Software/Hardware issues in modelling insect brain architecture

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Abstract. The concept of cognitive abilities is commonly associated to humans and animals like mammals, birds and others. Nevertheless, in the last years several research groups have intensified the studies on insects that posses a much simpler brain structure even if they are able to show interesting memory and learning capabilities. In this paper a survey on some key results obtained in a joint research activity among Engineers and Neurogeneticians is reported. They were focussed toward the design and implementation of a model of the insect brain inspired by the *Drosophila melanogaster*. Particular attention was paid to the main neural centers the Mushroom Bodies and the Central Complex. Moreover a Software/Hardware framework, where the model could be tested and evaluated by using both simulated and real robots, is described. This research activity aims at introducing an insect brain to act as a controller for very smart and sophisticated insectoid body structures, to give rise to a new generation of novel embodied intelligent machines.

Keywords: Insect brain, Drosophila melanogaster, hybrid robot, dynamic simulation

1 Introduction

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. The study of animal brains leads to new control systems that could allow robots to be able to orient themselves in complex environments, to take decisions, to accomplish dangerous missions, in order to become completely autonomous. Robotic implementation of biological systems could also lead to the introduction of new models for basic sciences, in particular when investigating the emergent properties of models. Several attempts are present in literature related to algorithms or bio-inspired networks able to mimic the functionalities of parts of the brain. A lot of work has been done in several animal species belonging to mammals, mollusks and insects [1]. Looking into the insect world different research groups around the world are trying to design models which are able to reproduce interesting behaviors shown by insects: cooperation mechanisms in ants [2], navigation strategies in bees [3], looming reflex in locusts [4], homing mechanisms in crickets [5], central pattern generator and obstacle climbing in cockroaches [6, 7], reflex-based locomotion control in the stick insect [8], just to cite some examples. It is evident that the effort is focused on specific peculiarities associated with the different insect species that can be also useful for robotic applications. Nevertheless, a more challenging task consists of trying to model the main functionalities of an insect brain, looking from an higher level, trying to identify the mechanisms involved in the sensing-perception-action loop. The proposed work is focused on the development of an insect brain computational model mainly focused on the *Drosophila melanogaster*, the fruit fly. The insect brain architecture, structured in functional blocks, has been developed in a complete software/hardware framework in order to evaluate the capabilities of this bio-inspired control system on both simulated and real robotic platforms. In order to develop an useful and suitable architecture, the proposed framework is flexible and robust and presents a structure suitable to decouple simulations from control algorithms. The functional separation helps to isolate the application itself from graphic interfaces and the underlying hardware. The main aim is to develop an extensible and general purpose architecture. The insect brain model has been evaluated in scenarios strictly linked to the neurobiological experiments to make a direct comparison. Moreover the available data on wild type flies and mutant brain-defective flies allows to identify the main role of each neural assembly in performing specific tasks like visual orientation, olfactory learning, adaptive termination of behaviours and others. Finally the main guidelines used for the definition of evaluation criteria and the creation of benchmarking scenarios where the system performance can be evaluated, are also reported.

2 Insect Brain Model

In the last years, biological experiments unraveled details of the Drosophila brain, with particular emphasis to Mushroom Bodies (MBs) and Central Complex (CX), and a number of functional blocks, explaining the main functionalities of such centers. Starting from these results a new computationally-oriented model of the insect brain, specifically focused on the *Drosophila melanogaster* has been designed and implemented [14, 15].

In the insect brain scheme, reported in Fig.1, it is possible to distinguish four main sensorial pathways; the olfactory and the visual pathways allow to perceive the environment, whereas gustation and nociception are indispensable to obtain information about the goodness or badness of the current situation. In particular the gustatory sensory modality, placed in the front legs of the fly, is reproduced in robotic experiments through signals coming from light sensors placed in the ventral part of the robots, facing with the ground. This modality is used in experiments like the adaptive termination of behaviours. Nociceptory signals, used for punishment, are reproduced through sound signals (or through the ventrally placed light sensors) and applied in such experiments as visual/odour learning. These sensorial pathways are linked together to make the system able to perform anticipatory actions to improve efficiency in finding rewards and to avoid dangerous situations. In the actual structure, learning is attained using mechanisms based on classical as well as operant conditioning. Olfactory and visual inputs, due to their complexity, are considered as pre-processed at the sensory level. Olfaction, has been studied at the aim to derive the corresponding MB neural models. Regarding the olfactory sensors, since the artificial ones are still too slow and difficult to be efficiently characterized, they were substituted by sound sensors, which are more reliable and able to provide both unconditioned and conditioned inputs to the neural processing network. Soon after the visual pre-processing stage we can find the Central Complex neuropil model, containing all its main components:

PB - The Protocerebral Bridge (PB), which, in our model, performs its three main functions (Object Detection, Distance Estimation and Object Position extraction), as drawn by the biological experiments and neuro-anatomical evidence [12, 13];

FB - the Fan-shaped Body (FB), which performs two main functions: feature extraction (color, orientation, size, center of gravity, wideness, height) and feature evaluation/learning (the robot collects features and is able to associate those features to punishment or neutral situations.

EB - the Ellipsoid Body (EB), where the robot spatial and the newly discovered decision making memory is formed and contained.

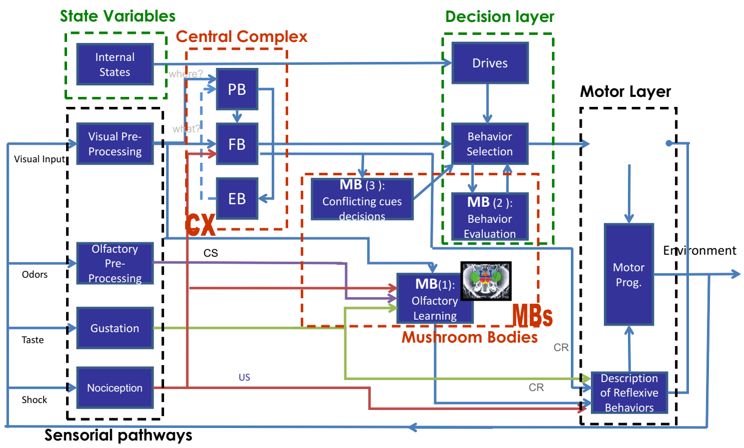

Fig. 1. Block diagram of the insect brain model.

The other fundamental neuropil of the insect brain is constituted by the Mushroom Bodies (MBs). MBs were found to influence many different aspect of the insect brain plasticity. The main function of MBs is olfactory learning: this was implemented in our architecture through a hebbian or STDP based learning scheme in spiking networks. The other function experimentally found in MBs is behaviour evaluation, mainly acting at the decision level. For this reason this MB functionality, here called MB2 (Fig. 1) is included into the decision layer and implemented as a separate block with respect to the olfactory learning block. Another addressed function is decision making: this function was discovered working with MB defective flies which were unable to make a sharp choice among two different contradictory visual features (color and shape) in front of the fading of the preferred one (color). This is a function that, involving visual learning, cannot be ascribed to the conventional functionality of MBs (olfactory representation and leaning). So this function was modeled as a separated block (MB3) and placed at the decision layer (Fig.1). Moreover, from the block-size perspective, direct connections among FB and MB cannot be directly drawn for the lack of experimental evidence in the fly. So it is hypothesized that particular visual information, like color saturation reaches the MBs indirectly through other brain parts (like for example the Lateral Horn) and gives it the possibility to concurrently act on the Behaviour Selection block at the level of decision making.

A series of internal states are monitored through a set of virtual proprioceptive sensors; these internal states undergo a continuous interaction with the ongoing external state of the agent, recorded through the exteroceptive sensors. Internal states are chosen according to the applications prepared, discussed within each experimental scenario. An internal state (like hunger or "need for charging", need to sleep, etc.) is supposed to be directly related to drives which are typically reference control signals for the following Behaviour Selection Network (BSN) block (like desired battery level, zero home distance, etc.). In order to satisfy its drives, the robot has to choose a precise behaviour from a pre-defined set of available behaviours, each one oriented to satisfy one or several contemporary drives. Up to this stage, the BSN is implemented through a spiking network with dynamic synapses, leaving opened the possibility to learn other behaviours better satisfying the strongest drive. This functionality within the BSN takes place at the highest layer in the insect brain architecture. Till now, there are not yet specific experiments that can demonstrate the existence of such a network in the Drosophila brain; therefore the hypothesized artificial BSN was maintained to represent the highest level control functionality. The BSN was endowed, at this stage, with auto-excitatory synapses to avoid a continuous switching among the selected behaviours.

The other block residing at the decision layer is Behavior Evaluation. Experiments on the MB less flies show that this function is ascribed to MBs, even if apparently separated by the common MB functionality. So also this block was modeled separately with respect to the main MB block and so called MB2, as also mentioned above. This block evaluates the capability of the selected behaviour to satisfy the active drive, represented by a given setpoint to be reached. As soon as a given behaviour is initiated (behaviour initiation is ascribed as a specific CX role) the MB2 block starts an increasing inhibitory function on the ongoing behaviour in order to completely inhibit this one if the drive is not satisfied within a certain time window. In this case another behaviour wins the competition and is selected.

The Motor layer contains the following blocks: The Description of Reflexive Behaviours describes the fixed actions that allow the robot to take the right direction in the case of punishment. Here additional functions are included, considering the fact that a fly, repetitively punished, can reach a "no-motion state": i.e. the insect is frozen for a certain amount of time.

The Description of Behavior block describes the available behaviours that the robot can follow. The type and number of the possible behaviours the robot can exhibit depends on the robot applications. As an example implemented is the targeting behaviour. This behaviour, when selected in the BSN, causes a series of actions focussed at moving the robot towards the visual target that elicited that behaviour, while maintaining it at the center of the visual scene. In the proposed model a hierarchical procedure is used to solve possible conflicts between learned behaviours and reflexive ones, in fact the reflexive block inhibits the activity of other potential behaviours. However other conflict resolution strategies can be used including a feedback into the behaviour learning loop.

The Motor Programs block contains all the possible elementary actions the robot can perform. They are supposed, up to now, to be pre-programmed unless a wide space for hosting learning strategies exists, which is currently under investigation. This block is strictly dependent on the robotic architecture to be used. It contains a series of control signals for the wheels/legs in order to realize the desired advancement, steering or rotation. In particular, dealing with legged robots, the central Pattern Generator paradigm was taken into account. This approach was recently accompanied to some powerful theoretical conditions which a-priori guarantee global exponential convergence to any imposed gait that the structure is asked to show [9].

3 Software/Hardware Framework

In a modular architecture the mechanisms used by each module to access to the shared computational resources are extremely important together with the communication rules. Modularity and functional separation, together with reusability and robustness, are the most basic software design principles that can be ensured in software applications. The aim of modularity is to encapsulate all the physical and logical characteristics of the main entities to decouple specific implementations, defining a set of access functions. For this reason, it is possible to divide our structure in specific parts, in order to decouple its functionalities. The Architecture, named **RealSim for Cognitive Systems (RS4CS)**, can be structured as reported in Fig. 2 where five main elements have been identified: The *Graphical User Interface (GUI)* provides tools to display real-time data while allowing the user to control robot and execute algorithms. It is directly connected to the *Algorithm module* in order to obtain data to show and to convey external commands during executions. Interconnected with the Algorithm module there are other two important parts of the architecture, the *Algorithm libraries*, useful to obtain specific and peculiar functionalities related to Algorithm implementations and the *Log Handler* dedicated to log fundamental information to create historical traces. Finally, *Robot Hierarchy* part gives an abstract view of robots, decoupled from specific implementations.

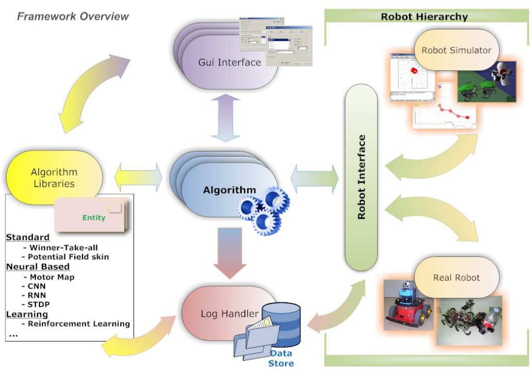

Fig. 2. Overview of the interactions between components in the software architecture for cognitive systems

An overview about already existing robotic simulation environments can be found in [17] where the novelty of the proposed framework are also underlined.

4 Robotic platforms and experiments

The software/hardware RS4CS framework implemented and evaluated, transparently uses, as a final actor, either a robot (wheeled, legged or hybrid) simulated in a detailed dynamical simulator (included within the simulation environment), or a real robot roving on a real environment. From the hardware point of view, mainly two robotic structures were used to test the architecture performance, one wheeled robot, the Rover, and one hybrid robot, the Tribot [10, 11]. The latter appears in two different versions, adopting two different sensor configurations. Tribot I hosts contact, distance, sound, inertial and low-level light sensors; the visual architecture used here is the Surveyor SRV-1 Blackfin color camera, endowed with a series of image processing routines. Tribot II, hosts the new tiny version of the Eye-Ris visual processor [20], adopted for real time visual motion-based segmentation and classification, considered as a pre-processing functionality hosted in the insect optic lobe. From there, signals are sent to the CX block and the remainder of the insect brain model, hosted in the remote PC station. The Rover was equipped with contact, distance, sound and two different visual sensors: a classical camera and the Eye-Ris platform in a panoramic configuration, useful for implementing a stand alone, autonomously working model of the CX, where the orientation strategy is demonstrated in action [19]. For the testing of the motor layer in legged machines, also the MiniHex, a 12 dof autonomous walking minirobot was used [21]. The robot is able to communicate their whole sensory status to a host PC via a wireless communication. The proposed insect brain architecture was tested against the corresponding experiments already performed in the various worldwide laboratories on the fly. In particular the architecture was tested in experiments involving visual orientation, visual learning, visual detour against distractor, adaptive termination of behaviors, decision making in front of contradictory cues and others. Moreover, when experimental data are available, also robot experiments mimicking the damaged behaviours met in mutant flies were reproduced; more details about the experiments are reported in [16, 18]. A series of different robotic platforms, as shown in Fig. 3, has been used to formalize robotic experiments in accordance to the neurobiological set-up used for insects in order to test the capabilities of the insect brain model.

Fig. 3. Robotic platforms used to evaluate the insect brain model.

5 Definition of Scenarios

When a Cognitive architecture is designed and developed, one of the most important aspects to be considered is the definition of evaluation criteria and the creation of scenarios where the system performance can be evaluated. One of the most relevant attempts in this direction, can be found in the Darpa Project named BICA (Biologically Inspired Cognitive Architectures) that began in 2005 with the aim to create the next generation of Cognitive Architecture models of human artificial intelligence.Among the activities of the BICA, a core set of functions typical of a two-year-old human child was depicted with particular attention to cognitive, perceptual, and motor skills. These include behavioral tasks related to search, navigation, manipulation, memory, language, and three pathways to procedural knowledge: instruction, demonstration, and reinforcement/exploration [22].

From these experiences it is evident how several difficulties can be encountered when testing scenarios for cognitive architectures have to be designed. To facilitate the problem, we considered the formalization of scenarios like an integration process that involves several different elements that take part in the definition process. Due to the complexity of the problem, four different design principles have been considered.

Bottom-Up A bottom-up process can be followed starting from the information about the basic behaviours of the robotic platforms taken into account. Each structure due to its mechanical peculiarities allows the definition of different basic behaviours that can be used in a scenario to solve a given task (e.g. the hybrid robot Tribot thanks to the frontal manipulator is able to move objects just pushing or carry them).

Top-down The top-down approach is based on the formalization of scenarios that should be of interest for the robotic field. The idea is to include real life scenarios where the cognitive architecture can be evaluated considering the impact in solving open problems of interest for people producing an impact in the society (e.g. Rescue robots helping in post-disaster scenarios).

Biologically-driven The validation of the insect brain model passes through tests and experiments that can show the similarity between the robot behaviour and the Drosophila. Starting from the experiments reported in literature, the elementary blocks that constitute the insect-inspired cognitive architecture are evaluated and compared with the biological data. The biologically-driven scenario definition is important to confirm the hypotheses formulated during the cognitive architecture design phase. Moreover, new experiments can be defined to be performed with wild-type and mutant flies to extract new data to be compared with the robot simulations and experiments to identify the part of the insect brain involved in these memory mechanisms.

Robot oriented Finally the definition of scenarios can be considered following a robot-driven approach. Starting from the capabilities of the insect brain architecture, it is possible to extend the structure to solve tasks that are far beyond the drosophila capabilities. The relevant blocks of the architecture can be improved, in a simple way, expanding the memory available or duplicating elementary blocks. Following this design flow, the complexity of the scenarios and the insect brain computational model can grow up in parallel on the basis of the real fly's abilities to create a more powerful agent.
This is in line with the biological evidence that, for example bees brain can be considered as a grown model of the fly brain, where essentially the same areas can be identified (MB, CX, etc). This enables the enhanced capabilities of the bees (eg. labyrinth solving, social behaviour emergence, etc) with respect to the fly.

Among the proposed strategies for the design and assessment of robotic experiments, the biologically-driven and the robot-oriented approaches have been considered the most promising due to the direct links to the neurobiological results and to the possibility to further extend the robot capabilities slightly improving the insect brain blocks controlling the robot behaviour. The considered scenarios include situations of increasing complexity to show the acquisition of cognitive capabilities like multisensory integration, contradictory cues resolution, efficient information storage and retrieval. Those capabilities can be tested starting from classical exploration and foraging tasks, going up to tasks involving motivation, based on reward functions. The neural structures responsible for these behaviors have been very recently enriched with new substructures inspired by very recent discoveries in the insect counterparts. This gave the opportunity to design and simulate new networks that, via processes that can be described via reaction-diffusion dynamics, are able to lead to the emergence of complex behaviors like attention and expectation, which can be considered the basis of a cognitive behavior, i.e. the capability of planning ahead [23].

The experiments can be tailored to the sensory-motor loop available in each robotic structure. The scenarios envisaged will have to emphasize the model capabilities, using the robots as test beds.

6 Conclusion

In this paper some key results of a recent research activity among Neurogeneticians and Engineers to model an insect brain architecture are briefly presented. A block size model of an insect brain computational structure has been reported, outlining the main blocks and their specific roles and enhancing some emerging capabilities related to reaction-diffusion aspects, which open the way to a further refinement of the overall structure. A complete software/hardware framework has been developed in order to evaluate the insect brain model and performing experiments directly linked to the neurobiological experimental set-up. The developed architecture can be easily interfaced with both dynamic simulation environments and robotic platforms by using a communication interface layer in a client-server based topology.

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