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Monitoring Dynamic Spatial Fields Using Responsive Geosensor Networks

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Final Report for Period: 08/2009 - 07/2010

Submitted on: 08/28/2010

Principal Investigator: Worboys, Michael .

Award ID: 0534429

Organization: University of Maine

Submitted By:

Worboys, Michael - Principal Investigator

Title:

Monitoring Dynamic Spatial Fields Using Responsive Geosensor Networks

Project Participants

Senior Personnel

Name: Worboys, Michael

Worked for more than 160 Hours: Yes

Contribution to Project:

Michael Worboys is director of the project and advisor of the graduate assistant, Cheng Zhong, replaced in 2008 by Jixiang Jiang..

Name: Nittel, Silvia

Worked for more than 160 Hours: Yes

Contribution to Project:

Nittel is advisor to graduate assistant Danqing Xiao.

Post-doc

Graduate Student

Name: Zhong, Cheng

Worked for more than 160 Hours: Yes

Contribution to Project:

Cheng was appointed as the PhD student to work on this project. He is supported by the NSF award. He left the project in 2008 for family reasons.

Name: Jiang, Jixiang

Worked for more than 160 Hours: Yes

Contribution to Project:

This student replaced Cheng Zhong as the PhD graduate assistant. He completed his PhD on the topic of the project in 2009.

Name: Xiao, Danqing

Worked for more than 160 Hours: Yes

Contribution to Project:

This student began in 2007 as an MS student funded by the project.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

University of Melbourne

We collaborate with Drs Matt Duckham and Patrick Laube, in the Faculty of Engineering at University of Melbourne, Australia. In addition, Dr. Worboys visited Melbourne to collaborate on this project. This visit was funded by University of Melbourne. Worboys was appointed a Visiting Professor.

University of Leeds, UK

Worboys spent part of his sabbatical at Leeds, discussing granularity and its impact on distributed computing. Stell from Leeds has visited Maine twice during the project.

University of Oxford

Co-PI Silvia Nittel spent part of her sabbatical at this institution, collaborating on the usage of mobile data collection sinks for fixed sensor networks. Arising out of this collaboration, Nittel is co-chair and Worboys is on the program committee of the 3rd International Conference on Geosensor Networks, Oxford, England 2009.

Other Collaborators or Contacts

Alex Klippel, Penn State University, has contributed to discussions on the project relating to human cognition of dynamic geographic phenomena.
Holly Taylor and Tad Bruny?, Tufts University, on aspects of level of detail related to dynamic geographic phenomena.
Dr John Stell, University of Leeds, UK, on formal and ontological aspects of dynamic spatial systems.
Dr Niki Trigoni, University of Oxford, UK, on usage of mobile data collection sinks for fixed sensor networks.

Activities and Findings

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

Findings: (See PDF version submitted by PI at the end of the report)
Please see attached file

Training and Development:
Year 2

Graduate assistant Cheng Zhong has taken the following courses as part of his training: Introduction to Graduate Research, Formal Foundations of Informations Systems, Sensor Foundation Course, Graduate Seminar, Spatial Databases, Reasoning with Uncertainty, Principles of GIS, Spatial Analysis. For personal reasons he is having to curtail his studies, and so has trasferred to an MS by research. His dissertation is entitled: GENERATING CONTOUR MAPS FOR DYNAMIC FIELDS MONITORED BY SENSOR NETWORKS. He has worked with advisor, Dr. Worboys, on his research topic.The project also contributed to the IGERT Sensors: Science, Engineering, and Informatics.
Graduate assistant Danqing Xiao joined the project this year. Her training consisted of graduate courses: Introduction to Graduate Research, Formal Foundations of Informations Systems, Spatial Reasoning, Spatial Databases, Spatial Analysis. She has worked with advisor, Dr. Nittel, on her research topic.
Graduate assistant Jixiang Jiang has just joined the project to replace Cheng. He has completed the course component of his graduate degree.

Year 3
Graduate assistant Cheng Zhong has taken the course Research methods in Fall 2008 as part of his training. He successfully defended his masters thesis titled 'Generating Contour Maps by Dynamic Fields Monitored by Sensor Networks' and graduated in Oct. 2008.

Graduate assistant Danqing Xiao has taken the following courses as part of her training: Research Methods, Spatial Cognition and Computation, Graduate Seminar, and Graduate Thesis. She has been working with her advisor, Nittel Silvia, focusing on the research of modeling non-topological changes of continuous phenomena in geosensor networks.

Graduate assistant Jixiang Jiang has been working his advisor Dr. Worboys and the Co-PI Dr. Nittel on the implementation of distributed algorithms to topological change detection. He has also completed his Ph.D. dissertation titled 'Specifying and Detecting Topological Changes

to an Areal Object' and defended it in June 2009. Based on his research work in this and the previous projects, Jixiang Jiang received the 2008 research award from College of Engineering, University of Maine.

Year 4
Graduate assistant Danqing Xiao successfully defended her Masters thesis on Modeling and monitoring non-topological spatial changes of continuous phenomena in geosensor networks.

Outreach Activities:

Sensors and Emergency Management
The investigators led the project SenseME, that applied sensor technology to monitoring critical infrastructure and tracking logistical assets in the case of disasters and emergencies. This project is supported by the Maine National Guard and Maine Emergency Management Agency, with industry support from Global Relief Technologies.

IGERT
The project is closely integrated with a new NSF IGERT Program on Sensor Science, Engineering, and Informatics (SSEI). Both PIs Dr. Worboys and Dr. Nittel are Executive Committees of the program, and both are the panelists of the informatics panel, SSEI IGERT summer institute workshop in 2008 and 2009, respectively.

Conferences and workshops organized
Dr. Nittel serves as the Program Committee and General Co-Chair of the 1st International Workshop on Privacy-Aware Location-Based Mobile Services (PALMS'07), in conjunction with Mobile Data Management, Mannheim, Germany, May 2007. She also serves as a Steering Committee of the 3rd Conference on Geosensor Networks (GSN3.0), Oxford, UK, July 2009.

Academic service
Dr. Worboys is a Program Committee Member for the following conferences and workshops:
ACM Sigspatial 2010, ISGIS 2010, SSTD 2009, GSN 2009, ACM-GIS 2009, AGILE 2009, MEDES 2009, GeoS 2009, COSIT 2009, SMPS 2008, AR2008, ACM-GIS 2008, GIScience 2008, GIDays 2008, GeoS 2007, DG/SUM 2007, ITSC 2007, AGILE 2007, COSIT 2007, ACM-GIS 2007, GIDays 2007
Dr. Worboys serves as the editor-in-chief for the Journal of Spatial Information Science since 2009. He is also serves on the other editorial boards, including Oxford University Press Spatial Information Science Series, International Journal of Geographical Information Science, Transactions in GIS, Geoinformatica, Computers in Environmental and Urban Systems, Cartography and Geographic Information Science, USISA, and Geography Compass.
Dr. Nittel is a Program Committee Member for the following conferences and workshops:
SSDBM 2010, DMSN 2009, ACM-GIS 2009, VLDB 2009, DKSS 2009, MDM 2009, ACM-GIS 2008, SSDBM 2008, ICDE 2008, DMSN 2008, MobiDE 2008, DMSN 2007, VLDB 2007, SSDBM 2007, ICDE 2007, ESNs 2007

National service
Dr. Worboys was selected as member of Mapping Science Committee (MSC) of the U.S. National Academy of Sciences/National Research Council.

Awards
Dr. Worboys received University Consortium for Geographic Science (UCGIS) Research Award in 2008, and the Distinguished Scientist Award from Association of Computing Machinery in 2006. He also holds an Honorary Professorial Fellow in the Department of Geomatics, University of Melbourne, Australia since 2005.

Presentations, keynotes and invited lectures at multidisciplinary conferences
1. Jiang, J. and Worboys, M. Preliminaries for topological change detection in sensor networks. 3rd Int. Conf. on Geosensor Networks, Oxford, England, 2009.
2. Worboys, M.F. senseME: tracking critical infrastructure and logistical assets for emergency management. Workshop on Emergency Management, Augusta, ME, 2009.
3. Danqing Xiao, 'Modeling spatial changes in geosensor networks', poster presentation at Graduate Expo, University of Maine, April 2009
4. S. Nittel, 'Geosensor Networks: New Challenges in Environmental Monitoring using Wireless Sensor Networks Sensing in a Changing World', keynote, November 20, 2008, Centre for Geo-Information, Wageningen, Netherlands
5. Jixiang Jiang, 'Detecting basic topological changes in sensor networks by local aggregation', ACM-GIS 2008, Orange County, CA, Nov. 2008. [presentation slides]
6. S. Nittel, 'Geosensor Networks: State of the Art', invited talk, Computing Lab, Oxford University, Oxford, UK, October 3 2008.

7. S. Nittel, 'Geosensor Networks: State of the Art', invited talk, Computing Lab, Cambridge University, Cambridge, UK, October 1 2008.

8. S. Nittel, 'Geosensor Networks: State of the Art', invited talk, Chungji University, Cheongjy, Korea, June 2008.

9. Mike Worboys, Invited keynote address at the Workshop on Temporal GIS, the Past 20 Years and the Next 20 Years, Park City, Utah, 23 Sept. 2008

10. Mike Worboys, 'Models of geospatial change. 'Invited seminar given to the Department of Computer Science, University of Minnesota, Apr. 28, 2008.

11. Mike Worboys, 'Geography in motion. 'Invited lecture to University College London, England, Centre for Advanced Spatial Analysis, CASA Seminar, Jan. 23, 2008.

12. Mike Worboys, 'Geography in motion. 'Invited lecture to University of Edinburgh, Scotland, EScience Centre Guest Lecture, Mar. 11, 2008.

13. Mike Worboys, 'Geospatial change. 'Invited presentation, delivered to the Third Environment Ontology Workshop at The University of Manchester, England, Mar. 13-15, 2008.

14. Mike Worboys, Invited lectures on spatio-temporal formation systems, delivered remotely to the IFGI Spring School, University of Munster, Germany, Mar. 2008.

15. Cheng Zhong begin_of_the_skype_highlighting?????end_of_the_skype_highlighting. 'Continuous contour mapping in sensor networks. ' CCNC 2008, Las Vegas, NV, 2008. [presentation slides]

16. Silvia Nittel. 'Geosensor networks: state of the art and looking ahead.'Keynote, Muenster GI-Days, 2007 Muenster, Germany, Sept. 11 2007.

17. Silvia Nittel. 'Geosensor networks: a vision perspective.'Invited Talk, Invited Workshop on Ubiquitous Spatial Computing, Portland, ME, Jan. 15 2007.

18. Cheng Zhong 'Generating contours in a sensor network using isovector aggregation. 'The 5th IEEE Upstate NY Workshop on Communications, Sensors and Networking, 2007. [presentation slides]

19. Danqing Xiao, 'Study of cultural impacts on location judgments in eastern China. 'COSIT 2007. [presentation slides]

Related research awards (accepted/submitted)

1. M. Worboys (PI), K. Beard, S. Nittel, A. Abedi, Global Relief Technologies, Critical Infrastructure and Logistical Assets, $490,000, 2009-2010.

2. M. Worboys, Government of South Korea, Indoor Spatial Awareness, $270,000, 2008-2011.

3. K. Beard, R. Lad, R. Smith, J. Vetelino and M. Worboys, National Science Foundation, Research Grant DGE-0504494, IGERT, Sensor Science, Engineering, and Informatics, $3,339,065, 2005-2010.

4. M. Worboys, Ordnance Survey of Great Britain, for research with Oracle Inc. to develop a spatiotemporal data model, $138,000, 2005-2007

5. M. Worboys, N.Guidice, National Science Foundation, Research Grant, Proposal No: 0916219, III:RI:Small: Information integration and human interaction for indoor and outdoor spaces, $478,715, submitted Dec. 2008.

6. M. Worboys, J. Saros, J. Peckenham, National Science Foundation, Research Grant, Proposal No:0916255, III:Small: Decentralized spatiotemporal computing for monitoring environmental phenomena, $494,968, submitted Dec. 2008.

Journal Publications

Worboys, M; Duckham, M, "Monitoring qualitative spatiotemporal change for geosensor networks", INTERNATIONAL JOURNAL OF GEOGRAPHICAL INFORMATION SCIENCE, p. 1087, vol. 20, (2006). Published, 10.1080/1365881060085218

Klippel, A., Worboys, M.F., and Duckham, M, "Geographic event conceptualization", Cognitive processing, p. 52, vol. 7, (2006). Published,

Bruny? TT, Taylor HA, and Worboys MF, "Levels of Detail in Descriptions and Depictions of Geographic Space", Spatial Cognition and Computation, p. 227, vol. 7, (2007). Published, www.informaworld.com/smpp/content~content=a788009381~db=all~jumptype=rss

Klippel, A; Worboys, M; Duckham, M, "Identifying factors of geographic event conceptualisation", INTERNATIONAL JOURNAL OF GEOGRAPHICAL INFORMATION SCIENCE, p. 183, vol. 22, (2008). Published,

Jiang, J. and Worboys, M.F., "Event-based topology for dynamic planar areal objects", International Journal of Geographic Information Science, p. 33, vol. 23, (2009). Published,

Duckham, M, Worboys, M., and Galton, A., "Efficient generation of simple polygons for characterizing the shape of a set of points in the plane", Pattern Recognition, p. 3224, vol. 41, (2009). Published,

Jiang J., Worboys M., and Nittel S., "Qualitative change detection using sensor networks based on connectivity information", GeoInformatica, p. , vol. , (2010). Published, 10.1007/s10707-009-0097-0

Nittel, S, "A Survey of Geosensor Networks: Advances in Dynamic Environmental Monitoring", SENSORS, p. 5664, vol. 9, (2009). Published, 10.3390/s9070566

Books or Other One-time Publications

Nittel, S., Labrinidis, A. and Stefanidis, A., "Advances in geosensor networks", (2008). Book, Published
Bibliography: Springer LNCS 4540

J. Jiang, and M. Worboys, "Detecting basic topological changes in sensor networks by local aggregation", (2008). Conference proceedings, Published
Collection: Proc. of ACM GIS, Orange County, CA
Bibliography: ACM Publications, ISBN:978-1-60558-323-5

G. Jin and S. Nittel, "Supporting Spatio-Temporal Queries in Wireless Sensor Networks by Tracking Deformable 2D Objects", (2008). Conference proceedings, Published
Collection: Proc. of ACMGIS, Orange County, CA
Bibliography: ACM Publications, ISBN:978-1-60558-323-5

Web/Internet Site

URL(s):
http://www.spatial.maine.edu/~worboys/sensor.htm
Description:

Other Specific Products

Contributions

Contributions within Discipline:

The project demonstrates how combinatorial maps may be used as the underpinning for distributed algorithms for sensor activity in a geographic space, and monitoring dynamic geographic phenomena, such as change of a pollution plume.

This project also developed distributed and energy-efficient approaches to capturing the dynamic topology of evolving geographic phenomena, which enables sensor networks to monitor and generate qualitative reports on those phenomena.

Contributions to Other Disciplines:

The project had an interdisciplinary component, in that the domain was spatial, and many of the results have been published in journals and conferences related to geographic information science.It has also been applied to the discipline of emergency management.

Contributions to Human Resource Development:

Training of one PhD student and two MS students in sensor networks. All three students completed their degrees successfully. Impact on our IGERT program on sensor science, engineering, and informatics.

Contributions to Resources for Research and Education:

The project feeds directly into the NSF IGERT program in Sensors: Science, Engineering, and Informatics, running at University of Maine. The graduate students attend the sensor foundation course associated with this program. Educational materials for this program are being generated from the research from the project.

Contributions Beyond Science and Engineering:

Results from this project are feeding into a new project funded by the state of Maine, concerning the critical infrastructure and logistical assets of Maine.

Conference Proceedings

Jiang, JX;Worboys, M, Preliminaries for Topological Change Detection Using Sensor Networks, "JUL 13-14, 2009", GEOSENSOR NETWORKS, 5659: 112-121 2009

Farah, C;Zhong, C;Worboys, M;Nittel, S, Detecting Topological Change Using a Wireless Sensor Network, "SEP 23-26, 2008", GEOGRAPHIC INFORMATION SCIENCE, 5266: 55-69 2008

Stell, J;Worboys, M, Theory of Change for Attributed Spatial Entities, "SEP 23-26, 2008", GEOGRAPHIC INFORMATION SCIENCE, 5266: 308-319 2008

Zhong, C;Worboys, M, Continuous contour mapping in sensor networks, "JAN 10-12, 2008", 2008 5TH IEEE CONSUMER COMMUNICATIONS AND NETWORKING CONFERENCE, VOLS 1-3, : 152-156 2008

Jung, YJ;Nittel, S, Geosensor Data Abstraction for Environmental Monitoring Application, "SEP 23-26, 2008", GEOGRAPHIC INFORMATION SCIENCE, 5266: 168-180 2008

Categories for which nothing is reported:

Any Product

Results

Research Task 1: Dynamic spatial fields
RT1 is concerned with characterizations of the qualitative aspects of the dynamic field and their relationship to the combinatorial map structure.

1. We have focused on the development of an ontology of spatial changes in OWL (web ontology language) using Protégé 3. This ontology contains over 200 classes, including the classes terminological definitions and formalized restrictions.

2. We have worked on the formal modeling of continuous spatial phenomena for geosensor networks. We thoroughly reviewed the former studies in the wireless sensor network field on boundary detection. Then we looked at how to track boundary deformation over time.

3. We have proposed the local tree model for representing spatial changes, based on which a complete set of types of topological changes is specified. The local tree model provides a foundation for topological change detection using sensor networks.

4. A two-layer framework was developed for analyzing spatial and temporal entities for sensor networks. In the first layer, basic objects and events directly from collected sensor data are conceptualized. In the second layer, the data level entities are projected onto the information level to be expanded to global-level and semantic-rich entities.
5. We have provided an analysis and classification of events associated with the changes in topological structure of spatial areal objects as they evolve through time. The classification results provide a foundation for converting the qualitative spatial-temporal sensor readings into quantitative description.

Research Task 2/3: Combinatorial maps and their use in communication network topology

RT2/3 (combined) concerns the combinatorial map as the underlying topological structure of the sensor network, and its relationship to the sensor network, and responsiveness the dynamic field. RT3 focuses on algorithms to use combinatorial maps as communication network topology.

1. Using Delaunay triangulation to set up the communication network topology, a new topological change detection approach was developed. This approach collects the information required by the local tree model, and determines the type of change by the model. Communication cost is reduced using a boundary group based framework.

3. The approach proposed in stage 1 has been improved. A more flexible boundary group framework is proposed that enables reusing the time-invariant data during the monitoring. Communication cost is further reduced based on the new framework.

4. Based on the combinatorial map model, a data structure has designed that enables each sensor to store its neighbor information efficiently. This data structure helps to save

network energy. Simulation experiments agreed very well with the design.

5. As an extension of the work in 2, an energy-efficient technique, isovector aggregation, has been developed. This technique reports and reconstructs the contour maps at the base station, which provides an efficient way to visualize and monitor the dynamic fields.

6. We have modeled a specific combinatorial map as the basic topological structure for the triangulation over the nodes of a sensor network. The model provides a framework for the detection of global high-level events based on local low-level "snapshot" spatiotemporal data.

Research Task 4: Monitoring the field based on qualitative information (Dr. Nittel)
RT4 relates to real-world experiments with qualitative properties of continuous phenomena.

1. A simulation environment was developed based on Prowler, a Matlab-based network simulator. Both topological change detection approaches proposed in RT2-3 were implemented and tested. Sample videos that show the detection procedure of both approaches can be downloaded at our project website.

2. We have defined topological change and present in-network algorithms to detect such changes. An adaptive sensor network management strategy is applied, and energy efficiency is achieved by dynamic sensor activation and deactivation.

3. We generated and published results related to processing real-world sensor data collected over a campus area in Korea, and to represent the sensor data as layers for further processing and spatial queries.

4. We developed a SNAKE-based model to incrementally monitor the boundary deformation of continuous phenomena using an alternative approach based on the phenomenon's boundary geometry.

5. We participated in the spring 2008 IGERT testbed class, which constructed a wireless sensor network to measure the light field around tomato plants in a commercial greenhouse in Madison, ME.

Activities

Activities for this project are structured according to the following tasks:

- RT1: Dynamic Spatial Fields (Worboys)
- RT2: Combinatorial Maps (Worboys)
- RT3: Using Combinatorial Maps as Communication Network Topology (Nittel)
- RT4: Monitoring the Field based on Qualitative Information (Nittel)
- ET1: Training Ph.D. students (dual advising)
- ET2: Training MS student (dual advising)
- ET3: Incorporation of research topics into undergraduate and graduate courses
- ET4: Incorporation of research into IGERT Sensor Science Engineering and Informatics Program and CAREER research
- OR1: Dissemination results in academic journals and conferences
- OR2: Collaboration with University of Melbourne
- OR3: Collaboration with multidisciplinary sensor group on campus

The detailed breakdown follows.

Research Tasks:

RT1: (Worboys)

--development of an ontology of qualitative continuant entities in dynamic spatial fields (DSFs), taking account of specific domains of application

-- development of an ontology of qualitative occurrent entities in DSFs, taking account of specific domains of application

-- characterization of qualitative continuant and occurrent entities in DSFs in terms of local properties of combinatorial maps (CMs)

-- analysis of uncertainty components in DSFs

-- development of application domain-specific mappings from quantitative measurement vectors to discrete qualitative domains, thus converting quantitative sensor readings to points in a qualitative space

-- development of application domain-specific mappings from aggregations in space and time of quantitative measurement vectors to qualitative space-time entities (e.g., trajectories, regions, hole developments in regions, region splittings)

RT2 & RT3: (Worboys, Nittel)

-- modeling a specific combinatorial map as the basic topological structure for the triangulation over the nodes of a sensor network: this includes

-- modeling a sensor node as a CM vertex based on technological characteristics of sensor nodes, their communication properties and location

-- based on network-covering maps modeling submaps (detailing of a map)

-- defining a mapping between an initial map and a submap to assure that assures network connectivity

-- theoretical foundation for granularity changes of a CM, that assures network connectivity considering sensor network characteristics

-- analysis of uncertainty components in a sensor network related to DSFs

-- based on the model of a sensor node as a combinatorial map vertex, data and storage structures were developed to augment a node to implement its role as map vertex and find appropriate map neighbors

-- algorithms are developed to initialize and calibrate a sensor network communication topology

-- modeling of a sensor network simulation prototype, and adapting the results from RT2/RT3 into the prototype, i.e. using combinatorial maps as communication infrastructure for sensor networks

-- implementation, simulation and testing the robustness of the designed algorithms under different sensor network assumption, i.e. idealized assumption (stable links, stable nodes), and varying degrees of failure (link failure, node failure, or sensor failure).

-- measures for evaluation of the theoretical component of the work were developed in the context of the simulated sensor testbed.

-- The ontology, combinatorial map model, mappings from quantitative to qualitative domains, and uncertainty model, were validated in the simulated sensor network .

-- Testing the strategies and adaptivity of the simulation prototype with regard to monitoring, responding, assessing and adapting a simulated phenomenon.

RT4: (Nittel)

-- modeling and implementation of the test-cases (e.g., temperature, toxic cloud), and simulated behavior (moving, splitting, converging)

-- implementation of the part of the prototype that is relevant for measurements, data assessing, change detection based on qualitative change and leverage of the map-based communication topology to detect and adapt to discovered entities.

-- Based on the simulated phenomena and their behavior, we tested the in-network query processing, which uses both the map-based topology and the algorithms to create submaps to detect and track phenomenon based on qualitative information exchange about the phenomenon of interest.

Educational Activities

Hiring and training a Ph.d. student who focused in the theoretical and mathematical foundations. The student participated in the IGERT Sensor Science Engineering and Informatics Program and its lectures as well as in departmental class work. The first research results were presented in Spring 2007 in an IGERT colloquium.

Hiring and training a Master student who will focuses on the simulation prototype.

Both students collaborated as part of the team and also participated in the IGERT Sensor Science Engineering and Informatics Program and its lectures as well as in departmental class work.

Development of a new project for the sensor testbed course with regard to the IGERT program for Spring 2007.

Dr. Worboys incorporated the uncertainty model into a graduate course he teaches on Spatial Uncertainty.

Collaboration activities

OR2 and OR3: Periodic meetings of the multidisciplinary team. PI Worboys visited the University of Melbourne to work with collaborators there.