Network-centric Actuation Control in Sensor/Actuator Networks based on Bio-inspired Technologies

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Abstract— **Self-organization mechanisms have been 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.**

I. 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).

WSN 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 onboard computing power. While the application scenarios are manifold [2], the operation of such WSN 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 have been made to develop energy-efficient algorithms and protocols for communication in WSN [6].

Usually, WSN 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, SANET 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 WSN and SANET. 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 generated. 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 WSN, e.g. directed diffusion as a data-centric communication paradigm [10], and on stateless task allocation in SANET [11]. 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 WSN and SANET 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.

The network-centric control system allows to operate even

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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 that 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 II depicts the shifting paradigms to network-centric operation and control in massively distributed sensor/actuator networks. In section III, the rule-based state machine for localized actuation control is explained. This description is followed by a discussion in section IV and a conclusion in section V.

II. SHIFTING PARADIGMS: NETWORK-CENTRIC OPERATION AND CONTROL

The objective of this paper is to discuss the potentials of network-centric control of the operations 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.

A. 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. 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. 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 unnecessary communication overhead in the network, i.e. possible network congestion and energy wastage.

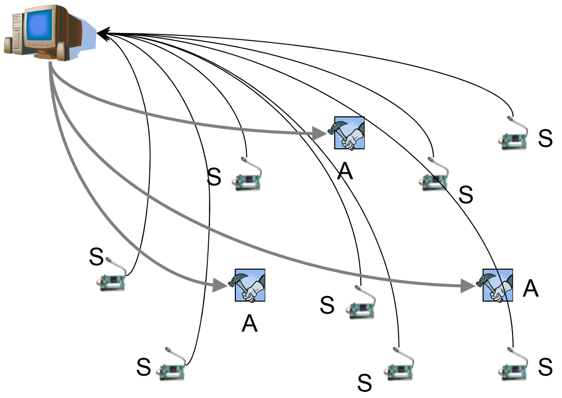

Fig. 1. Centralized control in a SANET

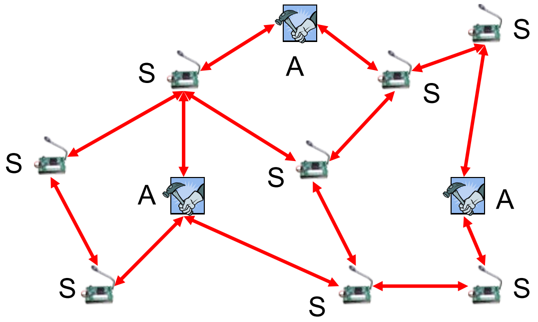

Fig. 2. Network-centric, i.e. distributed operation and control in a SANET

The favored behavior is shown in figure 2. 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 and that shows the desired emergent behavior? We tried to adapt mechanisms as known from biology described in the previous 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

B. An excurse 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

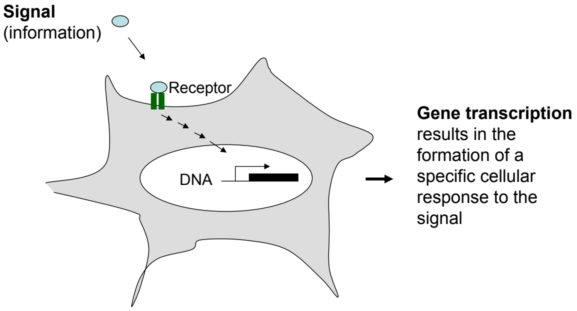

Fig. 3. Information exchange in the cellular environment

employing mechanisms known from biological systems. For this work, we concentrate on information transmission and reaction capabilities employed by signaling pathways for intercellular communication [12].

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 [13], [14]. Similar to the structure, the intercommunication within both systems is comparable [15], [16]. Information exchange between cells, called signaling pathways, follows the same requirements as between 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. A specific 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. This process is depicted in figure 3. 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. Depending 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). Therefore, the processing can incorporate previously received information as well. 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 are used as information particles between cells. A signal can be released into 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). The interesting property of this transmission is that the information itself addresses the destination. Only cells with specific receptors are able to receive the information, i.e. the protein binds at the receptor.

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 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 shown biological mechanisms.

III. RULE-BASED STATE MACHINE FOR LOCALIZED ACTUATION CONTROL

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

- *Data-centric operation* - Each message carries all necessary information to allow this specific handling.
- *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. 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 4. 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.)

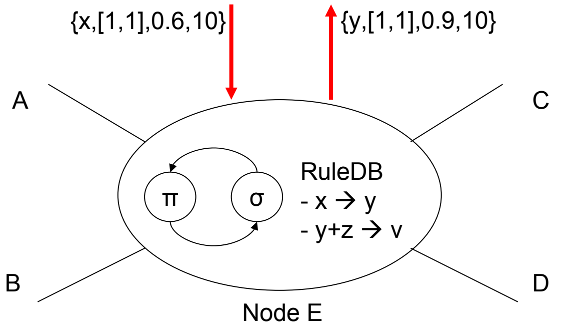

Fig. 4. Architecture and behavior of a local node

A. Data-centric operation

Classically, communication in ad hoc networks is based on topology information, i.e. routing path 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 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].

B. 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:

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

Again, an example is provided to reflect the flexibility and power of the data-centric operation:

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

C. 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 5.

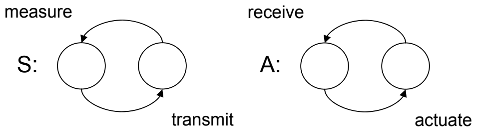

Fig. 5. Simple state machines for sensors (S) and actuators (A)

The rule interpreter and its queuing system are depicted in figure 6. 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 low. Periodically, the rule interpreter compares all received messages against the programmed rule set. A matching rule terminates the search and the rule is applied.

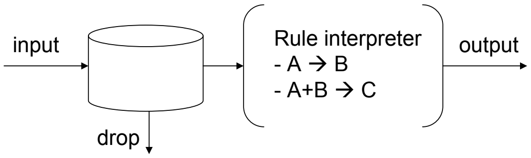

Fig. 6. Rule interpreter with system input and output

IV. 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.
- 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, i.e. 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 [17]. 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 [18] and robot-assisted solutions [19] available to provide this functionality.

V. 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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