ANNEX B – CALL FOR PROPOSALS

STUDY DESCRIPTIONS

08/6302	Quantifying the Landing Reaction of Cockroaches (Medium Study : 4 months, 25Keuro)
08/6303	Neuromorphic Computation of Optic Flow Data (Medium Study : 4 months 25Keuro)
08/8201	Curiosity Cloning – Neural Modelling for Image Analysis (Medium Study : 4 months 25Keuro

08/6302 QUANTIFYING THE LANDING REACTION OF COCKROACHES

Type of activity: Medium study (4 months)

Background and motivation

Planetary exploration missions include an entry-descent-landing phase, where the spacecraft descends on a relatively steep trajectory to the surface. In order to minimize the loads during landing, a deceleration system is employed, consisting essentially of some or a combination of parachutes, retrorockets and airbags. Due to the communication round-trip delay time between spacecraft and ground control, external supervision of the descent is limited. As a consequence, a landing device is desired that can autonomously stabilize the descent and guide the spacecraft to a safe landing place.

In the research field of unmanned autonomous vehicles, animal models have become intensively studied models for potential technological transfer. Inspiration is drawn from various aspects such as neuronal control, aerodynamics, material properties, and actuators. Studying the neuronal control (biocybernetics) of insect flight is appealing for a number of reasons. First, in insects neurons can be addressed individually and hence, their function can be well determined. Secondly, flight control is realized in a fly-by-wire manner: Sensory data is acquired and processed in a way that only one individual steering signal for each flight situation is generated and sent downstream to the motor control. From this single signal, the appropriate motor reactions are generated. The present study aims at a 'technological transfer' of the neuronal architecture involved in triggering the landing reaction of steeply descending cockroaches.

Cockroaches obtain flying capacities of robustly designed wings but are rarely observed to fly. From observations of scientists we know that cockroaches use their wings mostly in emergency situations, i.e. when forced to jump off elevated spots. Once air born, the cockroaches quickly deploy their wings and use them to glide to the ground, controlling their trajectory and choosing a landing site. This task requires fast reactions and quick decisional strategies. The cockroaches' flight system is therefore assumed to be tuned specifically towards fast landing and not to e.g. flying or take-off. In consequence, it is assumed that the cockroach model – compared to other potentially flying insects – is simpler in its neuronal architecture and hence faster in its reaction and hence displays a potential model for a biomimetic transfer to an engineered landing system. Proposing universities and research centres are encouraged to include in their proposals relevant additional scientific information or a critical analysis of these assumptions.

Cockroach behaviour

Cockroaches are a popular model animal in the study field of dynamic legged locomotion, mostly because of their self-stabilizing dynamic legged locomotion skills. Up to now the flying behaviour of cockroaches has not received much attention. Apart from neurophysiological studies on the flight onset [3,4], there are only anecdotal remarks on flight behaviour available. Mid sized cockroaches of e.g. *Periplaneta spec.* show gliding behaviour combined with wing movement (Ritzmann, personal communication). If such a cockroach (usually the male types fly) falls off from an elevated point, it can be observed using its rigid and small wings to obtain control over its descent and hence minimize the impact on the ground [1,5]. From all the observations made, it can be assumed that the entire flight system of cockroaches is a rather simple one, both in terms of mechanical design and control architecture. Compared to the fragile and transparent wings of the commonly studied flying insects, cockroaches obtain of rather rigid and robust wings and hence could be a more feasible model in terms of biomimetic transfers. The cockroaches' flight control system, which deals only with landing and obstacle avoidance tasks, is expected to be of a rather robust and simple design. In consequence, the sensory processing could be among the quickest and simplest to be found.

In the present account, we want to study the performance of the cockroaches' sensory-motor loops during landing and develop a control model of the neuronal processes involved in landing [6].

Study description

Two main research themes of approximately equal importance are proposed to assess these hypotheses.

These are, (i) the identification and quantification of the landing parameters of a cockroach model under a number of constraints (e.g. quality of visual data). The results shall then (ii) serve for computer modelling of the cockroach control system. Throughout the entire project only the landing of spacecraft (i.e. approximately the last 500m) will be considered. Other phases of a space mission such as de-orbiting are not within the scope of this project.

1. Quantifying the biological model as a basis for a biomimetic transfer

We aim at mimicking the cockroach's descent behaviour without trying to achieve autonomous free flight or take-off capabilities. The goal of this study is to design a controller using the working principles of the neuronal system of flying insects, when confronted with the situation of a steep descent. Since the cockroach's neuronal system deals with such situations, we aim at getting a deeper insight into the currently not well quantified behaviour of the animal model.

In order to do so, the model animal will be confronted with an experimental situation where it has to control descent and choose a landing site. By manipulating boundary conditions the properties of the behaviour in question will be assessed. In the present case, cockroaches will be released unexpectedly from an elevated platform and, while trying to navigate safely to the ground, they will be recorded with video cameras (approx. 100-200 frames per second) from different perspectives. The trajectory can then be reconstructed as well as the exact moments when stereotypic reactions (unfolding wings, steering reactions, and deceleration) are triggered.

A) The boundary conditions to be manipulated are: height of release, presence of visual cues (lateral, ground), optic contrast of visual cues, field of view (i.e. reducing the visual field by partially obscuring the visual field), airflow direction and speed, mass of the animal. (This is to be considered a preliminary list and proposals with additional or different argued parameters are welcome.)

B) After a first characterisation of the cockroaches' behaviour, the influence of different parameters on the performance of the cockroach is to be assessed: Presenting the cockroach with repellent cues, such as obstacles in the preferred landing area as well as attractive cues, i.e. a dark shelter outside the common landing area, will allow to characterize the potential and the limitations of the cockroaches steering abilities. Attaching weights to the animals' body will accelerate the descent and hence characterize the minimum reaction times.

C) A small work-package deals with observing the animals' steering reactions to non-frontal air flow. In a setup different from the one used for A and B behaviour of the wings of a tethered cockroach is to be analyzed qualitatively when the animals are subjected to wind hitting the body at different yaw and pitch angles, both with free and mechanically blocked antennae. Here, again the reaction properties of the neuronal system will be evaluated but this time focussing on the air-flow sensitive antennae.

From the trajectory of the animal, the instantaneous visual cues can be calculated and parameters found which trigger certain reactions. From this data, we can assess important properties of the insects' visual piloting capabilities, especially in terms of separating translational optic flow and expanding optic flow.

In addition, extrapolation on the requirements for landing in e.g. Titan-conditions and used in spacecraft of different size will be performed in close cooperation with the ACT-researchers.

Finally, the results of the trajectory analysis will be used to quantify the flight apparatus' performance indicators: Maximum deceleration, maximum steering angles, estimations on lift and drag of the wings. It is important to note that this study is <u>not</u> proposing to include an in depth aerodynamics analysis. However, a few basic estimations on aerodynamic performance will be necessary since neuronal control and mechanical performance interact with each other.

2. Creating a functional model of the cockroach behaviour

In a second part of about equal importance, the findings of the quantification of the cockroach-landing behaviour will be used for the design of a universal control scheme realized in a common software environment. With this simulation environment, the results on the biological model have to be verified and an extrapolation to "artificial cockroaches" of varying weight, size, and flight performance will be performed. These results will be discussed in the view of an autonomous lander for application on earth surface.

Collaboration with the Advanced Concepts Team

This study is mainly addressed to research laboratories in the fields of neuroethology, biomechanics, neuroinformatics and biocybernetics. The project will be conducted in tight scientific collaboration with ACT-researchers. Next to the scientific discussions, the ACT-researcher will also provide both knowledge concerning space related issues and behavioural neurobiology. It is proposed that also most of the modelling activities will be performed by the ACT-researchers, with input and in close cooperation with the research laboratory/ies.

References

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08/6303 NEUROMORPHIC COMPUTATION OF OPTIC FLOW DATA

Type of activity: Medium study (4 months)

Background and motivation

Introduction

Animals are confronted with ill-conditioned and highly parallel [1] data that need to be processed reliably and in a sufficiently short time to allow for rapid decision taking. For a number of reasons, information processing in living organisms follows different principles than the ones commonly applied in engineered devices. In general, data is mostly computed analogue and not digital, exploiting the physical principles of analogue electronics and the membrane characteristics of the neurons. Computation is also expensive in terms of energy consumption and volume requirements. Since both of these parameters may limit the reproductive success of an animal, it can be assumed that the strategies of neuronal computation must have undergone optimization, both in terms of algorithmic design and energy expenditure [2,3,4]. As a consequence, neuromorphic architectures, i.e. technical devices derived from biological ones are realized for research purposes but also in implantable visual and auditory prosthetics. Although in general analogue computation has been rather neglected in the past, its immanent potential for technical applications is reflected in an increasing number of recent activities [5,6].

Principles of neuromorphic computation

The nervous system considerably differs from commonly known computational architectures [7]. In particular, following the reasoning developed by Mead [8], there are differences in elementary functions, in the representation of information and in organizing principles. The elementary functions are fundamentally different from the ones used in digital technology (e.g. AND, OR) and take advantage of inherent physical properties. These are e.g. creating exponential functions, integration over time (both using characteristics of membrane potential), and addition by Kirchhoff's law. In conclusion, most of the operations performed in neuronal circuits are similar to analogue technology. The obvious problem of noise intolerance of analogue electronics is counteracted by a parallelization, which allows for a cancellation of errors [8]. The information used for situation analysis and decision-making is extracted at the earliest stages possible within the system. In neuronal systems, analysis and hence reduction of sensory data initiates at the very first instances. Indeed, the retina of any higher developed visual system is already involved in feature detection and analysis. In consequence only relevant data is transmitted to the higher centres in the brain.

Typical features of neuromorphic electronics

Neuromorphic electronics have to be tailor-designed for the specific purpose they have to fulfil. In consequence, the computational algorithms are not programmed in software but reflected in the electronic circuit. The system - once thoroughly set-up - will then function robustly without the need of booting programmes and operating systems.

- The immanent error sensitivity of analogue computation is reduced in the biological model by redundant parallel processing and averaging [8].

- By a tailor-made design of sensors, computation can - as in the biological model - take place at the earliest steps. Instead of performing analyses based on bitmaps delivered from a CCD-camera [e.g. 9], movement detection takes place directly after signal acquisition, i.e. at the sensor level.
- Unnecessary data is eliminated at the very first instant and hence, miniaturization efforts may lead to a drastic reduction in size, weight, and energy consumption [2,3,4].

Visual information processing

One typical example of biological computation of highly parallel data is the visual system in flying insects, which has been under research for a number of decades [10,11,12]. Research on insect neuronal systems allows for single-neuron analysis and hence provides very detailed information on the acting mechanisms. In consequence a huge amount of data on behavioural, anatomical and neurophysiological experiments on visual neuronal systems is available.

Active locomotion in both animals and autonomous vehicles requires the perception of self-motion in relation to the environment. The elaborated auto-piloting capabilities of insects, such as flies and bees, are a model for neuromorphic engineering since there exist a strong task-related analogy. Both – the animal and the machine – need to act fairly autonomously and reliably, structural mass should be kept low with respect to payload mass, landing accuracy is a key performance parameter. In consequence, it appears appealing to reverse-engineer the system of the (biological) competitor and attempt to transfer its working principles into a technical concept for a thorough assessment.

Neuronal processing of visual data is organized in several levels. The primary source of motion analysis is the so-called EMD - **Elementary Motion Detector** (e.g. [13,14]). This theoretical concept displays a minimal architecture that is able to extract directional sensitive motion information from two photoreceptors. Although not anatomically proven, the functional principle of the whole is present in behavioural and neurophysiological studies [11]. In order to discriminate between different flight situations (translational and rotational movements as well as obstacle avoidance and landing) specific **large-field neurons** integrate over the outputs of a number of EMDs and fire only when the visual data matches the addressed flight situation. The resulting signal is then sent to the flight motor (i.e. the complex of muscles that drive the wings) in a fly-by-wire mode. The flight motor control translates the steering signal into an appropriate activation of the flight musculature.

One peculiarity of visual piloting abilities lies in the necessary discrimination between transversal optic flow as experienced during forward flight and expanding optic flow as experienced when approaching a large object to land on. The aim of this study is to <u>design a neuromorphic controller, which is able to perform this differentiation and to trigger a landing reaction at the right instance</u>.

Expected profit

Robust electronics: Neuromorphic engineering aims at designing circuits in analogue technology using its inherent physical principles for computation. These architectures work without the use of a central processing unit and hence, allow for physically more robust designs. Neuromorphic principles (e.g. parallelization [1,8]) allow for compensation of typical negative issues of analogue electronics.

Intelligent sensors: Sensors may become simpler (photo-diodes instead of CCD-cameras) but will perform data-reduction, feature extraction and other processing by themselves and at a very early instance. In consequence, behaviourally relevant optic flow is to be monitored via elementary motion detectors whose signals get processed via analogue electronics.

Minimal algorithms: Neuronal mechanisms have been optimized towards functionality in the evolutionary process. From the analysis of animal behaviour it will be possible to estimate the minimum set of information required to perform a certain task. Short reaction times and low energy consumption are an additional goal to be met.

Study description

Objectives

1. Identifying and analyzing working principles of neuronal circuits of flying insects involved in landing process. In particular, isolate the principles that could be linked with the discrimination of the two different optic flows.
2. Create a neuromorphic controller meeting the characteristics of analogue computation and able to discriminate transversal and expanding optic flow.
3. Validate the hypothesis that landing process control is based on discrimination between the two optic flows.

Elements of the study

This study intends to assess the potential of neuromorphic engineering for space applications using the example of the landing reaction of flies evoked by pattern expansion of visual cues. The work involves identifying, analyzing, and transferring the working principles of the neuronal circuits of flying insects which are involved in the control of landing and transfer the biological results into a technical concept which will be tested. This includes at least the following tasks:

1. Set up a control scheme able to react to visual expansion, i.e. control landing on a surface from a steep approach angle. As a basis, use and eventually adapt functional models reacting upon pattern expansion taken from the fly's visual system [17,10]. The controller has to detect visual expansion using elementary motion detectors and analogue computation following results from research on the biological models. The controller has to be able to react to a stimulus of visual expansion and trigger the landing reaction in the appropriate moment. The control scheme shall be realized in a computational model, using a common simulation environment. It is essential that only visual data is available to the controller and only neuromorphic analogue control circuits are used throughout.
2. The controller shall then be tested. It has to be able to cope with typical reaction latencies of the animal's flight system, such as the limitations in manoeuvrability of the biological model animal. Different approach speeds and angles shall be accounted for by the control scheme as well - without providing these values externally. Using different types of visual stimuli with

varying contrast (e.g. created from a virtual environment or reconstructed from recorded trajectories as well as a set of existing planetary pictures) the controller shall be assessed in terms of performance of the neuromorphic architecture in fulfilling the task of landing especially in suboptimal conditions.

3. Once the controller is sufficiently optimized, a simplified hardware model should be designed and – if possible – realized and tested in a laboratory environment. During the study, the involved ACT researchers will closely interact with the experts from the ESA Laboratory of Robotics and Automation in view of integrating the controller in some of the there available test platforms (Aerobot, robotic arm).
4. Finally, the controller shall be evaluated in terms of energy consumption, estimated size and weight, and failure tolerance to contradicting data.

Mission type

The neuromorphic architecture will, in its final state, work without using a video acquisition system and only process real time sensory data without the possibility of subsequent saving and replay. In consequence, it is envisioned that especially missions with very small landing spacecraft e.g. in swarm type missions with a limited set of tasks but also a highly limited energy budget for each lander could profit from a neuromorphic landing system. The major task for the envisioned architecture is to autonomously control the landing of a spacecraft on a planetary body. The environmental conditions of Titan [15,16] shall be taken for an exemplary performance assessment.

Collaboration with the Advanced Concepts Team

This study is mainly addressed to research laboratories in the fields of neuroinformatics, biocybernetics, and biorobotics. The project will be conducted in tight scientific collaboration with the ACT-researchers in the field of biomimetics, artificial intelligence and informatics. The ACT-researchers will provide both knowledge concerning space related issues and behavioural neurobiology. Especially the state of the current biological knowledge on processing of visual data involved in landing will be evaluated and added to the study by an ACT-member. A principal agreement has been made with the ESA Laboratory of Robotics and Automation to get access to scientific platforms (Aerobot, robotic arm) for verification tests.

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Further reading

In the following you find an overview in alphabetic order of supporting literature concerning the project description. An extensive list of publications is available in the references of the following manuscript:
http://www.esa.int/gsp/ACT/events/workshops/ACT-PRE-Bridge2Space-Franceschini.pdf .

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08/8201 CURIOSITY CLONING - NEURAL MODELLING FOR IMAGE ANALYSIS

Type of activity: Medium Study (4 months)

Background and Motivation

Neurophysiological correlates of human curiosity

Human and animal curiosity can be defined as the natural inquisitive behaviour, which engenders exploration, investigation, and learning. Being these inherent qualities and abilities of intelligent beings, it was not by chance that the Artificial Intelligence community had an attempt to replicate them into artificial agents like robots or specific programmes. Still, what curiosity really is remains a mystery: product of a complex evolutionary chain, there are some details, some particular combination of sensorial data and experiences, which forces attention out from the background noise. These “triggering” details often remain out of our consciousness and they can be hardly reported and fully described.

Consequently, for the Artificial Intelligence community curiosity as such remains a “black box”. It is remarkable that until now only rather simple decision-taking modules trying to replicate a similar final behaviour [1] have been elaborated, but still no curiosity engines for AI agents based on a reproduction of curiosity patterns have reached concrete results.

Even if complex, curiosity still remains a mental activity, and as such hinges upon basic chemo-electrical activities of networks of neurons. One can therefore expect that research in the field of neurophysiology could one day answer the question of *what* curiosity is. As by today, neurophysiology could already answer *when* curiosity happens.

“Curious” is often synonymous of inexplicable, highly unusual, odd, or strange. In other terms, curiosity is associated with phenomena, which arouse speculation, interest, or particular attention. These features have been reported to excite the parietal cortex in a very characteristic way. Actually, such a stimulus produces a synchronized peak in the global electrical activity of large groups of neurons in this area, which is perceived from the outside (for example via an EEG) as an electric potential wave. Since this wave has a positive voltage peak and follows the stimulus after 300 ms, it is called P300 [2]. P300 shows interesting features: its magnitude is associated with the level of attention the stimulus is arousing; it can not be fine controlled and it was reported to be, at least partially, independent from consciousness.[2]

Thus, the underlying assumption of the proposed study is that the P300 can serve as a correlate of the level of curiosity of an individual.

Exploiting neuronal correlates for remote data evaluation

Extra-orbital missions can be equipped with several high-definition sensors, allowing to autonomously collecting a potentially enormous amount of data. Typically, the bottleneck in retrieving these data-sets is manifested firstly in the available storing capabilities and secondly in the limited communication bandwidth, which prevents from sending the whole data-set back to Earth. This issue is particularly severe for image data, which is usually quite demanding in terms of dimension (bits) and, since the best possible resolution and quality is normally required by scientist, even hardly compressible in size.

Hence, even if explorative robots could take a vast amount of pictures, these will eventually have to be reduced in number. Separating the scientifically relevant pictures from the less relevant ones is the crucial task. In consequence, the robot has to evaluate in real-time the scientific content of a picture currently by assigning so called Scientific Richness Indexes [3].

These indexes take into account basic features of the picture, like e.g. entropy, contrast, etc. The sorting mechanism is designed a priori, and no learning is involved in the algorithm itself. Classifier systems based on supervised learning could therefore be used as an alternative. Able to learn a possible dependence between those indexes (and maybe other sets of features), with the subjective scientific richness of a picture as evaluated by experts, these systems could give improved performances.

In order to learn how to evaluate pictures, all the supervised learning based systems require a precise and long lasting protocol of actions. First of all several human operators, expert analyzers of scientific pictures (i.e. geologists with an expertise in Martian rocks analysis), will have to evaluate hundreds or thousands of pictures, by rating them with one or several numbers to define their interest(s) value(s). The very same pictures, together with their evaluation, would form the data set required for the training and testing of a classifier, or function approximator.

The learning algorithm will then be run on a subset of the whole data, the so called training set. Parameters will be adjusted by optimizing its performance on that set, or a subset (cross validation), and then the performance of the algorithm will be measured on a separate test set, to assess whether the trained network is finally able to reproduce the same evaluation of the human experts. This approach - which is usually very expensive in terms of human-power and effort required to produce adequate data-sets and systems for images' scientific content evaluation - has not been implemented yet in any space mission.

By systematically detecting P300 events and analyzing their features, it is possible to infer curiosity in terms of timing, magnitude, and persistence [4]; by correlating it with the corresponding sensorial stimulus, it becomes possible to assign an interest level to each single stimulus presented. A curiosity-level derived set of data can then be used to train and test a classifier. Ideally such classifier would react to stimuli showing the same level of curiosity that had been monitored from the person who was "curiosity-recorded" in the first place. In short, the person's curiosity would somehow be replicated – or "cloned" – into an artificial system.

Moreover, since the P300 shows curiosity-raising at its very beginning, it should be possible to classify the interest-level of an image faster than by the commonly performed interview technique, and without a possible bias operated by the subject's conscious filtering. For a large set of images, as it is required for the training-testing data-set, reducing the time dedicated to the analysis of an image can have drastic effects on the total time required to the subject to spend "looking at images".

How far this approach can simulate the human curiosity and actually improve the performance of an artificial network is the open question at the core of this study. To focus on a well-defined problem we propose an experiment on image evaluation, which is a serious issue for most of the extra-orbital space missions.

The idea is to perform an experiment, where a group of test subjects – instructed to look for 'scientifically interesting' images - is confronted with a set of images, while EEG recorded. Data coming from EEG recordings are analysed to find correlations between the level of P300 expressed by the subjects and the picture displayed. Once the EEG recording and analyzing experimental sessions has provided enough information, this data-set can be used to train a classifier.

Eventually, the system should be able to work as a trained artificial image sorter, sorting out a test-set of pictures for their ability of arousing the scientific curiosity of the subject

Research and Study Objectives

The objective of this study is to prove that the scientific curiosity about images can be detected by reading EEG measurements, including the P300 signal. This should be achieved by performing a set of experiments at the universities' or research centres' premises.

Assuming success and following this study, these data will be used to develop an artificial image sorter trained with these curiosity measurements. The research centres and university/ies participating in the first phase will be invited to participate also to this follow-up activity.

As part of its contribution, the ACT will provide at the study kick-off sets of appropriately pictured, representative images. These will consist of approximately 3 times 2000 pictures.

In their proposal, university(ies) and research centres are asked to provide an experimental protocol allowing to answer the question whether the P300 signal can effectively measure the curiosity level of humans on these picture sets. Universities and research centres are encouraged to propose the use of additional signals to measure curiosity.

The proposed system should be aimed to monitor the level of curiosity aroused by each individual picture presented. University(ies) and research centres may also propose an additional set of images, pictured in order to maximise the responsiveness and the effectiveness of the proposed system.

As part of the proposed protocol, the proposals should include measurements allowing understanding the maximum reliable picture display rate (pictures displayed per minute) achievable, by correlating error rates with picture display rates.

In summary, proposals for this study to be performed together with the ACT should contain information on:

- the proposed experimental procedure in order to continuously record the level of P300 of a subject while he/she is analyzing the scientific interest of a set of randomly sorted pictures.
- the proposed procedure to correlate the P300 peaks (or other proposed signals) with the exact picture-stimulus, which triggers them.

- the proposed protocol to find the fastest picture display-rate which will still permit the arousing and correlation of P300 peaks and to define the relationship between performance of the correlating system and picture display-rate.
- the proposed facilities to perform the experiments.

Universities and research centres are required to possess or have access to all the facilities required to perform the proposed study within the specified time frame.

The processed data sets should be made available in ascii format.

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