Bio-inspired Network-Centric Operation and Control for Sensor/Actuator Networks

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Abstract. Self-organization mechanisms have been investigated and developed to efficiently operate networked embedded systems. Special focus was given to wireless sensor networks (WSN) and sensor/actuator networks (SANET). Looking at the most pressing issues in such networks, the limited resources and the huge amount of interoperating nodes, the proposed solutions primarily intend to solve the scalability problems by reducing the overhead in data communication. Well-known examples are data-centric routing approaches and probabilistic techniques. In this paper, we intend to go one step further. We are about to also move the operation and control for WSN and SANET into the network. Inspired by the operation of complex biological systems such as the cellular information exchange, we propose a network-centric approach. Our method is based on three concepts: data-centric operation, specific reaction on received data, and simple local behavior control using a policy-based state machine. In summary, these mechanisms lead to an emergent system behavior that allows to control the operation of even large-scale sensor/actuator networks.

1 Introduction

In the communications area, there is a strong research focus on networked embedded systems because of their broad diversity in application domains. Especially, wireless sensor networks (WSN) have become popular for many applications. Similarly, there is a growing demand for sensor/actuator networks (SANET).

Sensor networks are composed of numerous small, independently operating sensor nodes [1]. Such sensors nodes are self-contained units consisting of a battery, radio communication, sensors, and some minimal amount of on board computing power. While the application scenarios are manifold [2], the operation of such WSNs is still challenging [3], basically due to the limited resources in terms of CPU power, storage, and, first of all, energy [4]. Within a WSN, nodes are thought to be deployed, to adapt to the environment, and to transmit data among themselves and/or to a given base station. The research topics include efficient communication in terms of resource consumption, reliability, and scalability [2, 5]. Because sensor nodes are usually battery operated, many efforts

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have been made to develop energy-efficient algorithms and protocols for communication in WSNs [6].

Usually, WSNs are thought to be dynamic in terms of the current availability, i.e. they care about the potential removal and addition of sensor nodes. Dynamics in terms of mobility is concerned in sensor/actuator networks. Basically, SANETs consist of sensor networks that are enhanced by additional actuation facilities [3]. In most application scenarios, mobile robot systems are used as actuation facilities [7]. Nevertheless, we concentrate on general purpose actuation controlled by measures from corresponding sensor nodes. Therefore, the same network infrastructure is used for actuation control as well as for sensor data collection.

There are many application scenarios for WSNs and SANETs. The most popular examples include the service as first responders in emergency situations [8] and the supervision and control of challenging environments such as the monitoring of animals [9].

Operation and control of such networks is one of the most challenging issues. Typically, a central control loop is employed consisting of the following actions: measurement, transmission to a base station, (external) analysis, transmission to the actuation devices, actuation. Besides the increased network load, severe delays might be introduced. Driven by the limited resources, mechanisms for network self-organization have been proposed for higher scalability. Most of these approaches focus on efficient communication in WSNs, e.g. directed diffusion as a data-centric communication paradigm [10], and on stateless task allocation in SANETs [11]. Similar issues have been addressed in the artificial intelligence domain. Agent-based systems have been developed that enable an efficient distributed control in uncertain environments [12]. Nevertheless, there are still many unsolved issues such as predictability of an action, reliability of the communication, and boundaries for response times.

In this paper, we present and discuss an approach for *network-centric operation and control* in WSNs and SANETs that prevents the necessity of the described control loop or reduces the loop to a few neighboring nodes within the network, respectively. Inspired by the information handling in cell biology, we have built a rule-based system that allows to achieve all decisions within the network itself. There is no external control required. Nevertheless, we propose to allow such external intelligence for the handling of unexpected situations. The adaptive rule system has the inherent property of being self-learning by inducing new rules that match previously unknown situations. Therefore, our method provides at least limited control in a system showing an emergent behavior.

The network-centric control system allows to operate even in scenarios with the following challenging properties:

- Mobility of nodes – commonly it is believed that sensor networks being stationary, nowadays, mobility is a mayor concern
- Size of the network – much larger than in a infrastructure networks
- Density of deployment – very high, application domain dependent
- Energy constraints – much more stringent than in fixed or cellular networks, in certain cases the recharging of the energy source is impossible

The main contributions of the paper can be summarized as follows. An approach is presented that features localized data analysis and diffuse communication of measurement and computation results based on the content of the information instead of topology information and central management. We adapted signaling pathways known from cell biology to achieve an emergent behavior of the addressed complex system consisting of sensors and actuators. Using simple rules that are pre-programmed into network nodes, the network becomes able to solve aggregation or decision problems without having a global view to the behavior of the entire system.

The rest of the paper is organized as follows. Section 2 depicts the shifting paradigms to network-centric operation and control in massively distributed sensor/actuator networks. In section 3, the rule-based state machine for localized actuation control is explained. This description is followed by a discussion in section 4 and a conclusion in section 5.

2 Shifting Paradigms: Network-Centric Operation and Control

The objective of this paper is to discuss the potentials of network-centric control and operation in sensor/actuator networks. We developed a scheme based on three principles: data-centric operation, specific reaction on received data, and simple local behavior control using a policy-based state machine. We start with a high-level motivation for the presented approach, followed by a detailed description of the involved algorithms, and a discussion that is meant to be a starting point for further contemplation.

2.1 Need for Network-Centric Control

The coordination and control of sensor/actuator networks is still an emerging research area. Sensor networks have been enhanced by mobile robots. The resulting system is continuously examining the environment using sensors (measurement). The measurement data is transmitted to a (more or less) central system for further processing, e.g. optimizations using global state information. Then, the actuators are controlled by explicit commands that are finally executed (actuation). Basically, this scheme is usually used because the involved components (sensors, actuators) do not have resources that allow to cover the global state. The scheme is depicted in figure 1 (left). The measurement and the control loop are shown by corresponding arrows. Obviously, long transmission distances have to be bridged leading to unnecessarily high transmission delays as well as to a questionable communication overhead in the network, i.e. possible network congestion and energy wastage.

The favored behavior is shown in figure 1 (right). Self-organization methodologies are used to provide a network-centric actuation control, i.e. a processing of measurement data within the network and a direct interaction with associated, i.e. co-located actuators. How can we build a system that behaves in this fashion

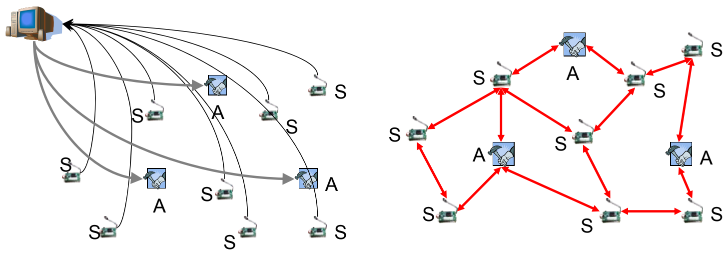

Fig. 1. Operation and control of a SANET: centralized (left), network-centric (right)

and that shows the desired emergent behavior? We tried to adapt mechanisms as known from cell biology as described in the next section. The result is a data-centric message forwarding, aggregation, and processing. The key requirements can be summarized as follows:

- Self-organized operation without central control
- Allowance for centralized "helpers" and self-learning properties
- Reduced network utilization
- Accelerated response, i.e. in-time actuation

2.2 An Excursion to Nature - Cellular Signaling Pathways

The turn to nature for solutions to technological questions has brought us many unforeseen great concepts. This encouraging course seems to hold on for many aspects in technology. Many efforts were made in the area of computer technology employing mechanisms known from biological systems [13]. For this work, we concentrate on information transmission and reaction capabilities employed by signaling pathways for inter-cellular communication [14].

The focus of this section is to briefly introduce the information exchange in cellular environments and to extract the issues in computer networks that can be addressed by the utilization of these mechanisms [15, 16]. Similar to the structure, the intercommunication within both systems is comparable [17, 18]. Information exchange between cells, called signaling pathways, follows the same principles that are required by network nodes. A message is sent to a destination and transferred, possibly using multiple hops, to this target.

From a local point of view, the information transfer works as follows. The cell expresses a specific surface molecule, the receptor. In consequence this receptor is activated, e.g. by a change in its sterical or chemical conformation (phosphorylation of defined amino acids). The activated receptor molecule is able to further activate intracellular molecules resulting in a "domino effect". The principle is not as simple as described here. Many of these signaling pathways are interfering and interacting. Different signaling molecules are affecting the same pathway. Inhibitory pathways are interfering with the straightforward signal transduction. To sum up, the final effect is dependent on the strongest signal. The effect of

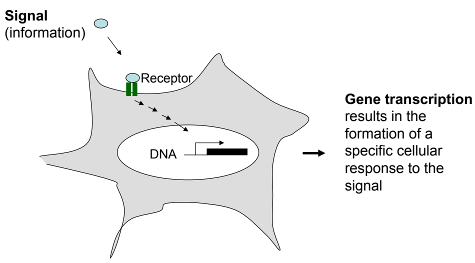

Fig. 2. Information exchange in the cellular environment

such a signal transduction pathway is mostly gene transcription, other possibilities are the reorganization of intracellular structure such as the cell cytoskeleton or the internalization and externalization in and out of the cell. Gene transcription means that the cell respond to incoming the signal by production of other factors which are then secreted (transported out of the cell), where it can induce signaling processes in the cell's direct environment. This process is depicted in a simplified manner in figure 2. A cell is shown with a single receptor that is able to receive a very specific signal, i.e. a protein, and to activate a signaling cascade which finally forms the cellular response.

This *specific response* is the key to information processing. It depends on the type of the signal and the state of the cells (which receptors have been built and which of them are already occupied by particular proteins). Finally, a specific cellular response is induced: either the local state is manipulated and/or a new messaging protein is created. The remote information exchange works analogue. Proteins, peptides, and steroids are used as information particles (hormones) between cells. A signal is released into the blood stream, the medium that 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 Renin-Angiotensin-Aldosteron system [19] and the immune system). The interesting property of this transmission is that the information itself addresses the destination. During differentiation a cell is programmed to express a subset of receptor in order to fulfill a specific function in the tissue. In consequence, hormones in the bloodstream affect only those cells expressing the correct receptor. This is the main reason for the specificity of cellular signal transduction. Of course, cells also express a variety of receptors which regulate the cellular metabolism, survival, and death.

The lessons to learn from biology are the efficient and, above all, the very specific response to a problem, the shortening of information pathways, and the possibility of directing each problem to the adequate helper component. Therefore, the adaptation of mechanisms from cell and molecular biology promises to enable a more efficient information exchange. Besides all the encouraging properties, bio-inspired techniques must be used carefully by modeling biological and technical systems and choosing only adequate solutions.

So, how to use the described methods to WSN and SANET operation and control? The biological model needs to be checked and - partially - adapted

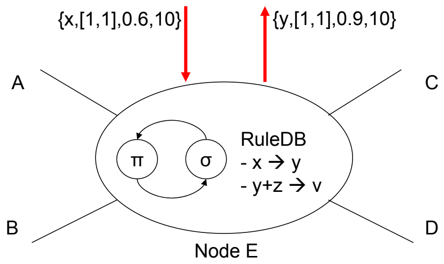

Fig. 3. Architecture and behavior of a local node

to match the tasks in sensor/actuator networks. In the following section, we describe and discuss a solution for network-centric operation and control based on the described biological mechanisms.

3 Rule-Based State Machine for Localized Actuation Control

As already mentioned, three basic mechanisms are used to achieve the demanded goals:

- *Data-centric operation* – Each message carries all necessary information to allow the specific handling of the associated data.
- *Specific reaction on received data* – A rule-based programming scheme is used to describe specific actions to be taken after the reception of particular information fragments.
- *Simple local behavior control* – We do not intend to control the overall system but focus on the operation of the individual node instead (see discussion on emergent system behavior in section 4). We designed simple state machines that control each node whether sensor or actuator.

The complete scheme as adapted from cellular behavior is shown in figure 3. Even though the principles are described later, the general architecture and the behavior can be shortly explained. Depicted is a network node that has four directly connected neighbors (A, B, C, D). The local behavior is controlled by a state machine (π, σ) and a set of rules (RuleDB). In this example, a data message of type x is received and transformed locally into a message of type y. Finally, this message is distributed to all neighbors. (Remark: we consider wireless communication. Therefore, each message that a node sends is basically a broadcast to all neighboring nodes.)

3.1 Data-Centric Operation

Classically, communication in ad hoc networks is based on topology information, i.e. routing paths that have been set-up prior to any data exchange. Additionally, each node carries a unique address that is used to distinguish the desired destination. We follow the approach used in typical data-centric communication schemes, e.g. directed diffusion [10], and replace topology information and addressing by data-centric operation. Each message is encoded as follows:

M:={type, region, confidence, content}

Using this description, we can encode measurement data as well as actuator information (type and content). Additionally, the region is included to distinguish messages from the local neighborhood from those that traveled over a long distance. Finally, the confidence value is used to evaluate the message in terms of importance or priority. Measures with a high confidence will have a stronger impact on calculations that those with a lower confidence. The confidence can be changed using aggregation schemes, i.e. two measures of the same value in the same region will lead to a higher confidence.

The following examples demonstrate the capabilities of the message encoding for data-centric operation:

- {temperatureC, [10,20], 0.6, 20} :: A temperature of 20C was measured at the coordinates [10,20]. The confidence is 0.6, therefore, a low-quality sensor was employed.
- {pictureJPG, [10,30], 0.9, "binary JPEG"} :: A picture was taken in format JPEG at the coordinates [10,30].

3.2 Specific Reaction on Received Data

An extensible and flexible rule system is used to evaluate received messages and to provide the "programming" that specifies the cellular response. Even though the message handling in biological cells is more sophisticated, the basic principles including the processing instructions (the DNA) are modeled. Each rule consists of two parts: a number of input values and some output: INPUT → OUTPUT. Therefore, typical rules could look like that:

- $A \rightarrow B$ :: message A is converted to message B
- $C \rightarrow \{\}$ :: message C is discarded
- $A \wedge B \rightarrow C$ :: if both messages A and B were received, a message C is created

Using all the other information available in each message, more complex rules can be derived:

- $A(\text{content} > 10) \rightarrow A(\text{confidence} := 0.9)$ :: if the measured value was larger than 10, a copy of A is created with confidence set to 0.9
- $A(\text{content} = x) \wedge A(\text{content} = y) \rightarrow A(\text{content} := x + y)$ :: two messages of type A are aggregated to a single one by adding their values

Again, an example is provided to reflect the capabilities of the data-centric operation:

- temperatureC(content> 85) →alarmFire(confidence:= 0.8)

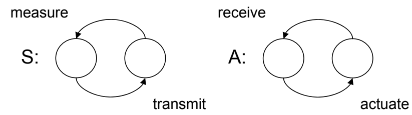

Fig. 4. Simple state machines for sensors (S) and actuators (A)

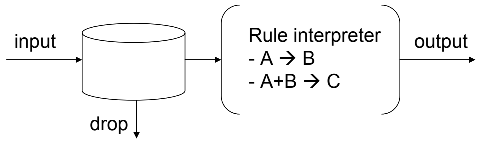

Fig. 5. Rule interpreter with system input and output

3.3 Simple Local Behavior Control

The local behavior is controlled by simple state machines acting as sensors or actuators. Additionally, an interpreter is checking the installed rules to previously received messages. It uses a queuing subsystem that acts as a generic receptor for all messages and keeps them for a given time. This time control is necessary to prevent queue overflows due to received messages of unknown type. The basic state machines for sensing and transmitting data and receiving and acting on data for sensors and actuators, respectively, are shown in figure 4.

The rule interpreter and its queuing system are depicted in figure 5. Basically, this is the standard behavior of each communication system. Received messages are stored in a local database. After a given timeout, each message is dropped in order to keep the size of the database below a given threshold. Periodically, the rule interpreter compares all received messages against the programmed rule set. A matching rule terminates the search and the rule is applied.

3.4 Case Studies

Two case studies are provided in this section to elaborate the principles and the flexibility of the proposed network-centric operation and control method for sensor/actuator networks: first, data aggregation and emergency calls, and secondly, in-network actuation control. Both examples were also chosen in order to show the benefits of our approach compared to traditional WSN mechanisms.

Data aggregation and emergency calls. We consider a typical scenario for wireless sensor networks. Sensor nodes are distributed over a given area. All nodes are equipped with sensors measuring a particular physical phenomenon, e.g. the temperature. In order to obtain information about the territory, the measurement results are transported to a given sink that analyzes the received temperature information. Additionally, measures exceeding a given threshold represent emergency situations that must be handled separately. In both examples, we assume a priority-based message forwarding scheme on the network layer.

1. Data types

   M_{temp} := {temperature, position, content, priority}
   M_{alarm} := {alarm, position, content, priority}

   Examples:
   - {temperature, [10.5, 4.89], 26, 0.1}
   - {alarm, [0.8, 10.0], 75, 0.8}

2. Rule set

   Aggregation:
   $A_{temp}(content) eq B_{temp}(content) \rightarrow C_{temp}(priority := priority_A + (1 - priority_A) * priority_B)$
   Emergency:
   $A_{temp}(content > 70) \rightarrow B_{alarm}(priority := max(priority, 0.8)$

   The aggregation rule combines multiple messages containing the same measurement results into a single message. Such aggregated messages must be handles with more care in the network since a packet loss of an aggregate of n messages can be compared to n separate lost packets without aggregation. In our example, the priority of the aggregated message is increased in order to enable the network layer to handle this packet specifically. The emergency rule creates new alarm packets if measurements above 70 degrees were observed. Additionally, the priority is explicitly set to a high value representing the importance of such a message.

3. Evaluation

   The benefits of the aggregation and emergency example can be shown easily. Consider the following scenario. All sensor nodes are directly connected to a central base station. In this case, each message must travel exactly one hop before processing. There is no possibility for aggregation to take place. In every other case, multi hop communication is involved and multiple messages can be aggregated. Compared to a pure central processing, the approach always leads to a noticeable reduction of the network load.

In-network actuation control. A second example includes additional actuators. Based on the temperature measurement as discussed before, temperature control should be performed, e.g. by using AC or heatings. Such actuators are controlled by special control messages. In the following description, only the differences and additions to the previous example are shown.

1. Data types

   $M_{control}$:= {control, position, delta, priority}

   Examples:
   - {control, [10.0, 10.0], +5, 0.1}
   - {control, [1.0, 10.0], -10, 0.8}

2. Rule set

   Control$_1$: $A_{temp}(content! = 20) \rightarrow B_{control}(delta := 20 - content_A)$
   Control$_2$: $A_{control}$ $\rightarrow$execute actuation command

   Two types of control rules exist. The first one (Control$_1$) can be seen as the in-network processing part. Received messages are verified whether actuation control should take place. In our example, a mean temperature of 20 degrees should be maintained. The second rule (Control$_2$) depicts the actuation initiation. After receiving a control message at an actuator, it performs the necessary actuation as encoded in the message (after checking if it can provide the needed service).

3. Evaluation

   Similarly to the previous example, a fully connected network (all sensors and actuators have a direct connection to the base station) will always perform optimal in terms of network overhead. Nevertheless, such a topology is unrealistic considering larger areas to be observed and maintained. In this case, each sensor message must traverse a multi hop path toward the base station. Then, after a meaningful evaluation, the actuation control must travel back to the actuators.

   In this case study, another possible topology can be imagined that also leads to a non-optimal operation of the proposed solution: if all sensors build a separate network partition as well as all actuators, then the base station will become the gateway between both networks. In this case all messages must traverse the base, i.e. there is no overhead in terms of duplicate network utilization for sensor and actuation control messages. Admittedly, this scenario is unrealistic as well.

   In conclusion, our solution for network-centric operation and control will perform at least as good as a central base station approach and outperform it in most realistic network scenarios, i.e. in networks consisting of a mixture of sensors and actuators.

4 Discussion

Based on the previously stated key requirements, the benefits of the proposed solution are reviewed in the following. Additionally, potential disadvantages or problems are stated and discussed:

- Self-organized operation without central control – The presented approach is based on locally available information only. Using the flexible rule system, arbitrary data-centric operations can be defined enabling the systems to specifically act on each received message.
- Allowance for centralized "helpers" and self-learning properties – Rules can be specified to forward all unknown messages to a central "helper". This system can examine the message, create according rules, and submit these rules to replace/enhance the rules installed in the SANET nodes. Therefore, our method provides at least limited control in a system showing an emergent behavior.
- Reduced network utilization – The network utilization no longer depends on the amount of measurement data to be transmitted to a base station. Instead, the rule system is responsible if and how messages have to be forwarded to more distant regions of the network.
- Accelerated response / actuation – The response time is much smaller than in the centralized approach due to the shortened data paths from measurement to processing, which takes place directly within the network, and the actuation. Depending on the installed rules and their spatial distribution, even boundaries for the response time can be derived.

Potential problems can appear through the inherent characteristics of such self-organizing processes [20], i.e. issues such as predictability of an action, reliability of the communication, and boundaries for response times must be considered. In general, there is no global state information available. Therefore, optimal solutions for the entire network cannot be calculated based on all theoretically available measures. Nevertheless, depending on the rule set, solutions can be derived that approximate the globally optimal solution quite well. Another issue is the necessary pre-programming of the rule sets into all the nodes. If new algorithms should be deployed, which is easy and straightforward using a central control, all or at least many of the distributed nodes must be changed. Fortunately, there are already network-based reprogramming techniques [21] and robot-assisted solutions [22] available to provide this functionality.

5 Conclusion

In this paper, we presented and discussed a methodology for network-centric operation and control of sensor/actuator networks. Inspired by biological information processing, we developed three easy to handle building blocks: data-centric communication, a state machine, and a rule-based decision process. Using these algorithms, the handling and processing of sensor data within the network itself becomes possible. In particular, we demonstrated that a collaborative sensing and processing approach for sensor/actuator networks based on local intelligence is possible. The interaction and collaboration between these nodes finally leads to an optimized system behavior in an emergent way.

Further work is needed in two directions: first, a detailed performance analysis for different application scenarios is necessary in order to rate the practical usability of the approach depending on the scenario. Secondly, it might be helpful if the rule sets are not "programmed" into each node but exchanged and updated on-demand by the nodes themselves in terms of a learning process.

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