Conceptualization of an Insect/Machine Hybrid Controller for Space Applications

Antonella Benvenuto, Fabrizio Sergi, Giovanni Di Pino, Domenico Campolo, Dino Accoto, Eugenio Guglielmelli and Tobias Seidl

***Abstract*— This paper reports the preliminary results of a research effort aiming at conceptualizing novel insect/machine hybrid controllers for autonomous exploratory vehicles. In particular, we investigate the possibility to include pre-developed animal intelligence capable of sensory-motor integration, decision-making and learning behaviors.**

In this context we present an in-depth review of insect neurophysiology focussing on mechanisms related to navigation. In addition we critically review current approaches towards hybridity and insect/machine interfaces.

Finally, a novel insect/machine hybrid control architecture is proposed. It includes biological/artificial modules and deliberative/reactive behaviors.

I. Introduction

Space operations in general face difficulties when real-time direct control is involved. Both time delay and limited bandwidth narrow the possibility to implement effective real-time remote control of space operations from earth. Hence autonomous behavior is a key element towards an advanced operational scope during space missions.

Fundamental analogies exist between the behaviors that insects exhibit and basic skills which one would expect from autonomous robots in space. Mobile robots, such as space rovers, should be able to perceive the static and dynamic aspects of an unknown, unstructured environment and modify their behavior accordingly, very much like real insects do.

Navigation capabilities are the key basic characteristic of mobile robots. Insects such as bees, ants and cockroaches have become particularly appealing models for investigation in the context of biomimetic robotics since they present remarkable navigational capabilities [1]-[4]. They developed navigational mechanisms, which are optimized in terms of simplicity and robustness, both of which are invaluable features of robotic systems.

Some ongoing research activities at the interface between engineering and neurobiology show working demonstrators meant for understanding and reproducing a range of isolated components of complex behaviors such as flight stabilization, obstacle avoidance, altitude control, directional control, landmark recognition, social interaction and division of labor [5]-[10].

What seems natural for an animal is difficult to understand and even more so to reproduce in a robot. For example, navigation in a foraging animal involves planned, directed locomotion towards a goal (i.e. food source, nest) while negotiating various obstacles and possibly trading off between a successful foraging run (i.e. reaching the desired goal), the time of the run (i.e. the energy budget) and predators (i.e. fatal threats).

The difference of performance between a living organism and a conventional robot becomes most apparent in unstructured environments with unknown and potentially hazardous situations occurring in a non-predictable manner.

However, unmanned exploratory missions to e.g. Mars or Moon are in general preferred to missions with human presence since these manned missions always present a risk to the astronaut and are extremely costly. Facing the challenges of autonomous exploration, the range of future automated mission vehicles strongly correlates with the capability of the control architecture to successfully integrate a whole range of decision parameters. In other words, the use of insect intelligence could create an intermediate type of mission bridging between purely robotic and human controlled missions.

In this context we investigate the integration of "animal intelligence" into the control architecture of exploratory vehicles and proper modalities to harvest the full potential of insect intelligence. The aim is to reproduce high level insect behaviors where decision making is involved. In particular we aim at integration of tasks such as navigation towards a distant goal, route learning, energy budget maintenance, compensating reaction towards unexpected perturbations, abilities to memorize new experiences and to learn new strategies. These high-level tasks require a level of complexity that current control architectures are still far to successfully manage. A biomechatronic and interdisciplinary approach has been followed by starting from an in-depth review at the intersection of insect neurophysiology/ethology and robotics.

This work was supported by the ESA Ariadna Medium Study "Machine/Animal Hybrid Controllers for Space Applications (21256/07/NL/CB)".

A. Benvenuto, F. Sergi, G. Di Pino, D. Campolo, D. Accoto and E.Guglielmelli are all with Università Campus Bio-Medico di Roma, 00128 Rome, Italy (corresponding author e-mail: a.benvenuto@unicampus.it, phone: +3906225419610, fax: +3906225419609)

T.Seidl is with the Advanced Concepts Team, European Space Agency, 2201 AZ Noordwijk, The Netherlands (email: tobias.seidl@esa.int)

Considering the inherent technological challenges we have made the following assumptions in order to facilitate our work:

i. We assume that it is feasible to keep alive and functional the animal brain tissue (or the whole insect) for a period of time appropriate for space missions.

ii. The robotic platform can be designed according to *good practices* taught by biomimetics. In particular we will not take care of control issues which can be solved with a smart (e.g. biomimetic) design.

iii. Since we want to profit of highly elaborated behaviors observed in living animals, we focus on the use of pre-developed living tissue and do not consider in-vitro development of biological neuronal networks.

II. Background on Insect Behavior

In the last years several studies have been performed highlighting that insects process and learn information to flexibly adapt to their environment [1],[2],[11].

Insect brain provides intelligent solutions to a wide range of ecologically relevant problems, therefore the possibility of a central integration that horizontally combine different domain specific modules to form new behaviors and new solutions has been considered [2].

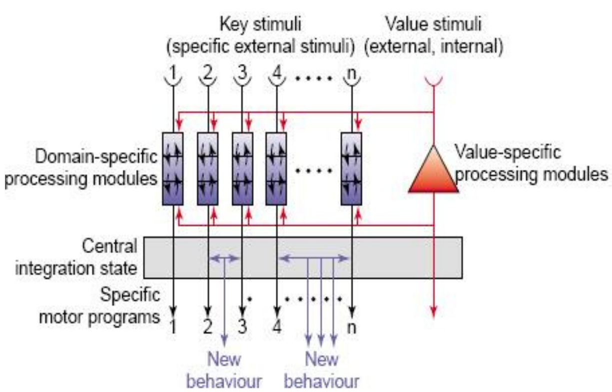

Figure 1: Insect brain architecture (from [2])

Two areas of insect brain have been individuated as association sites of multisensory convergence: the mushroom bodies (MB) and the central complex (CX). The mushroom bodies have major roles in spatio-temporal sensory processing and learning [2].

The role of the central complex seems to be related with (pre-)motor processing, higher locomotion control, including initiation and modulation of behavior, goal directed motion and possibly path integration [5].

Path integration (PI) and landmark-based navigation (LN) are the main navigation processes used by insects when exploring new terrain. PI depends on simultaneous inputs from a neural compass and a neural odometer, i.e. from systems that incrementally record direction and distance of travel; landmarks in contrast acts as signposts triggering the insect to perform a particular action rather than notify them of specific location [1].

In some species, i.e. bees and ants, the compass direction can be gained from celestial cues (allothetic cues) [1] that can be also used in space environment (i.e. Martian atmosphere) [6]. Different approaches are used for distance estimation, e.g. bees record optic flow [3], while cockroaches and ants mainly use proprioceptive information (idiothetic cues) [4],[12].

Information provided by PI and LN systems is used by ants in a strictly cue-dependent procedural way [1]. A "general landscape memory" with the capacity to combine the information from multiple views and movements in a world–centered representation with a hierarchical navigation system has been hypothesized in honeybees [11].

Insects are able to generate rich behaviors by merging path integration, place recognition and landmark routes integration. The objective of the novel proposed architecture is to harvest such capabilities for developing better autonomous explorative robots. In the next paragraph we briefly show current approaches towards hybridity.

III. Current approaches towards hybridity

Bidirectional exchange of information between the biological and artificial components of an hybrid controller can be achieved by *i)* natural interfacing (cockpit-based approach), *ii)* neural interfacing and *iii)* combination of both.

Natural interfaces use the capability of the animal to use legs, wings or muscles to exchange information with the system.

Neural interfaces are tools that decode the neural activity and translate it into specific instructions for a mechanical device or a computer application. To complete this task they do not involve any muscle activity of the user, thus they can be considered as new output pathway for the nervous system [13].

To the authors knowledge, the first attempt in the direction of robot control by means of in-vivo intelligence is the Khepera robot controlled by a lamprey brain [14], which we describe although it does not integrate insect tissue. Other examples are the Cockroach Controlled Mobile Robot (Roachbot) [15] and the moth-robot [16]. These attempts will be described in a synthetic way for better focusing on their peculiarities.

A. Natural interfacing (Cockpit-based approach)

The cockroach-robot has been developed at Irvine University by Hertz [15].

A bidirectional natural interface consisting of eight distance proximity sensors, LED panels and a modified trackball is reported. The robot is used to execute motor commands decoded from movements of an insect positioned on a modified trackball, and to acquire sensorial data about the environment through proximity sensors, encoded into a light stimulus for the cockroach.

The system is limited to fleeting behavior (one of the few behaviors bypassing the central complex), which is simply triggered by stimulus-response very predictable reflexes, thus the hybrid system does not exploit the high-level autonomous behaviors afforded by the insect's brain.

B. Neural interfacing

One remarkable example of neural interfacing between animal and controller is the lamprey-robot by Mussa Ivaldi and co-workers at University of Chicago [14].
In this case, a neural bidirectional interface is presented.
It consists of recording electrodes for acquiring neural data related to the lamprey turning intention, and stimulation electrodes for applying electrical stimuli encoding light intensities recorded by robot sensors.
This ingenious system, however, faces some limitations. First, the purely neural interfacing does not exploit the advantages deriving from the natural capability of the animal to use legs, wings or muscles that can be usefully adopted as input and output signals to/from the system. Moreover, the system can only trigger highly predictable stimulus-response reflexive behaviors.

C. Natural and neural interfacing

The moth-robot represents the combination of both natural and neural interfacing, it was realized by Higgins and co-workers at Neuromorphic Vision and Robotic Systems Lab, University of Arizona [16].
In this concept we find bidirectional interfacing consisting of *i)* a natural interface through a continuous optic flow provided by a 14-inch-high revolving wall painted with vertical stripes, and *ii)* a neural interface for measurements of electrical activity of visual motion neurons. In order to realize this approach the moth is immobilized inside a plastic tube mounted on a wheeled robot, which is used only to turn left or right, according to neural signals translated by a computer into action.
It is not reported how robot movements influence vertical stripes motion, therefore a closed loop sensing and action behavior could not be achieved.

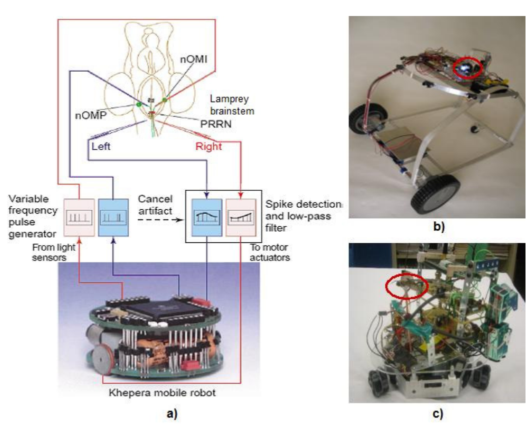

Figure 2: Current approaches towards hybridity (from [14]-[16])

Figure 2a schematizes the Lamprey-robot: the electrical stimuli are delivered to the axons of the intermediate and posterior octavomotor nuclei (nOMI and nOMP, respectively). Glass microelectrodes record extracellular responses to the stimuli from the posterior rhombencephalic neurons (PRRN). The roachbot and the moth-robot are represented in Figure 2b and Figure 2c respectively (red circles indicate the insects on the robotic platform).

IV. NATURAL AND NEURAL INTERFACES

Some of the most significant examples of natural and neural interfaces are reported in the following.
As regards natural interfaces, a programmable visual arena for tethered insects, based on panels composed of an 8 × 8 array of individual LEDs has been developed. The panels have been designed in order to provide flexibility of individual-pixel brightness control, allowing experimentation over a broad range of behaviorally relevant conditions [17].
A system for characterizing flight behavior of tethered fruit flies has also been implemented [18]. The fruit fly has been tethered to a MEMS-based force sensor probe and the force sensor wire bonded to a PCB.
The fruit fly initiated tethered flight either spontaneously or after a puff of air was applied. Experimental results demonstrate the effectiveness of this technique for reliable and precise real-time measurements of flight forces in tethered flying fruit flies.
Neural interfacing on insects presents advantages compared with other animals due to the one-to-one correspondence between nerve stimulation and muscle activation, the low voltage required for stimuli and the simplicity of the whole system [19]. A breakthrough in this field happened in 1995 when electrodes similar to cuffs were implanted in the nerve cord of a tethered cockroach (Periplaneta Americana) for about two months [20]. The increase in neural activity linked with spontaneous walking has been described. Moreover, after antenna touching stimulation, the presence of large amplitude impulse evoked in the descending interneurons controlateral to the touched antenna and ipsilateral to the escape direction has been reported.
Shape Memory Alloy (SMA) electrodes clipped around the nerve cord along the thorax have been developed for neural activity recording in freely walking animal by using a radio telemetric system in a spatial range of about 16 meters [21].
In the same year an interesting microsystem has been proposed, which is able to stimulate and record from the nervous system of a flying insect (Manduca sexta); it is light enough to permit free-flying experiments [22].
A significant example of co-existence of different modalities of insect-machine interfaces has been recently presented in a cyborg beetle; the system consists of muscular stimulators, embedded microcontroller and batteries, microfluidic tubes and LED visual stimulator, together with a silicon neural probe introduced during the pupal stage. Four neural stimulators are implanted in the flight control area of the brain and close to the wings muscles on both sides. The device reproducing the optic flow is mounted hanging the LEDs array in front of the insect head [23].

Unfortunately none of these systems has the characteristic to be at the same time bidirectional, telemetric and fully-implantable, which are essential requisites for our aim. From our analysis it does not seem viable to use only a neural interface for assigning deliberative control functions to the insect, because of the low grade of robustness achieved today by those devices.
Nevertheless the meaning to establish the insect-machine connection at the neural level still persist, taking into account that it can assure the multimodality of communication and the redundancy of information exchanged. Following these considerations, we propose a system where both neural and natural interfaces closely interact.

V. Towards an Insect/Machine Hybrid Controller

The proposed Insect/Machine Hybrid Controller hinges upon the following concepts:

- *Operating environment*: in general very different from the natural environment where an insect may live.
- *Tasks*: the tasks of interest for space applications are restricted to *navigation* and *exploration*. The *low-level tasks* are those which can be handled autonomously by the artificial robotic platform.
- *Degree of hybridity:* defined as a trade-off between low-level and high-level tasks.

A double hybrid controller is proposed consisting of both biological/artificial (insect/robot) modules and deliberative/reactive behaviors.
We assume that for a given operating environment, robotic platforms are available which are specifically designed to overcome low-level navigation issues. For example, for the case of the Martian soil, proper vehicles have been specifically designed to cope with the nature of the soil, e.g. asperities, presence of sand/dust, local gravity and radiations [6]. These are 'details' which the insect should not get involved with.
From a mechatronic perspective each vehicle is endowed with a set of specific sensors, mechanisms, actuators and control algorithms. Such sub-modules are necessary to solve low-level tasks and, eventually, will also be part of the proposed controller.
With reference to Figure 3, the relevant sub-modules of the mechatronic system are:

- Sensors: low-level sensors (LLS) used for locomotion control and proprioception sensors used for information related to robot internal state (e.g. energy and failures). Such modules may include proximity sensors, wheels encoders, inertial modules and wheel slide sensors for self-stabilization.
- Controllers:
  - Low-level controller is devoted to self-stabilization (adaptation to complex terrain) and obstacle avoidance. Its outputs are sent to the executive controller.
  - Executive controller weights inputs from low level controller, proprioceptors and middle layer controller.

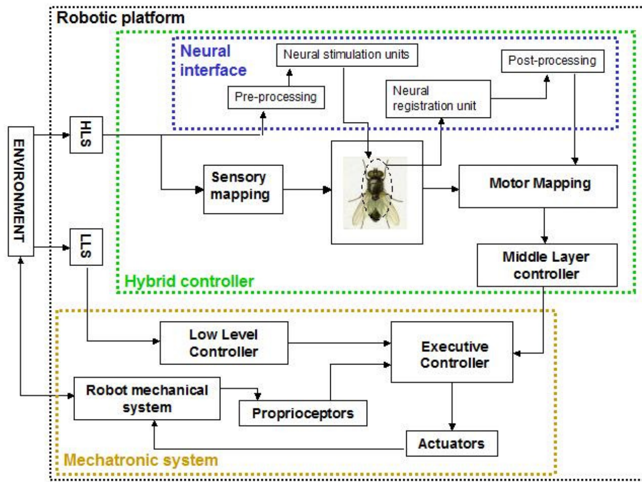

Figure 3: The proposed control architecture

As an example, an oversimplified arena is a cockpit where a tethered insect has the perception to gain compass direction by celestial cues and to estimate distance by optic flow; both motor and neural activities are properly registered.
We wish to exploit the insect *pre-developed intelligence* which is tightly linked to the insect's previous experience, to its body (*embodied intelligence*) and to its natural environment.
In the present account, we will not turn our attention on the abilities of an insect to re-learn to use a different body (e.g. learning to cope with wheeled navigation or use an extra robotic pair of limbs). Rather more we focus on the already acquired knowledge of the insect model. Ideally, the underlying robotic platform shall be made *transparent* to the insect, i.e. the platform should provide signals as natural as possible. In fact, motor commands from the insect shall be used to steer the robotic sub-module. *The Middle Layer Controller* shall purposely be designed to fulfill this aim.
In order to match the pre-developed navigation and exploration skills of an insect with the specific operating environment, a *sensory mapping* mechanism should be implemented. Navigation and exploration of insects are basically driven by *attractors* and *repellers* elements present in their natural environment. The different typologies of such elements can be simplified in two classes: *static* and *dynamic*.
The basic behaviors implemented during exploration and navigation can be reduced as indicated in Table I that represents the inputs of the sensory mapping mechanism in Figure 3.

TABLE I
Exploration/Navigation basic behavior

	attractors	*repellers*
static	pursuit	avoidance
dynamic	hunting	fleeting

These inputs are then mapped onto the set of the output elements, as schematized in Table II.

TABLE II
SENSORY MAPPING OUTPUTS

	attractors	*repellers*
static	food/home	obstacle
dynamic	prey	predator

Since the operating environment is not the natural environment for the insect, specific sensors shall be deployed (High-Level Sensors, HLS in Figure 3) which complement the original set of sensors of the robotic sub-module (LLS). These sensors may include vision systems, temperature sensors, polarization sensors for direction estimation, etc. All inputs coming from these sensors are mapped in such a way that they can represent one of the output classified in Table II. Simultaneous stimulation of multiple sensory cues will lead to unpredictability of the outcome of the hybrid system due to the complexity of insect decision making mechanisms. Therefore, representation of multi-modal sensorial inputs in an environment able to replicate a situation which is natural for the insect may lead to a true decision making and thus to an autonomous behavior.

The flow of information to and from the insect occurs via a combination of both natural and neural interfaces in order to have redundancy and robustness. The communication established has to assure enough stability and bandwidth to allow the insect driving the actuators of the robot.

Insect motor response to this set of input data is properly mapped in order to be processed by the middle layer controller, which sends the information to the executive controller.

VI. Conclusions and Future Work

A double hybrid controller is conceptualized consisting of both biological/artificial (insect/robot) modules and deliberative/reactive behaviors. In order to reach the goal an interdisciplinary approach has been followed *i)* by investigating insects neurophysiology and ethology, with the aim of identifying which behaviors are suitable to be triggered in space environments, and *ii)* by critical reviewing current achievements on biological/artificial controllers. It has been assumed that low-level tasks are managed by the robot, while the "insect intelligence" acts when decision making is required.

Even though much work is required in order to address still open issues, e.g. potential conflicts management and explicitation of the functions implemented in all sub-modules of the proposed architecture, the discussed concepts represent a first step towards the development of completely autonomous space exploratory vehicles taking advantages from the integration of pre-developed insect intelligence.

References

[1] R. Wehner, "Desert ant navigation: how miniature brains solve complex tasks", *Journal of Comparative Physiology A*, vol.189, pp.579–588, 2003.

[2] R. Menzel and M. Giurfa, "Cognitive architecture of a mini-brain: the honeybee", *Trends in Cognitive Sciences*, vol.5, no.2, pp.62-71, 2001.

[3] M. V. Srinivasan, "How bees exploit optic flow: behavioural experiments and neural models", *Philosophical Transactions: Biological Sciences*, vol.337, no. 1281, pp. 253-259, 1992.

[4] R. Jeanson and J. Deneubourg, "Path selection in cockroaches", *The Journal of Experimental Biology*, vol.209 pp.4768-4775, 2006.

[5] A. Abbott, "Working out the bugs", *Nature*, vol.445, pp:251-254, 2007.

[6] M S. Thakoor, J. M. Morookian and J. Chahl, "BEES: Exploring Mars with bioinspired technologies", *Computer*, pp.38-47, September 2004.

[7] O. Franz and H. A. Mallott, "Biomimetic robot navigation", *Robotics and Autonomous Systems*, vol.30, pp.133-153, 2000.

[8] N. Franceschini, "Visual guidance based on optic flow: a biorobotic approach", *Journal of Physiology*, vol.98, pp.281-292, 2004.

[9] R. Pfeifer, M. Lungarella, F. Iida, "Self-Organization, Embodiment, and Biologically Inspired Robotics", *Science*, vol.318, pp.1088-1093, 2007.

[10] M.Waibel , D. Floreano, S. Magnenat and L. Keller, "Division of labour and colony efficiency in social insects: effects of interactions between genetic architecture, colony kin structure and rate of perturbations", *Proceedings of the Royal Society B*, vol.273 pp. 1815-23, 2006.

[11] R. Menzel, R. Brandt, A. Gumbert, B. Komischke, J. Kunze, "Two spatial memories for honeybee navigation", in *Proceedings of the Royal Society London B*, 267:961-968, 2000.

[12] T. Seidl, M. Knaden, R. Wehner, "Desert ants: is active locomotion a prerequisite for path integration?", *Journal of Comparative Physiology A*, vol.192, pp.1125–1131, 2006.

[13] J.R. Wolpaw, "Brain-computer interfaces as new brain output pathways", *Journal of Physioogyl*, vol.579, pp.613-619, 2007.

[14] B. D. Reger, K. M. Fleming, V. Sanguineti, S. Alford, F. A. Mussa-Ivaldi, "Connecting brains to robots: an artificial body for studying the computational properties of neural tissues", *Artificial Life* vol. 6, pp.307-324, 2000.

[15] http://www.conceptlab.com/roachbot/

[16] http://neuromorph.ece.arizona.edu/

[17] M. B. Reiser, M. Dickinson, "A modular display system for insect behavioral neuroscience", *Journal of Neuroscience Methods*, vol. 167 pp. 127–139, 2008.

[18] Y. Sun, S. N. Fry, D. P. Potasek, D. J. Bell, and Brad J. Nelson, "Characterizing Fruit Fly Flight Behavior Using a Microforce Sensor With a New Comb-Drive Configuration", *Journal of Microelectromechanical Systems*, vol.14, no.1, pp.4-11, February 2005.

[19] J. Mavoori, B. Millard, J. Longnion, T. Daniel, C. Diorio "A miniature implantable computer for functional electrical stimulation and recording of neuromuscular activity", in *2004 IEEE International Workshop on Biomedical Circuits & Systems*, pp S1/7/INV - S1/13-16.

[20] S. Ye, J.P. Dowd, C.M. Comer, "A motion tracking system for simultaneous recording of rapid locomotion and neural activity from an insect", *Journal of Neuroscience Methods*, vol. 60, pp.199-210, 1995.

[21] S. Takeuchi, I. Shimoyama, "A radio-telemetry system with a shape memory alloy microelectrode for neural recording of freely moving insects", *IEEE Trananctions of Biomedical Engineering*, vol. 51, pp.133-137, 2004.

[22] C. Diorio, J. Mavoori, "Computer Electronics meet animal brains", *Computer*, vol.36, pp.69-75, 2003.

[23] H. Sato, C. Berry, B. Casey, G. Lavella, Y. Yao, J. VandenBrooks, M. Maharbiz, "A Cyborg Beetle: Insect Flight Control Through an Implantable, Tetherless Microsystem", in *MEMS 2008*, pp. 164-167.