Benefits of Bio-inspired Technologies for Networked Embedded Systems: An Overview

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Abstract – The communication between networked embedded systems has become a major research domain in the communication networks area. Wireless sensor networks (WSN) and sensor/actuator networks (SANET) build of huge amounts of interacting nodes build the basis for this research. Issues such as mobility, network size, deployment density, and energy are the key factors for the development of new communication methodologies. Self-organization mechanisms promise to solve scalability problems – unfortunately, by decreasing the determinism and the controllability of the overall system. Self-organization was first studied in nature and its design principles such as feedback loops and the behavior on local information have been adapted to technical systems. Bio-inspired networking is the keyword in the communications domain. In this paper, selected bio-inspired technologies and their applicability for sensor/actuator networks are discussed. This includes for example the artificial immune system, swarm intelligence, and the intercellular information exchange.

1 Introduction

The proliferation of wireless sensor networks (WSN) and similar ad hoc networks based on huge amounts of spontaneously interacting nodes is changing the world of telecommunications. In addition to the increasing number of communicating nodes, node mobility is an issue as addressed, for example, in sensor/actuator networks (SANET). Previously, controllability and determinism were the keywords during protocol development and network research. Based on the primary objectives of WSN, nodes communicate using a radio interface, they are battery-driven, small, and cover only few resources. Therefore, new key factors have been identified for developing communication methodologies. Above all, the scalability of employed mechanisms has to be questioned.

Researchers anticipate self-organization methods as the general solution to the depicted communication issues in WSN and SANET. Centralized management and optimized control will be replaced by methodologies that focus on local knowledge about the environment and adequate decision-making processes. Similar problems are known and well-studied in nature. Therefore, such biological solutions should be adapted to enhance the communication in ad hoc networks and WSN.

The goal of this paper is to give an overview to some bio-inspired networking mechanisms and to introduce the underlying biological functionality as well as the adaptation to technical processes. Even though this paper is not intended as a general review, it summarizes the best-known approaches and explains selected mechanisms in more detail. The rest of the paper is structured as follows. Section 2 motivates the research on WSN and SANET and summarizes the major objectives and issues. Section 3 introduces biologically inspired self-organization and its applicability to technical systems. Then, section 4 explains selected methodologies in more detail. Finally, section 5 concludes the paper.

2 Networked Embedded Systems

Networked embedded systems are used in many application scenarios. Above all, wireless sensor networks (WSN) are widely studied [2, 6]. Sensor networks consist of multiple, usually hundreds or even thousands of sensor nodes. Such networks do not have a predominant topology but are created dynamically, ad hoc on demand. The nodes themselves can be of any size. Nevertheless, most publications understand sensor nodes as small, battery-driven devices with little processing power and memory, radio communication, and sensors to measure physical parameters such as the temperature.

Similarly, sensor/actuator networks (SANET) extend the idea of wireless sensor networks to mobile actuation systems, i.e. robot-like systems. In general, such SANET are build of cooperating mobile autonomous systems that allow some kind of actuation, e.g. handling, mobility [3].

With WSN and SANET, new issues appeared that are not covered by existing communication methods and protocols. Some of these issues are inherent in the idea of interconnecting thousands of networked embedded systems, other evolve based on particular application scenarios of WSN:

- Node mobility – In general, sensor networks are believed to be stationary, i.e. to have a fixed topology – at least in terms of node location. Admittedly, node mobility is becoming a major concern of new application scenarios such as logistics. SANET, on the other hand, inherently include location dynamics and mobility.
- Network size – In contrast to other networks, the number of nodes that are building a network on demand can be very high. Structured networks such as the Internet benefit from a hierarchical organization and a centralized management of subnetworks. WSN and SANET are infrastructure-less networks facing scalability problems if too many nodes are concerned.
- Deployment density – Depending on the application scenario, the node density in a WSN can be very high. This may break existing medium access control protocols and lead to energy exhaustion just for neighborhood detection.
- Energy constraints – Instead of having unlimited energy for computation and communication, energy constraints are much more stringent that in fixed or

cellular networks. Usually, sensor nodes are battery operated and in certain cases, the recharging of the energy source is impossible. We distinguish replenishable power sources, e.g. for wearable sensors, non-replenishable power sources, e.g. for sensors deployed in remote, hazardous terrain, and regenerative power sources.

- Data / information fusion – Limited bandwidth as well as the mentioned power constraints demand for aggregation techniques. Each data packet that has to be transported through a WSN is expensive. Aggregated data reduce the energy consumption and provide higher usefulness.

In summary, it can be said that self-organization mechanisms are needed for higher scalability in WSN/SANET communication [14]. The basic mechanisms that are available include neighborhood discovers, topology (re-)organization, and probabilistic approaches. Since optimization on a global level is no longer possible, there is always a discrepancy between multiple objectives. For examples, the latency of path-finding with on-demand routing protocols may be too high and periodic routing overhead in a table-driven routing protocol may consume a significant amount of bandwidth [1]. On the other hand, the probability of successful transmissions might be too low for stateless approaches. Therefore, hybrid architectures may improve the scalability and optimize the network behavior depending on the application scenario.

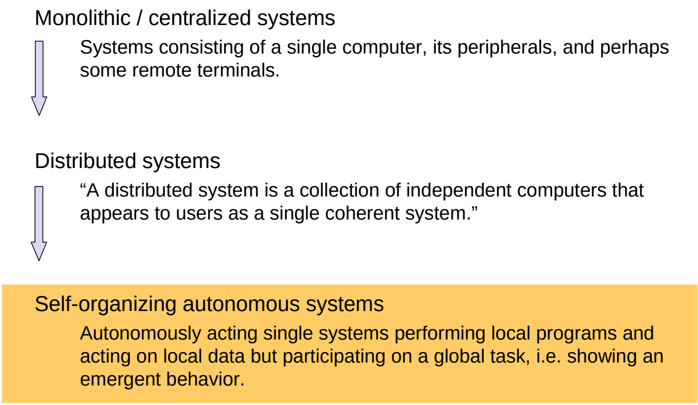

Fig. 1. The changing world: centralized systems, decentralized control, and self-organization

Fig. 1 illustrates the control and management of systems consisting of multiple subsystems. Centralized control is primarily used to operate in an environment consisting of a few nodes. Using centralized information about all systems, optimized solutions for communications and task allocation can be derived. Examples are perfect schedules for medium access and real-time failure detection and repair. Distributed control allows to manage larger numbers of systems in a scalable way by preserving most system characteristics such as controllability. Nevertheless, optimization becomes harder and the predictability is reduced. Finally, self-organizing systems should help to overcome all scalability problems. Nevertheless, the determinism and the controllability of the overall system are reduced. Another issue is the challenging change of the programming of such less predictable systems that are showing an emergent behavior. The relation between determinism and scalability is depicted in Fig. 2.

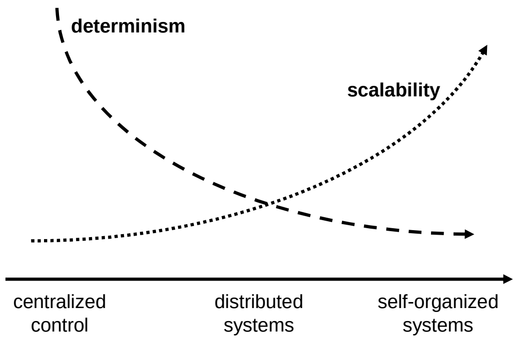

Fig. 2. Antagonism between determinism or controllability vs. scalability in system control

Referring to networked embedded systems and their management and control, self-organization mechanisms are needed in order to support a large amount of simultaneously intercommunicating nodes. In WSN and SANET, we need new methods to identify available communication paths, nodes, their capabilities, and resources. Additionally, the handling of data including storage, aggregation, and distribution must be changed and adapted to the new requirements. All the mentioned operations should be possible even without knowledge about the current network topology, available nodes, their addresses, their location, and others.

3 Self-Organization: "From Nature to Engineering"

The turn to nature for solutions to technological questions has bought us many unforeseen great concepts. This encouraging course seems to hold on for many aspects in technology. First studies on biological self-organization and its possible adaptation to technical solutions date back to the 1960ies. Von Foerster [24] and Eigen [15] proposed to employ self-organization methods as known from many areas in biology. They saw the primary application in engineering in general. Nevertheless, it has been shown that communications can benefit from biologically inspired mechanisms as well.

3.1 Basic Principles of Self-Organization

There are three major principles of self-organization mechanisms: feedback loops, local state evaluation, and interaction between individuals. Additionally, probabilistic methods that provide scalability and some degree of predictability can be found in nature and adapted to technology.

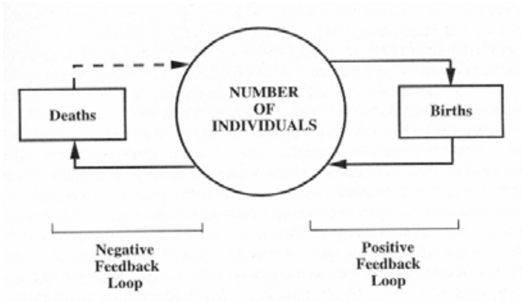

Fig. 3. System control using positive and negative feedback loops [5]

- Feedback loops – One major component in understanding the interaction of components producing a complex pattern are positive and negative feedback loops as shown in Fig. 3. Positive feedback acts as an amplifier for a given effect. In order to prevent overreactions and mis-regulations, negative feedback is used to efficiently control the system behavior.
- Local state – The second ingredient is the local state. This means that all subsystems are acquiring and action upon information that are stored locally. Any global control or dependency is prevented in order to enable fully autonomous behavior embedded into a global context.
- Interactions – Information transfer between individuals is necessary to update the local state. There are two ways to conduct such interactions: direct interaction or communication between related subsystems and indirect information exchange by interacting with the environment (also known as stigmercy [8]).

3.2 Application in Technical Systems

The development in the area of bio-inspired engineering is basically relying on the artificial immune system, swarm intelligence, evolutionary (genetic) algorithms, and cell and molecular biology based approaches. Some of the best known approaches should be summarized here whereas selected methodologies are depicted in more detail in the following section.

The immune system of mammals builds the basis for research on the artificial immune system (AIS). The reaction of the immune system, even to unknown attacks, is a highly adaptive process. Therefore, it seems obvious to apply the same mechanisms for self-organization and self-healing operations in computer networks. Security scenarios including virus and intrusion detection already benefited from AIS approaches [16, 18].

The behavior of large groups of interacting small insects such as ants and bees builds the basis for field of swarm intelligence. Simple and unrelated autonomously working individuals are considered to compose complex cooperative tasks. Similar actions are required in various areas of engineering and computer science and should build a basis for building self-organizing systems [5, 17]. A main focus lies on the formation of groups or clusters that allow efficient task allocation mechanisms.

Evolutionary (genetic) algorithms (EA) are self-manipulating mechanisms. The evolution in nature is the basis for such methodologies. In particular, there are multiple ways for organisms to learn. A natural selection process (survival of the fittest) is going on letting only the optimal prepared organisms to survive and to reproduce. Changes appear for example by mutations. An overview to evolutionary algorithms is provided for example in [4, 7].

An emerging research area looks for cell and molecular biology based approaches. All organisms are built in the same way. They are composed of organs, which consist of tissues and finally of cells. This structure is very similar to computer networks, which is also true for the signaling pathways. Therefore, research on methods in cell and molecular biology promises high potentials for computer networking in general and adaptive sensor networks and network security in particular [12, 21].

4 Bio-inspired Networking

Primarily, the focus of this section is to demystify the concepts of bio-inspired networking. Based on selected approaches, the objectives and solution paths of biologically inspired methods are depicted in more detail.

4.1 Swarm intelligence

The collaborative work of a multitude of individual, i.e. autonomous systems is necessary in many areas of engineering. Swarms of small insects such as bees or ants address similar issues. For example, ants solve complex tasks by simple local means. There is only indirect interaction between individuals through modifications of the environment, e.g. pheromone trails are used for efficient foraging. Finally, the productivity of all involved ants is better than the sum of their single activities and ants are “grand masters” in search and exploration.

The basic principles are simple. All individuals, i.e. the systems that collaborate on an overall task, follow simple rules that lead to an impressive global behavior, i.e. emerging behavior based on the simple rules and interactions between the systems, either directly or indirectly via the environment. An example is described in Fig. 4. The foraging algorithm used by termites to collect wood chips is shown on the left hand side. Using a simulation model, the overall visible behavior was studied [5]. Quickly, the chips are heaped together and structures emerge from the scene as shown on the right hand side.

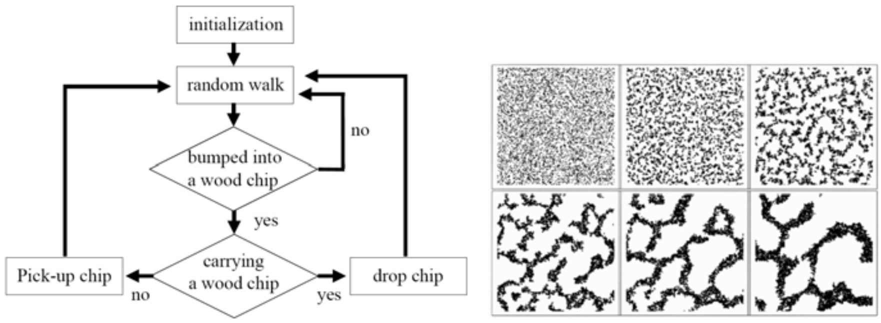

Fig. 4. "The emergent collective intelligence of groups of simple agents" [5]

Algorithms and methods as studied in the domain of swarm intelligence are used in many domains. One example is the efficient labor division or task allocation [10, 11]. The collaborative work of multi-robot systems, i.e. an example of sensor/actuator networks, is organized using simple rule-based coordination schemes that follow the same principles as described for ants. Another example is the ant based routing approach [8, 9]. The pheromone trail mechanism is exploited to search for optimal paths thought ad hoc networks. After a short learning phase, the optimal solution can be derived from previously (over suboptimal paths) transmitted messages.

4.2 Artificial Immune System

The primary goal of an artificial immune system (AIS) is to efficiently detect changes in the environment or deviations from the normal system behavior in complex problems domains. The role of the mammal immune system can be summarized as follows. It should protect the bodies from infections. The most interesting working behavior is the self-optimization and learning process. Two immune responses were identified. The primary one is to launch a response to invading pathogens leading to an unspecific response (using Leucoytes). In contrast, the secondary immune response remembers past encounters, i.e. it represents the immunologic memory. It allows a faster response the second time around showing a very specific response (using B-cells and T-cells).

The scope of AIS is widespread. There are applications for fault and anomaly detection, data mining (machine learning, pattern recognition), agent based systems, control, and robotics. One of the first AIS was developed by Kephard [18]. Based on this work, misbehavior detection and attack or intrusion detection systems were developed based on the working principles of the natural immune system [19, 20, 22]. Besides network security applications, the operation and control of multi-robot systems was addressed by AIS approaches. The collaborative behavior of robots collecting objects in an environment is difficult to optimize without central control. It was shown that an emerging collective behavior through communicating robots using an AIS overcomes some of the problems. The immune network theory was used to suppress or encourage robots behavior [23].

4.3 Intercellular information exchange

Regarding efficient networking, the investigation in the structure and organization of intercellular communication seems to be valuable. Molecular biology is the basis of all biological systems. It features a high specificity of information transfer. Interestingly, we find many similar structures in biology and in technology, especially in computer networking [21]. The primary concepts are intra- and intercellular signaling pathways and diffuse communication in large scale structures. Considering the knowledge about molecular biology and its similarity to communication networks, it is possible to extract the following lessons to learn: efficient response to a request, shortening of information pathways, and directing of messages to an applicable destination.

The information pathways can be distinguished into local and remote. Local: a signal reaches only cells in the neighborhood. The signal induces a signaling cascade in each target cell resulting in a very specific answer which vice versa affects neighboring cells. Remote: a signal is released in the blood stream, a medium which carries it to distant cells and induces an answer in these cells which then passes on the information or can activate helper cells (e.g. the immune system).

An example for successful application of the described communication method in WSN is the feedback loop mechanism [13]. Here, the Angiotensin-based regulation process for the blood pressure was used to model the control loop for an efficient regulatory process in an organism. This process was adapted to work in a sensor network by using the following two concepts:

- density of the sensor network allows for alternate feedback loops via the environment: directly via the physical phenomena which are to be controlled by the infrastructure
- indirect communication, allows for more flexible organization of autonomous infrastructures, reduces control messages

The benefit lies in a better system efficiency and reliability, explicitly in unreliable multihop ad-hoc wireless sensor networks.

5 Conclusion

In summary, it can be said that many approaches for bio-inspired networking have been studied and we can already see first impressive solutions and applications. Basically, the following mechanisms have been adapted to solve open issues in networking: feedback loops, i.e. positive feedback to initiate actuation or data aggregation, and negative feedback for network congestion control and smooth regulation; local state information for efficient data fusion, energy control, and clustering; and weighted probabilistic approaches for task allocation, controlled communication and congestion control. Finally, we are facing a multi-objective optimization process that balances between overhead (latency vs. energy) vs. predictability.

Self-organization mechanisms for communication and coordination between networked embedded systems need further research and development. There are many objectives and many directions, but similar solutions can be derived. Bio-inspired networking is just one but powerful approach. Ongoing research objectives include the efficient data dissemination, handling and storage in WSN as well as task allocation schemes and distributed control in SANET.

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