1 Introduction

1.1 Why do we need to harvest ideas from Nature?

For the longest time in human history the senses and extraordinary abilities of animals and plants have been a matter of guess-work, speculation and plain ignorance (e.g. Descartes' infamous assertion that animals cannot feel pain like humans). On the other hand, keen observers realized that some animals and plants were equipped with sensory capabilities that went far beyond human performance in the classical five senses that we are able to use: vision, hearing, smell, taste, and touch. It is common knowledge that the hearing of most animals is superior to our own; that the eyes of hawks, eagles, and other birds produce a clearer picture than a human eye; that tendrils of climbing vines have a thousand times higher sensitivity to touch than the tip of our index finger; and that in finding tracks, truffles or flowers, dogs, pigs, and insects show smelling abilities far exceeding ours. However, only after humans made highly advanced technical instruments that converted infra-red (IR) and ultra-violet (UV) light into our visible range, did we stumble upon the fact that animals and plants were able to see in these parts of the spectrum; snakes, reptiles, insects, and plants make use of IR, and many insects can see in UV as well. Some fishes and insects have an electrical sense that allows them to orient and hunt in opaque muddy waters. This leads us to conclude that not only are there creatures with senses far superior to ours, but that some of them, like the insects, sense features of our world that remain hidden from us. No other living beings show as sensitive olfactory abilities as insects. They include not only the sensitive detection of signal substances (pheromones) that serve communication within the species, but also signals from other species and even other kingdoms, such as, plants and even common gases, such as CO_2, that together with IR radiation reveal breathing animals.

Another extraordinary ability of animals is that they can communicate among themselves as a group and take actions toward common goals, which may be a function of time, thus, they can reconfigure their body systems and shapes to cope with different environments and missions. These self-assembling, morphing, reconfiguration abilities of animals are more characteristic of lower-level animals, higher level animals such as humans cannot perform these functions.

Nature is not to be conquered by humans; rather humans should preserve nature as she is. Human actions and plans need to be harmonized with nature to sustain the rich life of the natural world, from which we will be able to obtain both rich ideas (bioinspirations) and sustainable food and energy resources.

In the current scientific and engineering literature, two adjectives are frequently used: biomimetic and bioinspired. The former describes a copy of natural design up to 100%, while the latter means to harvest a mechanism used in a given biological species during the initial design stage. The present authors believe that use of "bioinspired design" is a more accurate description of any human-designed materials and devices. It is this initial design stage when we fully use the bioinspired design concept, rather than copying whole aspects of a given biological system.

The early history of human beings shows varied evidence of bioinspired design of tools and clothes; animal horns and furs were copied into the weapons and clothes of earlier humans. In the modern history of human activities in the early twentieth century, gliding seeds of *Zanoia* trees were copied to make tailless gliders and the motor plane "Taube". Tendrils of climbing plants were copied in the form of extendable wires for phones and industrial robots. Thorny branches of Osage orange trees were copied to make barbed wire (Basalla 1988). Adhesion. of burdock *Arctium* seeds was transformed into polymer-based Velcro adhesive tapes (de Mestral, 1961).

Bioinspired designs of human-made materials and devices have been intensified recently, covering a variety of fields, from biomedical materials and devices to unmanned air and underwater vehicles, where design of sensing and active materials and their integrations are focused. Vaia and Baur (2008) discussed a number of bioinspired materials and structures with emphasis on aerospace systems. There exist no enabling technologies for the above unmanned vehicles in an autonomous fashion for *longer duration* due to lack of the subcomponent technologies and also their integration technology. Among these subcomponent technologies, lack of portable, durable batteries is severely limiting the merit of using such unmanned monitoring systems for a longer duration than is currently possible. However, if an unmanned system can harvest the energy from its surrounding environment, this would increase the use time of the unmanned monitoring system. In order to actuate an unmanned system, we cannot rely only on commercially available electric motors and transmission components. Instead, we need to develop a set of compact and energy-efficient actuators, which would be possible if a set of new active materials were designed and synthesized to provide larger stress and strain capability with minimal energy consumption. Similarly, a set of new sensing materials needs to be designed and synthesized, which can detect a number of toxic odors of even the smallest amounts flowing in air or in water. These sensing and active materials need to be mounted in the unmanned monitoring systems, or be portable if they are carried by a human inspector. In addition, the bioinspired scientific knowledge of cognition and diagnosis capabilities of the sensing data need to be established before these are combined and integrated into the actuation components. Among those technologies, the most critical is integration technology, by which design of a set of unmanned systems, particularly of smaller size, could be possible. However, the processing of smaller sized sensing and active components, and diagnosis elements is challenging. Processing time is too long using 100%

biomimetic processing from real biological growth mechanisms; therefore, nanotechnology processing, where the processing time is much shorter, has been designed.

1.2 Biological sensing

Plants are exquisitely sensitive to their surroundings; perhaps it could be argued that because they are rooted in place they must detect environmental circumstances constantly in order to acclimatize and defend themselves. Detection of light is accomplished by more than ten so-far-characterized photoreceptor molecules, including phytochromes (absorbing red and far red wavelengths), phototropins and cryptochromes (blue), which are photomorphogenic pigments, and chlorophyll (red and blue), which is the pigment responsible for photosynthetic capture of light energy. Plants are able to detect and respond to as little as one photon; they discern presence and absence of light, light quality, and amount, as well as duration and photoperiod. Along with sensing of light, plants sense the gravity vector to orient growth of roots, stems, and leaves. In many cases gravity is detected within gravity-sensing cells by the pressure of dense cellular bodies against cytoskeleton elements. There is some evidence that plants sense magnetic fields and lunar forces, but the mechanisms of these detections are unknown. Recently it has been reported that plants can detect sound, both noises emitted by insect jaws clamping on leaf tissue, and environmental sounds such as running water.

The extent to which plants communicate with other organisms in their habitat via volatile emissions and sensation is a field of intense interest in plant physiology and ecology. Aside from the well-known examples of plant aromas attracting pollinators, it is now recognized that plants emit chemical signals that activate defenses in their own tissues as well as in neighboring plants. Plants are able to detect self versus non-self in the soil, presumably by emission of chemicals dissolved in the soil solution. Some plants locate prey by “smelling” volatiles emitted by those organisms; a good example is the dodder that parasitizes tomato preferentially. In all these cases, the volatiles must be sensed by chemical receptors on the surface of plant tissues, but so far the only volatile receptors described are for the hormonally active compounds ethylene and jasmonic acid.

Among various groups of animals, insects provide many hints for designing sensors and actuators. Insects adapted to life in diverse environments on land and acquired wings to utilize aerial environments. Insects are the most prosperous animal groups in terms of species abundance. There are more than 950,000 known insect species, accounting for two-thirds of all known species of animals. Sophisticated sensory capabilities, rapid movement on land and in the air, and efficient but relatively simple central nervous systems of insects are ideal for application to artificial sensors, actuators, and controllers.

Insects often exhibit amazing sensory capabilities. Compound eyes (principal eyes) of insects are characterized by a wide visual field and a high temporal resolution, which are particularly suited to detect motion of the self against the background and equip insects for rapid steering in flight. Antennae of insects are equipped with receptor neurons that can respond to odors with a very high sensitivity. This is evidenced by the fact that male moths can find females located several hundred meters away by tracking the plumes of sex pheromones emitted by the females. The capacity of insects to detect sound, humidity, temperature, infrared light, and a geomagnetic field are all potential sources for designing artificial sensors. A recent finding that bumblebees detect static electric fields and use this capability to recognize and learn flowers (Clarke et al., 2013) has provided further evidence for unusual richness of sensory capacities of insects.

1.3 Biological actuations

Actuation observed in plants is often based on motor cells, whose volumes are rapidly decreased or increased. The resulting actuation in terms of shape change of plant leaves and branches can be very fast (<1 sec) as in Venus Fly Trap and *Mimosa pudica*, or slower (minutes), as in the case of leaf rolling/unrolling of Kentucky bluegrass *Poa pretense* under decreasing/increasing moisture in the surrounding environment, and the slower shape change in a plasmodial slime mold (*Physarum polycephalum*) under favorable/unfavorable surrounding environment. Rapid plant movements are also caused by dehydration of dried tissues; for example, seeds and spores are often expelled from their cases when their cases dry and subsequently are triggered to fly open, or sometimes when the dry material is rehydrated such as in some plants in the desert where longer dry conditions are followed by shorter wet conditions. The combination of complex, rigid cell wall materials (cellulose, lignin) and the ability of plant cells to inflate and deflate osmotically provide the actuation mechanisms for most movements in plants.

The key active elements observed in animals are muscles that contract upon switching on, ignited by the neuronal signals originated from a threshold value being exceeded by crossing sensor inputs. Normal design of muscle-based actuation in higher order animals involves coordinated motions of contractive muscles (contractor) and paired relaxing muscles (relaxor), both muscles are attached to the bone (either endoskeleton or exoskeleton). The actuation associated with lower-level animals, such as earthworms, is a series connection of the contractual segments and relaxing segments along the entire body, where the former touches on the ground with some friction. As to the faster motions of insect wings, indirect muscles are steady-state beating with natural resonant frequency.

1.4 Integration of sensing and actuation in biological species

Integration of sensing and actuation in biological species is seen at two different levels, (i) local basis and (ii) organismic basis, which in animals is via central neuro-control.

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The former is often observed in lower-level animals and plants, and also some local elements of higher-level animals, which are closed loop without passing through central brain diagnosis. Locally based integrated sensing and actuation consumes the least energy and also accomplishes a faster response, while centrally controlled integrated sensing and actuation can provide more accurate response at the cost of longer response time and higher energy requirement.