Advances in insect brain/behavior simulation using HNN and robotics

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ABSTRACT

Genetic algorithms have been used to construct a neural model for insect path integration in order to help understand how insects navigate. Over the last four decades some novel experiments have been carried out to simulate navigation using autonomous robots that hoped to not only explain certain factors relevant to insect navigation but also increased our knowledge toward the understanding of insect/robot modular systems. Hardware examples of the neural model using the brain of an insect have been proposed and the concept that a simple model is best could give rise to a new generation of intelligent machines.

The idea of the artificial neural network to help describe how an insect’s “cognitive map” is used for navigation has been designed for use on robot control as a decentralized model, chemical sense and in visual predictive models among others.

Technical advances in analog integrated circuitry along with micro electro mechanical systems (MEMS) have given rise to compact systems (with hardware inspired architecture HNN or Hardware Neural Networks) that may someday help us understand how insects do what they do so well.

INTRODUCTION

Insect brains are small but still they are enormously complex. Artificial neural networks (ANN) simulate neurons in the brain. The simulation of a biological neural network via computer software requires digital computer technology. A hardware-based analog ANN is smaller, faster and more closely emulates functions of biological neurons.

The function of a robot in these experiments is to illustrate a particular behavior based on the output of these ANNs. Emulation of insect behavior in these types of experiments seems the logical choice as many of the early entomological researchers have painstakingly collected an enormous amount of data on this subject while in the field.
New advances in neuromorphic engineering may hold the key to our understanding of how the brain works. The underlying issues of understanding the genetic transfer of information to the formation of neurons may be greatly enhanced when comparable artificial neurons are produced in the laboratory.

**GENETIC ALGORITHMS**

Some of the early models for autonomous robot control have involved a neural component with the intent to help describe common behavioral traits often observed in biological organisms. The robot serves as a platform with various inputs and outputs that help researchers evaluate the outcome. For instance, Path Integration, an important navigation strategy in many insects, can be simulated using a simple mobile robot. While many of the “brains” of these robots in the early years were software based artificial neural networks, a number of other methods derived from biological concepts were also used for robotic control that fall into a classification of computer programming called artificial intelligence (AI). A method called Genetic Algorithms is one such type of AI programming.

Genetic Algorithms (GA) mimic evolution and can be used to evolve certain kinds of neural networks. In GA processing, data groupings are arranged into strings of binary data called chromosomes. These randomly generated chromosome strings are evaluated for fitness. Good fitting pairs are selected and new sets of chromosomes are created to form a new generation. More evaluations are then performed on the new pool of data. Random mutations are thrown in to make it interesting and more generations are created until an adequate degree of fitness is achieved. (Haferlach, Wessnitzer et al. 2007)

![Marker-Based Genetic Encoding](image)

**Figure 1** Marker-Based Genetic Encoding

A chromosome consisting of integers is interpreted as a neural network. For marker-based encoded chromosomes, each neuron is defined by a group of connections specified between a start and an end marker in the chromosome (Figure 1). The method allows the complete build of
the network structure including the number of nodes and their connectivity which is evolved through genetic algorithms.

**Figure 2** GA method composed of cellular automata, neural networks, incremental evolution and behavior selection.

Cellular Automata (CA) are populations of interacting cells. These cells are each computers (automatons) and can represent many kinds of complex behaviors by building appropriate rules. Each cell has a state value and this value changes at each step. Change of state is based on the predefined rules and is also based on the current state of the cell and the conditions of the neighboring cells. CA can model ecological systems or the behavior of insects, and can be also used for image processing and the construction of neural networks. (Kim and Cho 2006) In Figure 2, as the problems become more difficult, the basic evolutionary algorithm needs to be modified in a stepwise manner. For example, if a roving robot moves into a new and more challenging environment, the straight line movements previously learned are compared with turning movements. When the CA-based neural networks module learns a manoeuvr correctly, the successful chromosomes are copied to the next population. The robot evolves to fit the new environment and is able to make turns. These steps are repeated until the robot learns how to navigate the new environment.
BRAIN-MACHINE HYBRIDS

In the bio-inspired robotics field, robots can be used to reproduce animal behavior in order to study their interaction with the environment. Robots help to improve the understanding of animal behavior and animals help to create efficient and robust robotic systems.(Arena, Patane et al. 2011)

Robot engineers have often marveled at how adept an insect can be; how it can navigate through a wide range of obstacles and undergo any number of harsh environments and still successfully do what it has to do stay alive. While the current technology cannot build a cockroach sized robot as agile as the real thing, some researchers have built a cockroach control interface that communicates via a wireless receiver mounted on the roach’s back. The remote control signals sent to the receiver cause electrical impulses to be sent to the cockroach’s antenna. The impulses stimulate a touch response sending the roach in the intended direction.(Latif, Bozkurt et al. 2012)

For similar reasons, hybrid concepts have been proposed for space exploration because of an insect’s remarkable navigation capabilities. These “insects-in-a-cockpit” would be able to master the higher-level decision making that a space robot couldn't.(Di Pino, Seidl et al. 2009) Fundamental analogies exist between the behaviors that insects exhibit and the basic skills that one would expect from autonomous robots in space. Insects such as bees, ants and cockroaches have become particularly appealing models for investigation in the context of biomimetic robotics since they have optimized navigational mechanisms in terms of simplicity and robustness.(Benvenuto, Sergi et al. 2009)

Figure 3 shows a proposed input/output diagram of a honeybee pilot tethered in its cockpit. Inserted into the bee are electrodes for neural registration and stimulation. MEMS-based sensors can detect motor patterns and a system is in place for offering visual and olfactory cues. The external environmental sensors can send signals to both the low level controller and the hybrid controller unit which can influence the low level control system.
Some unique research involving insect hybrids were used to reproduce the behavior of an insect and understand how silkworm moths process information in the brain during adaptive odor searching behavior. In this study, electrical spikes from the neck motor neuron of a silkworm moth were converted into appropriate control signals for steering a two wheeled robot. (Minegishi, Takashima et al. 2012) Similar experimental models were used on silkworm moths to explore the neural mechanisms of odor-source searching behavior but in this case, the robot was controlled via signals from the moth antenna (electroantennogram). (Kanzaki, Nagasawa et al. 2005)

Figure 4 shows a comparison of stimuli processing of a hybrid system and a real organism. In the research of Minegishi and Kanzaki, the sensory input is olfactory; there is a pheromone to which the silkworm moth reacts. The input to the brain model is different in each experiment in that response signals are either from moth neck neurons (Minegishi) or antenna output (Kanzaki). The signals are interpreted by the brain model which sends the appropriate control signal to the robot.
Figure 4 Framework of brain-machine hybrid system (right) compared to that of a real organism (left) from the viewpoint of how they process stimuli from the external environment.

The diagram in Figure 5 shows some of the initial steps in creating the brain-machine hybrid (Minegishi) for an experiment to help understand how silkworm moths process information in the brain during odor searching behavior.
The actual odor sensing robot is shown in figure 6. The results from the experiment showed that the hybrid system could reproduce the moth’s odor tracking pattern and orientation behavior. The robot was fitted with a marking pen that created a marked path during the experiments to easily document the direction of the hybrid system.
Cruse and Wehner have proposed an artificial neural network that allows for landmark guidance and path integration. It is suggested that desert ants and honeybees might use a global neural workspace instead of a cognitive map.

Figure 7 is an example of a network used to simulate ant navigation during foraging. The three main structures are the path integration unit on the left hand side of figure 7, the recurrent network that controls motivation (in red) and the bank of procedural elements (in blue).
Figure 7 The network controlling path integration and landmark navigation. (Cruse and Wehner 2011)
Models of the insect brain inspired by *Drosophila melanogaster* have been proposed (Arena, Patane et al. 2011) with particular attention paid to the two main neural centers, the Central Complex and Mushroom Bodies (See Figure 8). This particular brain model was simulated on some software called RealSim for Cognitive Systems that included robotic hierarchy type drivers that could interface with several commercial robots.

![Figure 8 Block diagram of the insect brain model](image)

**Generic Models for Locomotion by Modular Neural Networks**

A bio-inspired walking robot named HECTOR (Hexapod Cognitive auTonomously Operating Robot) was created following the example of a walking stick that utilizes important aspects of the morphology, biomechanics and neurobiological control. (Schneider, Paskarbeit et al. 2011)(See Figure 9)
Another neurobiological walking scheme for multiple legged robots involves a modular neural network control system (von Twickel, Hild et al. 2012) with sensory motor feedback control per joint. While this system is quite complex (See figure 10) the researchers have admitted that neurobiological networks for locomotion control are so complex that deriving an understanding of the control system solely by experimentation is almost impossible.
**Figure 10** Different types of motor control: (c) Optional muscle models, (d) Virtual agnostic drive and (e) pure servo control.

**Analog circuit neuron models**

The study of biological neural networks are for the most part limited by classical experimental approaches. While one can overcome these limitations by studying the networks from a theoretical point of view and then solve the neural model equations via software, there still is the element of time. It appears that an alternative solution for neural computation is to go analog. (Douence, Laflaquiere et al. 1999)

Saito, et al, have proposed a MEMS (micro electromechanical systems technology) insect robot with six legged motion with control via an analog CMOS HNN. (Saito, Takato et al. 2012).

The insect robot is electrically pulse driven without software or A/D converters and uses memory metals for the artificial muscle (See Figure 11).
Figure 11 Exploded diagram of an actuator for the biomimetics micro robot

This robot introduces the P-HNM or pulse type hardware neuron model that can be used to drive a six legged walking robot by sending pulsed current to memory metal wires.

In another case, a robot that uses insect visual homing via analog electronic circuits that share a number of info-processing principles with biological systems has been proposed by Moller, et.al. This robot system uses an Average Landmark Vector (ALV) navigation which is much simpler than the “snapshot” method of navigation.

While Moller’s work is not per se an artificial neural network model, some of the processing methodology still might be considered a part of the “neuromorphic engineering” trend. That is, that the models and simulations conducted with the robot to emulate insect behavior are closer to the biological entity when the signal processing is purely analog, asynchronous and parallel. Using just discrete analog components, Moller has constructed a robust system where he claims:

1) The ALV model works on mobile robot homing experiments, 2) Some results obtained in experiments with bees could be reproduced with the robot, and 3) Analog circuits leads to suggestions about neural circuits that might mediate homing in insect brains. (Moller 2000)
Although conventional CMOS technology is capable of emulating the integrate-and-fire operation of a neuron, the functionality of a synapse is more difficult to mimic in a simple electrical circuit. It turns out that a passive two-terminal device called a memristor can easily realize synaptic behavior. (Thomas 2013) The memristor is a relatively new circuit device discovered in 2009 that may be the missing component that the artificial intelligence community has been looking for since it was first theorized by electrical engineer Leon Chua more than 40 years ago.

A memristor is a passive circuit element that changes its resistance depending on the amount of current passing through it. The memory part of the memristor is that the component retains the final resistance after the current is shut off. In other words, the memristor "remembers" the last bit of electrical current passing though it and since it is a passive element, it retains this information quite efficiently.

As part of a large scale integrated process, a memristor array can be layered over traditional semiconductor material and with the proper nano-scale interconnection between the memory and the circuit layers below it makes an ideal low-powered high density flash memory. This concept hasn't escaped researchers at Hewlett Packard who have been vigorously obtaining patents on memristive memory devices for future computer systems.

Another feature of the memristor is its relationship between biological neurons. As Chua first theorized, a device such as the memristor could replace what is known as the Hodgkin-Huxley cell (Figure 12, left).

![Figure 12 Electrical circuits of Hodgkin-Huxley (HH) model (left) and the Chua memristive model (right)](image)

In figure 12, the Hodgkin-Huxley cell is a concept model of a squid axion where biological synaptic diffusion couplings are modeled using a time-variable resistor for sodium and potassium concentrations ($R_{Na}$ and $R_{K}$). Chua has realized that a simple memristive circuit (Figure 12, right) could replace the HH model and more reasonably recreate a circuit that mimics a biological synapse in real time.

One agency that has taken note of Chua’s memristor is the Defense Advanced Research Projects Agency (DARPA). DARPA has started a group called the Systems of Neuomorphic Adaptive Plastic Scalable Electronics (SyNAPSE) that will help fund projects building synaptic computers based on devices like the memristor. That this this low-powered device is easily
adapted to current IC fabrication techniques it's no wonder that an analog based, high
density artificial neural network that simulates an insect brain is just on the horizon.


