International Journal on Advances in Networks and Services, vol 3 no 3 & 4, year 2010, http://www.iariajournals.org/networks_and_services/

Live Geography: Interoperable Geo-Sensor Webs Facilitating the Vision of Digital Earth

Bernd Resch [1,2]
Research Scientist
bernd.resch@researchstudio.at

Thomas Blaschke [1]
Head of Department
thomas.blaschke@sbg.ac.at

Manfred Mittlboeck [1]
Key Researcher
manfred.mittlboeck@researchstudio.at

[1] Research Studios Austria
studio iSPACE
Leopoldskronstrasse 30
5020 Salzburg, Austria

[2] MIT
SENSEable City Lab
77 Massachusetts Avenue
building 10, room 400
Cambridge, MA 02139, USA

Abstract – **In the last decade, rapidly declining sensor costs and intense research in sensor technologies lead to the deployment of a number of sensor networks. However, most of these sensor networks are monolithic stovepipe-like systems causing limited interoperability and reusability of both data and workflow components. We present a Live Geography approach which integrates real-time measurement data in a fully standardised infrastructure and couples it with Complex Event Processing (CEP). We demonstrate the interoperability of this geo-sensor web approach and the resulting high degree of flexibility and portability beyond single monitoring applications generally and for five concrete real-world implementations in different application fields. We prove that the Live Geography approach allows for reacting to observed changes through sophisticated embedded processing based on OGC standards such as Sensor Observation Service (SOS) and Sensor Alert Service (SAS). Finally, we discuss how this approach contributes to the vision of Digital Earth as described by Al Gore in 1998 and how it contributes to monitor continuously the status of the environment, of urban infrastructure and the location and health conditions of persons to support an understanding of dynamic processes, to enhance prediction of developments, and to serve Spatial Decision Support Systems.**

Keywords – Live Geography; Standardised Geo-sensors; Embedded Sensor Webs; OGC Sensor Web Enablement; Interoperable Monitoring Systems; Digital Earth.

I. INTRODUCTION

Monitoring single environmental parameters is established in many fields such as measuring water levels, precipitation, air quality, or traffic volume, and plenty more. Especially in urban areas the need for monitoring capabilities is increasing both from a technical side in regard to urban management, infrastructure planning and development capabilities, as well as from a more citizen-centered perspective aiming to support health applications, quality of life, or „geodemographics". The latter term shall be a synonym for analysing the „Where" of people, groups and populations based on tight coupling of absolute locations of individuals, relative movements and – if available – further parameters of the individuals.

The ability to monitor the behaviour of people is still very limited for most city administrations. A mayor or a responsible security manager is usually not able to state how many people are at a certain place at a certain time. One department may know the number of vehicles travelled at an inbound route over the last hour, another information system may report on air quality. Existing demographics may reveal where people sleep or work but do not directly tell how many persons may be present at a certain central place in a city, e.g., at 10am on a Monday morning. Surveillance cameras may provide a first picture at critical locations, but are typically not meant to be quantitatively exploited or in regard to spatial movement patterns.

In other words, integrated monitoring capabilities are critical in cities to ensure public safety including the state of the national infrastructure, to set up continuous information services, and to provide input for spatial decision support systems [1].

However, establishing an overarching monitoring system is not trivial. Up to now, different authorities with heterogeneous interests each implemented their own monolithic sensor systems to achieve specific goals. For instance, regional governments measure water levels for flood water prediction, while local governments monitor air quality to dynamically adapt traffic conditions, and energy providers assess water flow in order to estimate energy potentials. However, these data are mostly not combinable due to different data formats, proprietary protocols or closed-off data access.

This restricts automated workflows and machine-to-machine communication, and prohibits the achievement of the long-term vision of a „digital skin for the Earth" [2], comprised of innumerable heterogeneous sensors, discoverable and accessible over the internet.

In this regard, it is interesting to read how the future of the year 2010 was predicted in 1999: "Ten years from now, there will be trillions of such telemetric systems, each with a microprocessor brain and a radio. Consultant Ernst & Young predicts that by 2010, there will be 10,000 telemetric devices for every human being on the planet. They'll be in constant contact with one another" [2]. This optimistic view may have been inspired by the famous speech of the American Vice-President Al Gore in 1998 [3].

"Digital Earth" was and still is a vision of a multi-resolution, three-dimensional representation of the planet that would make it possible to find, visualise, and make sense of vast amounts of geo-referenced information on the physical and social environment. Such a system would allow users to navigate through space and time, access to historical data as well as future predictions based for example on environmental models, and support access and use by scientists, policy-makers, and children alike [3].

At this time, this vision of Digital Earth seemed almost impossible to achieve given the requirements it implied about access to computer processing cycles, broadband internet, interoperability of systems, and above all data organisation, storage, and retrieval [4].

Generally speaking, the integration of inhomogeneous data poses great challenges, e.g., regarding multi source and heterogeneous, multi-disciplinary, multi-temporal, multi-resolution, and multi-media, multi-lingual information. It is more and more believed that interoperability is key to a success of ubiquitous monitoring. This requires data pre-processing following strict and rigid rules in monolithic sensor systems, in order to fit the specific non-recurring interfaces of the analysis system. Such analysis systems mostly analyse data in a closed black-box model, and usually provide data in a singular and application-tailored format preventing open use and re-use of processed data. When these systems are deployed in an isolated and uncoordinated way automatic assembly and analysis of these diverse data streams is impossible. However, making use of all available data sources is a prerequisite for holistic and successful monitoring for broad decision support using pervasive measurement systems. Thus, recent research increasingly addresses standardised interoperable sensor devices enabling the establishment of portable domain-independent sensing infrastructures [5], [6], [7].

This vision of fully integrated and interoperable sensing workflows fosters awareness for the benefits of open measurement systems. This is especially important for critical monitoring tasks such as emergency management, environmental monitoring or real-time traffic planning, which are not only relevant to the sensor network operators, but also for the city management and for the citizens.

This paper presents the Live Geography approach, which proposes a fully standards-based distributed infrastructure combining current sensor data with Complex Event Processing (CEP) mechanisms, alerting and server-based analysis systems for a wide range of monitoring applications [8]. This approach's main contribution is the creation of a generic standardised sensing and analysis infrastructure, which can be applied to a variety of end applications. This paper illustrates how the developed technical infrastructure can be applied in a broad range of application contexts. The architecture itself and its performance are described in more detail in [8] and in [9], respectively.

This paper is structured as follows. After this introduction, Section II presents related work in the field of distributed sensing infrastructures; Sections III and V describe the Live Geography approach and its deployment in various heterogeneous application areas; Section IV illustrates the challenges and our specific implementation of geo-sensor webs, while Section VI contains a short conclusion.

II. RELATED WORK

The Oklahoma City Micronet [10] is a network of 40 automated environmental monitoring stations across the Oklahoma City metropolitan area. The network consists of 4 Oklahoma Mesonet stations and 36 sites mounted on traffic signals. At each traffic signal site, atmospheric conditions are measured and transmitted every minute to a central facility. One major shortcoming of the system is that it is a highly specialised implementation not using open standards or aiming at portability. The same applies to CORIE [11], which is a pilot environmental observation and forecasting system (EOFS) for the Columbia River. It integrates a real-time sensor network, a data management system and advanced numerical models.

Another sensing infrastructure named *CitySense* is described by Murty et al. [12]. The CitySense project uses an urban sensor network to measure environmental parameters and is thus the data source for further data analysis. The project focuses on the development of a city-wide sensing system using an optimised network infrastructure.

King's College London designed an urban sensor network for air quality monitoring. The London Air Quality Network (LAQN) [13] currently consists of about 150 monitoring sites being a very promising approach to real-time monitoring as it also offers on-the-fly creation of statistic graphs, time series diagrams and wind plots. However, the network does not make use of open standards as a whole, meaning that it is built up in a closed system, although sensor data are accessible over the internet and despite the fact that this solution has a great local significance, but limiting trans-regional inter-linkage with other similar approaches.

One more example is the Networked Soil CO2 Sensing Systems developed by UCLA with the objective to examine the spatial and temporal heterogeneity of a soil environment within a forest area in the James Reserve. The soil environmental measurements are collected with ten stations, each of which consists of an array of belowground sensors including soil CO2, soil temperature, soil water content, and aboveground air temperature, relative humidity, and photosynthetic active radiation. Models are used that relate the aboveground microclimate and the soil measurements to belowground measurements made by the project's sensors to „map“ the microclimate in a fine-grained resolution, and investigate soil CO2 fluxes depending on the local characteristics of the forest cover story [14].

Volcano activity observation of the volcano Reventador in Ecuador in 2005–2008 is technically interesting with regard to the remoteness and inaccessibility of the area [15]. Two US Universities have collaborated for several sensor network deployments in the remote, inaccessible area at the active volcano. The objective of the sensor network was to test the ability to detect and measure tremor events of the volcano. The geo-sensor was deployed over a linear centrifugal stretch of 3Km network consisting of seismo-acoustic sensors. The sensor nodes used short-range, battery-preserving wireless multi-hop communication to communicate with each other and relay data, and the sensor network was connected via a long-distance radio communication link to a Freewave radio modem powered a solar-panel powered car battery at a make-shift observatory. The goal of the sensor network deployments was to detect and measure tremor events saved batteries lifespan. The nodes were programmed to compare a short-term average with a long-term average based on locally stored samples. If the difference was bigger than a threshold, a node would send a message to the base station. If a sufficient number of nodes reported an event, the base station triggered a data collection request to all nodes in the sensor network.

Among various examples for mobile geo-sensor networks consisting of individual sensor nodes that are mobile or attached to mobile objects one convincing example is the management of ocean buoys [16].

More recently, the Martha's Vineyard Coastal Observatory (MVCO), owned and operated by the Woods Hole Oceanographic Institution (WHOI), provided the test bed for the first part of the Q2O project, returning the GetCapabilities, DescribeSensor and GetObservation responses for real time offerings of waves every twenty minutes. Wave parameters are computed using an acoustic Doppler current meter, deployed at the 12m isobath continuously measuring pressure and horizontal velocity at 2 Hz. SensorML instances and SOS offerings were developed, describing the sensor characteristics, system provenance and lineage, and the computation of the derived wave height parameters. Quality control tests recommended by the Waves Team of QARTOD were implemented and reported through the SWE offerings [17].

Most of these examples – and many others - exhibit pioneering efforts and contributed significantly to the development of Geo-Sensor Webs. However, common shortcomings of the approaches described above and other related efforts are that the system architectures are at best partly based on open (geospatial) standards, and thus limit interoperability of data and services. Such systems are not able to tackle the challenges of numerous sensors which are built in masses today to observe the Earth surface, atmosphere, solid Earth, and the ocean in different dimensions. At a global level efforts to overcome these challenges are increasingly channelled by the Global Earth Observation (GEO) within the developing Global Earth Observation System of Systems (GEOSS) [5], [6].

Sensor derived information is not only been produced at various locations, with various accuracies, different timely and spatial acquisition patterns but also archived at widely distributed locations. The Live Geography approach employs the „Digital Earth“ vision for concatenating sensor information and other geospatial information which is also widely collected and archived with the aim to providing information services and ultimately solving challenging environmental and societal issues beyond single application domains. The Live Geography approach seeks to fully utilise all available information resources and to apply them „intelligently“. In the following section we will lay out how we ensure the information is being gathered, processed and distributed in a fully interoperable way through open, community-consensus standards among current users and how to process information on demand in order to use non-expert users.

III. LIVE GEOGRAPHY APPROACH

Utilisation of real-time data in GIS applications requires a rethinking of existing practices. The authors even believe that the next generation of GIS will be driven by process models in a sense that users' requests trigger algorithms and heuristics to perform specific services. An „on demand“ connection to information networks and an „intelligent“ harvesting of existing information in combination with real-time or near real-time data will be key in such a service-centred architecture. This may also require further advances in space-time data models ultimately contextualising Hägerstrand's vision of a time geography [18]. *The time-space path*, devised by Hägerstrand, shows the movement of an individual in the spatial-temporal environment with the constraints placed on the individual by these two factors. Only for the last few years, we are able to utilise location information from GPS, mobile phones or indoor navigation systems to make such concepts operational. Even more recently, researchers study the behavior of groups or larger populations of cities or accessibility aspect based on the space-time model [19].

At present, we may diagnose that Geographic Information Systems begin to evolve from „classic“ geospatial data analysis to more „on demand“ analysis. The GIS workflow established in the 1960ies and 1970ies may be deliberately characterised that analysis is performed in costly specialised software involving a high degree of manual intervention for data gathering, pre-processing and quality assurance. Furthermore, geospatial analysis has in a vast majority of cases been applied to „not up-to-date" data (at the very time of the analysis) with typically long cycles from data generation to analysis output and a real-world impact. While custodial GIS may predominantly still be associated with this style of information processing research in Geographic Information Science has paved the road towards „information harvesting“ on demand in spatial data infrastructures (see various publication in the recent issues of „International Journal of Digital Earth" or „International Journal of Spatial Data Infrastructures Research“).

Generally speaking, sensor webs have only emerged very recently because of increasingly reliable communication technologies, affordable embedded devices and growing importance of sensor data for (near) real-time decision support (see discussion in Section V). They monitor phenomena in Geographic space [20].

The criteria for sensor webs are threefold. The first characteristic is *interoperability*, which means that different types of sensors should be able to communicate with each other and produce a common output. The requirement of *scalability* implies that new sensors can be easily added to an existing topology without necessitating aggravating changes in the present hardware and software infrastructure. Finally, *intelligence* means that the sensors are able to „think“ autonomously to a certain degree, which could for instance result in a data processing ability in order to only send required data.

In a recent overview on Geo-Sensor Webs [21] three major trends are identified: the first trend is the currently more readily available technology of seemingly ubiquitous wireless communication networks, including access in remote and inaccessible areas without a wired communication infrastructure and often without even power lines. Furthermore, significant progress has been made in the development of low-power, short-range radio-based communication networks, which augment existing long-distance wireless communication networks. Second, the miniaturisation of computing and storage platforms has led to low power consumption and has enabled novel computational platforms that can run on battery power for extended periods of time (e.g., several months with today's technology). The third major trend is the development of novel sensors and sensor materials; this includes improved and size-reduced traditional sensors as well as the development of novel micro-scale sensors and sensor materials. For example, novel bio-chemical sensors may be used in the marine sciences or air pollution monitoring, or highly sensitive vibration and sound sensors have been applied for volcano monitoring.

Operational real-world sensor network applications are still rare and the majority still serves a single purpose, which limits broader usage of measurement data. This section presents the Live Geography approach. It proposes a flexible and portable measurement infrastructure enabling a wide variety of real-time and near real-time monitoring applications. The system makes extensive use of open (geospatial) standards throughout the entire process chain – from sensor data integration to analysis, Complex Event Processing (CEP), alerting, and finally information visualisation. The basic architecture for such applications is illustrated in Fig. 1.

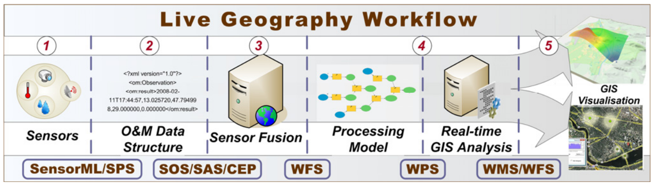


Figure 1. Basic Architecture Components and Standardised Interfaces of the Live Geography Infrastructure.

Generally speaking, the infrastructure shown in Fig. 1 can be sub-divided in five components, i.e., stand-alone parts, which have to be conflated. Component **1** is the geo-sensor network itself including measurement devices Global Navigation Satellite System (GNSS) connectivity and basic processing capabilities. Component **2** covers the communication of the sensor network with a data centre via a variety of wireless and wired transmission technologies. Component **3** deals with sensor fusion, i.e., the harmonisation of measurements stemming from different heterogeneous sensor networks. Component **4** comprises the application-specific analysis of the sensor data on the server side. This operation does not only include pure sensor data processing, but also the integration of static and legacy geospatial data. Component **5** finally treats the presentation of analysed data depending on the particular requirements of end users or user groups.

As the Live Geography approach accounts for the entire workflow, it builds the architectural bridge between domain-independent sensor network development and use case specific requirements for end user sensitive information output.

The implementation of the Live Geography approach only became feasible through the sharp decline of sensor costs over the last decade and intense research in sensor technologies (for an overview see [21]). This fact, together with miniaturisation efforts, increasing monitoring demands due to increasing pressure on resources, environmental regulations, security regulations and – at least partially - rising awareness of the benefits of automated real-time sensor applications, resulted in the deployment of a number of geo-sensor networks.

This in turn will result in the emergence of vast amounts of sensor data during the next years. A main challenge will be to harmonise these data and integrate them in real-time into geospatial analysis systems.

IV. LIVE GEOGRAPHY: IMPLEMENTATION OF AN INTEROPERABLE EMBEDDED GEO-SENSOR WEB

A. Standardisation Enabling Open Measurement Infrastructures

The increasing amount of data measured triggers a more extensive use of open standards and geospatial web services for structuring and managing heterogeneous data. The Open Geospatial Consortium (OGC) has achieved remarkable progress in setting up necessary standards (see Sub-section IV.C). One of the remaining challenges is the distributed processing of large amounts of sensor data in real-time, as the widespread availability of sensor data with high spatial and temporal resolution will increase dramatically with rapidly decreasing prices [8], [21], particularly if costs are driven down by mass utilisation.

From a political and legal standpoint, national and international legislative bodies are called upon to foster the introduction of open standards in public institutions. Strong early efforts in this direction have been made by the European Commission through targeted, including the INSPIRE (*INfrastructure for SPatial InfoRmation in*

Europe), which aims at Europe-wide harmonisation of discovery and usage of geographical data for analysing and solving environmental problems [22].

These regulations both trigger and support the development of ubiquitous and generically applicable real-time data integration mechanisms. Shifting development away from proprietary single-purpose implementations towards interoperable analysis systems will not only enable live assessment our environment, but can also lead to a new perception of our surroundings in general, e.g., expressed by the vision of a “digital skin” [1]. Consequently, this trend may in turn foster the creation of innovative applications that treat the city as an interactive sensing platform, as the *WikiCity* concept [23], involving the people themselves into re-shaping their own socio-technical context. This way, we may enable a manifestation of the vision of “citizens as sensors” [24].

B. *Embedded Device Hardware*

The measurement device for the concrete implementation presented in this paper has been particularly designed for pervasive GIS applications using ubiquitous embedded sensing technologies. The system has been conceived in such a modular way that the base platform can be used within a variety of sensor web applications such as environmental monitoring, biometric parameter surveillance, critical infrastructure protection or energy network observation by simply changing the interfaced sensors.

The sensor pod itself consists of a COTS embedded device, ISEE IGEPv2 platform including an ARM7-based Cortex A8 600MHz processor with 512MB RAM and 32MB flash memory. Generally speaking, ISEE offers a highly modular and easily expandable system. The computer-on-module (the actual embedded device including CPU, memory and some interfaces) offers two I/O ports, which allows for extensibility of the basic system by specific modules such as GPS, Bluetooth, WiFi, LAN, interface breakouts or a console board for programming the device.

In the configuration for the specific implementation presented within this paper, different sensors (GPS module, LM92 for ambient temperature, SHT15 for air temperature and humidity, NONIN 8000SM oxygen saturation and pulse, or SSM1 radiation sensors) have been attached via standardised interfaces like UART, I^2C, USB, etc. The technical specifics of the sensor pod are described by Resch et al. [9].

The size of the complete sensor pod is approximately 93x65x10mm, i.e., about the size of a chewing gum package. In full load, the device features an energy consumption of <2.2W including a running data query, the GPS module and data transmission via UMTS, which is known to be comparatively energy intensive way of broadcasting data. This configuration yields an operation time of 9.1 hours given a battery capacity of 4000mAh, which is held by a reasonably-sized rechargeable Lithium-ion Polymer (LiPo) battery (140x40x10mm) – whereby capacity and required sizes depend on the specific use case.

C. *Embedded Software Infrastructure*

The sensing device runs a customised version of the *Ångström* Linux distribution (kernel version 2.6.33) with an overall footprint of about 2MB. The software infrastructure comprises an embedded secure web server (Lighttpd), an SQLite database and several daemons, which convert sensor readings before they are served to the web. The database serves for short-term storage of historic measurements to allow for different error detection procedures and plausibility checks, as well as for non-sophisticated trend analysis.

The hardware drivers for interfacing sensors and reading their measurements make up the low-level part of the embedded software infrastructure. As the geographical position is an essential must-parameter in geo-sensor networks, the sensor pod interfaces a location sensor (e.g., a GPS/Galileo module, a ZigBee/WiFi-based positioning component, etc.).

These measurements are then read by a special sensor daemon that essentially builds the bridge between the sensors and the internal software components. These data are then stored into an embedded database (SQLite), which is held at a maximum data set volume, currently 12500 readings.

The sensor data, which is stored in the database, is then accessed from two different web servers (HTTP/HTTPS and XMPP [Extensible Messaging and Presence Protocol]), which make the measurements accessible from the internet. HTTPS is considered a high enough security level for this implementation providing a secure channel between server and client using the Secure Socket Layer (SSL) protocol. Web Service Security (WSS) would be a viable alternative providing message-based security. However, as WSS is using the SOAP protocol, it is characterised by large overhead, which is not suitable for embedded sensor unit implementations.

Communication of the sensing device with other components in the workflow is based on open standards of the Sensor Web Enablement (SWE) family [25]. This requires a SensorML-conformal description of the measurement platform, Observations and Measurements (O&M) compliant encapsulation of measurement values, as well as an SAS-compliant alerting module. In addition, an embedded database has to be implemented directly on the sensor device to provide for the possibility of short-term data storage, which enables trend analysis and quality assurance, and reduces communication overhead with the central archive database. Thus, the device also implements the following essential standards of the SWE family:

- *Observations & Measurements (O&M)* – O&M allows for the formalised description of sensor measurements in a structured XML-based encoding schema. Thus, O&M can map sensor parameters and their relations. Measurements are organised by quantities, categories as well as their spatial and temporal characteristics.
- *Sensor Model Language (SensorML)* – The Sensor Model Language (SensorML) is a general schema for describing functional models of the sensor.

Information provided by SensorML includes observation and geometry characteristics as well as a description and a documentation of the sensor, and a history of the component's creation, modification, inspection or deployment.

- *Sensor Observation Service (SOS)* – SOS allows for standardised access to sensor measurements (return type O&M) and their platform descriptions (return type SensorML) via a web service interface [26].
- *Sensor Alert Service (SAS)* – SAS is a service for the surveillance of pre-defined rules and trigger specified actions in a particular workflow in case of violation of these rules.

D. In Detail: Embedded Sensor Observation Service (SOS) and Sensor Alert Service (SAS)

The embedded SOS implements the three mandatory methods, *DescribeSensor*, *GetCapabilites* and *GetObservation*. Basically, the service, which is implemented in Common Gateway Interface (CGI), parses the request and creates the according response using appropriate XML templates.

The SOS harmonises raw sensor measurements by encapsulating them into pre-defined XML-based OGC O&M format. This allows for the provision of sensor measurements (numerical values, raster images, binary states, complex or combined measurement data, etc.) in a structured and standardised format.

For generating alerts, the OGC Sensor Alert Service (SAS) standard has been implemented for mobile sensor devices. SAS, which is part of the SWE initiative, specifies interfaces (not a service in the traditional sense) enabling sensors to advertise and publish alerts including according metadata. Alerts are defined as "data" sent from the SAS to the client, which may as well comprise alerts/notifications (e.g., OGC Web notification service [WNS]) as observational data (measurements matching pre-defined criteria) or a Complex Event Processing Engine (CEP). As SAS is based on the standardised XMPP protocol, alerts can be broadcasted very efficiently over the internet to subscribed consumers.

The service implementation presented in this paper supports the mandatory operations as specified in the standard, namely *DescribeSensor*, *DescribeAlert*, *GetCapabilities*, *Subscribe*, *RenewSubscription* and *CancelSubscription* [27].

In this case, SAS is an asynchronous service connecting a sensor in a network to an observation client. In order to receive alerts, a client subscribes to the SAS. If the defined rules apply, a pre-defined alert is sent to the client via XMPP. It shall be stated that the whole communication between the embedded XMPP server (jabberd2) and the client is XML-based for simplifying M2M messaging.

V. LIVE GEOGRAPHY PORTABILITY – IMPLEMENTED END APPLICATIONS

This section describes five concrete real-world implementations in different application fields in order to demonstrate that the approach is highly portable, interoperable and flexible in terms of trans-domain usage and integration of heterogeneous data sources. This again builds the basis for the deployment of an overarching monitoring infrastructure for solving real-time analysis questions across a variety of research and service areas.

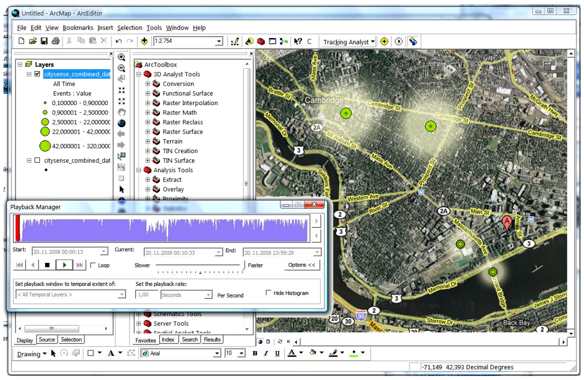
A. Live Pollutant Monitoring for Public Health

The Common Scents project focuses on real-time pollutant monitoring for public health. As Zardini [28] states, "we have renounced the utopian idea of a socially, politically, and economically perfect city, but not the promise of a perfectly clean and sanitised environment with pure air for breathing."

Thus, the goal of the project, which is a concerted effort of the MIT SENSEable City Lab, the Research Studio iSPACE, the Harvard University Sensor Networks Lab, the City of Cambridge's Public Health Department, and BBN Technologies, is to provide fine-grained air quality information layers in near real-time. To achieve this vision, the CitySense sensor testbed [12] is utilised, measuring CO_2 concentrations along with environmental parameters like wind speed, air temperature, and relative humidity.

The empirical project goal is to provide citizens with up-to-date information to support short-term decisions in real-time. Here, the term "real-time" is not defined by a pre-set numerical time constant, but more by qualitative expressions such as "immediately" or "ad-hoc", i.e., information layers are created in a timely manner to serve application-specific purposes. Detailed results are presented by Resch et al. [29].

The actual implementation shown in Fig. 2 allows for correlating temporal measurement data fluctuation to traffic density, and other day-time related differences. The lower left part of Fig. 2 shows the temporal development of the sensor values, which have been integrated in the standardised O&M format. Running the time series dynamically changes symbologies in the map on the right side accordingly.



Untitled - ArcMap - ArcEditor

1:2.754

Layers

citysense_combined_dat

All Time

Events : Value

0,100000 - 0,900000

0,900001 - 2,500000

2,500001 - 22,00000(

22,000001 - 42,00000(

42,000001 - 320,000(

citysense_combined_dat

Playback Manager

Start: 20.11.2008 00:00:13

Current: 20.11.2008 00:10:33

End: 20.11.2008 23:59:29

Set playback window to temporal extent of: < All Temporal Layers >

Set the playback rate: 1,00 Seconds Per Second

☐ Loop

☐ Hide Histogram

-71,149 42,393 Decimal Degrees

Figure 2. Time Series Visualisation of Pollutant Measurements in an ESRI ArcGIS software environment.

B. *Fine-grained Air Temperature Variations*

Another implementation of the Live Geography has been done in the course of the Real-time Geo-awareness project in a cooperative effort of the Research Studio iSPACE and SYNERGIS Informationssysteme GmbH. Apart from the establishment of the technical components (sensor devices, data integration and analysis), the project's aim was to create a sensor network for fine-grained temperature variation assessment.

The pervasive deployment of temperature sensors can lead to a detection of urban heat islands with a fine spatial resolution. Furthermore, the temperature measurements can be used for correlation with other environmental parameters such as air pollution, ozone or emissions caused by increased traffic emergence. Thus, an essential part of this particular implementation is the alerting functionality, which is achieved by the use of an OGC Sensor Alert Service (SAS), generating alerts according to pre-defined events, i.e., exceedance of pre-defined thresholds. These events are detected by a Complex Event Processing (CEP) engine that also serves for data quality control by identifying measurement outliers and performing other spatio-temporal plausibility controls.

Fig. 3 shows the three-dimensional Inverse Distance Weighting (IDW) interpolation result of air temperature values provided by various OGC Sensor Observation Services (SOS). More implementation details are described by Resch et al. [8].

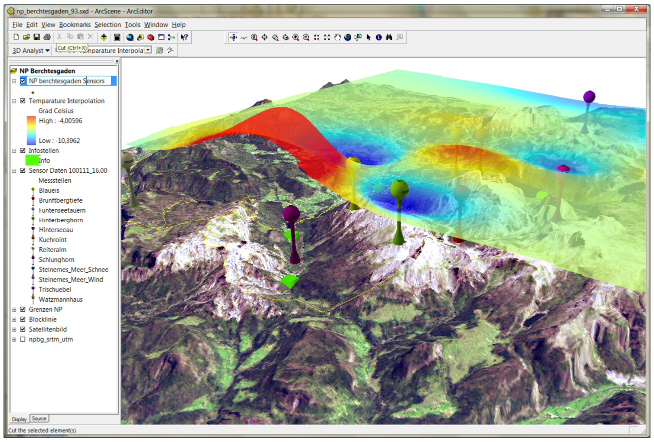


Figure 3. Real-Time Interpolation of Ambient Temperature Values for Monitoring Optimal Environmental Parameters for the Local Fauna and Flora in the National Park Berchtesgaden, Germany.

C. *Ubiquitous Biometric Parameter Surveillance*

The geoHealth Monitor instance of the Live Geography approach responds to the needs of pervasive medical care. The system uses biometric sensors measuring a person's pulse and oxygen saturation in the blood. The project itself has been carried out in cooperation between the Research Studio iSPACE and Salzburg University of Applied Sciences.

The web interface shown in Fig. 4 comprises three sections. Firstly, a configuration panel to select a particular sensing device including different measurement parameters such as the update frequency or the number of measurements stored in the history. The middle section presents the temporal history of OGC Sensor Web Enablement conformal sensor data, which allows for intuitive visual assessment of the measured parameters. Finally, the map on the right side of the interface shows the last few positions of the measurement device to keep track of its spatial trace.

It shall be stated the geoHealth Monitor application cannot only be used for patient surveillance, but may also be employed for equipment tracking, control of the food supply chain including the goods' measured quality condition, or for keeping track of a stolen car.

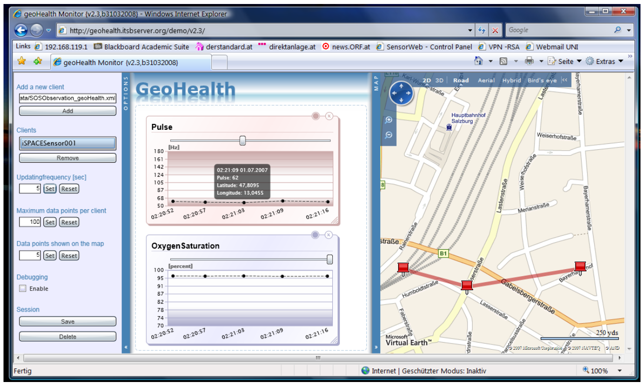


Figure 4. Illustration of a "GeoHealth" application: Biometric Parameter History with Geographical Location Illustration demonstrated in a MS Silverlight environment.

D. *Real-time Air Quality Assessment*

GENESIS (GENeric European Sustainable Information Space for environment), an FP7-funded collaborative research project, has two basic aims: 1.) to establish an open and standards-based infrastructure for managing, analysing and providing environmental information, and 2.) to demonstrate the efficiency of the solution through thematic pilots in different areas within environmental pilot deployments for air quality, water quality and associated health impacts.

The Live Geography approach supports the GENESIS project as it builds the technological foundation for the thematic pilots by providing mechanisms for measurement data provision (Sensor Observation Service), sensor fusion (GeoServer data store), alerting (SAS and CEP) and server-based data analysis (ArcGIS Server application). Fig. 5 illustrates the web interface for live geo-data analysis of environmental information implemented in a kriging process. A special focus in GENESIS is on the coupling of SAS and CEP including the evaluation of the OGC Sensor Event Service (SES), which is widely seen as the successor of SAS. In the project, CEP serves for detecting complex patterns in sensor data related to spatial and temporal parameters as well as measurement values. Another emphasis is on integrating legacy GIS systems (ArcGIS Server, GRASS GIS, etc.) with the standardised OGC Web Processing Service (WPS) interface to achieve a wholly standardised workflow coupled by a Business Process Execution Language (BPEL) engine.

The Live Geography solution is likely to be integrated into the overall GENESIS infrastructure, which finally aims at Europe-wide Spatial Data Infrastructure (SDI) harmonisation and provision of a complete infrastructure for standardised data access and analysis. For more information on the architecture and outcomes, see [30].

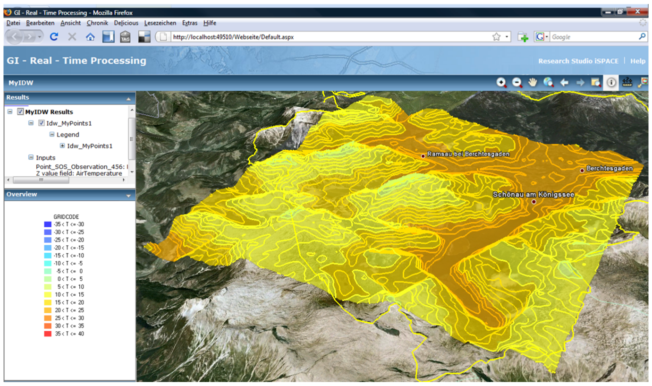


Figure 5. Web-based Live Geo-processing for Fine-grained Real-time Assessment of Urban Air Quality.

E. *Real-time Decision Support for Radiation Safety*

Finally, the Live Geography workflow has been applied and evaluated in the course of the FP6 ERA Star *G2real* project exercise 'Shining Garden' in Seibersdorf, Austria. The field trial setup consisted of modules for live in-situ sensing of gamma radiation (using the SSM-1 radiation detection unit developed by Seibersdorf Laboratories), live geo-processing of radiation measurements, and rapid mapping of up-to-date multi-dimensional sensor information.

The purple dots in Fig. 6 represent the trace of the radiation safety expert carrying the sensor device. Location data and radiation measurements were collected every second. These sensor data were spatially interpolated (in this case using the Inverse Distance Weighting – IDW algorithm). Partitions 1-6 in the figure below show the growing interpolation result in chronological order.

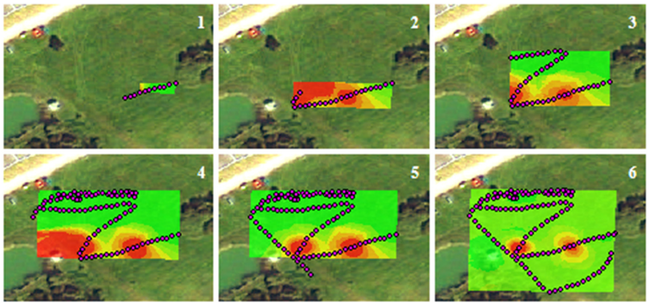


Figure 6. Growing Interpolation Result for Radiation Source Identification.

Results of this experiment confirm that the Live Geography workflow significantly enhances both spatial and situational awareness of people in charge. This in turn enhances time-critical spatial decision support. Detailed results of the field test can be found in [31]. General design challenges are discussed in [9].

VI. DISCUSSION AND CONCLUSION

With the prerequisites and challenges of real-time monitoring in mind, we developed the Live Geography approach. It provides an interoperable, modular and flexible distributed sensing and data analysis infrastructure – as opposed to previous monolithic sensor networks. Thus, it stands for the integration of real-time measurement data in a fully standardised infrastructure for real-time monitoring applications including web-based data processing.

The main benefit of the Live Geography architecture presented in this paper is its composition in loosely-coupled and service-oriented building blocks. This allows for decoupling sensor fusion from CEP, data analysis and visualisation components, enabling flexible and dynamic service chaining. Consequently, the whole infrastructure can be ported easily to various application domains by changing the sensors (what shall be measured) and the process models (how shall the measurements be analysed).

To demonstrate the Live Geography approach's portability, five concrete real-world implementations in different application fields have been presented in this paper. This is to show that the approach is highly portable and flexible in terms of trans-domain usage and integration of heterogeneous data sources. This again builds the basis for the deployment of an overarching monitoring infrastructure for solving real-time analysis questions across a variety of research and service areas. In the future, platforms may generally get more lightweight and portable, which opens up a plethora of new application areas for which platforms have been too expensive or too difficult to deploy before. Another important aspect is real-time data delivery of information on demand.

Consequently, it can be stated that a substantial benefit of the approach is that the developed infrastructure is applicable to a wide variety of cross-domain use cases due to its high degree of interoperability, modularity and flexibility.

With the dramatic decrease of sensor costs as occurring recently, it can be assumed that even larger and even more heterogeneous amounts of measurement data will be available in the near future. A major future research task will be the standardisation and combination of these heterogeneous data sources using internationally standardised interfaces. Recently, several „testbed", „experiment", or „pilot" activities are carried out worldwide such as the Web Services-OWS7 Testbed initiative the OGC which demonstrated the advantages of interoperable measurements infrastructures generally, the OGC Ocean Science Interoperability Experiment (Oceans IE) or the GEOSS Architecture Implementation Pilot. To summarise, although SWE is still evolving and new services will be developed to satisfy emerging requirements of sensor web development OGC and ISO standards for „localised information“ discovery, retrieval and communication are increasingly providing a baseline needed for interoperability and portability. Furthermore, SensorML can be used outside the scope of SWE enabling long-term archive of sensor data to be reprocessed and refined in the future allowing software systems to process, analyse and perform a visual fusion of multiple sensors [32].

Further research will elucidate the applicability of the Live Geography approach for situation awareness. Although preliminary work has demonstrated the potential of using combination of prevailing sensor data with real-time processing mechanisms to achieve situational awareness for an instantaneous assessment of environmental conditions [33] the advantage of the complete system described in this paper is that hitherto GIS approaches, which offered GIS functionality only in resource-consuming desktop applications, can be replaced by web-based analysis tools. GIS operations are performed on server-side whereas the results are sent to the client, which can for instance be an internet-connected personal computer in the mission control centre or also a tablet PC used by action forces on-site. This will allow for a real-time situational awareness making emergency and rescue actions much more efficient. Situational awareness is the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future [28]. In the context of sensor data about the real world, this may be translated to: (1) detecting and recognising objects and events, (2) determining how they are interrelated, and (3) predicting how things are going to change over a period of time going forward [34]. These developments may change the GIS community significantly and they do so already. Geo-processing featured prominently in the early origins of online GIS where server-based GIS delegated much of the work that a desktop-client would perform to the background, hidden from the user [35].

The Live Geography approach has been made possible through the availability of both the body of standards described herein and the GIS-based investigation tools: we can build the means to facilitate analyses and appropriate characterisations of various processes involved many application areas proofed for five different applications. In turn, we might hope to achieve the further problem formalisation steps thanks to the result of our better understanding of complex systems. This is a prevalent topic in Geographic Information Science [36]. We are making progress beyond a reconstruction of the current state of the world from sensor data to reasoning from observed effects to possible causes. Predicting the future states or course of action is akin to deduction in logic, that is, reasoning from causes to effects [34]. In the future, situation awareness applications may benefit from symbolic representation of the state of the world by adding spatial reasoning capacities to our interoperable framework and by incorporating schemes from time geography into the Live Geography approach allowing structured queries to be performed on data’s temporal and spatial attributes simultaneously.

The ability to obtain all kinds of sensor information at decreasing costs with higher measuring accuracies unlocks research potential and potentially end user applications to creating information at ever higher abstraction levels. This may cause now types of problems. The ability to determine and view locations and associated sensing information with high accuracy is increasingly in the hands of millions of people. Commonly available high-resolution digital terrain and aerial imagery, coupled with GPS-enabled handheld devices, powerful computers, and Web technology, is ultimately changing the quality, utility, and expectations of GIS to serve society. Analytic methods for non-expert users will need to be provided as millions of internet users learn to use data with greater detail and intensity, especially in terms of temporal resolution and the resulting amount of data and level of detail but they may not be aware of basic statistical and cartographic principles. GIS is more and more to be viewed as a media that helps data producers to communicate Geographic information in various forms to receivers, just as newspapers and television communicate more general forms of information [37].

Concluding, it shall be constituted that the main challenge in geo-sensor web research for monitoring applications in the coming years will be to harmonise existing networks with upcoming initiatives in order to guarantee optimal data availability for assessing environmental dynamics. As laid out, this requires a shift from monolithic single-purpose sensor systems to interoperable measurement infrastructures, which necessitates adequate public awareness and policy frameworks. This in turn allows for the straight-forward use of live sensor data in existing spatial decision support systems.

ACKNOWLEDGMENT

Our approach requires expertise in a wide variety of research areas such as sensor networks, data integration, GIS data and analysis, visualisation techniques, etc. We would like to thank all contributing groups at the Research Studio iSPACE, at MIT, at Salzburg University of Applied Sciences for their valuable inputs and contributions in different stages of the development process.

Parts of the developments presented in this paper have been funded by the European Commission (FP7 project *GENESIS*, ref. no. 223996 and ERA STAR Regions project *G2real*, ref. no. 819747) and the Austrian Federal Ministry for Science and Research.

REFERENCES

[1] Resch, B. and Mittlboeck, M. (2010) Live Geography - Interoperable Geo-Sensor Webs Enabling Portability in Monitoring Applications. In: Proceedings of the 2nd IEEE International Conference on Advanced Geographic Information Systems, Applications, and Services - GEOProcessing 2010, St. Maarten, Netherlands Antilles, 10-15 February 2010, pp. 74-79.

[2] Gross, N. (1999) 14: The Earth Will Don an Electronic Skin. http://www.businessweek.com, BusinessWeek Online, 30 August 1999. (2 January 2011)

[3] Gore, A. (2010) The Digital Earth: Understanding our planet in the 21st Century. Speech by Vice President Al Gore, Given at the California Science Center, Los Angeles, California, on January 31, 1998. http://www.isde5.org/al_gore_speech.htm. (4 January 2011)

[4] Craglia, M., Goodchild, M.F., Annoni, A., Camara, G., Gould, M., Kuhn, W., Mark, D., Masser, I., Maguire, D., Liang, S., and Parsons, E. (2008) Next-Generation Digital Earth: A Position Paper from the Vespucci Initiative for the Advancement of Geographic Information Science. International Journal of Spatial Data Infrastructures Research 1(3), pp. 146-167.

[5] Yang, C., Li, W., Xie, J., and Zhou B. (2008) Distributed Geospatial Information Processing: Sharing Distributed Geospatial Resources to Support Digital Earth. International Journal of Digital Earth, 1(3), pp. 259–278.

[6] Nativi, S. (2010) The Implementation of International Geospatial Standards for Earth and Space Sciences. International Journal of Digital Earth, 3(S1), pp. 2–13.

[7] Percivall, G. (2010) The Application of Open Standards to Enhance the Interoperability of Geoscience Information. International Journal of Digital Earth, 3(S1), pp. 14–30.

[8] Resch, B., Mittlboeck, M., Girardin, F., Britter, R., and Ratti, C. (2009) Live Geography – Embedded Sensing for Standardised Urban Environmental Monitoring. International Journal on Advances in Systems and Measurements, 2(2&3), ISSN 1942-261x, pp. 156-167.

[9] Resch, B., Lippautz, M., and Mittlboeck, M. (2010) Pervasive Monitoring - A Standardised Sensor Web Approach for Intelligent Sensing Infrastructures. Sensors - Special Issue "Intelligent Sensors 2010", 10(12), 2010, pp. 11440-11467.

[10] University of Oklahoma (2009) OKCnet. http://okc.mesonet.org, March 2009. (12 January 2011)

[11] Center for Coastal and Land-Margin Research (2009) CORIE. http://www.ccalmr.ogi.edu/CORIE, June 2009 (14 July 2009)

[12] Murty, R., Mainland, G., Rose, I., Chowdhury, A., Gosain, A., Bers, J., and Welsh, M. (2008) CitySense: A Vision for an Urban-Scale Wireless Networking Testbed. Proceedings of the 2008 IEEE International Conference on Technologies for Homeland Security, Waltham, MA, May 2008.

[13] King's College London (2009) The London Air Quality Network. http://www.londonair.org.uk, August 2009. (3 February 2011)

[14] Vargas, R., Allen, M., Swenson, W., and Hamilton, M. (2005) Soil Embedded Networked Systems for Studying Soil Carbon Dynamics: the A-MARSS Project. In Proceedings of Third USDA Symposium on Greenhouse Gases and Carbon Sequestration in Agriculture and Forestry, Baltimore, MA, USA, March 21–24, 2005.

[15] Werner-Allen, G., Lorincz, K., Ruiz, M., Marcillo, O., Johnson, J., Lees, J., and Welsh, M. (2006) Deploying a Wireless Sensor Network on an Active Volcano. IEEE Internet Computing 2006, 10, pp. 18–25.

[16] Nittel, S., Trigoni, N., Ferentinos, K., Neville, F., Nural, A., and Pettigrew, N. (2007) A Drift-tolerant Model for Data Management in Ocean Sensor Networks. Proceedings ACM MobiDE'07, Beijing.

[17] Fredericks, J.J., Botts, M., Cook, T., and Bosch, J. (2009). Integrating Standards in Data QA/QC Into OpenGeospatial Consortium Sensor Observation Services. IEEE Xplore Oceans, 2009.

[18] Hägerstrand, T. (1953) Innovationsförloppet ur korologisk synpunkt, C.W.K Gleerup, Lund, Sweden. Translated as Innovation Diffusion As a Spatial Process, Chicago, University of Chicago Press, 1967.

[19] Pulselli, R.M., Romano, P., Ratti, C., and Tiezzi, E. (2008) Computing Urban Mobile Landscapes Through Monitoring Population Density Based on Cell-phone Chatting. International Journal of Design & Nature and Ecodynamics, 3(2), pp. 121-134.

[20] Nittel, S., Labrinidis, A., and Stefanidis, A. (2006) Introduction in Geosensor Networks. In: Geosensor Networks Nittel, S., Labrinidis, A., Stefanidis, A. (eds.), Springer Lecture Notes in Computer Science 4540, Heidelberg, pp. 1-6.

[21] Nittel, S., (2009) A Survey of Geosensor Networks: Advances in Dynamic Environmental Monitoring. Sensors 9(7), pp. 5664-5678.

[22] European Commission (2009) INSPIRE Directive. http://inspire.jrc.ec.europa.eu, August 2009. (7 February 2011)

[23] Resch, B., Calabrese, F., Ratti, C., and Biderman, A. (2008) An Approach Towards a Real-time Data Exchange Platform System Architecture. In: Proceedings of the 6th Annual IEEE International Conference on Pervasive Computing and Communications, Hong Kong, 17-21 March 2008.

[24] Goodchild M.F. (2007) Citizens as Sensors: Web 2.0 and the Volunteering of Geographic Information. *Geofocus*, 7, pp. 8-10.

[25] Botts, M., Percivall, G., Reed, C., and Davidson, J. (Eds.) (2007) OGC® Sensor Web Enablement: Overview and High Level Architecture. http://www.opengeospatial.org, OpenGIS White Paper OGC 07-165, Version 3, 28 December 2007. (17 January 2011)

[26] Na, A. and Priest, M. (Eds.) (2007) Sensor Observation Service. http://www.opengeospatial.org, OpenGIS Implementation Standard OGC 06-009r6, Version 1.0, 26 October 2007. (12 January 2011)

[27] Simonis, I. (Ed.) (2007) Sensor Alert Service. http://www.opengeospatial.org, Candidate OpenGIS Interface Standard OGC 06-028r5, Version 0.9.0, 14 May 2007. (19 January 2011)

[28] Zardini, M. (Ed.) (2006) Sense of the City: An Alternate Approach to Urbanism. 352 pp., ISBN 3-03778-060-6, Lars Müller Publishers, Baden, Switzerland, 2006.

[29] Resch, B., Britter, R., and Ratti, C. (2011) Live Urbanism - Towards the Senseable City and Beyond. In: Pardalos, P. and Rassia, S. (Eds.) (2010) Sustainable Architectural Design: Impacts on Health.

[30] Resch, B., Mittlboeck, M., Lipson, S., Welsh, M., Bers, J., Britter, R., and Ratti, C. (2009) Urban Sensing Revisited – Common Scents: Towards Standardised Geo-sensor Networks for Public Health Monitoring in the City. In: Proceedings of the 11th International Conference on Computers in Urban Planning and Urban Management - CUPUM2009, Hong Kong, 16-18 June 2009.

[31] Sagl, G., Lippautz, M., Resch, B., and Mittlboeck, M. (under review) Near Real-Time Geo-Analyses for Emergency Support: An Exercise for Radiation Safety. In: Proceedings of the 14th AGILE Conference on Geographic Information Science, Utrecht, The Netherlands, 18-21 April 2011.

[32] Chu, X. and Buyya, R. (2007) Service Oriented Sensor Web. In: Mahalik, N. (ed.) Sensor Networks and Configuration Fundamentals, Standards, Platforms, and Applications, Springer, Berling, Heidelberg, pp. 51-74.

[33] Endsley, M. R. (1995) Toward a Theory of Situation Awareness in Dynamic Systems. Human Factors 37(1), pp. 32-64.

[34] K. Thirunarayan, Henson, C., and Sheth, A. (2009) Situation Awareness via Abductive Reasoning from Semantic Sensor Data: A Preliminary Report. International Symposium on Collaborative Technologies and Systems (CTS2009), Workshop on Collaborative Trusted Sensing, Baltimore, Maryland, 2009.

[35] Torrens, P. (2009) Process Models and next-Generation Geographic Information Technology. ArcNews 31(2), pp. 1-5.

[36] Blaschke, T. and Strobl, J. (2010) Geographic Information Science Developments. GIS.Science. Zeitschrift für Geoinformatik 23(1), pp. 9-15.

[37] Sui, D. (1999) GIS as Media? Or How Media Theories Can Help Us Understand GIS and Society. In: Sheppard, E. and McMaster R. (eds.), GIS and Society: An International Perspective.