic concepts collected in Task 2 and the subsequent grouping of concepts into underlying principles present the results of task 2 that were used as basis for Task 3. Here, the 10 principles were first converted into 10 scenarios that were then reduced to 3 and then to one during the milestone meetings (DSR: Design Space Review; DRSR: Debris Removal Selection Review; FSSR: Final Scenario Selection Review). The final decision on the demonstrator will be used in Task 4 to manufacture, build and validate the chosen design.

3.1 Task 1

As a first step of the project, different concepts for active debris removal missions have introduced. The goal of all presented methods was to reduce the velocity of the target and the deorbiting of the object can be accelerated. Most of the concepts require a complex rendezvous manoeuvre consisting of launch, phasing, far- and close-range operations and mating. To establish a physical connection different concepts were compared that can be classified as stiff and flexible connection. Stiff connections provide easier control of the target during the deorbiting phase. However, establishing such a connection is not always feasible. This drawback can be avoided by using flexible connections. Nevertheless, this introduces the risk of a collision between both objects. One of the most promising methods to capture the target is using a net since it is less complex compared to other methods. Additionally, the net can be released from a safe distance. In general, the appropriate capturing method depends on the target properties and the measurement accuracy that can be achieved by the sensors. Stiff connections require often an interface or a grappling structure that is fixed to the target. If these mechanisms are not available adhesives like gecko materials provide promising alternatives.
There are several options to exert a force to the target in order to reduce its velocity. This force can be provided by lasers, propulsion systems or the interaction with the earth's magnetic field or atmosphere. Using the chaser's propulsion system is the only option that is feasible for controlled re-entry where high velocity changes must be provided in a

short time frame. However, this requires a physical connection between chaser and target and thus, also complex rendezvous und mating operations. Moreover, the deorbiting of multiple objects might become infeasible or at least more expensive with respect to fuel consumption and mission duration. Exploiting atmospheric drag or the earth's magnetic field often requires additional equipment, such as an inflatable ball or a tether, to increase the exerted forces and to limit the mission duration. In case these devices are not already aboard the target, again complex mating operations are required. Contactless concepts are often less complex. However, the momentum that can be transferred to the target is limited.

One of the most critical aspects during the capturing and removal operation is the risk of causing new debris pieces. This can happen due to erroneous mating operations, impacting inappropriate parts of the target due to inaccurate position measurements or excessive impact energy. Additionally, parts of the material that is used to increase the surface of the target, such as foam material, could be released into space during the rendezvous operations or when being hit by other objects. Another important issue is the procedure when failing to capture the target. An appropriate mechanism would be required to retrieve and reload the capturing device. Moreover, many of the proposed concepts still need to be analysed with respect to the applied material that has to meet the requirements while withstanding the harsh environmental conditions prevailing in space like low temperature and radiation.

Few missions were performed that can be considered as preliminary steps towards the first actual ADR mission, however, no ADR mission has been accomplished yet.

3.2 Task 2

In Task 2, all of the collected biomimetic concepts related to debris removal were evaluated based on the factors of technical feasibility, biomimetic and space applicability as well as their novelty factor. This allowed the assessment regarding their relevance for this particular project and the concepts were grouped into overlying principles (within single ADR stages). These overlying principles were presented at the Design Space Review meeting and the monthly meeting on February 24th 2021, using the most promising concepts within each principle group as exemplary biological mechanisms for the principle functioning. As the final step of Task 2, the number of principles was reduced from 24 presented overlying principles to 10 to be further investigated and integrated into holistic ADR scenarios. In the folowing, the 10 overlying principles are briefly described:

1) Compound Eye (Detection)
   Based on the compound eye of many insects that consist of many individual units called ommatidia, this principle describes a system integrating an array of different cameras and sensing elements as individual units for a complete 'eye'
2) Adhesive Gripper (Capturing – preliminary attachment)
   Modelled after the reversible adhesion capabilities of the gecko's feet enabling it to climb smooth vertical surfaces, this principle presents a gripper with an adhesive surface that allows for the temporary attachment to debris without transferring a lot of force onto the object

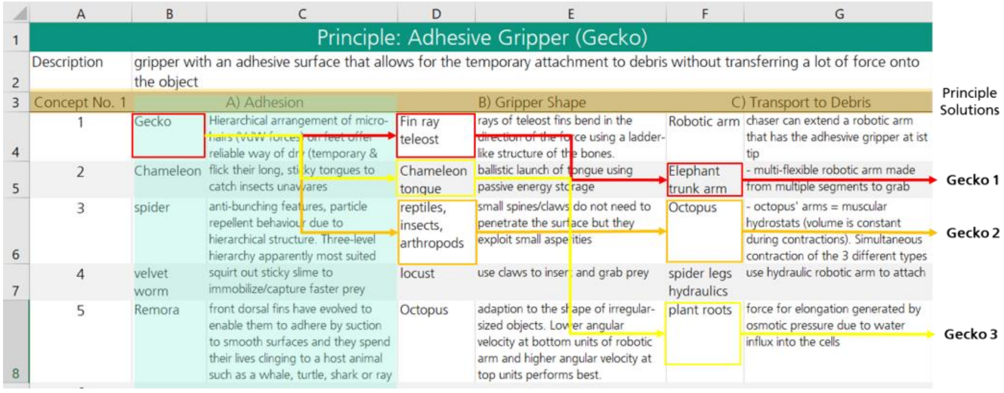
3) Harpoon (Capturing – rigid connection)
   Many animals portray the ability to pierce or drill into a variety of organic substrates in efficient and low-energy manners. Hence, this principle deals with the penetration of debris walls to hook into the material and form a rigid and permanent connection between the object and the chaser vehicle
4) Containment (Capturing –contactless)
   This principle utilizes a mixture of flexible materials and a stiff roboticed opening to surround especially tumbling debris and containing it without making any physical contact with it and was inspired by the mouths of many biological models. For example, pelicans, dragonfly larva, toads and snakes all use a flexible and stretchable membrane connected to their mouth opening that allows them to swallow bigger objects without first making a rigid connection with them.
5) Bi-Stable Mechanism (Capturing – flexible connection)
   Just like the Venus flytrap, openly waiting for prey to approach and trigger a couple of its hairs on the inside of its catching lobes, this principle describes a structure that allows approaching debris to trigger a couple of stimuli before the contraption is closed around the object. This way, inadvertent closing is prevented while also increasing the chances of capturing all of the debris not just a small part of it.
6) Parachute (Removal – Deorbiting)
   This principle combines the existing net idea with a containment and removal system all at once, based on the seed parachutes of the plant *Tragopogon dubius*. Here, the seed is attached to a sail made from multiple sticks and stuff on end to slow its descent and therefore allow for the wind to carry it away. As ADR method, a similar sail is made in form of robotic arms connected with a net-like structure that allows for the capture of debris. Then, the debris is transferred into the connected sack so that the sail can unfold again and act its purpose of increasing the atmospheric drag while the debris is the 'seed' being transported to a different orbit.
7) Folding (Removal – Deorbiting)
   Many flying animals such as birds and insects use drag and lift properties to their advantage when flying. Similarly, attaching a wing to debris that can unfold and thus increase the natural atmospheric drag on an object presents a viable principle for removing debris from designated orbits.
8) Tactile Sensing (Vibrissae)
   A tactile sensing chaser attachment system can circumvent common issues associated with optical detection of objects because artificial vibrissae connected to a robotic arm are able to feel around and determine parameters such as velocity or rotation of a target, maybe even determine an appropriate docking area without the chaser getting too close to the debris itself.
9) Shock Absorption (Pomelo Fruit)
   The great impact damping and energy dissipating capabilities of the pomelo fruit's peel can be used as protective foam to cushion the docking of two objects in space. It can reduce the counterforce applied on the chaser by making physical contact with its target.
10) Swarms (Ants)
   Swarms and their ways to communicate could be transferred onto miniature robots able to organize in particular patterns, collectively navigate and make decisions all in the pursuit to succeed in their common goal. The chaser can approach

its target with care, then release multiple individual propulsion units that make physical contact with the target. After the attachment of a sufficient number of units, the target can be deorbited in a controlled manner.

In addition, the newly established biomimetic database was presented in TN2 delivers a vast diversity of information about organisms, their features and how they may be integrated into technical solutions for not only space debris removal but within the entirety of aerospace engineering. Thanks to its classification between existing or new biomimetic concepts, interesting yet understudied or unknown biomimetic principles with further potential were identified and demonstrate great content for future research. In addition, it summarizes the available literature for existing concepts and details the state-of-the-art, thereby indicating the gaps and again future study potential.
Yet, it leaves room for the addition of newly found concepts (e.g., concepts previously neglected because of missing relevance for ADR) that can easily be integrated into the database and therefore delivers a comprehensive but adaptable tool for future use. Moreover, due to the arrangement and inclusion of technical key words and function categories, the database does not only apply to ADR but space applications in general, making it a diverse tool applicable to a variety of projects and topics of interest.

3.3 Task 3

In Task 3, the overlying principles from Task 2 were broken down again into individual component-and mechanism-related principle elements to investigate and assess each principle in more detail. Those principle elements represent different columns of the evaluation matrix of the Zwicky boxes and were populated with available solutions. The ideal combination of concept entries for each element was determined by considering their functionality in relation to one another, and were integrated into the final principle solution for the respective principle. Since there were many combinations to choose from, a maximum of three solutions per principle were established as depicted in Figure 3. Subsequently, one of the solutions was combined with those of other principles for different ADR stages to build the entire scenario within the ecosystem approach. Hence, one scenario can integrate multiple principles and even more biological concepts depending on the number of principle elements encompassed within each principle.



	A	B	C	D	E	F	G
1	Principle: Adhesive Gripper (Gecko)						
2	Description	gripper with an adhesive surface that allows for the temporary attachment to debris without transferring a lot of force onto the object					
3	Concept No. 1	A) Adhesion		B) Gripper Shape		C) Transport to Debris	
4	1	Gecko	Hierarchical arrangement of micro-hairs (VdW forces) on feet offer reliable way of dry (temporary &	Fin ray teleost	rays of teleost fins bend in the direction of the force using a ladder-like structure of the bones.	Robotic arm	chaser can extend a robotic arm that has the adhesvive gripper at ist tip
5	2	Chameleon	flick their long, sticky tongues to catch insects unawares	Chameleon tongue	ballistic launch of tongue using passive energy storage	Elephant trunk arm	- multi-flexible robotic arm made from multiple segments to grab
6	3	spider	anti-bunching features, particle repellent behaviour due to hierarchical structure. Three-level hierarchy apparently most suited	reptiles, insects, arthropods	small spines/claws do not need to penetrate the surface but they exploit small asperities	Octopus	- octopus' arms = muscular hydrostats (volume is constant during contractions). Simultaneous contraction of the 3 different types
7	4	velvet worm	squirt out sticky slime to immobilize/capture faster prey	locust	use claws to insert and grab prey	spider legs hydraulics	use hydraulic robotic arm to attach
8	5	Remora	front dorsal fins have evolved to enable them to adhere by suction to smooth surfaces and they spend their lives clinging to a host animal such as a whale, turtle, shark or ray	Octopus	adaption to the shape of irregular-sized objects. Lower angular velocity at bottom units of robotic arm and higher angular velocity at top units performs best.	plant roots	force for elongation generated by osmotic pressure due to water influx into the cells

Figure 3: Exemplary Zwicky box setup and selection of principle elements to form principle solutions. The table shows the description for principle of the adhesive gripper inspired by the gecko feet adhesion. The orange highlighted row presents the individual principle elements representing the parameters of the Zwicky box, while the green highlighted column shows the all appropriate concepts identified for the respective element. The red, orange and yellow pathways indicated throughout the table define the three optimal principle solutions established for this particular principle.

During the establishment of the scenarios, it became apparent that the ADR ecosytem defined in Task 1 may not suffice to describe a step-wise approach with bio-inspired concepts d provide additional and necessary information for close-range maneuvering between two bodies in space.. In addition, several sources have already discussed the option of additional phases that would be most helpful during the approach and mating with uncooperative targets. For example, the removal phase, describing the activity, where the target body is removed from its original location in the orbit and either brought to re-entry or banished to a graveyard orbit is an important one to consider when planning missions. Different forms of removal may require trajectory tracking and drag development simulations to prevent removal measures to cause collisions between one operational and one (slowly) deorbiting system. Therefore, as depicted in Figure 4 the three supplementary phases proposed to refine the existing ADR ecosystem were added.

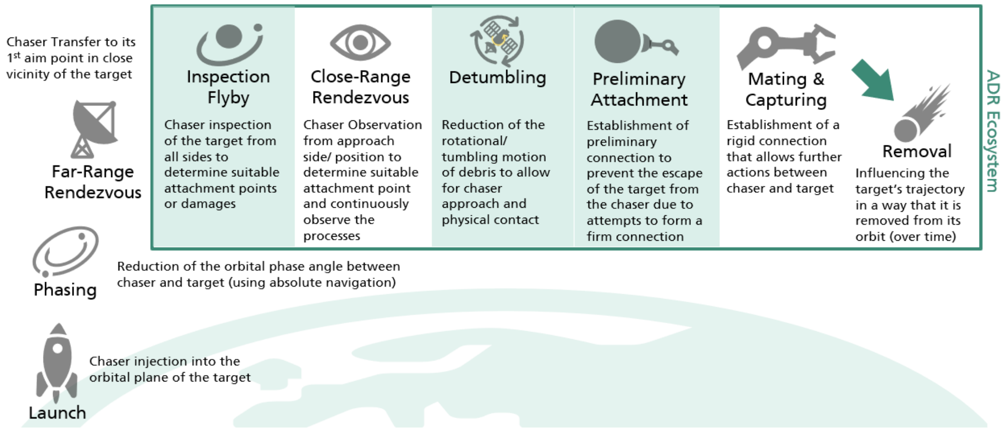


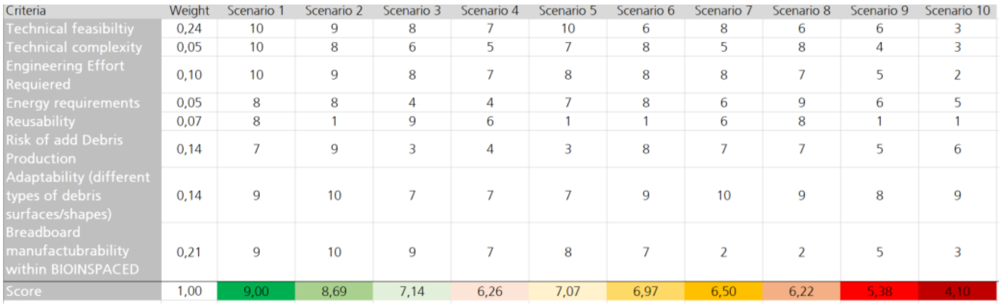
Figure 4: Refined ADR ecosystem. It shows the three additional phases of inspection flyby, detumbling and pre-liminary attachment and indicates the ADR ecosystem considered within the BIO-INSPACED project with the help of the green border. The three first phases of the conventional ADR ecosystem were neglected as they are the same regardless of the mission purpose (debris removal or not).

After the holistic scenarios were established according to the refined ecosystem approach, a trade-off analysis was conducted with respect to the following parameters:

- Technical feasibility, referring to the ability to implement a scenario and included things like the incorporation of moving parts and if the scenario's success relies on time critical components
- Technical complexity, determining the interaction between scenario components and if the solution requires precise motion control, which would significantly increase the system's complexity

- The engineering effort required, assessing the technological readiness level of included concepts as well as if components and materials have already been approved for their implementation within the space environment
- Energy requirements, evaluating the amount of motion and course control required, as well as the expected masses to be moved around
- Reusability, defining the possibility if a system or subsystems qualify for reuse on multiple targets, if removal is possible without losing its functionality or if it would be irreversibly deformed during the capturing process
- Risk of additional debris production, determining the potential of damaging the target due to penetration, the application of high speeds or style of attachment
- Adaptability, assessing if the mechanism could be applied to a diverse range of debris shapes and surfaces or if specific geometries or surface materials are required
- And lastly the breadboard manufacturability, evaluation if the possibility exists to build a demonstrator using the equipment and devices available at Fraunhofer CML, the accessible time and financial budget, and if a working demonstrator could be recreated despite the lack of e.g. vacuum condition as experienced in a space environment

Then a paired comparison was used to weigh these parameters against one another, by assigning them the value 2 if one was more important than another parameter, the value of 1 if they are both equally important and a 0 if the first is less important than the second. The final scores for a single parameter were summed up and divided by the overall number of assigned points to establish the parameter's own weighting factor.
Subsequently, the same parameters were evaluated for each scenario, assigning them a number between 1 and ten, where ten presents the best possible score (indicating e.g. the highest feasibility but also lowest energy requirement of risk of additional debris production). Those values were then multiplied by the respective weighting factor for the parameter established with the paired comparison and summarized again, resulting in the final trade-off score. The trade-off scores for each of the ten scenarios ranged from 9.14 for scenario 1 to 4.1 for scenario 10 as shown in Figure 5.



Criteria	Weight	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
Technical feasibiltiy	0,24	10	9	8	7	10	6	8	6	6	3
Technical complexity	0,05	10	8	6	5	7	8	5	8	4	3
Engineering Effort Requiered	0,10	10	9	8	7	8	8	8	7	5	2
Energy requirements	0,05	8	8	4	4	7	8	6	9	6	5
Reusability	0,07	8	1	9	6	1	1	6	8	1	1
Risk of add Debris Production	0,14	7	9	3	4	3	8	7	7	5	6
Adaptability (different types of debris surfaces/shapes)	0,14	9	10	7	7	7	9	10	9	8	9
Breadboard manufactubrability within BIOINSPACED	0,21	9	10	9	7	8	7	2	2	5	3
Score	1,00	9,00	8,69	7,14	6,26	7,07	6,97	6,50	6,22	5,38	4,10

Figure 5: Trade-Off Analysis. The table shows the criteria selected for the evaluation of the trade-off analysis as well as the weighting factor established with the previously described paired comparison. Each scenario was evaluated and the scores summarized at the bottom of the table. The color scheme follows the traffic light colours, with dark green indicating the best scoring scenario and dark red indicating the worst.

After these 10 scenarios were established, they were presented to the ESA Technical Officer at the Debris Removal Selection Review (DRSR) and further discussed to reduce them to only 3 scenarios. The resulting three were developed into realistic and holistic approaches including procedure and product specifications for the already existing components and features of the scenario (e.g. space cameras). The three scenarios were then presented during the Final Scenario Selection Review (FSSR), where not only the project team at CML but also the ESA Technical Officer and other members of ESA agreed on the final scenario to be continued and build as a demonstrator in the next Task.

3.4 Task 4

In order to produce a versatile demonstrator, capable of facilitating the diverse applicability of biomimetics in ADR, the three most interesting features were combined within one demonstrator system. Thus, the demonstrator comprised three main subsystems. The first subsystem is comprised of a catapult mechanism inspired by the grasshopper's jumping mechanism, which is designated to launch a deorbiting kit towards stationary and free-floating objects. In addition, this subsystem includes a compliant structure standing in for a robotic arm that enables the investigation of the benefits associated with a preceding preliminary attachment to the target. This subsystem presents the main part of the demonstrator and shows how to attempt physical connections between the chaser and the target when including biomimetic concepts.

The second subsystem was defined as the drag sail incorporated in the deorbiting kits. This sail is supposed to be folded up efficiently to create the most space efficient packaging within the kit. After the kit is launched and has made successful contact to the target surface, a release is triggered that automatically causes the sail to unfold and expand, thereby increasing the atmospheric drag of the target and reducing its orbital lifetime.

Lastly, a reciprocating drill inspired by the wood wasp was defined as the third and last subsystem of the demonstrator. This drill was decided to be an external addition to the demonstrator and simply showcase the wood wasp's drilling mechanism. It is not functional in the sense that it is able to drill into any kinds of substrates and purely for presentation purposes. Nevertheless, it focuses the attention onto a valid and extensively studied biomimetic concept with a wide range of potential application in ADR.

All of the subsystems were carefully conceptualized, manufactured nad built together t form one final demonstrator depicted in Figure 6. Furthermore, they underwent experiments to validate their functionality and provide a proof-of-concept. integrated into one demonstrator and

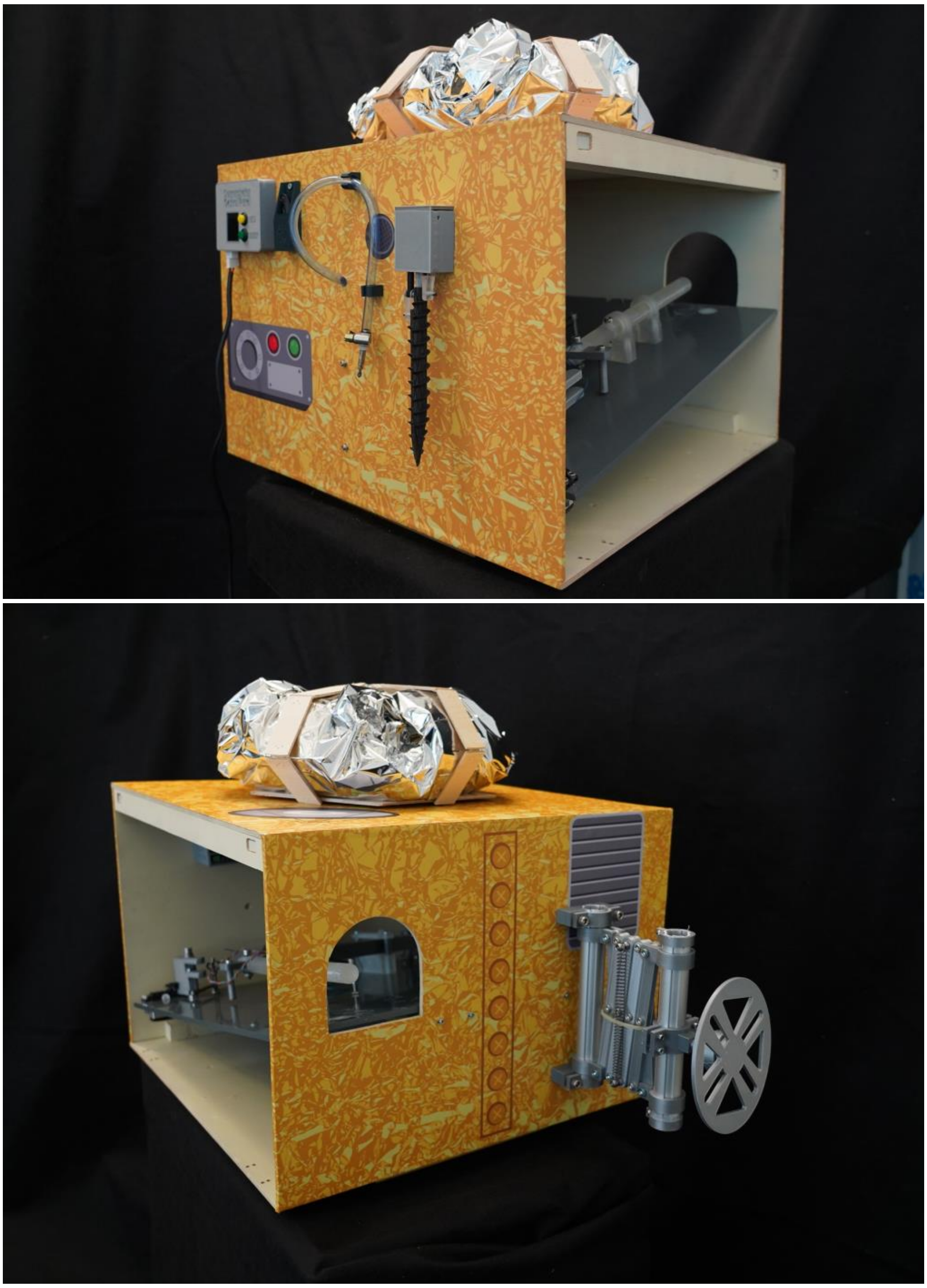


Figure 6: Photographs of the final demonstrator.

4 DISSEMINATION EFFORTS

Within the scope of the BIOINSPACED project, two articles were published, one as a proceeding at the 8th European Conference on Space Debris (20. – 23. April 2021) (Banken et al. 2021b) and one in a special issue of the CEAS Aeronautical Journal (Banken et al. In press). The first included a detailed description of the concepts collected during Task 2 and the most promising concepts with application to space debris. The later described the conducted feasibility study and thus, common methodologies used for biomimetic product design. In addition, it contained a summary of the entire biomimetic concept catalogue in its supplementary material.

In addition, a presentation was held during the same conference, where the BIOINSPACED project was introduced as well as the developed principles to be investigated further. One more presentation was held within the scope of the 'Maritime Innovation Update', an online series of short videos where Fraunhofer CML researchers provide answers and present innovative solutions, current studies and new optimization approaches relating to topics of maritime economics, logistics, technology and biomimetics.

The idea of biomimetics in space systems was further disseminated during the workshops, where experts within the fields of aerospace engineering, biomimetics and biology collaborated to brainstorm for new biomimetic concepts for space debris removal. In addition, the Fraunhofer CML social media platforms were frequently used to promote the project and the importance of activities focussed on space debris removal.

In conclusion, the potential benefit of biomimetics in aerospace engineering, and thus the importance of the BIOINSPACED project, was not only recognized by ESA and Fraunhofer CML, but was distributed to a wider circle in the space sector but also created awareness for biomimetics and space debris in the general public.

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