ASSESSING BIOINSPIRED CONCEPTS FOR SPACE DEBRIS REMOVAL AND EVALUATING THEIR FEASIBILITY FOR SIMPLE DEMONSTRATOR DESIGN

E. Banken$^{(1\ddagger)}$, **V. E. Schneider**$^{(1\ddagger)}$, **L. Pohl**$^{(1)}$, **J. Kniep**$^{(1)}$, **R. Ströbel**$^{(2)}$, **M. K. Ben-Larbi**$^{(2)}$, **E. Stoll**$^{(2,3)}$,
L. Pambaguian$^{(4)}$, **C. Jahn**$^{(1)}$, **J. Oeffner**$^{(1\ddagger)}$

(1) *Fraunhofer Centre for Maritime Logistics and Services CML, Am Schwarzenberg-Campus 4, Building D, 21073 Hamburg, Germany, Email: johannes.oeffner@cml.fraunhofer.de*
(2) *Institute of Space Systems, Technische Universität Braunschweig, Hermann-Blenk-Str. 23, 38108 Braunschweig, Germany, Email: robert.stroebel@tu-braunschweig.de*
(3) *Chair of Satellite Technology, Technische Universität Berlin, Marchstr. 12-14, 10587 Berlin, Germany, Email: e.stoll@tu-berlin.de*
(4) *ESA-ESTEC, Keplerlaan 1, TEC-MSP Ef074 - PO Box 299, NL-2200 AG Noordwijk, The Netherlands, Email: laurent.pambaguian@esa.int*
(‡) *These authors contributed equally*

ABSTRACT

The ESA-funded project BIOINSPACED intends to find biomimetic solutions for new technologies that can contribute to ESA's 'Clean Space' initiative by mitigating space debris. Analyzing existing biomimetic examples and screening nature's idea pool helps defining new bioinspired solutions that have the potential to fulfil the technical requirements related to an active debris removal mission. This paper will expand the current state of the art of active debris removal by describing a newly developed catalogue of 130 collected concepts with potential for future debris removal missions. A feasibility analysis was conducted, evaluating and subsequently enabling clustering and ranking of different concepts regarding their functionality and applicability. The ten most promising principles are presented in this study, and will be used to conceptualize holistic debris removal scenarios and manufacture one simple demonstrator during the next phase of the project, harvesting and illustrating their biomimetic potential for innovative solutions.

Keywords: Biomimetics; Bioinspired Space Solutions; Active Space Debris Removal, Space Debris Remediation.

1. INTRODUCTION

Space exploration has not only provided much information about Earth and the universe, but has also resulted in a vast number of technological advances based on "classical" engineering. To develop innovative and efficient new technologies the classical engineers view can be sometimes too straitened. Looking at nature can help. Although the often simple but elegant concepts that emerged from millions of years of evolution have been overlooked for some time, today inspiration for technological development is often found in nature: Biomimetics (or bio-inspiration or bionics) is the transfer of the found biological models into innovative technical applications [9]. Well-known biomimetic examples are drag reduction obtained via shark skin [59] and the Lotus-effect for self-cleaning surfaces [4]. However, also less popular concepts such as the water collection by beetles in the desert show the broad potential of biomimetics [45]. Some biomimetic concepts such as drag reduction via the Salvinia Effect, have been known for decades before their transfer into a real technical application is thoroughly studied [60].

Hence, for some time, nature has been used as inspiration for technical development in space, yielding, for example, a lightweight and energy efficient micro-drill for planetary exploration and sample acquisition modelled after the ovipositor of the wood wasp [31, 53, 55], an x-ray telescope with lobster eye optics deployed on a Czech nano-satellite launched in 2017 [21], or dry adhesion inspired by spider and gecko feet [73, 80, 16, 15]. This supports the notion that biology presents potential for innovation in space systems, however the extent of the potential for bio-inspired space technologies is unknown. Space debris is a well known and significant problem [43], which continues to grow at an increasing rate due to the extensive current and future use of space [6, 7]. Nevertheless, active debris removal (ADR) has not yet been successful and the need for novel technologies is high. Therefore, this study provides a catalogue of biomimetic concepts for ADR as an example for bio-inspired space technologies.

The BIOINSPACED Project

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Debris removal) with 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 [73, 80, 16, 15]. 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. After describing the idento process for the biomimetic concepts suitable for ADR and the conducted feasibility analysis applied to determine the most promising biological concepts and ideas, the resulting top 10 concepts will be presented within this article.

Based on the presented concepts and ranking method, the project's next step is to establish several ADR scenarios out of which the most promising BIOINSPACED solution will be modelled and built into a simple demonstrator validating the new bio-inspired concepts within ESA, while harvesting the biomimetic potential of such innovative solutions.

2. ELEMENTAL STEPS OF ADR MISSIONS

Within the scope of this project elemental steps and sequences of space debris removal processes were analysed and requirements were established for each stage, defining technical specifications where possible. This allowed a target-oriented identification of a broad range of biomimetic solutions in the next step.

Six mission phases for ADR missions were identified and defined, each of which requiring successful completion to enable the initiation of subsequent phases. The first phase is the launch of the chaser spacecraft into orbit, followed by the adjustment of its position with respect to the target (phasing), ranging over far-range and close-range approach of the target, to the actual mating manoeuvre (capture) and the final phase of removing the target from its current orbit (deorbiting). The definitions of each stage were derived from [26] and read as follows:

Phase 1: Launch

The launch phase of an ADR mission describes the injection of the chaser (spacecraft designated to conduct ADR actions) into orbit by the launcher and ends with the chaser (possibly using its own propulsion system) successfully reaching a slightly lower orbit within the target's orbital plane [26].

This phase is preceded by a number of preparations and mission planning activities, such as launch window determination and mission duration scheduling, and specifies parameters like payload capacities, type of targeted debris and number of targets to be removed, as well as the overall structure, energy requirements, and thermal controls of the chaser explicitly designed for ADR missions [52, 86].

Phase 2: Phasing

Once the chaser is successfully brought into orbit, the phasing stage is initiated to execute a number of manoeuvres to correct launch injection errors and trajectory deviations [89], since especially corrections related to the rotation of the orbit plane require significant amounts of fuel and should be avoided [52]. Additionally, the phase angle between the chaser and the target object is adjusted, using a lower orbit and its shorter orbital period to converge on the target [51].

The goal of this phase is to reach an initial aim point, which depends on several factors like the mission specific docking mechanism that is typically located behind the target at a slightly lower altitude. Another strategy is to achieve a state vector that is within a distinct range of position and velocity values. Up to this point, the system uses absolute navigation, and is required to achieve the desired relative state before the far range rendezvous commences [26].

Phase 3: Far-Range Rendezvous

For far-range observation and approaching of the target, the chaser uses relative navigation to converge on the target with the help of radar or (R)GPS systems. Besides moving into the orbit of the target, the relative velocity between the two vehicles needs to be decreased and the mission time line synchronized [26].

Phase 4: Close-Range Rendezvous

The close-range operations usually begin at a relative distance of a few hundreds of metres [39]. Due to this comparatively small separation between chaser and target, there exists a high risk for collisions, which calls for the minimization of orbit errors. The close-range rendezvous phase can be divided into two steps: closing and final approach. During the closing approach, the relative position is further decreased, carefully choosing a safe approach trajectory of the spacecraft to guarantee collision free operations even when manoeuvre executions fail. At the end of the closing step the required state and attitude for the final approach is achieved.

The observation and measurement requirements for the final approach are highly dependent on the chosen capturing method and respective needs for example information on precise relative velocities and angle rates. The overall goal of the final approach is to achieve the required conditions that are necessary to achieve an actual connection between chaser and target [26].

Phase 5: Capturing
In general, connection formed between the chaser and the target can be distinguished between stiff and flexible connections, or defined as contactless. [75] presents a short overview of existing ideas for different capturing techniques, which include using robotized tentacles and one or multiple robotic arms (stiff connections), net capturing and tether-gripper mechanisms, as well as firing a harpoon onto the target (flexible connections). Contactless concepts describe techniques that use e.g. ion beams [12] or laser systems [68] to alter an object's trajectory without making any physical contact beforehand. During mating operations that require direct physical contact, it is essential to achieve the connection shortly after the initial contact since there exists a high risk of chaser-target separation due to residual motions [26].
The success of the capturing phase is essential and the entire ADR mission rests mainly on the effective completion of this phase. It is, however, most often reliant on accurate data provided by earlier stages or information obtained from the ground such as the objects' attitude, position and velocity, center of mass as well as other physical properties [75]. Moreover, contrary to conventional rendezvous missions with cooperative targets, the debris often does not provide any grappling fixtures, and local attitudes and rotational speeds are often unknown, which makes mating and capturing attempts very complex [13]. Other concerns related to this phase are maintaining a safe distance between the chaser and the target to prevent collisions, minimizing the risk of generating new debris or fragments and how to proceed in case the capturing attempt fails [8].
Nevertheless, once a connection was made successfully without transferring a great deal of (rotational/tumbling) energy onto the target, the next step for the ADR mission can be initiated.

Phase 6: Removal
Several options are available to remove a target from its orbit. The conventional one used during rendezvous missions is to release the target after making a physical connection once the mission has been accomplished e.g. re-supply missions for the ISS [26]. For ADR missions, options separate into two classifications: Deorbiting and transport to a graveyard orbit [3]. Since the latter option simply delays the problem of space debris in well-traversed orbits and may create other issues in the future, the re-entry of debris presents the preferred option. There are several options available for deorbiting, including propulsion systems, atmospheric drag, using electro-dynamic tethers or by contactless systems based on laser and ion beams, most often with the goal to re-enter Earth's atmosphere (for targets located in LEO) [75].

3. CATALOGUE OF BIO-INSPIRED PRINCIPLES

For the purpose of this study, collected concepts presumed suitable for ADR in any way were documented in a comprehensive and informative database that provides rated information on several types of biological and biomimetic systems. This tool was structured to allow the documentation, classification and presentation of concepts and ideas by specifying an organism's biological domain, functioning principle and describing the feature of interest. Likewise, the ADR phase of intended application was added and ideas related to its biomimetic implementation summarised briefly, while also stating its technical domain, biomimetic readiness levels, and relevant references dealing with the organism at hand. Making use of dropdown menus, this tool structure further provided concept clustering and function filtering according to different temporary categories.

As indicated in Figure 1, the initial phase of the project comprised specification of the ADR phases and related requirements as well as the establishment of the extensive catalogue of concepts. After conducting a feasibility analysis, only the 10 most promising ideas will be integrated into different holistic scenarios specifying appropriate and combinable concepts for each ADR phases. Through further trade-off analysis, these scenarios will then be reduced to only one, that proves most promising for ADR and allows for implementation as a simple land based demonstrator within this 18-months project.
Hence, the constructed database is the key element of the entire project and was not only used for documentation purposes but also for evaluation and ranking matters. Thereby it proved useful throughout the entire design process as it delivers information on various parameters and features of respectively chosen concepts.

3.1. Methodology

Two different approaches were used to examine existing biomimetic and investigate new biological concepts for space debris removal that will be described in the following. However, all collected concepts were documented and added to the collective catalogue, enabling further filtering and sorting using so-called 'dropdown menus', providing a great overview of nature's pool of valuable mechanisms and features. In total, 130 ideas and concepts were identified, comprising a diverse range of functions and applications within different elements of the six ADR mission phases.

3.1.1. Reviewing Existing Biomimetic ADR Concepts

Within the scope of this study, 'existing biomimetic concepts' describe biological models that have already been

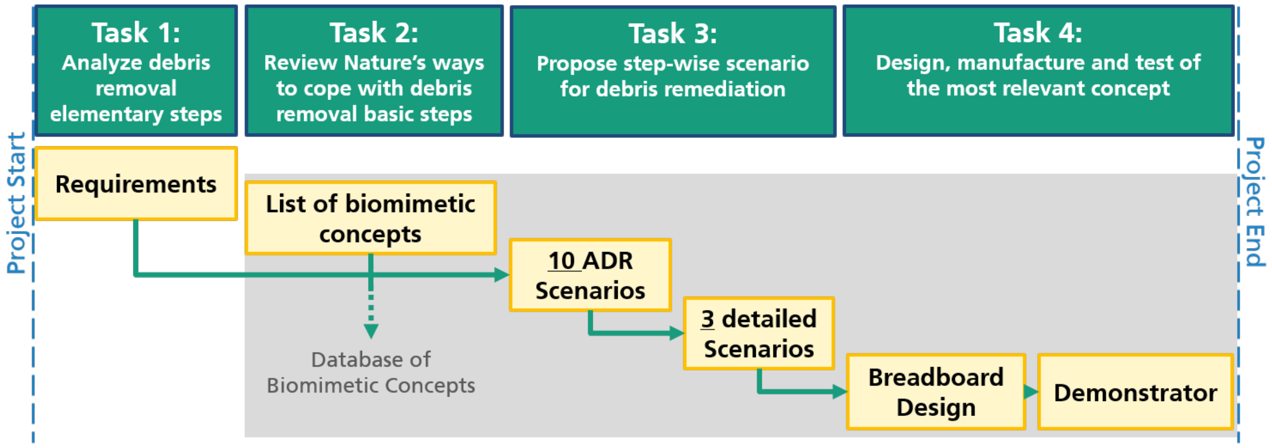

Figure 1. Sketch of the planned tasks and outcomes and their interactions within the project BIOINSPACED.

identified, studied, discussed in any way and/or implemented as prototypes or products. Databases such as sciencedirect, springerlink, google scholar, and scopus have been used to review papers, articles, and studies using keywords like biomimetics, bioinspiration, bionics, biology, space, active debris removal, detection, capturing, deorbiting and robotics among others. Particularly resourceful sources were found to be the 'Journals of Experimental Biology' and the 'Journal of Bioinspiration & Biomimetics'. All identified sources and further referenced scientific bodies of work were examined and, once identified as relevant, added to the catalogue.

3.1.2. Finding New Biomimetic ADR Concepts

'New biomimetic concepts' within this context refer to biological organisms that display interesting features, which may result in promising mechanisms for ADR but have not yet been transferred and/or adapted into a technical solution in any shape or form.

The search for new and innovative concepts was conducted by collecting interesting biological organisms found in literature, documentaries and known during educational or professional training of employees. The context and relation to space or biomimetics was purposefully ignored in order to focus on individual aspects of plant/animal behaviours and features. Promising ideas were first checked against the aforementioned 'traditional' databases to rule out any existing research towards biomimetics, which would classify the idea as an existing biomimetic ADR concept. With this cross-check turning out negative, the idea was investigated in more detail and researched to gain a full understanding of their functioning. Ideas evaluated as suitable for their application to the scope of this project were added to the catalogue of concepts.

Furthermore, experience has shown that bringing together interdisciplinary experts from different professional fields as well as communication and a casual exchange of ideas and theories can be a kick-starter of ground-breaking new technologies. Hence, in addition to collecting ideas through somewhat randomized brainstorming of employees, three creativity workshops were conducted, two with experts in the fields of space, biology and biomimetics and one with undergraduates studying biomimetics at different universities throughout Germany. Due to the restriction imposed by the Covid-19 pandemic, the workshops were conducted virtually, using the '6-3-5' brain-writing method [50] in smaller breakout sessions, which resulted in the generation of a large pool of new ideas. A total number of 34 senior experts (professor, senior scientist and employees), 4 experts (doctorates, research scientists, technical employees) and 12 junior experts (undergraduates students and student assistance) came together for these workshops.

3.2. Resulting Catalogue

The newly developed catalogue consists of 130 collected concepts and ideas, and encompasses information of about 149 journal publications, articles and reports. While 107 concepts were identified as existing biomimetic examples that have been at least discussed in literature for their biomimetic potential, it was possible to identify 23 novel biological concepts. The complete and detailed catalogue of biomimetic concepts is available at Fraunhofer CML, who can be approached for further information.

4. SELECTED CONCEPTS

The enormous collection of existing and new biological concepts with presumed potential for application in ADR were included in a feasibility analysis, producing a ranked list. The resulting 10 most promising concepts presented in chapter 4.1 will be investigated, assessed and pursued further to determine their suitability for a holistic ADR mission scenario and implementation potential into a working demonstrator.

4.1. Ten Most Promising Principles

The best ranking concepts were grouped into overlying functioning principles, which were discussed by project members together with experts of different fields within ESA. Ten of these principles, demonstrating the highest potential for implementation were selected and agreed upon. In the following, those ten principles summarized in Table 1 and displayed in Figure 2 will be briefly introduced.

Table 1. List of the selected ten most promising bio-inspired principles along with their biological models. Note that No. does not reflect a ranking but a clustering: While 1 and 2 are detection principles, 3 to 7 represent solutions for capturing principles and 8 to 10 indicate removal concepts.

No.	Principle	Biological Model
1	Optical Sensing	Compound Eye
2	Tactile Sensing	Vibrissae
3	Adhesive Gripper	Gecko Feet
4	Harpoon	Bee Stinger
5	Containment	Mouth
6	Bi-Stability	Venus Flytrap
7	Shock Absorption	Pomelo Fruit
8	Parachute	Plant Seed Dispersion
9	Origami Sail	Bird Wings / Leaves
10	Swarms	Ants

4.1.1. Principles for Debris Detection

Principle 1: Compound Eye

Compound eyes (see Figure 2-1) are a very common visual system found in many invertebrates including insects and crustaceans. Each eye is typically made of a spherical arrangement of numerous independent photoreceptors called ommatidia. Due to their specific arrangement setup and functioning, they enable a three-dimensional vision, the detection of light from narrow angles and provide a wide field of view, minimal deviation and fast motion tracking. Many dragonfly species in particular have further evolved great depth perception and high detection accuracy's particularly useful as flight responses or for hunting purposes [61, 35, 23]. Based on its many favorable features, the compound eye has caught the attention of researchers and has been analyzed and modelled extensively for application in surveillance systems, medical examination [23], remote sensing [87], and even for space technologies [91].

Contrary to existing biomimetic implementations and models, the idea for compound eye detection within an ADR mission does not only use biomimetic photoreceptor vision systems as ommatidia-mimicking structures. The idea also includes a mixed arrangement of different types of existing detection technologies such as radar, cameras, stereo, lidar, and infrared sensors. Such a system could provide a range of information and observe different focal lengths, wide and narrow angles, orientations, and focus on a range of wavelengths simultaneously, thus, improving the identification and tracking of space debris.

Besides being able to measure different information at the same time, the spatial arrangement of the compound eye also invites a great abundance of same systems to be included, therefore, providing a much needed redundancy and correlated reliability and fail-safe [66].

Principle 2: Tactile Sensing

Tactile sensing using vibrissae or whiskers can be found in many mammals and insects, which demonstrate a range of evolutionary convergences and divergences, permitting tactile sensing in different media such as air and water. Vibrissae are thin and long hairs attached to sensitive hair follicles underneath an organism's skin that are affected by change of air or water currents. Such external forces cause the hairs to bend, creating a deflection stimulus, which can be registered by the animal. The whisker systems of rats (see Figure 2-2) have evolved particularly well, enabling them to adjust and control the orientation of their vibrissae to better explore their environment. Depending on the vibrissae direction and alignment, animals can use them for orientation and even sense the presence of other animals [65, 69, 70, 88]. Seals, for example, have evolved a complex tacto-vibrissal sensing system in order to detect hydrodynamic trails of fish while hunting for prey [37, 54, 84].

Implementing tactile sensing with artificial vibrissae into a technical system has already been studied extensively and even realized in the field of robotics [65, 70]. It has also been proposed for the application in space for servicing and repair operations on satellites [44]. Vibrissae are especially attractive for such operations due to their ability to circumvent common issues associated with optical detection of objects such as the relative navigation towards uncooperative targets, dynamic illumination conditions or the challenges of solar glare [86]. Additionally, tactile sensing can provide high force, temporal and spatial resolution; the latter is particularly important for manipulation and maneuvering tasks executed in space to avoid collisions of two objects. Hence, this idea holds high potential for the removal of space debris as it offers the opportunity to explore and manipulate an object from a safe distance. Paired with haptic sensors dragged along the surface of the target, it could even allow for the recognition of detailed surface structures and search for distinctive tactile patterns to determine an ideal spot to create a permanent connection between the chaser and the target. Artificial vibrissae would allow the exploration of objects and their structures merely by groping rather than based on optical systems and identify important parameters such as rotation velocities and angles, while the chaser does not have to get too close to the target itself [38].

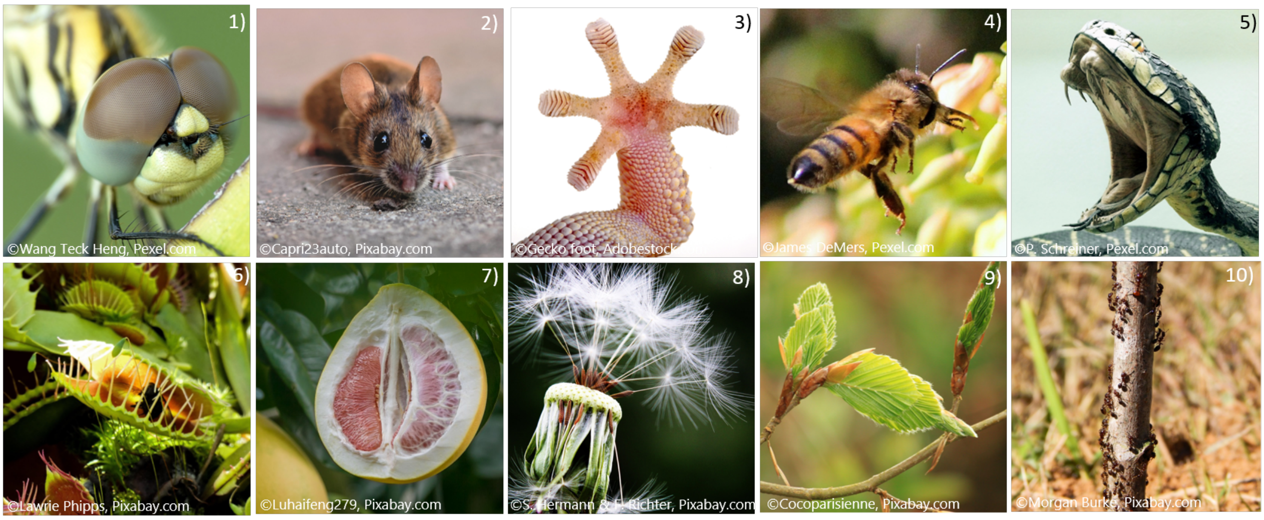

Figure 2. Photographs of the biological models that were selected for the biomimetic principles, 1) dragonfly compound eye, 2) mouse tactile hairs, 3) gecko foot, 4) bee stinger, 5) snake mouth, 6) venus flytrap, 7) pomelo fruit, 8) plant seed parachutes, 9) folded plant leaves, 10) swarming ants

4.1.2. Principles for Debris Capturing

Principle 3: Gecko Feet Gripper

A vast variety of adhesives can be found in nature that allow the attachment to a diverse collection of surfaces under different environmental conditions throughout many ecosystems. The probably most well-known biomimetic adhesive technique are gecko feet (see Figure 2-3) and their adhesive properties used for locomotion. Of course, many different species of geckos exist, displaying a range of morphological differences [10]. Hence, the mechanism most often studied describes gecko feet that are able to conform to rough surface and produce sufficient adhesion to enable climbing up even smooth vertical surfaces [42]. This is possible due to the hierarchical compliance of micro-scale hairs (called setae) on the bottom of their feet that make use of van der Waals and capillary forces. Even more attractive is the reversible attachment that can be easily detached on command [10].

The great potential of this concept is, widely recognized and has resulted in a number of commercially available products [18, 33]. Furthermore, it is not new to the space context either and has been considered for e.g. the repair, maintenance and servicing of orbiting spacecrafts [2], and more recently, has been proposed for debris removal [5, 41, 16, 15, 79]. While details such as maximum adhesion forces, performance on curved surfaces, and impact of space dust on existing adhesive materials require further testing [80, 81], it presents a valuable concept for debris removal. The idea is to integrate the gecko material into a gripper connected to the end of a robotic arm. This offers the opportunity to form a temporary connection to the debris before initiating a final attachment concept for a more secure and long-term connection. While the gecko adhesion may not be suitable to maneuver large and heavy objects, it grants the possibility of stabilizing the connection and maintain a safe distance between chaser and target, without greatly altering the targets trajectory or cause the chaser to drift away due to forces applied during the capturing with more conventional capturing methods.

Principle 4: Bee Stinger Harpoon

In biology, many inspirations can be found that make use of a piercing and interlocking strategy, often used for hunting prey or as defense mechanisms. Honey bees (see Figure 2-4) , for example, only use their stinger as a last resort in immediate danger, since it causes their poison bladder connected to the stinger to be ripped out, which kills the bee. They do so to protect their hives and queen, and, to guarantee the delivery of the poison into the skin of the attacking organism. Their stinger demonstrates a serrated surface on its outer edge that, on the one hand, enables a smooth, effortless and quick piercing of the target's skin, while on the other, is able to hook into the skin and therefore provide a secure attachment [83].

A conventional harpoon presents one of few mechanisms already tested during an in-orbit ADR mission simulation conducted by the Surrey Space Centre, the Airbus group and other companies [29], demonstrating its high potential for the successful capture of debris. However, conventional harpoons are usually released with substantial power and resulting in high impact forces that have been shown to create fragments and spalling [25], which only adds to the problem of space debris and the associated Kessler syndrome. Contrarily, bees evolved and present piercing structures that still require careful application but only minimal energy and few precise movements, therefore, significantly reducing of the risk of secondary debris production. The sharp stinger of bees has already been of particular interest within medical engineering and proposed as inspiration for painless transdermal drug delivery or bio-signal recording [90, 22, 49]. Hence, replacing a system such as the tested harpoon with one that encompasses a bee stinger inspired tip may result in an even better capturing performance, while requiring less force and related energy application, therefore lowering the risk of the ADR mission.

Principle 5: Mouth Containment

A major obstacle of ADR is the targeting of uncooperative targets, whose behavior and actions are widely unknown or determined via sensors with limited resolutions and accuracy's. Thus, concepts that do not require this kind of information to capture debris are very attractive. Nature presents a variety of animals that portray flexible mouth openings with adjustable jaw ranges and flexible skin to swallow their prey as a whole (e.g. snakes (see Figure 2-5) [19], pelicans [85], baleen whales [34], *Melibe leonia* snails [47], Goblin sharks [56]).

Using this type of mouth as inspiration for ADR options would allow the containment of a target without requiring a preceding physical contact, which is associated with all kinds of challenges (e.g. determining an appropriate docking point, maintaining a safe distance and performance while converging on the target) [13]. Allowing a larger capturing structure to approach a target and close around it (with some distance between the target and the structure's walls) could allow its capture, while eliminating the risk of additional debris generation caused by faulty contact and manipulation operations. Once the structure is closed, the structure's walls' diameter can continuously and slowly be reduced, until the target is wrapped tightly within, allowing for further removal actions to commence. This concept can be applied to a wide range of debris types and remains unaffected by potential tumbling or rotating actions of the object.

While a similar, non-biomimetic approach was proposed by artists under the NASA initiative to design missions to capture near-Earth asteroids [57], no actual plans to implement such a system exist. Yet, it presents promising potential to be used for the capture of not only asteroids but also space debris.

Principle 6: Venus Flytrap

Similarly to the containment concept of the mouth, the Venus flytrap (see Figure 2-6) presents an interesting way of capturing its prey as a whole. These plants have developed a specialized trapping mechanism based on a bi-stable system that is triggered when prey touches the embedded mechanosensory hairs on the inner surface of their trapping structures. It consists of two curved lobes presenting the inside surfaces with the mechanoreceptors. To close its trap, the Venus flytrap requires multiple mechanical stimuli, usually caused by prey settling on the lobes due to the flytraps's vibrant color, excreted nectar or released prey-appealing volatiles. Only when multiple of the sensory hairs are deflected, an action potential travelling across the entire surface of the lobes is triggered, causing the outer surface of each lobe to extend and thus, alter the curvature of the lobes to point towards each other. This creates the snapping motion and traps the prey between both lobes [74, 46, 30].

This bi-stable mechanism has already been adapted and transferred onto robotic Venus flytraps [74] and therefore presents a promising principle for ADR. An artificial flytrap with open lobes can approach a target until it makes contact with the center of the trap. Integrating artificial mechanosensory hairs can cause the creation of an indirect mechanical trigger to automatically close the lobes around the debris. Independent of size (within a certain range) and shape of the target, the artificial flytrap can contain debris without establishing a physical connection beforehand. An additional benefit is the passive state of the bi-stable trapping mechanism, reducing the system's energy demands. Power can be diverted to the precise navigation and controls required for such a system. Simultaneously, the artificial hairs only trigger the closure of the trap after receiving multiple stimulus, avoiding inadvertent triggering of the mechanism by dust, particles or small debris fragments.

Principle 7: Shock Absorption

The pomelo fruit (see Figure 2-7) grows on trees of up to 15 meters height and has a net weight of about 6 kilograms, resulting in an enormous kinetic energy during impact when the ripened fruit falls from tree top to the ground. Thus, to protect the flesh and seeds inside, the pomelo evolved to produce a protective outer layer as its peel, which is capable of dissipating almost all of the kinetic energy upon impact and significantly dampen its fall [27]. The peel demonstrates an open cell foam structure of varying pore sizes distributed over its 2-3 cm thick peel, responsible for its excellent impact damping and energy dissipating capabilities [62]. More recently, many beneficial features of the pomelo's peel have been recognized by the scientists and several studies have been published assessing further utilization options of the peel as a byproduct for the chemical industry [78], and modelling the foam-like structure to further investigate its cushioning properties [14, 62, 48].

Naturally, the field of aerospace engineering can profit from the impact absorption capabilities of the pomelo fruit in more than one way. As an example, the concept can be adapted and implemented as protective foam to dampen the forces experienced by any technical device and equipment during launch of the carrier rocket. Furthermore, it offers the opportunity to decrease the impact between two objects during the capturing phase. Since the pomelo's peel can absorb and dissipate about 90% of the fruit's initial potential energy, transferring this feature would allow for the absorption of most of the docking forces, reducing the backlash experienced by the chaser, while simultaneously lowering the risk of creating new debris.

Pairing this concept with the self-sealing powers exhibited by plants can further improve its applicability and feasibility for space systems. As previously mentioned, redundancy and reliability are crucial for any extra-terrestrial mission to increase the odds of its success [67]. Hence, integrating an automatic repair mechanism can provide just that. Biological organisms, animals and plants alike, have developed a broad range of self-repair mechanisms that allows them to recover from injuries and wounds, while retaining the injured body part's function (as long as the damage is not too severe). Vascular plants in particular are great at self-sealing by excreting a substance at injured areas, thus producing a protective layer over the fissure and preventing further damage or contamination [76].

Transferring this biological mechanism into a pomelo foam in the form of small pockets filled with a glue-like substance similar to the cells of a latex-bearing plant, integrated into the foam-materials offers the opportunity to immediately seal occurring fissures and cracks, and therefore maintain its structural function. When damage occurs, it would rip open the foam and integrated glue pockets simultaneously, releasing the sealant. This is, of course, only one idea where the self-sealing capabilities found in nature can be beneficial for space systems.

4.1.3. Principles for Debris Deorbiting

Principle 8: Plant Parachute

The seeds of plants such as the *Tragopogon dubius* display a very peculiar way of descending from the plant top upon release. These types of plants depend on wind to disperse their seed, thereby propagating the species over large areas. Therefore, seeds have developed stalked parachutes (see Figure 2-8) made from plumed and hierarchically arranged fibers that are assumed to be the largest in nature. These structures enhance their aerodynamic drag, hence, increasing the distance travelled during their descent [63, 17].

In an ADR context, this biological concept offers a great solution for the capturing and removal phase at the same time. While the parachute itself can be used to increase an object's natural atmospheric drag, thus accelerating its orbital decay and following re-entry on Earth's atmosphere [75], adapting it and converting the stiff fibers into controllable robotic arms that are connected with fabric in between can provide the opportunity to steer towards a target and capture it by wrapping the robotic arms around it. Once captured, the object can be transferred into a chaser attachment, allowing the robotic arms to open up again and fulfil their purpose of deorbiting the debris. While the biomimetic potential of this concept has been recognized mainly due to its lightweight and robust properties, its adaptation and implementation are still lacking.

Principle 9: Origami Sail

Another common deorbiting method using atmospheric drag is the attachment of drags sails onto targets that can autonomously unfold, increasing the surface-to-mass ratio of the object and therefore decrease its orbiting time frame due to the amplified drag experienced by the object [11, 1, 82]. Additionally, it is frequently discussed as novel end-of-life management for future missions [20, 71]. However, ideal shapes, sizes and expansion mechanisms are still being discussed.

Highly efficient folding and unfolding techniques can be observed in nature, such as the wings of birds or plant leaves(see Figure 2-9) emerging from their sheath, providing evolutionarily optimized and resourceful folding [64, 28]. Due to the shape and movability of their wings, birds have mastered the art of maneuvering even in complex environments, enabling them to fly through the smallest openings even at high speeds. Once landed, a bird tucks away its wings and efficiently stores them on its back to sit or walk around [77]. Plants such as the *Mimosa Pudica* are capable of nastic movements and have developed their folding technique as part of their threat response. They are able to rapidly fold up their leaflets upon touch, thereby significantly decreasing the size of their surface [64].

Hence, biomimetic folding techniques can improve folding efficiencies and storage during the chasers' launch, but also provide effective concepts for the autonomous unfolding and expanding of the drag sail. This concept can further be applied to other space systems that can profit from efficient area reduction/increase such as solar arrays [58, 40].

Principle 10: Swarms

Large groups comprising many individuals of one species that behave almost as one organism are often referred to as swarms and can be found in a variety of animals such as ants (see Figure 2-10). This behavior has evolved to provide protection from predators, increase dwelling building and foraging efficiencies or navigation for migratory purposes. The main features of interest related to swarms are their intelligence, and ways to communicate and execute a common goal without giving every individual specific instruction on what to do [32].

This potential to collaborate with other individuals is particularly of interest in the field of robotics, and was already researched thoroughly, resulting in a range of existing robotic swarms capable of autonomously achieving tasks [36, 24]. These miniaturized robots are able to arrange in specific patterns, collectively navigate and make decisions all in the pursuit to achieve their shared goal. Hence, application is diverse and ranges from the military industry, emergency rescue, agriculture, environmental monitoring, and has even been considered for deployment in space [72].

Transferring the idea of multiple units moving and acting in unison onto a propelled deorbiting scheme shows potential, particularly for larger debris. While the chaser approaches its target at a safe distance and merely releases multiple individual propulsion units, those units converge onto the target and make the actual physical contact. Hence, the chaser can remain in its orbit while the smaller units propel the target to burn up upon reentry on earth's atmosphere. Since the system provides redundancy as multiple units are released targeting the same object, it increases success rates of any mission and can account for potential errors or malfunctions. Furthermore, it can be applied to multiple targets and a diverse range of target sizes, as the number of released propulsion units can be adjusted to individual needs.

5. CONCLUSION AND OUTLOOK

The literature review conducted within the BIOINSPACED project demonstrates the high potential for bio-inspired technical solutions that can be sourced from nature's pool of mechanisms and features. A profound catalogue of 130 bio-inspired solutions with

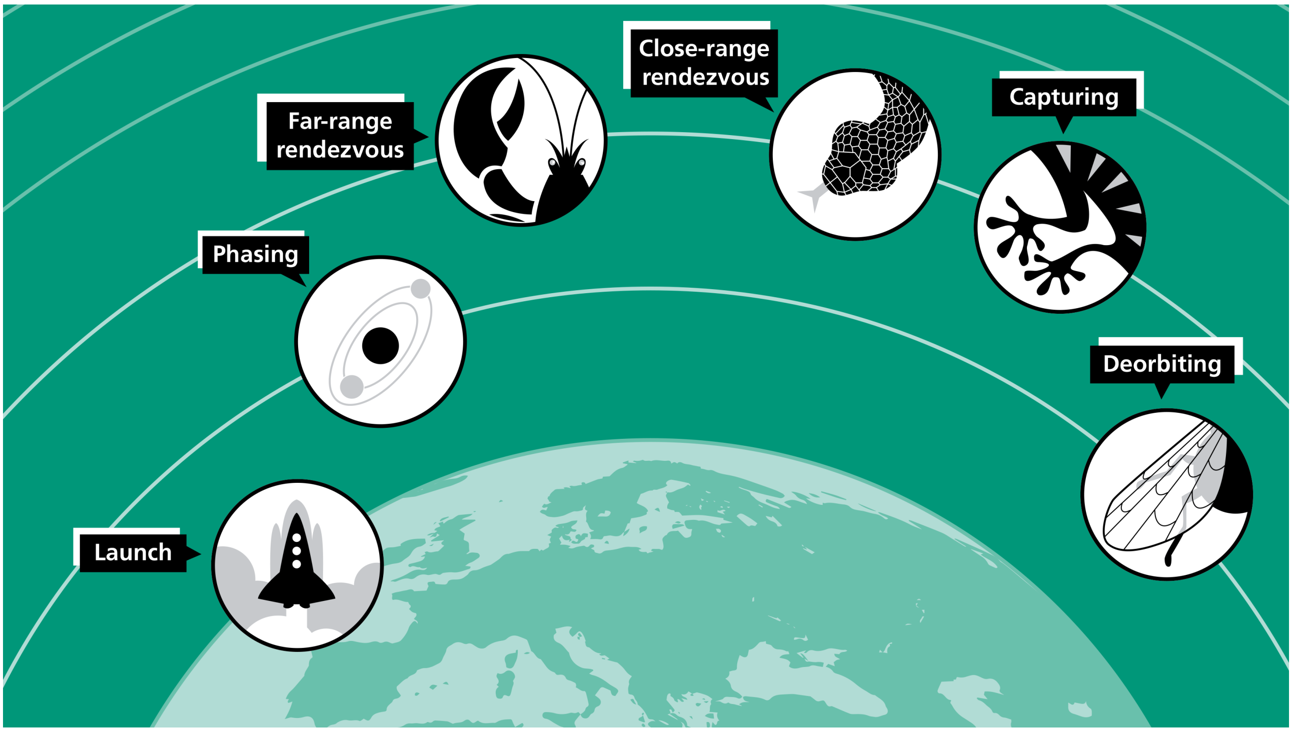

Figure 3. Example drawing of one possible bio-inspired ADR scenario. The first two phases of launch and phasing make use of conventional technologies. The following ADR phases include an x-ray telescope with lobster eye optics for far-range rendezvous, infrared sensors modelled after the snake's pit organs for close-range rendezvous, a capturing mechanism with incorporated gecko feet adhesion and a drag sail folding and expanding on the example of insect wings for the removal phase.

relevance for future ADR missions was established. Thereof, ten most promising concepts were identified and elaborated into possible principles. Those principles will further be investigated and integrated into holistic ADR mission scenarios as depicted in Fig. 3, which shows one example of a biomimetic ADR scenario. The final projects aim is to build a working demonstrator of one of the scenarios (or at least of one the underlying biomimetic concepts) to present and validate the value of biologically inspired technical solutions for the space sector.

While the presented catalogue was constructed within the scope of the BIOINSPACED project and its predefined requirements, it can also be implemented and utilized in the future for finding biomimetic solutions that prove beneficial other space contexts (not only ADR). Seeing the BIOINSPACED methodology as an interactive and customizable tool for accessing and utilizing available information according to user needs, while summarizing biology's potential for its application in space engineering, it provides a suitable step towards integrating biomimetics into space technologies.

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