Executive Summary of the Dagstuhl Seminar "Form and Content in Sensor Networks"

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Abstract

Form the September 18th until September 23rd, 2005 a Dagstuhl Seminar took place with the topic "Form and Content in Sensor Networks". 26 participants from four different countries, which are experts in sensor networks from the topics information processing, communication and robotics, presented current state of the art in the field of algorithm for sensor networks and how content and structure impact information processing in the networks. The presentations ranged from very theoretical computational models and algorithms to prototype implementations for monitoring the environment.

1. Goals and Structure of the Seminar

Advances in computing hardware and wireless networking technologies have enabled low-cost, low-power miniature sensor devices. By combing these tiny sensor nodes, which comprise sensing, data processing, and communication components, a sensor network for distributed sensing is obtained. For example, thousands of these nodes could be spread across a large geographical area in order to perform weather monitoring. Since every node suffers from limited sensing, computing, networking, and energy resources, collaboration between nodes is required, which stimulated the development of new types of communication and information processing algorithms.

Sensor networks have received increasing attention over the last few years. For example, DARPA's SensIT program envisioned the development of dense fields of simple, inexpensive, micro-sensor-processors to exhibit emergent behaviour which should be collectively brilliant, operationally effective, long-lived, and robust to failure. David Culler's work on sensor networks explores the rich design space of low-power processors, communication devices, and sensors. NSF recently funded an STC Center for Embedded Network Systems headed by Deborah Estrin that will develop algorithms for distributed wireless sensing systems.

Some examples of issues addressed by these various projects include self-configuration, data handling, systems issues, power minimization, and fault tolerance. In general, higher-level exploitation of sensor networks requires the application of distributed algorithms to the data. Corresponding applications include distributed source localization, calibration, and habitat monitoring. Other areas addressed include: algorithms for sensor tasking and control, including distributed techniques for the formation of sensor collaboration groups, tracking large-area phenomena, information storage and in-network aggregation, identity management, and relational tracking and reasoning, as well as the application of optimal estimation techniques to multisensor data analysis, nonlinear filtering, position estimation and tracking, and the application to mobile robotics, cellular mobile phones, and virtual reality, and finally, the creation of an information layer on top of the sensor nodes, including distributed algorithms for leadership protocols, coordinate frame, and gradient calculation, reaction-diffusion pattern formation and level set methods to compute shortest paths through the net.

The aim of this seminar is to summarize the current state of the art in the field of algorithms for sensor networks and how content and structure impact information processing in the network, and to identify open problems in the following areas:

- Low-level Processing (e.g., distributed signal processing, compression, estimation, detection, error handling)
- High-Level Processing (e.g., network structure, dynamic self-organization, tracking, monitoring, system behavior evaluation).

The seminar brings together workers from these areas to establish a stronger dialog with the goal of achieving a coherent view of the communication and information processing aspects which are typically treated separately today.

2. Participants

The following researchers participated in the seminar:

- Natalie Bender, Universität Karlsruhe (TH), Germany, (*Design of an Artificial Swarm: The I-SWARM Project.*)
- Frederik Beutler, Universität Karlsruhe (TH), Germany
- Bir Bhanu, University of California, USA, (*Sensor Fusion for Diurnal Scene Understanding*)
- Uwe Brinkschulte, Universität Karlsruhe (TH), Germany, (*Organic Middleware for Self-Organizing Sensor Networks*)
- Dietrich Brunn, Universität Karlsruhe (TH), Germany, (*Model-Based Placement and Scheduling in Stochastic Sensor Networks*)
- Peter Corke, CSIRO, Australia, (*Sensor networks for environmental and pastoral monitoring Part I*)
- Sándor Fekete, TU Braunschweig, Germany, (*Deterministic boundary recognition and topology extraction for large sensor networks*)
- Stefan Funke, Stanford University, USA, (*How much Geometry hides in Connectivity?*)
- Edward Grant, North Carolina State University, USA, (*From an Acoustic Array on a Textile Substrate to Wearable Sensor Systems*)
- Frans Groen, University of Amsterdam, Netherlands, (Distributed Perception Networks)
- Leonidas Guibas, Stanford University, USA, (*Routing and Information Discovery in Sensor Networks*)
- Uwe D. Hanebeck, Universität Karlsruhe (TH), Germany, (*Sensor-Actuator-Networks - Research at Karlsruhe*)
- Thomas C. Henderson, University of Utah, USA, (Verification and Validation of Sensor Networks)
- John E. Hershberger, Mentor Graphics Corp., USA, (*Geometric Summaries for Sensor Nets*)
- Seth Hutchinson, University of Illinois, USA, (*Permutation-Invariant Multi-Agent Formations*)
- Wolfgang Karl, Universität Karlsruhe (TH), Germany, (*Towards Dynamically Adaptable Processor Architectures*)
- Alexei Makarenko, University of Sydney, Australia, (*Probabilistic Methods in Robotic Sensor Networks*)
- Pedro José Marrón, Universität Stuttgart, Germany, (*Generic Model and Architecture for Cooperating Objects in Sensor Network Environments*)
- Gregor Pavlin, University of Amsterdam, Netherlands, (*Robustness and Accuracy of Bayesian Information Fusion Systems*)
- Nageswara Rao, Oak Ridge National Lab., USA, (*A Training Method for Source Isolation of Simple Product-Form Plumes by Sensor Networks*)
- Daniela Rus, MIT, USA, (*Sensor networks for environmental and pastoral monitoring Part II*)
- Peter Sanders, Universität Karlsruhe (TH), Germany, (*Energy efficient routing in sensor networks*)
- Sergio Servetto, Cornell University, USA, (*On the Structure of Data Sets Observed by Physically Embedded Networks*)
- Subhash Suri, University of California, USA, (*Detecting Cuts in Sensor Networks*)
- Peter Wieland, Universität Stuttgart, Germany
- Christian von der Weth, Universität Karlsruhe (TH), Germany, (*Querying Stochastic Model-Based Sensor Networks*)

3. Seminar Schedule

The five days were filled with discussions and 24 formal presentations. Time was also allocated to group discussions to attempt to characterize the most pressing, issues (e.g., platforms, systems, algorithms, best practices, etc.). The seminar was organized around the following schedule:

Monday (Chair: Tom Henderson)

9:00	**-**	**9:30**	Introduction	**Uwe D. Hanebeck**
9:30	**-**	**10:15**	*Verification and Validation of Sensor Networks*	**Thomas C. Henderson**
10:30	**-**	**11:00**	*Distributed Perception Networks*	**Frans Groen**
11:15	**-**	**12:00**	*Geometric Summaries for Sensor Nets*	**John E. Hershberger**
12:15	**-**	**13:15**	Lunch	
14:45	**-**	**15:15**	*Detecting Cuts in Sensor Networks*	**Subhash Suri**
15:30	**-**	**16:00**	Cake & Coffee Break	
16:30	**-**	**17:00**	*How much Geometry hides in Connectivity?*	**Stefan Funke**
18:00	**-**	**19:00**	Dinner	
20:00	**-**		Discussion	

Tuesday (Chair: Uwe Hanebeck)

9:00	**-**	**9:45**	*Sensor-Actuator-Networks - Research at Karlsruhe*	**Uwe D. Hanebeck**
9:45	**-**	**10:15**	*Model-Based Placement and Scheduling in Stochastic Sensor Networks*	**Dietrich Brunn**
10:30	**-**	**11:00**	*Querying Stochastic Model-Based Sensor Networks*	**Stefan von der Weth**
11:15	**-**	**12:00**	*Organic Middleware for Self-Organizing Sensor Networks*	**Uwe Brinkschulte**
12:15	**-**	**13:15**	Lunch	
14:45	**-**	**15:30**	*Generic Model and Architecture for Cooperating Objects in Sensor Network Environments*	**Pedro José Marrón**
15:30	**-**	**16:00**	Cake & Coffee Break	
16:30	**-**	**17:00**	*On the Structure of Data Sets Observed by Physically Embedded Networks*	**Sergio Servetto**
17:15	**-**	**17:45**	*Probabilistic Methods in Robotic Sensor Networks*	**Alexei Makarenko**
18:00	**-**	**19:00**	Dinner	
20:00	**-**		Discussion	

Wednesday (Chair: Leo Guibas)

9:00	**-**	**9:45**	*Routing and Information Discovery in Sensor Networks*	**Leonidas Guibas**
9:45	**-**	**10:15**	*Energy efficient routing in sensor networks*	**Peter Sanders**
10:30	**-**	**11:15**	*Deterministic boundary recognition and topology extraction for large sensor networks*	**Sándor Fekete**
11:30	**-**	**12:00**	*Design of an Artificial Swarm: The I-SWARM Project.*	**Natalie Bender**
12:15	**-**	**13:15**	Lunch	
13:15	**-**		Excursion to Trier	

Thursday (Chair: Uwe Hanebeck)

9:00	**-**	**9:30**	*Sensor networks for environmental and pastoral monitoring Part I*	**Peter Corke**
9:45	**-**	**10:15**	*Sensor networks for environmental and pastoral monitoring Part II*	**Daniela Rus**
10:30	**-**	**11:00**	*Sensor Fusion for Diurnal Scene Understanding*	**Bir Bhanu**
11:15	**-**	**12:00**	*From an Acoustic Array on a Textile Substrate to Wearable Sensor Systems*	**Edward Grant**
12:15	**-**	**13:15**	Lunch	
13:45	**-**	**14:30**	*A Training Method for Source Isolation of Simple Product-Form Plumes by Sensor Networks*	**Nageswara Rao**
14:45	**-**	**15:15**	*Robustness and Accuracy of Bayesian Information Fusion Systems*	**Gregor Pavlin**
15:30	**-**	**16:00**	Cake & Coffee Break	
16:15	**-**	**17:45**	Plenary Discussion	
18:00	**-**	**19:00**	Dinner	
20:00	**-**		Discussion	

Friday (Chair: Uwe Hanebeck)

9:00	**-**	**9:45**	*Towards Dynamically Adaptable Processor Architectures*	**Wolfgang Karl**
10:00	**-**	**10:30**	*Permutation-Invariant Multi-Agent Formations*	**Seth Hutchison**
10:45	**-**	**12:00**	Final Plenary	
12:15	**-**	**13:15**	Lunch & Departure	

4. Conclusions

The participants separated into groups which provided analysis of high-level issues like: conceptual challenges in the field, best practices, open problems and application challenges. We summarize those here.

The number of degrees of freedom in sensor networks is great: platforms, sensors, objects, environment, context, etc. Existing tools which allow exploration of this space include Matlab, simulation systems, Tiny OS (which handles communication, security, tasking, etc.) other sensor node vendors are entering the arena as well.

A major problem is that today's sensor networks are getting increasingly complex and therefore are hard to develop and operate. Issues involved include:

- Communication and networking
  - Partitioning, robust and reliable communication
  - Rapidly deployable reliable networks
- Scalability of deployments and methods
- Distributed algorithms
- Intelligent hierarchical clustering for performance
- Information/data integration and fusion
- Security (encryption, authentication, etc.)
- Privacy protection
- Context interpretation
- Optimal utilization of heterogeneous and complementary sensor functionalities
- Mobility (optimally assist in tasks)
- Algorithms for sensor networks
- Self-organizing, optimizing, calibrating methods

Some possible new approaches to answer these challenges include:

- Organic computing paradigm: build complex computing systems to be more life-like with self-organization, configuration, optimization, healing, protecting, explaining and aware.
- Computational computing paradigm: provide a strong mathematical model of the phenomenon being sensed, and exploit that to explore the structure of the sensor network as well as the phenomenon.
- Benchmarks for testing, performance analysis and calibration
- General Programming Interface and simple interface to physical world
- Hierarchy of services and algorithm design

Some sample application challenges include:

- Space exploration
- Healthcare
- Security monitoring
- Weather prediction
- Traffic monitoring and vehicle interaction
- Disaster and rescue

Finally, social challenges were raised concerning the appropriate use of sensor networks: privacy protection, context interpretation and the need to avoid: *Small Brother is Watching!*