Introduction to the World-Wide Sensor Web

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Introduction

In 1991, Mark Weiser described his vision of ubiquitous computing: *"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it."* (Weiser, 1991) Many technologies have been seamlessly integrated into our daily lives and become invisible. The Internet and the World Wide Web (WWW) are two great examples. Today, we give little thought about them and what our lives would be like without them. Although the WWW has existed for only two decades, it has changed the way we do banking (e.g., online banking), shopping (e.g., ebay.com and amazon.com), listen to radio (e.g., online radio stations), and communicate with friends (e.g., Skype™), etc. Many new technologies, just like the WWW 10 years ago, are seamlessly immersing themselves into our daily lives. In this article, we will introduce one such technology: The Sensor Web (SW).

What is the World-Wide Sensor Web?

Neil Gross' article, "The Earth Will Don an Electronic Skin,"[1] provides a compelling explanation of the Sensor Web concept: *"In the next century, planet Earth will don an electronic skin. It will use the Internet as a scaffold to support and transmit sensations. This skin is already being stitched together. It consists of millions of embedded electronic measuring devices: thermostats, pressure gauges, pollution detectors, cameras, microphones, glucose sensors, EKGs, electroencephalographs. These will probe and monitor cities; endangered species; the atmosphere; our ships, highway traffic; fleets of trucks; our conversations; our bodies—even our dreams."* Figure 1 illustrates the concept of the Sensor Web as an electronic skin of planet Earth.

Figure 1. Sensor Web, an electronic skin of planet Earth.

With the ongoing development of cheaper miniature and smart sensors; abundant fast and ubiquitous computing devices; wireless and mobile communication networks; and autonomous and intelligent software agents, the Sensor Web is rapidly emerging as a powerful technological framework for geospatial data collection, fusion and distribution. The Sensor Web is a Web-centric, open, interconnected, intelligent and dynamic network of sensors that presents a new vision for how we deploy sensing devices, collect data, and fuse and distribute information. In short, the Sensor Web is a revolutionary concept for achieving collaborative, coherent, consistent and consolidated sensor data collection, fusion and distribution.

The Sensor Web vision is enabled by: (1) the recent rapid advancement of sensors, and (2) sensor network technologies. Before we explain the Sensor Web concept in more detail, we will outline the above two key technologies, which underlie the Sensor Web.

Sensors

A sensor is a device that is capable of detecting and responding to physical stimuli such as movement, light, heat, etc. Today, various physical, chemical and biological properties can be measured and monitored by sensors (Estrin *et al.,* 2003). Within the context of geospatial data collection, given differences in sensing range, sensors are typically classified as either *in-situ* sensors (*i.e.,* ground-based) or remote sensors (*i.e.,* typically carried by airplane or satellite). Sensors are everywhere, ranging from commodity sensors designed for everyday use, such as webcams, thermometers, microphones, smoke detectors, cell phones, etc., to specialized sensors for science and engineering applications, such as meteorological stations, seismic monitors, and radar detectors. Recent technical advances are allowing sensors to be smaller, lighter, and more energy efficient.

Sensor Networks

A sensor network[2] (SN) is a computer network linked to spatially distributed sensors with the purpose of cooperatively monitoring physical and environmental conditions, such as temperature, humidity, precipitation, wind, stream water levels, pollutants, etc. (Akyildiz *et al.,* 2002) In addition to being composed of one or more sensors, each node in a sensor network is typically equipped with a communication device which incorporates a variety of means of transmitting data, from wires to cellular phones and to microwave radios (Zuniga and Krishnamachari, 2003).

Today, it is feasible and economically viable to deploy enormous numbers of sensor networks to continuously monitor our environment. In fact, many sensor networks, including both *in-situ* and remote, have been built and deployed over the past few years.[3] The combination of these heterogeneous sensing systems can provide enormous amounts of timely, comprehensive, continuous and multi-resolution observations for applications, including environmental monitoring (Hart and Martinez, 2006), underwater monitoring (Waterworth and Chave, 2004), habitat monitoring (Mainwaring *et al.,* 2002; Polastre, 2003), battlefield surveillance (Paul, 2006), and disaster management (Lorincz *et al.,*2004; Ray *et al.,* 2003).

Recently, a new breed of sensor networks, called wireless sensor networks (WSN), has drawn a lot of research attention (Figure 2). A wireless sensor network is a network of sensors, each with an embedded processing unit and wireless communication device, that is placed into the physical world and which interacts with its environment (Hill *et al.,* 2000). New technologies, such as Micro-electromechanical Systems (MEMS), allow the WSN nodes to be constructed at the micro- or even nano-scale (Warneke *et al.,* 2001), resulting in greater portability and flexibility than is otherwise possible.

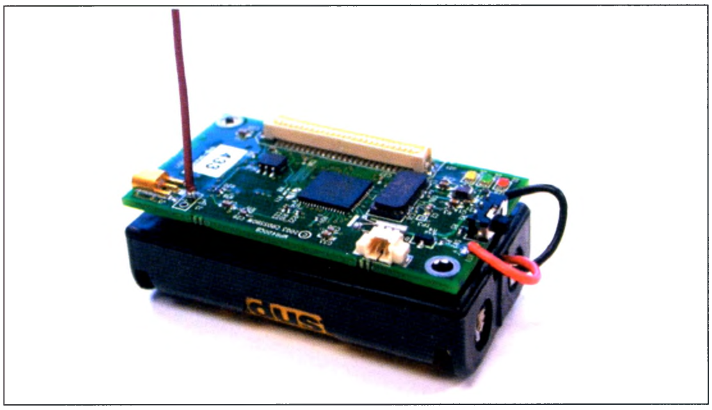

Figure 2. A MICA2 wireless sensor network node from Crossbow Technology Inc.

World-Wide Sensor Web

Although sensor networks have to date been deployed for a wide variety of applications, the communication links among these sensor networks have typically been lacking. By this we mean that these *ad-hoc* sensor networks are unable to access or interchange each other's resources. The sensing resources currently not being shared include sensors' data (e.g., sensor observations, sensor metadata, and other associated information) and sensors' processing capabilities (e.g., sensor tasking, aggregating, filtering, notifying, and alerting capabilities, etc.).

Why can't these sensor networks (SNs) access or interchange each other's resources? The reason is that SNs are computers in the field. The design and deployment of the sensor networks are constrained by the application and the environment. Different environmental conditions in the field represent different challenges (e.g., remote location of the sensors, power constraints, extreme weather conditions, etc.). Different challenges lead to different designs. As a result, these specialized sensor network systems have become islands of information systems (Zhao, 2006).

Consequently there is a strong and immediate need to connect these heterogeneous sensor networks for resources sharing. For example, coastal zone emergency management draws on data that has been obtained from a variety of sources and collected through different sensor networks, such as the seismic monitoring network, weather network, traffic network, and flood monitoring stations, etc.

The situation of today's sensor networks is similar to that of computers two decades ago, before the emergence of the World Wide Web (WWW). The WWW is an Internet-scale information infrastructure allowing heterogeneous computers to share their computing resources (*i.e.,* data and processing). By allowing computing resources to be shared among computers, the WWW enables today's many web applications, which have had a dramatic influence on our everyday lives. Just as computers need the WWW to interact, today's sensor networks need an information infrastructure that allows heterogeneous sensors to share their sensing resources (*i.e.,* sensor observations and sensor processing). We envision such an information infrastructure for sensor networks: it is termed the ***'Sensor Web' (SW).***

Within the context outlined above the Sensor Web is defined as a world-wide information infrastructure of sensor networks. Once developed, the Sensor Web allows heterogeneous sensing resources, *i.e.,* sensor data and sensor processing, to be connected and accessible from anywhere at any time. Similar to the WWW, which acts essentially as a World-Wide Computer (Berners-Lee, 1997), the Sensor Web can be considered as a World-Wide Sensor. In this worldwide Sensor Web, users, applications, and sensors can access, as a single unit, vast amounts of data and processing power from thousands or even millions of widely distributed, heterogeneous sensor networks or individual networked sensors.

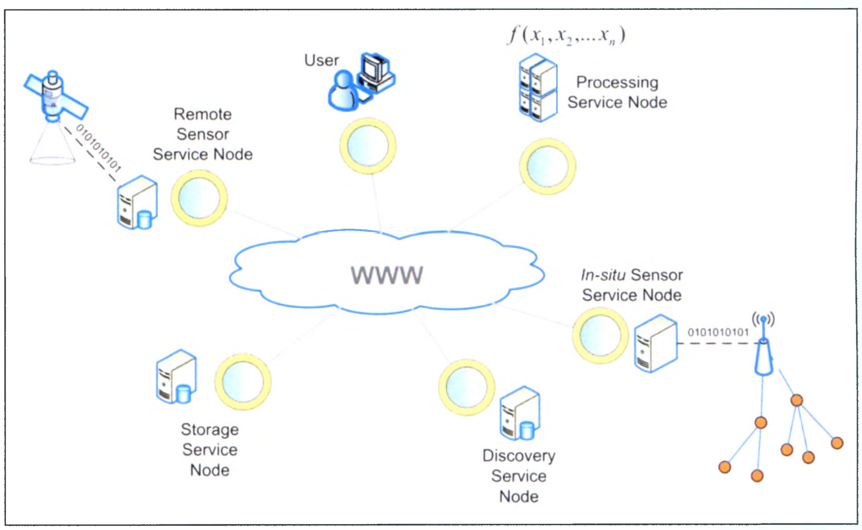

Figure 3. The Sensor Web consists of many Sensor Web nodes.

Some references refer to this system as the ***World-Wide Sensor Web (WSW),*** because the connection among these sensor networks is typically achieved via the World Wide Web. It is worth noting that the concept of the Sensor Web is evolving, as evidenced by the wide range of Sensor Web definitions (Delin and Jackson, 2001; Gibbons *et al.,* 2003; Liang *et al.,* 2005; NASA, 2007; Tao *et al.,* 2003; Teillet *et al.,* 2002), and some references do not differentiate between the sensor networks and the Sensor Web.

Spatial Sensor Web

Sensing is essentially a spatially based sampling process whereby each sensor observation can generally be associated with location information. Without information on their spatial context, sensed results are much less meaningful and useful. The following example effectively illustrates the importance of the spatial characteristics of the Sensor Web:

Mike is driving from suburban to downtown Toronto for a meeting. Before his arrival he uses his PDA phone to send out a query to a parking/routing sensor web agent. Mike specifies the destination of his meeting in the query. His PDA phone's built-in GPS also provides Mike's current location in the query message. Through the sensor web agent, a network of parking sensors in the specified location is connected in order to find the availability of the parking space. The traffic-monitoring network is also connected to provide real-time traffic information. The agent constantly sends Mike a dynamic navigation map with driving directions, while constantly taking into consideration real-time traffic conditions and the closest location of the parking space.

The above scenario illustrates that, for many applications, the spatial property is an integral component of the Sensor Web. The term "spatial is special" (Egenhofer, 1993; Worboys, 1995) is particularly relevant to Sensor Web development. Within the context of the Sensor Web, the term of "spatial is special" means that handling spatial properties of the sensor networks requires special algorithms, data models, databases, query languages, data presentations, graphical user interfaces, system architectures, etc. In other words, we require a special type of Sensor Web; one that is concerned with the spatial properties of the sensor networks.

Therefore, the ***Spatial Sensor Web (SSW)*** is defined as a special type of Sensor Web; one that is concerned with the spatial properties of the sensing entities within the Sensor Web. Such a Sensor Web should allow: (1) sensors to publish their geographically referenced sensing resources (including both the sensor data and sensor processing); (2) users to find sensing resources in their areas of interest; and (3) users to access, understand and use these geographically-referenced sensing resources.

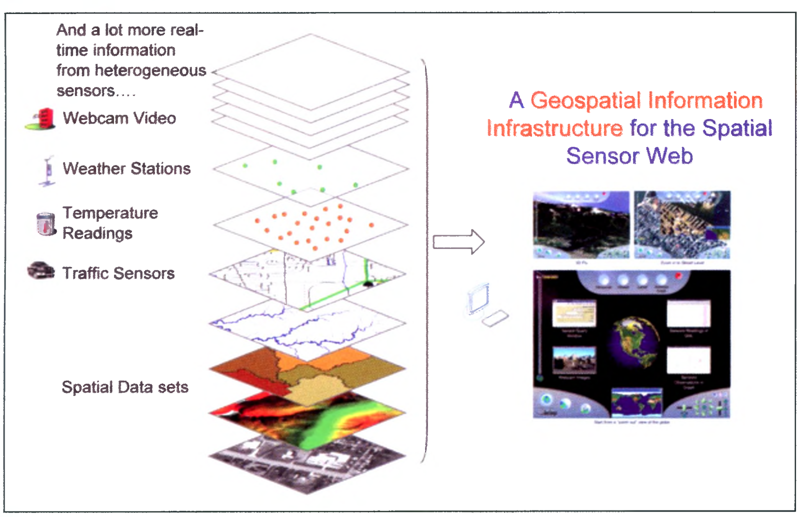

Figure 4. A conceptual diagram of the SSW from a SSW client's perspective

Figure 4 shows a conceptual diagram of a Spatial Sensor Web (SSW). The left side of the figure shows that the SSW connects and organizes distributed and heterogeneous sensor networks in a way similar to GIS layers and makes them accessible according to their spatial properties through an SSW browser/client, which is shown at the right side of the figure. In other words, we can see the SSW as a geospatial information infrastructure for sensor networks.

A Spatial Sensor Web Example: the OGC Sensor Web Enablement (OGC SWE)

The most practical way to demonstrate the Sensor Web concept is to show a Sensor Web example and to show how to use the Sensor Web to solve real-world problems. In this section, we use a wild fire scenario, composed by Open Geospatial Consortium (OGC), to show readers the OGC Sensor Web components and how these components work together for a real-world application. OGC is one of the pioneers leading the research and development of Sensor Web. OGC's Sensor Web Enablement (SWE) provides an architecture and a suite of standards that serves as the building blocks for an interoperable Sensor Web.

At the GeoICT Lab, we developed an OGC Sensor Web browser, called GeoSWIFT 1.0 SWE 3D Client[4]. GeoSWIFT client is a 2D/3D geospatial information visualization system capable of connecting to multiple OGC geo-data web services and OGC SWE services. It provides a unified global context where users can access, visualize and analyze geospatial information from standards-based interoperable OGC web services. Starting from a 'zoomed out' view of the globe, users can select an area of interest anywhere on earth, navigate to it, search and discover sensors, query the sensors (e.g., observations and sensor metadata), task sensors, and receive notifications from the sensors. Next, we use the GeoSWIFT client to illustrate the wildfire scenario, which was a live demonstration that was executed in an OGC demonstration event (OWS-3) in October 2005.

Background

A wildfire in the hills surrounding San Diego was reported to a wildfire monitoring facility. The location of the fire was identified in the report. The report indicated that the wildfire was threatening a chemical warehouse nearby. Recognizing the risk that a resulting wildfire could spread to the chemical warehouse, a disaster manager in the fire monitoring facility quickly started the GeoSWIFT 1.0 client and connected to the Sensor Web in order to monitor and evaluate the wildfire scene and to support the response effort.

Scene 1: Wildfire was identified

Scenario: A disaster manager started the GeoSWIFT client, and from a "zoomed-out" view of the globe, navigated to the area of interest. The map shown on the screen (Figure 5) was composed of geo-data drawn from multiple Web Map Servers (WMS) and Web Coverage Servers (WCS) over the Internet, where the WMSs provided satellite images and WCSs provided the digital elevation model.

Figure 5. Load the base map of the identified wild fire site

Scene 2: Discover sensors within the interested area

Scenario: The disaster manager queried Sensor Registries in search of any weather sensors near the area of interest. This was initiated based on domain expert knowledge that real-time weather conditions are vital in chemical fire emergencies; this stems from the fact that wind speed and wind direction are important factors effecting the direction of the movement of fire and chemical plumes.

The disaster manager used the GeoSWIFT client to connect to multiple Sensor Registries[5]. Through the registries, he submitted a keyword search with the keyword "weather" in order to find any Sensor Observation Services (SOS) (Na and Priest, 2005) offering some real-time weather observations geographically close to the chemical fire. The registries found one SOS fulfilling the search criteria, and the information about the SOS (e.g., capabilities of the SOS) was shown on the GeoSWIFT client window (Figure 6).

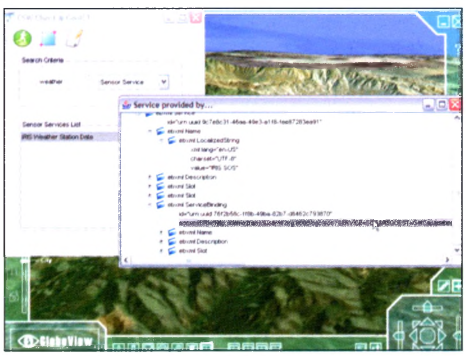

Figure 6. Discover sensors within the area of interest

Scene 3: Access to the weather SOS for timely observations

Scenario: Following this, the disaster manager connected to the weather SOS[6], and fetched the real-time weather observation streams. After the connection was established, the weather SOS started streaming the real-time weather observations to the client. The streamed readings were then shown on the map screen. Once data had arrived, the readings were updated every few seconds (Figure 7).

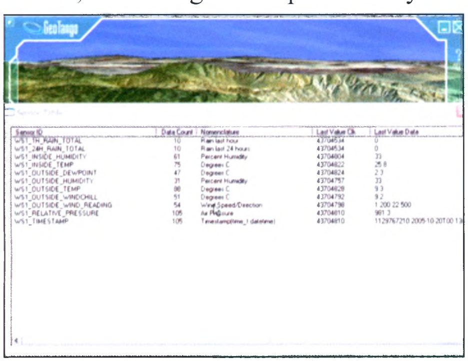

Figure 7. Accessed to the weather SOS for timely observations

Scene 4: Task an Unmanned Aerial Vehicle (UAV) Sensor Planning Service to perform a sensing mission

Scenario: The disaster manager then submitted a second geographical query to the registries in search of more relevant sensors. He was interested in knowing the geographical extent of the wildfire and he wished to locate a sensor that offered information on the spread of the wildfire. Luckily, he found a Sensor Planning Service[7] (SPS) (Simonis, 2005) of a fire scanner mounted on a UAV. Through the SPS, he realized that the UAV's sensing range covered the wildfire scene.

Interacting with the SPS, the disaster manager established a feasible sensing task plan, submitted the plan, and received a task id. In the sensing task plan, he requested the fire scanner to scan the fire scene and to notify him via email after the mission was completed. With the task id, he could even use the GeoSWIFT client to modify or cancel the sensing task before the start of the mission.

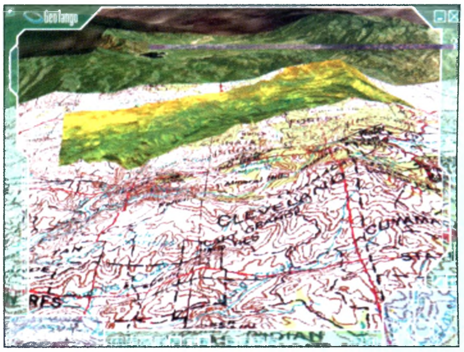

Figure 8. Display the result of the UAV SPS

Figure 8 shows the scanning result of the UAV SPS. Through the image captured by the fire scanner, the disaster manager realized that the wildfire had not yet spread to the chemical warehouse.

Scene 5: Task a video camera SPS to perform a sensing mission

Scenario: Despite knowing that the wildfire had not yet spread to the chemical warehouse, the disaster manager was still interested in monitoring the inside of the factory building. He thus submitted another geographical query to the sensor registries in search for any relevant sensors available within the warehouse. One of the sensors found by the registries caught the disaster manager's attention. The registries showed a network video camera located in the chemical warehouse. It would allow the emergency response team to monitor the chemical warehouse via the SSW before arriving at the building. Moreover, from the information offered by the registry, the disaster manager realized that the network video camera was controllable through an SPS[8]. Through the SPS, the disaster manager retrieved the SensorML document describing that particular camera and learned that the camera offered zoom in/out, pan, and tilt functions (Figure 9).

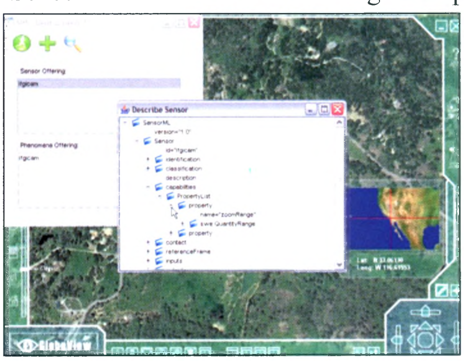

Figure 9. Display the capabilities of the network video camera

After learning the capabilities of the camera, the disaster manager could then use the client to interact with the SPS and compose a feasible sensing task plan. After the SPS confirmed that the task was feasible, the disaster manager submitted the sensing task to control the camera to point toward his view of interest. Once the sensing task was executed, the disaster manager could then forward the real-time video stream to the ground crews (Figure 10).

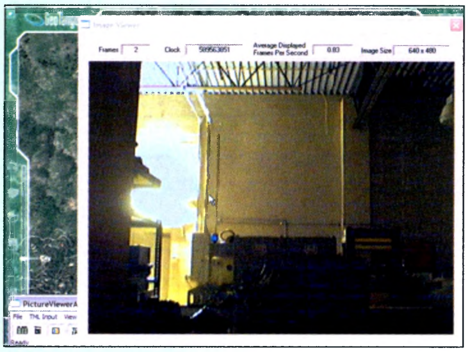

Figure 10. Access the video captured by the network video camera SPS

The above scenario looks just like a story in a Hollywood movie. However, it was a real Sensor Web prototype demonstration that was executed in 2005. Although it was just a prototype and only a few Sensor Web nodes were involved, we believe soon there will be more new nodes joining the Sensor Web. More and more innovative Sensor Web applications will also be developed in the very near future. Next, we conclude with a discussion of the implications that the emerging Sensor Web concept has for GIS research.

Discussion: Sensor Web and GIS

Bell's Law of Computer Classes (Bell *et al.,* 1972) predicts that roughly every decade a new, lower priced computer class forms based on a new programming platform, network, and interface, resulting in new usage and the establishment of a new industry. The computer classes that have formed based on Bell's Law include: mainframes in the 60's, minicomputers in the 70's, personal computers in the 80's, and the Internet computing in the 90's. According to Bell's personal web site (http://research.microsoft.com/~GBell/) he considers the wireless sensor network as the newest computer class that is gradually forming now.

We should not be surprised by the fact that the GIS architectural evolution actually follows Bell's Law. In the last three decades, GIS architecture has evolved from mainframe GIS, to desktop GIS, to Internet GIS. As a result, we can foresee that sensor networks, as the next upcoming computer class, will bring significant impacts and challenges to the existing GIS architecture. The new computer class will once again stimulate the next GIS architecture evolution.

We believe that we are currently in a transition period between the old and new GIS architecture. Sensor networks are one major force behind the ongoing GIS evolution. Today, the new wave of GIS architecture evolution has just begun. We now anticipate the 'next wave' in sensing, where the Sensor Web represents a new generation GIS that links to massive numbers of distributed sensors and provides enormous amounts of real-time spatially relevant data.

Let's revisit the famous quote by Mark Weiser in 1991: *"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it."* (Weiser, 1991) We believe this vision is also applicable to describing the Sensor Web. Today, we give little thought to the modern electrical grid and what our lives would be like without it. Tomorrow we will give little thought to sensor networks and the Sensor Web that has grown to impact every aspect of our lives. The Sensor Web will weave itself into our everyday lives until it is indistinguishable.

References

Akyildiz, I.F., Su, W., Sankarasubramaniam, Y. and Cayirci, E., 2002. A Survey on Sensor Networks. IEEE Communications Magazine, 40(8): 102-114.

Bell, C.G., Chen, R. and Rege, S., 1972. Effect of Technology on Near Term Computer Structures. Computer, 5(2): 29-38.

Berners-Lee, T., 1997. World-Wide Computer. Commun. ACM, 40(2): 57-58.

Delin, K.A. and Jackson, S.P., 2001. The Sensor Web: A New Instrument Concept, SPIE's Symposium on Integrated Optics, San Jose, California, USA.

Egenhofer, M.J., 1993. What's Special about Spatial?: Database Requirements for Vehicle Navigation in Geographic Space, Proceedings of the 1993 ACM SIGMOD international conference on Management of data. ACM Press, Washington, D.C., United States, pp. 398-402.

Estrin, D., Michener, W. and Bonito, G., 2003. Environmental Cyberinfrastructure Needs for Distributed Sensor Networks, National Scientific Foundation.

Gibbons, P.B., Karp, B., Ke, Y., Nath, S. and Srinivasan, S., 2003. IrisNet: An Architecture for a Worldwide Sensor Web. IEEE Pervasive Computing, 2(4): 22-33.

Hart, J.K. and Martinez, K., 2006. Environmental Sensor Networks: A revolution in the earth system science? Earth Science Reviews, 78: 177-191.

Hill, J. et al., 2000. System Architecture Directions for Networked Sensors. ACM SIGPLAN Notices, 35(11): 93-104.

Liang, S.H.L., Croitoru, A. and Tao, V., 2005. A Distributed Geospatial Infrastructure for Sensor Web. Computers and Geosciences, 31(2): 221-231.

Lorincz, K. et al., 2004. Sensor Networks for Emergency Response: Challenges and Opportunities. IEEE Pervasive Computing, 3(4): 2004.

Mainwaring, A., Polastre, J., Szewczyk, R., Culler, D. and Anderson, J., 2002. Wireless Sensor Networks for Habitat Monitoring, 2002 ACM International Workshop on Wireless Sensor Networks and Applications, Atlanta.

Na, A. and Priest, M., 2005. OpenGIS Sensor Observation Service Implementation Specification. OGC 05-088.

NASA, 2007. Report from the Earth Science Technology Office (ESTO) Advanced Information Systems Technology (AIST) Sensor Web Technology Meeting, NASA, San Diego, CA.

Paul, J.L., 2006. Smart Sensor Web Web-based Exploitation of Sensor Fusion for Visualization of the Tactical Battlefield, IEEE Aerospace and Electronic Systems Magazine, pp. 29-36.

Polastre, J.R., 2003. Design and Implementation of Wireless Sensor Networks for Habitat Monitoring, University of California at Berkeley, Berkeley, 67 pp.

Ray, S., Ungrangsi, R., Pellegrini, F.D., Trachtenberg, A. and Starobinski, D., 2003. Robust Location Detection in Emergency Sensor Networks, IEEE INFOCOM 2003.

Simonis, I., 2005. OpenGIS Sensor Planning Service Implementation Specification. OGC 05-089.

Tao, V., Liang, S.H.L., Croitoru, A., Haider, Z.M. and Wang, C., 2003. GeoSWIFT: an Open Geospatial Sensing Services for Sensor Web, GeoSensor Network Worshop 2003, Portland, USA.

Teillet, P.M., Gauthier, R.P., Chichagov, A. and Fedosejevs, G., 2002. Towards integrated Earth Sensing: Advanced Technologies for In Situ Sensing in the Context of Earth Observation. The Canadian Journal of Remote Sensing, 28-6: 713-718.

Warneke, B., Last, M., Liebowitz, B. and Pister, K.S.J., 2001. Smart Dust: Communicating with a Cubic-Millimeter Computer. IEEE Computer Magazine.

Waterworth, G. and Chave, A., 2004. A New Challenge and Opportunity for the Submarine Telecommunications Industry - Ocean Observatory Networks, SubOptics 2004, Monaco.

Weiser, M., 1991. The computer for the 21st century. Scientific American, 265(3): 66-75.

Worboys, M.F., 1995. GIS: A Computing Perspective. Taylor & Francis.

Zhao, F., 2006. Keynote Speech: Sensors Meet World Wide Web: Searching and Organizing World's Real-time Information, Ubiquitous and Trustworthy Computing (SUTC' 06), Taiwan.

Zuniga, M. and Krishnamachari, B., 2003. Integrating Future Large-scale Wireless Sensor Networks with the Internet. USC Computer Science Technical Report CS 03-792.

[1] BusinessWeek, Aug. 30, 1999; http://www.businessweek.com/1999/99_35/b3644024.htm

[2] By sensor network, here we mean a group of networked sensors. This can be a wireless sensor network (e.g., MICA2 motes), a group of networked weather stations, a group of webcams, or even a group of micro-satellites.

[3] A list of deployed sensor networks for environmental applications can be found in Hart, J.K. and Martinez, K., 2006. Environmental Sensor Networks: A revolution in the earth system science? Earth Science Reviews, 78: 177-191.

[4] GeoSWIFT 1.0 SWE 3D Client's visualization engine is built upon GeoTango's GlobeViewTM 3D software.

[5] Sensor Registries were provided by Ionic SOFTWARE (http://www.ionicsoft.com/index.jsp) and CubeWrex (http://www.cubewrex.com)

[6] The Weather SOS was offered by IRIS Corp. http://www.iriscorp.org/index.html

[7] The UAV SPS was provided by NASA Ames Research Center. http://www.nasa.gov/centers/ames/home/index.html

[8] The SPS was provided by Institut für Geoinformatik, University of Muenster, Germany