Sensor World – A Flexible Distributed Architecture for Simulating Sensor Strategies

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INTRODUCTION

Sensor networks are an important means for capturing information about physical, chemical, and biological phenomena (Stefanidis, 2006). In this article, we focus on sensor networks used for earth observation. Those networks are used in a broad range of applications, e.g. monitoring of environmental pollution, disaster management, or meteorology. Besides conventional static sensors that are fixed to a single location, we address mobile sensors, i.e. sensors that are attached to some sort of platform for mobility.

Mobile sensor platforms provide a new approach for creating highly efficient sensor networks. One main advantage of mobility is the ability to dynamically adapt the sensor distribution to the sensing task (e.g. to ensure a higher sensor density in regions with peak values) (Dantu et al., 2005). Furthermore mobility makes it possible to enhance the area that can be covered by a single sensor. For taking advantage of these capabilities, the movement of each individual sensor needs to be defined with regard to number and types of the sensors and in response to stimuli like observed values, behaviour of other sensors, mobility of the observed property etc.

The evaluation of mobility strategies is a very important step during the design phase of a mobile sensor network. If the sensors can hardly be reached (e.g. in an inaccessible area) or the movement strategy cannot be modified during operation, it has to be ensured before deployment that the sensor strategy works properly. Aspects like the general functionality but also detection quality and energy consumption are important factors that must be considered when deploying a mobile autonomous or semi-autonomous sensor network.

In this paper we present a simulation framework that allows evaluating sensor strategies without the need of deploying a sensor network in a real world environment. By evaluating parameters like detection quality and adaptability to external and internal factors among other aspects before deployment, the development of sensor networks is significantly facilitated. Also the costs for implementing strategies on real nodes multiple times for testing purposes are reduced by using the proposed simulation approach.

Resembling physical sensor networks was one of the design goals of Sensor World. The following challenges are addressed in our proposed simulation framework in order to allow a realistic simulation of (mobile) sensor networks.

Communication: In wireless sensor networks, the communication range of each node is limited (Agre et al., 2000). The limiting factor is usually a combination of the energy supply, the maximum payload of the sensor platform, and the topography of the environment. The frequently changing topology of the sensor network requires adaptive data transmission and routing protocols (Rahimi et al., 2003).

Limited energy supply: Wireless sensors are often equipped with batteries or solar panels that constrain the usability of the sensor. For enhancing the sensor lifetime it is necessary to develop sensors that perform an energy efficient behaviour (Taherian, 2004). Especially the amounts of communication, sensor movement and computation are direct factors of influence to the energy consumption.

Limited computation power and memory size: Closely related to the limited energy supply is the limitation of computing power and memory size.

Scalability: Data collection and transport is challenging, as the bandwidth of the underlying communication system might not be sufficient to transport the data of thousands of sensors to a single data sink within a certain amount of time. Intelligent filtering and on-the-node data fusion mechanisms determine the scalability of the network.

Autonomy: In wireless sensor networks, a central control might not always be feasible, depending on the amount of message that have to be transported. Additionally, communication capabilities of the specific sensors, mobility aspects, as well as the terrain might prevent permanent connections to sensors. In those cases, the sensors should still contribute to the task of the sensor network. In order to follow on with the observation task, (temporary) autonomous sensors might be more efficient than sensors that rely entirely on command messages from a central controller (Estrin et al., 1999). In case of a lost connection autonomous behaviour might be the only way to re-establish the communication link (e.g. by moving away from obstacles that obstruct the communication).

Quantity and quality of the different constraints differ across sensor network scenarios and are often not fully predictable or even change during operation. The requirements vary based on the observed phenomenon, measurement frequency, resolution of the observation etc. To match those requirements, sensor behaviour patterns have to be developed and tested against various scenarios.

In summary Sensor World provides a framework that allows the quick evaluation of sensor behaviour patterns. It makes low-level programming for testing purposes redundant. In fact, Sensor World makes it possible to decide about the feasibility of sensor strategies for certain problems and scenarios before starting with a complex implementation on the sensor level.

Sensor World supports the evaluation of algorithmic aspects of sensor strategies and their general feasibility for different scenarios. Complementary to this, most other lower-level simulation approaches are focused on checking the correctness of concrete strategy implementations that are based on algorithms developed with the support of Sensor World.

The remaining paper is structured as follows: First we introduce the aims that lead to the development of Sensor World. Subsequently we explain the requirements for the simulation environment and their realization in Sensor World. After this the Sensor World Framework is described and the Sensor World architecture is discussed. In a next chapter the simulation components for sensors, phenomena and communication are presented. Experiences gained during the implementation and first results are discussed after this. Finally an outlook on potential future enhancements and a conclusion are given in the last two chapters.

AIMS OF SENSOR WORLD

Existing sensor network simulation tools often come from the wireless sensor network community and focus mainly on the various aspects of the underlying communication protocols. Most of these sensor simulation tools focus on communication networks and testing of embedded sensor software. The approach of Sensor World can be distinguished by a more high level oriented approach as we do not intend to simulate real code that is written in a sensor specific language. Furthermore the simulation of low level communication protocols (e.g. MAC layer protocols) is not within the direct scope of Sensor World. The option to integrate sophisticated external simulation models (i.e. for phenomena and sensor behaviour) which constitutes a main feature of Sensor World is usually not extensively supported by the existing simulations as well as an easy integration of higher level application frameworks like the OGC Sensor Web Enablement architecture.

With Sensor World we aim at providing an efficient tool that allows evaluating general algorithmic solutions for sensor network optimization and coordination. This means that Sensor World avoids the need of having to deal with sensor specific problems and implementation issues related to concrete sensor platforms. Furthermore Sensor World provides means for focusing on special aspects of sensor strategies while avoiding the simulation of other factors that may not be relevant for a certain task. For example it might be desirable to assume a completely connected sensor network when evaluating strategies for sensor coverage so that the developer can focus only on coverage optimisation without caring about the message transport between sensors. However it has to be mentioned that in a later stage more complex simulations are needed, which are also supported by Sensor World. The open interfaces of Sensor World allow every user to implement and integrate such specific simulation components. Thus, the Sensor World architecture facilitates the integration of additional simulation models. Especially the integration of complex phenomenon simulations allows a realistic evaluation of sensor network strategies that are influenced by phenomenon-related factors (e.g. strategies that adapt the sensor constellation to the phenomenon distribution).

Finally Sensor World is characterized by an extensive support of mobile sensors. Especially the sensor behaviour model presented later in this paper provides a solid foundation for evaluating strategies for mobile sensor networks.

SENSOR WORLD APPROACH

In order to meet the challenges discussed in the introduction, Sensor World provides a nested simulation environment. Three additional models complement the simulation of the sensor network:

- Simulation of observed properties (the phenomena), which shall be detected by a sensor network. This part of the simulation environment supports the set-up of arbitrary scenarios and the optional usage of historical or even live real world data is supported.
- Simulation of the physical communication between sensors in order to determine the connectivity within the sensor network but also to simulate different communication protocols.
- Simulation of sensor behaviour (in-situ and remote sensors), which primarily addresses the movement of sensors, the execution of observations, and the communication (e.g. messages a sensor sends). Additional aspects like energy consumption will be integrated at a later stage.

During the design phase, emphasis was put on a distributed simulation architecture with loosely coupled components. This allows better scalability and maintainability compared to monolithic systems and provides support for very expensive simulation models. A second aspect was the additional support of physical sensors that are deployed in a real world environment. This allows calibration as well as determining the effects of additional sensors (with specific strategies) added to existing sensor networks. Thus Sensor World supports the optimisation of existing sensor networks. A third aspect is the exchangeability of simulation components. Sensor World provides well-defined interfaces that allow the usage of different simulation models, e.g. for phenomena or communication. Consequently Sensor World can be adapted to any use case by developing additional components.

A communication overlay-layer links the different simulation components. This layer provides interfaces for sending messages, but hides all details about message transport and delivery to allow sensor development independently of other sensors. Each sensor receives messages directed to it, but does not have to care for potential receivers.

Finally a logging component is required that allows measuring the performance of the simulated sensor strategies. This could be a visualization component that allows the visual assessment of strategies by users, or could be an automated benchmarking mechanism that measures certain predefined criteria (e.g. message rate, detection rate etc.).

SENSOR WORLD FRAMEWORK

Particular focus was put on the evaluation of sensor behaviour patterns, in particular regarding movement strategies. Sensor networks consisting of mobile sensors are capable to adapt their constellation. The adaptation is a continuous process that follows the internal strategy of the sensors and optionally also the nature and behaviour of the observed phenomenon. Dynamic adaptation is the basis for a more efficient use of sensors, as the total number of sensors that is necessary to achieve a certain monitoring quality is usually lower in a mobile sensor network than in a stationary one (Lie et al., 2005). The evaluation of such movement strategies is one of the main advantages of Sensor World.

Testing a sensor strategy in realistic conditions is a complex task. Usually, it would be necessary to implement it on a concrete sensor platform and to deploy the sensor network in a real world environment. This approach is necessary in order to test the sensor in connection with real world phenomena under realistic conditions. As a result the testing of sensor network strategies is a very cumbersome task.

Sensor World supports realistic conditions though three different subsystems. All three of them make use of a common core in order to support interoperability among the components.

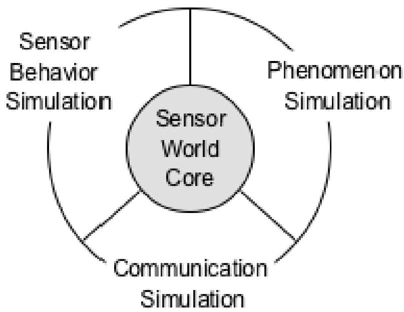

Figure 1: Sensor World subsystems.

The phenomenon simulation can be used for reproducing a phenomenon similar to the one the sensor network will be working on. As sensor behaviour is usually designed for a specific type or class of phenomenon, a solid classification system becomes necessary and will be subject of future work. The communication simulation approach supports simulations of any complexity. If required, it takes additional factors into account, e.g. radio shadows calculated on the basis of terrain models that hinder communication.

The modular design of Sensor World supports encapsulation of a range of different sensor behaviour aspects (i.e. mobility, communication, computation) and is a solid base for developing sensor strategies. Sensor World provides the foundation for creating building blocks (basic strategy elements) that can be used for easily assembling more complex sensor behaviours. The used aggregation pattern fosters re-use of simple or atomic strategies.

GLOBAL ARCHITECTURE

The global architecture of the simulation framework comprises four components: sensors, phenomena, communication, and control layer.

The sensor simulation component is formed by a number of sensor processes. These processes, which are independent from each other, simulate the behaviour of sensors. For each sensor it is possible to simulate its movement, communication and measurement patterns.

In order to allow the simulated sensors to execute measurements it is necessary to simulate at least one phenomenon on which the measurements can be performed. The phenomenon simulation component provides a method that returns the phenomenon value (e.g. the temperature) at a certain position.

The communication simulation is intended to provide a model which allows determining the connectivity between the sensors of the network. The basic function of this model is to check if one sensor is within the communication range of another sensor. Based on this elementary operation it is possible to calculate the connectivity in multi-hop networks.

Whereas the simulation components are used for simulating the sensor behaviour, phenomena and communication processes, the control layer ensures that the different simulation components interact properly. As all individual simulation components act autonomously they do not possess knowledge about how to access other components within the simulation framework. For example a sensor that wants to perform a measurement on a virtual phenomenon does not have knowledge where to access the phenomenon simulation which might run on a different computer that is connected to the simulation framework. A control layer solves such coordination and communication and handles the interaction between the different simulation components. In Sensor World this functionality is provided by a so-called control layer which connects all simulation components. This layer provides the mechanisms for message exchange and thus controls the interactions between all simulation components within the framework.

SIMULATION COMPONENTS

Sensor Simulation

The sensor simulation component usually consists of a number of separate sensor simulation processes. Each of these processes emulates the behaviour of a single sensor. The behaviour includes movement of the sensor, the way measurements are executed and the communication (e.g. definition which messages are sent in which situations).

A run-method is executed continuously throughout the sensor's lifetime. This run method describes a loop in which the different aspects of the sensor behaviour are controlled. Relevant tasks that are executed in this context are: sensor movement, execution of measurement, processing of messages that are sent to a sensor.

The sensor mobility model described in this paragraph is intended to provide an efficient way for developing new and for enhancing existing strategies for sensor movements. This strategy model can also be used for defining other aspects of sensor behaviour (e.g. communication behaviour). However these topics are not treated in more detail in this paper as the solutions for these aspects are relatively similar to the sensor mobility model.

The basic element is a movement strategy. Such a movement strategy offers an operation which determines the new position of a mobile sensor taking into account a set of predefined parameters and influencing factors, e.g. incoming messages, measurement results, and the positions of other sensors that can influence the sensor movement. There are two subclasses of movement strategies:

A basic movement strategy describes rather simple sensor movement schemes (e.g. maximizing the distance to neighbouring sensors). These basic strategies also constitute the elementary building blocks for the development of more complex strategies.

A complex movement strategy is composed of a number of other movement strategies (basic and/or complex strategies). In a complex movement strategy it is defined which of the composing strategies is executed in which situation. This can be compared to a state machine: depending on the state the proper strategy is chosen.

The basic concept of a modular strategy design is based on the “Strategy” and “Composite” design patterns (Gamma, 1995).

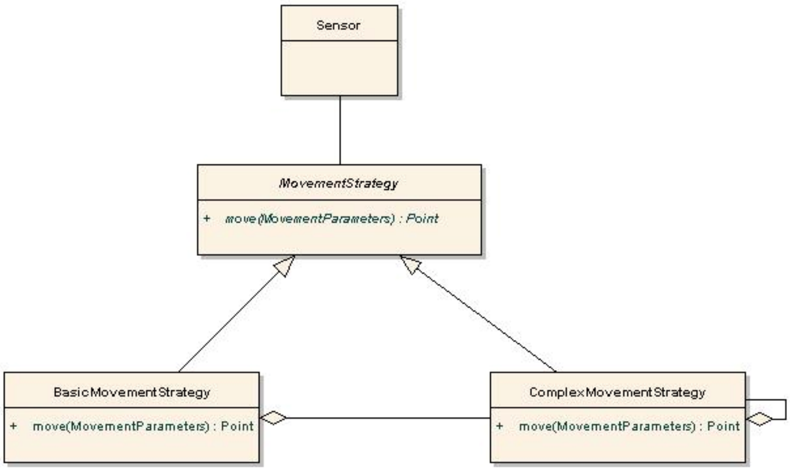

Figure 2: Diagram showing the sensor world movement strategy model.

This modular design allows rapid development of new strategies. The encapsulation of strategies makes it possible to build new sensors by just selecting the appropriate strategy modules. If the needed strategy implementations are already available, it is just necessary to select a combination of strategies for sensor movement and communication for creating a new sensor type.

Phenomenon Simulation

The phenomenon simulation has the task to simulate the phenomena observed by the sensor network. As the sensors of the simulation environment are usually just virtual objects it is necessary to provide a simulated phenomenon on which virtual measurements can be performed.

The phenomenon simulation can be implemented in several ways. It is possible to use simulation algorithms for generating virtual phenomena. For example a user defines the chemical substance and the amount that is released, as well as weather conditions, and a propagation model simulates the dispersion of the phenomenon.

Another option is to evaluate the performance of a sensor network in real world scenarios. Here, historical data are used to provide the virtual measurements. The integration of this type of data allows the evaluation of sensor networks on a realistic basis and especially the comparison of new sensor technologies with those that are currently in use.

Communication Simulation

A common problem in sensor networks arises if the individual sensors are not connected by wire. The communication link needs to be simulated in order to determine the connectivity within the sensor network. The communication simulation interface supports two important aspects:

- Input: the communication simulation needs information about the structure of the sensor network (e.g. sensor positions). The necessary data is delivered to the simulation using the input methods.
- Connectivity: these methods allow determining which sensors are connected so that they are able to exchange messages; this includes especially operations for checking if two given sensors are connected and for retrieving all sensors that are connected to a given one.

Control Layer

The control layer connects all previously described components. It provides functionality to determine which message has to be received by which components and it is capable of executing the delivery. The mapping of a message type and in some cases also the IDs of specified receivers is based on a dictionary system. The message transport relies on a control layer based on the Java Message Service (JMS) technology.

IMPLEMENTATION AND EVALUATION

The architecture presented in the previous section is implemented in JAVA. Emphasize was put on the concurrency aspect of the simulation components (sensors, phenomenon simulation and control layer) in order to avoid time synchronization problems and to ensure a timely message delivery. Additionally the implementation allows dynamic addition and removal of simulation components like sensors or phenomena.

A visualization component was developed for testing purposes. The output of this visualization component consists of video files that show the history of sensor positions and the phenomenon during the course of a simulation run. This component can also be used for determining other performance measures like the number of messages that are exchanged within the sensor network. A screenshot from the video is shown in Figure 3.

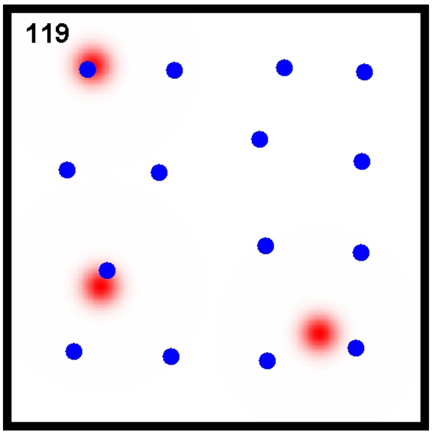

Figure 3: Example of the visualization output (sensors shown as dark spots).

Finally an enhancement that allows the integration of the simulation framework into the standardized OGC Sensor Web Enablement (SWE) framework has been developed. This allows not only testing strategies of sensors and sensor networks but also their interaction with higher level application layers.

The Sensor World architecture as it is described within this paper was evaluated within the OSIRIS project. Components delivered by several project partners were successfully integrated into the system and used for executing simulation runs. These components comprised sensor behaviour simulators as well as phenomenon and communication models.

Furthermore the performance of the system has been tested within the OSIRIS project. Simulation runs comprising up to hundreds of sensors were successfully performed. However, a formal comparison of the performance of other sensor network simulators has not been conducted. As Sensor World follows a different approach, which aims rather at a realistic simulation of any kind of external influences and stimuli than at optimizing primarily the number of simulated sensors, conventional performance measured would have a limited significance. We are therefore still in the process of defining the performance criteria and evaluation matrix. First test runs have already been conducted and the results of how different movement strategies influence discovery and tracing of phenomena will be published in a separate paper later this year.

OUTLOOK

Several ideas exist for enhancing the current version of the simulation environment.

- Time synchronization: Currently the time synchronization relies on timestamps that are added to all messages, which are exchanged within the system. These timestamps contain the local system time of the sending system. In the future a system wide coordinated simulation time would be desirable.
- Additional simulation models: At the moment several basic models for simulating phenomena and connectivity are available. For more complex simulation runs it will be useful to integrate further models (especially for the simulation of connectivity based on terrain information).
- Evaluation of strategies: In a future version a component for an automatic benchmarking of sensor strategies based on user defined criteria shall be added.

- Additional layer that allows running multiple sensor simulations within one process: At the moment every sensor simulation runs as a single process.
- Graphical user interface: For allowing an interactive use of the simulation environment a graphical user interface is needed.

For the simulation of sensors the development of energy models is a very useful enhancement. By simulating the energy consumption and supply it becomes possible to determine the lifetime of sensors more realistically. Furthermore the analysis of sensor network strategies with regard to their energy efficiency can be improved. The integration of such models is supported by the sensor simulation architecture so that it is mainly necessary to develop sophisticated models.

CONCLUSIONS

In this paper, we have presented a flexible distributed framework for evaluating sensor strategies. The Sensor World architecture supports the realistic simulation of sensor behaviour by providing interfaces for the integration of phenomenon and communication models. This allows a realistic evaluation of sensor strategies without having to implement them on concrete sensor platforms. Sensor World provides a sound basis for developing very sophisticated simulation scenarios not only by integrating complex models, but also by integrating real sensors and by the implementation of bridges to application layer components like the OGC Sensor Web Enablement services.

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