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Biomimetics: Insect - inspired technologies

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Abstract

It has long been recognized and documented that insects are the most diverse group of organisms on earth, including more than a million described species and representing more than half of all known living organisms.During the course of evolution, insects have developed several features such as the capability of flight, their small size that allows for survival in various habitats, their ability to store sperm for delayed fertilization, and their general adaptive abilities for the environment. Such versatile structural adaptations and further study, can enable us to solve many problems in the modern world through the science of biomimicry. Principles of insect structures, materials, sensors, actuators, locomotion and control systems could provide valuable solutions to the scientific community and give inspirations to create biomimetic models out of it (Bar-Cohen, 2006). The rich sensory equipment of insects including complex eyes, various chemoreceptors, mechanoreceptors, etc. taken together with a compact brain, reveals interesting motion-control patterns and remarkable behavioural features.Hence insects formwonderful source of inspiration to find solutions for a large variety of challenges faced by the mankind.Biomimetics have helped scientists in coping with challenges faced in building light weight building materials, nano technology, equipment in medical fields, implements for agricultural operations, disaster management operations, packaging industries and even in paint industries with further vast scope of development of ideas in many sectors useful for mankind.

Keywords: Biomimetics, Biomimicry, Insects

Introduction

It has long been recognized and documented that insects are the most diverse group of organisms on earth, including more than a million described species and representing more than half of all known living organisms.During the course of evolution, insects have developed several features such as the capability of flight, their small size that allows for survival in various habitats, their ability to store sperm for delayed fertilization, and their general adaptive abilities for the environment. Such versatile structural adaptations and further study, can enable us to solve many problems in the modern world through the science of biomimicry.

Biomimetics or Biomimicry

Biomimetics is derived from the Greek word, *biomimesis*. The word was coined by inventor and biophysicist Otto Schmitt in 1957.The Biomimicry Institute, located at Montana, USA was founded by Janine Benyusin 2006. According to the institute, Biomimetics can be defined as a practice that learns from and mimics the strategies found in nature to solve human design challenges.

The field of biomimetics is highly interdisciplinary. It involves the understanding of biological functions, structures and principles of various objects found in nature by biologists, physicists, chemists and material scientists, and the designing and fabrication of various materials and devices of

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commercial interest by engineers, material scientists, chemists and others (Bhusan, 2009).

Biomimetic Inspirations From Insect Diversity

Insectsystems inspire the design of novel materials for addressing modern challenges in bioengineering, energy capture and conversion, sensing, communication, light shaping or data processing. This information can be utilized to mimic them for industrial applications. Insect system inspired solutions may be applied in the following main technology areas such as,material science and technology, surface science, science of adhesives, optics, photonics, sensorics, robotics etc. (Gorb, 2011).

1. Surfaces

Insect surface is of withgreat structural and chemical complexity that allows it to serve various diverse functions. They have structural and behavioural modifications to regulate the phenomenon such as friction, lubrication, thermoregulation etc. This ability of insects can be exploited to reduce the friction and wear and tear in micro-electro-mechanical devices (MEMS), as they face high friction, stiction, and wear rate of joints (Gorb and Gorb, 2016)

Rapid progress in this field has generated significant interest in the implementation of micro devices in various commercial applications. In insects, the cuticular microstructures and their modification facilitatefor their precise movement and functioning. The similar properties can be achieved by adopting these ideas and construction of a database of the same. Biomimetic inspirations from surfaces could be either from insectsurface structures or insect-build structures. Insect surface structure implies the various structural modifications present over the insect body for various adaptations, whereas insect-build structure implies the structures they maketo provide shelter or nest for off-springs.

Mosquito-Inspired Needle

Insects steer their stingers effortlessly to a specific target and release their venom in a certain path through the skin with minimal pain. This unique trait inspired the idea to develop bioinspired needles to reduce the insertion forces and to decrease the needle path deviation (deflection) for improved targeting accuracy.

The mosquito-inspired needle design specifically consists of maxillashaped and labrumtip design.The insertion force was measured using a force sensor, which was fixed at the needle end to measure the uniaxial force of needles. It was observed that the insertion forces of the proposed needle design with vibration showed a reduction by 27 per cent compared to that of a conventional needle. It has been demonstrated that geometrical shape modification such as labrumtip (needle-tip) and modified maxilla shape inspired by mosquito proboscis could be utilized to significantly decrease the insertion forces (Gidde and Hutapea, 2020).

Bee-Stinger Inspired Surgical Needles

The bioinspired needlewas designed by mimicking the barbs found in honeybee stingers. The needle deflection (deviation) during insertion can be varied by significantly changing the needle geometry. It was observed that the decrease in insertion force was due to the reduction in the frictional surface between the needle and the tissues.

Experimental testing was done by insertion of needles into a PVC gel phantom to investigate the effect of the barbs on the needle tip deflection; which reported a 17 per cent decrease in tissue deformation in bioinspired needles compared to conventional needle.The results shows that the bioinspired needle could potentially have less needle path deviation and therefore, it could be easily controlled for better target accuracy (Hutapea and Sahlabadi, 2018).

Honeycomb Composite Structures

Honeycomb sandwich composites are suitable for making structural materials that are mainly characterized by their lightweight and high stiffness strength, inspired from the honeycomb structure constructed by the honeybees. Lightweight honeycomb structures would be made from different materials namely, kraft paper, thermoplastics, aluminium, carbon, steel, cardboard, fiberglass, ceramic, Nomex®, plastic and aramid fibre. Aluminium honeycomb structures are known for their excellent specific strength, energy absorption, heat transfer, and electromagnetic shielding properties. Aluminium honeycomb structures consist of a smooth, thin-walled cell, easily machinable and also, they are relatively lower in cost.

The lightweight honeycomb core is sandwiched between two thin panels. This sandwich effectively couples the lightweight and superior strength properties of honeycomb. Although each component is relatively weak and flexible, when combined in a sandwich panel, it would provide a stiffer and durable lightweight structure.Due to the striking features of honeycomb sandwich composites namely, lightness, resistance to compression, high rigidity, fire classification, no combustibility, no toxic fumes, acoustic insulation, easy to assemble, reduced time, and assembly costs, it is preferred in many applications under different domains such as light weight honeycomb model structures for building aircraft and spacecraft, in automobile industries the honeycomb composite building structures can be used for making bumpers, chassis, panels and rear rails.They can also be in used in railway industry for making sturdy lightweight materials in the construction of high speed trains and in marine industry for construction of ship vessels, hulls, skis and maintaining buoyancy.(Chandrasekaran and Arunachalam, 2021).

2. *Adhesives*

In insects, adhesiveness is provided by smooth pads or hairy structures, which are known as attachment devices. These structures are further modified to facilitate movement in smooth and rough, wet or dry, compliant or stiff, hydrophobic or hydrophilic surfaces. The presence of adhesive fluid helps to increase the pad's contact area on rough surfaces and its special rheology combines capillary adhesion with resistance against sliding.Insects employ adhesives for various functions such as tarsal attachment during locomotion, resisting external detachment forces, mating, phoresy and parasitism, egg anchorage, retreat building, self-grooming, prey capture, and active and passive defence. Insect adhesives have the advantage of substances and/or mechanisms that allow multiple attachments and detachments, and enable attachment to a variety of surfaces (Erramilli and Genzer,2019).

The constituents found in insect adhesives belong to aliphatic compounds, to carbohydrates, to phenols, to isoprenoids, to heterocyclic compounds, and to amino acids, peptides, and proteins (Gorb, 2011).Generally two different designs of adhesive pads are found in insects like the smooth pad of an ant *Oecophylla smaragdina* (Fab.) or the hairy pad as in case of a beetle *Gastrophysa viridula* (DeGeer)(Bauer and Federle, 2009).

Insect Mimicking Adhesive Patch

Bio-adhesive patch for electrocardiogram inspired by the unique structures on the foreleg of male divingbeetles, giving enhanced multidirectional adhesion and high water/air permeability to both dry and wet conditions with minimal skin irritation.Bio-adhesive patch inspired from diving beetles, featured enhanced wet adhesion in both the normal and shear directions due to the synergistic effect of suction and capillarity, resulting from microcavities and tiny wrinkles.

Bio-inspired patches act as the interface material for the electrodes, which enables direct electrocardiogram measurements on both wet and dry skin with minimal discomfort and signal noise. It can solve challenges to maintain adhesion on the application of shear and pulling forces, especially on rough, curved, and wet surfaces, such those of the human body (Min et al., 2021).

3. *Materials*

Insect cuticle is a typical example of natural bio composites of light weight, high strength and toughness (Chen et al., 2006). Insect cuticle may inspire material scientists with its helicoidal arrangement of nanofibers in successive layers and with its gradient like material properties (Gorb, 2011). The SEM observation show thatthe insect cuticle is a kind of fiber-reinforced composite consisting of chitin fibers and sclerotized protein matrix (Chen et al., 2006). The natural elastomeric protein, insect resilin, is the most efficient elastic material known, used to store energy for jumping and flight in a variety of insects (Wong et al., 2012). In fleas, click beetles, and froghoppers, resilin plays a role in storing energy via prolonged muscular action and releasing this energy very rapidly when needed.

The studies conducted by Kundanati et al. (2018) to determine the puncture and wear resistance of beetle elytra; elytra resisted puncture up to a force of 1.8±0.4 N and have puncture resistance compared to that of commercially available puncture resistant gloves. Also, the scanning electron microscope images of elytron cross-section showedembedded chitin microfibrils withchanging fibreorientation in consecutive sublayers called as Bouligand structure, which imparts the strengthand hence,there are many areas of potential applications for such a material

Beetle elytra as role models for lightweight building construction

Being natural lightweight constructions, elytra of beetles constitute promising role models for biomimetic development.Hence light weight building composites were made inspired from the elytra of two beetles i.e., Colorado potato beetle, *Leptinotarsa decemlineata* (Say) and the green tortoise beetle, *Cassidaviridis* L.in which, the elytra serve as protective shields for the membranous hindwings and the abdomen.

Functional principles of elytra were analysed and abstracted, and through development of a custom robotic fabrication method, these principles were transferred into a light weight prototype. Two collaborating industrial robots were employed to wind 36 individual glass and carbon fiber-reinforced elements, which were assembled into the final prototype. The specific robotic fabrication process includes the winding of six individual layers of glass and carbon fibers. In total, 36 individual elements were fabricated, whose geometries wereabstracted from the beetle elytra. Each of them has an individual fiber layout which resulted in a material efficient load-bearing system. The biggest element has a 2.6 m diameter with a weight of only 24.1 kg. Beetle elytra, thus proved as suitable role models for lightweight constructions in architecture(van de Kamp et al., 2015).

Insect cuticle inspired composite bioplastics

Insect cuticle provides protection from harsh adverse conditions due to the peculiar composition of proteins, chitin and chitosan. The sustainability and mechanical properties of the insect cuticle inspired in the creation of 'Insect cuticle inspired composite bioplastics', which incorporated chitosan with a structural protein in insect cuticle namely CPAP3-1 through bioengineering (Wu et al., 2024).

Studies proved that the toughness and strength of the bioplastics outperformed the conventional synthetic plastics and previous chitosan-based composites. Since the product also showcased stretch and strengthening properties similar to living muscles, it has wide potential for medical and bioengineering applications.

4. *Optics*

Insect compound eyes have specialised features such as large field of view (FOV), compact structure, high sensitivity and object distance detection. Compound eye has optically cooperating ommatidia, so that a bright image is produced by the combined action of many identical units (Cao et al., 2020).The light from multiple facets combines on the surface of the photoreceptor layer to form a single erect image of an object. Artificial implementation of compound eyes has attracted significant research interest due to their exceptionally wide FOV, high sensitivity to motion, and nearly infinite depth of field, which exhibits substantial potential for medical, industrial, and military applications(Floreano et al., 2013).

Artificial compound eyes using femtosecond laser technology

The insect eyes have always been the source of inspiration and information regarding the minute details of fabrication where thousands of ommatidia are united and produce images in synchrony. Application of biomimicry from insect eyes can have wide applications in the sectors such as medical endoscopy, radar detection, robotics and military (Zhang et al.,2024) .

Artificial eyes mimicking the compound eyes of insects were manufactured using the femtosecond laser two-photon polymerisation technology, which is popularly used in the polymer and liquid crystal processing. Using the technology complex form of multi-lens optical system can be manufactured with multiple layers. Artificial compound eyes posses' expansive field of view due to the curved surface. There lies further scope in developing novel strategies for increasing the processing efficiency to overcome the obstacles in the manufacturing of artificial compound eyes.

Biologically inspired ultrathin camera

Miniaturized Multi-Camera System for Endoscopic Imaginginspired by the twistedwing parasites- *Xenospeckii* (Kirby), characterized by 'eyelets' of unusually large diameter, surrounded by dense setae, each of which contains its own extended retina. Which helped the scientists to create an ultra thin camera gives an imaging of 180æ% × 180æ% degrees field of view and 1.1 megapixels imagingThisultrathin arrayed camera provides a novel and practical direction for mobile, surveillance or medical applications. High-contrast imaging was successfully achieved using an ultrathin arrayed camera. Various images captured by the arrayed camera is reconstructed using the super-resolution imaging technique. The calculated results showed that the combination of array images enhance the image resolution (Kim et al.,2020).

Miniaturized Multi-Camera System for Endoscopic Imaging

A miniaturized high-definition vision system inspired by insect eyes hasa distributed illumination method, which can work in dark environments for proximity imaging applications such as endoscopy. The camera was built with 5 mm radius hemispherical compound eye, imaging a 180° × 180 degrees field of view. With its size, illumination and resolution capabilities, it has wide applications in areas like colonoscopy or laparoscopic surgery where there is a need for large field of view high-definition imagery(Cogal and Leblebici, 2016).

5. *Photonics*

The structural coloration in insects is attributed to thepresence of scales, bristles, micro trachea or pigments in epidermis or cuticle. The coloration pattern serves for species and sex recognition, and also for camouflage and mimicry (Vukusic et al., 2000). Certain members of the order Lepidoptera display vivid iridescent coloration that exists largely independently of pigmentary colour e.g. Morpho butterfly. This colouring derives both from the optical absorption associated with pigment and the strong blue reflection from the structure on the top surface.

The multilayer structure of wing scales is based on alternate air layers and pillar-supported chitinous layers, which leads to optical interference (Jullien et al., 2020). Structural color is color derived from the nanostructure of a surface which acts like a prism, interacting with light waves. Depending on the nanostructure, light wavelengths can undergo constructive interference or destructive interference (Ganguli, 2014).

Color Without Pigments, Dyes, Metals or Expensive Engineering Processes

Biomimicry based on the structural colors of the butterfly wings was created by Cypris Materials, a Berkeley US based organisation to develop a paint that is devoid of pigments, dyes, metals or expensive engineering processes. The developed paints consist of nao-structured coatings from synthetic polymers like the deposited brush block copolymers capable of rapid self-assembly, achieving highly reflective structures in minutes after application under ambient conditions. This can reduce the amount of volatile organic compounds, eliminating bisphenol A (BPA), and removing additives like phthalates present in conventional paints available in markets. They also have industrial adaptability that is from cosmetics to electronics to packaging(Cypris Materials, 2021).

6. *Sensorics*

Insects have sensory structures such as the auditory, mechanosensory, vision and chemosensory (gustation and olfaction) systems. Insects have evolved a set of extremely effective sensory systems that are structurally simple, functionally versatile and with highly distributed networking.These sensory structures have been inspirational to new communications and computing paradigms, which have led to accomplishment of significant advances in the field (Ma and Krings, 2009).

Insect life cycles are exposed to a variety of environments and conditions; accordingly, they have evolved an array of sensory systems with which to sense and respond to a complex set of environmental stimuli and biological cues. These signals are received by a range of sensory cells, most notably neurons of the peripheral nervous system that transduce external signals into neuronal activity or inhibition through a variety of mechanisms. This information is subsequently collected, integrated and otherwise processed by downstream regions of the central nervous system (CNS) in order for insects to make the salient behavioural decisions that are required to successfully complete a set of discrete lifecycle tasks (Montell, 2016).

Insect-inspired Microphones

Parasitoid fly *Ormiao chracea* (Bigot) has subwavelength directional hearing.*O.ochracea* ear mechanism has been used as inspiration for microelectromechanical acoustic sensors.*Ormia* sp. inspired microphones have higher directionality and are more suitable for micro-fabrication than conventional microphonesandareused in hearing aids.

Gravid *O. ochracea* females can locate their host cricket's 5 kHz mating calls to an accuracy of less than 2° despite having a distance of approximately 500 μm between the ears. The parasitic female *Ormia* sp. uses auditory cues to localize the mating call of a host *Gryllus*, a genus of cricket, and then deposits its predaceous larvae on the host.This high accuracy is attributed to the mechanical coupling structure of *Ormia*'s ear, known as the see-saw model, amplifying the tiny differences in the sound wave arriving at each ear drum. The design focuses on increasing acoustic frequency response at low-frequency range below 3 kHz to improve use for human speech recognition and with multiple working frequency bands operation.Their small size and compact nature enables wide application in modern world (Zhang et al.,2018).

7. *Robotics*

Insect behaviour has been a rich source of inspiration for the field of robotics as the perception and navigation problems encountered by autonomous robots are faced also by insects. Biomimitic robots can mimic the movements of insects and work with more responsiveness, sensitivity, precision and movement in varying conditions with specified adaptability. Such models of biomimetics insect robots are able to dwell and deliver payloads to locations that are difficult to access.

To mimic the features of insects in a similarly sized robot, it requires miniature and high-efficiency mechanical components. Key challenges in the design and manufacture of soft robots include the complex fabrication processes and the interfacing of soft and rigid components. Recent advances have demonstrated insectscale robots that crawl, run, fly, and swim (Li et al., 2019).

Micro-Robot capable of skating on water

Since walking or jumping on water is exactly the lifestyle for some aquatic insects such as the water strider, water spider and mosquito, a full understanding of the physical mechanism of their motion ability have inspired various researchers to design novel micro robots and structures (Shi et al., 2017). A biomimetic robot was developed by Zhou et al. (2017),inspired from aquatic insects such as the water strider, water spider and mosquito.

A coinsize micro skating robot with flapping wings was developed that act as the thrust to propel the robot to move quickly. The robot is supported by four hydrophobic elastic legs which are made of titanium alloy. To reduce the weight, the body, flexure hinges and the vein of wings are made of carbon fibre, and the wing membrane is made of thin polyester film. The maximum speed when robot slides on water is measured as 151 mm/s. The total weight of the robot is 165 mg while the size is about $46 \times 37.5 \times 21.4$ mm^3. The lighter structure of the robotics designed to reduce the resistance of water, efficient flapping wing mechanisms is researched to obtain larger propulsion force (Zhou et al., 2017).

Applications o Insect Biomimicry in Agriculture

The intense land and resource use and modern systems of agriculture will quickly become inadequate to sustain the future projections of global food demand. Furthermore, the widespread environmental impacts, including land degradation, loss of biodiversity and wildlife habitats, and public health threats, of conventional agriculture underscore the urgency for an imperative transformative change on the systemslevel towards agricultural sustainability (Du, 2012).

Mould board plough based on surface morphology of soil burrowing insects

The body surface morphology of soil burrowing insects has non-smooth units such as convex domes, concave dips, ridges or wavy structures, which play important roles in their anti-soil adhesion and anti-friction functions. These soil burrowing insects prevent soil from sticking to their bodies because of evolution of their biological systems through exchange of matter, energy and information with soil over centuries. It was found that the cuticle surfaces of soil-burrowing animals have the ability to reduce adhesion and friction against soil.

Based on the surface morphology of dung beetle head portion, two non-smooth surface pattern mould board ploughs of semi-oblate protuberances with a height base diameter ratio of 0.25 and semi-sphere protuberances with a height base diameter ratio of 0.5 were developed. The imitation of surface morphology of the head of a dung beetle on mould board plough surface reduced the average sliding resistance by 13.2 per cent when compared to conventional plough surface. The parameters used for designing the convex domes were mild steel with a base diameter of 25 mm and height of 7 mm (Manoharan and Surendrakumar,2019).

Beetle Inspired Dew Harvesters

In arid areas such as the Namib desert of Africa, one of the dominant water resources is fog. It is typically formed when warm, moist air from the land moves above the cold water and condenses, and the winds bring the condensed moist air or fog back to the land. Species, such as desert beetles, gain about 10 per cent of their weight in 2 h though fog interception on their body, having a surface area of about 400 mm^2. The back of the beetle is comprised of an array of smooth, hydrophilic (water loving) spots which are surrounded by an area covered with microstructure hydrophobic (water fearing) wax. Water droplets from the fog accumulate on the spots, grow until they reach a critical size, detach, and then roll/slide down the beetles' tilted back towards the mouth.

Gurera and Bhushan (2019)created a water harvester substrate with the integration of both the wettability gradient and shape gradient on the surface which can speed up the process by collecting tiny water droplets. All of the water reaching the base of the cones can be channelled to the collection point. Gravity dominates the water collection rate at 45-degree inclination angle, which results in the higher water collection rate for larger surface area. This concept has gained popularity in the last decade, and a commercial model of Namib beetle inspired water harvester was manufactured by an international brand called Yanko Design.

Applications of Insect Biomimicry in Disaster Management

When an earthquake, landslide, tsunami or flood occurs, the disaster frequently results in huge damages. Taking urgent actions to explore and recue is of vital importance to save people's lives and minimise commercial losses. However due to the risk involved in rescue, the loss of lives of human rescuers could be overwhelming, compared to the number of victims rescued. Therefore, robotic technologies have been widely adopted in the rescue field.

Flying-Insect- Inspired Drone Robot for Disaster Exploration

Hu et al. (2017)created an innovative design for an insect-inspired hybrid robot for disaster exploration, which can enable the rescue robots to go through narrow spaces for disaster exploration in high rise buildings. They can provide a solution to significantly increase the work time of wireless rescue robots.

Inspired from the flying insects, the recommended robot model can automatically fold and deploy its frame to meet the disaster exploration in complex terrains. The overall weight of the hybrid robot is 2.1 Kg; the running time of the ground module was recorded up to 6h 35min. and running time of the flying module was recorded as up to 21 min. The total time taken to fold the frame completely is 7 seconds. These results indicate the efficient potential of the robot for surveillance and disaster exploration.

Conclusion

Years of evolution, environmental constraints and limited resources have turned insects into an efficient bioresource from which immense ideas were extracted for biomimicry.Various insect inspired biomimicry technologies such as honey comb inspired construction materials, mosquito proboscis inspired surgical needle, beetle elytra inspired light weight building materials, insectcompound eye inspired ultra-thin camera , these all innovation are a proof that insect inspired technologies can be unveil further novel strategies and ideas of mankind. Incorporating more biological knowledge into the design of artificial systems provide more sustainable approaches. Additional research on insects and systems are required for further biomimicry technology development.

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