INSECT SENSORY SYSTEMS INSPIRED COMMUNICATIONS AND COMPUTING (II): AN ENGINEERING PERSPECTIVE

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Abstract: This is the second article in a two-part series in which we briefly review state-of-the-art research in communications and computing inspired by insect sensory systems. While the previous article focuses on the biological systems, the present one briefly reviews the status of insect-inspired communications and computing from the engineering perspective. We discuss three major application areas: wireless sensor network, robot and micro aerial vehicle (MAV), and non-cooperative behaviours in social insects and their conflict resolution. Despite the enormous advances in insect vision and mechanosensory inspired robot and MAV, micro-flight emulation, motion detection and neuromorphic engineering, etc., the potential inspiration from insect sensory system is far from being fully explored. We suggest the following promising research topics: (1) A new grid computing architecture emulating the neuronal population such as the visual neurons that support the compound eyes, the PN (Projection Neurons) in AL (Antennal Lobe) or the ORN (Olfactory Receptor Neurons) from insect sensory organs (sensilla). This may be further integrated and enhanced with the dendritic neuronal computing. (2) New generation of *multimodal* wireless sensor and ad-hoc networks that emulates insect chemosensory communication. The inspiration of multimodalities in insect sensory systems also implies that there are multiple *parallel* networks operating concurrently. Furthermore, the insect chemosensory is significantly robust and dependable with built-in anti-interference mechanisms. (3) Non-cooperative behaviours in social insects may offer insights to complement swarm intelligence (inspired by cooperative behaviours) or to devise new optimization algorithms. It may also provide inspiration for proposing survival selection schemes in evolutionary computing. We suggest using evolutionary game theory to model conflict resolution in social insects, given its success in modelling conflict resolution of other animals.

1 INTRODUCTION

Organisms interact with each other and with their environments through sensory and motor systems; so do the engineered systems. Their stability and control depend on continuous sensing and actuation (Miesenbock and Kevrekidis, 2005). This argument shows the universal significance of sensory systems to both biological and engineered systems, which is particularly true to insects given insect sensory systems are one of the top four reasons contributing to their status as the most abundant organisms on earth (Ma and Krings, 2007).

Two terms often appear in bio-inspired computing: biomimetic and biomorphic. The former is more common and emphasizes the mimic or emulation of nature and the latter is more of a metaphor (Lodding, 2004). The applications we survey below largely fall into one of the two categories, but in reality, the distinction is rarely clear-cut. In some occasions, a biologically inspired approach is *recursively* applied to solve biological problems (e.g., biosensoring in section 3).

To harness the biological inspirations from insect sensory systems, being familiar with the biological aspects is necessary. We refer to the following excellent monographs (Christensen 2005, Drosopoulos and Claridge 2006), both of which are dedicated to insect sensory systems. An excellent and up-to-date monograph, rightly acclaimed by reviewers as providing "a remarkably holistic yet detailed view" on insect physiological systems including the sensory systems, should be an ideal reference for studying insect sensory system in more comprehensive context (Klowden, 2007). General knowledge on insect sensory systems can be found in an entomology textbook such as Gullan and Cranston (2005). Numerous proceedings from

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symposiums and conferences on bio-inspired computing have been published since the 1990s and a significant amount of research is inspired by insects (e.g., Detrain et al. 1999, Dressler and Carreras 2007). A possible starting point, which provides an article-level review of the insect sensory systems from the perspectives of inspiring communications and computing, could be the Ma and Krings (2007). Given the extensive existing literature, which continues to accumulate faster than ever, we choose a significantly narrow scope in this article to focus on insect sensory system related topics. Even with the narrowed-down scope, it still seems impossible for us to present a comprehensive review in such a short article. Therefore, we choose to focus on three research areas and exclude the others. In addition, priority was given to the state-of-the-art review papers, monographs, and research papers representing a major category of studies (often limited to one per topic). Consequently, we have to regrettably omit a number of excellent research papers. As a minor remedy to the excluded fields, in section 3, *the other topics,* we mention five areas and a few review references about them.

2 INSECT SENSORY SYSTEMS INSPIRED COMMUNICATIONS AND COMPUTING

2.1 Wireless Sensor Networks

It seems that insect sensory systems may inspire the design of wireless sensor networking on both the node (sensor node *vs*. individual) level and network level (sensor network *vs*. insect population).

The inspiration at the individual sensor node level is the most obvious. Essentially, a robot emulation of insect vision and navigation provides a typical example for this kind of research, where each individual insect is *mapped* to an engineered sensor. Many of the neural sensory mechanisms in insects can be emulated in individual sensor design. In particular, multimodality capability is very desirable in sensor networks (Ma and Krings, 2007).

From the population perspective, potentially two types of “mappings” can be construed. The first type is the neuron population or the group of neurons behind a sensory organ such as antenna or compound eyes. This type of neuron population forms a *grid computing* infrastructure (similar to the cellular computing paradigm). The populations of ONRs (olfactory neural receptors) and PNs (projection neurons) in the olfactory system are examples of this type (Ma and Krings, 2007).

The other type of population organization *mapping* can be the population of insect individuals *vs*. *population* of wireless sensor nodes, i.e. wireless sensor network. An insect population that distributes over habitat space forms an information network. This network may depend on infochemicals (in chemosensory system) or vibrations (in audition) as "packets" communicating via air, water, or other types of substrate medium. Indeed, the infochemicals-based *wireless* communication network is probably more complex than electron-based networks. Several categories of infochemicals are involved, e.g., pheromones are utilized in intra-specific communications and allelochemicals (allomones, kairomones, and synomones) in inter-specific communications (Ma and Krings, 2007). What may be even more inspiring is that there are several *parallel* communications networks—visual, olfactory, auditory, etc.—in an insect population, or the so-called multimodality sensory. All of the sensory networks are *wireless* except for the taste sensory network. This is essentially the demonstration of multiple modalities at the population level.

In terms of sophistication and functionalities, no other organisms may match insects in the chemosensory systems. The differences between the insect chemosensory *wireless* network and the engineered wireless network lie in message encoding (infochemicals vs. radio frequencies) and computing node (insect brain vs. microchip). The research of insect sensory systems may inspire the engineering of reliable and secure wireless sensor networks. Obviously, the insect sensory *wireless* network is operated under heterogeneous and unstable natural environments. The network has to deal with possible exploitations by other species, which may be their competitors or natural enemies. For example, the natural enemies may try to find their prey by following the infochemicals, and the insects may release interference infochemicals to confuse their competitors. This is similar to malicious intrusions in computer networks.

2.2 Insect-Inspired Robots and Micro Aerial Vehicle (MAV)

The study of the aerodynamics of insect flight was conducted as early as the 1950s. Grasshoppers and flies seem to be the most common model insects. Both walking (including crawling) and flying robots based on insects have been developed. Insect sensory systems, mainly vision and mechanosensory, have offered inspiration for those designs. It can be said that the research of insect-inspired flight has been the most intensive and extensive field studied among all insect-related engineering studies.

Micro Aerial Vehicles (MAV), also known as Mini Aerial flight Vehicles, have been studied for over a decade. An MAV is based on UAV (Unmanned Aerial Vehicle) technology, but there are significant differences. According to DARPA's definition, an MAV has a wingspan of less than 15 cm. It turned out that the 15 cm is an interesting threshold to separate two types of flights: flapping flight (*micro-flight*, used by insects) vs. fixed wing soaring flight (Pornsin-sirirak et al. 2001).

At least seven laboratories started insect-inspired robots research in approximately the same period about a decade ago. The Biomimetic Millisystem at U.C. Berkeley has been developing the so-called minimally-invasive flying robots, weighing 0.1g, using insect-inspired wing kinematics (Wood et al. 2005, Steltz 2005). The group at CalTech's (Pasadena, CA) Micromachining Lab focused on the design and manufacturing of flight wings for MAV. For example, they developed the first MEMS-based (Micro Electro Mechanic Systems) wing technology with titanium-alloy metal as wingframe and parylene-C as wing membranes (Pornsin-sirirak et al., 2001). The "Entomopter" is a multimode (flying/crawling) robot designed by the joint team of Georgia Tech Research Institute (GTRI) and Cambridge University. The effort has been made to develop an Entomopter-based Mars surveyor (Michelson, 2002). The Biorobotic Vision Laboratory at the Australia National University has focused on the insect vision-driven behaviors and their inspiration for machine vision, as well as visually guided robots (Srinivasan et al., 2001, 2003). Their researchers, in cooperation with the Jet Propulsion Laboratory at Cal-Tech and NASA, have developed robots for Mars exploration based on the study of ocelli of dragonflies. The design of Mars exploration robots has taken inspiration from the unique skills of dragonflies in navigation, hazard avoidance, altitude hold, stable-flight, terrain-following and smooth deployment of payload (Thakoor, 2003). The Center for Intelligent Mechatronics at Vanderbilt University studied Mesoscale Crawling Robots based on insect model (Lobontui et al., 1999). CAVIAR is a European Commission funded project to develop a multi-chip vision system based on Address-Event Representation (AER) communication of spike events (http://www.ini.uzh.ch/~tobi/caviar/). This system emulated biological visual pathways (Liu et al. 2002). *Fly-by-Sight-Microrobots* is a project headed by Nicolas Franceschini in France. His team developed neuromimetic robots by emulating the fly's compound eyes (www2.cnrs.fr/en/582.htm).

Besides the previous groups' comprehensive research projects, quite a few researchers have conducted relatively ad-hoc studies in the field. Motamed & Yan (2005) is a review of insect-inspired micro-flight. Ma and Krings (2007) reviewed more case studies in insect-inspired robots and MAV.

2.3 Non-Cooperative Behaviours in Social Insects — Conflicts Resolution

Non-cooperative behaviors in social insects are contrary to the cooperative ones that have inspired swarm intelligence and similar algorithms, also referred to as ants colony optimization algorithms. The reason we single out this type of insect behavior is an intuitive argument: If the solution for the opposite side of a problem is inspiring, one may be able to get the solution by conducting inverse transformation. This is often true in optimization.

The society of social insects, like any society, is never a perfect world. The dominant organization of the insect societies such as bees, ants and termites is the caste system, and individual *rights* are often not fully protected. Two major conflicts exist in social insects: (1) direct reproduction rights and (2) the manipulation of fellow colony members. Ratnieks and Foster et al (2006) reviewed five major reproductive conflicts in insect societies, including: (1) sex allocation, (2) queen rearing, (3) male rearing, (4) queen-worker caste fate, and (5) breeding conflicts among totipotent adults. These reproductive conflicts exist widely in the colonies and sometimes have dramatic effects on the colonies. Three essential mechanisms: kinship, coercion, and constraint typically jointly limit the effects of conflicts and often the reproductive conflict is resolved totally. The *inclusive fitness theory* has been proposed to explain both cooperation and conflict. Essentially some individuals of a colony relinquish their direct reproductive rights to help rear and defend the offspring of other colony members. A major factor in conflict resolution is the kinship, since the great relatedness suppresses the incentive to be selfish. Whether or not the pheromones, which play crucial roles in cooperative behaviors, are involved in conflict resolution is still unknown, and neither are the genes affecting conflict resolution (Ratnieks and Foster et al. 2006). There has been no modeling research of the conflict resolution in social insects.

Whether or not pheromones are involved in the conflict resolution is really not important for their potential inspiring in devising new computation strategies or extending the existing swarm intelligence. (The latter is based on pheromone-regulated cooperative behaviors.) We see three potentially rewarding explorations. (1) Extending swarm intelligence. In real world populations, both cooperative and non-cooperative (conflict resolution) mechanisms exist simultaneously and the successful resolution of conflict may enhance cooperation. Therefore, introducing conflict resolution into swarm intelligence algorithms should make the algorithms match biological mechanisms more consistently. Cooperative behavior is essentially a positive feedback mechanism, and non-cooperative behavior often acts as the negative feedback mechanism. A system should become more stable with both types of feedback regulations. Certainly, what we suggest here is just a conjecture. (2) The mechanisms of conflict resolution may be inspirational for designing survival selection mechanisms in evolutionary computation, or extending the existing survival selection schemes. (3) Mathematical modeling of the conflict resolution in social insects has not yet been explored. Given the dominant role of evolutionary game theory in modeling conflicts resolution in other animals (Maynard-Smith 1982), it makes great sense to apply evolutionary game theory first. Obviously, the studies of (2) and (3) should be compared to inspire each other, since the topic of (2) is essentially an evolutionary computation issue and that of (3) belongs to evolutionary biology.

3 THE OTHER TOPICS

Insect Vision Inspired Motion Detection and Neuromorphic Engineering. This topic was addressed in the first article of this two-part series (Ma and Krings 2007), since it was more convenient to discuss it in the context of insect vision sensory systems. Given its extreme importance, we include the following brief summary.

One field that has made enormous progress in recent years is the motion detection of insect eyes and their applications to bio-inspired robot sensors. This is one area of neuromorphic engineering. *Parallel* and *analog* are two trademark properties of insect neural systems. It is now possible to design and manufacture a fully integrated neuromorphic olfaction chip (Liu et al. 2002, Stocker 2006, Koickal et al. 2007). A possible reason for the advancement is that motion-detection neurons are some of the largest in insect vision systems and easy to observe (Rind, 2005). Rind (2005) summarized three types of contributions where man-made vision systems are based on insect vision system: (1) Bio-inspired circuits embedded in the control structure of mobile robots. Examples are the Lobula Giant Movement Detector (LGMD) for collision detection based on locust eyes (Blanchard et al., 2000) and flying motion detectors. (2) Neuromorphic chips based on fly eyes (Harrison, 2000) and VLSI retinal circuits (Liu and Kramer et al., 2002), and (3) Bio-inspired behavioral strategies (Srinivasan et al 2001). In these insect vision-inspired designs, the goal has been to make fast, robust, lightweight and low-power vision systems. Another feature is that analog-VLSI has been the dominant choice in insect-vision-based chips. Ruffer and Franceschini (2004) have designed neuromorphic eyes for a mini-UAV with eye weights of only 0.8g and a weight of only 100g for the entire rotorcraft. Tests reveal that these artificial vision chips (even the most flexible analog-VLSI fly eye) still have significant gaps with real insect visions systems upon which the chips are based. This indicates that a better understanding of insect eye motion detection has to be gained to make further breakthroughs (Rind, 2005). More recently, Fife and Archibald (2007) applied FPGA approach to support real-time vision processing for the small UAV.

Neural Network Modelling and Dendritic Neuronal Computing. It is interesting to note that recent advances in neural biology may change our thinking about modeling neural networks, perhaps including the ANN (Artificial Neural Network). Vogels and Rajan et al. (2005) present an excellent critical review on neural network dynamics, and they call for the models that go beyond describing and adapting to the input-output dynamics. The mathematical modeling has to address the fundamental property of the brain, that is, the neural circuits perpetually generate complex activity patterns of extraordinarily rich spatial-temporal structure, yet they remain highly sensitive to sensory inputs. London and H¨ausser (2005) offered the perspective from the computation capability of single neuron, the so-called *dendritic computation*. They argue that the computing "tool kit" of dendrites may play roles well beyond currently acknowledged properties. Ma and Krings (2007) suggested that the neuronal population in insect sensory system such as the visual neurons that support the compound eyes, the PN (Projection Neurons) in AL (Antennal Lobe), or the ORN (Olfactory Receptor Neurons may be emulated to develop a new grid computing architecture. It seems that the integrated model of grid computing with dendritic computing may offer new insights. That is, a grid-computing infrastructure is supported by tool kits from dendritic nodes.

Biosensoring. A biosensor is an integrated device that combines a biological component with a physicochemical detector component that converts a biological response to specific substances being monitored into an electrical signal. An annual review has been published by Rich and Myszka since 1999 (Rich and Myszka, 2005).

Cellular Computing, Agent-based Computing and Swarm Intelligence. Amos et al. (2004) and Dogaru (2003) presented two of the latest review on cellular computing. Ma and Krings (2007) contrasted cellular grids in cellular computing *vs. neuron populations* in insect sensory systems. The latter can be the visual neurons that support the compound eyes, the PN (Projection Neurons) in AL (Antennal Lobe), or the ORN (Olfactory Receptor Neurons) from insect sensory organs (sensilla). This neuronal population can be emulated to develop a new grid computing architecture.

Agent computing is another field where insect model plays a significant inspirational role. The most well- known paradigm should be Swarm intelligence (Bonabeau et al. 1999, Dorigo and Stützle 2004), which is inspired by ants pheromone-modulated cooperative behaviors. This is in contrast with the non-cooperative behavior we discussed in subsection 2.3. Lodding's (2004) biomorphic software and the design patterns of Babaoglu and Canright et al. (2006), and Dobson and Massacci's (2006) are more examples of agent-based adaptive computing.

Molecular Networks and System Biology. A biological cell is a complex "network of networks" from the information processing perspective. Physiologically, it is an integrated device consisting of several thousands of types of interacting proteins. Molecular network is often used as a generic term to refer to the networks involved in cell biology (Alon, 2007). The gene regulatory networks and various molecular networks in cells involved extremely complex yet robust networks, which is one of the focuses of the newly emerged *system biology*. There are enormous opportunities for computer scientists to contribute and to learn from the fields. The following are a few review references: on genome project by Ideker and Galitski et al. 2001, the bio-mimetic nano-scale reactors and networks by Karlsson et al. (2004), molecular networks by Galitski (2004), gene regulatory networks by Davidson (2006).

4 PERSPECTIVE

In the following, we mention some promising research topics that seem not yet being explored. In various previous sections and Ma and Krings (2007), we briefly discussed them in corresponding context; the following is simply a list of summary statements. (1) The new grid computing architecture that emulates neuronal population such as vision neurons for insect compound eyes. This neuronal population architecture may be further integrated and enhanced with dendritic computing (2) Wireless sensor networks that emulate the insect chemosensory networks and the multimodal architecture that has several *parallel* networks concurrently in operation (such as audition, vision chemosensory, etc.). In addition, the bio-robustness mechanism in these insect sensory networks should be captured. (3) The implications of non-cooperative behaviors in social insects to swarm intelligence, evolutionary computing, and to devising new optimization algorithms. (4) Insect audition, which was considered as less developed in insects until recently, is recognized now as underestimated in entomology (Drosopoulos and Claridge, 2006). Still the field of insect audition has received little attention from the bio-inspired perspective. It is interesting to note that insects audition truly resembles the engineered wireless communications. (5) The integration of technologies that are developed for sensors, robots, MAVs, and neuromorphic technologies, in particular, the multi-modality integration may provide better solutions for the sophisticated MAV flights control, especially in unstable and hostile military operations environments.

In the recent report on "Computing and Biology" from the US National Academy of Sciences (National Research Council, 2005), the ants colony optimization and neural-inspired sensors, together with hundreds of other research topics, were recommended as fields of strategic scientific and technological significances. However, the majority of topics on insect sensory systems, such as those discussed in this series of articles, were omitted. There was significant coverage (nearly 4 pages) on ants colony optimization in the National Academies' report. This coverage may also indicate the significance of the areas omitted in the report, which, in our opinion, should prove to be as promising as the ants colony optimizations, if not more.

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