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Biomimetics: Applications in Structural Design

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ABSTRACT: Biomimetics or biomimicry is the process of emulating and incorporating natural phenomenon in mechanical design. These ideas can be used to help designers overcome complex problems with relative ease. The premise being that nature over years of evolution has resulted in near perfect and highly efficient designs that serve as a constant source of innovation for humans. Generally, these developments tend to be the most sustainable and energy-efficient, as expending minimal energy is an evolutionary advantage for all beings. This technical case study attempts to elucidate some of the advances and implementations of bio-inspired engineering in design. First, a general introduction to the whole process of bio-inspired design and some key examples of its implementation are presented. It is followed by a detailed synopsis of a few popular products and some computational tools used in the field. Finally, a few implementations in architecture and material science are covered. With the increasing stress on sustainability, bio-inspired design certainly has the potential to revolutionize every industry with unique, efficient and prudent solutions.

KEYWORDS:Biomimetics, Bio-inspired design, Structural Analysis, Optimization, CFD, Architecture, Bio-inspired materials, Sustainable design, Product design

I. INTRODUCTION

"Survival of the fittest", a phrase commonly used in evolutionary biology refers to the principle that in nature, organisms that can navigate their eco-system more efficiently tend to have higher chances of survival. All species pass on these advantageous traits to future generations and thus, over time evolution results in the most optimal design for organisms. This is true at both the microscopic and macroscopic level. At the same time, energy and resources are of paramount importance to organisms, thus these design features must also ensure minimal energy consumption and not require too many resources. Biologists and designers are constantly studying the mechanisms that give rise to these optimal designs and their applicability in product innovation. [1]

From these studies arose a new branch of engineering design, Biomimetics. Bio-mimicry or bio-inspired design incorporates natural phenomenon and evolutionary advantages into product or process design. Some very common examples include using paddles and swimsuits for swimming, and Velcro straps, which were inspired by duck feet, shark-skin and burr needles respectively [2]. Nature has a massive pool of design innovations to draw inspiration from. In order to extract

useful information, a systematic approach is necessary to bridge the biological and engineering domains. A comprehensive overview of biomimetics [3], sheds light on this approach and has been used as the basis of this review. Along with this overview some interesting examples like an octopus inspired catheter and crab inspired legged robot are also provided in the paper. The hexagonal cell arrangement of beehives is a perfect example of a structure that has the highest packing efficiency while using minimum resources. This structure has massive applications in the aircraft industry (control systems in wings tail and floors) where high structural strength and low weight are in great demand.

As resources are limited, sustainable development and judicious use have become the norm. There is a need to innovate and optimize the efficiency of designs so that products use the least amount of resources and energy. At times like these, biomimetics can be implemented to identify solutions that have been developed over millions of years in nature and provide a high degree of efficiency. Simultaneously, there is a pressing need for conserving ecosystems. Human action has caused large scale decline in population of fauna. This upsets the balance in nature and can lead to disaster. By studying and taking inspiration from these organisms, we can in turn, increase awareness on their plight and help bolster conservative efforts too. Bio – inspired design is therefore not only helping bring about sustainable technologies but also increase conservative approaches and maintain the natural order.

In the following passage, some examples of modern interpretation of biomimetics in structural engineering have been elaborated on.

II. THEORETICAL FRAMEWORK FOR BIOMIMETIC APPROACH

The theoretical framework considered involves categorizing each problem statement into familiar categories, so they can be approached in a systematic manner. Design approaches fall under 2 basic needs: I) a top-down approach and II) a bottom-up approach, which have been elaborated upon by M.S. Aziz, A.Y. El sherif [4].

1.1.1. TOP – DOWN APPROACH

Defining a human need, and then looking to nature to find ways to tackle the solution is called a "Problem driven Bio-Inspired design" or "Design looking to biology". Here the problem for which we require a solution is already known and designers need to identify organisms that have dealt with similar problems in order to identify the natural solution. [Fig. 1]

1.1.2. BOTTOM – UP APPROACH

Unlike the previous framework, this approach involves implementing prior knowledge about some biological phenomenon or organism, to generate unique solutions to design problems. It is also known as "Solution-Driven Biologically Inspired Design" and "Biology Influencing Design". The key component of this approach is that the design problem is not known in detail before the biological observations take place, rather these observations lead to new solutions to problems [Fig. 1].

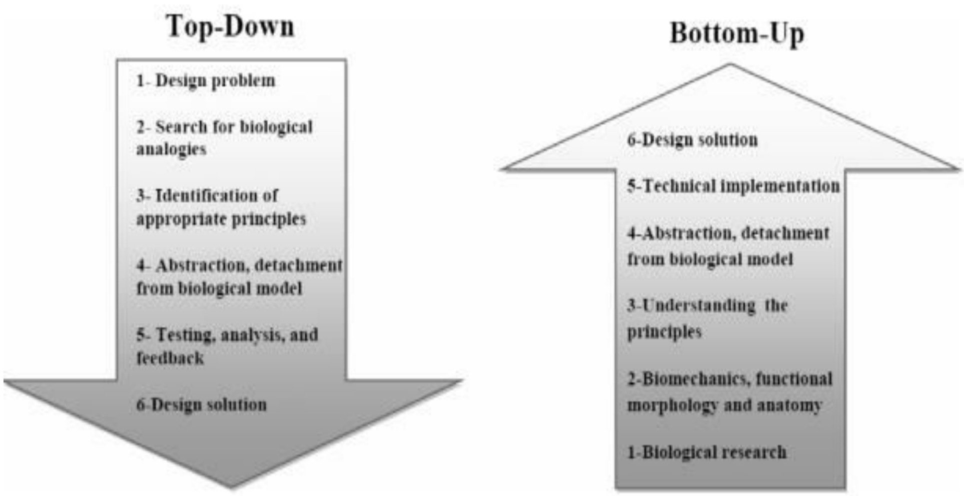

Fig. 1. Approaches to Bio-inspired Design, *(Sourced from: M.S. Aziz, A.Y. El sherif [4])*

On probing deeper into the framework, we observe 3 levels to biomimetics: 1) Organism level 2) Behaviour level and 3) Ecosystem level, that refer to the strata of nature that is being mimicked [4,16]. Furthermore, each of these levels can be expanded to the kind of mimicry that is being done. They are: Form/Shape, Material, Construction, Process and Function.M.S. Aziz, A.Y. El sheriff [4] thengo on to provide examples of these applications and then delve into the implementation of computation in bio-inspired design. They look into CAD design, surface generation and modification tools and the explore idea of minimal surface generation.

III. BIO-INSPIRED ENGINEERING

2. BIO-INSPIRED PRODUCTS

Organisms have an amazing ability to build complex structures to serve them specific purposes, like spiders' webs and birds' nests. Products like fishing nets can be said to draw inspiration from spider webs. These can be viewed as very specific engineering problems with a set of defined requirements, such as the temperature that the nest must be at, or

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the number of eggs it can contain. Then we can begin to breakdown the function of the biological structure in terms of design parameters. Similarly, for the spider web, the shape, strength of the thread and the size of the hole determine the average size of the prey and amount of prey the web can trap. For fishing nets, the size of the net directly correlates to the size of fish that can be caught and their number. These similarities can be observed from the Fig. [Fig. 2] below.

(a) (b)

Fig. 2. This frame compares the functional and structural similarities of a fishing net and spider web: (a) Shows a fishing net, which is superior in terms of catching volume, and relative time required when compared to other means like fishing poles; (b) is an image of a spiderweb laid out to trap insects. *(Both Sourced from google images)*

1.2.1. THE JAPANESE BULLET TRAIN

The Shinkansen or the Japanese bullet train is one of the fastest, most efficient means of land transport in the world capable of reaching speeds of up to 320 kmph. It is known for its peculiar deigns that is unlike most other trains[Fig.3.(a)]. This is because the Shinkansen draws inspiration for its design from the beak structure of the Kingfisher, a bird that is commonly found near waterbodies. It has a very distinct long, pointed beak, with short legs and stubby tails. The kingfisher's diet primarily consists of fish and they generally swoop down at high speeds to impale prey with their beaks, which they later go on to consume.

Over millennia, the kingfisher beak has evolved to be the least drag inducing design that is capable of sustaining high acceleration and top speeds. Multiple studies have been conducted studying the fascinating structure of this beak for its drag reducing properties. One particular study [5] examined the relation between beak morphology and dive performance by simulating dives with 3D printed models and CFD analysis.

The physical models used have been described in detail, the dive test was conducted by dropping the beak structure from a height of 75 cm above the water surface. The model was allowed to fall along a fishing line wire and the accelerometers were mounted on a falcon tube body with weights to record the deceleration due to drag. To account for the variations due to slight changes in entry angle, 10 tests were conducted for each model (Test only involved vertical drop into water). The CFD analysis was conducted on Autodesk CFD 2019 and a virtual flume was simulated. The parameters for the analysis have been elaborated upon and the beaks were given the properties of ABS Polycarbonate.

The results of both the tests generally agreed with each other with some variations due to the fact that the CFD models were smoothened unlike the physical ones and did not account for transition between air and water (Simulated movement in one fluid only). In general, all tests showed that aquatic kingfishers had improved drag reduction properties in their beak structures and thus were more suited for diving in comparison to their terrestrial relatives. This same principle has been applied to design the front of the bullet train and has massively decreased the drag, improving the speed and fuel economy. The beak structure is displayed below
[Fig. 3. (b)]. in comparison with the bullet train.

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(a) (b)

Fig. 3. Comparison of the similarities in the design of the shinkansen and a kingfisher: (a) the frontal design of the Japanese bullet train capable of high speeds and exiting tunnels without generating a pressure "boom"; (b) beak and head structure of a Kingfisher (piscivorous). *(Both Sourced from google images)*

1.2.2. WOODPECKER INSPIRED HELMET

Helmets form one of the most crucial aspects of protection while riding motorbikes. They protect the head from major injury and absorb the crash impact. Even so, the sudden jerk passed on from the helmet to the brain during impact can cause concussions. One idea that has picked up recently is to structurally modify the helmet based on studies of woodpecker skulls [6]. The woodpecker is a bird that is known for drilling holes in trees by vigorously tapping them with its beak. So naturally its skull has evolved to withstand this constant impact without passing on the impact to the brain or developing concussions.

A detailed analysis of the shock absorbing capability of the woodpecker has been studied by *Sang-Hee Yoon &Sungmin Park* [7]. They began by noting that the bird's posture and body remained perpendicular to the beak as it strikes, and that the head remains fixed and does not move or rotate in a "yes – no" manner. This is said to greatly mitigate any shear force acting on the brain. X-ray CT scans were used to study the head structures of the woodpecker, including the beak, hyoid, skull and spongy bone tissue [Fig. 4]. They also noted that the woodpecker has a relatively long and sturdy tail that acts as a "counter-balance" and props up the bird during the drumming action.

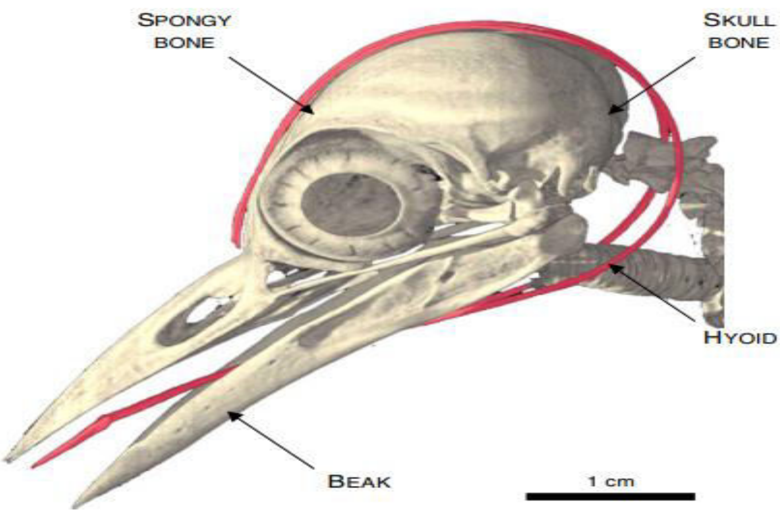

Fig. 4. Shock absorbing endo-skeletal system of woodpecker. The 4 major components are: The Beak, Hyoid, Spongy bone layer and Skull bone layer. *(Sourced from Sang-Hee Yoon &Sungmin Park [7])*

An elaborate overview of the mechanical vibration analysis has been provided, including the assumptions for the simplified mass-damper-spring lumped parameter model [Fig. 5]. It has been noted that when the woodpecker strikes

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its target, its endoskeleton structures: the beak, hyoid, spongy bone and skull bone "stand in a row sequentially" to absorb the impact of the drumming action. This ensures that maximum stress is mitigated before it reaches the brain tissue.

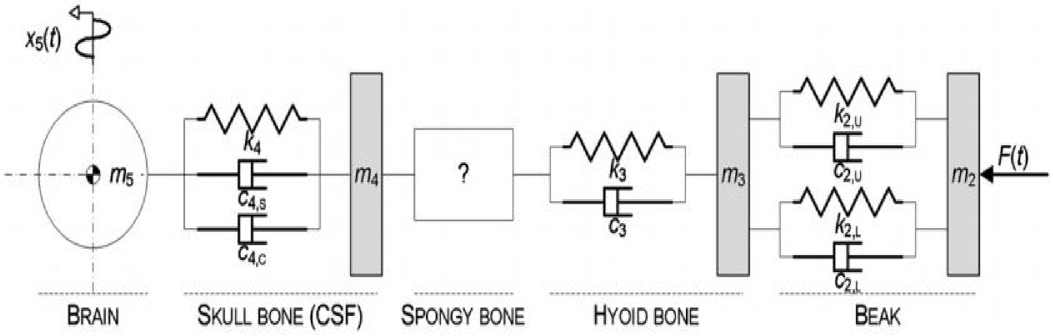
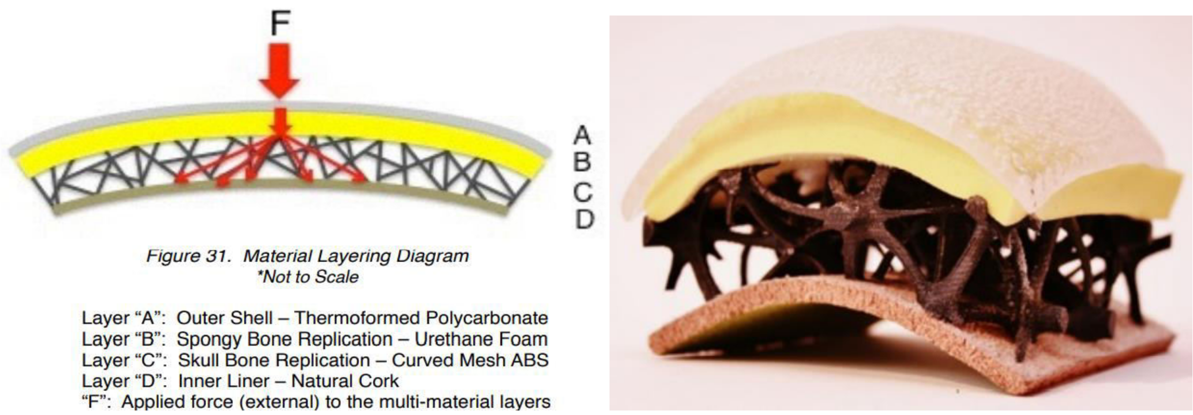


Fig. 5. Mass-spring-damper model of the woodpecker's shock absorbing system. *(Sourced from Sang-Hee Yoon &Sungmin Park [7])*

Nayeon Lee & R. Prabhu et. Al [8] have particularly focussed on the geometric shape of the hyoid and its contribution to stress wate mitigation. Based on experimental measurements, a FE model of the hyoid structure with its material properties, shape and microstructure was made. Following this, force impact analysis was conducted to study the pressure dissipating capacities of the 3 models. On probing the pressure levels at 4 distinct points on the models, it was found that the hyoid shape was much more successful in dissipating pressure and tensile strength. They also noted that the hyoid registered the most shear stress. It is stated that this increased shear stress can be due to the split in geometry and reduction in cross sectional area.

Shock absorption mechanisms are the need of the hour especially in micromechanics, as there are huge losses in performance and material due to vibration during operation. By studying such structures, we can gain insights in order to overcome such issues in a sustainable manner. Apart from micromechanics, shock absorption is necessary in improving the crash worthiness of certain products. David Evenski from RIT attempted to develop a concussion reducing helmet [6] through biomimicry.

Looking at the spongy tissue in the woodpecker cranium, he chose a microcellular urethane foam which was light, flexible and had great endurance to repeated blows. In order to imitate the skull bone layer, he used a curved 3D printed ABS mesh. Finally, an outer layer of Thermoformed Polycarbonate and the innermost layer of cork completed the helmet prototype [Fig. 6. (a)].



(a) (b)

Fig. 6. Layers of the proposed woodpecker inspired helmet: (a) The schematic diagram of the 4 proposed layers of the helmet; (b) Final developed prototype of helmet layers ready for testing *(Both Sourced from David Evenski [6])*

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This design was built with the purpose of improving rider safety and structure, without compromising on comfort and weight. The final prototype [Fig. 6. (b)] is for functional testing and requires experimental analysis to see how it compares to the behaviour of the woodpecker skull.

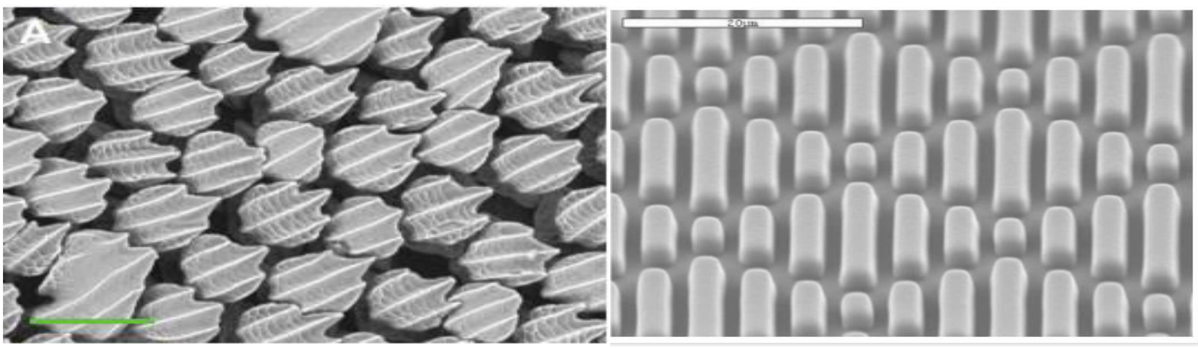
IV. BIO-INSPIRED MATERIALS

Man has always looked to nature for raw materials, be it silk and wool from animals or cotton from plants. Manufacturing of biologically derived materials results in minimal pollution produces no waste and the end products are largely biodegradable [3]. Thus, increased utility of such products will reduce the load of pollutants we release into the earth.

1.2.3. SHARK-SKIN INSPIRED MATERIALS

Shark skin has been studied immensely due to its unique properties. It may look smooth to the naked eye, but closer examination reveals that it is covered by minute v shaped scales that feel like serrations. These scales possess excellent hydrodynamic properties, decreasing turbulence and drag, allowing sharks to swim much more quietly and quickly.

Li Wen et. Al [9] studied, designed and fabricated a model of flexible shark skin membrane. They constructed a model from micro–CT Imaging of shark-skin [Fig. 7. (a)]. Then through 3D printing, the denticles were placed carefully onto a flexible membrane to generate the finished prototype. This was tested as a flapping mechanism and the results were compared with a smooth control model. They observed that the 3D printed shark skin showed increased swimming speed and decreased energy consumption for certain kinds of motion. They found that at slower speeds their model showed around 8.7% drag reduction which increased at higher speeds for the static fin condition. They noted that the direction of flow and fin propulsion affected the degree to which the drag reduction effects were observed. The results for different conditions have been discussed in the paper. Swimming suits are now being built on this principle to decrease the effort of swimmers in propelling themselves.



(a) (b)

Fig. 7. Shark scales form patterns increasing streamline nature of flow, allowing them to swim faster: (a) The microscopic scales from the head of a Mako shark. Denticles form serrations and patterns that direct flow *(Sourced from Li Wen et. Al [9])*; (b) Surface product developed by sharklet that protects from biofouling. *(Sourced from Sharklet [10])*

Another phenomenon observed in sharks is that there are no algal growths on their body unlike whales and ships. The surface also does not kill microorganisms, thereby preventing natural selection of resistant bacteria. *Sharklet* [10] is a technology that copies the surface texture of sharks and is being implemented on the hulls of ships [Fig. 7. (b)]. This unique texture prevents biofilms from forming, and therefore doesn't allow colonies of bacteria and algae to form on the surface. This has the potential to save a lot of money needed for repairs.

1.2.4. SPIDER-SILK

Spider silk is known for its immensely high tensile strength and low weight. It is said to possess greater strength than a sample of steel of the same weight [11]. By studying the molecular composition and arrangement of the proteins in spider silk, we can replicate these low density, flexible and strong fibres to utilize their mechanical properties to our advantage.

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Jeffrey Turner & C Karatzas [12] studied the gene pattern that encodes for silk proteins in spiders. They identified the mechanism through which the silk webs get their mechanical strength and spatial arrangement. They then ventured into mimicking this system and synthesising silks in- vitro via the yeast *Pichia pastoris* and bacteria *E. coli.* A comprehensiveexplanation of the process of producing dragline silk from this yeast is provided in [13]. They then proceeded to expand on the mechanism on in -vivo via the mammary glands of transgenic animals. Similarities drawn between the milk producing glands and spider silk glands led to tests using transgenic founder mice, which was later extrapolated to transgenic goats. Finally, they shed light on the process of spinning silk proteins into fibres and the properties of these resultant fibres.

1.2.5. BUTTERFLIES, BEES AND OTHER ORGANIC MATERIAL

Butterflies are some of nature's most vibrant creatures, with a multitude of colours and patterns on their wings. It is not commonly known that this vibrancy does not arise from coloured wings, rather minute arrangements of scales that refract light [14]. Scientists observed that these scales help the butterfly absorb sunlight and provide heat to the body (It is a cold-blooded creature). They have used these principles to develop thin film solar cells of much higher efficiency [16] [Fig. 8].

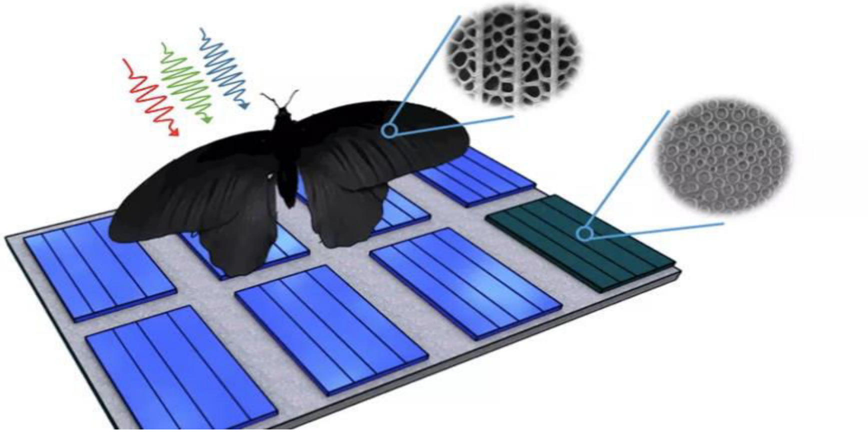

Fig. 8. Thin film solar cells based on the ability of butterfly wing scales to absorb sunlight from any incident angle. *(Sourced from: www.theverge.com/2017/10/19/16503258/)*

R.H Siddiqui, Y.J. Donie et.al [15] performed micro-spectroscopic analysis the structure of the scales on a particular species of butterfly and conducted 3D optical simulations of the scaled structure on COMSOL. They then emulated this structure with hydrogenated amorphous silicon through reactive ion etching (RIE) and observed that their pattern displayed optimized absorption of solar irradiance over a broader spectral and angular range.

Extracting value out of natural substances is not a new phenomenon. Humans have toyed with natural resources for millennia, be it weaving cotton for clothes, leather and milk from animals or extracting silk from the silkworm cocoons. The adhesive nature of gecko feet and Hemisphaerotacyanea (a beetle) have been studied to generate controlled adhesion, used in suction pads and floor mats [3]. Honeybees too have provided resources like honey and beeswax. Studies of the lotus petals gave rise to water repellent textures and the arrangement of muscles fibres in muscles also looks very similar to how wires are arranged in tensile cables used for suspension bridges [3,16,17]. In this manner we see that biology has a never-ending pool of resources and innovations that we can emulate and use to solve our problems in an efficient, sustainable manner.

V. BIOMIMETICS IN ARCHITECTURE

While talking about structural design, one cannot omit architecture. As the human population increases, settlements demand more efficient use of both space and resources. Architects need to look for novel methods to develop structures capable of incorporating all the necessary requirements, while using minimal resources and energy to maintain structural integrity.

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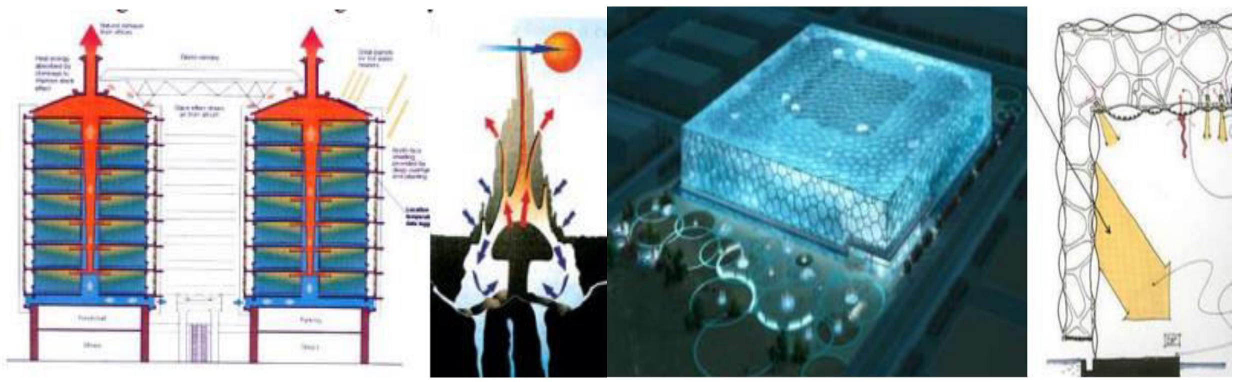
VI. APPLICATIONS IN ARCHITECTURE

Dr.M. Elango, Dr. K Pratheep Moses [17] conducted studies on the structural superiority of the honeycomb structure. They found hexagonal packing of the honeycomb turns out to be exceptionally stable and useful for light weight high strength applications. It can hold the maximum amount of "wax" and requires the minimum amount of resources to be built, in comparison with other cell shapes. They have cited the example of a Tokyo capsule hotel inspired by beehives and then expanded on the cooling mechanism and technical specifications of the beehive. The paper also probes into whether architects consider material efficiency during the predesign stage and if multi criteria decisions taken by architects during the progress of the plan have an impact on material consumption. Their analysis of the research survey reveals these to be true and the details have been laid out in the paper.

Other organisms have helped in the creation of some architectural marvels too. Research on the cooling effects of termite mounds emulated through negative ventilation technology, were implemented in East Gate [16]. This enables control over thermal stability as termites in Zimbabwe maintain nest temperatures of 87^{o}F even as the outside temperatures fluctuate from 35^{o}F – 104^{o}F. This is achieved by constantly opening and closing various vents located in the mound over the course of the day. This technology helped East Gate building consume almost 10% less energy than the average building [Fig. 9. (a)].

The Water cube National Swimming centre is another splendid example of how nature has provided the most sustainable solutions to man. Architects modelled the building on clinging soap bubbles [Fig. 9. (b)]. The bubbles are composed of a fluoropolymer ETFE which is very light and has better optical and thermal properties when compared to glass [16,18]. The design forms a "Voronoi" diagram, found extremely frequently in nature that have excellent structural stability in both 2D and 3D and easy way or arrangement. This has been explained in detail by Khaled Dewidar [18].



(a) (b)

Fig. 9. Biomimetic inspiration in architecture resulting in low-cost energy efficient designs: (a) East Gate Termite mound inspired building with natural ventilation system *(Sourced from Shahda et.al [16]);* (b) Water cube National Centre, inspired by soap bubble clusters and Voronoi diagrams to reduce requirement of artificial lighting *(Sourced from Dewidar, Khaled [18]).*

There are other famous examples like the green roof project of the California academy of sciences, that has an undulating green roof that mimics natural contours, massively cutting down the buildings carbon footprint and saving rainwater [16]. Natural ventilation systems that use evaporation as their chief mechanism are being implemented too as they can cut energy consumption costs. A German company ISPO has created *Lotusan*that is a super hydrophobic (water-proof) paint based on the water repelling property of lotus petals and leaves. [16,19].

VII. FUTURE SCOPE

There have been numerous approaches to a variety of design problems with biomimicry in the past. Moving forward, this focus must only be reinforced. In recent years, biomimetics has played a significant role in computing. Artificial intelligence and Machine learning borrow heavily from natural systems. For example, neural networks (NN and ANN) and genetic algorithms (GA) that form a core part of modern computing are based on emulating the network of neurons in the brain and optimization based on natural selection, respectively. They find substantial use in forecasting, statistics and system optimization problems. Biomimetics has also influenced upcoming industries like robotics, with legged mechanisms proving to be very effective in dealing with undulating terrain, and the medical field with steerable needles and prosthetics greatly optimized by taking notes from nature. Bacteria and microbial locomotion are also being studied to improve the micro and nano technology industries (MEMS). Stress mitigating phenomenon are being pursued to improve the dynamics of micro machines and vibration sensitivity of devices like accelerometers and sensors.

Structural design will always need to improve and generate more efficient designs as resources get scarce. Biomimetics can be described as a niche field now, but its vast and varied reach makes it a useful tool that can penetrate every industry. As more research is conducted in this field, and we gain deeper insights into various echelons of nature, we will appreciate our resources more, and conservative efforts will get consolidated. Inspiration from nature has, and will continue to provide mankind with sustainable and efficient solutions that will revolutionize how we perceive and approach our design problems.

VIII. CONCLUSION

This article was compiled to shed some light on the efforts directed at bio-inspired design and their success at economically solving the posed design problem. Naturally it doesn't begin to scratch the surface of this diverse, ever-growing field, but its purpose is to act as an introduction so that readers may get acquainted with it. For a rigorous and comprehensive scrutiny of the field the book *"BIOMIMETICS Biologically Inspired Technologies*" [20], is highly suggested. It is a compilation of some of the best work in various sub- branches of the field and is a great pool of knowledge.

Nature has developed structures, mechanisms and algorithms over millions of years through evolution. What remains are organisms that are equipped functionally to thrive in their ecosystems. Therefore, we can observe these organisms interact with their surroundings and understand these mechanisms. Humans have always looked to nature for resources and ideas to improve our lives and we are at a point where we can imitate these phenomena much more accurately. Effectively as we hone and polish our technology, we can extract the most out of natures' innovations and emulate them to a greater degree. Biomimetics makes this process systematic and more streamlined. It is certainly convenient to have this stockpile of ideas and framework that we can observe and work with to better tackle our problems. And increased awareness and respect for the creatures we share the planet with will direct us toward a more holistic, organic and sustainable model for development.

Conflict of interest

The author declares no conflict of interest. All inferences and information provided in this document are the work of the individuals as reflected in the appropriate references.

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