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.

References

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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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