PerAdaMagazine
towards pervasive adaptation
10.2417/2201010.003286

Biological principles and sensor networks: self-organized operation and control

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Nature provides a number of model solutions to the problem of managing and controlling networked, embedded systems, from synchronizing distributed nodes to detecting misbehaviour.

The concept of sensor networks provides a framework for investigating algorithms and methods related to massively distributed systems. Sensor networks—i.e., networked embedded systems—are strongly constrained in terms of computational and communication resources, and, most importantly, energy. Because classical techniques do not scale owing to the inherent overhead required to maintain global state information, operation and control in such networks calls for completely new paradigms. Aside from several technical solutions that address data management and routing as well as programming, it turns out that sensor networks possess structures and behaviours that are very similar to those observed in nature. Here, we aim to introduce some of the ideas relating to specific programming and data-management solutions that have been inspired by the signalling principles of molecular biology.

A wide variety of solutions

Biologically inspired solutions have been developed in many different domains of investigation. In the area of sensor networks, for example, a number of extremely efficient solutions allow handling of available resources in a completely self-organized way.[1] Routing and data management are essentially based on topology, which is cumbersome if the number of connected nodes is large, the communication links are unreliable or nodes become mobile. Because these problems typically require heuristics for route estimation, bio-inspired approaches, such as ant-colony optimization, provide very robust and efficient solutions.[2] Another problem, that of synchronizing distributed nodes, has been addressed using multiple conceptual ideas borrowed from the Internet. However, it was nature that showed the way to handling similar problems in massively distributed systems. In particular, the synchronized

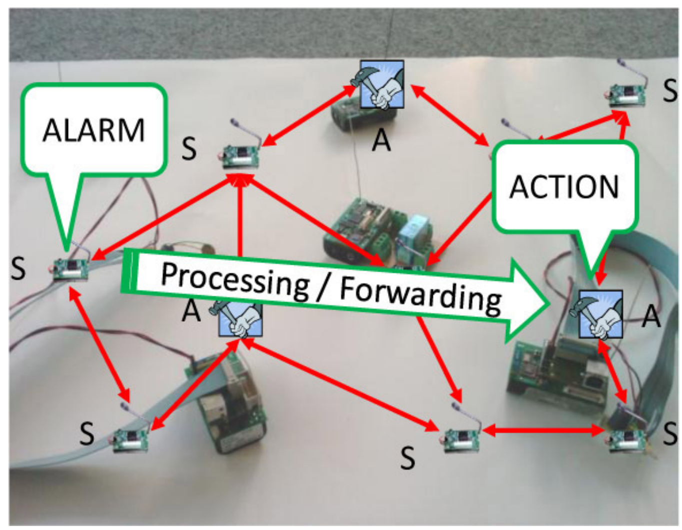

Figure 1. Application scenario for heterogeneous sensor and actor nodes that observe events and trigger appropriate actions. S: Sensor. A: Actor.

blinking of fireflies has been successfully adapted to the technical-application domain.[3] Detecting misbehaviour for improved security has given rise to multiple concepts, the most promising among which is the artificial immune system.[4] The key idea is to model detection of unusual events by learning the system's behaviour and then measuring deviations from it. Such algorithms can be executed in a fully distributed way without having to monitor and analyse the entire network. Finally, in the area of software engineering, the issue of heterogeneity means coming to grips with programming and, especially, reprogramming large-scale sensor networks. Technical solutions rely on a flooding or multicasting scheme that broadcasts code fragments to all sensor nodes in a network. Aside from problems such as determining successful transmission to every node and orchestrated switching to the new software, it is almost impossible to program individual nodes because of the large footprint of these

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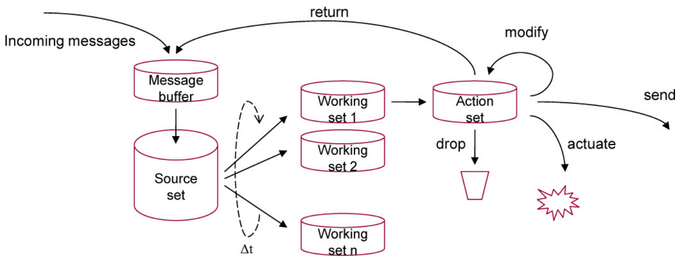

Figure 2. The working behaviour of a single rule-based sensor-network node. Received messages are stored in a buffer, selected to a working set according to specific criteria and finally processed, i.e., forwarded, dropped and so forth.

updates. Here, too, concepts from molecular biology are being investigated.[5]

Rule-based sensor networks

We developed the rule-based sensor network (RSN) as a lightweight programming scheme for sensor networks. It is conceptually based on an architecture for data-centric message forwarding, aggregation and processing. Instead of relying on network-wide unique address identifiers for all nodes, RSNs use self-describing messages. This concept is also known as data-centric routing. We have shown that RSNs can outperform other sensor network protocols for distributed sensing and network-centric data preprocessing in two dimensions, including the network's reactivity—i.e., a reduction in response time for network-controlled actuation—and communication overhead, i.e., more efficient use of bandwidth on wireless-transmission channels.[6]

Figure 1 shows a typical situation. A number of heterogeneous sensor nodes constantly check for specific events and Report detected alarms to distributed actors. The key challenge is the heterogeneous programming of all nodes, which will likely have to be adapted over time. Figure 2 shows the working behaviour of a single RSN node. After a message is received, it is stored in a buffer. The rule interpreter is either started periodically (after a fixed Δt) or after reception of a new message. An extensible and flexible rule system evaluates received messages and provides the basis for the node-programming scheme. The specific reaction to received data is decided by means of predicate-action sequences of the form if PREDICATE then {ACTION}. First, all messages matching the predicate are stored in so-called working sets. Then, the specified action is executed on all messages in the set. Using such rules makes it possible to model complex and dynamic behaviour. Examples include event-monitoring applications in sensor networks and target tracking under energy constraints. In biological systems, such behaviour can be modelled (or studied) using signalling networks and repetitive patterns, or motifs. The period of RSN execution, Δt, has been identified as a key parameter for controlling the reactivity versus energy performance of the entire RSN-based network. Basically, the duration of the messages stored in the local node introduces an artificial per-hop delay. The optimal value for Δt affects aggregation quality versus real-time message processing. We have successfully applied a promoter-inhibitor system to this problem.

Mutual benefits

Even though biologically inspired approaches are often elegant and appear to be very efficient, they require meticulous modelling, combined with detailed validation and performance evaluation. Understanding and modelling the biological counterparts to technical systems requires collaborative and interdisciplinary research between engineers, computer scientists and biologists. Models are frequently used to inspire novel technical artefacts without any reciprocal benefit to these disciplines. However, initial projects have shown that mathematical models of a biological principle are useful in both developing technical solutions and supporting the learning process on the biological side. For example, mathematical models of ant foraging have contributed to both development of self-organized multirobot systems and new insights about path selection among ants. In addition, investigations into artificial immune systems have led to models that can be directly applied in the study of immune malfunction.

A challenge for the future is development of nanonetworks.[7] Researchers have begun to work on developing technical systems of nanometer dimensions. Many of these systems rely directly on the biological and chemical particles used to build them. Inter-networking on the nanoscale introduces new problems, because it cannot make use of classical communication techniques. Instead, molecular communication principles replace, say, radio communication. Consequently, we will need to understand all capabilities of this communication channel to be able to operate devices at this scale. Currently, we are investigating the use of bio-inspired solutions in the context of vehicular networks. In particular, we discovered that routing heuristics based on ant-colony optimization show extremely robust behaviour, even in very dynamic environments.[8]

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