4-14-2011

CAREER: Data Management for Ad-Hoc Geosensor Networks

Silvia Nittel
Principal Investigator; University of Maine, Orono, nittel@spatial.maine.edu

Final Report for Period: 12/2009 - 11/2010
Submitted on: 04/14/2011
Principal Investigator: Nittel, Silvia .
Award ID: 0448183
Organization: University of Maine
Submitted By:
Nittel, Silvia - Principal Investigator
Title:
CAREER: Data Management for Ad-Hoc Geosensor Networks

Project Participants

Senior Personnel

Name: Nittel, Silvia
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Liang, Qinghan
Worked for more than 160 Hours: Yes
Contribution to Project:
Qinghan Liang is working on the topic of spatio-temporal data streams, especially the data stream model support of sensor data streams capturing continuous phenomena. He will defend his thesis proposal in June 2011.

Name: Nural, Arda
Worked for more than 160 Hours: Yes
Contribution to Project:
Arda Nural has started as a Ph.D. student at the University of Maine in Fall 2003. His research topic is in the area of mobile geosensor networks and data streams management systems. In particular, he focuses on the detection of emerging flock patterns in crowds of moving objects and the tracking of topological behavior such as splitting and merging of flocks, and the identification of leader patterns. He defended successfully defended his thesis proposal in April 2009.

Name: Jin, Guang
Worked for more than 160 Hours: Yes
Contribution to Project:
Guang Jin was a Ph.D. student and graduated successfully in April 2009. His research area was in the realm of quantitative and qualitative detection of events in geosensor networks.

Name: Xiao, Danqing
Worked for more than 160 Hours: Yes
Contribution to Project:
The female student is currently funded by the correlated NSF project 'Monitoring dynamic spatial fields using responsive geosensor networks', PI M. Worboys, Co-PI S. Nittel. She successfully defended her MS thesis in April 2010, and her topic was detection of non-topological changes in geosensor networks.

Name: King, Kraig
Worked for more than 160 Hours: Yes
Contribution to Project:
Kraig King is IGERT Program Ph.D. student, and started in Fall 2008. His Ph.D. is in the area of tiny model based data collection of wireless sensor networks. He will defend his thesis proposal in June 2011.

Name: Dorr, Christopher
Worked for more than 160 Hours: Yes

Contribution to Project:

Christopher Dorr is a MS student, and works on the research topic of decentralized adhoc collaboration in emergency situations using wireless sensor network communication strategies. He is planning to defend in May 2011.

Name: Hennessey, Michael

Worked for more than 160 Hours: Yes

Contribution to Project:

Mike Hennessey worked as a system programmer for a real-time sensor database systems for the Maine Emergency Management Agency on one of my projects that was funded through the Maine National Guard in 2008-2010. Mike graduate with a MS in May 2010.

Name: Whittier, John

Worked for more than 160 Hours: Yes

Contribution to Project:

JC Whittier is a former undergraduate student from our Department, and started his Ph.D. training in Fall 2010 supported via NSF IGERT program in Sensor Science and Informatics at the University of Maine. His current research interest is in the area of participatory sensing using geosensor networks.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

University of Melbourne

@University of Melbourne: I have collaborated with Dr. Matt Duckham, Geomatics, with regard to organizing a MDM workshop, 'Privacy-Aware Location-Based Mobile Services' (PALMS) (Mannheim, May 2007) and the organization of the 4th Geosensor Network Conference in Melbourne, Australia in 2011.

Oxford University

@Oxford University, University of London: I collaborate with Prof. Niki Trigoni in regard to mobile adhoc sensor networks for ocean environments, we published several papers on this topic. In 2008, during my sabbatical at the University of Oxford, we extended our collaboration to bio-inspired self organization methods for sensor networks. Dr. Trigoni organized the 3rd Conference on Geosensor Networks in 2009.

University of Pittsburgh, PA

@University of Pittsburgh: I have been collaborating with Dr. Alex Labrinidis, Computer Science, with regard to the organization of the 2nd Geosensor Networks conference in October 2006, and the publication of the follow-up book 'Advances in Geosensor Networks', published by Springer.

University of Maine

@UMAINE: I have collaborated with faculty at my department, Drs. Kate Beard and Mike Worboys on 2 other NSF grants.

Dr. Beard is the PI of the NSF-funded IGERT Sensor Science, Engineering and Informatics. I am teaching for the IGERT program and I serve on its Executive Committee. Dr. Worboys and I collaborated on another NSF grant.

Furthermore, I collaborated with Dr. Neal Pettigrew, School of Marine Science (Physical Oceanography) with regard to mobile, ad-hoc geosensor networks in a coastal observation setting.

I also collaborated with Drs. Clayton Wheeler and Mauricio Pereira da Cunha on a project designing, developing and producing a microsensor devices using a microhotplate and a SAW device for the detection of small quantities of HF gases.

Other Collaborators or Contacts

Global Relief Technology, Portsmouth, NH

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Findings: (See PDF version submitted by PI at the end of the report)

Training and Development:

During the course of the project, a primary focus has been placed on academic research advances. Three Ph.D. students have been working within the scope of the project.
Students on this project:
? Guang Jin graduated with a Ph.D. in April 2009.
? Arda Nural advanced to Ph.D. candidacy in April 2009.
? Qinghan Liang: Thesis proposal defense planned for April 2011.

These Ph.D. students have been part of the Geosensor Networks Laboratory at the University of Maine, which during the project period has also included the IGERT students Kraig King and JC Whittier, Michael Hennessey (MS), Christopher Dorr (MS), and a female MS student, Danqing Xiao. Both Michael Hennessey and Danqing Xiao graduated in Spring 2010. Additionally, a postdoctoral researcher, Dr. Y.J. Jung was a member of the lab from 2007-2009.

Advising my Ph.D. students, I select topics that overlap. Each student is responsible for an assigned aspect of this area, but I conduct regular group meetings in which the students present related work of their research topic or their own work in progress. Hereby, I train them in presenting and communicating their ideas, gaining confidence and language abilities in case of international students, and foster a 'safe' environment to deal with questions and critique. Additionally, I meet with students individually to discuss their current research ideas and train them in writing research papers weekly. I mostly opted to list them as first authors in work in which they were involved, even though this typically represents my own research initiatives. For the same reasons, I provide funds for my students to travel nationally or internationally in order to attend major conferences and present their work.

Several of my advisees have received international and University awards for their scholastic and research achievements.

? Guang Jin received the Most Innovative Paper Award at the Atlantic Institute held at Laval University in May 2005.
? Arda Nural received a University of Maine Fogler Library Assistantship for 2005/2006.
? Guang Jin received a UGRA Fellowship, a highly competitive fully-paid fellowship for 2007/2008 at the University of Maine. Per year, only 10 of those fellowships are awards to the entire University of Maine.
? Kraig King won first prize in the University of Maine Graduate Research Review poster competition in 2010.

Furthermore, I am co-advising several doctoral students from our department (Chris Farah, Jixiang Jiang, Cheng Zhong) and the Electrical Engineering Department (Robert Strauss, Negar Hariri, Bennett Meulendyk).

When the SIE Department still had an undergraduate program, I was primarily engaged in teaching the DBMS class and an information system architecture class as well as the annual Capstone class. The undergraduate program ended in spring 2010.

Currently, I am also an instructor and a member of the executive committee of the UMaine NSF IGERT 'Sensor Science, Engineering and Informatics'. In the program, I teach the sections on introduction to sensor networks, and data management for sensor networks, as well as conducted the labs to program Intel/Berkeley motes for the initial years of the program (we now have a senior IGERT student mentoring program in place).

In my IGERT Sensor System Testbed class in 2006, Dr. Rosemary Smith (ECE) and I posed a sensor network implementation task to multidisciplinary Ph.D. students with various backgrounds and enrolled in different Ph.D. programs. The assignment for the group is to work as a team, and to design and implement a functional sensor network prototype that contains a novel research component so that it can be published in a sensor network conference. Dr. Smith and I served as advisors to the students in their process from design to implementation. The results of the year's class demonstrate that this approach serves as an excellent team building experience as well as hands-on training for the students to gain confidence in a technology that is central to their interdisciplinary research training via the IGERT program, and their future careers.

Outreach Activities:

There were several research outreach activities that were funded via the Early CAREER project. Foremost, I collaborated with Drs. C. Wheeler (Chemical Engineering) and Pereira da Cunha (Electrical Engineering), University of Maine in 2005-2008 to gain more expertise in the area of microsensor devices. We collaborated on a project in which microsensors were designed and fabricated that were a combination of a microhotplate and SAW device for the detection of small quantities of HF gases. This is a typical sensor device ultimately used to detect toxic concentrations of HF gases in geographic spaces. Drs. Wheeler and Pereira da Cunha focused on production and tuning of the sensor device, I focused on the aspect of sensor data analysis. The ultimate objective was to look into opportunities to combine microsensor within a sensor network deployment for the detection of continuous gas phenomena.

Another outreach activity consisted in hands-on support of the NSF IGERT cohorts during their testbed activities, especially in spring 2007 and 2008. The 2008 testbed consisted of the programming and deployment of a growing light-sensing sensor network based on Intel motes within a commercial tomato greenhouse, managed by Backyard Farms, Madison, ME. The 24 hectar-sized tomato greenhouse is a first of its kind in the US; the objective is to grow tomatoes locally during the winter months using a combination of daylight and growing lights during the night. The students developed a sensor network to measure the light profile along a row of tomato plants over a 2 week period; furthermore, the light profile along the vertical axis of plants was measured. During the students' weekly visits to the greenhouse, I supported the group with hands on help of mote deployment, battery replacement and rearrangement of the sensor network.

During the project period, I was started several international collaborations with regard to geosensor networks:
-- In 2005-2006, I collaborated with Dr. Winter, Geomatics, University of Melbourne, Australia with regard to applying geosensor networks to intelligent transportations systems.

-- In 2006-2009, collaboration with Dr. Trigoni, Oxford University. We collaborated both with regard to application of mobile geosensor networks to ocean sensor networks and later self organization strategies in geosensor networks.

-- In 2008, I visited Chungbuk University in South Korea, to give several invited talks and start collaborating with faculty in the area of geosensor networks.

-- Between 2005-present, I have collaborated with Dr. Matt Duckham, University of Melbourne, on different topics of geosensor networks.
In 2010, I started collaborating Dr Femke Reitsma, Geography Department, Canterbury University, New Zealand with regard to dynamic continuous phenomena.

During the project period two outreach project involved technology transfer of the research to several companies and a state agency. In collaboration with Milcord and Streambase, I worked on developing prototypes for sensor data stream management.

In 2009-2010, I collaborate with Global Relief Technology, Portsmouth, NH on a project for the Maine Emergency Management Agency to enhance Emergency Response and Coordination with an integrated sensor database management, which uses an OGC-standard based sensor observation service ingest engine for the sensor database management, and harvest sensor data from the web. The sensor data is integrated and can be correlated and queried via SQL-queries and visualized using Google Maps.

Conference organization
=====================

One of the most influential outreach activity of this Early CAREER project is the start of a new conference series with regard to Geosensor Networks. The initial conference took place in October 2003, in Portland, ME. During the project period, I organized the 2nd Conference on 'Geosensor Networks'. The Geosensor Networks conference is today the only conference that brings together the communities of sensor networks, databases, spatial information science and environmental application areas. In this 2.5 day conference, we focus on advances in data management for sensor networks, sensor network applications in the oceanography domain, visual sensor networks, and mobile sensor networks. The 2nd conference was attended by 60 people with significant international attendance from South Africa, Australian, Japan and

Korea. We published a book with the results of the conference (Springer LNCS). I was a member of the 3rd and 4th conference, taking place in 2009 in Oxford and 2011 in Melbourne.

-- 2nd Conference on Geosensor Networks (GSN2.0), Boston, MA, October 2006 (General and Program Chair)
-- 3rd Conference on Geosensor Networks, Oxford, UK, July 2009 (Steering Committee)
-- 4th Conference on Geosensor Networks, Melbourne, Australia, July 2011 (Steering Committee).

In 2006, I also was the general and program chair of the 14th ACM Conference Advances in Geographic Information Systems (ACM-GIS), Arlington, VA, November 2006. This conference is one of the longest standing and the premier conference in the computer science field of spatial data and information systems. The conference had a competitive submission of 90 papers, and a program committee consisting of 40 researchers selected 33 papers for the 2-day conference. The conference was very well attended, and lead to interesting discussion and exchange of idea.

Furthermore, I organized a 1-day workshop on the novel topic of 'Mobile Ad-hoc Location-Aware Sensor Networks' in conjunction with the Conference on Mobile Data Management (MDM) in Nara, Japan 2006. The workshop focused on the mobility aspect of several or all nodes of a sensor network, and its implications on the data processing. Results were published at the MDM conference proceedings, and are available on the workshop website.

In 2007, I was a co-organizer of he 1st International Workshop on Privacy-Aware Location-Based Mobile Services (PALMS'07), in conjunction with Mobile Data Management, Mannheim, Germany, May 2007.

Editorial boards
=================
During the project period, I was invited to be the editor for the field 'Geosensor Networks' as part of the Encyclopedia of GIS, Ed: Shashi Shekhar, Springer Publisher (publishing date, 2007). This section contains for articles on the area of geosensor networks.

S. Nittel, 'Geosensor Networks', Encyclopedia of GIS, Shekhar, Shashi; Xiong, Hui (Eds.) 2008, XL, 1377 p. 723 illus. ISBN: 978-0-387-30858-6

I also authored the encyclopedia entry on 'Geosensor Networks' for the Encyclopedia of Geography, Ed: Barney Warf, and published as a SAGE Reference publication in 2010.

S. Nittel, 'Geosensor Networks', Encyclopedia of Geography, Ed: Barney Warf, Sage Publications, Inc, 2010, ISBN: 1-4129-5697-8.

In 2010, I contributed the entry on 'Geosensor Networks' for Springer 'Handbook of Geographic Information', which is edited by Wolfgang Kresse and published in 2011.

Invitations:
============
-- Spatial Information Science Seminar, Geomatics Department, University of Melbourne, March 16 2006.

-- In fall 2006, I was invited to the NSF Workshop 'Development of new research directions at the intersection of the Information/Intelligent Systems (IIS) and the Global Environment for Networking Innovations (GENI) Programs' of the National Science Foundation. My subgroup focused on 'Requirements of Sensor-rich Environments and Location-oriented Computing on the Next Generation of Networking Innovation'.

-- Invited NCGIA-Workshop on 'Ubiquitous Spatial Computing', Portland, ME, January 15 2007.

-- NSF-sponsored Workshop on 'Mobile Adhoc Sensor Networks', Pittsburgh, PA (Jan 15-17 2007).

-- Department of Computer Science, Chungji University, Cheongjy, Korea, June 2008.

-- Computing Lab, Cambridge University, Cambridge, UK, October 1 2008.

-- Computing Lab, Oxford University, Oxford, UK, October 3 2008.

-- Conference 'Sensing in a Changing World', November 20, 2008, Centre for Geo-Information, Wageningen, Netherlands

-- Workshop on Geospatial Information for Developing Countries: Science and Technology, December 16-18, 2009, IIT Bombay India

-- 2nd Workshop on Research Directions in Situational-Aware Self-managed Proactive Computing in Wireless Sensor Networks, in Conjunction with Mobile Data Management, May 2010, Kansas City, USA, May 22 2010

Keynotes, Invited Talks, and Presentations
==
S. Nittel: In-Network Spatial Query Estimation for Sensor Networks, Workshop on 'Databases and Sensor Networks', Denki University, Tokyo, June 2005 (keynote)
S. Nittel: When Database Systems Meet Sensor Networks (invited talk), IEEE Communication/Computer Societies Joint Chapter DTS, Fairchild Semiconductors, South Portland, ME, September 30 2005.
S. Nittel: Spatial Query Estimation in Sensor Networks (invited talk), Dagstuhl-Seminar, 'Spatial Data: mining, processing and communicating', Wadern, Germany, March 6-10 2006.
S. Nittel: Spatial Query Estimation in Sensor Networks (invited talk), Spatial Information Science Seminar, Geomatics Department, University of Melbourne, March 16 2006.
S. Nittel: Shared Ride Trips in Large Transportation Networks (paper presentation), Symposium on Societies and Cities in the Age of Instant Access, University of Utah, September 2006.
S. Nittel: Geosensor Networks: A Vision Perspective (invited talk), Invited Workshop on 'Ubiquitous Spatial Computing', Portland, ME, January 15 2007.
S. Nittel: A drift-tolerant model for data management in ocean sensor networks (paper presentation), MobiDE'07, in conjunction with SIGMOD, Bejing, China, 2007.
S. Nittel: Geosensor Networks: State of the Art and Looking Ahead (keynote), Muenster GI-Days, 2007, Muenster, Germany, Sept 11 2007.
S. Nittel: Geosensor Networks: State of the Art (invited talk), Chungji University, Cheongjy, Korea, June 2008.
S. Nittel, Geosensor Networks: State of the Art (invited talk) Computing Lab, Cambridge University, Cambridge, UK, October 1 2008.
S. Nittel: Geosensor Networks: State of the Art (invited talk), Computing Lab, Oxford University, Oxford, UK, October 3 2008.
S. Nittel: Geosensor Networks: New Challenges in Environmental Monitoring using Wireless Sensor Networks, at Sensing in a Changing World, (keynote), November 20, 2008, Centre for Geo-Information, Wageningen, Netherlands
S. Nittel: Advances in Geosensor Networks (invited talk), Workshop on Geospatial Information for Developing Countries: Science and Technology, December 16-18, 2009, IIT Bombay India

Program Committees
==================
PC, ACM 13th International Symposium of Advances in Geographic Information Systems (ACM-GIS), 2005.
PC, 5th International Workshop on Web and Wireless GIS (W2GIS), Lausanne, Switzerland, December 15-16 2005
PC, 2nd VLDB-Workshop 'Data Management for Sensor Networks' (DMSN), Trondheim, Norway, September 2005.
PC, International Workshop on Networked Sensing Systems (INSS), Chicago, USA, May 31-June 2 2006.
PC, 1st Workshop on Mobile Geospatial Augmented Reality (AR), May 29-30 2006, Banff, Alberta, Canada.
PC, 3rd VLDB-Workshop 'Data Management for Sensor Networks' (DMSN), Seoul, Korea, Sept 11, 2006.
PC, Workshop on Middleware for Sensor Networks, in conjunction with 7th ACM/IFIP/USENIX Middleware Conference, Melbourne, Australia, Nov 2006.
PC, Workshop 'Mining Spatial and Spatio-Temporal Data' (SSTDM), Hong Kong, December 18, 2006.
PC, 6th International Symposium on Web and Wireless Geographical Information Systems (W2GIS 2006), December 4 ~ 5, 2006, Hong Kong
PC, 23rd International Conference on Data Engineering (ICDE), Istanbul, Turkey, April 17-20, 2007.
PC, 19th International Conference Scientific and Statistical Database Systems (SSDBM), Banff, Alberta, Canada, July 2007
PC, Environmental Sensor Networks (ESNs) Workshop, in conjunction with 18th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Athens, Greece, September 7 2007.
PC, Workshop 'Data Management for Sensor Networks' (DMSN), in conjunction with VLDB, Vienna, Austria, September 2007.
PC, 33rd International Conference Very Large Data Bases (VLDB), Vienna, Austria, September 2007.
PC, 24th International Conference on Data Engineering (ICDE), Cancun, Mexico, April 7-11, 2008.
PC, 7th ACM International Workshop on Data Engineering for Mobile and Wireless Access (MobiDE), in conjunction with SIGMOD, Vancouver, Canada, June 2008.
PC, 20th International Conference on Scientific and Statistical Databases (SSDBM), Hong Kong, China, July (tentative), 2008.
PC, 5th International Workshop Data Management in Sensor Networks (DMSN), in conjunction with VLDB, Auckland, New Zealand, Aug 25 2008.
PC, Workshop 'Data Management for Sensor Networks' (DMSN), in conjunction with VLDB, Lyon, France, August 2008
PC, MDM-Workshop Indoor Spatial Awareness (MDM), May 18 2009, Taipei, Taiwan

PC, 10th International Conference Mobile Data Management (MDM), May 18-21 2009, Taipei, Taiwan
PC, 1st International Workshop on 'Data Warehousing and Knowledge Discovery from Sensors and Streams' (DKSS 2009), held in conjunction with the 5th International Conference on
PC, 16th International ACM Conference on Geographic Information Systems (ACM-GIS), Los Angeles, CA, Nov 5-7 2008.
Distributed Computing in Sensor Systems (DCOSS 2009), Marina del Rey, CA, June 8-10 2009.
PC, 35th International Conference on Very Large Data Bases (VLDB), August 24-28 2009, Lyon, France.
PC, 17th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems (ACM GIS) 2009, Nov, Seattle, WA.
PC, International Conference on Mobile Data Management (MDM 2010), May 23-26 2010, Kansas City, Missouri
PC, International Conference on Scientific and Statistical Database Management (SSDBM), June 30 ? July 2, Heidelberg, Germany.
PC, 1st International Workshop on GeoStreaming, in conjunction with ACM GIS, November 2-5 2010, San Jose, CA
PC, 18th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems (ACM GIS), November 2-5 2010, San Jose, CA

Other
=======
Panelist, 'Life in a Small Department', SIGMOD, Panel on Life after Graduation, Chicago, IL, 6/2006.
ACM-GIS Conference 2009, poster chair.

Journal Publications

Winter, S. and Nittel, S., "Ad-hoc shared-ride trip planning by mobile geosensor networks", International Journal of Geographic Information Science (IJGIS), p. 899-916, vol. 20(8), (2007). Published,

Guang Jin and Silvia Nittel, "UDC: A self-adaptive uneven clustering protocol for dynamic sensor network", International Journal of Sensor Network, p. 25-33, vol. 2(1/2), (2007). Published,

S. Nittel, G. Jin and Y. Shiraishi, "In-Network Spatial Query Estimation in Sensor Networks", IEICE Transactions (A), p. 1413, vol. J88-A, (2006). Published,

G. Jin and S. Nittel, "UDC: A self-adaptive uneven clustering protocol for dynamic sensor networks", International Conference on Mobile Ad-hoc and Sensor Networks (MSN), Wuhan, China, 2005, p. 897-906, vol. , (2005). Published,

G. Jin and S. Nittel, "NED: Efficient Event Detection in Sensor Network", Workshop Mobile Location-Aware Sensor Networks, in conjunction with MDM, Nara, Japan, p. 153, vol. , (2006). Published,

Jin, G. and Nittel, S., "Towards Spatial Window Queries Over Continuous Phenomena in Sensor Networks", IEEE Transactions on Parallel and Distributed Systems, p. 559-571, vol. 19(4), (2008). Published,

S. Nittel, N. Trigoni, K. Ferentinos, F. Neville, A. Nural, and N. Pettigrew, "A drift-tolerant model for data management in ocean sensor networks", Proceedings of MobiDE'07, in conjunction with SIGMOD, Bejing, China, 2007, p. , vol. , (2007). Published,

A. Nural, S. Nittel, N. Trigoni, and N. Pettigrew, "A model for motion pattern discovery in ocean drifter networks", Proceedings of Costal Environmental Sensing Networks Conference, Boston, MA, April 12-13 2007, p. 19, vol. , (2007). Published,

Y. J. Jung and S. Nittel, "Geosensor Data Abstraction for Environmental Monitoring Applications", Proc of International Conference on "Geographic Information Science" (GISCience 08), p. , vol. , (2008). Published,

Y.J. Jung, Y. K. Lee, D. G. Lee, K. H. Ryu, S. Nittel, "Air Pollution Monitoring System using Geosensor Networks", International Geoscience and Remote Sensing Symposium (IGARSS), Boston, MA, July 2008, p. , vol. , (2008). Published,

G. Jin and S. Nittel, "Tracking Deformable 2D Objects", Proceedings of ACM Conference ?Advances in Geographic Information Systems? (ACM-GIS?0), p. , vol. , (2008). Published, Farah, C. Zhong, M. Worboys and S. Nittel, "Detecting Topological Change using Wireless Sensor Networks", Proceedings of the International Conference ?Geographic Information Science? (GIScience?08), Springer LNCS, p. , vol. , (2008). Published,

Silvia Nittel, "A Survey of Geosensor Networks: Advanced in Dynamic Environmental Monitoring", Sensors, p. 5664, vol. 9(7), (2009). Published, 10.3390/s90705664

J. Jiang, M. Worboys and S. Nittel, "Qualitative Change Detection in Sensor Networks based on Connectivity Information", Geoinformatica, p. , vol. , (2009). Accepted, 10.1007/s10707-009-0097-0

Jin, G. and Nittel, S., "Efficient tracking of 2D objects with spatio-temporal properties in wireless sensor networks", Journal of Parallel and Distributed Databases, p. , vol. , (2010). Accepted,

Nittel, S., Winter, S., Nural, A., and Cao, T., "Shared Ride Trip Planning using Geosensor Networks", Societies and Cities in the Age of Instant Access, Springer, p. , vol. , (2006). Published, ISBN-10: 1402054262

Trigoni, N., Ferentinos, K., Pettigrew, N., and Nittel, S., "Impact of drifter deployment on the quality of ocean sensing", Advances in Geosensor Networks, Springer LNCS 4540, p. , vol. , (2008). Published,

Duckham, M., Nittel, S. and Worboys, M., "Monitoring dynamic spatial fields using responsive geosensor networks", Proceedings of International ACM Symposium on ???Geographic Information Systems??? (ACM-GIS), p. , vol. , (2005). Published,

Books or Other One-time Publications

S. Nittel and R. de By, "Proceedings of International ACM Symposium on Geographic Information Systems? (ACM-GIS?06)", (2006). Book, Published
Editor(s): S. Nittel and R. de By
Collection: roceedings of International ACM Symposium on ?Geographic Information Systems
Bibliography: Sheridan Publishers, Netherlands.

S. Nittel, S. Winter, A. Nural, and T. Cao, "Shared Ride Trip Planning using Geosensor Networks", (2007). Book, Published
Editor(s): H. Miller
Collection: Societies and Cities in the Age of Instant Access
Bibliography: Springer, NL.

A. Nural, S. Nittel and S. Winter, "Shared Ride Trips in Large Transportation Networks", (2005). conference proceedings, Published
Editor(s): Harvey Miller
Bibliography: Symposium on Societies and Cities in the Age of Instant Access, University of Utah, November

Silvia Nittel, Alex Labrinidis, Anthony Stefanidis, "Geosensor Networks, Second International Conference, GSN 2006, Boston, MA, USA, October 1-3, 2006, Revised Selected and Invited Papers", (2008). Book, Published
Editor(s): Silvia Nittel, Alex Labrinidis, Anthony Stefanidis
Collection: Springer Lecture Notes in Computer Science, Vol. 4540
Bibliography: ISBN: 978-3-540-79995-5

Duckham, M., Mokbel, M. and Nittel, S. (Eds), "Special Issue: Privacy-Aware and Location-Based Mobile Services", (2007). Special Issue Journal, Published
Editor(s): Duckham, M., Mokbel, M. and Nittel, S. (Eds)
Collection: Journal of Location-Based Services
Bibliography: 1(3): 161-164

S. Nittel, "Geosensor Networks", (2008). Encyclopedia, Published
Editor(s): Shekhar, Shashi; Xiong, Hui

Collection: Encyclopedia of GIS
Bibliography: XL, 1377 p. 723 illus. ISBN: 978-0-387-30858-6

S. Nittel, "Geosensor Networks", (2010). Encyclopedia, Published
Editor(s): Barney Warf
Collection: Encyclopedia of Geography
Bibliography: Sage Publications, Inc, 2010, ISBN: 1-4129-5697-8

Web/Internet Site

URL(s):

http://www.geosensornetworks.net

Description:

We have created the "Geosensor Network Laboratory" website at the University of Maine. It announces news items, publications, activities, and lists relevant conferences in the interdisciplinary domain of sensor networks, database systems and geoinformatics.

Other Specific Products

Contributions

Contributions within Discipline:

The main contribution to the principle discipline (computer science/DBMS) is in the research papers that have been published in research conferences and journals, as well as the conference presentations given.

A major contribution is my initiation and organization of 2 major conferences and 2 workshops, which also reflects the interest in this area. Furthermore, my contributions to the principle discipline are several invited talks and keynotes (Tokyo, Muenster/Germany, Oxford, Cambridge, Wageningen/Netherlands, Korea and IIT Bombay/India).

? Further, to reflect my key role in introducing this novel technology area to the community, I have been ask to serve as editor for the topic Geosensor Networks for three newly published encyclopedias in Geoinformatics and Geography.

? Furthermore, I taught and advised successfully several Ph.D. and MS students in data management for wireless sensor networks.

? I served on 30 program committees during the project duration.

In 2009, I published a first survey article summarizing the state of the art in geosensor networks, summarizing the technology, research contributions in the field of spatial information science and database systems, described example applications and provided a survey of the current state of the art and relevant research problems.

S. Nittel, Advances in Geosensor Networks, Workshop on Geospatial Information for Developing Countries: Science and Technology (invited talk), December 16-18, 2009, IIT Bombay India.

I hope for a continued and healthy growth of this research topic in this multidisciplinary domain of sensor devices, sensor networks, programming, data management and geographic information science.

Contributions to Other Disciplines:

My research is inherently multidisciplinary, and at the intersection of computer science, electrical engineering, sensor materials, spatial information science and environmental sciences. I have also been invited to talks and keynotes in the field of earth sciences, geoinformatics and geography (see keynotes and invited talks). There were several contributions to other disciplines, especially Electrical Engineering, Chemical Engineering, Spatial Information Science, Geography as well as Oceanography.

Foremost, I collaborated with Drs. C. Wheeler (Chemical Engineering) and Pereira da Cunha (Electrical Engineering), University of Maine in 2005-2008. Drs. Wheeler and Pereira da Cunha focused on production and tuning of the sensor device, I brought in the aspect of sensor data analysis. The ultimate objective was to look into opportunities to combine microsensor within a sensor network deployment for the detection of continuous gas phenomena.

I contributed to the disciplines other disciplines by teaching in the NSF IGERT program at the University of Maine. My background and research focus bridge the areas between hardware, computer science, sensor networks, and informatics. Especially, during the testbed classes, I advised the students with regard to software engineering, programming and deployment sensor networks.

During collaboration with Dr Pettigrew, Marine Science, and one of his doctoral students, I introduced mobile ocean sensor network technology to ocean observation areas using networked buoys instead of individual drifters, which is the state of the art today.

One of the major contributions to other disciplines is the start of the Geosensor Networks Conference series, which brings together the communities of sensor networks, databases, spatial information science and environmental application areas in this inherently interdisciplinary research topic, and provides a forum for exchange, collaborations and presentations.

Contributions to Human Resource Development:

none.

Contributions to Resources for Research and Education:

I have created the research lab space in Boardman Hall that is used for the IGERT testbed teaching (Motes), and the graduate students in my spatial database class. I also volunteer a Dell computer for the undergraduate capstone project, which was very successful in 2007.
? The senior class implemented and ran a website that allows UMaine students to search for housing, and for landlords to post their listings (UMaine Rents). The capstone project eventual received national press coverage, and is today managed by UMaine Student Affairs.
? In 2008, the senior capstone class used the same server for their web servers, serving a 3D model of the University of Maine campus using Google Earth, and allowing user to query the University's event calendar with result being displaying in the 3D Google Earth model.
? Several of my Ph.D. students serve as TA for the IGERT Sensor Foundation lab courses to train new incoming Ph.D. students in programming Intel/Berkeley motes.
? The Geosensor Networks Lab currently also serves as a showcase lab for the applications we have developed for the Maine Emergency Management Agency.

Contributions Beyond Science and Engineering:

I co-organized a 1-day workshop on the topic of 1st International Workshop on Privacy-Aware Location-Based Mobile Services (PALMS'07), Germany, May 2007. This workshop addresses the important topic of privacy concerns, protection and algorithmic and technical mechanism to do so using sensor networks.

I started and co-organize the Geosensor Networks Conference series. It is a significant success that the conference series that I initiated by being funded via this grant now has been picked up by independent organizers, and is continued into its 4th installation. This was the only conference, which brings together the communities of sensor networks, databases, spatial information science and environmental application areas. It is now organized by academics in the spatial information science and remote sensing community.

In the summer of 2009, we have started collaborating with the company Global Relief Technology, NH to apply sensor data management technology to a research/commercial product to assist Emergency Management Operations in the State of Maine. This project is funded by the Maine National Guard. The purpose is to transfer research results into practical use to improve the State of Maine's emergency readiness.

The project focuses on 2 key aspects: logistical asset tracking and critical infrastructure monitoring. So far, we have implemented a mote and RFID-based logistical asset tracking system that uses a checkpoint based tracking systems and assess the temperature of packages during transport. We implemented and successfully demonstrated a H1N1 vaccine distribution scenario in September 2009 to the Maine National Guard and key decision makers in Augusta. We have implemented both the tracking using motes and temperature sensors as well as a database system to manage the tracking data and a google map based interface to display the tracking in real-time. Currently, we are working on a critical infrastructure monitoring prototype using stream gauge and rain gauge data streams from sensor stations in Maine to provide an integrated flood monitoring system for the state of Maine.

In 2008 and 2009, I presented a keynote and an invited talk at international conferences. In 2008, I have a keynote at the conference 'Sensing in a Changing World', organized by one of the leading European Geomatics departments in Wageningen, Netherlands. The keynote was title 'Geosensor Networks: Novel Challenges in Environmental Monitoring' and was targeted towards an audience of ca. 60 researchers, many of whom already apply sensor network technology for environmental observation. In December 2009, I was invited to the NSF-funded US-Indo Collaboration Workshop on Geospatial Technology for Developing Countries in Mumbai (Dec 2009). The workshop was funded by the National Science Foundation for technology transfer between US research and projects, education and research in India. It was a rewarding experience to see opportunities to apply geosensor networks to environmental problems in India, such as water observation in the Himalaya for new agricultural areas, or landslide observation. It was interesting to see that several geosensor networks have already been deployed in India.

Conference Proceedings

Categories for which nothing is reported:

Any Product

Any Conference

THE UNIVERSITY OF MAINE

Department of Spatial Information Science and Engineering

5711 Boardman Hall, Room 348
Orono, Maine 04469-5711
207/581-2188
FAX 207/581-2206
SIEinfo@spatial.maine.edu
http://www.spatial.maine.edu

National Science Foundation

January 11, 2010

To whom it may concern:

This letter constitutes my further continuing endorsement of Dr. Silvia Nittel's project research and education plans related to her National Science Foundation Early Career Award. As with last year, Dr. Nittel continues to demonstrate high quality in teaching, research and public service to date, and the solid promise of continued growth and excellence.

Since writing my support letter last year, Dr. Nittel continues her excellent work in research. Her new research in "tiny models" for geosensor networks and in dynamic spatial field abstractions for sensor data stream engines is proving to be promising. She published a single author journal paper, published in *Sensors* that provides a survey of geosensor networks, as well as a collaborative journal article on change detection for sensor networks, published in *Geoinformatica.* She also gave an invited talk: "Advances in Geosensor Networks" at the Workshop on Geospatial Information for Developing Countries: Science and Technology.

Her Ph.D. Student Guang Jin successfully graduated, and her Ph.D. student Arda Nural successfully defended his Ph.D. thesis proposal and advanced to Ph.D. candidacy.

Regarding contributions to technology transfer, she is involved in research for the benefit of the State of Maine showing the application of sensor technology in emergency management.

Her teaching reviews have been around the average for a faculty member in our department (all good), and has taught our capstone courses, as well as courses in Spatial Database Systems, Information System Architecture, and courses that are part of our IGERT in sensor networks.

She has been active in service to the academic community, serving on the organizing committee for 3rd Geosensor Networks Conference, and on six international program committees. She is editor for Geosensor Networks entry for Encyclopedia of Geography to be published in September 2010.

Her achievements and contributions to date have continued to be excellent. She continues to become a role model for females in our discipline. I strongly support her continuing NSF Career Award.

Sincerely,

Mike Worboys

Dr. Michael Worboys
Chair, Department of Spatial Information Engineering

NSF-CAREER: Data Management for Ad-hoc Geosensor Networks
IIS-0448183, Funding 2005-2010
FINAL REPORT

Silvia Nittel
Department of Spatial Information Science and Engineering
University of Maine
5711 Boardman Hall, Orono, ME 04469
nittel@spatial.maine.edu

Research Activities

The objectives of this NSF Early CAREER project have been energy-efficient algorithms for diverse, intelligent, in-network data management and query execution for geosensor networks. Geosensor networks are wireless sensor networks mostly deployed in outdoor geographic space for environmental applications. Over the course of the five year project, we focused on a particular research problem specifically for geosensor networks: the *estimation* of continuous phenomena such as the ozone distribution over a region, and the *identification*, *boundary definition* and *tracking* of events within such continuous phenomena such as a toxic cloud. The research activities and findings for this problem fall into two categories: a) approaches for the quantitative estimation of continuous phenomena and b) approaches for the *qualitative* identification of boundaries and tracking their changes. Other focus areas were basic data management for GSN, abstraction from sensors for data management, and several research problems in the area of *mobile* geosensor networks.

Quantitative in-network estimation of phenomena in geosensor networks

One of the tasks of geosensor networks is the *quantitative* estimation of the value distribution of a continuous environmental phenomenon such as the ozone distribution over an urban area. Here, we do want to know the exact *measured* values and their distribution, not the 'presence' of a 'high risk zone' and its boundary, which would be a qualitative assessment. Assuming a dense sensor node distribution, it is more energy-efficient if the sensor nodes collaborate with regard to in-network estimation and localized partial spatial interpolation, i.e. perform the estimation within the network instead of sensing massive amounts of raw sensor measurements outside of the network. Thus, to estimate the spatial distribution and density of phenomena, in-network algorithms for in-network processing of light-weight spatial interpolation between sensor nodes is inevitable. During the project, we have developed several approaches to solve this problem, i.e. **QUAKE**, a Kriging-based in-network estimation algorithm, the **UDC** method, and **SWOP** (see Findings in 1.2.1).

1.1.2 Qualitative estimation of continuous phenomena in geosensor networks

To estimate underlying phenomena, encoding sensing data and exchanging the information among nearby sensor motes are necessary. Since wireless communication is the biggest drain on the batteries of sensor nodes, we are forced to find innovative and efficient ways of detecting events that require sending fewer data and/or smaller messages for the same quality result.

In a complementary approach to the *quantitative* assessment and measurement of continuous phenomena as described in 1.1.1, we pursued the notion that for many uses, measured metric sensor values are less important than the knowledge of an 'event'. For example, instead of estimating the metric values of all points in a spatial field, we instruct the geosensor network to detect only the boundary of an 'event' such as a toxic plume. For representation of this information, we can map the measured values into abstract representation using user-defined threshold, and for example transform a measure value into a qualitative representation such as 'not dangerous', 'likely dangerous', or 'very dangerous'. We call this approach a *qualitative query approach*, since we extract higher-level information that is useful to the human user, and use the abstract simplified representation to shorten message and thus, reduce energy consumption during in-network communication. In this area, the developed in-network algorithms fall into the categories of

a) boundary *point* detection (**NED** approach)
b) boundary *line formation* using boundary points
c) boundary *deformation tracking* over time (**SNAKE** approach, **topological change tracking** approach).

In the **NED** approach, we propose an algorithm, which deals with identifying sensor nodes that detect an event, and have those nodes start communicating with their neighboring nodes to determine the boundary of the event. The nodes save energy by converting local sensor reading to qualitative representations of the event, and shorten the messages that are communicated between neighbors. The conversion from a measured value to a qualitative representation is based on user-defined thresholds, but due to sensing noise it might not be possible to perform the mapping with high confidence by the sensor node if the measure value is close to the boundaries of the thresholds. NED proposes a novel algorithm to deal with the inherent noise in sensor readings and still make qualitative event detection feasible.

NED is an approach to find boundary nodes; these nodes need to collaborate to actually establish the boundary with minimal, yet robust representation. Once the boundary is identified, the sensor nodes along the boundary are activated, and the boundary loop is closed. The next step is to develop algorithms to track the changes of the boundary over space and time, and adjust the communication topology of the sensor nodes collaborating along the deforming/moving boundary. We have explored two complementary approaches with regard to boundary tracking: a) a ***geometric approach***, in which we represent the boundary by a 2D object and tracking its deformation over time and space (see for more details in 1.1.3), and b) a higher-level approach in which we ***track the topological changes*** of such a region (e.g. split, merge, self-merge, etc) (see more details in 1.1.4).

1.1.3 In-network boundary change tracking based on a incremental, geometric approach

Geosensor networks are deployed to detect, monitor and track continuous environmental phenomena such as toxic clouds or dense areas of air pollution in an urban environment. As we assessed in our work, it is often sufficient and considerably more efficient to only detect the contour line or boundary of an event such as a toxic cloud within a dynamic spatial field. However, many of such phenomena are dynamic, i.e. they move in time over space and boundary shape changes. For example, imagine a wildfire that is monitored with a sensor network. Over time, the wildfire will move based on availability of fuel, and wind and also obstacles, but it will not move with the same velocity and direction in the entire area of the geosensor network.

We developed an approach to track the changes of a boundary *incrementally*, thus, the geometric shape that represents the boundary is only adjusted where actual changes happen, and other boundary nodes are kept inactive (or performing their maintenance observations). Only nodes that are local to the boundary change start collaborating, while all other nodes stay in sleep mode. The proposed approach is based on the SNAKE model used in traditional digital image analysis for feature extraction. In principle, the SNAKE model and associated algorithms provide a 'rubberband' around a feature such as a coastline in a remote sensing image. The algorithm starts with a coarse approximation, and provides an iterative search algorithm to find appropriate points between existing point to 'snap' the 'rubberband' closer to the feature, and represented it in greater, accurate detail while optimizing the number of points necessary to represent the feature.

We revised the SNAKE model for boundary definition of continuous phenomena and developed several decentralized collaboration algorithms to define the best-fitting curve to the boundary and incrementally observe new best-fitting points based on measurements and a weight model. Our revised SNAKE approach matches SNAKE boundary points to sensor node locations, and locally finds appropriate boundary point presentations and sensor node location for the incremental changes to the boundary using only local communication between neighboring nodes. See findings 1.2.3 for the details of the approach and our findings.

1.1.4 In-network tracking of complex topological changes

In a different approach, I collaborated with Dr Worboys. In this research, the focus is on deriving qualitative descriptions of salient changes to areas of activity that occur during the evolution of the continuous phenomenon. The approach is based both on developing and extending the theory of complex *topological* changes and describe their possible transitions formally, and applying the theoretical results to geosensor networks and developing appropriate in-network algorithms to capture and track such complex topological changes. For example, a toxic cloud can split into two clouds independent clouds, or it could form a hole, split, and then self-merge again. Such changes were formally characterized.

Furthermore, a distributed qualitative change reporting (QCR) approach has been developed that detects the qualitative changes simply based on the connectivity between the sensor nodes without location information (see 1.2.4 for the findings).

1.1.5 Data Management in Mobile Ad-hoc Geosensor Networks

A relevant application of geosensor network applications is *mobile* geosensor networks, i.e. GSN in which some or all nodes are mobile in geographic space. In this aspect of the project, we have investigated novel usage of this technology for several application domains, i.e. *intelligent transportation* and *mobile ad-hoc ocean drifter networks*, and *flock detection* and monitoring.

Intelligent Transportation Systems

Technology developments such as IPhones with built-in GPS and a multitude of other sensors, and ubiquitous wireless networks have enabled new types of social behaviour such as ad-hoc meetings of people in co-located geographical space or participatory sensing. In this work, we investigated novel usage type of this technology for *intelligent transportation system*, in particular *ad-hoc shared-ride trip planning* in transportation networks. This work was performed within an international collaboration with Dr. Winter, University of Melbourne in 2005/2006. Shared-ride trips involve transportation seekers such as pedestrians arranging on a short-term basis with transportation providers such as private automobiles or taxi cabs for flexible travel provision. However, assigning clients and hosts in an ad-hoc, timely manner does challenge centralized trip planning approaches, in particular for non-scheduled hosts. Centralized service approaches based do not scale well nor provide optimal trip assignment in such a highly flexible, dynamic and ad-hoc environment.

Thus, we investigated a novel approach considering the transportation network as an ad-hoc mobile geosensor network using a short-range, self-organizing strategy. This approach can be fully scalable if every new transportation request can be solved locally in the geosensor network, a property that we investigate by comparing different communication strategies between nodes in the system.

Mobile Ad-hoc Ocean Sensor networks

In 2006, I started collaborating with Dr. Trigoni (Oxford University) and Dr. Pettigrew (School of Marine Science, University of Maine) on the application of mobile ad-hoc sensor networks as a network of ocean drifters. The objective was to investigate deployment strategies for ocean sensor network nodes consisting of inexpensive drifters that stay in communication range with each other. These networked ocean drifters now sample and report *region*-based ocean information such as ocean currents, salinity or microorganism information via mobile base station to the internet. Establishing a fine-grained model of local ocean currents is important since currents carry nutrients and other substances, which affect ecosystems in coastal regions. For example, researchers are interested in establishing current models for the Gulf of Maine (US) since they distribute a specific type of algae to shellfish off the coast of Maine during the warm summer months; the shellfish consuming the algae turn toxic for humans. Today, major ocean currents are established using coastal radar; however, the information is spatially and temporally coarse. The deployment of a fleet of inexpensive ocean drifters, which are passively propelled by the current and report their GPS-based location and trajectories to the end user, is a promising alternative.

Flocks Detection and Monitoring in Mobile Geosensor Networks

In a third research investigation with respect to mobile ad-hoc geosensor networks, we investigated the topic of *flock detection* and *monitoring* using real-time location update streams from moving objects. Flocks detection and monitoring is relevant in habitat monitoring of endangered wild life, emergency rescue operations in large public spaces and also battlefield applications. Flocks are a term specifically used for birds, but we use it as a concept for emergent group behaviour of moving objects such as animals or humans or cars. For example, it is simpler to observe a 'flock" of people showing the same 'escape' behaviour during an emergency situation, and predict future behaviour or organize rescue efforts.

Technologically, the objective is to perform real-time flock detection in a centralized spatio-temporal data stream management system. Our goals was to develop stream-based algorithms to detect the occurrence of flocks as a emergent behaviour of the location update streams of individually moving objects in real-time, and the observation of the behaviour of flocks over time, such as splitting, merging with other flocks, and dispersion. We made the assumption that DSMS technology can handle a very large collection of incoming update streams of moving objects in real-time and deal with bursts in update traffic. On the other hand, there are currently no solutions available on efficiently querying and analyzing the trajectories of large groups of moving objects and detecting the relations between them over time as a basis of discovering flocks in real-time.

Since flocks can also be defined as emergent behavior characterized without a predefined moving direction, understanding the spatio-temporal relationships between individual objects such as *proximity*, *matching speed* and *direction* are the key factors to detect flock mobility and requires specialized operators with efficient algorithms to support real-time detection and tracking. Appropriate information management strategies to handle real-time detection and monitoring of flocks efficiently are a challenging task.

Our main research questions are:

- How can we formalize flocks and flock behavior as an appropriate basis real-time detection?
- How can we feasible implement a real-time flock detection and management system?.

1.1.6 Data management in Geosensor Networks

One of the original proposed research objectives in this CAREER project was to find appropriate abstractions for sensor devices for sensor DBMS. The idea was to provide an abstraction layer similar to the separation of concern between the file storage organization and representation of relations in traditional DBMS in order to enable physical data independence. This is vital in sensor DBMS, since data is acquired on demand and the sensor networks structure can easily change due to failure and link nodes. In particular, I was interested in the 'knobs' of sensor devices that should be made available to the users, and which ones to hide.

To gain more expertise in the area of sensor devices, especially microsensor devices, I collaborated with Drs. C. Wheeler (Chemical Engineering) and Pereira da Cunha (Electrical Engineering), University of Maine in 2006-2008. Drs. Wheeler and Pereira da Cunha designed and fabricated specific microsensors, which are a combination of a microhotplate and SAW device for the detection of small quantities of HF gases. This is a typical sensor device ultimately used to detect toxic concentrations of HF gases in geographic spaces. Drs. Wheeler and Pereira da Cunha focused on production and tuning of the sensor device, I focused on the aspect of sensor data analysis.

In a related problem area, I was working with Dr. Y.J. Jung, a Korean post doctoral researcher in my laboratory. Dr Jung had worked on large scale geosensor network deployment in urban environments during his Ph.D. in South Korea, i.e. the geosensor networks consists of a set of 10 air quality sensor distributed over a campus area.

Both collaborations led to findings and publications in the area of sensor data management.

1.1.7 Spatio-Temporal Sensor Data Streams Management

In a different, related aspect of this CAREER project's data management for geosensor networks, we assume a more traditional setup with a combination of remote, distributed sensor stations that wirelessly transmit their reading to a central processing computer. Today, such a true mix of sensor platforms of all types of sizes, sensors, configurations and deployments are used in the geosciences, which are appropriate for the problem at hand. Wireless sensor networks can be considered a component of such environments. We assume that ultimately their sensor data streams will be integrated to analyze phenomena in geographic space.

In this aspect of the project, we assume we have a distributed, real-time sensor platform infrastructure in place that allows us to monitor dynamic environmental phenomena such the distribution of NO_2 and other gases in the air in a major metropolitan area and detect relevant events related to it such as high pollution areas. All the information is continuously collected, and directly communicated from each individual sensor station to a centralized processing computer. Further, we assume that the distributed sensor platforms consist mostly of stationary sensors, and their locations are known (however, mobile stations can also be part of the system as long as they provide location information about sampled data). The sensors are deployed in a more or less uniform spatial distribution over the observation region, with a resolution of about one sensor node per square mile. Each sensor node produces a stream of data tuples per sensor attached to the node, and each stream is ordered by sampling time. The sensor sampling can vary with the sensor device, and is application driven, i.e. depends on the monitored phenomenon.

The common objectives of applications of such distributed sensor platforms and their data streams is monitoring real world phenomena and extracting useful information and events from the sensor data in real-time. Each sensor data stream represents a time series of single, point-based sensor sample at the node's location; however, for many sensor data queries, instead of a stack of raw sensor readings, a higher level data representation is required to pose queries targeting to identify and track the changes and continuous phenomena in the underlying sensor field. Such an abstraction can shield users from disordered details of real-world streaming data, and present a consistent view of the monitored environment. Historically, the concept of spatial field used to be abstracted from individual sensor readings and represents a value distribution over a spatial region. For a sensor stream environment, the concept of a *dynamic continuous spatial field* is an ideal conceptual framework for querying such data. The term "continuous" here is used to indicate that the domain of a field is continuous. The term “dynamic” emphasizes that the physical spatial field changes gradually over time.

We focused extensively on the area of data stream processing, and the extension of general-purpose data stream management systems for representing, managing and processing sensor sources producing real-time spatio-temporal sensor data streams. This work is necessary to lay a common formal foundation for the integration of real-time data streams from small-scale, wireless geosensor networks and the production of real-time data streams from more traditional, larger single-point sensor platforms already in place today, however, only recently enable with wireless uplinks. This technology will enable a wide-scale real-time integration of different types of sensors in the notion of a sensor web.

1.1.8 Self-Organization in Geosensor Networks

During the project duration, I spent a sabbatical stay at Oxford University, UK. During this time, I started investigating a new research problem related to data management and programming sensor networks, which has ultimately great promise. A major drawback of today’s data management approaches is that it relies on a fairly robust sensor network, i.e. with regards to node and communication link availability. Most query plans are based on a communication tree topology, but if links between parents and children break this approach of in-network aggregation can be become flawed; it also does not scale well to very large geosensor networks with 1000s of nodes. During my collaboration with Dr. Trigoni, we started exploring bio-inspired self organizing approaches to programming sensor networks. In this approach simple local rules and decision making are applied to create emergent global behavior. It is a great challenge today, however, to break down general sensor networks problems such as e.g. duty cycle synchronization and optimization, or sensing collaboration into simple local rules, and correct global emergent behavior.

I reviewed a large part of the different approaches with regard to self organization such as game-oriented approaches, market-oriented approach, and bio-inspired approaches. We investigated ant colony and swarm-based strategies in more detail and now have focused on Gene Regulatory Networks (GRNs) as our approach of choice (see Findings 1.2.8).

NSF-CAREER: Data Management for Ad-hoc Geosensor Networks
IIS-0448183, Funding 2005-2010
FINAL REPORT

Silvia Nittel
Department of Spatial Information Science and Engineering
University of Maine
5711 Boardman Hall, Orono, ME 04469
nittel@spatial.maine.edu

Findings

1.1.1 *Three approaches for quantitative in-network estimation of continuous phenomena in geosensor networks*

Kriging/Quake Approach: Assuming a spatial DBMS approach to managing, programming and querying geosensor networks, we have considered the spatial query predicates of *estimation point* and *estimation window*. For example, a user might request the *estimated value* of a point in the observation region; however, if there might be no sensor node located exactly at this location, we need to estimate the value using the sensed values of nodes located in proximity to the query point. Similarly, for the estimation of an entire region, the nodes in spatial proximity and inside the query region are necessary for the estimated values of the sub region of the phenomenon.

To save energy, estimation and spatial interpolation has to be executed in the network to save energy. A traditional spatial interpolation method is Kriging; it is used to predict the value of a point in space of a continuous phenomenon by weighing the contribution of sensor samples to the estimated value, and it provides well-defined error guarantee. Kriging also contains information to evaluate the quality of the estimation result, i.e. quantify the error. Several variations of Kriging are available; ordinary Kriging has the benefit that it estimates the first order and second order effects of the monitored phenomenon both in one process.

We introduced the ***QUAKE*** approach (Query Answering Using Adapted Kriging Estimation), which encompasses a novel algorithm for *in-network Kriging computation* that minimizes the acquisitional cost of query processing for spatial queries. The approach taken in QUAKE is based on calculating the minimal subset of sensor nodes, which are necessary to compute an estimation result that guarantees the user-defined acceptable error tolerance for a query. QUAKE significantly decreases the number of messages sent within the sensor network, and assures that the message size between nodes stays constant throughout estimation process.

S. Nittel, G. Jin, and Y. Shiraishi, (2005) In-Network Spatial Query Estimation in Sensor Networks, *IEICE Transactions* (A), Vol.J88-A (12):1413-1421

UDC: We had the objective of finding an efficient clustering algorithm to process aggregation queries in uneven clustering patterns. Due to the physical properties of radio transmission of data to a farther node, a sensor mote consumes much more energy than sending data to a nearby location. We observe that if sensor motes can cluster smaller groups nearby the central base, and larger groups at distant location, the energy consumption rate can be improved. We proposed a model on how to estimate the energy consumption based on sensor clusters' location and size and presented a novel algorithm, called UDC (Uneven Dense Clustering), which allows sensor motes to form uneven dense clusters according to motes' location. In short, UDC enables smaller sensor clusters to merge together if further energy can be saved. We have simulated the sensor mote's energy consumption rate and our experimental results prove that UDC can extend a sensor mote's life up to two times longer than evenly clustering strategies.

G. Jin and S. Nittel, 2005. UDC: A self-adaptive uneven clustering protocol for dynamic sensor networks, in *International Conference on Mobile Ad-hoc and Sensor Networks (MSN)*, Wuhan, China.

G. Jin and S. Nittel, (2007) UDC: A self-adaptive uneven clustering protocol for dynamic sensor network, International Journal of Sensor Networks. Vol 2(1/2):25-33.

SWOP: For continuous phenomena, represented as spatial fields, additional estimation methods are required to process the sensor readings in order to generate the estimation results. Estimation methods, however, are computationally intensive, even when computed in a centralized setting. We developed the SWOP (Spatial Window query Over Phenomena) approach, which breaks the dependency link between estimation results and sensor readings, and conserves the network's resources by compressing the data extracted from the sensor network. The SWOP processes spatial window queries over a continuous phenomena based on *Gaussian kernel* estimation. The key of the approach is using a Hermite series to approximate the Gaussian kernel function; as a result, the number of messages transmitted in the networks is relaxed by logarithmic operation. Hence, a large amount of network resources are saved, while the network still returns estimation results with neglectable errors.

We tested SWOP in different settings. SWOP archives the compression by grouping the sensors into sub clusters. Therefore, the clustering algorithm plays an important role in SWOP, i.e. if more dense clusters are found a higher compressing rate can be achieved. We choose HEED as the clustering algorithm for SWOP since HEED is more appropriate for mobile settings. HEED, on the other hand, can only return a ``randomized" clustering layout. Therefore, we measure the mean, min and max data size as illustrated. Compared with centralized solutions, SWOP requires significantly less data extracted from sensor networks. To get the same quality of estimation results as the original phenomenon, the ordinary distributed solution needs much more data to represent the estimation result. For a small data set, SWOP only requires as half as data required by centralized solution. SWOP, however, is designed for a larger sensor networks. For those cases, SWOP can compress the data up to 1/4 as required by centralized solution, and thus, save communication cost significantly.

G. Jin and S. Nittel: Towards Spatial Window Queries Over Continuous Phenomena in Sensor Networks, IEEE Transactions on Parallel and Distributed Systems (TPDS), Vol 19(4), pp. 559-571, April 2008.

1.1.2 Qualitative estimation of continuous phenomena in geosensor networks

In a *qualitative query approach* to geosensor networks we extract higher-level information that is useful to the human user, and use the abstraction to also reduce energy consumption during in-network execution. In this research domain, the developed in-network algorithms fall into the categories of

a) boundary *point* detection (NED approach, (see 1.2.3))
b) boundary *line formation* using boundary points, and
c) boundary *deformation tracking* over time (SNAKE approach (see 1.2.3), and topological change tracking approach (see 1.2.4)).

1.2.3 In-network boundary change tracking based on a incremental, geometric approach

NED Approach: As described before, for applications and users it is often sufficient to describe phenomena in a *qualitative* way, for example identify a wildfire instead of reporting the temperature variations over the area. Encoding quantitative information can be significantly smaller (single bit or two bits). When the nodes in a sensor network collaborate to determine the boundary of the event (e.g. the wildfire), they only need to exchange the encoded bit between neighboring sensor motes. However, the more simplistic, qualitative representation of sensor values may cause faulty estimation/representation due to the noise inherent in sensor readings. We proposed a the NED algorithm, which uses a confidence level of local estimation results, and allows sensor nodes to exchange information in varying length of messages, depending on the confidence level. Generally speaking, NED uses 1 bit of data to represent local event estimation if the local estimation is trustful. Otherwise, sensor motes allow exchanging local estimation results in the raw format of data.

We have tested different data sets including continuous and discontinuous data in NED [1]. Our experiment results reveal that NED can significantly improve the energy consumption rate of sensor motes while still providing high quality estimation results.

G. Jin and S. Nittel, 2006. NED: Efficient Event Detection in Sensor Network, Workshop *Mobile Location-Aware Sensor Networks*, in conjunction with MDM, Nara, Japan.

Boundary detection/identification using an adaptive geosensor network topology: In another approach, we investigated algorithms for detecting the occurrence of phenomena in large sensor networks using a qualitative approach using a communication topology based on triangulation between the sensor nodes. If no event takes place, most of the network's nodes are asleep and the remaining nodes cover the network with a coarse, large-celled TIN-based topology. Once an event occurs, the network topology adjusted to a more fine-grained communication topology, however, only on the perimeter of the events. The communication topology dynamically adjusts to the temporal-spatial behavior of the phenomenon, and shows a fine-grained activity around the event's boundary while the rest of the network and even inside the phenomenon is still covered using a coarse communication topology.

Duckham, M., Nittel, S. and Worboys, M. (2005) Monitoring dynamic spatial fields using responsive geosensor networks, ACM-GIS 2005, Bremen, Germany, November 2005.

SNAKE - *In-network boundary tracking of based on an incremental, geometric approach*: We also developed a new approach to incrementally track the *boundary changes* of such an event. First, we abstract a phenomenon such as a toxic cloud as a 2D object and only consider its boundary and monitor the boundary and its geometric deformation over time. We use a model, known in the field of image processing as the SNAKE model, to represent the boundary as a deformable curve instead of a simple polygon. Based on the deformable curve, which has optimal number of boundary points to represent the boundary itself, we use an adjustment of a combination of weights associated with the curve points in addition to the sensed input of the sensor nodes to adjust the curve like a 'rubber band' to the new shape of the phenomenon. This allows us to incrementally track the changes to the phenomenon over time with minimal and only localized adjustments to the overall curve. We developed an in-network algorithm that only used localized communication between nodes to adjust the curve based on sensed values and weights. Neighboring nodes decide on the t_{i+1} curve points.

We showed that the in-network incremental boundary tracking approach based on deformable curves collects sufficient information efficiently to track the overall spatiotemporal properties about a 2D object. Once the boundary is detected and connected as a curve, we are interested in tracking the change of the boundary with minimal number of messages and energy consumption. In our proposed in-network algorithm, in which nodes have local knowledge about the curve and collaborate with neighboring nodes to monitor the deforming of the curve over time. By computing aggregated information about the deformable curve, a WSN does not need to report the detailed geometric representation of the entire 2D object but only local changes, and can save energy. Our simulation results show that our tracking algorithm requires a small amount of communication cost to maintain the structure of the deformable curve. This information can be computed by in-network aggregation algorithms with a minimal amount of communication cost, while providing qualitative spatiotemporal properties of 2D objects such as shrinking and expanding.

The results of this model were published as a paper in ACM-GIS 2008 and a journal article in 2010.

G. Jin and S. Nittel, *Tracking Deformable 2D Objects*, Proceedings of ACM Conference "Advances in Geographic Information Systems" (*ACM-GIS'0)*, Los Angeles, CA, Nov 5-7 2008.

Jin, G. and Nittel, S. (2010) Efficient tracking of 2D objects with spatio-temporal properties in wireless sensor networks, *Journal of Parallel and Distributed Databases,* (in press).

1.2.4 Tracking complex topological changes

Collaborating with Dr. Worboys and a current NSF IGERT program "Sensor Science, Engineering and Informatics", we have worked on topology-based appraoch of boundary tracking. In this approach, we proposed an in-network algorithm to for sensor nodes to make correct local decisions about global *topological changes* taking place in the geosensor network, while only being able to see local changes and collaborate locally. This work resulted in a full paper published in GIScience 2008.

C. Farah, C. Zhong, M. Worboys and S. Nittel, *Detecting Topological Change using Wireless Sensor Networks*, In Proceedings of the International Conference "Geographic Information Science" (*GIScience'08)*, Park City, Utah, September 2008, in Springer LNCS 2008.

In other work, we focused on developing and extending the theory of complex *topological* changes and formalize their possible transitions, and applying the theoretical results to geosensor networks and developing appropriate in-network algorithms to capture and track such complex topological changes. Here, an in-network algorithm to capture and track such complex topological changes via a qualitative change reporting (QCR) approach has been developed; it detects the qualitative changes simply based on the connectivity between the sensor nodes without location information. The efficiency of the QCR approach is investigated using simulation experiments. The result shows that the communication cost of the QCR approach in monitoring large-scale phenomena is as low as that of the standard data collection approaches where each node is assumed to have no information about its location.

The results of the collaboration accepted for publication in the journal *Geoinformatica* in 2009.

J. Jiang, M. Worboys and S. Nittel, Qualitative Change Detection in Sensor Networks based on Connectivity Information, *accepted for publication, Geoinformatica, 2009 (in press).*

1.2.5 Mobile Geosensor Networks

Transportation Systems

Shared-ride trips involve matching transportation seekers such as pedestrians with transportation providers such as private automobiles or taxi cabs for flexible travel provision in an ad-hoc way. Assigning clients and hosts in an ad-hoc, timely manner needs to scale well, and decision making is influenced by rapid changes in ride offerings and acceptance. Centralized service approaches do not scale well nor provide optimal trip assignment in such environment. We investigated novel approaches considering the transportation network as an ad-hoc mobile geosensor network using a decentralized, short-range, self-organizing strategy. This approach scales well if every new transportation request can be solved locally in the geosensor network, a property that we investigate by comparing different communication strategies between nodes in the system. We demonstrated in several published papers that with short-range communication, and hence, incomplete transportation network knowledge a system still can deliver near-to-optimal trips.

S. Nittel, S. Winter, A. Nural, and T. Cao, 2006. Shared Ride Trip Planning using Geosensor Networks, In: H. Miller, H. (Ed.), *Societies and Cities in the Age of Instant Access*, Springer, NL.

S. Winter, and S. Nittel, 2006. Ad-hoc shared-ride trip planning by mobile geosensor networks, *International Journal of Geographic Information Science*, Vol 20(8):899-916.

Ocean Sensor Networks

Today, drifters are often deployed in a singular fashion, and use satellite communication to upload data to a centralized computer. We explored the use of a fleet of inexpensive wireless drifters as an alternative flexible infrastructure for fine-grained ocean monitoring. We view the fleet of drifters as a wireless ad-hoc sensor network with two types of nodes: i) a few powerful drifters with satellite connectivity, acting as mobile base-stations, and ii) a large number of low-power drifters with short-range acoustic or radio connectivity. Our objective was twofold: using a fleet of small-scale sensor nodes that communicate with each other using lower-energy acoustic signals instead of a satellite uplink saves large amounts of energy. Additionally, the fleet provides more detailed information by covering an ocean region in high density. The passive movement of drifters can be used to derive actual ocean currents on a detailed scale.

Our study on network connectivity and sensing coverage of the drifter network led us to the following conclusions: For most drifters, their one-hop connectivity increases sub-linearly with the communication range (instead of quadratically) revealing non-uniform drifter distribution. Deployment locations and deployment periods seem to play an important role in one-hop connectivity.

Multi-hop connectivity is clearly improved by the increase in the number of available base-station drifters; an average connectivity of around 60% with one base-station becomes around 80% with two base-stations and almost 90% with three base-stations based on our Liverpool Bay measurements. Given a fixed number of base-stations, we observed that different deployment locations and deployment periods play an important role in the network's multi-hop connectivity, with connectivity varying between 60% and 100%.

Sensing density is drastically affected by the deployment period and by the initial drifter location. Moreover, generally, the difference between sensing density and network connectivity increases with time, indicating that drifters may stay highly connected in several cases after a long period of time (over one day) but this does not necessarily mean that they are kept inside the corresponding area of interest. Actually, in most cases, sensing density decreases significantly after the first 24 hours.

Finally we observed no clear trends showing how deployment locations and deployment periods influence the values of sensing uniformity of connected drifters. In fact, the observed differences in uniformity values across different deployment scenarios was shown to be negligible, at least during the relatively short simulation periods (1.5 days).

Our findings are published in 2 publications and were presented at the corresponding conferences.

S. Nittel, N. Trigoni, K. Ferentinos, F. Neville, A. Nural, and N. Pettigrew. A drift-tolerant model for data management in ocean sensor networks, MobiDE'07, in conjunction with SIGMOD, Bejing, China, 2007, pp 49 - 58.

A. Nural, S. Nittel, N. Trigoni, and N. Pettigrew, A model for motion pattern discovery in ocean drifter networks, Costal Environmental Sensing Networks Conference, Boston, MA, April 12-13 2007.

Flock Detection

The main focus of our findings is the creation of a conceptual framework of flock formalization and assessments of flock durations and their movement characteristics developing data stream algorithms for location update streams.

Our approach to the flock detection problem was to formalize the definition of a flock entity that can be detected in a DSMS setting, such that the moving nodes report their location data as input feeds for a DSMS. This formal reasoning system extends the available flock models, e.g. Boids model and SNAP/SPAN ontology. The focus of formal our definitions are:

- Describing of individual and group mobility
- Characteristics of flock emergence. Particularly, the fundamental group behavior that triggers emergence of flocks.
- Defining temporal pseudo flocks. (i.e. some random flock like patterns occur for short phases which is impractical to declare as flocks)
- How to track lineage of flock mobility?
- Behaviors of flock mobility, such as detecting splitting flocks and merging flocks.

Flocks are an emerging phenomenon based on the behaviour of individual moving objects. To capture the emergence, we need to observe all moving objects, and 'measure' the similarity of movement of the objects. The key parameters are *distance* between objects, *direction* and *cohesion* of the objects. These parameters change with each time step so that we cannot easily classify an object immediately as a flock member, but more like a flock candidate. A certain degree of uncertainty is associated with the flock detection.

We developed a formal model based on fuzzy sets to formalize flocks and flock behavior. This allows us to define the flock parameters as a set of fuzzy rules, and parameterize the degree of uncertainty that we want to allow for a specific application. Evaluating the rules, we can define whether a moving object is a flock candidate or flock member. A first approach to flock detection is a model defined on distance relationships between two moving objects over time; this can easily be represented as the similarity between 2 line strings, which represent the objects' trajectories. Ultimately, one would observe the trajectory relationships of n objects concurrently. However, such an approach does not scale well to large number of moving objects, which need to be analyzed in real-time. Therefore, our model is based on fuzzy set theory, i.e. an object 'approximately' belongs to the candidate set of a flock. We base the membership on several parameters such as *location*, *velocity*, and *proximity* over time. Flock membership is defined based on a set of rules defining conditions with regard to those parameters defined above. We developed similar rules to monitor the flock behaviour over time such as splitting, merging and dispersing.

The results have been written up in the Ph.D. thesis proposal by the student Arda Nural; in April 2009 he successfully defended his proposal and is currently working on the stream operators based on the fuzzy logic rules.

1.2.6 Data Storage and Indexing in Geosensor Networks

To gain more expertise in the area of sensor devices, especially microsensor devices, I collaborated with Drs. C. Wheeler (Chemical Engineering) and Pereira da Cunha (Electrical Engineering), University of Maine in 2006-2008. Drs. Wheeler and Pereira da Cunha designed and fabricated specific microsensors, which are a combination of a microhotplate and SAW device for the detection of small quantities of HF gases. Currently, I am a Ph.D. committee member for the IGERT student Bennett Meulendyk, who who is now a doctoral candidate. A major advantage of being part of this highly interdisciplinary team is the exposure to the development process of microsensors, to learn the language, and the research problem settings posed in physical microsensor production and development.

Related to the project goal of sensor data management, I have been working with Dr. Y.J. Jung, a postdoc in my laboratory. He worked on large scale geosensor network deployment during his Ph.D.; the GSn consisted of a set of 10 air quality sensor distributed on the roof tops of Chungbuk University, and deliver sensor data streams in real-time to a centralize processing engine. Continuing with this research, we have published two papers. The first paper describes the overall system, and the second paper is published as a full paper at GIScience 2008. In this paper, we propose a GIS-layer approach to represent individual incoming sensor data streams as basis for further processing and sensor data integration. An additional multidimensional index structure is proposed for more efficient processing.

Y. J. Jung and S. Nittel, Geosensor Data Abstraction for Environmental Monitoring Applications, *GIScience*, Park City, Utah, September 2008.

Y.J. Jung, Y. K. Lee, D. G. Lee, K. H. Ryu, S. Nittel, Air Pollution Monitoring System using Geosensor Networks, International Geoscience and Remote Sensing Symposium (IGARSS), Boston, MA, July 2008.

With regard to in-network storage and indexing, in our experimental results we showed in the DIG approach avoids unnecessary wireless communication and processes range queries in a resource-efficient way. Compared to the approach of flooding queries, DIG can save 50% or more for the total communication consumption and 80% or more for the query dissemination cost.

Jin, G. Nittel, S., Park, J.-S., and Liang, Q.: DIG: A Query and Data Driven Index for Sensor Networks, Technical Report 2008.

1.2.7 Spatio-Temporal Sensor Data Streams Management

We have surveyed the related work in stream data management systems and performed a requirement analysis with regard to a data models and query languages for spatio-temporally extension to support sensor data. Qinghan Liang, a Ph.D. student focusing on this research area, has been writing the first three chapters of his thesis proposal since October 2008; we also started working on the formalization of a new data model and query language for sensor data streams.

In a related activity, we worked with Milcord and Streambase Inc. to extend the Streambase system with operators for processes spatial data, especially raster images.

1.2.8 Bio-inspired self organization in geosensor networks

During my sabbatical stay at Oxford University, UK, I reviewed a large part of the different approaches with regard to self organization such as *game-oriented* approaches, *market-oriented* approach, and *bio-inspired* approaches. We investigated ant colony and swarm-based strategies in more detail and focused on Gene Regulatory Networks (GRNs) as our approach of choice since it supports the complex notion of multiobjective optimization best without the need for a global feedback loop when using fitness functions. The current application of this technique to sensor networks in very limited, but our first experiments and simulation results show promise with regard to the expected behavior of such systems and the time necessary to reach a stable state of the system using self organizing methods. In principle, a sensor node is considered to be a ‘cell’ and different types of ‘proteins’ resemble entities to communicate between ‘cells’ and ‘promote’ and ‘inhibit’ gene expression and more protein production. “Genes” or chromosomes are strings encode the ‘memory’ of successful behavior under different circumstances.

We have experimented with very simple tasks, very simple ‘cells’ and very simple rules and operators, and ran a set of simulations to analyze the behavior of the system after several generations of solution and applied mutations and cross-overs of solutions. My preliminary results were presented in a keynote about geosensor networks in Wageningen, NL.

S. Nittel: Geosensor Networks: New Challenges in Environmental Monitoring using Wireless Sensor Networks, at Sensing in a Changing World, (***keynote***), November 20, 2008, Centre for Geo-Information, Wageningen, Netherlands

1.2.9 Survey of state of the art in ad-hoc geosensor networks

Over the last 6 years, I have co-organized three conferences on Geosensor Networks, and edited 2 books related to the conference series. In spring 2009, I published a *journal survey paper about the state of the art in the field of geosensor networks*. I will survey the field of geosensor networks, and mainly focus on the technology of small-scale geosensor networks, example applications and their feasibility and lessons learnt as well as the current research questions posed by using this technology today. Furthermore, my objective is to investigate how this technology can be embedded in the current landscape of intelligent sensor platforms in the geosciences and identify its place and purpose.

S. Nittel, A Survey of Geosensor Networks: Advanced in Dynamic Environmental Monitoring, *Sensors* **2009**, *9*(7), 5664-5678; doi:10.3390/s90705664, published: 15 July 2009.