CEAS Space Journal
https://doi.org/10.1007/s12567-022-00438-z

ORIGINAL PAPER

Biomimetic space debris removal: conceptual design of bio-inspired active debris removal scenarios

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Received: 5 July 2021 / Revised: 31 January 2022 / Accepted: 28 February 2022

Abstract

The ever-increasing number of man-made space debris creates the need for new technologies to mitigate it. Therefore, within the ESA-funded project BIOINSPACED, biologically inspired solutions for active debris removal were investigated, conceptualized and integrated to innovative and comprehensive scenarios. In the following, the collection process of existing and new biomimetic concepts as well as the evaluation of ten concepts based on a feasibility analysis will be presented. Out of the ten, the three most promising scenarios, were chosen for further investigation and further elaborated in detail specifying the biological models incorporated as well as how the scenario could be implemented in a simple demonstrator. The first scenario (A) is a gecko kit canon and describes a system that fires deorbiting kits towards the target from a safe distance. The second scenario (B) involves a robotic arm with a gecko-adhesive end-effector and a bee-inspired harpoon to achieve a preliminary and subsequent rigid connection to the target. The last scenario (C) is mimicking a Venus Flytrap and its bi-stale mechanism to capture its prey. One of these scenarios will be manufactured and built into a demonstrator to showcase biology's potential for the development, optimization and improvement of technologies, especially within the space industry.

Keywords Biomimetics · Bioinspired space solutions · Active space debris removal · Space debris remediation

1 Introduction

The increasing utilization of the extraterrestrial environment is associated with a rising number of satellites, spacecrafts and devices occupying the orbits around Earth [1, 2]. In 2020, only about 10% of the approximately 28000 trackable objects in space were active satellites. Thus, the majority of these objects is space debris, which are man-made objects without functional use, such as retired payloads, spent upper stage rocket bodies, and fragments from collisions and explosions. However, the growing population of debris objects orbiting Earth poses a serious risk to current and future missions. Collision processes can cause a chain reaction and render entire orbital regions unusable. The highest risk is associated with large inactive objects, which contribute 99% to the environmental index, a metric used by ESA to measure the risk of an object within the space environment [3]. It has, therefore, become apparent that reliable and affordable systems for non-functional object removal or servicing is essential to guarantee safe and sustainable access to orbits around Earth. This evolution has led to the formation of a novel research field investigating active space debris removal (ADR) with an increasing number of activities. However, many of the existing ADR concepts still remain in the developmental stage, require proof-of-concept efforts or real scenario field testing.

Biomimetics and its application to find innovative technical solutions has proven beneficial throughout many

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industries and bio-inspired products, such as lotus paint (Lotusan), Gecko-tape, sharkskin inspired swimsuits, and Velcro [4–8] have been successfully established on the market. Thus, its potential is more and more recognized and increasingly considered for product design, development and optimization. For some time now, biological organisms have also served as an inspiration for technical development in aerospace engineering and space exploration. For example, the wood wasp drilling into the bark of trees with its ovipositor has been used as a model for surgical instruments on Earth, but has also been considered as a solution for extraterrestrial drilling and sampling for decades [9–11]. An X-ray telescope with lobster eye optics presents another, more recently developed biomimetic technology to discover remote objects in space outside Earth's atmosphere and was used on the Czech nanosatellite launched in 2017 [12]. Some of the recently established 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 [13–15].

Therefore, looking at biology, its great diversity of mechanisms and its evolved features often reveals transferable concepts and may provide valuable contributions to ADR. Nature presents an abundance of features that have evolved to fit certain environmental requirements or cope with external pressures. Thus, multiple approaches exist to fulfil similar tasks and activities, which present many qualities also essential for space systems, such as response-stimuli adaptability, robustness and lightweight construction, autonomy and intelligence, energy efficiency, and self-repair or healing capabilities [16, 17]. Hence, biological mechanisms can be transferred and adapted to improve or even revolutionize traditional engineering approaches.

2 The BIOINSPACED project

BIOINSPACED is an acronym that stands for bioinspired solutions for space debris removal. The project was funded by the European Space Agency (ESA) and is conducted by Fraunhofer CML with Technical University of Braunschweig (TUBS) as a subcontractor. It commenced in June 2020 with the goal to contribute to ESA's CleanSpace initiative by developing biomimetic solutions for innovative technologies to support the removal of space debris, especially in low earth orbit (LEO).

During the project's initial phase, the elementary steps for ADR were analyzed, identifying the phases included in such a mission as well as related requirements. Afterwards, nature's pool of existing concepts and possibly new biological mechanisms were reviewed with the prospects of finding ones with potential for ADR. All of these concepts were collected within the BIOINSPACED catalogue, a comprehensive and interactive database, and evaluated using a feasibility analysis (see Sect. 3). 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, in preparation of choosing one to be build into a demonstrator and undergo preliminary experiments. BIOINSPACED aims to not only present the diversity of biological examples that hold potential for implementation within ADR missions, but to demonstrate the bio-inspired concepts within ESA and showcase the potential of biomimetics for the space industry in general.

3 BIOINSPACED catalogue and feasibility analysis

To collect existing biomimetic and new biological concepts suitable for processes involved in ADR, three different approaches were applied: First, a thorough literature review was conducted, studying existing biomimetic models, prototypes and products within the fields of robotics, materials science, kinematics, and space technology among others. Then, nature's pool of ideas was screened by browsing biological research papers, nature documentaries and flipping through other materials to propose new solutions, which include those demonstrating great challenges for "traditional engineering". Finally, three biomimetic brainstorming workshops were held with participants from the fields of space industry, biology and biomimetics, resulting in a great amount of new biological principles and mechanisms as well as intensive discussions of their suitability for space application. More information on the collection process and the three approaches can be found in Banken et al. [18].

All of the collected concepts were added to the BIOINSPACED catalogue, a comprehensive and informative database with rated information on several types of biological and biomimetic systems. It also provides an interactive and customizable tool for accessing and utilizing available information according to user needs and summarizes biology's potential for its application in space engineering. While the presented catalogue was constructed within the scope of the BIOINSPACED project and its predefined requirements, it can also be utilized in the future for finding biomimetic solutions that prove beneficial in different space contexts. The complete and detailed catalogue of biomimetic concepts is presented in the Supplementary Material. Fraunhofer CML can be approached for further information.

Based on the established BIOINSPACED catalogue, a feasibility analysis was conducted to evaluate the importance and relevance of collected concepts. This analysis was based on the four parameters that were calculated into an overall score called 'BIOINSPACED Applicability Score' (BAS). :

- Technical feasibility (TF): presents a basic indicator for a concept's functionality and evaluates the overall idea concerning the possibility of its implementation into a technical system, especially with regard to the final goal of building a demonstrator and associated design as well as manufacturing constraints.
- Biomimetic applicability (BA): analyses a biological model and indicates its potential to be adapted and transferred into a technical system
- Space applicability (SA): assesses the possibility of the model's implementation and employment within the space environment. This, too, includes considerations of the predicted concept reliability.
- Novelty factor (NF): examines the originality of concepts and investigates currently available ideas in literature. This factor is heavily influenced by the amount and type of literature published, discussing either a concept's aerospace application, any kind of industry application, its mere biological functioning or none whatsoever.

The parameters were evaluated by six scientists from Fraunhofer CML and two from TUBS individually by assigning a score from 1 to 6 (1 indicated the best ranking and assumed performance) to each parameter for every concept. These ratings were summarized, averaged for the individual parameters and then multiplied by the weighting factor as indicated in Eq. 1.

While TF and BA were assigned the highest weighting factors as they determine whether a technology can be established based on the pre-defined biological model at all, the project was aiming for technical solutions within the space industry. Thus, the SA factor was assigned an only slightly lower weighting factor. Finally, another project requirement was the development of a demonstrator showcasing new and innovative biomimetic concepts, therefore, making the novelty an important requirement within the scope of the project, yet less important than the overall development and implementation potential. It is important to stress that the results are dependent on the chosen weighting factors. Several evaluators from Fraunhofer CML and TUBS with extensive backgrounds in the different fields of biomimetics, aerospace and mechanical engineering were included and participated in discussions about the weighting factors, and provided input based on their respective expertise. Nevertheless, the assessment of the individual factors is ultimately based on subjective ratings, thus, a different group of evaluators may draw different conclusions. Within the scope of this project and in consultation with the ESA project officer, the selected weighting factors were considered sufficient to rate the biological concepts.

Summing up those four parameter scores resulted in the overall BAS for each concept. Those ranked concepts were then grouped into overlying working principles to provide a better overview of available mechanisms that may aid the process of an ADR mission. The best performing 24 grouped principles were then presented and discussed by project partners and ESA employees, collaboratively deciding on 10 principles to be further investigated and integrated into holistic scenarios. The selected principles and a short description of their functioning are summarized in Banken et al. [18]:

$$BAS = TF \times 0.3 + BA \times 0.3 + SA \times 0.25 + NF \times 0.15 \quad (1)$$

Equation 1: Formula to calculate the overall score for 'BIOINSPACED applicability score' (BAS) including all four parameters evaluated by CML and TUBS and the respective weighting factor. TF: technical feasibility, BA: biomimetic applicability, SA: space applicability, NF: novelty factor.

4 ADR environment and mission requirements

4.1 The adapted ADR ecosystem

The conventional phases associated with rendezvous missions are detailed by Fehse [19], covering the launch, phasing, far- and close range rendezvous with the target, capture and finally the removal. Aiming to integrate the established principle solutions into holistic ADR scenarios demanded for an adaptation of these steps. Since launch, phasing and far-range rendezvous remain very similar to common rendezvous missions (with cooperative targets, such as the ISS), they were excluded from the ADR ecosystem of this study to focus available resources on finding solutions for the other phases. In addition, sufficient information during the execution of the first three ADR phases can be obtained from ground-based systems, such as radar and passive optical telescopes, providing a great amount of data on debris detection, tracking and identification [20]. In addition, the abundance of biological models for the remaining phases was assumed to be much greater, which was supported by the quality and quantity of concepts collected within the catalogue.

The ADR ecosystem was, however, extended by other steps in case the established scenarios demanded additional actions to guarantee a successful removal mission as suggested by for example Maediger and colleagues [21], and possibly included an inspection flyby, detumbling actions or a pre-attachment as per requirement. During the inspection flyby phase, the chaser uses its on-board detection and sensing systems continuously pointing at the target while traveling around it at a constant distance on the expense of spending additional fuel. This allows the procurement of an adequate amount of information especially related to the integrity of the target and its rotational motion [21]. Detumbling actions can be applied before or after the capture or physical contact between the chaser and the target, ranging from plume impingement [22] or magnetic torque generation [23, 24], to the use of a kinematically redundant robotic arm [25, 26] or a brush-type contractor [27]. Those actions are necessary if the rotational velocities of the target exceed servicing capabilities and, therefore, prohibit a safe approach for the attachment and capture [28].

In terms of permanent connections formed between the chaser and the target, nets and harpoons are prominent capture concepts, and among the only ones demonstrated on-orbit during the 'RemoveDebris' mission in 2019 [29–31]. While this mission displays a huge leap in space debris removal and tests showed promising results, harpoons are still associated with high risks of additional debris production due to the forces required to penetrate the target's surface material while preventing a large impulse generation and thus pushing the target from its current course. Furthermore, complex rope dynamics between chaser and target have not been investigated in this mission and present a technical challenge. Therefore, the last additional phase included within the ADR ecosystem is a preliminary attachment that enables a safe but less rigid connection with the target first that does not generate high impulse forces, prohibits the target's escape, and facilitates a subsequent rigid connection using more complex and high-energy approaches.

The adapted ADR ecosystem defined within the scope of the BIOINSPACED project as indicated in Fig. 1 is used to specify and visualize the complete process of space debris removal, where a holistic point of view on the composition of the overall mission is delivered.

4.2 From concepts to mission scenarios

Over the course of this project, concepts and their application within biomimetic ADR were adapted and re-defined as the project progressed. Therefore, Fig. 2 presents the conversion from individual concepts over principles into scenarios and the final demonstrator. As described in Sect. 3, the 130 individual existing and new biomimetic concepts were collected using literature review, brainstorming activities and several biomimetics workshops. These concepts, each covering a single feature of one or several species of an organisms (demonstrating similar features) were grouped into overlying principles to simplify their evaluation and selection. These principles described the same function, for example 'adhesion', 'penetration' or 'folding' without using the same process, feature or mechanism. Out of these principles, ten were selected during the 'Design Space Review' meeting to be integrated into ten holistic scenarios, offering solutions for the ADR phases defined in subsection 4.1. In the following subsection 4.3 and 4.4, the process of integration,

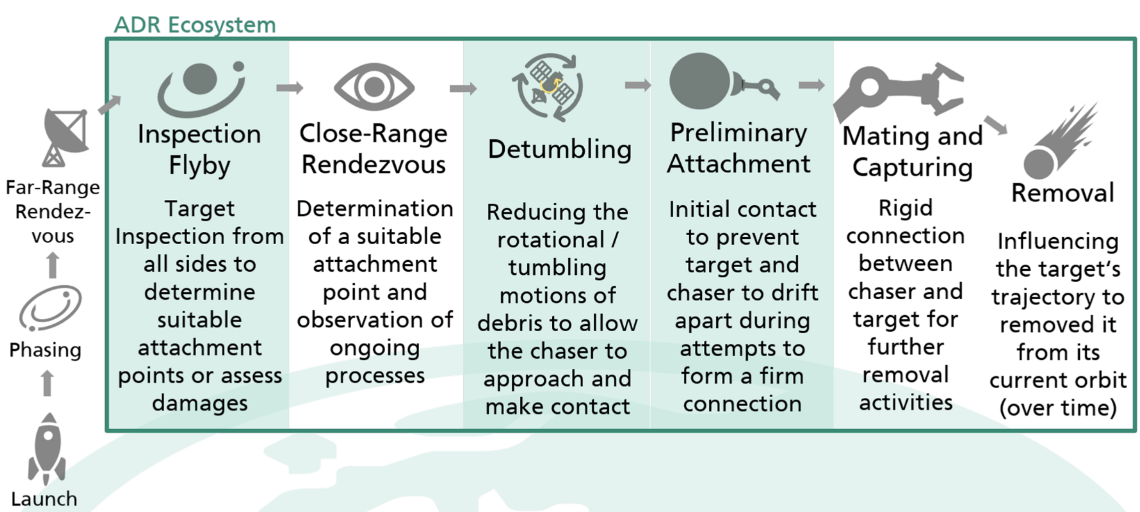


Fig. 1 Representation of the adapted ADR Ecosystem. The phases outside the green rectangle as well as the ones highlighted in white inside the rectangle present the conventional ADR phases identified by the BIOINSPACED project. These phases were later adapted to include the ones specifically tailored to biomimetic ADR scenarios (highlighted in light green) and excludes the ones not exclusively applicable to ADR. Thus, within the scope of the project, only the phases inside the green frame represent the ecosystem for bio-inspired ADR scenarios

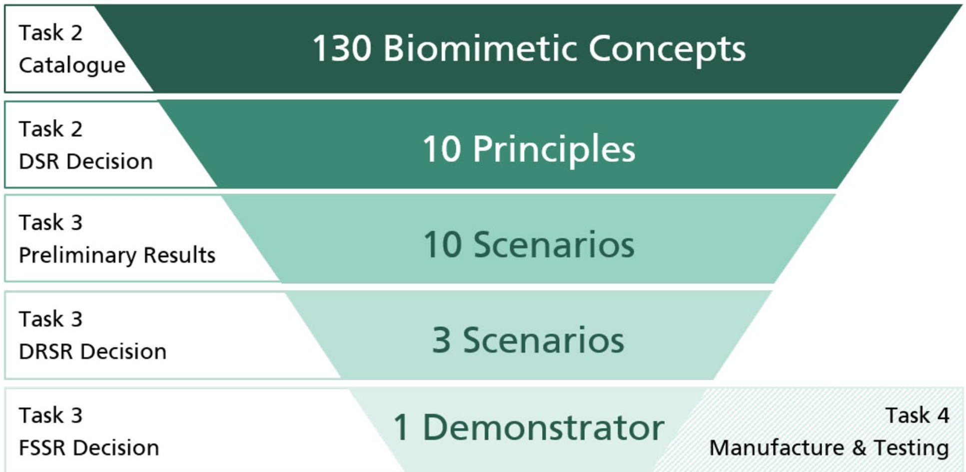


Fig. 2 Transformation flow of collected concepts over principles to scenarios. It demonstrates the selection process over the course of the project and the conversion of collected concepts in the beginning into overlying working principles. These principles were then combined and integrated to form ten scenarios out of which three were chosen for further investigation. In the final task of this project, one of these scenarios will be built into a demonstrator. The individual task decisions refer to the milestone meetings: *DSR* design space review, *DRSR* debris removal selection review, *FSSR* final scenario selection review

development and assessment of the ten scenarios will be described in great detail. Finally, the three scenarios selected for further detailed investigation in regard to the final demonstrator were decided upon during the 'Debris Removal Selection Review' meeting. These scenarios will be presented in Sect. 5.

During the 'Final Scenario Selection Review' meeting, one of these three scenarios will be chosen for further development and ultimately be transferred into a preliminary functioning demonstrator. This demonstrator will display the incorporated biomimetic concepts and indicate how they can be transferred into basic but working technical solutions. This demonstrator can then be used by ESA to show the beneficial role biomimetics can play in the development of aerospace technologies and will be presented at the upcoming International Conference on Advanced Manufacturing (ICAM22), displaying the manufacturing and integration of the most promising concepts.

4.3 Building biomimetic ADR scenarios

With the help of individual Zwicky boxes for each principle, which are a favoured tool for structuring and investigating complex problems with multiple solution approaches and are, thus, often used as means for analysis in biomimetics [32, 33], all possible solutions for the implementation of each principle were established. Afterwards, the three most promising principle solutions were determined and used for their integration and combination with the solutions of the remaining principles into ten holistic ADR scenarios. This resulted in the inclusion of not only chosen principle mechanisms but also concepts from the BIOINSPACED catalogue that demonstrated beneficial improvements over conventional mission technologies. Therefore, the number of concepts contained within one scenario reached up to the maximum of 13 different ones.

Subsequently, the ten scenarios were evaluated using a trade-off analysis to evaluate the feasibility of each regarding their implementation potential into a demonstrator under consideration of the following mission critical parameters:

- Technical feasibility: in this analysis referred to as '*T*' to demonstrate the difference to the prior technical feasibility factor used before in Sect. 3: potential of implementing a scenario into a technical system (no. of moving parts, time critical activities)
- Technical complexity (*Tc*): intricacy of the system (component interactions, motion control requirements)
- Engineering effort (*E*): technological readiness level (Use of existing materials/ devices, environment appropriate)
- Energy requirements (*Er*): requirements for motion and course control required (movability of system components, force requirements)
- Reusability (*R*): possibility of multiple attempts/ targets (loss of functionality, reversibility, deformation)
- Risk of additional debris (*Dp*): production of secondary debris (target damage, application of high speeds, style of attachment)
- Adaptability (*A*): Attachment surface requirements (surface material/ shape/ structure, geometries)

– Breadboard manufacturability (*Bm*): possibility to build a demonstrator using the equipment and devices available at Fraunhofer CML (financial/ time resources, land-based demonstrator)

Since not all of these parameters are considered to have equal effects on the implementation potential of a scenario, weighting factors were established. Using the commonly known practise of a paired comparison, each individual parameter was compared to only one other parameter at a time, reducing the evaluation to the decision whether the first parameter has more (2), equal (1) or less (0) influence compared to the second one. As an example, it is possible to determine that the overall technical feasibility, and therefore, the probability of technology implementation has a higher influence on the success of a scenario than the reusability of the mechanism, since the latter is dependent on the first one. Thus, when the technical feasibility is compared to reusability, it is assigned the number ’2’, indicating a higher influence as depicted in Fig. 3. In turn, when reusability is considered as the first parameter, it is assigned a ‘0’ when opposite to technical feasibility as it has less influence on the implementation potential. This process was repeated with all parameters, resulting into a comparison matrix that was then used to determine the overall weight of individual parameters. This paired comparison technique is said to produce highly reliable rankings [34] and was conducted by several aerospace and biomimetics experts with backgrounds in mechanical engineering to determine sensible weighting factors.

Afterwards, the parameters were evaluated with respect to each scenario by assigning them a rank between one and ten (10 = best possible score). Those values were then multiplied by the respective weighting factor for the respective parameter established in the paired comparison and summed up as shown in Eq. 2, resulting in the final trade-off score (TOS). This score was then used during discussions with ESA representatives to put each scenario’s manufacturability into perspective and decide which three would be investigated further. All of the ten established scenarios are described in the *Supplementary Material*, where they are presented in descending order according to the analysis results:

$$TOS = T \times w_T + Tc \times w_{Tc} + E \times w_E + Er \times w_{Er} + R \times w_R + Dp \times w_{Dp} + A \times w_A + Bm \times w_{Bm} \quad (2)$$

Equation 2: Formula to calculate the trade-off analysis score (TOS) for each of the scenarios individually. T: technical feasibility (different parameter than in Sect. 3, *Tc*: technical complexity, *E*: engineering effort, *Er*: energy requirements, *R*: reusability, *Dp*: risk of additional debris production, *A*: adaptability, *Bm*: breadboard manufacturability, the character *w* indicates the respective weighting factor for each of the parameters created by the paired comparison.

4.4 Mission parameters and goals

The ten established scenarios presented a very diverse range of ADR options and significantly differed in, e.g., their applicable size of debris as well as their removal strategies. Therefore, mission constraints described in the following were defined and identified for each of the scenarios. The conceptual project boundaries, however, were predefined as aiming to remove large objects in LEO.

– Debris type: Describes the type of debris targeted with the described mission. Within the scope of the project, targets were defined according to their mass and dimensions as displayed in Table 1. Each type was categorized from I to V and lists an exemplary debris object within each category and its current orbital position. As explained above, fragments while listed in the table, were excluded from the conceptual mission design.
– Debris condition: While most end-of-life procedures nowadays require the disconnection of batteries and shedding of remaining fuel reserves [35], these precautions cannot always be executed. Especially when spacecrafts and satellites unexpectedly malfunction, these processes are not carried out. Therefore, if a scenario includes the piercing of the debris surface and penetration further into the object, contained modules as well as their position need to be known to prevent piercing critical or hazardous parts of the debris [36]. Hence, the conceptualized scenarios presented in the following include an indication

Parameters	Technical Feasibilty	Reusability	Energy Requirements	Score
Technical Feasibilty		2	2	4
Reusability	0		1	1
Energy Requirements	2	1		3

Fig. 3 Excerpt from the paired comparison matrix, showing the evaluated influence of one parameter on another and vice versa. The sum of all scores (right column) was divided by the sum of all cells in a row, resulting in the respective weighting factor

Table 1 Definition of different types of debris, including their size, mass, and orbital location. The specified objects are examples of the type of debris that fall under the defined classification. Similarly, dimensions, masses and orbits are based on estimates or measurements upon launch and, therefore, may be subject to change. These figures are merely used to roughly indicate the characterized types of debris

Type	Debris Object	Dimensions [m]	Mass [kg]	Orbit [km]	Reference
I	Envisat	$25 \times 10 \times 5$	8140	767	[37, 38]
II	Ariane 5 upper stage	4.7×5.4 (d)	4540	GTO	[39, 40]
III	Cosmos M3 2nd stage	6.5×2.4 (d)	1400	650–1050	[41]
IV	Vega upper stage (4)	2×2.2(d)	688	300–1500	[42, 43]
V	Fragments	< 10 cm	Total sum: 8,782,500	160–36,000	[3, 44]

if this kind of information is relevant for the successful implementation of the scenario.

- Orbit: Some deorbiting strategies such as drag sails requiring atmospheric drag and electromagnetic tethers using Earth's magnetic field are limited to LEO, where these forces are at work. In GEO, the remaining option is to use propulsion systems to deorbit a target. While this project concentrates on debris orbiting in LEO, possible GEO applications are specified nonetheless.
- Number of targets: Depending on their method of capture and deorbiting as well as the encompassed refill/reusability options, some scenarios are not only able to target and remove one object from its current trajectory but continue after achieving its first mission and pursue another target. While targeting multiple objects decreases the cost to benefit ratio significantly, these systems are often complex and are based on slow deorbiting time frames. In addition, while the initial target needs to be prioritized to ensure the success of a conceptualized mission, this parameter indicates whether a created scenario may be applicable to multiple targets instead of a single one.
- Number of biomimetic concepts: since the focus of this project are bio-inspired solutions, each scenario also includes an estimate of biomimetic concepts that are combined within one holistic scenario. Low numbers of biomimetic concepts, however, do not indicate insufficient results. It merely gives an indication of the complexity and innovation potential involved.
- Type of transport: When defining ADR scenarios, they can be differentiated according to the role of the chaser. In some scenarios, the chaser performs all of the required detection, capturing and deorbiting activities, while in others, it merely presents a transport system able to release submodules responsible for the removal of the target. Here, it is specified for each scenario if the chaser is used as the spacecraft that it is carrying out the mission or if its contained payload takes over this task.

5 Selected biomimetic ADR scenarios

In the following, the three selected scenarios will be presented including all of the encompassed biomimetic concepts and the scenario's requirements for the mission parameters introduced above (Sect. 4.4).

5.1 Scenario A: gecko kit canon

This scenario requires precise data on debris parameters to find an appropriate surface for the subsequent attachment. Therefore, the close-range rendezvous concept has to deliver all necessary information and provide a good fail-to-save approach to enable a successful mission while preventing a collision between chaser and target.

Many invertebrates demonstrate a so-called compound eye, which consists of numerous spherically arranged and cone-shaped sensing units called ommatidia. These units portray high sensitivities, a variety of dimensions, and accept light from narrow angles [45, 46]. Hence, the idea of creating artificial compound eyes has been studied before, even in the context of space applications for object detection and space laser communications [47, 48]. Taking this concept one step further, the idea is to combine the compound eye and its detection abilities with other biomimetic visual sensing concepts. Sticking to the spherical arrangement of a compound eye, the individual ommatidia are partially replaced by a variety of additional optical sensing options. Those can help overcome limitations of the compound eye detection mechanism itself as well as issues of current detection technologies.

The first technology to be included is based on the lobster's eyes that provide an especially wide field of view as well as sufficient focusing energies, making it particularly suitable for all-sky- and sun-monitoring. Due to its advantages, it has already been implemented in X-ray telescopes, one of which was employed on a Czech satellite [12, 49–51].

Targets orbiting Earth are exposed to an alternating illumination cycle. Hence, the reflected light coming from an object is increasing and decreasing. Therefore, to detect reflected lighting patterns from an object facing away from the sun, the light sensitivity of systems needs to be improved. The white lady spider has developed an efficient neural mechanism that uses temporal and spatial summation of visual stimuli, which allows multiple stimuli to be integrated to capture visual information in dim lighting conditions [52, 53]. Using this type of visual and neural mechanism could offer the possibility to increase the detection of poorly reflecting objects in space.

Conventional optical systems for in-orbit detection and identification of target parameters often suffer dynamic illumination conditions or solar glare [54]. Thus, recent ideas regarding the detection and tracking of space debris have revolved around technologies using different types of light. One of which is using wavelength in the infrared spectrum instead, which several animals are able to detect. Especially certain species of fire beetles have developed a sensing organ equipped with photomechanic sensors able to detect infrared radiation from far distances. The radiation and subsequent temperature increase cause the liquid inside their receptor cells to expand, resulting in a rise in pressure and a subsequent deformation triggering a neural response [55–58]. However, Yilmaz and colleagues [54] argue that a thermal profile of all objects in space has to be established before this technology will find application in the space industry.

Another type of illumination that can be used to avoid issues associated with visible light-based optical sensors is presented by (un)polarized light. In nature, insect pollinators, particularly bees utilize polarized light patterns for navigation, since it is independent from the time of day [59–61]. Preliminary research has concentrated on determining the polarimetric properties of different commonly used materials for space technologies and establish recognizable patterns to allow a remote characterization and identification of debris [20].

When it comes to the final approach of a target in space, real-time tracking is important to avoid faulty maneuvers. In nature, the dragonfly is able to pursue its prey within a turbulent environment with distracting stimuli present and still manages to capture a selected target with a 97% success rate. They do so by using so-called small target motion detector neurons, which are very sensitive to target contrast. Hence, they present an efficient and highly adaptable visual processing system that has already been adapted and transferred into tracking algorithms [62, 63]. These could improve the processing of collected data from the combined technologies within the compound eye. In addition to the highly efficient target tracking and processing of visual input of the dragonfly, the locust demonstrates another attractive mechanism to avoid collisions between the chaser and the target. Using their lobula giant movement detector neurons, locusts are able to recognize approaching obstacles even in low-contrast conditions or textured backgrounds in motion. Once a collision alert is triggered, the locust can adapt its behavior mid-flight to alter its trajectory and avoid the collision. This collision avoidance mechanism seems very promising and has already been considered for the implementation in smart vehicle technology [64, 65].

The biological models mentioned above are depicted in Fig. 4. Using a compound eye with different optical sensing technologies incorporated that are not only included once but multiple times for the close-range rendezvous in orbit provides an elaborate range of information that can, for example, improve the aiming process at appropriate docking areas on the target. In addition, having multiples of one technology demonstrates a high redundancy and thus, security in case of partial system failure.

Once a sufficient amount of information on the target's behavior and surface features is determined, the chaser shoots a deorbiting kit towards the target, aiming at a previously determined attachment point. The kit launch system includes a passive energy storage based on the grasshopper hind leg to efficiently propel the kit towards the target. The grasshopper can achieve high catapult forces by slowly contracting one of its muscles while spending only little of its energy. A release triggered by the relaxation of another muscle causes the very fast and strong resulting action [66, 67]. Using this kind of system decreases the power consumption by the chaser, but provides an efficient firing mechanism. In addition, the force is sufficient to shoot the kit onto the target, allowing the chaser to maintain a safe distance between itself and the target, thus, decreasing the risk of collision, yet low enough to avoid damages and potentially generate additional debris as well as knocking the target onto a dangerous trajectory. The kit itself is dodecahedronally shaped to provide a high storage volume inside while allowing for large and omnidirectional attachment surface on the outside. The latter is covered with an adhesive mimicking the gecko's feet to automatically attach whenever it comes into contact with the target. The gecko's feet make use of a hierarchical compliance of microscopic hairs paired with the van der Waals forces to conform to rough surface and produce sufficient adhesion to enable walking over smooth and vertical surfaces [68]. Gecko adhesives have been studied extensively and have already been considered partially tested within the space environment [69–72]. Thus, they provide a promising concept to gently attach to objects in space. Furthermore, during the shooting process, the kit remains attached to the chaser by a rope that enables the reeling in of the kit in case the first aiming and hitting attempt is not successful. Thus, the approach can be repeated until the mating is achieved. While preliminary tests have resulted in first ideas

Fig. 4 Photographs of the biological models included in the compound eye, 1) fly compound eye, 2) lobster 3) white lady spider, 4) locust, 5) fire beetle, 6) bee, 7) dragonfly

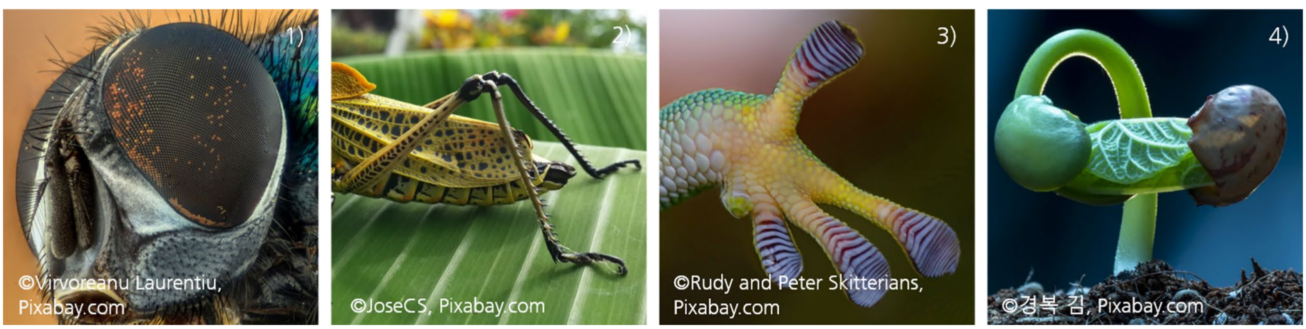


Fig. 5 Photographs of the biological models included in scenario A. Picture 1) shows the fly compound eye that incorporates the biomimetic technology concepts presented in Fig. 2, 2) grasshopper hind leg, 3) gecko feet adhesion, 4) plant leaf folding

about velocities and spin rates required in order to form a successful connection [69], further experiments need to be conducted to determine the adhesive capabilities of gecko adhesive materials when shot towards a target.

Since the chaser in this scenario does not approach the target very closely and will not make a physical connection itself, there is no need to detumble the target or form a pre-attachment before initiating the contact phase. However, in case of dealing with a highly uncontrollable target, the shooting of the kits can be timed so that it adds a counterforce to the spin, thereby slowly reducing its rotational velocity by shooting multiple kits as proposed by Kawamoto and colleagues [73].

Once the connection to the target is made, the rope from the chaser to the kit is cut, thereby separating the chaser connection to the target. The chaser can go on towards a next target. Inside the deorbiting kit, a drag sail is folded up very small and efficiently based on the folding observed in the leaves of plants [74, 75] that can automatically unfold. A thermal release mechanism, passively controlled by external temperature changes (similar to the thermal knife without using current to heat up the system [76]), triggers the automatic unfolding of the sail. The initial temperature of the target (and all its components) increases through the natural radiation of the sun (depending on orbital location and rotation of the target) that causes the release mechanism to snap and release the sail. All of the remaining biological models for this scenario are depicted in Fig. 5.

The chaser setup designed for this scenario is demonstrated in Fig. 6. This scenario is designed for the removal

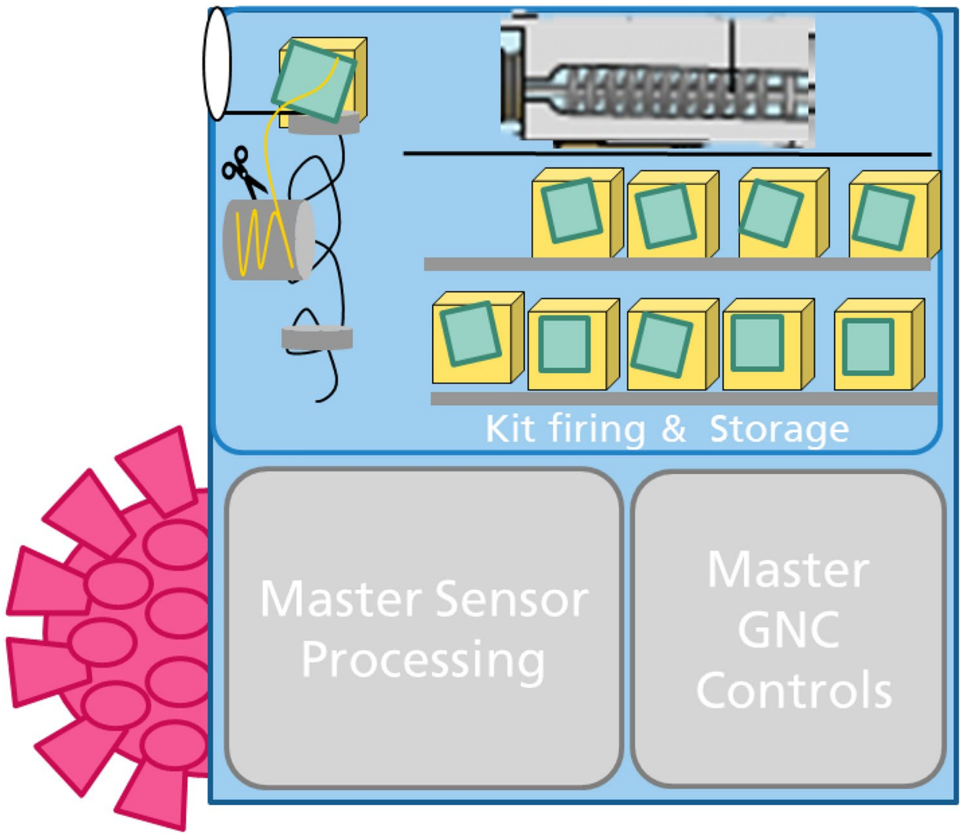


Fig. 6 Sketch Representation of the chaser conceptualized for scenario A. The chaser contains a payload of multiple deorbiting kits (yellow cubes) that can be loaded in front of a catapult that shoots them towards the target once the compound eye (pink) has determined an appropriate position and timing. The kits have a gecko adhesive on their outer surface (green squares) that allows them to stick to the target once they come into contact. If the launch of the kit is successful, the string connecting the target and chaser is cut and the chaser moves away from the target so that the kit can release its drag sail folded up inside

of type I targets, since the chaser includes multiple deorbiting kits and can adjust the number of fired kits based on the size of the target. Hence, a sufficiently large drag reduction can be created by multiple drag sails, thereby accelerating the deorbiting despite the rather large mass of the objects. This, however, also limits its application to LEO, since augmenting an object's atmospheric drag is only possible in this orbital region. Still, it circumvents the additional investment of fuel associated with propulsion deorbiting, since the chaser can remain in its orbit and go on to approach and target new objects.

5.2 Scenario B: gecko pad and bee harpoon

Similar to scenario A, this one, too, requires very precise data for the detection and identification of debris parameters, since the chaser approaches the target very closely and performs difficult mating activities. Therefore, the previously introduced compound eye concept (Sect. 5.1) is adopted here as well, providing increased safety for the chaser as it offers better determination of appropriate approach lines and maneuvers. In addition to the compound eye, all remaining biological models incorporated in this scenario are depicted together in Fig. 7.

Furthermore, this scenario encompasses a pre-attachment in form of a kinematically redundant robotic arm, which is a frequently conceptualized idea to detumble a target [25, 26]. This robotic arm is modelled after an elephant's trunk, a highly flexible organ consisting of many muscles, therefore, providing multiple degrees of freedom and high compliance. This demonstrates high maneuverability and adjustability to complex debris motions, shapes and structural features [77–79]. The length of this robotic arm, however, also determines the maximum possible distance between the chaser and target to initiate the first contact.

To reduce the risk of pushing the target away from the chaser during the capturing phase, a preliminary connection is established using an adhesive pad inspired by the gecko's feet, similar to the one described above, attached to the artificial trunk as an end-effector. This allows for the establishment of a connection to the target without the application of large forces or velocities. In addition, in case the first connection is not successful or the placement is not ideal, the connection can be undone and the approach repeated until the perfect spot for the preliminary mating is found, since the gecko's dry adhesion is reversible. Furthermore, Trentlage and Stoll [69] showed that a foam-like suspension layer underneath the gecko material can enable the capture of curved objects such as the surface shape of rocket upper stages. Hence, underneath the gecko material, a layer of foam inspired by the pomelo fruit's peel is included. The pomelo demonstrates an open

Fig. 7 Photographs of the biological models included in scenario B, 1) the compound eye as described above for scenario A, 2) elephant trunk, 3) gecko feet adhesion, 4) pomelo fruit peel dampening, 5) chameleon tongue, and 6) bee stringer.

cell foam structure of varying pore size distributed over its thick peel, which protects the fruit inside when falling from trees of up to 10 meters in height. It, therefore, presents excellent impact damping and energy dissipating capabilities. More recently, the beneficial features of the pomelo's peel have been recognized by the science community and articles have been published studying and modelling the foam-like structure [80, 81]. Therefore, it is hypothesized that a bio-inspired material is equally able to dampen the impact between the arm and the target as well as reduce the impact of the preliminary connection onto the target's trajectory [27].

Once the preliminary contact is established and the debris cannot escape the hold of the chaser, a harpoon is fired towards the target. On the example of the chameleon's tongue, the system is charged and fired in a very energy efficient way, reducing the overall energy demand of the mission scenario. Chameleons display the ability to achieve accelerations exceeding 400 m/s^2 due to their rapid elastic recoil of collagen tissue incorporated within its tongue [82]. While this speed is much higher than the forces necessary to pierce the surface layer of the target and penetrate deep enough into the outer insulation layer to accomplish a firm connection (approximately 20 m/s necessary according to [83]), it enables the firing of the harpoon from larger distances, which is only limited to the length of the robotic arm. The chameleon achieves such accelerations by slowly contracting one of its tongue muscles that stretches another muscle. The latter is released, while the usual muscle contraction is decoupled, imparting the entire stored energy onto the harpoon [82, 84].

The shaft of the harpoon itself presents a conventional harpoon design of a smooth and hollow tube. The tip of the harpoon, however, is modelled after the stinger of the bee that is very sharp and can easily penetrate the surface of the target. In addition, the bee's stinger demonstrates small hooks at its end to interlock with the skin of the attacked organism [85]. Thus, this feature is also adapted and transferred to the harpoon's tip to ensure that it remains in physical contact with the debris' inner wall. This method creates very high impact forces at the target, which increase the danger of producing additional debris. The required impact force is assumed to be reduced with an additional and preceding contact between chaser and target, since the penetration speed of the harpoon into the target's wall material can be reduced. While the robotic arm requires a lot of processing, control and navigational power, it is not expected to create a sufficiently rigid attachment to manipulate and manoeuvre very heavy target towards re-entry alone. Hence, the preliminary attachment to the debris with said arm can be used to further prevent the two spacecrafts from drifting apart, while the lengthy processes of aiming and alignment of harpoon and target are conducted. After an appropriate area on the target has been determined, the harpoon is fired. Once a rigid connection is made, the robotic arm can be detached from the target and stored away back in the chaser. The harpoon connected to the chaser with a rope remains inside the debris, while the chaser slowly moves away from the target to create a safe distance between the two. Then, the chaser's own propulsion system can be used to pull the target behind it and deorbit the object.

The developed chaser for this scenario is depicted in Fig. 8 and shows the combination of all the mentioned techniques in one spacecraft. This scenario allows for the targeting of debris in the LEO and GEO, since it uses its own propulsion system to remove the target from its current trajectory. Moreover, this method presents a short-term deorbiting approach that is very suitable for large targets such as EnviSat in type I. It also does not require a large structure for the capturing but attaches to a comparatively small area on the target itself.

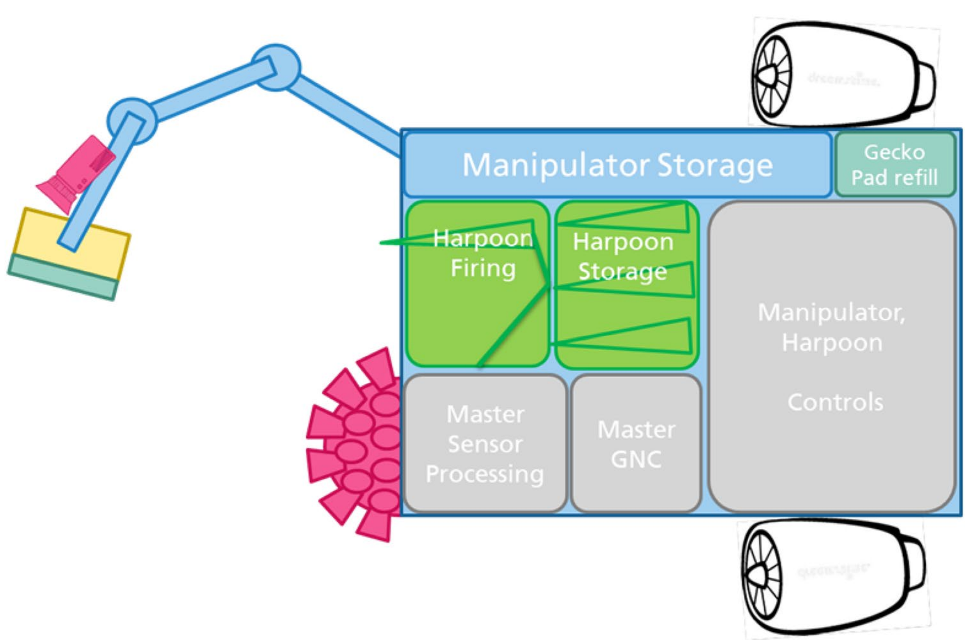
5.3 Scenario C: venus flytrap

Contrary to the other two scenarios presented above, the accuracy and precision of data obtained from the target prior to the capturing activities are not as crucial. Hence, one can rely on the existing conventional optical sensing systems such as videometers, advanced video guidance sensors, rendezvous and docking sensors, or laser mappers [86] to detect and track the target.

The chaser in this scenario has a containment structure attached to one of its sides that is designed after the model of the Venus flytrap that presents two outward bending lobes in one of their bi-stable positions. Carnivorous plants such as the Venus flytrap shown in Fig. 9 exhibit trigger hairs on the inside of their jaw-like lobes. Once prey is attracted through the sweet nectar that is excreted, it settles on the lobes, simultaneously touching several of the flytrap's hairs. The bending of the hairs triggers an electric signal and initiates

Fig. 9 Photographs of the biological model included in scenario C, showing a Venus flytrap that has caught a fly.

Fig. 8 Sketch Representation of the chaser conceptualized for scenario B. The chaser has a kinematically redundant robotic arm (light blue) with an end-effector consisting of a pomelo fruit peel dampening foam (yellow) and a gecko adhesive surface (dark green). This end-effector displays the component of the chaser that actually attaches to the target. In addition, it has a harpoon firing system (light green) that shoots one harpoon towards the target after the pre-attachment has been successful. The aiming process of the harpoon is done via the compound eye (pink). Using the chaser's own propulsion system, the target is deorbited



a rapid closing of the lobes to capture the prey [87–89]. Similarly, this principle can be adapted and transferred to debris removal, since it has already been implemented as a small-scale robot [88], showing the potential of this mechanism for its technical implementation.

The chaser approaches the target against the travel direction, so the hairs make the initial contact once the target has traveled far enough into the lobes. Up to this point, the target is not impacted by the removal mission. When it is in close vicinity to the chaser's body, however, a sufficient number of the mechano receptor hairs will have been triggered and the bi-stable mechanism autonomously switches from its outward-facing to its inward facing stable position. This allows a complete surrounding of the target without requiring preceding attachment or detumbling actions. Moreover, it does not pose much risk of damaging the target during the capturing process, since it makes very little contact with the debris itself before it is fully contained. Yet, the containment structure is limited in size based on the payload constraints of the carrier rocket. Thus, this scenario is designed to target debris of type III and below. Since this system does not require additional energy for the closing and thus capturing process, it is very energy efficient. In addition, this bi-stable mechanism demands the triggering of multiple stimuli before closing, thus, avoiding inadvertent triggering of the mechanism by dust, particles or small fragments.

Once the target is safely contained by the chaser, it can use its own propulsion system to remove the target from its current orbit. While it is only applicable to one target as the chaser deorbits together with the debris, it allows for the targeting of objects in LEO and GEO, because it uses its own propulsion system and, therefore, does not rely on certain forces or dynamics to be present.

The chaser design for this scenario is depicted in Fig. 10. Since the chaser's own propulsion system is used for the deorbiting of the target, the chaser is the active spacecraft performing the removal activities. This scenario is limited in its application to a single target, however, independent from its orbital location. Due to the anticipated constraints for the size of the containment chamber, this scenario will most probably be effective when targeting debris types III and IV. Since this scenario will not make contact with the target at a specific point but will enclose it instead, the conditions of the targets are irrelevant.

6 Conclusions

Within this article, the BIOINSPACED project and its catalogue of valuable biological models for technical implementation in ADR were introduced along with the method of evaluation of collected concepts. The supplementary material contains the complete catalogue of the biomimetic concepts sorted according to their function and ability. It also summarizes the ten initially established scenarios, that hold great value and innovative ideas for biomimetic ADR. The three most promising and innovative conceptual designs for ADR scenarios were presented in this article. All of them display fundamentally different approaches, targeting different debris objects and are applicable in different orbits. All of them, however, display many beneficial traits due to the consideration and integration of biomimetics and many diverse biological models. The BIOINSPACED project has

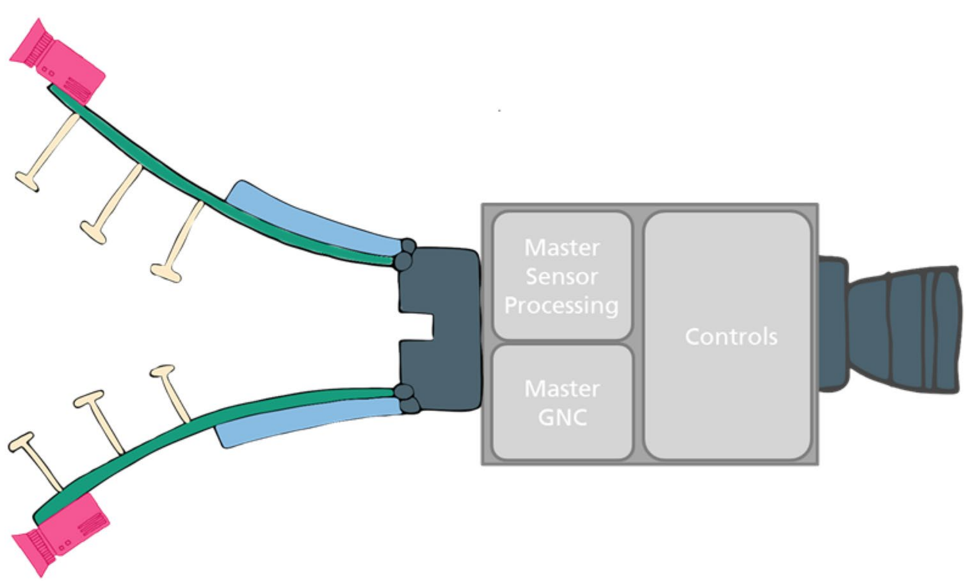


Fig. 10 Sketch representation of the chaser conceptualized for scenario C. The chaser presents a containment structure that is bi-stable, meaning it has two resting positions and requires the application of energy to change from one into the other position. The green outward facing arcs represent the Venus flytrap's lobes. The yellow T-shaped structures attached to the lobes are the trigger hairs that are able to receive a stimuli and the blue bars represent the cells that swell due to the triggering of the hairs that causes them to extend and thus force the lobes to switch to their alternate position

already demonstrated the value that nature's pool of ideas has to offer when it comes to the development of innovative and improved systems even within the space industry. In the last phase of the project, one of the three presented scenarios will be chosen and implemented as a demonstrator to showcase the functionality of the established concepts and present the potential of biomimetics.

Besides the three selected scenarios within the scope of this project, many of the remaining collected concepts and developed scenarios hold much potential for the application to ADR. Especially the concepts of tactile sensing in space applications to circumvent common limitations of conventional optical systems and passive entanglement of debris (particularly small scale fragments) are of much interest and should be investigated in future. Furthermore, encapsulating the target before making actual contact with it and, therefore, almost completely eliminating the risk of additional debris production present interesting opportunities especially for in-orbit maintenance and servicing.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12567-022-00438-z .

Acknowledgements The BIOINSPACED study has received funding from the European Space Agency under grant agreement no. 4000130585 "Biomimicry (Biomimetics) for space debris mitigation" in the frame of ESA's Discovery & Preparation studies. Special thanks goes to all brainstorming workshop participants, who contributed to the collection of biomimetic concepts and ideas and the remaining project members, especially our student assistance Lotte Pohl and Jula Kniep for outstanding support and organisation.

Funding Open Access funding enabled and organized by Projekt DEAL.

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