Beyond biomimetics: towards insect/machine hybrid controllers for space applications

ANTONELLA BENVENUTO*, FABRIZIO SERGI*, GIOVANNI DI PINO*, TOBIAS SEIDL**, DOMENICO CAMPOLO*, DINO ACCOTO* and EUGENIO GUGLIELMELLI*

**CIR - Laboratory of Biomedical Robotics and Biomicrosystems, Università Campus Bio-Medico,*
Via Álvaro del Portillo, 21-00128 Roma, Italy
e-mail: a.benvenuto@unicampus.it
***Advanced Concepts Team, European Space Agency, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands*

Abstract

Robots for space applications require a level of autonomy while operating in highly unstructured environments that current control architectures cannot manage successfully.

We investigated on including pre-developed insect brain tissue into the control architecture of space exploratory vehicles. A doubly hybrid controller is proposed that hinges around the concept of "insect-in-a-cockpit" towards an evolution of the classical deliberative/reactive paradigm, featuring a biological (insect brain) high-level deliberative module coupled with low-level reactive behaviours embedded in a robot. The proposed concept, its design methodology and functional description of the submodules are presented, along with a preliminary feasibility assessment mainly derived from in-depth review of the state-of–the-art.

Keywords: Biomimetics; Hybrid Robot Control Architectures; Insect navigation; Neural Interfaces; Biomechatronics

1. INTRODUCTION

Facing the challenges of autonomous space exploration, the range of future automated mission vehicles strongly correlates with the capability of the controller to successfully integrate a whole range of decision capabilities. Nowadays, working devices reproduce a range of isolated components of complex behaviours, such as flight stabilization, obstacle avoidance, altitude control, directional control and landmark recognition [1-3]. But some tasks, such as navigation without drift towards a distant goal, reaction to unexpected perturbations, memorization of new experiences and learning of new strategies, require a level of complexity that current control architectures are still far to successfully manage.

Fundamental analogies exist between the behaviours that insects exhibit and the basic skills which 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 [4-5]. In this context, the use of insect intelligence could create an intermediate type of mission bridging between purely robotic and human controlled missions.

This paper presents the conceptualisation and the design methodology of a doubly hybrid controller that includes a living insect in a cockpit. The insect intelligence controls the robotic platform when decision-making and/or cognition (i.e. reasoning) are required. The interfacing between the insect and the robotic platform can be accomplished by means of natural and neural interfaces. Well beyond biomimetics, insect/machine hybrid systems represent a new challenging approach merging biomimetics, neurophysiology, ethology and microengineering.

Given the inherent technological challenges, some simplifying assumptions are required in this study so to address the most challenging goals from the strict robotics research viewpoint:

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

ii. 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.

iii. The robotic platform can be designed according to good practices taught by biomimetics. In particular we will not take care of any specific control issues, which can be already solved with a smart (e.g. biomimetic) state-of-the-art design.

In order to reach our design goal, an interdisciplinary approach has been followed which moved from an in-depth review at the intersection of insect-inspired robotics, insect behaviours and insect/robot interfacing to end-up with a detailed proposal of the novel hybrid control architecture, as reported in the following sections of this paper.

2. BIOMIMETICS VS BIOLOGY: TOWARDS HYBRIDITY

2.1. Insect-inspired robotics

The biologically inspired approach in the design of robotic agents intends to refer to natural evolution of species as an endless source of design solutions, which are optimized for a given ecological niche. Although the focus of traditional biologically inspired robotics has been mainly on neural modelling for mimicking animal behaviours, recent developments in the field have centred on the concepts of embodiment, which is the reciprocal and dynamical coupling between brain, body and environment [6]. This approach has led to the development of new robotic agents, which are more suitable to deal with the real world and perform successfully in uncertain conditions. In recent years many robotics laboratories have worked on the design of bio-inspired agents trying to put in practice these design principles, so that a wide collection of animal-like robots can be reported at the present time. We will mainly focus in the following on robotic solutions concerning bio-inspired locomotion.

In these years, research effort has been devoted to the development of cockroach-inspired walking and running hexapod robots [7-8] with robust self-stabilization intrinsic capabilities which allow locomotion even on irregular terrains. This is achieved by exploiting the dynamical coupling between the legs and the ground, which enormously simplifies the control.

The capabilities of adaptation to different terrains have also been demonstrated in snake-like robots, by varying either ground friction [9] or slope [10].

Furthermore, flying microrobots inspired on flies have been designed [11-12]. These robots can generate the necessary high-dimensional wing trajectories by a smart, bio-inspired design of wings kinematics and passive dynamical properties, thus simplifying the number of actuators required to accomplish the task of flapping flight. The beneficial generation of multiple Degrees of Freedom (DOF) trajectories with a single DOF of actuation has been also achieved in a fish robot called Wanda [13]. In this realization the unbalanced buoyancy of the structure is exploited to map, through the dynamical interaction with the environment, the wiggling frequency, amplitude and waveform of the tail with the speed, attitude and heading direction of the robot, respectively.

The case of underwater walking has been investigated for developing a robot inspired on the American lobster [14] such system reproduces many salient properties of lobster locomotion, ranging from the ability of adapting to a complex variety of bottom types to the ability of performing a “tactile” navigation through flow and contact sensors.

A very interesting feature of the locomotion of some animal forms is gait transition capability, which allows energy optimization and adaptation to different types of environments. Gait transition is also very interesting in the perspective of highlighting the underlying neural mechanisms at its bases. As an example, the transition from swimming to walking of salamanders is of great relevance for studying vertebrate evolution through the analysis of spinal locomotor circuits [15]. A model simulating a central pattern generator has been implemented in a salamander-like amphibious robot [16] as a system of coupled non-linear oscillators, which receives a simple high-level command signal as input, triggering and modulating the transition among swimming, serpentine crawling and walking.

Another very interesting feature well addressed by bio-inspired robotics is climbing on vertical surfaces [17-18] which has been obtained in robotic agents by using a micropatterned fibrillar dry adhesive inspired by geckos’ foot morphology.

These examples show that a bio-inspired design approach can improve the locomotive performances of mobile robots in terms of maneuverability and adaptation to uncertain situations. Higher-level tasks like navigation in unknown environments [1], social behaviours and division of labour [19-20], which require some abstraction and decision-making, have also been addressed in autonomous mobile robots with a bio-inspired approach.

The results obtained by research in this field are promising in the perspective of improving the capabilities of autonomous robots in uncertain conditions. Despite of that, reproducing a global animal behaviour in a mobile robot through a bio-inspired design is still far from being successful. For this purpose, we consider the option of interfacing the robot with a pre-developed intelligence worth to be pursued, from the perspective of exploiting the insect basic cognition abilities to directly implement deliberative functionality in a robotic artefact.

2.2. Main features of insect behaviours

The addition of a pre-developed intelligence can improve robot performances for complex high-level tasks management. Among several animal species, fundamental analogies exist between the behaviours that insects exhibit and the basic skills which we would expect from autonomous robots in space.

In the last years, several studies have demonstrated that the insect neuronal system is capable of dealing flexibly and adaptively with a wide range of ecologically relevant problems; the possibility of a central integration that horizontally combines different domain specific modules to form new behaviours and new solutions has also been considered [21-22]. Two areas of the insect brain are commonly associated with multi-sensory convergence: the mushroom bodies (MB), that play a major role during spatio-temporal sensory processing and learning [23], and the central complex (CX), that is involved in (pre-)motor processing, higher locomotion control, including initiation and modulation of behaviour, goal directed motion and path integration [24]. In most insect species, e.g. bees and ants, the compass direction can be gained from celestial cues (allothetic cues), while different approaches are used for distance estimation, e.g. bees record optic flow, while ants and cockroaches mainly use proprioceptive information (idiothetic cues) [25]. In consequence, data from different sensors need to be integrated sense-fully in the brain in order to acquire the desired vector information. For the “insect-in-a-cockpit” scenario, which will be presented in detail in Section 3, we considered honeybees to be the most suitable specie, since their odometer works via visual cues and it is well characterised [26]. Moreover, honeybees have unique cognitive capabilities and their nervous system is well accessible [21-22].

2.3. Current approaches towards hybridity

In this paragraph current approaches towards hybridity are presented with a twofold aim. On one side, we aim to better underline the novelty aspects of the different proposed approaches; on the other, we review the state of the art in order to establish what is already feasible and what will likely be feasible in the near future.

There are several different technological possibilities to interface living tissue with robots. The first choice is between non-invasive cockpit-like interfaces, where the intact animal's sensors are confronted with natural stimuli, and invasive interfaces. The invasive technique allows choosing between neural interfaces, in which information is transmitted through neurons, or non-neural approaches (e.g. through muscle stimulating/recording electromyography (EMG) electrodes). Non-neural interfacing is a more practical approach compared to neural interfacing, but it presents some drawbacks. The amount of information that can be transferred via a non-neural interface is lower and this may hinder the detection of complex behaviours. Moreover, the electric current intensity required to directly stimulate a muscle is about ten fold higher than that needed to stimulate the nerve to obtain the same movement (1mA - 100μA) [27].

Neural interfaces roughly divide into three groups: electrodes stimulate and monitor (i) cultured neurons or (ii) a pre-grown brain tissue removed from the rest of the body or (iii) a brain tissue still connected to the body. Neuronal cultures have been grown in two- and three-dimensional architectures and demonstrated astonishing performance [28-29]; however, it remains questionable if they will become capable to resolve high level control issues since their random arrangement does not correspond to any anatomical substrate for any complex function requiring interaction with the external environment.

The possibility to use brain-computer interfaces (BCI) with insects is a very promising field to investigate. One of the main challenges of invasive brain-machine interfacing lies in the surgical procedure and all issues related to it, such as mechanical and electrical stability of the interface along the time of implantation.

Currently, one of the most favoured techniques for neural interfaces in insect-BCIs uses flexible polymer-based multi-electrodes arrays. They can be bent around a nerve or around an insect appendage enabling multi-unit recording and stimulation without inhibiting animal's locomotion [30]. In the last decade, integrated circuitry and micro-fabrication technologies led to a drastic reduction of size, allowing the development of systems including neural probe, battery and micro-controller weighing less than 500 mg, which can be implanted in cockroaches [31].

As it regards natural interfaces, which are widely used in insect neuroethology research, programmable visual arenas allow reproducing optic flow to the insect [32], while force sensors [33] and magnetic coils [34] facilitate recording of motor responses to presented stimuli.

At the current state of the art, there are only a few reports on bidirectional insect-robot interfacing: the cockroach robot [35] and the moth robot [36]. The cockroach robot, implemented at Irvine University, has a bidirectional natural interface consisting of eight distance proximity sensors, LED panels and a modified trackball. The setup executes motor commands as decoded from movements of an insect positioned on the trackball; environmental sensory data are acquired through proximity sensors, and encoded into a light stimulus presented to the cockroach. The system is limited to fleeting behaviour (one of the few behaviours bypassing the CX), which is simply triggered by the very predictable stimulus-response reflexes. Therefore, the hybrid system does not exploit the high-level autonomous behaviours, such as navigation and exploration, afforded by the insect's brain.

The moth-robot displays a combination of both natural and neural interfacing. It was developed at the University of Arizona. In this system both natural and neural interfaces are implemented, the former through a continuous optic flow provided by a 14-inch-high revolving wall painted with vertical stripes, the latter by recording the electrical activity of visual motion neurons. In order to implement this approach, the moth is immobilised inside a plastic tube mounted on a wheeled robot. The robot itself can turn left or right, according to neural signals translated by a computer. The system can be useful to characterize visual motion detection neurons but it is not reported if a closed loop sensing and action behaviour was achieved.

The reported examples demonstrate the technological feasibility of insect/machine neural and natural interfacing. Considering the present level of knowledge about neural interfaces in insects, it does not appear possible to transfer all superior control functions from the machine to the insect, especially when connected through a neural interface exclusively. Then, we followed the approach of combining neural and natural interfaces in order to achieve multi-modal communication and hence a redundancy of information exchange.

3. THE DOUBLY HYBRID CONTROLLER

3.1. The proposed hybrid control architecture

As long as hybrid insect/machine control architectures are concerned, we propose to set the degree of hybridity as a trade-off between low-level and high-level behaviours. Given the whole set of desirable behaviours of an autonomous robotic platform, we classified as ‘high-level’ those behaviours requiring decision-making and/or cognitive capabilities (e.g. path planning), whilst all the remaining behaviours (e.g. obstacle avoidance) shall be considered as ‘low-level’. In practice, low-level behaviours will be those that can be carried out by state-of-the-art robotic platforms without an active involvement of the insect. Since extraterrestrial missions do not usually require fast reactions, several approaches are pursuable in order to have the robot performing the necessary low-level behaviours.

For space applications, we are mainly interested in navigation and exploration tasks with compensating reactions towards unexpected perturbations. An imaginary scenario would include a hybrid controlled exploratory rover navigating through various landscapes and returning to a fixed relay station on a regular basis. The operating environment, hence, is in principle very different from the natural environment where an insect may live. The inputs from the environment have to be translated into nature-analog signals before being provided to the insect. This is definitely a critical step towards the exploitation of pre-developed biological intelligence. Next section will describe how this can be achieved.

According to these assumptions and starting from fundamental control architectures paradigms [35-36], a novel doubly hybrid control architecture, including both biological/artificial modules and deliberative/reactive behaviours, has been hypothesized [39]. The architecture proposed here comprises four functional modules, (i) the sensor modules, (ii) the hybrid controller (HC), (iii) the adaptor, (iv) the underlying mechatronic system (UMS). Figure 1 shows the schematic of a robotic platform including the proposed doubly hybrid controller and its submodules.

((PLACE FIGURE 1 ABOUT HERE))

The sensor modules consist of both the low level sensors and embiotic (from Greek prefix "em-" meaning "in, into" and "biotic" meaning "pertaining to life") sensors. The low level sensors are included in the UMS (e.g. proximity sensors, inertial modules, wheel/leg encoders and wheel/leg slide sensors for self-stabilisation). The embiotic sensors complement the set of UMS sensors and may include: vision systems, temperature sensors, light polarisation sensors, etc., accordingly to the selected insect and the navigation/exploration tasks. The neologism “embiotic” highlights that these sensors mainly pertain to the insect perceptual capabilities and that are used to provide the necessary inputs to the insect for the implementation of those high-level tasks, which can be accomplished when the insect intelligence acts through the hybrid controller.

The hybrid controller is composed of the mapping modules (sensory and motor), the interfacing modules (neural and natural), and the cockpit. The sensory and motor mapping modules are the core elements of the proposed architecture and are detailed in paragraph 3.2. In particular, our main interest is to exploit insect pre-developed skills to tackle high-level tasks by a proper mapping that gives inputs as much natural-like as possible.

The mapped stimuli from a new environment (e.g. the Martian soil) are received from the insect tethered in the cockpit both via natural and neural interfaces. For example, the tethered insect may receive input stimuli via LED panels and via implanted electrodes, while the triggered motor responses can be detected by using different types of sensors, such as force sensors and EMG electrodes. A simplified representation of the “insect-in-a-cockpit” concept is reported in Figure 2.

((PLACE FIGURE 2 ABOUT HERE))

Insect’s motor commands are processed by an adaptor module, which gives input to the low level controller of the UMS. The adaptor enhances the HC interoperability with different hardware platforms (UMSs): since it is the only module that directly transmits data from the HC to the UMS, the HC can be used with different UMSs, tailored to the specific application scenario, by only changing the adaptor module.

Finally, the UMS includes:

- proprioception sensors used for information related to robot internal state (in particular sensors for energy and failures monitoring);
- low level sensors used to implement low-level behaviours (e.g. locomotion);
- a low level controller that properly weights inputs from sensors module, proprioceptors and the adaptor, thus allowing the correct driving of the robotic platform.

From a design methodological perspective, some basic steps have been systematised for guiding the development of a doubly hybrid controller for a robotic system. First, the specific task of interest has to be selected. The second step consists in choosing the most appropriate insect species that can be identified by means of a table that scores:

- the ability of the insect to respond to allothetic cues;
- the feasibility of triggering insect response by means of natural interfaces;
- insect's cognitive capabilities;
- technological feasibility of neural interfaces.

Once the choice of the insect is made, it is necessary to define the *level of hybridity* (third step), i.e. for a given task it should be decided which high-level behaviours should be implemented by the insect and which ones (low-level behaviours) should be allocated to the UMS. In the case that the hybrid controller has to be implemented starting from a specific existing robot, the degree of hybridity can be derived only following an attentive analysis of its actual capabilities.

The fourth step consists in choosing which signals should be conveyed to the neural stimulation path, and which to the natural stimulation path.

As a fifth step, the selection of the UMS has to be accomplished (only if an existing specific system was not already selected a priori). This choice basically depends on the available state-of-the-art robotic technologies. As an example, when considering navigation and exploration tasks, locomotion (either wheeled or legged) on rough terrains is reliably achieved by state-of-the-art robots. Proper vehicles have been specifically designed to cope with the nature of the Martian soil, e.g. asperities, presence of sand/dust, local gravity and radiations [2, 40]. These are 'details' which the insect should not get involved with. Note that more than one choice might actually be available to the designer.

Finally, the sixth step consists in the submodules design.

3.2. Sensory and motor mapping

The dynamics of complex behaviours such as navigation or exploration can be considered a product of more basic behavioural elements: *attraction* and *repellence* in relation to specific features of the environment. Attractors could be rendered with food sources, the nest or a prey, while repellers could be represented by predators and obstacles.

Navigation and exploration skills rely on the ability of insects to create internal maps of the environment. As part of the environment, both attractors and repellers need to be taken into account in the mapping process and therefore can be classified as *static,* if their position is fixed with respect to the map, or *dynamic* if their position within the map varies with time. For example, the nest can be considered as a static attractor, while a prey would be a dynamic one. Similarly, an obstacle such as a big rock would be a static repeller while a predator would represent a dynamic one. These behaviours are schematized in Table 1.

((PLACE TABLE 1 ABOUT HERE))

Each input resulting from embiotic sensors is then presented to the animal following the scheme of Table 1. Although each single behaviour *per se* might be considered as a reflex, simply triggered by the presence of the repeller or of the attractor, the simultaneous presentation of competing sensory cues would elicit a ‘decision-making’ process of the insect. From this perspective, multi-modal sensory inputs are more likely to elicit the higher level and autonomous behaviours.

In addition to the external stimuli representing the environment to the animal, internal stimuli, e.g. metabolic needs, may also have an influence on decisions to be taken. As an example, these needs can be used to trigger through olfactory cues the insect behaviour of navigation towards a nest, which can be mapped into the robot task of routing towards a recharge site. In such scenario, schematised in Table 2, olfactory cues can be combined with visual cues (optic flow and polarisation cues) to provide the insect with the information concerning heading and distance towards the virtual nest. Simultaneously, repellers occurring in the external environment can be presented visually to the insect, allowing the elicitation of avoidance or fleeting behaviours. Insect’s torso, head, and wing movements are measured and mapped into motor commands to robot actuators, which generate locomotion in the direction suggested by the insect. When the robot reaches the recharge site, the insect can be rewarded with real food.

((PLACE TABLE 2 ABOUT HERE))

Moreover, typical features of insect navigation such as the use of landmarks or visual route learning can be exploited to extend autonomy by e.g. removing typical drift errors occurring in robotic platforms without external reference systems.

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

4. CONCLUSIONS

The success of automated mission vehicles strongly correlates with the capability of the control architecture to successfully integrate a whole range of decision parameters. The addition of pre-developed insect intelligence in robotic platforms could create an intermediate type of mission bridging between purely robotic and human controlled missions. In this context we investigated on how to integrate "insect intelligence" into the control architecture of a hypothetical exploratory vehicle including the modalities to exploit the full potential of insect intelligence.

The architecture presented here delegates higher level behaviours, such as decision-making and planning, to the insect, while low level tasks are executed by the robotic platform. Its double hybridity, i.e. biological/artificial as well as deliberative/reactive, allows for managing concurrent behaviours such as accurate goal navigation and drifting compensation in parallel. The metaphor of the proposed interface is a cockpit, where the tethered insect receives both natural and neural stimuli.

Sensory-motor mapping is conceptualised in order to match the pre-developed navigation and exploration skills of the insect with the operating environment. An adaptor module is proposed to process the insect motor response and to give proper inputs to the low level controller of the robotic platform, thus enhancing the hybrid controller properties in terms of interoperability with different hardware platforms (UMSs).

Even though much work is required for the development and validation of the proposed control architecture (e.g. design and fabrication of the “cockpit” and of the neural bidirectional interface; definition of a suitable performance/benchmarking metrics in order to assess the achieved performance and compare it to that of state-of-the-art autonomous agents) the discussed concepts represent a first step for the integration of “pre-developed intelligence” in space robots.

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REFERENCES

[1] M. O. Franz and H. A. Mallot, Biomimetic Robot Navigation. *Rob. Aut. Sys*. **30**, 133-153 (2000).

[2] S. Thakoor, N. Cabrol, N. Lay, J. Chahl, D. Soccol, B. Hine and S. Zornetzer, Review: The Benefits and Applications of Bioinspired Flight Capabilities. *J. Rob. Sys.* **20***,* 687-706 (2003).

[3] N. Franceschini, Visual guidance based on optic flow: a biorobotic approach. *J. Phys.* **98**, 281-292 (2004).

[4] R. Wehner, Desert ant navigation: how miniature brains solve complex tasks. *J. Comp. Physiol. A*. **189**, 579-588 (2003).

[5] M. Dacke and M. V. Srinivasan, Honeybee navigation: distance estimation in the third dimension. *J. Exp. Biol.* **210**, 845-853 (2007).

[6] R. Pfeifer, M. Lungarella and F. Iida, Self-organization, embodiment, and biologically inspired robotics. *Science*. **318**, 1088-1093 (2007).

[7] J. G. Cham, J. K. Karpick, M. R. Cutkosky, Stride period adaptation for a biomimetic running hexapod. *Int. J. of Robotic res*. **23**, 1-13 (2004).

[8] R. Altendorfer, N. Moore, H. Komsuoglu, M. Buehler, H. B. Brown, D. McMordie, U. Saranli, R. Full, D. Koditschek, RHex: a biologically inspired hexapod runner. *Aut. Rob.* **11**, 207-213 (2001).

[9] Kosuke Inoue, Takaaki Sumi, and Shugen Ma, CPG-based Control of a Simulated Snake-like Robot Adaptable to Changing Ground Friction, in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, San Diego, pp. 1957—1962 (2007).

[10] Shugen Ma, Naoki Tadokoro, and Kousuke Inoue, Influence of Gradient of a Slope to Optimal Locomotion Curves of a Snake-like Robot. *Advanced Robotics*. **20**, 4, 413-428 (2006).

[11] R. J. Wood, The first takeoff of biologically inspired at-scale robotic insect. *IEEE Trans. on Robotics*. **24**, 341-346 (2008).

[12] R.S. Fearing, S. Avadhanula, D. Campolo, M. Sitti, J. Yan and R. Wood, A Micromechanical Flying Insect Thorax, in *Neurotechnology for Biomimetic Robots*, Ayers, Davis Rudolph (Eds.), pp. 469 - 480, MIT Press, Cambridge, MA (2000).

[13] R. Pfeifer, F. Iida, G. Gomez, Morphological computation for adaptive behavior and cognition. *Intern. Congr. Series*. **1291**, 22-29 (2006).

[14] J. Ayers and J. Witting, Biomimetic approaches to the control of underwater walking machines. *Phil. Trans. R. Soc. A*. **365**, 273-295 (2007).

[15] A. J. Ijspeert, A. Crespi, J. M. Cabelguen, Simulation and robotic studies of salamander locomotion. *Neuroinformatics*. **3**, 171-195 (2005).

[16] A. Ijspeert, A. Crespi, D. Ryczko, and J. M. Cabelguen, From swimming to walking with a salamander robot driven by a spinal cord model. *Science*. **315,** 1416-1420 (2007).

[17] M. Setti, Microscale and nanoscale robotics systems: caracteristics, state of the art, and grand challenges. *IEEE Rob. & Aut. Mag.* **14**, 53-60 (2007).

[18] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, D. Santos and M. R. Cutkosky, Smooth vertical surface climbing with directional adhesion. *IEEE Trans. on Rob.* **24**, 65-74 (2008).

[19] T. Fong, I. Nourbakhsh, K. Dautenhahn, A survey of socially interactive robots. *Rob. And Aut. Sys.* **42**, 143-166 (2003).

[20] 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. *Proc of the Royal Society B*. **273**, 1815-1823 (2006).

[21] R. Menzel and M. Giurfa, Cognitive architecture of a mini-brain: the honeybee. *Trends in Cogn. Sc.* **5,** 62-71 (2001).

[22] R. Menzel, G. Leboulle, D. Eisenhardt, Small brains, bright minds. *Cell*. **124**, 237-239 (2006).

[23] R. Menzel, Searching for the memory trace in a mini-brain, the honeybee. *Learn. Mem.* **8**, 53-62

(2001).

[24]H. Vitzthum, M. Muller, U. Homberg, Neurons of the Central Complex of the Locust Schistocerca gregaria are sensitive to polarized light. *J. Neurosc.* **22**, 1114-1125 (2002).

[25]T. Seidl, M. Knaden, R. Wehner, Desert ants: is active locomotion a prerequisite for path integration? *J. Comp. Physiol. A*. **192**, 1125-1131 (2006).

[26]M. V. Srinivasan, R. L. Gregory, How bees exploit optic flow: behavioural experiments and neural models. *Phil. Trans. Biol. Science*. **337**, 253-259 (1992).

[27]J. Mavoori, B. Millard, J. Longnion, T. Daniel, C. Diorio, A miniature implantable computer for functional electrical stimulation and recording of neuromuscular activity, in *Proc. of IEEE Int. Work. Biomed. Circ. Sys*, Singapore, S1/7-S1/13 (2004).

[28]A. Novellino, P. D'Angelo, L. Cozzi, M. Chiappalone, V. Sanguineti, S. Martinoia, Connecting neurons to a mobile robot: an in vitro bidirectional neural interface. *Comp. Intell. Neurosc.* **2007**, 1-13 (2007).

[29]S. M. Potter, D. A. Wagenaar, R. Madhavan, T. B. DeMarse, Long-term bidirectional neuron interfaces for robotic control, and in vitro learning studies, in *Proc. 25th Intern. Conf. IEEE EMBS*, Cancun, pp. 3690-3693 (2003).

[30]A. J. Spence, K. B. Neeves, D. Murphy, S. Sponberg, B. R. Land, R. R. Hy, M. S. Isaacson, Flexible multielectrodes can resolve multiple muscles in an insect appendage. *J. Neurosc. Meth.* **159**, 116-124 (2007).

[31]H. Sato, C. Berry, B. Casey, G. Lavella, Y. Yao, J. VanderBrooks, M. Maharbiz, A Cyborg Beetle: Insect Flight Control Through an Implantable, Tetherless Microsystem, in *Proc. of MEMS 2008*, Tucson, pp. 164-167 (2008).

[32]M. B. Reiser and M. H. Dickinson, A modular display system for insect behavioral neuroscience. *J. Neurosc. Meth.* **167**, 127-139 (2008).

[33]Y. Sun, S. N. Fry, D. P. Potasek, D. J. Bell and B. J. Nelson, Characterizing fruit fly flight behavior using a microforce sensor with a new comb-drive configuration. *J. Microel. Sys.* **14**, 4-11 (2005).

[34]C. Schilstra and J. H. Van Haeren, Blowfly flight and optic flow, thorax kinematics and flight dynamics. *J. Exp. Biol.* **202**, 1481-1490 (1999).

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

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

[37]R. A. Brooks, A robust layered control system for a mobile robot. *IEEE J. Rob. Aut.* **2**, 14–23, 2006.

[38]R. Murphy*, Introduction to AI Robotics*, MIT Press (2000).

[39]A. Benvenuto, F. Sergi, G. Di Pino, D. Campolo, D. Accoto, E. Guglielmelli, T. Seidl, Conceptualization of an insect/machine hybrid controllers for space applications, in *Proc. 2008 IEEE Int. Conf. on Biomed. Rob. and Biomech. (BIOROB 2008)*, Scottsdale, pp. 306-310 (2008).

[40]R. Beard, D. J. Lee, M. Quigley, S. Thakoor, S. Zornetzer, A new approach to future Mars missions using bioinspired techonology innovation. *J. Aer. Comp. Inf. Comm.* **2**, 65-91 (2005).