Group Report: The Behavior of Natural and Artificial Systems: Solutions to Functional Demands*

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Introduction

At the current state there is no unified view onto the functional demands and their solutions in natural and artificial systems. Artificial systems have well-defined inputs and their desired outputs are given in terms of system requirements that are defined by the users or designers of the systems. Natural systems, on the other hand, have evolved in order to survive in a complex environment. As we lack complete knowledge of the constraints given by the outside world, we cannot clearly define the actual optimization goal that implicitly underlies the observed organism. However, some striking features in natural organisms seem to be powerful solutions to functional demands. Some of these solutions are by far not yet achieved in artificial systems. The most striking examples are the capabilities of the human brain to process natural languages and to build up concepts of the world. However, also small brains, even in insects, seem to incorporate powerful solutions to tasks that are not yet captured by computer systems, e.g., in object recognition and flight control.

In the working group we discussed some areas where artificial and natural systems seem to have common problems, where they might influence each other, and where both neurobiology and computer science may profit from each other.

The first area discussed is concerned with building artificial models, their usefulness for understanding the brain, and how they might be used for applications.

The second area deals with a problem common for all systems that have limited computational power and the need to respond within a minimal delay, i.e., the question how systems deal with time.

The third area was concerned with the concept of motivational systems which seem to be the underlying mechanism of emotions. These are potent mechanisms that seems to be common in the animal kingdom and might be an explanation for some powerful performances of natural systems, but have not yet been implemented in artificial systems.

What Are the Mutual Benefits of Neurobiology and Models?

There are many attempts for a fruitful interaction of experimentalists and theoreticians. For the understanding of natural systems it is necessary to develop models that describe our experimental findings, incorporate our hypotheses in a formal theory, and help to check the consistency of our assumptions. The main points of interest in this field could be characterized by the following corner stones:

- Models should have a predictive attitude, that can be tested experimentally
- Models should be based on biological knowledge

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Regarding the large amount of published models, many of them disregard one of these points, i.e., they are either loosely connected to the biological substrate or do not produce predictions which are experimentally testable. However, there are several examples of fruitful interactions between theoreticians and experimentalists that have lead to mutual benefit. On the one hand, these collaborations gained more insight into the mechanisms implemented in natural organisms, and on the other hand some of them led to new solutions for artificial systems. In the following we outline some successful examples.

- Studies of the crayfish walking system led to a thorough understanding of the coordinating mechanisms between ipsilateral legs. A rostrally directed influence is active during the stance of the posterior leg that prolongs the swing movement of the anterior leg. A caudally directed influence is active at the end of the stance and the beginning of the swing of the anterior leg elicits the start of the stance in the posterior leg (Cruse and Müller, 1986). These mechanisms haven been derived from behavioral data. To test whether they really could describe the observed behavior when all four ipsilateral legs are coupled in this way, a simple model had been developed. This model showed that these two mechanisms are not only sufficient to describe normal walking coordination, but in addition can describe small intermediate steps that sometimes occur during walking. Although it was first assumed that an additional mechanism would be required for these intermediate steps, the model showed that this behavior was a „by-product“ of the walking mechanism.
- A recurrent network is proposed which can be used as a manipulable body model to solve different kinematic tasks as the inverse kinematic problem, the direct kinematic problem or any mixed problem. The model may be used for planning a movement, or „thinking“ , by being uncoupled from the motor output, or it may be used for direct motor control. The network is based on a new type of neuronal network called MMC net which is similar to but shows some essential differences to the Hopfield type network. These are (1) no symmetrical weights are necessary in the MMC net. (2) Furthermore, no clipping functions are necessary which allows for real valued outputs. (3) No limited number of discrete attractors, but an infinite number of attractors which form a continuum are possible in the MMC network. The network can easily be scaled up for the 3D case and any arbitrarily complicated geometry. There are no problems concerning singularities. Although there seems to be no immediate way of testing whether such a system is realized in the brain, this model may serve as a tool in helping to understand the properties of recurrent systems. In particular, it shows that within this recurrent system no distinction possible between "sensor" and "motor" elements. In addition, it shows a way how a dynamic and nonsymbolic representation of all possible arm positions is possible using only a very small number of neuronal units (Steinkühler and Cruse, 1998).
- A simulated flying autonomous agent has the task of avoiding obstacles in a virtual 3D environment. There are horizontal and vertical visual motion detectors which are attached to the body of the agent and linked to the motor system through weighted connections with a simple feed-forward architecture (Neuman *et al.*, 1997). The connection weights are optimized by a genetic algorithm that evaluates the flight performance of the agent in order to obtain its fitness value. One of the difficulties in 3D flight is the simultaneous control of 6 kinematically coupled degrees of freedom, 3 for rotation and 3 for translation. Given all 6 degrees of freedom, the system fails to evolve an appropriate behavior, because in some situations during flight the visual input is rotated, and the simple information processing architecture does not allow to compensate for this. If, on the other hand, the agent is stabilized with respect to the roll and pitch axes and therefore is restricted to 4 degrees of freedom, the system is able to learn full 3D obstacle avoidance and flight stabilisation. The stabilizing task can be realized by a separate mechanism that is responsible for the correct orientation of the visual input by rotating the head of the agent. In biology such mechanisms have been observed in flying insects. Flies, for example, always keep their head in an upright position, even when their body is rotated by 90° with respect to their head during curve flight.

- Another example of flight stabilization via the implementation of a principle found in biological systems was given by Franceschini (1996) in the discussion. The basic principle is based on the ocelli that are found in various insect species and usually consist of three eyes with special photoreceptors for UV light. With a UV-sensitive receptor, the detection of the horizon is relatively simple as the horizon will produce a sharp change from dark to light. Any shift in the position of the horizon could thus be easily detected by the ocelli, and this signal could be used for pitch correction.
- Several other examples, mostly from insect vision, were additionally discussed. The general principle seemed to be that natural systems try to reduce the amount of computation wherever possible. This is often achieved by peripheral adaptations that produce homogeneous data that can be easily computed. A fascinating example for this principle is the compound eye of the fly where the size of the facettes is enlarged in the periphery, thus yielding flow fields that can be computed by simple elementary motion detectors.
- An important aspect concerning the limitations of simulations is the emergence of new features that can be seen when algorithms are implemented in a hardware model. By studying the interactions of such a hardware agent, hitherto unknown benefits of crossmodal interaction between different sensors can be observed that lead to surprising effects (see Pfeifer *et al.,* 1998: this issue, pp. 480–503).

These examples illustrate that technical applications can benefit from biological models and vice versa. During evolution biological systems have developed information processing strategies that are optimized for survival in a particular environment. The essential elements for processing the information are not restricted to the nervous system or brain, but also include the morphology of the complete agent with all possibilities of interaction with the environment by sensory or motor systems. This has to be considered when biological information processing strategies are modeled in artificial systems. However, we want to stress that apart from these „tailored solutions", analysis of biological information processing can yield more general principles of information processing that can solve problems not found in natural situations.

Even though the examples listed above are exciting and well established models, it is rather astonishing that the number of fruitful interactions between experimentalists and theoreticians is not growing. Problems in collaborations exists on both sides. Theoreticians often do not focus on the biological details, that are in many cases not easily to be incorporated into a formal framework. Experimentalists, on the other hand, are concerned about acquiring new data that are publishable in highly rated journals from their field. Thus, experimentalists are often not willing to take the time to establish the thorough formal framework required by theoreticians, and they are often skeptical about predictions from people not from their own field.

An important aspect for a good cooperation is an intense contact between experimentalists and theoreticians. Successful interaction have so far mostly arised out of few individual collaborations, mostly within institutes. The major reason for that lies in the lack of a common language for both research fields. The establishment of interdisciplinary curricula is strongly recommended to overcome this communication problem. An additional problem for interdisciplinary research is the rigid system of university positions found in Germany. Although interdisciplinary research is most welcomed and needed, it is not sufficiently acknowledged when such a researcher applies for an academic position.

What Time Scales Are Important for Artificial and Natural Systems

A major problem imposed on both artificial and natural systems is the necessity to react appropriately to sensory stimuli in a minimal amount of time. Two contradictory needs have to be fulfilled: first of all, the agent has to react appropriately to avoid costly or even fatal wrong behavior. To achieve certainty about the sensory input, time consuming high-level computation is required. This, however, interferes with the second requirement: agents in a realistic environment do simply not always have the time for a high-level analysis. As an example, a mouse that is attacked by a cat should not try to make a detailed analysis of the visual features of the predator, but should rather make an escape reaction as quickly as possible. In other words, there is a trade-off between the expense of sensory analysis and reaction time.

Computer simulations can solve this problem by stepping out of the „real" time, performing the time-consuming computations, and going back into „real" time. Animals (that do not have that option) found another solution: they interpret sensory information predominantly on the basis of the actual behavioral context. By doing so, they implicitly form a hypothesis on the possible relevant stimuli that might occur in this context, allowing them to react as quickly as possible. A good everyday example is a person hiking through an area full of snakes; due to this knowledge, he will react very quickly when he encounters a snake or even a snake-like object (trading reaction time for level of analysis), whereas the same person would require a much longer time to react to a snake found, for example, in his office. For artificial agents that interact with the real world, an analogous extraction of a behavioral context might provide an interesting alternative to achieve fast performance.

Apart from this general principle, natural organisms display behavior on a large variety of time scales. Especially the resolution of very short times poses a formidable problem for neuronal systems as the neuronal hardware is not well suited to encode time differences of less than a millisecond. However, some specialists have evolved mechanisms to deal with even shorter intervals. As an example, neurons in the auditory system of barn owls have to phase-lock to frequencies above 5 kHz, that is, the cells have to phase-lock in the range of 20 microseconds. To deal with this problem, specialized membrane channels (outward-rectifying potassium channels) have evolved that shorten the postsynaptic potentials to allow these fast processes. In respect to longer time intervals, there seem to be elementary units that, in humans, are made up of either 30 milliseconds (within such a unit, sensory stimuli are perceived as simultaneous events) or roughly 200 milliseconds (fast movements, syllable rhythm of speech). To deal with longer time scales, different memory-related processes are involved. Taken together, natural organisms have evolved different mechanisms to deal with the large variety of time scales, ranging from specialized neurons over network dynamics up to memory processes.

Motivation in Natural and Artificial Systems

One important aspect in the development of autonomous agents is the development of fitness functions. One approach in the field of artificial life is the development of virtual worlds, in which autonomous agents fight for certain resources, for example CPU time. In this case it is possible to generate agents, which are well adapted to this problem.

In an example given by Maes (1991) on the basis of some kind of two-layered WTA system the internal activation of ten different modules (e.g. approach food, eat, fight, sleep) decisions are possible as they can be observed in behaving animals as are mutual inhibition of behaviors, opportunistic behavior, support of follow-up behavior, or displacement behavior. These agents have incorporated a motivational system based on an approach by Konrad Lorenz (the „hydraulic" model of motivation and behavior). The discussion of these examples led to the fascinating question about motivation and emotion in computer systems.

It was agreed that the aspects of emotion are not well understood even in natural systems, and so the term motivation was used in the restricted sense of priorizing a certain task out of a variety of options. An analogous situation in a computer would be a multitasking system that has to work on several problems and has to „decide" which task to perform first. The implementation of such motivational states would yield computers that are adapted to the needs of their user, making assumptions on the priorities of the user, and sequentially working on the different problems according to those. Such systems would be most welcomed in all situations where the complexity of the problem requires some sort of priorizing, e.g., in searching very large databases where a complete search would take too much time. The major problem for all approaches is the decision process and the variables it should be influenced by. However, it seems that even in humans the parameters that influence a decision are usually restricted to a very low number. An implementation of motivational and priorizing systems in computers might therefore not be out of reach.

It should however be noted that the analysis of emotional and motivational systems in humans and animals is still far from being complete. Few areas like, e.g., the amygdala, are undoubtedly involved in emotional processes, but most other structures and mechanisms contributing to these are still debated.

Resume

One point often raised during the discussions was the interdependence of function and structure. Several examples clearly showed that natural organisms have developed a lot of specialized organs or strategies (facette eye of the fly, interpretation of sensory inputs within the behavioral context), which are useful for the organism in the natural environment and reduce the necessary amount of computation. One major outcome for both computer scientists and neurobiologists was that artificial and natural organisms should be investigated in their interaction with the environment. Only by doing so, adaptations and specializations in natural organisms can be completely understood, and the fitness of an artificial organism can be assessed.

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