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Biomimetics for innovative and future-oriented space applications - A review

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Nature benefits from a progressive evolution over millions of years, always adapting and finding individual solutions for common problems. Hence, a pool of diverse and efficient solutions exists that may be transferable to technical systems. Biomimetics or bio-inspiration has been used as a design approach for decades, revolutionizing products and processes throughout various industries. Thus, multiple examples can also be found in the space sector, since many characteristics found in biological organisms are also essential for space systems like response-stimuli adaptability, robustness and lightweight construction, autonomy and intelligence, energy efficiency, and self-repair or healing capabilities. This review focuses on biomimetics within the field of aerospace engineering and summarizes existing bio-inspired concepts such as drilling tools (wood wasp ovipositor drilling), telescopes (lobster eye optics), or gasping features (gecko feet adhesion capabilities) that have already been conceptualized, partially tested, and applied within the space sector. A multitude of biological models are introduced and how they may be applicable within the space environment. In particular, this review highlights potential bio-inspired concepts for dealing with the harsh environment of space as well as challenges encountered during rocket launches, space system operations and space exploration activities. Moreover, it covers well-known and new biomimetic concepts for space debris removal and on-orbit operations such as space-based energy production, servicing and repair, and manufacture and assembly. Afterwards, a summary of the challenges associated with biomimetic design is presented to transparently show the constraints and obstacles of transferring biological concepts to technical systems, which need to be overcome to achieve a successful application of a biomimetic design approach. Overall, the review highlights the benefits of a biomimetic design approach and stresses the advantage of biomimetics for technological development as it oftentimes offers an efficient and functional solution that does not sacrifice a system's reliability or robustness. Nevertheless, it also underlines the difficulties of the biomimetic design approach and offers some suggestions in how to approach this method.

KEYWORDS
biomimetics, bio-inspired, space systems, on-orbit manufacture, debris removal, solar power

1 Introduction

1.1 Biomimetics within industry

Biomimetics, bio-inspiration or biomimetic design describes the process of getting inspired by nature and using biological concepts for the development of technical solutions. Features or mechanisms of interest are extensively studied to understand their functioning, before they are abstracted and transferred to technical applications, products and processes (Wanieck et al., 2017). Biomimetic design has been used for some time now and several biomimetic concepts have been adapted and implemented as different products and technologies, now well-established on the market. Prominent examples are the lotus paint mimicking the lotus leaves' hydrophobic tendencies to repel dirt and water (Solga et al., 2007; Spaeth and Barthlott, 2008), and Velcro inspired by the hooks of thistles to achieve reusable fastening (Velco, 1955; Menon et al., 2006). Many more concepts can be found in the prototype and testing stage, with the goal to establish products and technologies throughout industries. Within the maritime sector for example, biomimetics has been heavily researched in relation to reducing the frictional resistance of ship hulls on the example of shark skin (Figures 1A, B) (Ibrahim et al., 2021, 2018; Fu et al., 2017; Wen et al., 2014; Oeffner and Lauder, 2012) and the salvinia plant (Oeffner et al., 2021; Walheim et al., 2021), thereby significantly reducing the fuel consumption and emissions associated with waterborne transport. In the transportation sector, bio-inspired concepts have been applied for the development of cars (puffer fish) (Kozlov et al., 2015), trains (kingfisher bill) (Figures 1C, D) (Foo et al., 2017; Hu et al., 2018), and even airplanes (winglets of birds) (Figures 1E, F) (Guerrero et al., 2012). Furthermore, improved aerodynamic characteristics through whale-mimicking tubercles on the edge of wind turbine blades, ventilation fans, and windmills have been achieved within the energy sector (Figures 1G, H) (Fish et al., 2011; Ng et al., 2017; Zhang et al., 2020), and more efficient construction ways presented by using fold structures based on tree leaves or insect wings and growth patterns adapted from organism's exoskeletons within architecture and construction (Pohl and Nachtigall, 2015).

More recently, advances have especially been achieved in the fields of robotics with e.g., elephant trunk-inspired robotic arms (Zhao et al., 2018; Mazzolai et al., 2019) and compound eye-sensors (Bora et al., 2018; Agrawal and Dean, 2019) among many others. Lastly, biomimetics cannot only be used as direct design approach but has also been proven to improve processes such as 3D-printing (Zhu et al., 2021), design (Kamps et al., 2017), and manufacture and assembly (Schranz et al., 2020). The examples mentioned above describe only a small portion of available bio-inspired technical solutions, but already demonstrate that biomimetics is a viable approach for the design of a diverse range of solutions in extreme environments and under competitive requirements.

Just as in other industries, biomimetics is not a foreign approach when it comes to aerospace engineering. Since there is currently no proof of biological life within the harsh environment that is space anywhere but on Earth, no direct natural examples can be used as a model. Therefore, the space sector presents a prime use case for biomimetic design as it describes the process of understanding the underlying natural mechanisms and transferring them into technical applications no matter of the original biological function rather than simply copying them. Several systems such as drilling tools [wood wasp (Pitcher et al., 2020)], telescopes [lobster eye (Tamagawa et al., 2020)], gasping features [gecko feet (Jiang et al., 2017)] and many more have already been conceptualized and partially applied in space technology development and present solutions, where conventional technologies are not able to mimic and compete with the highly optimised biological model.

The space environment, however, presents an especially challenging setting due to the existing conditions of low to zero gravity, high temperature fluctuations, elevated levels of UV, electromagnetic and particulate radiation, reactive atomic oxygen, as well as natural micrometeoroids and space debris (Finckenor and Groh, 2015; Aïssa et al., 2019). Despite the initial assumption that biological concepts may be unsuitable for the space environment based on their evolution under significantly different environmental conditions, biomimetics oftentimes offers an efficient and functional solution that does not sacrifice a system's reliability or robustness (Menon et al., 2006). Due to the variety of features available in nature, many different approaches for similar actions can be found and selected based on specific system requirements. In addition, many features formed in biological organisms are 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 (Ayre, 2004; Egan et al., 2015). Such biological characteristics can be transferred and adapted to improve or even revolutionize traditional engineering

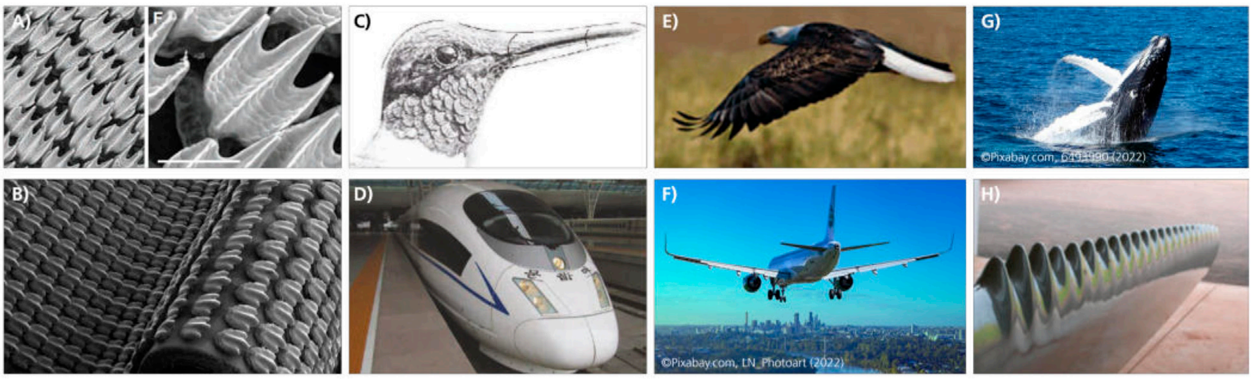

FIGURE 1
(A) Microscopic photograph of the riblet surface structure of shark skin. Reproduced from (Wen et al., 2014), with permission from COMPANY OF BIOLOGISTS LTD, **(B)** photograph of a bio-inspired riblet foil. Reproduced from (Wen et al., 2014), with permission from COMPANY OF BIOLOGISTS LTD, **(C)** sketch of a kingfisher bird. Reproduced under CC-BY-4.0, Hu et al. (2018), **(D)** photo of a train inspired by the kingfisher's beak shape. Reproduced under CC-BY-4.0, Hu et al. (2018), **(E)** photograph of a bold eagle showing of its winglets on its wing tip. Reproduced under CC-BY-4.0, Guerrero et al. (2012), **(F)** biomimetic transfer of winglets onto commercial airplanes Reproduced from Pixabay. **(G)** photograph of a humpback whales fin with turbercles in its edge. Reproduced from Pixabay, **(H)** concept transfer of turbercles onto a wind turbine blade. Reproduced from Fish, F. E. (2009), with permission from Spie (Karleena Burdick, Assistant editor) and Dr. Frank Fish.

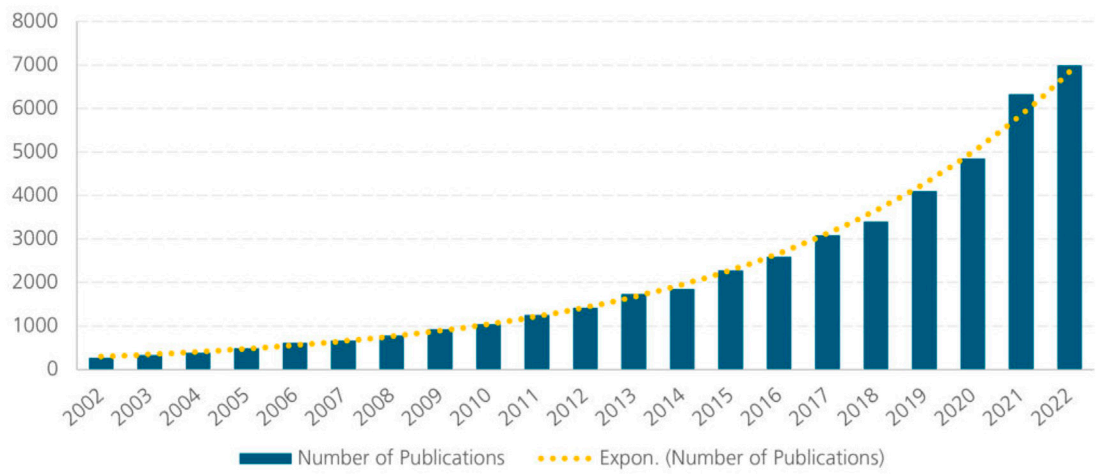

FIGURE 2
Graph indicating the exponential increase in the number of publications published related to the topic of biomimetics for aerospace applications. Key word search was conducted using the ScienceDirect database with the following key words: (*biomimetics OR bionics OR bio-inspired OR bioinspired*) *AND (aerospace OR space)*, from 2002 to 2022 (State 10.10.2022). Note that the number of publications in 2022 can be anticipated to increase slightly until the end of the year.

methods. Hence, several studies and research activities have already considered nature as model for aerospace technology development.

This article summarizes the most recent advances in biomimetic research and developments within the space industry and presents future-oriented concepts as well as ideas for various innovative technologies that could lead future development and revolutionize existing space systems. In addition, cutting-edge mechanisms that have not yet been investigated in detail but present great promise to improve conventional systems will be highlighted. Lastly, challenges and limitations of the biomimetic design approach are introduced to deliver a comprehensive overview over the potential and problems of biomimetics in general.

All of the mentioned biological concepts are summarized in Section 8 Supplementary Table S1 below, stating their feature or function of interest together with a short description of how it works as well as an example application within the aerospace industry, other industries or sectors of application, and the respective literature.

1.2 Literature review methodology

The interest in a biomimetic design approach applied to aerospace engineering is rapidly growing as indicated by the graph in Figure 2, showing an increase of articles, books and other scientific documents over the past 10 years.

This literature review was conducted based on reviews, research articles, book chapters, book reviews, and mini reviews from the databases ScienceDirect, SpringerLink, Google Scholar, and ResearchGate. The following keywords were used as sources of search records: biomimetics, bio-inspired, bionic, aerospace, and space. This review aims at presenting the most recent advances within aerospace research and highlighting innovative and prominent biomimetic concepts currently under consideration or with significant potential for the aerospace industry. Therefore, the results were filtered to include innovative research and studies from 2018 up to August 2022. Using the snowballing approach, more background information about valuable and interesting concepts was used to describe biological models in more detail and display the full picture in terms of existing research of single concepts. Only literature relevant to the research question was included, while articles with controversial content, methods or conclusions were excluded. Thus, this literature review provides context for the application of biomimetics within aerospace engineering and delivers background information for new research. It therefore acts as a general guide to what is already known and applied in regard to biomimetics and aerospace engineering, as well as what concepts and models hold potential for future investigation.

2 Biomimetics for the space environment

2.1 Defenses against the extreme space environment

As mentioned above, the space environment presents multiple extreme characteristics fatal to living beings on Earth. Nevertheless, mechanisms can be found that show promising performances in the protection of organisms to cope with ionization radiation, extreme temperatures, electromagnetic interference, micro asteroids and space debris.

In humans and other living beings as well as some fungi and bacteria, the biopolymer *Melanin* is found in cells and is mainly responsible to protect the cell from UV or ionizing radiation. Therefore, synthetic Melanin was produced and investigated for its wavelength absorbing and radiation protection potential with applications in aerospace engineering and other industries (Turick et al., 2011; Li W. et al., 2020; Vasileiou and Summerer, 2020). Another biological mechanism to deal with high levels of radiation can be found in bdelloid rotifers. They display a very effective DNA repair mechanism to restore ionization radiation damage (Gladyshev and

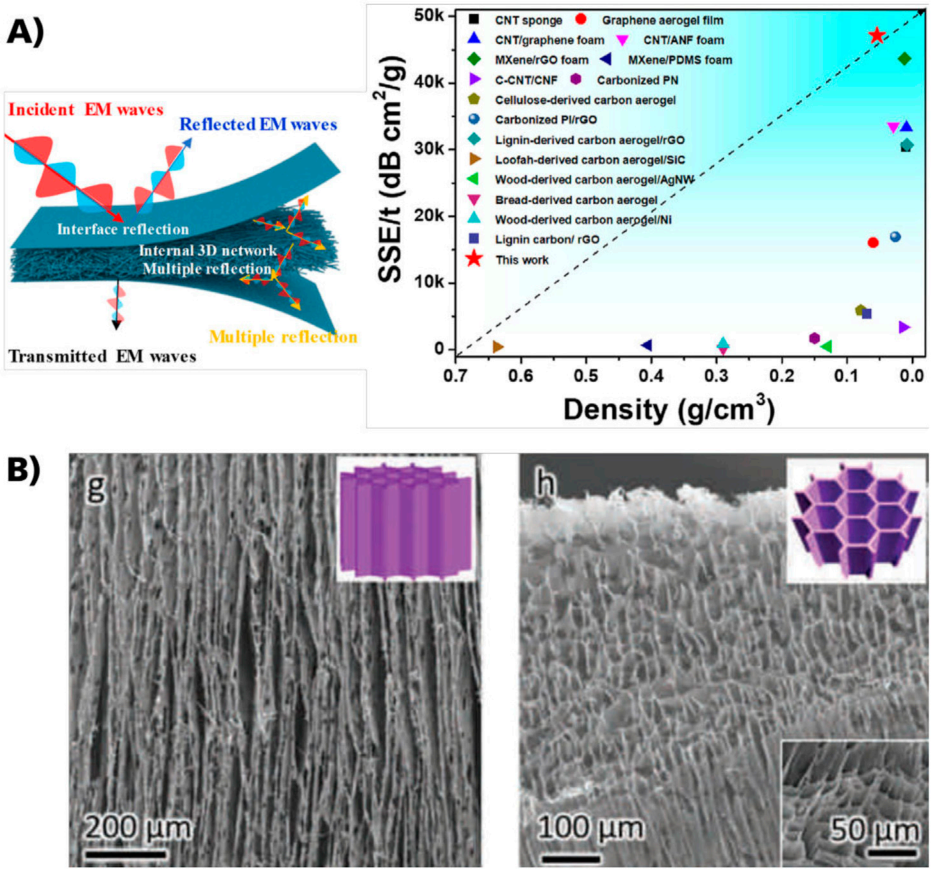

FIGURE 3
(A) Diagram how the electromagnetic interference shielding works with aerogels and a graphical representation of different sample performances throughout literature. Reproduced from Zhou et al (2021), with permission from Elsevier, **(B)** Photograph of the microstructure in the longitudinal (g)) and transverse (h)) planes of a MXene/CNF hybrid aerogels with 17wt% ultrathin cellulose nanofibrils content. Reproduced under CC-BY-4.0, Zeng et al. (2020).

Meselson, 2008; Wiles and Schurko, 2020), which may be transferrable or adaptable in the future to produce radiation-tolerant coatings and materials. Especially for manned missions, the protection against UV radiation is vital for the health and survival of humans spending extended periods of time in space (Williams, 2022).

Due to the highly fluctuating temperatures within the space environment and, therefore, the enormous range of extremes, heat flow as well as temperature management and control are crucial steps to maintain the integrity of space systems. By incorporating a circulatory systems inspired by biological organisms into solar panels, experiments have demonstrated the potential for a symbiotic use of a single structure for a component's structural efficiency as well as thermal management (Williams et al., 2007). Furthermore, bio-inspired porous carbon ablators were assessed regarding their thermal protection of spacecrafts during the re-entry process into planetary atmospheres, showing promising results to produce enhanced thermal protection even at high temperatures (Poloni et al., 2022).

On the other side of the temperature spectrum, many biological organisms can be found with distinctly evolved mechanisms to protect against freezing temperatures and the subsequent formation of ice crystals in their cells and tissue. Examples for this are ice-binding proteins or antifreeze proteins and glycolipids, which are currently applied within the fields of agriculture, cryobiology and food technology, but also hold great promise for material technology and therefore, aerospace engineering by preventing metals from frost formation and liquid materials from freezing (Bredow and Walker, 2017; Li and Guo, 2018; Zhou et al., 2019; Białkowska et al., 2020; Xiang et al., 2020).

Recently, researchers have taken first strides into developing lightweight and flexible materials for the protection of structures and equipment against electromagnetic radiation. Experiments show that electromagnetic interference can be successfully shielded by substituting conventional metal shields with ones inspired by cellular architecture with tiny pores mimicking cell walls as aerogels shown in Figure 3 (Liu et al., 2018; Zeng et al., 2020).

While micrometeoroids have been a threat to space systems since the beginning of space flight, the likelihood of a collision with one is rather small compared to the ever-increasing quantity of anthropogenic space debris circulating Earth's orbits. Hence, collisions with such debris become an ever more likely problem. Two options are available for dealing with space debris in orbit: avoidance maneuvers or shielding against collisions. Shielding is very expensive, only possible to a certain degree (dependent on size and velocity of debris) and adds to the mass of the system, inadvertently reducing payload capabilities. Avoidance maneuvers are often an alternative, sometimes, however, a must to escape collisions with large debris. While maneuvers are not only fuel-costly, they also require knowledge and tracking of existing debris (OECD, 2020). Until 2020, the International Space Station (ISS), continuously home to a crew of astronauts since 1999, was forced to conduct 27 collision avoidance maneuvers. Another four instances occurred, where debris was not detected in time, demanding an emergency evacuation by the crew (Johnson, 2012; ODPO, 2020). Other unoccupied space systems such as CubeSats, which are usually not equipped with their own propulsion system, are not capable of performing debris evading maneuvers. Besides these obvious challenges, more costs associated with space debris are related to the repair or replacement of spacecrafts, space situational awareness activities, data-blackouts when evading maneuvers are conducted, and insurance costs for operational space systems (OECD, 2020). Hence, finding cost-efficient and effective ways for debris detection and tracking can have enormous economic benefits and make space travel even safer.

In nature, several concepts can be found that deal with similar problems as well. Dragonflies, for example, are able to pursue their prey within a turbulent environment and distracting stimuli, yet still manage 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 to prevent collisions with their surrounding, which has already been modified and transferred into tracking algorithms (Bagheri et al., 2017; Colonnier et al., 2019). Investigations by Bagheri et al. (2017) showed that their dragonfly-inspired algorithm presented a higher average success (47.6%) in tracking small targets within a natural scene compared to conventional algorithms (maximum average success: 41.9%). Likewise, locusts demonstrate an attractive mechanism to avoid collisions using their *lobula giant movement detector neurons*. Those enable locusts 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. Since this collision avoidance mechanisms seems very promising, it has already been considered for the implementation of smart vehicle technology and robotic navigation with obstacle avoidance (Yue et al., 2006; Keil et al., 2018; Wang et al., 2021b). Therefore, it shows potential for application within the context of aerospace engineering and space exploration.

2.2 Vibration dissipation, fracture prevention and self-healing

Space systems designated for the exploration of extra-terrestrial bodies face an immense challenge right at the beginning of their mission. The landing of unmanned spacecrafts on the surface of another planet is oftentimes violent and associated with enormous impact forces. Therefore, several actions and measures have been taken to protect sensitive equipment and payloads against those forces. Likewise, nature too deals with great impact forces and has spent millions of years of evolutionary development cycles to evolve perfectly matched strategies and extraordinarily sophisticated systems to deal with the existing challenges such as great impacts. Thus, space technologies that have only been developed over the course of a few decades could highly benefit by learning from nature.

The seeds of trees fall from great heights to reach the bottom and have therefore developed multiple different protection mechanisms for the valuable payload of DNA contained within. The seeds of the plant *Tragopogon dubius*, for example, are attached to stalked parachutes, which have evolved to increase the aerodynamic drag of the seed and therefore slow its descent, which not only allows the seed to survive but also increase the distance travelled during its descent from the tree in order to propagate the species as far as possible (Pandolfi et al., 2012). While parachutes are the conventional solution for slowing the descent of space systems, velocity reduction may be optimized using parachutes of plants that have evolved over centuries.

In contrast to slowing the seed and thereby reducing the negative effects of hitting the ground, many species of nuts have evolved differently. Instead, they produce a rigid layer of protective shell around their seed, designated to protect it during impact (Islam et al., 2021). Likewise, insects form very stiff cuticles to protect against predators. These cuticles consist of hard composite structures formed with chitin fibers arranged in distinct patterns, which enable insects to cope with extensive amounts of strain and load. The composite structure is able to adapt to external forces and change its thickness, stiffness and orientation of fibers accordingly (Jullien et al., 2020; Stamm et al., 2021). This bio-material on its own has shown to produce a tensile strength of 130 MPa and an elastic modulus of 2,900 MPa, which can further be increased through combination with other materials such as polymers or resins (Gadgey and Bahekar, 2017; Hou et al., 2021). Marine species like mollusk shells, too, make use of a multilayered structure called *nacre* to build their own homes and as protection, which demonstrates a composite architecture of impressive mechanical characteristics (Yaraghi and Kisailus, 2018). Different species of shells produce different types of nacre some of which present a Young's modulus of 60–70 GPa and a tensile strength of 70–100 MPa. (Barthelat et al., 2016; Jiao et al., 2019; Askarinejad et al., 2021). Nacre is also known for its great fracture propagation and deflection properties based on their high stiffness and fracture toughness. Gao et al. (2017) compared the mechanical properties of the natural nacre produced by the species *Cristaria plicata* and artificial composite materials, demonstrating higher flexural strength (267 MPa) and similar fracture toughness (1.9 MPa/m^2) for the artificial material compared to natural nacre (172 MPa, 2.4 MPa/m^2, respectively). Other mechanical parameters of the artificial biomaterial like ultimate stiffness and elastic modulus reached values of 18.6 GPa (Gao et al., 2017) and 11 GPa (Raj et al., 2020), respectively.

A third option of dealing with high impact forces is demonstrated by the peel of the pomelo fruit. Instead of evolving hard materials capable of preventing fractures of the plant's fruit or slowing its descent, the peel of the pomelo fruit demonstrates a thick layer with open cell foam structure of varying pore size as depicted in Figure 4A), which protects the fruit inside from damage when falling from trees of up to 10 m in height. Experiments have uncovered a dissipation of up to 90% of the impact energy while testing on free falling pomelo fruits. They therefore present excellent impact damping and energy dissipating capabilities (Ortiz et al., 2018). More recently, the beneficial features of the pomelo's peel have been recognized by the scientific community and several articles have been published studying and modelling the foam-like structure (Thielen et al., 2013; Bührig-Polaczek et al., 2016; Ortiz et al., 2018; Li T.-T. et al., 2019). Hence, artificial versions of the foam may be applicable to dampen the effects of vibrations and reduce oscillations of space systems as well.

While some animals protect vital organs through fluid immersion, which absorbs the shock rather than transferring it to the valuable

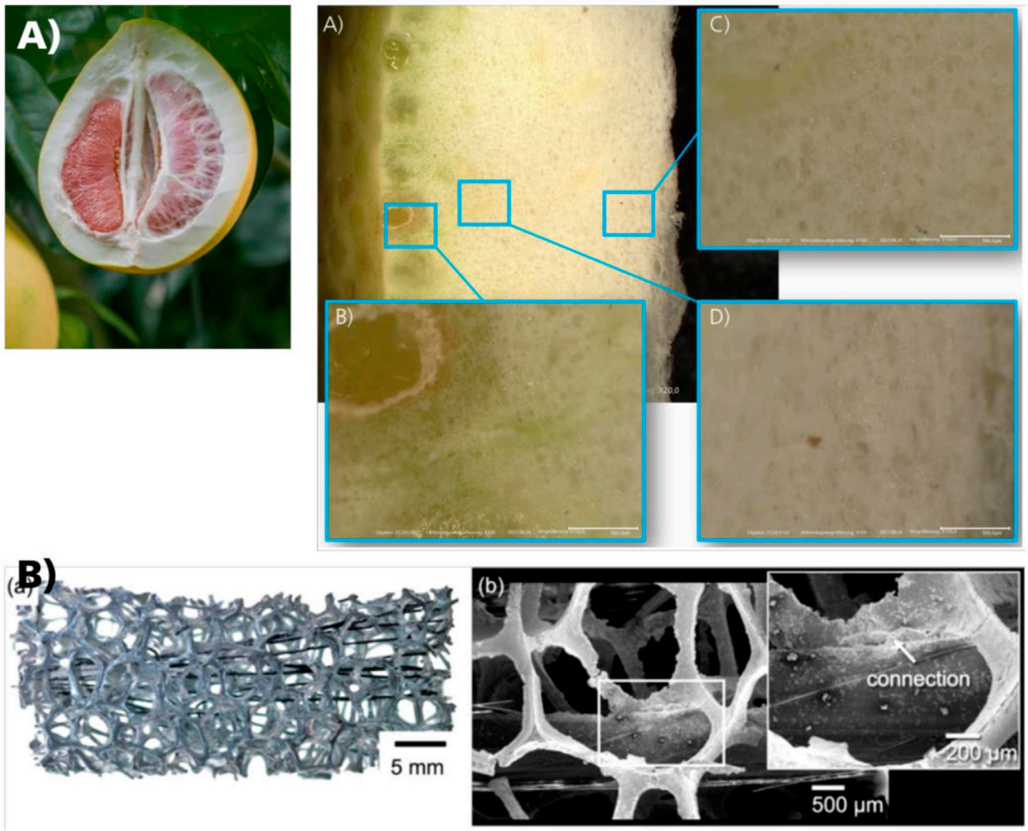

FIGURE 4
Pomelo peel as dampener, **(A)** Photographs of the honey pomelo's peel. Reproduced from Pixabay, and a view under a digital microscope taken at different regions of the peel at 150-times magnification (© E. Banken), **(B)** Photograph of an Aluminium foam sample with branched Al_2O_3-fibre bundles and a magnified view of a fibre reinforced Aluminium-alloy foam sample showing the connection between the fibre bundle and the foam matrix, Reproduced from Bührig-Polaczek et al. (2016), with permission IOP Publishing.

payload, the woodpeckers and Australian cassowary are two types of birds that have evolved different features to protecting their brains from high impact forces. The woodpecker uses its elongated and pointed beak to penetrate the bark of trees and find insects to feed on. It achieves the penetration through high percussive speeds of up to 22 times per second, accomplishing frequencies between 20–25 Hz and an acceleration between 600 g—1,000 g (Bian and Jing, 2014). Hence, to protect its brain, the skull has formed so that the brain is tightly held in its position, while its tongue reaches from its beak all the way around the brain along the back of the skull. Hence, even under extensive stress, the brain is protected and does not get damaged in the process (Hollin, 2021). Likewise, the Australian cassowary uses its head to ram it into tree trunks in order to knock down fruits. It has a hollow fin-shaped protrusion of keratin on its head connected to its skull that is filled with a soft, rubber-like matrix. This protrusion can protect the bird from impact velocities up to 50 km/h and absorbs the shock (Widholm and Jawaharlal, 2016).

Bio-inspired concepts like these are heavily researched for applications on earth, such as the prevention of brain injuries, as well as for the protection for sensitive equipment in engineering, and thus, present valuable insights for the protection of space systems, too.

In contrast, an example for damage forestalling and injury prevention is the natural principles of load flux dependent design. Trees and bones demonstrate the ability to direct and redistribute cell growth and therefore structural reinforcement in areas experiencing high amounts of stress (Menon et al., 2007). Conch shells, on the other hand, present curved lamellae that can increase fracture resistance by about 30% compared to straight ones (Li and Li, 2019). Self-reinforcing materials like these could significantly contribute to extending the lifespan of space systems and react to unforeseen internal and external system stressors.

Apart from high impact forces, space systems are also exposed to brutal vibrations upon launch of the carrier rocket and need to be securely fastened to prevent damages. Furthermore, moving parts in spacecrafts are usually avoided to prevent the creation of unwanted oscillations and rotational forces. Oftentimes, components are added designated to counteract persisting vibrations and associated negative impacts (Menon et al., 2007; Garcia-Perez et al., 2019; Guo et al., 2019). Yet, these measures limit functionalities and influence the system design. Even under consideration of major precautions, micro-vibrations can be created during a spacecraft's operation due to faulty calculations or external impacts. Thus, mechanisms to reduce oscillations and dampen the effect of vibrations find a broad range of application within the space sector (Kamesh et al., 2010; Yu et al., 2018).

Nature has brought forth multiple approaches to protect organisms from large oscillations and vibrations. One method of dealing with vibrations is their isolation as demonstrated by the human middle ear using an auxiliary mass mechanism among others (Kim and Kang, 2019; Wang et al., 2019; Yan et al., 2021). Fish, too, present a natural vibration dissipation through their hierarchical arrangement of scales in a compliant dermal tissue that allows for flexibility. They offer reversible non-linear stiffening and exhibit an interesting locking behaviour that is observed when the tissue is bent or twisted. First experiments show a viscous damping performance and direction-dependent frictional characteristics of the scales that can be adjusted and manipulated through alterations of the scale's geometry (Ali et al., 2019). In the plant world, oscillation dissipation can be observed as well. Plant roots as well as tree trunks have been shown to provide structural dampening and transfer of vibration energy throughout their branches (Barth, 2008; Kovacic et al., 2018).

If the force and experienced stress on single components or parts gets too large, biological organisms and technical systems alike tend to break, fracture, bend and deform. Nevertheless, nature displays various mechanisms to deal with such damages and is able to repair components to restore their mechanical and practical function. Healing capabilities can be found in almost every living being as it is crucial for survival to maintain structural integrity, fluid balance, and function. Self-healing in organisms can take shape in various different approaches, using stored elastic energy, hierarchical structures, self-assembly systems, liquid exchange, cross-linking of proteins and many more (Speck and Speck, 2019). During the wound-closing and healing process, activities such as coagulation, cell proliferation and matrix deposition are deployed to close holes and fissures, restoring the organism back to almost its original state (Aïssa et al., 2019). Bauer and Speck (2012) investigated the healing capabilites of tree bark species and found a 55% restoration after only 30 min of initial external injury. Thus, tissue can be sealed over a short period of time, restoring the parts functionality without repairing its full mechanical properties. Methods to structurally repair any fissures and (partially) restore mechanical properties exist too, however, take much longer (Speck and Speck, 2019).

Self-healing and -repairing systems are crucial for space systems as aerospace companies and manufacturers go through enormous efforts to protect components and parts from structural or electrical failure. Furthermore, maintenance operations are either very costly or not existent at all. Hence, systems like self-repairing components can extend the lifetime of spacecrafts and prevent total system failures due to propagating fissures and cracks. Some mechanisms inspired by animal, plant and human tissue have been abstracted and implemented as self-repairing materials, especially for polymer composite materials. Four main methods for repair have been established, and come in either a capsule, particle form or an organized net (filled with fluid or made from wires) that are spread throughout the material and are triggered by internal or external stimuli (Cohades et al., 2018; Aïssa et al., 2019). Liquid-filled fibers or capsules incorporated into materials can excrete a dye for visual detection of damages or a resin-hardener combination that fill any occurring cracks and restore their mechanical properties (Nellesen et al., 2011; Speck and Speck, 2019).

2.3 Planetary exploration and activities

In order to learn more about a planet or other extra-terrestrial body, the gathering of as much information as possible is crucial. While sensors and scans using optical and thermal equipment as payload on satellite flyby's deliver a great deal of data on those bodies, it is vital for a deeper understanding to gather physical evidence and take samples of various materials to be analyzed for mineral content but also for traces of life (Zhang et al., 2022b). Eventually, this information will be used to plan and execute *in situ* resource utilization to e.g., build a future space base. Other applications include asteroid mining for rare elements and finding life on other planets.

One of the most prominent applications for biomimetics within the space industry are drilling processes for planetary exploration and sample acquisition. Thus, multiple concepts exist that have conceptualized bio-inspired methods and procedures to improve and enhance these activities. One well developed biomimetic concept is based on the reciprocating drilling motion of the wood wasp. Wood wasps use their serrated ovipositors as depicted in Figures 5A,B to drill into the bark of trees to deposit their eggs. They can achieve a drilling speed of approximately 1–1.5 mm/min, while its ovipositor is assumed to have a Young's modulus of about 10 GPa (King and Vincent, 1995). This drilling method exhibits several favorable characteristics like its drilling efficiency and low overhead mass requirements. In addition, it circumvents the major challenge of rotary motion associated with conventional planetary drill designs. Several prototypes exist that have been tested intensively in a wide range of substrates ranging from fine regolith simulants to icy substrates as the one shown in Figure 5C. Sakes et al. (2020) developed a wood wasp inspired micro-drill prototype for minimal invasive surgery capable of achieving a stroke velocity of 4–8.77 mm/s and a transportation rate of up to 5.82 mg/s. Still, a wood-wasp inspired drills for aerospace applications have yet to be deployed and tested within the space environment (Gao et al., 2006; Gouache et al., 2010; Pitcher et al., 2020; Alkalla et al., 2021).

A similar concepts is demonstrated by the locust digging into the soil to deposit their eggs by pulling their abdomen into the hole while simultaneously clearing the debris out of the digging path (Gao et al., 2007). Other biomimetic concepts exist based on the earthworm or mole and operate with a similar approach (Kubota et al., 2007; Lee et al., 2019).

Other organisms besides earth-dwelling animals have proven effective ways to drill into substrates, too. Plants heavily rely on their roots to form a secure and permanent attachment to the soil and the distribution of water and nutrients to enable the development of a seedling able to outcompete its competitors and go on to grow into a mature plant. Hence, roots of different plants have developed various ways to achieve effective anchoring. One great example is displayed by the seeds of the plant *Erodium cicutarium*, which bury themselves into substrates. This mechanism is thought to have developed improving the seed dispersion process of the plant. Its fruits develop a seed with an elongated and spirally twisted tail that, once in contact with the ground, is humidity driven and causes the seed to autonomously bury itself into the material (Pandolfi et al., 2012; Mancuso et al., 2014). Developing such a passive drilling mechanism dependent on abiotic conditions in the surrounding environment could provide a very useful, resource-saving and energy efficient mechanism to allow probes to bury themselves into the surface material of planets. Furthermore, the formation of complex networks of smaller and bigger roots may offer great possibilities for underground pathfinding and mapping of structures under the surface, which can help to determine geological compositions, traces of water and other valuable resources (Menon et al., 2006; Seidl et al., 2008).

In order to transport different probes or scientific equipment across planetary surfaces from one interesting spot to another,

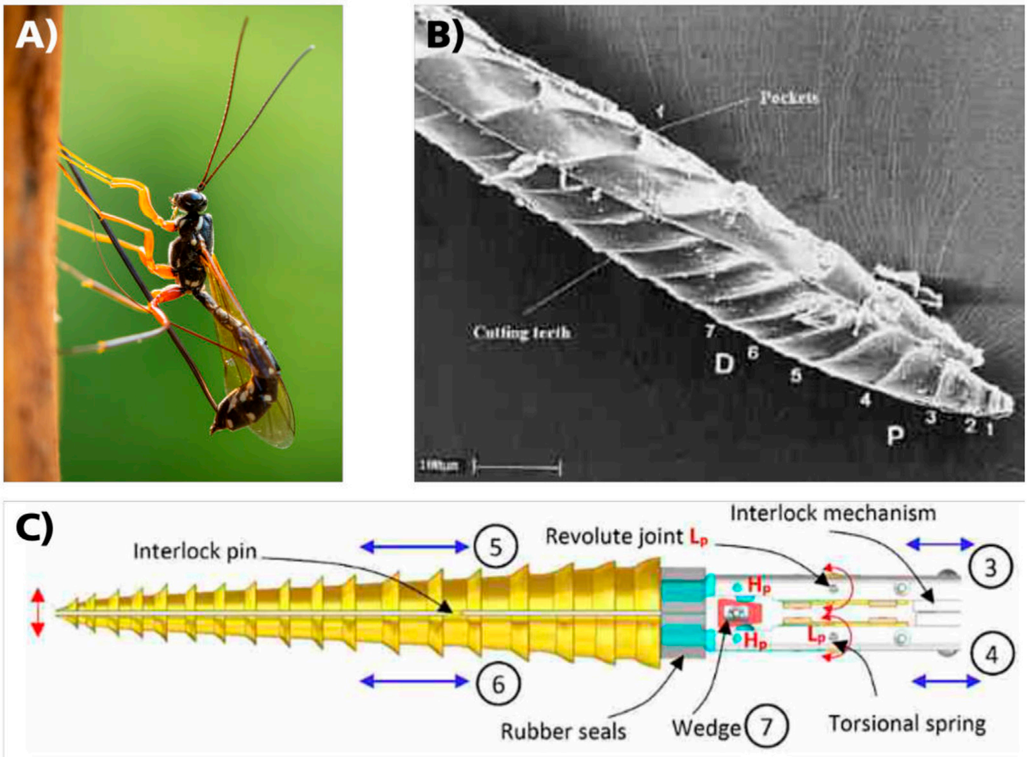

FIGURE 5
Wood wasp reciprocating drill, **(A)** Photograph of a wood wasp, **(B)** magnified view of its ovipositor consisting of two serrated valves, Reproduced from King and Vincent (1995), with permission from the authors, **(C)** schematic picture of a micro drill for aerospace applications. Reproduced under CC-BY-4.0, Pitcher et al. (2020).

autonomous or remote-controlled robotic systems are required. Extra-terrestrial terrains are often found to be difficult with many obstacles and rough surface textures, which frequently display challenges and limitations to conventional wheeled robotic systems (Armour et al., 2007). Many bio-inspired concepts exist and present different characteristics dependent on the local demands and requirements. Limbed robots, for example, are useful for rough terrain with large obstacles and are often designed to mimic multi-legged organisms such as spiders due to their high stability, range of motion and surface adhesion (Gasparetto et al., 2008; Dürr et al., 2019; Lopez-Arreguin and Montenegro, 2020). Other concepts are based on the jumping mechanisms of locusts, frogs, kangaroos and shrimps dismissing the highly complex control systems and the maximum height of obstacles (Armour et al., 2007).

After the success of the first-ever human-made flying object on Mars, the Ingenuity Mars Helicopter has paved the way for a new level of extra-planetary exploration (Balaram et al., 2018). Hence, flying drones and other flight systems have become of more interest for the exploration and investigation of foreign bodies throughout the Universe. On Mars, one of the most significant challenges is the thin atmosphere, which makes the generation of sufficient lift and thrust necessary to get a system airborne difficult. Nature offers a range of locomotion types for different media, and therefore provides a large pool of propulsion systems to get inspired by. Babu Mannam et al. (2020), for example, investigated several biological examples of flapping wings for their potential use in light atmosphere environments and summarized a design methodology and relevant hydrodynamic aspects to evaluate bio-inspired concepts for their application to different environmental conditions found on planets.

Eventually, the long-term goal of many space enthusiasts is to create manned habitats on other planetary bodies, elevating humanity from a single planet-based species to one that wonders the Universe. Hence, biomimetic concepts involved in the creation of habitats and continuously sustaining life under adverse environmental conditions will eventually become of much more interest. And with it, all of the biomimetic concepts already widely applied throughout many industries nowadays on Earth. This includes radiation protection, nutrition, waste management, as well as medical care (Jemison and Olabisi, 2021). ESA's *Advanced Concepts Team* even investigated the possibility of mimicking the hibernation behavior of mammalians (e.g., *Spermophilus tridecemlinneatus*) to achieve human hypometabolic state for long duration journeys (Menon et al., 2007).

One example with great potential are the water-living lotus plants, which have developed superhydrophobic surfaces that cause water droplets to simply roll off, naturally keeping the leaf clean and continously guaranteeing access to oxygen in the surrounding air. Another water-living plant species is *Salvinia molesta*, which is able to trap air on the leaf's surface and therefore can retain an air layer on top of their leaves in times where the leaves are temporarily fully submerged in water (Barthlott et al., 2016; Gobalakrishnan et al., 2020). Those mechanisms have been abstracted and applied throughout multiple industries but also hold merit for aerospace engineering. In fact, they have been proposed to prevent icing in small airplanes (Piscitelli et al., 2020) and water retention in a human life support system in spacecrafts (Rasheed and Weislogel, 2019). More importantly, such surfaces have been conceptualized for reducing dust and ice on solar panels on Earth (Wu et al., 2022), which is also of relevance for orbiting systems. Likewise, animals, too, have self-cleaning abilities similar to plants. The toe pads of geckos and tree frogs (Crawford et al., 2012; Hawkes et al., 2015) or the rigid forewings of dung beetles (Sun et al., 2012) present interesting methods keeping water from settling onto the surface of functional body parts. Mechanisms like these have been proposed for their implementation for anti-reflection, anti-fogging, micro-manipulators and self-healing in space systems (Xu et al., 2016), and are especially useful for things like lenses and visors, sensitive instruments such as batteries and power systems (Williams, 2022).

3 Biomimetics for space debris removal

3.1 Existing bio-inspired debris removal concepts

Space debris has become a major topic of concern, as defunct satellites, rocket upper stages and fragments are starting to threaten the operation of functional satellites, thereby endangering satellite communication, weather observations, and climate monitoring on earth (Sannigrahi, 2017; ESA, 2019; OECD, 2020). Hence, recent efforts have concentrated on space debris removal and mitigation measures (Ansdell, 2010), and options for more sustainable mission design as well as the establishment of mitigation guidelines have been proposed. These guidelines include provisions for incorporating removal systems such as drag sails into spacecraft design prior to launch for their eventual end-of-life (United Nations, 2010; Stokes et al., 2019). Especially drag sails have already been discussed within the scope of biomimetic design in terms of efficient folding and storage mechanisms, and several alternatives have been proposed, mimicking seeds and their dispersal mechanisms (Pandolfi et al., 2012; Pandolfi and Izzo, 2013) or tree and plant leaves (de Focatiis and Guest, 2002; Jasim and Taheri, 2018).

While space agencies and companies have focused on space debris capture and developing removal missions, to date no such mission has ever been performed. The first-ever operation simulating debris removal was conducted during the controlled activities of the RemoveDEBRIS mission in 2019, where a harpoon and a net were deployed to capture a previously released and well-known target body (Aglietti et al., 2020; Forshaw et al., 2020). In a joined venture of ESA and Cleanspace, the first debris removal mission Cleanspace-1 is scheduled to perform the first debris removal service of a VEGA secondary payload adapter as early as 2025 (Biesbroek et al., 2021). While these efforts 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 (Zhang et al., 2021). Both, nets and harpoons offer great opportunities for their adaptation by using biological models as inspiration. Nets have frequently been under investigation in biomimetic research ranging from textiles (Blamires et al., 2020; Gu et al., 2020) to optical fibers (Tow et al., 2018). Harpoons, too, have been studied extensively and concepts have been proposed for surgical tools, modelling tips and shafts after the bee's stingers (Sahlabadi and Hutapea, 2018) and mosquito's probiscis (Li A. D. R. et al., 2020), among others.

One of the most prominent and probably furthest developed biomimetic example for space applications is the gecko tape. The tape exhibits a specifically structured surface modelled after the example of a gecko's feet. Each toe of the gecko presents a highly adaptive microstructure with hundreds of hairs called *setae* as depicted in Figure 6A), each exertig a *van der Walls* force onto components, allowing the gecko to carry its own body weight up vertical surfaces or hang upside down (Kim et al., 2008). This mechanism has been replicated by multiple companies in form of a reusable adhesive tape with different microstructures as shown in Figure 6B), and tested extensively for various applications and consumer needs (Brodoceanu et al., 2016; Alizadehyazdi et al., 2020; Busche et al., 2020; Cauligi et al., 2020; Sameoto et al., 2022). One of these tapes was even sent to the ISS in 2019 to test its adhesive capabilities under micro-gravity conditions (Parness, 2017). Hence, gecko-inspired tape presents a great alternative that can achieve lasting and reusable attachment to objects in space. While some parameters such as the lasting adhesive capability or the effects of space dust on its performance still need to be explored further, gecko tape presents a great example for a substitute product within the space environment.

Current robotic arms used for extravehicular operations on the ISS (Roa et al., 2017) and debris capturing concepts (Estable et al., 2020) suffer from shearing areas, reserve movement capabilities or chaser movement among other things (Behrens et al., 2012; Estable et al., 2020). Several of these limitations can be improved by taking advantages of nature's diverse range of available biological examples. Octopi, for example, make use of eight identical and flexible arms for locomotion, grasping and reaching, as well as capturing food. These arms consist of mostly muscle tissue, which is able to selectively contract and therefore control their movements very efficiently (Cianchetti et al., 2015). Robotic systems inspired by octopi arms range from multi-actuator systems (Zhao et al., 2020) to soft robotics (Mazzolai et al., 2019) and have already been proposed for space debris removal (Le Letty et al., 2014; Shan et al., 2016; Jia et al., 2017). Their great mobility, maneuverability and adaptability makes them very suitable to wrap around complex target shapes. Likewise, other interesting biological models for similar tasks are presented by elephant's trunks or seahorse tails. The trunks of elephants are highly flexible organs with multiple degrees of freedom and therefore presents higher obstacle avoidance capabilities and an increased workspace flexibility (Yang and Zhang, 2014; Zhao et al., 2018). A similar segmented approach is demonstrated by seahorses, which use their tail mainly for grasping activities involving different diameter objects such as plant stems. Seahorses present a continuously decreasing square cross-section in their tail made from four individual plates connected through special joints. This arrangements provide the seahorse with great bending and torsion abilities for grasping, especially of a diverse range of shapes and sizes. In addition, thanks to its specialized construction, their tails shows great fracture resistances under crushing and impact forces (Porter et al., 2015). The concept has been transferred into a multitude of prototypes for robotic arms (Porter and Ravikumar, 2017; Li L. et al., 2019; Zhang et al., 2022a), one of which is displayed in Figure 7.

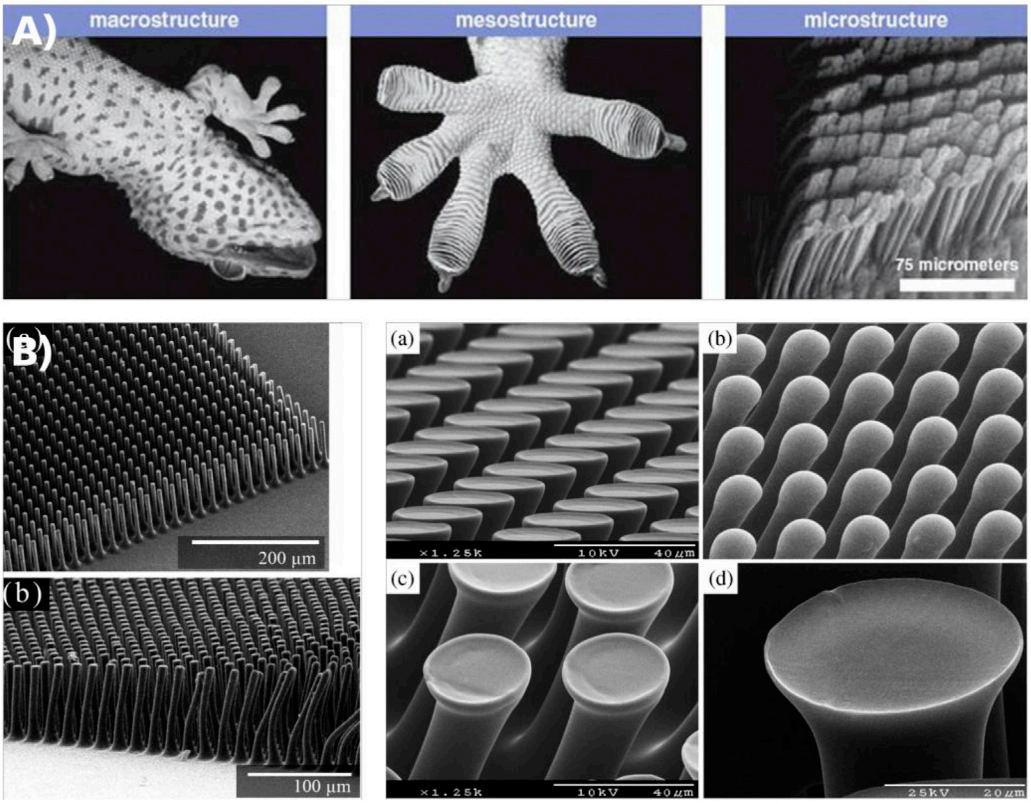

FIGURE 6
From gecko feet to adhesive tape, **(A)** Gecko foot and magnified view of the microstructures responsible for the adhesion thanks to van der Waals forces. Reproduced from Sameoto et al. (2022), with permission from Elsevier, **(B)** Magnified view of microstructures of different adhesive tape inspired by gecko feet, Reproduced from Aksak et al. (2007) Copyright 2007 American Chemical Society. Republished with permission; Reproduced from Murphy et al. (2007), with permission from Taylor and Francis.

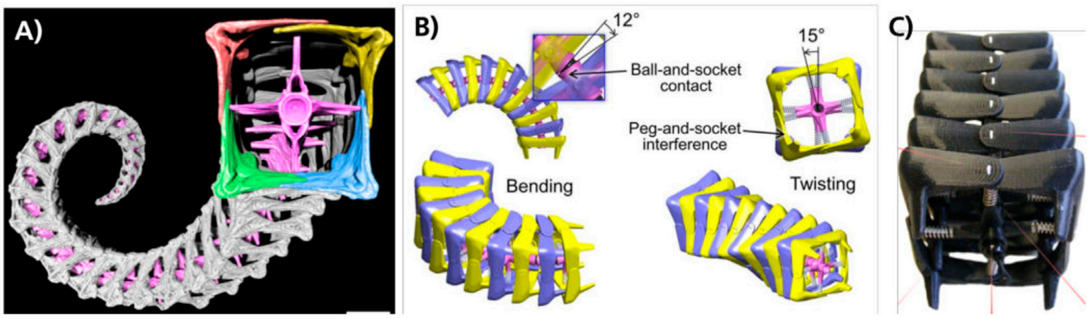

FIGURE 7
Seahorse tail inspired robotic arm. **(A)** nano-CT image of a seahorse tail skeleton, **(B)** CAD model of the square cross-sectioned prototype during twisting and bending movements, **(C)** photograph of a square cross-sectioned 3D printed prototype, Reproduced from Porter et al. (2015) , with permission from The American Association for the Advancement of Science.

3.2 The BIOINSPACED project

Within the scope of the ESA-funded BIOINSPACED project (acronym for *bio-inspired solutions for space debris removal*) conducted from June 2020 to February 2022, several bio-inspired space debris removal scenarios were established, incorporating a diverse range of biomimetic concepts. The project aimed to support ESA's initiative to mitigate space debris and reduce its negative impact on current and future missions. After analyzing the technical requirements for space debris removal missions, nature's pool of organisms was investigated to find suitable concepts and mechanisms with distinct benefits for space applications. Collected ideas were assessed to identify the most promising ones, that were then integrated into holistic mission scenarios. As the last step, one of

FIGURE 8
Photographs of the simple demonstrator developed within the BIOINSPACED project and the project logo.

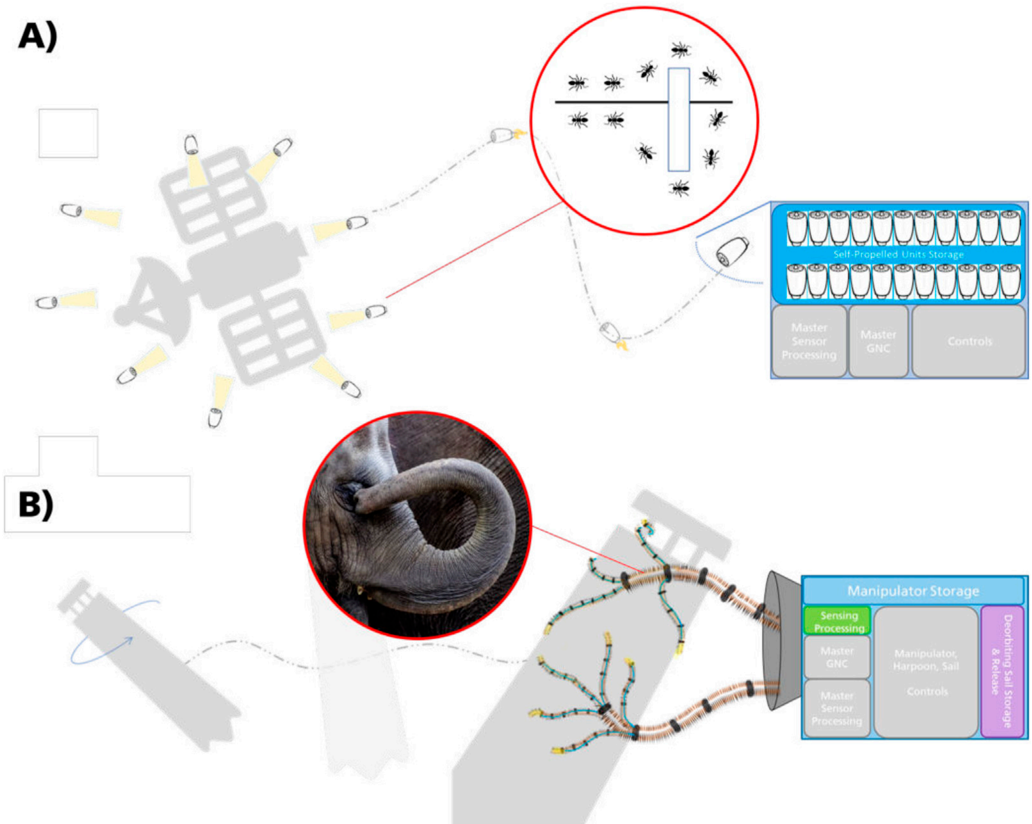

FIGURE 9
Sketches of the scenarios developed within the scope of the BIOINSPACED project. **(A)** Chaser vehicle carries several sub-units capable of observing, attaching, and deorbiting a target object in unison based on swarm algorithms (e.g., ant behaviour after Katiyar et al. (2015), **(B)** Chaser vehicle with tactile sensing appendages passively wrapping around slow-moving target upon contact modelled after the trunk of elephants (© 12138562, pixabay.com).

these scenarios was selected for a low-tech implementation in the form of a simple demonstrator depicted in Figure 8, underlining the benefits and variety of applications for bio-inspired technical solutions for space debris removal (Banken et al., 2021, 2022).

Besides the final demonstrator, the project also generated a comprehensive overview over biomimetic concepts and scenarios with further potential for aerospace engineering. One mission scenario conceptualized the use of the swarming behavior of ants to enable autonomous communication among several small and lightweight spacecrafts as shown in Figure 9A). These were theorized to organize themselves in specific patterns without requiring manual input commands, and therefore converge and arrange around a target object autonomously (Gro et al., 2006; Garnier et al., 2007; Divband Soorati et al., 2019). Processes like this can deliver a greater amount of details on target behavior, especially tumbling and rotational motion, which are important

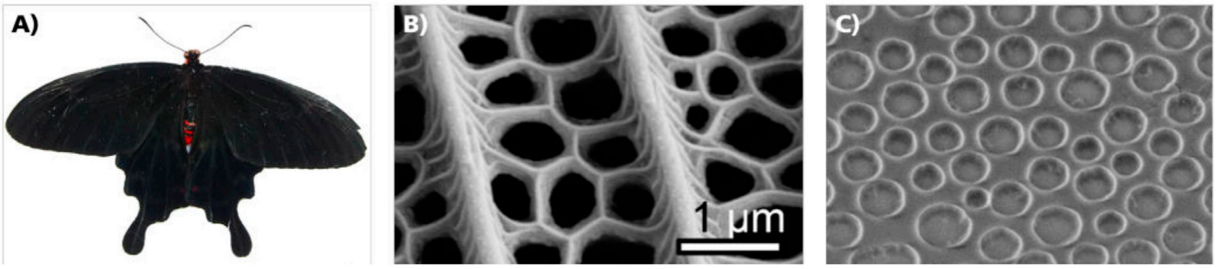

FIGURE 10
(A) Photograph of the *Pachliopta aristolochiae* butterfly, **(B)** Photograph of the nanostructure referred to as 'disordered nanoholes' that enhance light absorption, **(C)** Bio-inspired nanoholes etched into an amorphous silicon based photovoltaic absorber, Reproduced from Landgraf (2017), with permission from Julia Rohnstock (Assistant editor KIT).

factors for contact maneuvers (Stacy and D'Amico, 2018). In addition to target inspection, they can be used for target capture in the form of attachment to the debris and removal, using their own propulsion in unison to deorbit the object.

Another interesting feature identified during the project was tactile sensing within the space environment displayed in Figure 9B). Currently, most existing spacecrafts rely on optical sensors to determine a target's speed, rotation, and overall orbital mechanics. Yet, systems like these are known to suffer from e.g., dynamic illumination conditions or solar glare (Yilmaz et al., 2017). Nature provides a board range of organisms, which make use of tactile sensing as primary sensory input like mammals with vibrissae and insect antenna's. Some have already been explored in the field of robotics (Pearson et al., 2011; Lee et al., 2022). Paired with haptic sensors mimicking human skin and touch receptors capable of recognizing stimuli such as force, vibration and temperatures, as well as detecting hardness, force, slip, shapes, and textures (Yi et al., 2018), they offer great opportunities for on-orbit operations involving close contact with (un-)cooperative targets (Haschke, 2015; Pacchierotti et al., 2015; Xin et al., 2016; Yi et al., 2018), where high levels of flexibility and sensitivity are of great importance.

Further biomimetic concept extracted during the BIOINSPACED project with great benefits for aerospace systems are potential vibration sensors on the example of elephant feet (Lane et al., 2020), and touch recognition modelled after thigmotropism of plants (Vidoni et al., 2013, 2015).

Activities such as the BIOINSPACED project support the identification of new and innovative approaches for technical problems, while delivering an overview over existing concepts. Within the scope of the project, many promising concepts and scenarios were identified where mimicking a biological model could improve conventional aerospace systems or overcome current challenges. While none of the presented concepts comes without their challenges, they offer great alternatives and innovative ideas to approach conventional engineering limitations and disrupt existing constraints.

4 Biomimetics for on-orbit operations

4.1 Biomimetics for space-based solar energy

Solar-based power generation is one of the main sustainable energy carriers used on Earth. With ever-increasing global energy demands and rising pressure to switch to more sustainable fuel alternatives enforced by legislations and regulations such as the European Green Deal (specifically to reduce emissions by 55% until 2030 and to net zero by 2050 (European Commission, 2019), research has focused on improving solar-based efficiencies, storage capacities and overall performances.

Space-based solar power generation, which has recently become more of a priority to major space agencies around the globe (ESA, 2022), has clear advantages over Earth-bound solar power, because it does not suffer from a limited period for power generation. It is possible to produce solar energy independent of day- and night-times as well as atmospheric losses. Especially weather conditions, which usually highly impact production and storage capacities with risk of damaging involved devices, are eliminated with space-based systems. Hence, the main portion of collected solar energy can be converted into microwave power, which can then be beamed to any location on Earth as illustrated in Figure 10 free to use (Gosavi et al., 2021). Especially since the development of space-based solar cells is funded on the existing use of solar power as main sources of energy for many spacecrafts and satellites, technological development is rapid and in high demand.

Multiple biological examples can be found that use solar radiation to their advantage and either require it for internal temperature regulation [invertebrates, amphibians, reptiles (Norris and Kunz, 2012)] or photosynthesis (Hammarström and Wasielewski, 2011) for example. These effects can be adapted and transferred to technologies and processes involved in solar energy generation. Butterfly wings demonstrate periodic nanostructures producing an antireflective effect used to heat their flight muscles, which has been conceptualized and applied as lightweight solar concentrators. Similar nanostructures can also be found in the eyes of moths (Chen et al., 2011, 2014; Shanks et al., 2015; Vasileiou et al., 2021).

Solar cell development has also been influenced by the model of leaves, which present very efficient approaches for capturing and utilizing solar radiation. The combination of different types of tissue cells as well as intercellular air space was mimicked, producing a highly flexible organic solar cell with power conversion efficiencies of ca. 16% (Qu et al., 2020; Meng et al., 2021). Furthermore, to increase the wavelength spectrum absorbable by conventional solar cells, the charge transfer properties of biomolecules have been used as inspiration, adapted and transferred to achieve absorption of x-ray radiation (Cook et al., 2009b). Other applications for bio-inspired concepts include improved thermal characteristics of solar power systems mimicking hierarchical porous leaf structures (Shi et al., 2021), structural assembly and deployment of solar arrays on orbit, and radiation tracking (Sharma and Purohit, 2014; Jasim and Taheri, 2018).

4.2 Servicing, manufacture and assembly in space

Current research and developments for orbital spacecraft operations can be separated into on-orbit servicing, focused on extending the life of an existing spacecraft in orbit, and on-orbit manufacture and assembly, describing the construction of a new structure from modular components (Piskorz and Jones, 2018). Both operations have already been demonstrated successfully: on-orbit servicing by remotely inspecting and repairing the Hubble Space Telescope during its five servicing missions, allowing the telescope to deliver valuable science today, roughly 30 years after its launch (Boyd et al., 2017); and on-orbit assembly by the construction of the ISS starting in 1998, demonstrating the first multi-system structure designed for assembly in space. Over the past two decades, this structure has grown extensively, and with it its level of autonomy and control capabilities (Piskorz and Jones, 2018). Nevertheless, many of the previously specified bio-inspired concepts applicable to space debris removal can also be beneficial for servicing and repair activities. Contactless containment of a small satellite based on the example of a mouth or Venus flytrap (Shahinpoor, 2011; Banken et al., 2022), for example, would allow safe repairs and maintenance without the risk of spare parts, tools and spacecraft appendages to escape as additionally generated space debris. The Venus flytrap has already been used as an inspiration for advances in the fields of robotics (Shahinpoor, 2011; Falk et al., 2022; Tauber et al., 2022).

In addition, to make future space travel and exploration feasible from an economic and environmental standpoint, the lifetime of space systems need to be extended. While eco-design and self-repair can go a long way in preserving the function of operative systems (Ceschin and Gaziulusoy, 2016; Aïssa et al., 2019), they eventually fall victim to damages or their natural end-of-life. Hence, servicing, exchange and repair are proposed to re-use still functional parts and only replacing impaired or outdated components. The main biomimetic concepts found for on-orbit maintenance and repair are docking and grasping mechanisms for a servicing spacecraft to attach to an orbiting system. These include, for example, the previously introduced gecko adhesion and insect-like crawling robots (Xie et al., 2021). Furthermore, bio-inspired grasping and robotic manipulation have also already been discussed frequently for their use and application for on-orbit servicing and repair (Dai et al., 2020; Ellery, 2020; Ogundipe and Ellery, 2020).

On the ISS, several measures have been put in place for manual maintenance and smaller repairs, such as handrails along the entire outer module body for astronauts to safely maneuver to areas of interest. Hence, several intelligent, human-like robots have been developed within the past few decades, designated to perform tasks alongside astronauts and execute servicing on the space station (Jiang et al., 2022). One of them is the MonkeyBot with hands at the end of four appendages to navigate on the outside of the space station and carry out visual inspections (Wang et al., 2013). Other concepts for servicing the space station include chameleon-like (Ni et al., 2013), vine-like (Wooten and Walker, 2015) and tendril-like robots (Mehling et al., 2006).

Moreover, sustainable space exploration will and cannot be limited to earth-bound manufacture, assembly, and subsequent launch from Earth. This is especially valid for large structures, requiring an enormous payload capacity or multiple launches of separated subcomponents, leading to astronomical expenses (Sacco and Moon, 2019), and huge quantities of emissions contributing to climate change (Ross and Vedda, 2018). Hence, it has become apparent, that sustained future space exploration can only be achieved using *in situ* resources from other planets or asteroids (Ghidini, 2018), and manufacturing and assembling entire structures on-orbit (Rognant et al., 2019). On-orbit manufacture and assembly are not new ideas within aerospace engineering. They have been discussed for decades, and concepts and demonstrations have focused on the assembly of pre-made structures, enabling the construction of much larger erections than could be launched in a single spacecraft (Easdown, 2020). These present features like interfaces designed for modularity and connection to additional systems in space. In fact, the first mission including a structure for self-assembly, namely the new James Webb Telescope was launched in December 2021, and its successful erection will act as flagship for large-scale structures for autonomous self-assembly in space (Roa et al., 2019).

Another, even larger structure to be deployed within the space environment is the idea of the *International Planetary Sun Shield (IPSS)*. Global temperatures are rising, and climate change is moving quick, resulting in several goals and actions by international policymakers. Despite ongoing efforts of politicians and legislators, climate goals are predicted to remain unfulfilled until 2050, which would have disastrous temperature increases of 2°C as a consequence (IPCC, 2019). The IPSS concept presents a futuristic idea aiming to reduce global warming by expanding a huge ultra-light Sun shield in space to indirectly shade Earth from radiation. In order to present an effective outcome, this shield requires an enormous reflective surface area in the range of million square kilometers to be positioned rather close to the Sun at Sun-Earth Lagrange 1. At this size, launching parts and components separately from Earth becomes unrealistic and expensive, creating the need for on-orbit manufacture and assembly for the required solar sail (Centers et al., 2020; Jehle et al., 2020; Fuglesang and Herreros Miciano, 2021; Roy, 2022). Here, biomimetics could be a valuable attribute when looking for pioneering and ground-breaking solutions for extravagant applications.

Additive manufacturing is the most frequently discussed technique for the production of systems and components in space, and describes a process where a component is first sliced into 2D layers, and then traced with lines of material in a pre-defined manner to produce an entirely new 3D component (Dordlofva et al., 2016). The best known additive manufacturing technique by the public is 3D printing, where a variety of materials such as polymers, but also metals, biological substances and ceramics are layered to form a part (Gralow et al., 2020). This type of manufacturing offers a more diverse range of possible applications as it becomes easier to produce very complex geometries than with conventional subtractive manufacturing methods. Like the excitement and success of additive manufacturing on Earth, the space industry has been exploring these processes as a valid option for on-orbit manufacturing. Starting with printing individual spacecraft sub-systems to be included and launched in real life satellites (Sacco and Moon 2019), NASA launched the first 3D printer to the ISS and tested

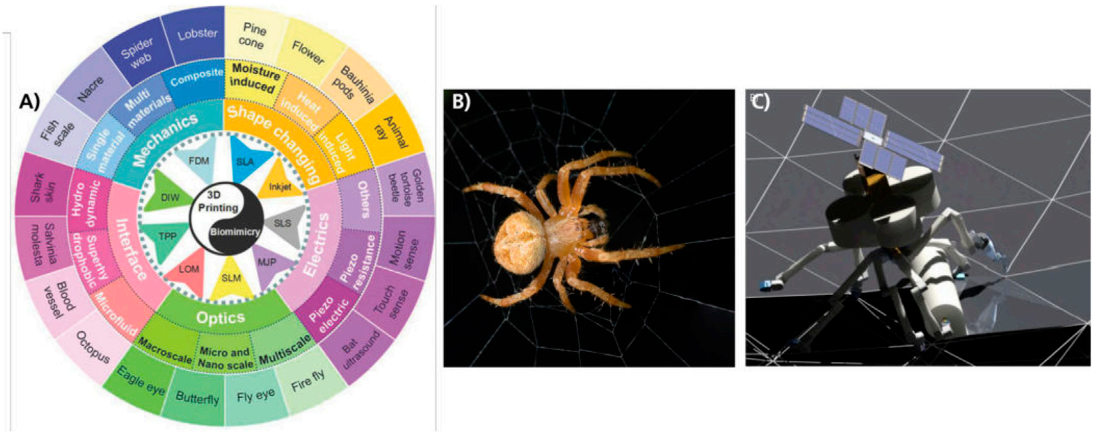

FIGURE 11
(A) Biomimetic concepts and their possible influence within different aspects of 3D printing and additive manufacturing. Reproduced from Yang et al. (2018), with permission from John Wiley and Sons. **(B)** Photograph of a spider spinning its net, **(C)** Model of SpiderFab, the bio-inspired assembly robot developed to construct large structures in space. Reproduced under CC-BY-4.0, Hoyt et al. (2013).

its printing capabilities in zero gravity, demonstrating the possibility for in-space production of parts (Prater et al., 2019). Since then, additive manufacturing has been investigated for its potential and feasibility for on-orbit manufacture ranging from single components to entire spacecrafts, as well as using "local" or *in situ* resources by sourcing the Lunar and Martian surface regolith (Grundström et al., 2021; Laot et al., 2021).

Additive manufacturing is particularly interesting for biomimetics because it is based on similar principles as can be found in nature. Intricate structures can be manufactured and formed while making efficient use of raw materials and available energy. As presented in Figure 11A), many biological concepts can be used for a diverse range of applications within the field of additive manufacturing (Yang et al., 2018), ranging from mechanics [formation of mollusk shells (Yang et al., 2018; Yaraghi and Kisailus, 2018)] and optics [compound eye of insects (Zhao et al., 2017; Yu et al., 2020)], to electrics [mechanoreceptors (Yi et al., 2018)] and shape-changing mechanisms [phototropism of sunflowers (Sharma and Purohit, 2014)] and medical applications [artificial organs and tissue (Zhu et al., 2021)]. Furthermore, biomimetics can be applied to achieve structural optimization, producing a part that uses less material but presents the same structural integrity as conventionally crafted parts. This allows the manufacture of more complex and new components without sacrificing any mechanical properties (Gralow et al., 2020; Yang et al., 2022).

Once individual components and parts are produced on-orbit, they need to be assembled. Assembling subsystems into highly stable constructs are common principles in biology on a micro- and macroscopic scale. Beavers, for example, demonstrate a great ability to build large structurally sound dams using wood to limit water flow in rivers. Their construction behavior is of great interest, since they are able to adapt to a range of hydrological features and species of wood, and still manage to build constructions comparable to human structures (Cheng and Hou, 2016). One advanced concept for on-orbit assembly was demonstrated by the SpiderFab, a self-fabricating satellite inspired by a spider spinning its web. Instead of a web, the system, as depicted in Figure 11B), is employed to build and assemble large apertures and multifunctional structures (Hoyt et al., 2013). On a microscopic scale, cells and organic components such as peptides have been under investigation for their self-assembly capabilities, especially in molecular biology and precision medicine (Levin et al., 2020; Yang and Jiang, 2020). Yet, it may be possible to learn from these assembly methods and apply them on a much larger scale for the application in space.

More processes involved in on-orbit manufacture and assembly can benefit from bio-inspiration, such as artificial intelligence [neural networks (Krichmar et al., 2019; Wang et al., 2021c)], robotics [gripping (Jiang et al., 2015; Jia et al., 2017)] (see Section 3), and resource acquisition [drilling (Pitcher et al., 2020)] (see Subsection 2.3). Therefore, biomimetics demonstrates an application potential in almost every aspect when it comes to on-orbit processes. They may vary in impact and benefit for the resulting system, and use different biological forms, functions, or processes as a model. Nevertheless, the existing literature and current increase of prosperity as well as the growing interest in the field of biomimetics imply that further research activities should be focused on including bio-inspired design into aerospace engineering.

At the pinnacle of on-orbit manufacture and assembly stands a very forward-thinking concept for long-duration space exploration missions of self-replicating robots. Space systems are equipped with all necessary parts and systems to be able to replicate parts and components that allow it to extend and exchange their own parts on demand. Self-replication in itself can already be considered a bio-inspired process based on the natural propagation and reproduction of species (Ellery, 2017). Nevertheless, other bio-inspired technologies and components necessary for the self-replication of space systems have already been tested and proven by e.g., the production of bio-inspired semiconductors for electronic integrated circuits manufacturing (Girish et al., 2022).

5 Challenges of biomimetic design

The literature presented in this review summarizes merely a snippet of the vast diversity of biological concepts and mechanisms available. The review highlights how they can be adapted and transferred to improve, optimize, and advance technical solutions within the space sector. It demonstrates the potential of biodiversity and offers insights into innovative design approaches by highlighting unconventional ways

TABLE 1 List of benefits and challenges of the biomimetic design approach covered within this review.

Benefits	Challenges
• multitude of solutions for similar technical problems (development of different ecological niches)	• Lack of understanding and investigatory techniques of the biological system and its functioning
• evolution over hundreds of years (long optimization process)	• Missing tools and methods to assess, investigate and determine biomimetic concepts
• resource-efficient erection and creation of structures, features and components	• Limitations of available Manufacturing technologies (especially for nano configurations in surface structures)
• collaboration of interdisciplinary experts in various fields like biology, biotechnology, engineering, medical science, architecture, and many more	• Expertise barriers causing a lack of communication between fields

for the development and design of processes, products, and interactions. Especially in terms of innovative and environmentally-friendly design, bio-inspiration has proven beneficial over the past decades. Therefore, it presents a multitude of advantages that might be explored within the fields of aerospace engineering and possibly support the evolution of a range of new products and processes necessary to pursue future-oriented goals within space exploration.

Nevertheless, despite the efforts conducted in this field of research, several challenges exist that hinder a persistent use of biomimetics throughout industries, which are listed in Table 1. The study of biomimetics has only experienced increasing momentum in recent years with more and more publications available over the past decades as presented in Figure 2 (Wanieck et al., 2017; Wanieck, 2022), even though the first ideas and methods have been identified as early as the 1950s in arts and design history (Montana-Hoyos et al., 2022). This phenomenon is attributed to three main limitations:

1. Lack of understanding and investigatory techniques of the biological system and its functioning
2. Missing tools and methods to assess, investigate and determine biomimetic concepts
3. Expertise barriers causing a lack of communication between fields

Many very interesting biological concepts remain poorly understood, since their function has mainly been linked to specific characteristics rather than putting them into context with the entire system (Bechtel, 2012). Therefore, part of the research is based on (educated) assumptions and ideas rather than proven knowledge about mechanisms and processes. Furthermore, nature oftentimes works on a microscopic level, with a multitude of tiny structures, arrangements and conditions that collaboratively achieve a function on a higher level. Hence, it is very complex to investigate the functionality of micro- and nanostructures as well as their interaction within the organism and what they are responsible for (Hwang et al., 2015). Even after system functionalities have been identified, much research has to be invested into the repeatability and scalability of concepts, which usually demonstrates to be the more difficult part for an adaptation and transfer (Sharma and Sarkar, 2019).

Moreover, biomimetic design and the process of investigating biological models is associated with great uncertainty as research does not always pan out to be applicable to technology. While this is true for most fields of research, the lack of systematic approaches, strategies and guidelines highlights this uncertainty further (Graeff et al., 2021). Even when biological models are sufficiently understood, their complexity often exceeds available technical capabilities and thus need to be scaled back during the implementation phase. The difficult part is to do that while keeping the biomimetic function in tact. Oftentimes, secondary effects or accompanying solutions help maintain or produce the desired function in the first place (Habib, 2011; Gralow et al., 2020). For example, while shark-skin inspired riblet hull coatings still suffer from some degree of fouling, sharks do not deal with the same issue. Their skin structure and body undulation are much more complex and interact with one another, which is assumed to prevent a permanent attachment of marine biomass (Ibrahim et al., 2021). Furthermore, during the implementation phase, technological constraints and manufacturability often become a limiting factor. While additive manufacturing techniques, for example, have come a long way and enable the production of very advanced shapes and products of various materials, they still present limitations that have to be considered when designing bio-inspired systems (Habib, 2011; Gralow et al., 2020). Once a biomimetic mechanism and technology performs well in a laboratory setting, it needs to be scaled up to match their real world application, which is just as difficult.

Within problem-driven design, it is important to determine the appropriate requirements and constraints that must apply to a solution. However, since biomimetics remains a relatively recent design approach, the quantity and quality of tools and methods to investigate biological organisms and evaluate the suitability of their function for technical applications is limited (Sharma and Sarkar, 2019). At the other end of the process, it is important to evaluate the value and functionality of the innovation and if it actually improves the desired aspects compared to the conventional product to achieve a competitive advantage (Yen et al., 2014).

Furthermore, the lack of communication and information dissipation between disciplines further impedes the use of the biomimetic design approach. In order to overcome expertise barriers, several entities and organizations are working on establishing and maintaining databases that are user-friendly and can easily be used to find solutions for experts of different sectors (e.g.,BiOPS, IDEA-INSPIRE, BioTRIZ) (Wanieck et al., 2017; Wanieck, 2022). The website *AskNature.org* even provides a publicly available database with more than 1700 biological strategies developed by living things that achieve thousands of different functions (Deldin and Schuknecht, 2014; Biomimicry Institute, 2021). Their intention is to provide readily available information for engineers, technicians, and scientists to adapt and transfer biological mechanisms onto technical products, processes, and systems. Yet, due to the vast diversity of models available in nature, these databases struggle to demonstrate the complete picture of the enormous possibilities. In addition, included models oftentimes refer to certain areas of application or types of organisms and appear skewed, thereby only providing an imbalanced array of models (Graeff et al., 2020). Moreover, tools and databases focusing on biological systems alone oftentimes neglect their extended use and function throughout the environment and their role among species, which can reduce comprehensibility of concepts drastically and cause loss of information. Hence, while many of these databases support biomimetic design, they can lead to misinterpretations and transfer failures, inevitably resulting in the abandonment of the entire approach (Graeff et al., 2021). Another problem for non-biology experts is how to find appropriate models to investigate regarding their suitability to technical challenges. On the one hand, existing literature involving biomimetic design has been found to lack the appropriate labelling, making it difficult to find. On the other hand, papers have falsely been branded 'biomimetic research', thereby not only confusing experts of different fields but also causing frustration (Lepora et al., 2013).

Since this issue was recognized by experts throughout various sectors and fields of research, they have come together to form networks such as BIOKON (German), The Biomimicry Institute (United States), Biomimicry Innovation Lab (United Kingdom), and the Global Biomimicry Network (international), to overcome these challenges and facilitate knowledge of biological phenomena into other disciplines like engineering (Sharma and Sarkar, 2019). However, one remaining constraint has been determined to be the difference in terminology throughout the disciplines, which has hampered the communication of concepts, benefits, and limitations among experts. In addition, concepts are often found to be too complex to compare them with anything known to the opposite party, thereby prohibiting the propagation of a detailed understanding of principles and systems required to transfer them into a working technical design (Yen et al., 2014). Therefore, to achieve the most effective biomimetic design approach, companies often prefer to have an interdisciplinary team of biologists, chemists, engineers, technicians and scientists working closely together to close the existing gaps and enable a more efficient and successful design process (Graeff et al., 2021). Still, transition gaps between the idea, its implementation and the creation of a profitable product persist (Sharma and Sarkar, 2019). Thus, biomimetics does not always deliver ideal solutions that can be perfectly and easily transferred onto technical systems. It can be viewed as more of an inspirational source that can deliver crucial input and understandings into the development process of products and processes (Wanieck (2022)).

6 Conclusion

This summary presents the most prominent currently existing biomimetic concepts, technologies and processes developed for space technologies and highlights innovative ideas to be investigated in the future. While the majority of these concepts and approaches are still under investigation and present a low technological readiness level, their benefits and potential to improve common aerospace technologies and strategies has been demonstrated. Due to the vast quantity of mechanisms and features found in nature, biomimetics can be applied to almost any area of technological advancements and can support traditional engineering in a large field of applications. This is especially related to the topics discussed in this review: protection against the harsh space environment, space debris capture and removal as well as on-orbit operations.

Certainly, more biological concepts with potential for adaptation and transfer into technical systems within the space sector exist. Nevertheless, the presented concepts provide a broad overview and insight into the diversity and multitude of possibilities available. Moreover, concepts were highlighted and proposed for some of the most interesting areas of application within the aerospace sector to date, namely planetary exploration, space debris removal, space-based solar power as well as on-orbit servicing, manufacture, and assembly.

Lastly, several challenges associated with biomimetic design have been identified that hinder the use of bio-inspiration during the development of innovative technologies for future applications. Yet, biomimetics has been proven to provide multiple helpful observations and can improve conventional space systems by proposing novel and creative ideas, even when dealing with the extremely challenging environmental conditions of space.

Author contributions

The authors confirm contribution to the paper as follows: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation: EB. Internal review: JO. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frspt.2022.1000788/full#supplementary-material

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