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Review

State of the Art Review about Bio-Inspired Design and Applications: An Aerospace Perspective

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Abstract: The field of bio-inspired design has tremendously transitioned into newer automated methods, yet there are methods being discovered which can elucidate underlying principles in design, materials, and manufacturing. Bio-inspired design aims to translate knowledge from the natural world to the current trends in industry. The recent growth in additive manufacturing (AM)methods has fueled the tremendous growth of bio-inspired products. It has enabled the production of intricate and complicated features notably used in the aerospace industry. Numerous methodologies were adopted to analyse the process of bio-inspired material selection, manufacturing methods, design, and applications. In the current review, different approaches are implemented to utilize bio-inspired designs that have revolutionized the aerospace industry, focusing on AM methods.

Keywords: bio-inspireddesign; additive manufacturing; aerospace

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1. Introduction

Bio-inspired design is a broad field of study, which emphasizes cognitive mechanisms to facilitate process-based inspiration. The method of utilizing biomimetic inspiration has been investigated since the 1950s by revolutionary thinkers, such as artists, engineers, and innovators. This was implemented in architecture, automotive, and the aerospace sector [1–4]. The incorporation of mathematics with architecture was used in the earliest construction of complex bio-inspired structures. Using such methods, the varying characteristics that can be adopted from different animals and birds were characterized, the primary focus being the wings of innumerable birds. Tucker and Parrott focused on the structure of birds, measuring the aerodynamic capabilities [2]. These include the gliding performance of the laggar falcon, emphasizing the soaring capabilities and the use of wind tunnels for testing the flight. In 1987, Norberg and Rayner saw potential in the optimal design of the bat wings and their varied applications in both mechanical systems and aerodynamic models [3], taking the aspect ratio and morphology as the primary measures and comparing it with the bat's specific movements. In later years, with the growth of industrialization and manufacturing techniques, there was a brisk development in rapid manufacturing techniques for bio-inspired design. The concept of biomimicry demands a scientific and engineering based approach, rather than to just be implemented in the form of a concept [5]. The application of bio-inspired concepts in the aerospace sector implements different inspired features, such as morphing and flapping methodologies [6]. The conceptual process flow for a bioinspired design follows the biomimicry methodology [7]. The initial steps focus on extensive research and laying the groundwork for existing biological systems and methods. These were further extended to specific areas where bio-inspired design was targeted and the methodologies it can follow for further scope. The entire framework was based on the process, structure, property, behaviour, which can further be elaborated for AM. These were expanded into the design spaces for the method of design of additive manufacturing (DFAM) [8]. One of the key examples was the wings of a beetle. It was chosen due to its large wingspan. After the study and research, experimentation is conducted to replicate this using a scotch yoke mechanism. This was used in drones and aerofoil structures. Subsequently, DFAM methods such as FEA (finite element analysis) and initial CAD (computer aided design) design were applied for manufacturing. The further scope for research emphasizes bio-inspired materials, which was combined with the plan for the optimization of parts [9,10]. The benchmark of design has evolved to a bio-inspired strategy to create artificial solutions with natural capability [11–16]. Systematic design literature and its methods have developed over the years, being much more relevant in today's world due to the approach of finding ecologically sustainable solutions. Figure 1 shows the different methods to implement the bio-inspired design, involving a top-down or bottom-up approach. The bio-inspired method [11] identified the unmet needs and translated these into the feasibility of an application. The bio-inspired method [15] used the biological functions to enable iterative solutions used to extract the neutral solutions, the combination of biology and mechanics followed by constraints. The Aalborg Method emphasized integrating the bionic design process that selected the natural system and evaluated the environmental factors [17]. The spiral design method [18] led to the development of a design brief that focused on the human need, with natural modes, and explored inventive principles to build ideas. The problem method analysed the micro to macro levels, to reframe the solution with parallels between the systems and components.

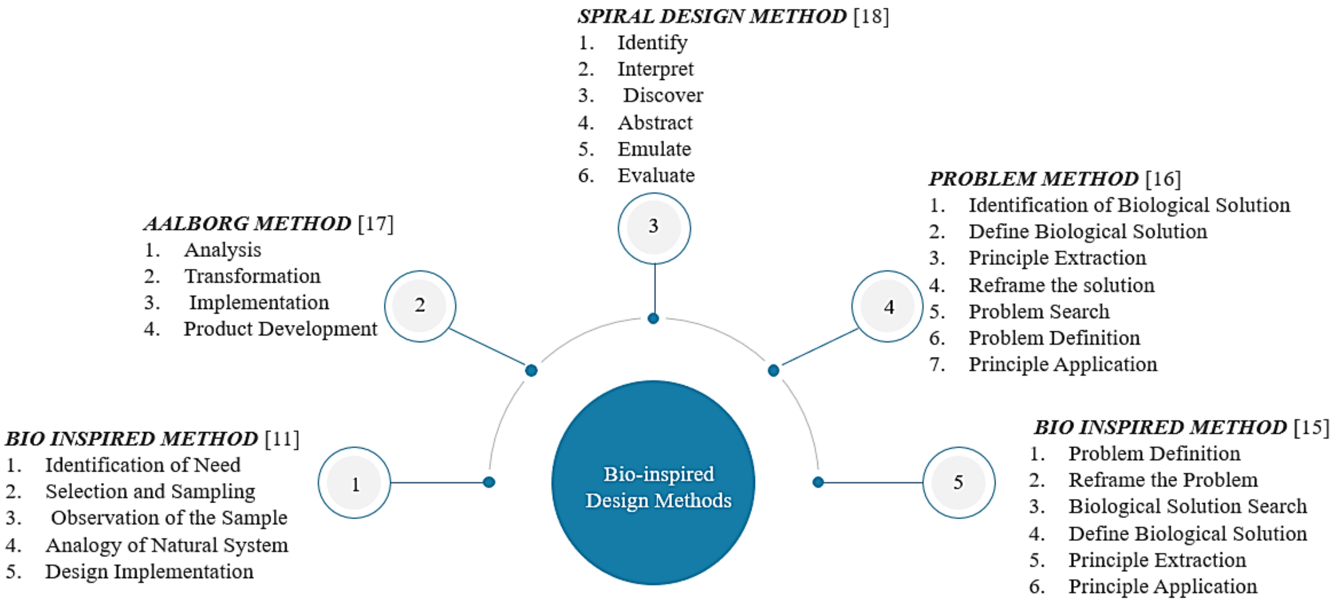


Figure 1. The bio-inspired design methods [19].

The replacement of conventional materials in aerospace with bio-inspired materials, techniques, and methods can damage tolerance, strength, and durability. The applications vary from specific rudder parts to aerofoil designs in aeronautical parts. Figure 2 shows the methodology adopted to review the bio-inspired design.

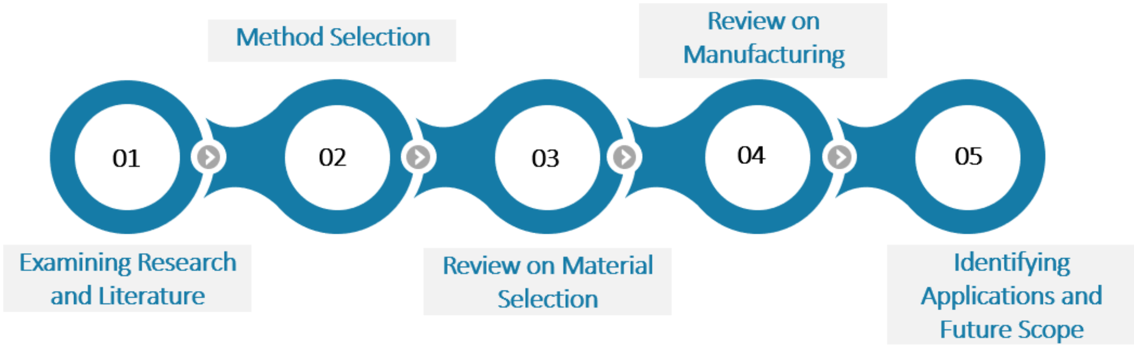


Figure 2. Methodology adopted in bio-inspired design review.

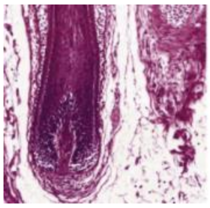
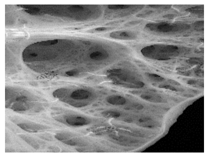
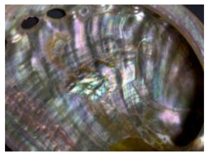
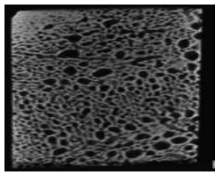
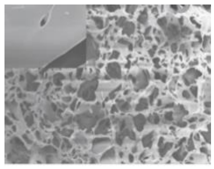
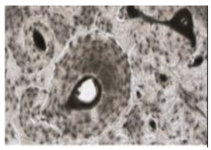
2. Review on Materials Used in Bio-Inspired Design

Bio-inspired materials mimic natural materials in terms of properties or functions, these are made of synthetic materials. Bio-inspired materials are a combination between biology and physical sciences. The combination of the various bio-inspired materials provides templates for performance enhancement. Hair-like structures consisted of a network of microfibrils, protruding from a surface. This inspired various devices, such as sensors, adhesion, and geometrical capturing arrangements [10]. Deep-sea glass sponges are capable of producing complex skeletal structures which were reconstructed using the laser additive manufacturing (LAM) technique. These reconstructed biomimetic structures displayed high buckling resistance for a particular material [14]. Nacre and other hybrids consisted of multiscale architecture which displayed high strength, high stiffness, and high toughness. These serve as great alternatives to synthetic materials, that improved structural integrity and provided ease of robust assembly [20]. In nature, the silk from the spider's web has the most common occurrence. These structures were made of microfibrils and the micro/nanostructures consisted of spindle knotted fibers. The interlinking of these amorphous chains were the domains of the supramolecular structure. The development of artificial biomaterials displayed water-controlling properties and impeccable strength [21]. One of the earliest bio-inspired structures was inspired by turtle shells which consisted of Ca, P, Cl, and Na, etc. These multilayer structures consisted of porous structures which were used in composite damping material. Moreover, the inspiration for composite structures that we see today was drawn from these porous shells [22]. Bone-inspired microstructures include bone regeneration to provide cell attachment and ingrowth. These materials were designed using a bottom-up approach and a hierarchical atomic structure [23]. Bio-inspired materials display impeccable material properties, such as self-repair, crack deflection, strengthening mechanisms, toughness, and lightweight structures [24]. These are used in aerospace, automotive, energy, architecture, agriculture, robotics, transportation, and healthcare.

Table 1 shows the bio-inspired materials, cellular structures, properties, and microstructures.

Burns et al. highlighted the tree trunk's internal structure [25]. It closely resembled a ball-socket joint structure arranged in a lay-up structure consisting of fibrils. In conclusion, the utilization of bio-inspired materials in composite and epoxy layers demonstrate properties, such as improved ductility and damage tolerance. Figure 3 shows the analysis of the T joint performance with respect to the buckling load to study the displacement for bio-inspired tree trunk material.

Table 1. Bio-inspired material properties [24].

Material	Cellular Structure	Properties	Diagram
Hair [10]	Keratin protein/Micro fibrils	Long degradation time	
Deep-Sea glass sponges [14]	Layers of silica glued with protein	Increased toughness and lightweight	
Nacre and other Hybrids [20]	Platelets of calcium carbonate/Aragonite	Anisotropic material properties	
Silk [21]	Long chains of amino acids	Toughness (comparable to Kevlar)/Biodegradable	
Turtle Shell [22]	Rib with suture touches	Flexibility/ lower density/Higher Strength	
Bone [23]	Lamellae and Osteons	Crack deflection, crack bridging, and deflection/Self-repair	

Honeycomb structures reduce the material density and honeycomb structures optimize the space to reduce deflection. Figure 4 displays the cellular structure of honeycomb, ladybug, and beetle which progressively show high strength properties [26].

The AM technique was employed in the materials; for bio-inspired design, the infill techniques in AM used ABS (Acrylonitrile Butadiene Styrene) it was used to vary the geometry. It offered the freedom to expand the various materials in specific designs [27]. The beetle structure with tubular showed the maximum strength performance, due to even weight distribution. Hogan et al. further emphasized the use of AM techniques to produce bio-inspired materials [28]. Figure 5 shows the methods for additively manufacturing bio-inspired materials and their subsequent properties.

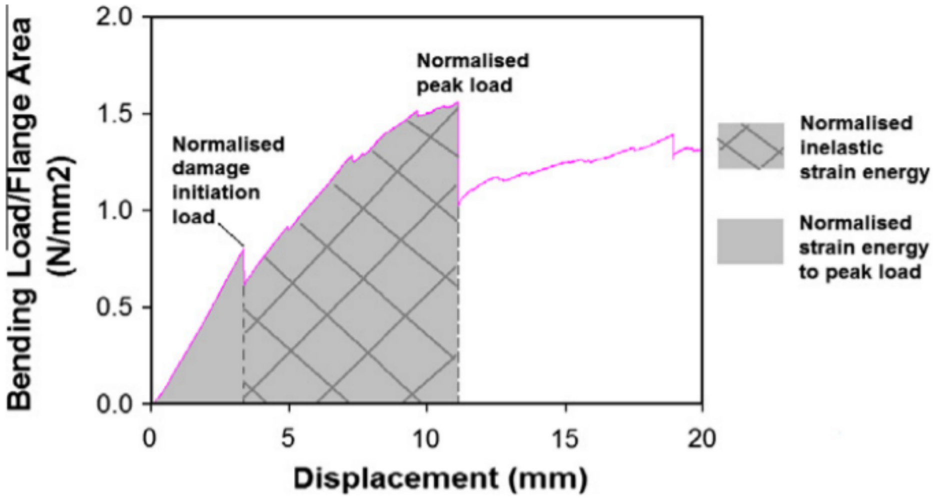


Figure 3. Definition of analysis metrics for T joint performance [25].

(**a**) (**b**) (**c**)

Figure 4. The various cellular structures in insects (**a**) Honeycomb Structure (**b**) Ladybug Structure- Tubular (**c**) Beetle Structure- Tubular Structure [26].

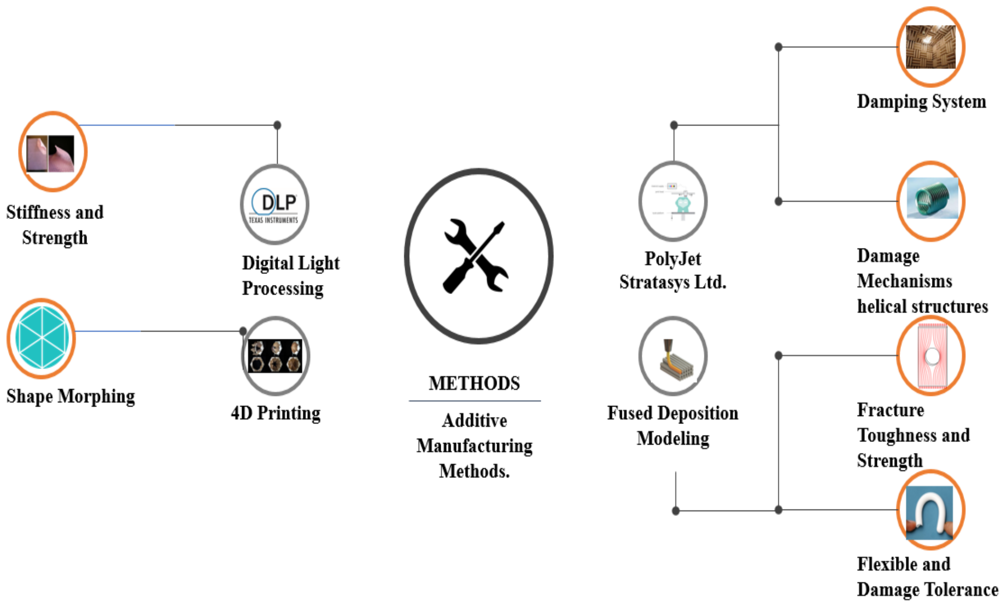


Figure 5. Additive manufacturing to reform optimize biomimetic [28].

The material properties inherit the design principles rather than duplicating the material design [23]. The honeycomb structures were printed using fused deposition modelling (FDM) that involved a layer-by-layer deposition of the ABS or any other required polymer to produce structures that were damage-tolerant with high fracture toughness. The complex geometry of nacre and deep-sea glass sponges were printed using Digital Light Processing (DLP) which ensured high stiffness and strength [28]. Skin structures are often one of the key inspirations in bio-inspired materials. Graphene manufactured with the chemical vapour deposition process displayed high compression strength [29]. The combination of cobalt naphthenate, ethyl ketone peroxide, and unsaturated polyester resins (UPR) were used to make fire retardant materials [30]. The braided epoxy composites were printed using AM techniques. The coolant material design in spacecraft was inspired by the earthworm that consisted of a film layer and porous surface [31]. This resulted in the most revolutionary features of bio-inspired materials that focus on properties, which has led to diverse applications in the aerospace, automotive, healthcare, defense, and architecture sector.

There are various methods of material selection as depicted in Figure 6 based on choosing a technique, artificial intelligence method, screening method, optimization, and fuzzy methods. The screening methods work based on an elimination method and the identification of multiple approaches for a particular problem. This involved the use of Ashby plots and considering the economic factors of materials. The materials were compared using ranking methods based on a multi-criteria decision-making process. The various processes followed a hierarchical approach to classify materials. The Artificial Selection methods used digital techniques for material selection, that rely on databases as compared to human experience, tools, and manuals. An extensive and optimized approach for material selection involved the use of programming tools to identify materials based on required parameters. Various strategies were analyzed with strengths and weaknesses for each specific material property. Life cycle energy analysis was used to identify materials with the least energy consumption. The use of fuzzy logic was to integrate specific assessment properties devoid of numerical rankings and the materials across various environments [32].

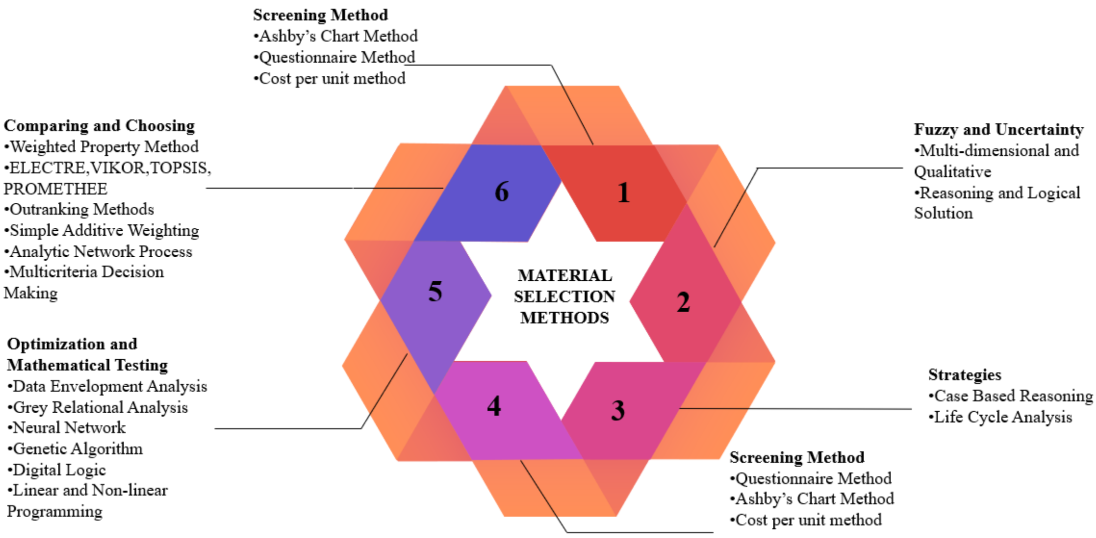


Figure 6. An assessment of material selection methods [32].

The various methods in Figure 6 used computing and strategic methods, which focused on mathematical calculations that chose methods based on performance indices. The methodology of material selection consisted of tools, strategies, and identification of limitations.

Table 2 gives a summary of the material properties, highlighting the contributions and inferences.

Table 2. Review of Materials used in Bio-inspired design.

Research Work	Contributions	Inferences
Burns et al. [25]	Investigation of T joint performance	Toughening mechanisms in tree branch joints
Gu [24]	Bio-inspired Composites	Use of AM technique in Bio-inspired
Wang et al. [33]	Fabrication of nano-graphene composites	Utilization of skin structure for material design
Xiang et al. [26]	Honeycomb structure under impact loading	Honeycomb structure (with circular tubes) is the best under impact loading by changing the structures' height.
Feng et al. [27]	Structural effects on ABS in nanostructure mixture	Impregnating CNC on ABS, inspired by wood
Hogan et al. [28]	Design method for bio-inspired structure	Using FEA to optimize bio-inspired structures

3. Review on Manufacturing Methods Used in Bio-Inspired Design

Greek architecture is the key inspiration for the earliest bio-inspired manufacturing methods Historically, accounts were seen in the Bolle di saponetraArte e Mathematica that described the geometry of a soap bubble. On a theoretical basis, it expanded from mathematics to architecture [1–4]. The distinction was made after identifying characteristics and noting the earliest ones being drawn from mathematics. Plateau described the energy distribution, and it was the onset for manufacturing bio-inspired design. The conventional manufacturing techniques lay the early onset for minimal surface production. [1–4].

The Topology optimization (TO) method was used across various industries, which followed the density-based approach. It used the DFAM aspect which resulted in more specific solutions to print bio-inspired structures which have a complex geometry [13]. Frascio et al. focussed on the adhesive-bonded specimens in a thermal cycle using 3D printing techniques [34]. The main advantage of AM techniques was the out-of-the-plane compressive response of panels, with bio fabrication. The inability of conventional manufacturing methods to produce complex geometries, limited applications, waste-production, and limited design structures led to the adoption a new manufacturing method [35]. Due to the complexity in nature, post-processing techniques were applied after powder-based processes [35]. The utilization of the selective laser sintering (SLS) method and its combination with six-design methods were used [36]. Aziz et al.broadly classified the different manufacturing processes of structures as depicted in Figure 7 [37]. This highlighted a hierarchical approach to manufacture bio-inspired structures, with eventual growth from the organism level to the ecosystem level.

Furthermore, the material structures were converted into the mason-slurry composition, which, incorporated by carbon nano tubes (CNT), amplified the reinforcing effects. The material layers and the hierarchical structure were proven successful in various applications, especially in aerospace [38]. These paved the way for the bio-inspired composites, which provide a near-net-shape for bio-inspired materials, which displayed anisotropic properties. It provided integration between AM and the techniques [39]. With the incorporation of 4D printing, there was an onset of shape memory transformations. In addition to 3D printed materials, it responded to environmental stimuli such as pressure, temperature, etc. [33]. The main advantage of AM was the key focus on sustainable development and production of high impact complex parts with material reduction. Product life cycle management was used for an all-encompassing bio-inspired method, from the physical characteristics to the design method. DFAM, sustainability, and bio-inspired design encompass the bio-inspired product [40]. SLS with a nylon powder and adhesive bonding was the technique used for this application. HoganVelsco et al. gave a detailed explanation and the characteristics of each AM technique, as shown in Figure 8 [28].

The structural–material properties were enhanced by the AM techniques, which were optimized for bio-inspired design, using generative design, topology optimization, and lattice structure design, as shown in Figure 9.

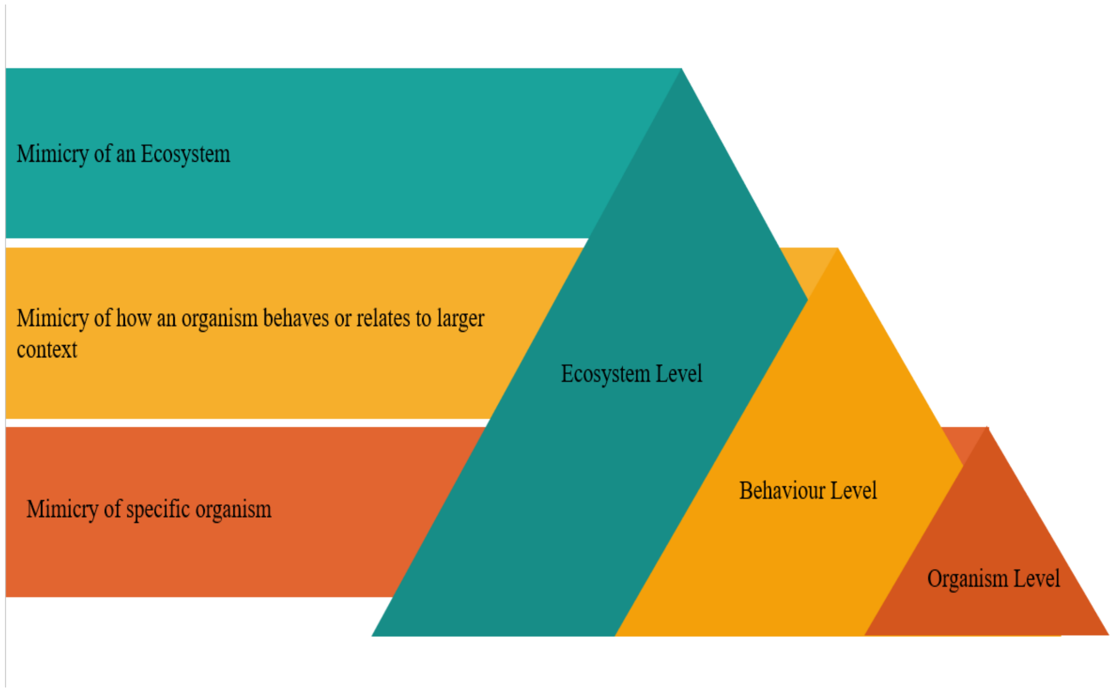


Figure 7. A framework for the application of biomimicry [37].

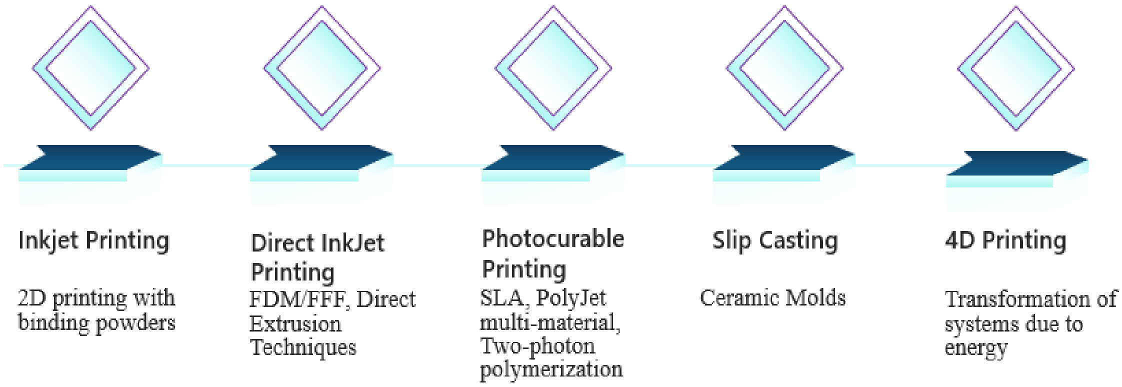


Figure 8. Additive Manufacturing Methods [28].

The constraints were further considered during manufacturing. The ideation to the design phase was solely dependent on experimentation [41]. This provided a synergistic system for bio-inspired applications. The research in bio-inspired design is inclined towards sustainable development, and this research methodology was implemented in the laser-based systems shown in Figure 10 [42].

The majority of the optimum ways of manufacturing bio-inspired design is multi-layered architecture [43]. They have higher energy absorption and hit capacity, which was increased by subsequent adhesion. Alternatively, fire-resistant properties were also noted using AM techniques. The GAP methodology establishes it for the design and manufacturing process. An extensive GAP method is shown in Figure 11, which implemented a product development cycle for bio-inspired processes.

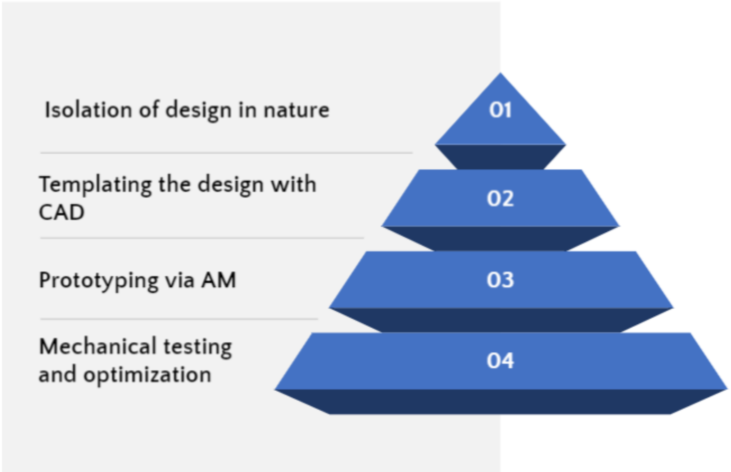


Figure 9. Procedure for AM testing [28].

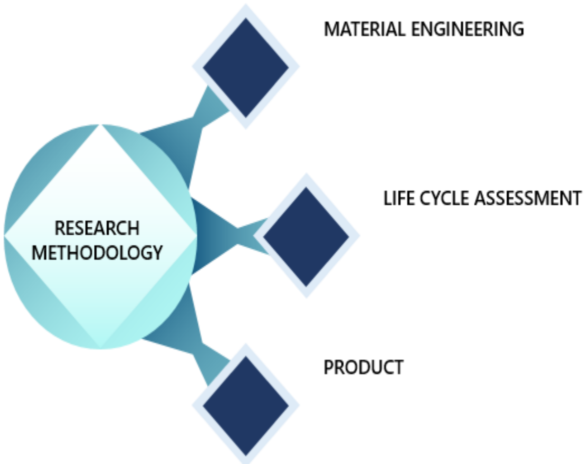


Figure 10. Research Methodology [42].

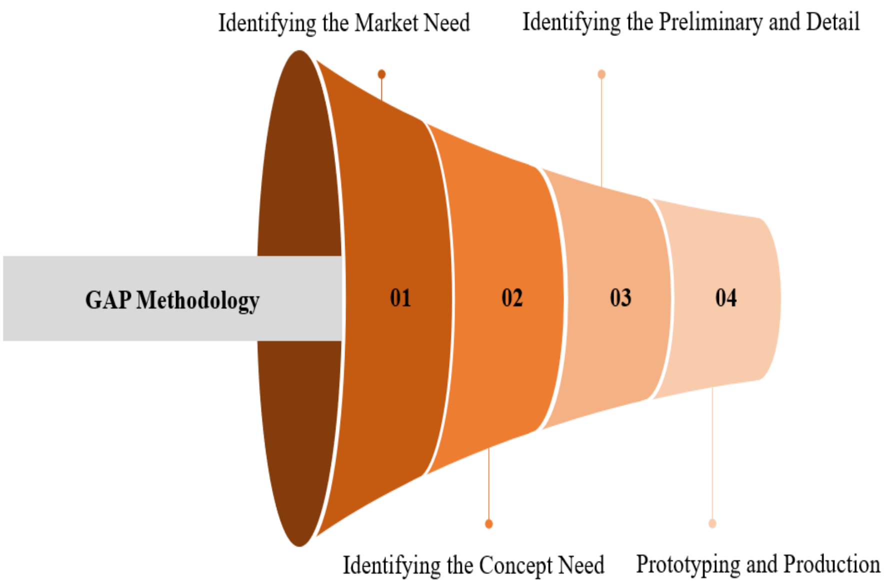


Figure 11. GAP Methodology [44].

CNC's infusion (cellulose nanocrystal) to print a composite structure [45]. The infill in ABS and the impregnation of CNC even at 100% infill opened new avenues for AM techniques. The bio-inspired design also inspired new frontiers in AM, including the gravo-elastic scaling using bio-inspiration [46]. The method emphasized the gravitational and aeroelastic scaling, it aimed at aeroelastic, centrifugal, and gravitational load acting on the load. The scaling-up process was followed by a ground testing method, with the blade structural scaling error. Along with the AM methods, optimization techniques such as TO, generative design, and shape optimization can be used [47]. Selective laser melting (SLM) techniques were used for the Ti-6Al-4 V fabrication. The compression testing was more efficient than conventional methods; it had strength beyond 300 MPa. Similarly, Sun et al. highlighted the mechanical properties of a bio-inspired tool path [48]. The parallel scan method was used for contour crafting, which involved printing honeycomb and nacre structures and assisted by FEA analysis. The growth in composite materials has increased in the past decade, which serves as an optimum technique for printing bio-inspired materials [44]. Toughness and strength were increased to 12% and 100%. The two main methods followed are given in Figure 12.

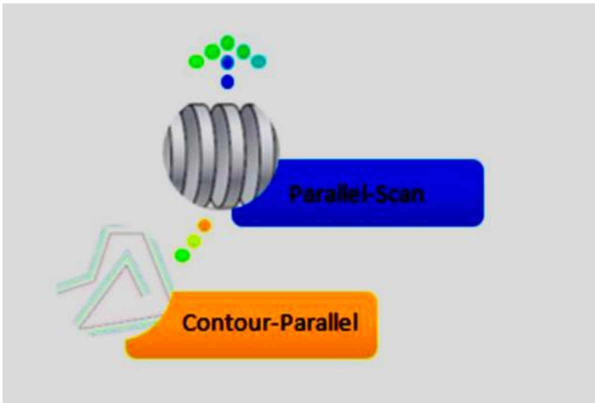


Figure 12. Types of filling paths [44].

The SLM techniques provide 10% more accuracy in designing corrugated, triangular, and square panels. Similarly, corrugated sandwiches with foam-related substances and metals with conventional structures sustained more shock and loading absorption [49]. One of the key features to be noted is the performance trade-offs for 3D printed designs, as shown in Figure 13. These represent the basic building blocks of bio-inspired materials, varying from brick mortar, concentric hexagon, cross lamellar, and rotating plywood [50].

In recent years, in combination with FEM techniques, the corrugated structures can aid homogenization [51]. The continuous growth of 3D printing from the nanoscale to the macroscale was aided by various structure formations shown in Figure 14 [52].

The CNC wire cut machine was used to impose manufacturing constraints in foam materials for groid fabrication. It highlighted the importance of using conventional manufacturing techniques combined with digital manufacturing [53]. Freeze casting methods were employed to manufacture bio-inspired structures that ensured the lamellar microstructures between ice structures that improved strength and complexities [23]. The beam-based dynamic model was proposed and could accurately transmit the waves and identify the multiparameter efforts. Furthermore, the thin-walled metal tubes provide superior mechanical properties, and these were the horse hoof inspired compared to vertex structure tubes [54]. The AM techniques utilized lattice structures with different process parameters, producing dense lattice structures, which provided successive transfer of load [55]. Conclusively, AM processes, in their futuristic approach, moved towards sandwich composites with re-entrant cores [56]. It ensured the balance between fatigue strength and loading. There is still scope for improvement due to crack development and fatigue failure. The compressive properties developed in both room and elevated temperatures [57]. The primary shortcomings noted were matrix softening and interfacial debonding. The presence of helicoidal structures reduced these failures. It is further enhanced by impact performance [58]. However, one of the critical concerns is the manufacturing defects due to the 3D printing techniques.

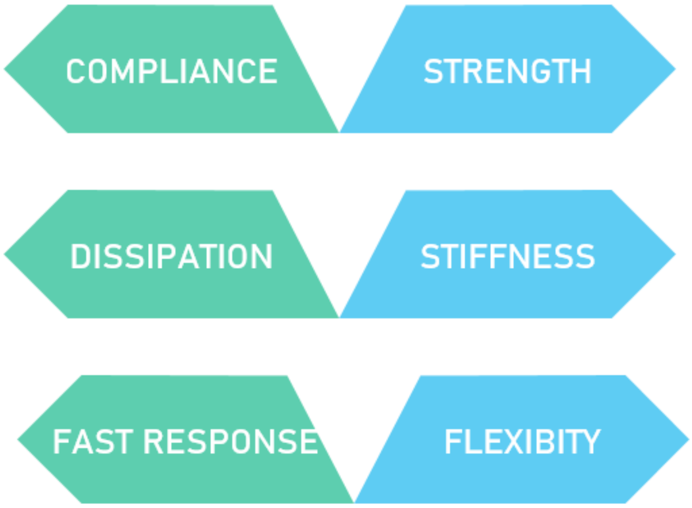


Figure 13. Performance Trade-offs in Bio-inspired structures [50].

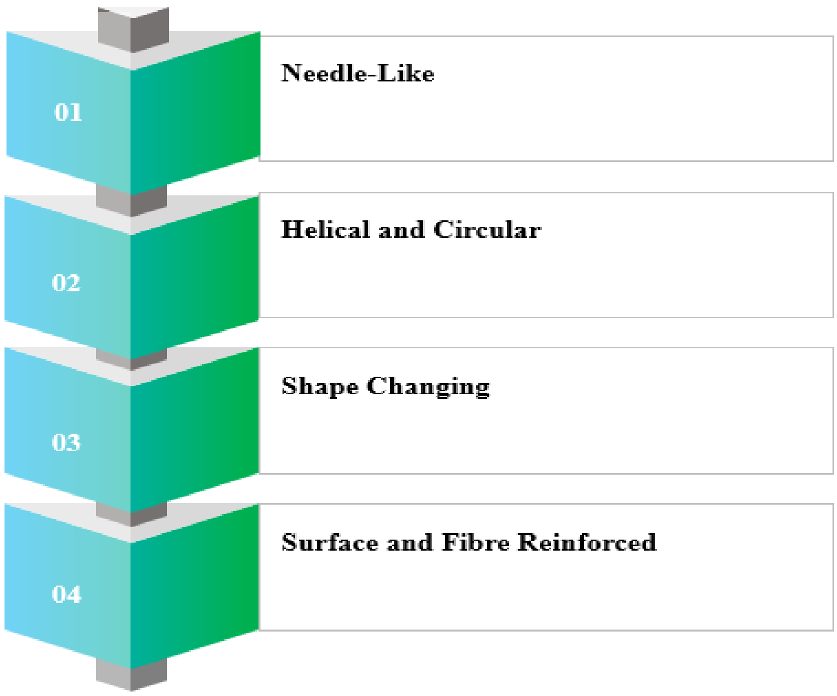


Figure 14. Bio-inspired Structure [52].

Bio-machining is a manufacturing technique that utilizes microorganisms to remove metal from the workpiece. The main advantages are the less utilization of energy and reduced thermal damage. It is a sustainable technique for machining micro components. These micro components are used in aerospace electronics and other technologies. The overall dimensions of the compact parts are around 100 µm. There are various kinds of machining processes which include physical, chemical, and biological. Bio machining is a controlled biological process that uses selective microorganisms to remove metals. It is a consecutive oxidation and reduction reaction, with an extracellular polymeric substance. Bio machining performed on a copper workpiece involved the conversion of Fe^{2+} to Fe^{3+}. Subsequently, the ferric ion acts as an oxidising agent, and Fe^{2+} was reduced by the microorganisms. This was a cyclic process inclusive of subsequent reduction and oxidation [59]. Tena et al. studied the machining of copper. The oxygen-free copper (OFC) consisted of a 10 × 15 × 2 mm disk rinsed with deionized water. The tests consisted of the OFC block in a culture medium, it was placed in a deionized sample and taken out in intervals. Extremophile bacteria was used in bio machining, and the efficiency was increased with the increase in the inoculum. This shows the potential to be implemented at an industrial level [60].

Slip casting was a technique used to manufacture bio-inspired materials and structures. The process consisted of the deposition of fluids into a mould. These were pre-dimensioned moulds, where the fluid is deposited and vacuumed after the wetting. The continuous assembly was used to prepare the bio-inspired structures. This technique when combined with AM can potentially be implemented for complex, nacre-based bio-inspired structures and tubular honeycomb structures [61]. The various manufacturing techniques with a focus on AM are highlighted and used to manufacture bio-inspired structures.

4. Applications of Bio-Inspiration in the Aerospace Industry

(a) Wing designs

A design based on seagulls' capability to morph their wings to provide reasonable aerodynamic and flapping control was mimicked [62]. The gulls' variable wing action was implemented in an aircraft design using lightweight airframe components and an actuator. This control linkage-based system helped change the wing's morphology. Figure 15 depicts the morphing wing structure in an aircraft. The experimental and analytical analysis results were found to agree with each other, thus proving the bio-inspired concept.

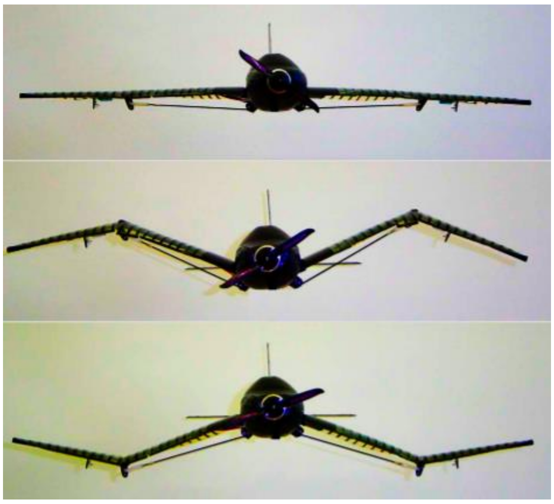


Figure 15. Change in wing structure based on variable gull morphing capabilities [62].

An implementation of a flapping wing mechanism attached rearwards to a fixed-wing in micro-air vehicles (MAVs) was studied in early 2005 [63]. Although the main, fixed element was found to provide most of the lift, the bio-inspired flappingwing provided more thrust and helped prevent flow separation for the main feature itself, thus improving the complete system's efficiency.

A bird's wing's three-dimensional flapping motion was implemented in a MAV design using a four-bar mechanism [64]. The motive behind implementing such a plan was to replicate the spatial flapping of wings to provide a similar aerodynamic advantage. The spherical mechanism was used for flapping, which when compared with a non-spherical mechanism, provided a favorable flapping mechanism for flight applications.

A humpback whale boasts a superior hydrodynamic performance by the tubercles on the leading edge of its flippers [64]. An inspired tubercle design on an aircraft's wing was developed to improve aerodynamic performance by increasing maximum lift and drag reduction. This could thus help reduce weight and fuel costs. Figure 16 depicts the implemented tubercle design on the wings and stabilizers of an aircraft.

Figure 16. Tubercles on the leading edge of the wings and stabilizers of an aircraft [64].

Leonardo da Vinci's plane design and inspired bird wing design to mimic the swift and effortless wing action of birds that enabled flight was discussed [65]. The designs were based on the anatomy of birds, which made them capable of flight.

A design inspired by a bird's wing's ability to change shape seamlessly, as indicated in Figure 17, depending on the flight itself was adopted to help provide enhanced performance [66]. A flexing parallelogram wing in place of a fixed, non-morphed wing element enabled an unmanned aerial vehicle (UAV) to reach its higher maximum velocity with a decrease in power requirement.

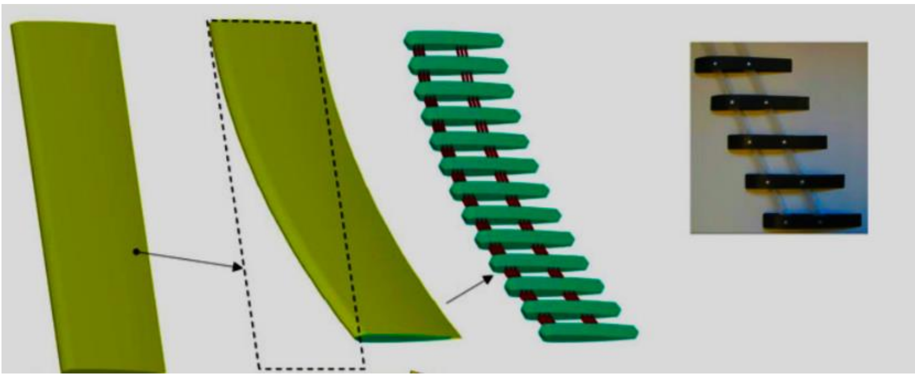


Figure 17. Design for a flexing parallelogram wing [66].

The impact that the shape of an insect's flapping wing has on its aerodynamic performance was analyzed [67]. When comparing the profiles of wings with equal wingspans, the bumblebee and honeybee were noted to possess ideal wing shapes. In contrast, on comparing wing conditions with a similar wing surface, it was observed that the bumblebee and the fruit fly had optimum wing shapes. Based on the shapes and other characteristics of an insect's wing, these data could be implemented successfully in larger aerodynamic applications to improve forward flight.

An elastically deforming wing design was explored as flexibility and capability of the wing to deform play an essential role in improving the system's efficiency [68]. Figure 18 depicts the flapping-wing design. Wing deformations are commonly observed in insects such as dragonflies, locusts, and honeybees, with wing deformations being necessary to maintain lift. A similar synthetic, flexible wing design made of carbon fiber, Kapton, and Mylar films was analyzed. The analysis revealed that the artificial wing's elastic deformations matched closely with that of an insect, thus proving the concept of the design.

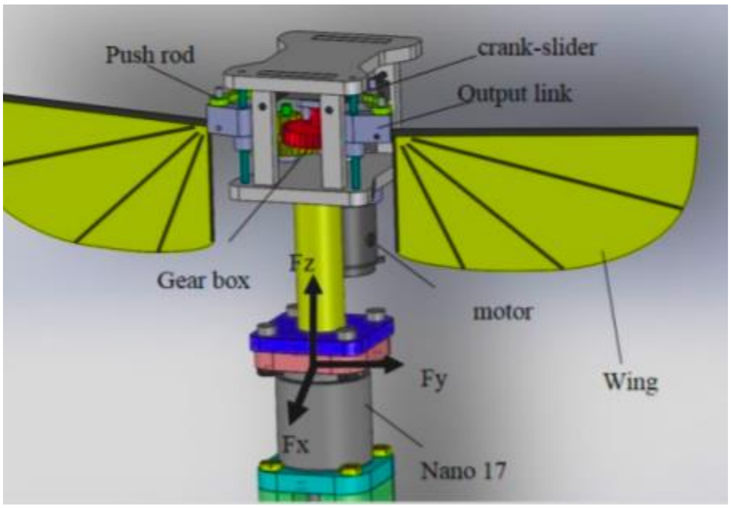


Figure 18. Mechanism for flapping to analyse wing deformations [68].

A study for flight in the Martian atmosphere was numerically analysed [69]. To offset the low density of such an atmosphere that directly impacts the aerodynamic performance and restricts commonly used space-flight techniques, a flapping wing, and a hovering mechanism was devised and studied numerically using the Navier–Stokes equation. It was predicted that a bumblebee's wing shape wouldn't sustain flight in the Martian atmosphere. However, an enlargement of the wing coupled with a flapping-based wing movement could help generate lift to counteract the increased weight on Mars.

A flapping wing MAV's noise control capabilities were improved by incorporating a wing design, commonly observed in insects such as bats and butterflies [70]. Dielectric elastomers and other similar materials were used as wings in MAV designs, namely an insect-inspired wing as a reference design, a moth-inspired fabric-based wing design, and an elastic wing design inspired by bats. It was found that the noise per unit thrust decreased with increasing flapping frequency for all the systems and that the rubber flaps provided a better noise reduction than the films.

A leading-edge alula inspired device (LEAD), influenced by a set of feathers on each wing of a bird, called the alula (refer Figure 19) was developed and verified for aerodynamic performance [71–73]. The LEAD provided optimal performance when placed along the wing's semi-span, increasing lift during post and deep stalling.

An investigation to improve the aerodynamic performance inspired by a pigeon's discrete wing structure. A continuous wing orientation revealed a better drag reduction with more increased lateral stability than a constant wing structure. This indicated the efficiency in the aerodynamic performance of a discrete wing design [72]. Figure 20 depicts the models developed for testing the discrete and continuous structures.

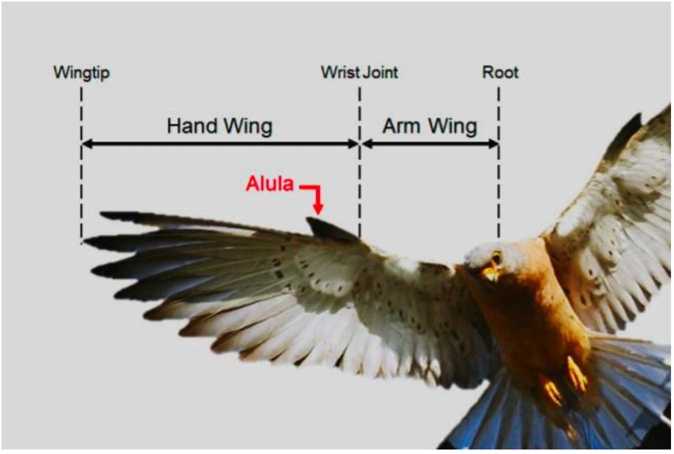
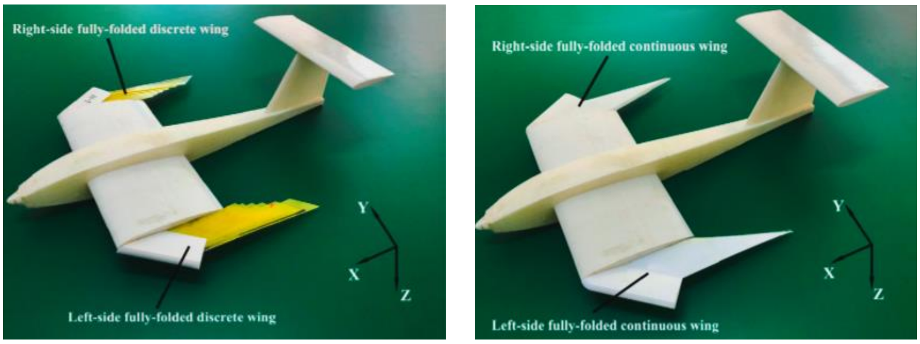


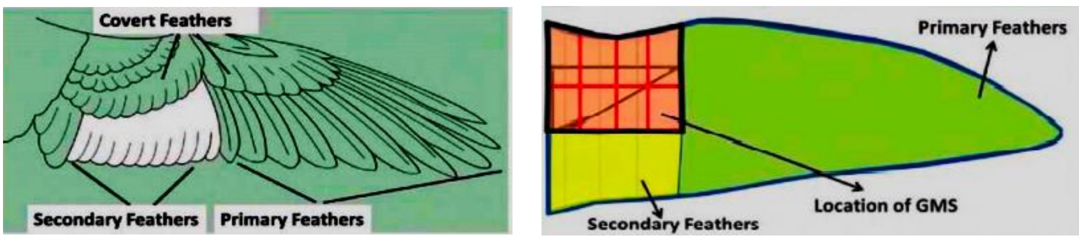
Figure 19. A deployed alula on the wing of the bird [71].



(a) (b)

Figure 20. Models fabricated for wind tunnel testing (**a**) Completely folded, discrete wing design (**b**) Completely folded, continuous wing design [72].

A corrugated wing designed based on a dragonfly was implemented on panels and verified experimentally, with results indicating an improvement in flow characteristics, with more considerable pressure differences between the upper and lower corrugated surfaces, causing an increase in a lift [73]. Another application of a flapping wing mechanism in a UAV to counter turbulence during the flight was approached [74]. During turbulent flights, birds tend to hover rather than flap their wings, which allow a set of covert feathers beside the primary feathers to deflect gusts of turbulent winds. Figure 21 indicates the natural and synthetic mechanisms for the same. The application of a gust mitigation system (GMS) in flapping wing UAVs served a purpose similar to the covert feathers, helping mitigate gusts of winds only while facing turbulence, and remained integrated with the entire wing at all other times to maintain the wing profile.



(a) (b)

Figure 21. Mechanisms to offset turbulent gusts of wind (**a**) covert feathers in birds (**b**) positioning of a GMS unit [74].

A Bat's wing possesses a very articulated musculoskeletal system, which assists them with multiple degrees of freedom, in addition to a compact and lightweight mechanism [75,76]. Mimicking this behaviour, Figure 22 depicts an arm wing structure that was modelled and analysed. The design showed successful wing performance during the flapping motion.

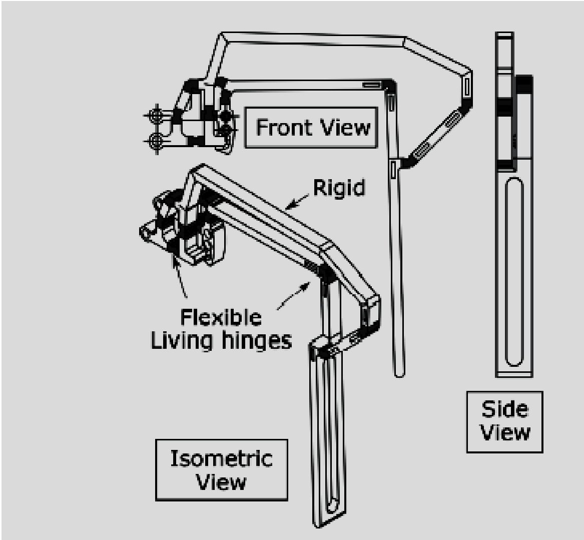


Figure 22. Computer-aided design of the arm wing structure mimicking a Bat's wing [75].

(b) Sensors

The implementation of sensors in aerospace engineering plays a crucial role in determining an aerial vehicle's response towards its surrounding stimuli. An early application of bio-inspired sensors can be traced back to 2003. The problems regarding the installation of environment perception sensors on small-scale aerial vehicles like MAVs and UAVs were the issue [6]. Small winged insects have particular neurons for the same purpose called elementary motion detectors, which helps them form a safe path through lit obstacles. Two micro-bots were mounted by optic flow sensors, to implement optical motion detection. Experiments revealed that this enabled one of the microbots to perceive a safe distance from the ground even after altering speeds and enabled the other to fixate itself on a contrasting target. The functioning of the International Space Station and the crew aboard can be in imminent danger in the event of a leak in the station's walls [77]. To counter this, various pressure sensors inspired by the sensory capabilities of a swarm of bees are distributed throughout the station to pick up signals in case of a pressure loss. In the event of a pressure loss, a swarm of pressure sensors around the region of failure is activated. An ultralight indoor aerial vehicle, inspired by flies' flight, was capable of autonomously steering the aircraft [78]. A fly's ability of trajectory control was incorporated into the system of the plane as well.

Another study based on a bio-inspired optic flow sensor-enabled a MAV to perform tasks such as take-off and leveling mid-flight [7]. Optic flow sensors were tested on serial vehicles for perception sensing of indoor and outdoor environments to assess their sensitivity to illumination [10]. The study proved the sensors to show sound visual processing under natural conditions. A low-cost optical sensor based on the compound eye of a fly was developed, which helped gauge the angular position of a distant edge with a minimum accuracy of 160 times, concerning the particular interceptor angle [79]. A bio-inspired optical device was developed based on a fly's ability to gauge speed, landing, and obstacles based on elementary motion detection [80]. A sensor similar to the compound eye was developed to mimic the large field of view and the exceptional ability of the insect to process light. This helped with terrain navigation and auto landing, with a 360-degree FOV. Figure 23 indicates the sensor developed inspired by a compound eye of a fly.

(a) (b)

Figure 23. Optic sensors based on Elementary Motion Detection (**a**) Compound eye of a fly (**b**) A bio mimicked synthetic compound eye [80].

A VODKA sensor was also implemented to locate a contrasting target, precisely an edge [81]. This optical sensor (refer Figure 24), inspired by insects' rapid eye movements such as a housefly was mounted onto a MAV and detected an opposite edge at an exceptional resolution.

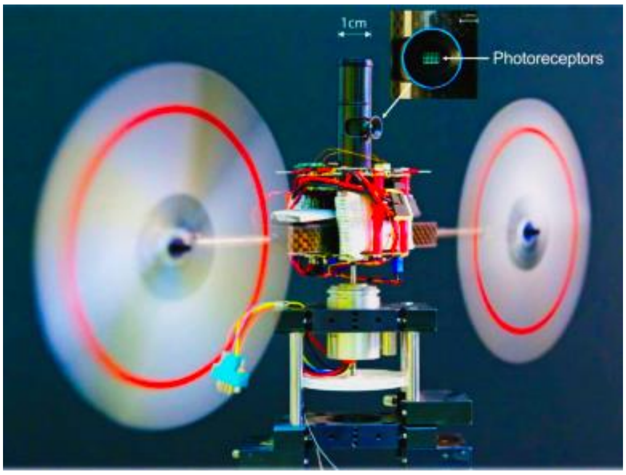


Figure 24. VODKA sensor mounted onto an MAV [81].

A bio-inspired pressure sensor installed chordwise on an unmanned aerial system was used to control the aircraft attitude using a trained artificial neural network [82]. A pressure sensor inspired by mechanoreceptors embedded in a bird's wing was implemented in a MAV to establish roll control in a turbulent environment by showing the correlation between the pressure variation on the wing surface and pitch angle variation of the upstream flow [83]. A bat possesses several sensory hairs on its wings. Influenced by these structures, a UAV was set up with strain sensors that controlled roll motions, and pressure sensors (chordwise) were able to control pitch motions [84]. A bio-inspired pressure sensor's robustness to detect airflow installed strategically on the leading edge of a small UAV wing was indicated by numerical analysis. It showed promising results under the change in external stimulus [85].

A quadcopter design inspired from the lobula giant movement detector neurons (LGMD) in locusts was designed to detect possible collisions [86]. A neural network based on LGMD was designed, modelled, and experimentally analysed, with results indicating reliability in terms of collision avoidance. A sensor to detect appropriate landing sites, considering the movements of landmasses on a planetary structure, was developed by NASA [87]. The optical sensor worked on the compound vision principle and could be used for remotely measuring the displacements. Implementing a 2D optic flow sensor based on the compound vision of flying insects in an autonomous MAV indicated that the sensor could track objects successfully at a maximum frame rate of 120fps [88]. Multiple sensors were efficiently assembled within the synthetic compound eye and also had low power consumption. Birds' ability to use atmospheric conditions to benefit their flight was exploited in a design based on harvesting energy under different wind conditions [89]. The experimental analysis revealed that harvesting energy using various pressure sensors and other components enabled the aircraft to maintain altitude. Another implementation of pressure and strain sensors using a trained artificial neural network helped detect unsteady flow and stall [90].

(c) Structures

The influence of biomimetics in the aerospace industry has led to the development and implementation of several bionic structures in advanced, high-end applications. There have been significant developments of bionic systems, other than the standard honeycomb and Kagome structures. Apart from applying a dragonfly-inspired wing in MAVs, dragonflies also possess a very optimized body structure and could ensure lightweight aerospace body parts. Their self-cleansing wings provide constant dirt removal that helps maintain stability [91]. The segmented body of a honeybee was used to influence an aircraft's nose cone [92]. A segmented nose structure helped the vehicle with enhanced manoeuvrability due to improved bending properties and the aircraft's axial scalability. The structure of the skin of an aerospace vehicle is of great prominence as a thermal protection layer. A bio-inspired quadrilateral shape structure (BIQS) was tested on a similar setup for its ability to reduce the vibrations due to impact with debris post-capture [93]. Figure 25 depicts the complete structure, including the BIQS, for an in-orbit capture. It was found that the BIS provided a better vibrational damping performance in comparison with a spring-mass damper.

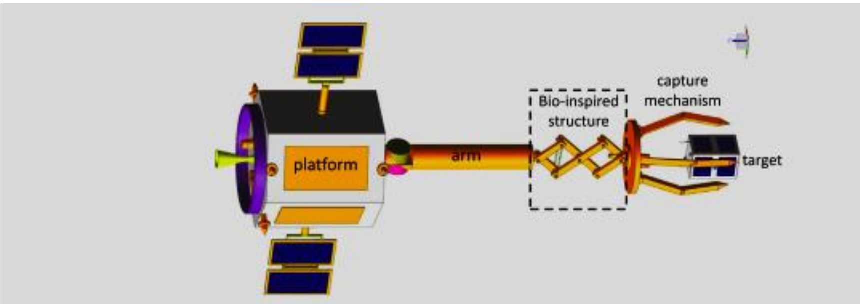
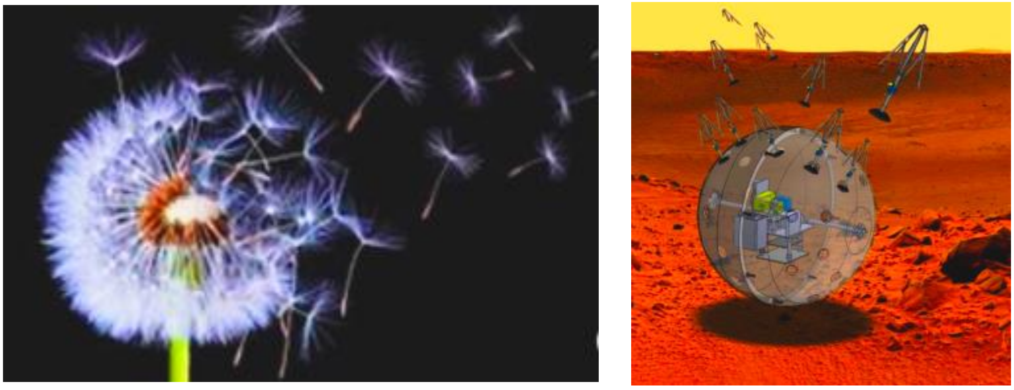


Figure 25. An in-orbit capture, with the BIQS system to suppress post-capture vibrations [93].

A lightweight, thermal resistant corrugated core sandwich structure inspired from a peacock mantis shrimp was preferred over a honeycomb structure owing to its lower weight, lower heating rate, and minimum deflection at high heating [94]. The heat flow (via transpiration) from the combustion chamber for a hypersonic vehicle was biologically mimicked. A parallelogram-style non-smooth structure was used which improved the cooling rate, like the skin of a tapeworm [31]. A rover to tackle the harsh conditions offered by Mars, which can lead to increased travel time, was theoretically designed at NASA [95]. The design idea involved a giant spherical robot equipped with several separate wind-driven micro flying rovers that would be detached from the spherical bot, just like the seeds of a dandelion, as observed in Figure 26.



(a) (b)

Figure 26. (**a**) The seeds of a dandelion being driven away by the wind (**b**) micro flying robots being detached from the spherical rover and being driven by the Martian wind [95].

A wheel design inspired by an African ostrich's feet was developed based on its ability to travel on the sand, owing to its unique toe structure [96]. The wheel design could be an effective means of traveling on Mars, with its capability of reducing soil resistance. Considering the debris present in space at the moment, the ISS and other satellites could be in danger of being struck at any moment. A bio-inspired anti-impact manipulator (BAM), based on kangaroos' spring-like movements, was developed and tested for in-orbit capture of this debris [97]. The spring-like motion of the bio-inspired structure helped reduce the impact velocity of the incoming waste. The scales embedded on the skin of a teleost fish provide stiffening and stabilizing mechanisms for protection and robustness [98]. The scales provide strain stiffening, which promotes the development of morphing structures for aerospace vehicles.

5. Conclusions

This review emphasizes bio-inspired design with its influence on materials, manufacturing methods, and aerospace applications. It highlights the properties such as strength, durability, and manufacturability. The approach aims at identifying upcoming materials such as Ti-6Al 4V which use SLM techniques and can potentially be utilized in gathering space debris. The methodology used in bio-inspired structures and surfaces can be manufactured using AM techniques, with its underlying focus on UAV and MAV designs based on bio-inspired systems, which have not been thoroughly exploited. The characteristics of various material properties, such as toughness, flexibility, and self-repair, displayed in silk, turtle shell, and hair can be employed for aerospace technologies pertaining to contour crafting. Bio-inspired materials could potentially aid 3D printing structures in space. The key to future aerospace technologies' growth lies in sustainability, which can be achieved by AM techniques and bio-inspired tools. The multiple design processes that can be utilized for conversion into products range from the Aalborg method to the GAP methodology.

MAV and UAV design is interpreted from flapping-wing mechanisms of birds and other winged insects and the presence of specific features of a bird's wings that aerodynamic aid flight has been explored. The possibility of developing a wing design based on the natural tendency of winged animals to take flight and adjust naturally to conditions that can alter the natural flight conditions has aided the development of similar aerial vehicles that have helped develop optimized designs. Coupling the newly developed techniques with lightweight materials, such as titanium alloys (Ti-6Al-4V), aluminium alloys, and bio-inspired composites, and simultaneous additive implementation manufacturing can genuinely help create lightweight structures that can further help improve flight. The sensors which guide the aerial vehicle have been developed based on bio-inspired phenomena as discussed. The ability of sensors to perform in harsher conditions of space and other planetary environments still has further research scope. The implementation of lightweight structures and AM to supportfabrication for space exploration can be further explored. The development of bio-inspired facilities in the aerospace industry can aid weight reduction without a compromise in reliability, as is already observed in the performance of efficient biological structures. The aerospace industry could be massively benefited provided the said design structures and sensing capabilities are applied on a much larger scale and to much larger systems.

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