Live Geography – Interoperable Geo-Sensor Webs Enabling Portability in Monitoring Applications

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Abstract – In the last decade, rapidly declining sensor costs triggered intense research in sensor technologies and vice versa. This fact led to the deployment of a number of sensor networks. However, these sensor networks tend to be deployed in monolithic stovepipe-like systems, limiting interoperability and reusability of both data and workflow components. This paper presents the Live Geography approach, which stands for the integration of real-time measurement data in a fully standardised infrastructure. A particular focus of this paper is dedicated to interoperable geo-sensor webs featuring a high degree of flexibility and portability can be deployed in various monitoring use cases in a variety of application domains.

Keywords – Live Geography; Standardised Geo-sensors; Embedded Sensor Webs; Interoperable Monitoring Systems.

I. INTRODUCTION

Ubiquitous monitoring is a critical process 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.

However, establishing an overarching monitoring system is not trivial. Currently, different authorities with heterogeneous interests each implement their own monolithic sensor systems to achieve very 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 (M2M) communication, and prohibits the achievement of the long-term vision of a “digital skin for the earth” [1], which is comprised of innumerable heterogeneous sensors, discoverable and accessible over the internet.

Moreover, data pre-processing has to follow 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.

The fact that these systems tend to be deployed in an isolated and uncoordinated way means that the 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 tends towards standardised interoperable sensor devices enabling the establishment of portable domain-independent sensing infrastructures.

This vision of fully integrated and interoperable sensing workflows fosters the 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 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 [2]. 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 [3] 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 [4], 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 is described in [5]. 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.

[6] presents an urban sensor network for air quality monitoring. The London Air Quality Network (LAQN) 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. However, this shortcoming makes it another stand-alone solution of great local significance, but limiting trans-regional inter-linkage with other similar approaches.

The most striking shortcoming of the approaches described above and other related efforts is that their system architectures are at best partly based on open (geospatial) standards, and thus limit interoperability of data and services.

III. Live Geography Approach

Utilisation of real-time data in GIS applications requires a rethinking process of existing practices. At present, geospatial data 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 is per definition applied on historic data with long cycles from data generation to analysis output and a real-world impact.

Moreover, current real-world sensor network applications are rare and mostly serve a single purpose, which limits broader usage of measurement data. This section presents the Live Geography approach, which proposes a flexible and portable measurement infrastructure enabling a wide variety of 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 coupled is illustrated in Fig. 1.

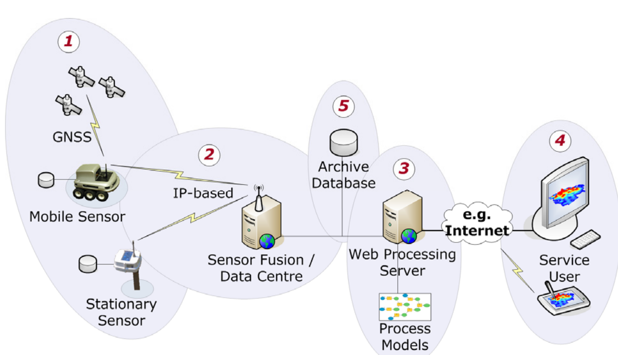

Figure 1. Basic Architecture Components of the Live Geography Infrastructure.

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, including data transmission, harmonisation and integration. Component **3** 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 **4** treats the presentation of analysed data depending on the particular requirements of end users or user groups. Component **5** finally deals with the archiving process of sensor data in order to store longer-term measurement histories and to disburden the sensor network itself, which can only store a limited amount of data.

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.

IV. Interoperable Embedded Geo-sensor Webs

The basis for the creation of our approach – as presented in section III – are strongly decreasing sensor costs during the last decade, which triggered intense research in sensor technologies and vice versa. This fact, together with miniaturisation efforts and 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.

A. Standardisation Enables Open Measurement Infrastructures

One way to address this issue is the extensive use of open standards and geospatial web services for structuring and managing heterogeneous data. In this context, the main challenge 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 [2], 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 (EC) 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. [7]

These regulations 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. 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 [8], involving the people themselves into re-shaping their own socio-technical context.

B. *Features of Geo-sensor Webs*

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 real-time decision support.

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 e.g. result in a data processing ability in order to only send the required data.

C. *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, a Gumstix Verdex XM4 platform including an ARM7-based 400MHz processor with 64MB RAM and 16MB flash memory. Generally speaking, Gumstix 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 size of the complete sensor pod is approximately 80x20x30mm, 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) – where its capacity and size is naturally dependent on the specific use case.

D. *Embedded Software Infrastructure*

The sensing device runs a customised version of the "Open Embedded" Linux distribution (kernel version 2.6.21) with an overall footprint of about 8MB. The software infrastructure comprises an embedded secure web server (Nostromo nhttpd), 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 the 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 occurs on the basis of open standards of the Sensor Web Enablement (SWE) family [9]. 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. [10]
- *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.

1) Embedded Sensor Observation Service

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.

2) Embedded Sensor Alert Service

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*, as described in [11].

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

To demonstrate our approach's portability, this section covers four concrete real-world implementations in different application fields. This is to show 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 the use case of real-time pollutant monitoring for use in the public health sector. As [12] 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 [5] is utilised, measuring CO_2 concentrations together with environmental parameters like wind speed, air temperature, and relative humidity.

The empirical project goal is to provide citizens with unknown up-to-date information to support their short-term decisions in real-time. In this case, 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 have to be created in a timely manner to serve application-specific purposes.

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.

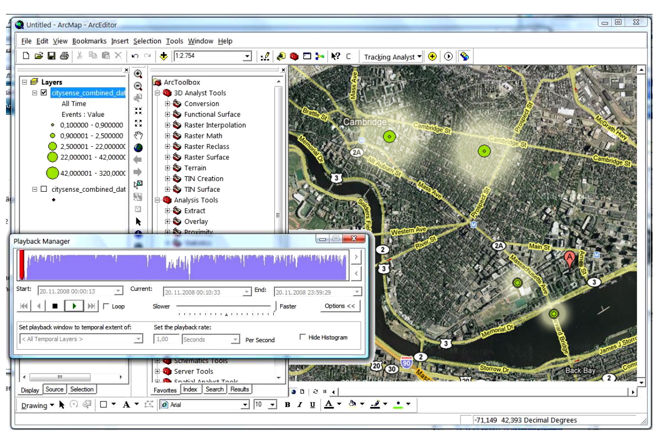

Figure 2. Time Series Visualisation of Pollutant Measurements.

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).

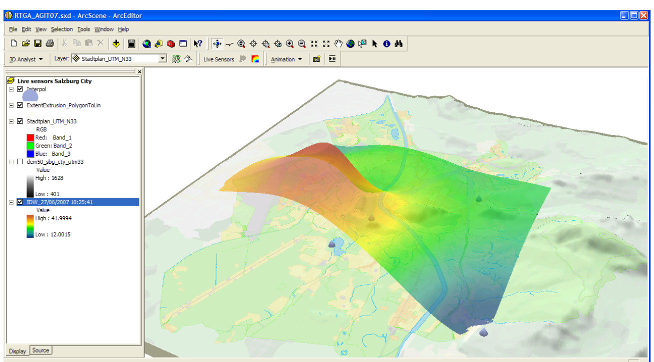

Figure 3. Interpolation of Temperature Values for the Detection of Urban Heat Islands.

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.

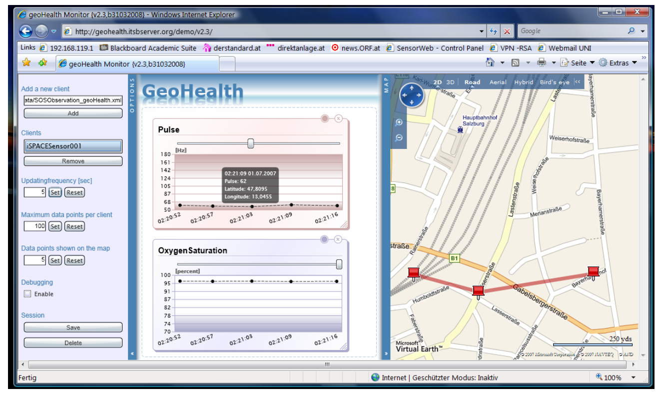

Figure 4. Biometric Parameter History with Geographical Location Illustration.

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.

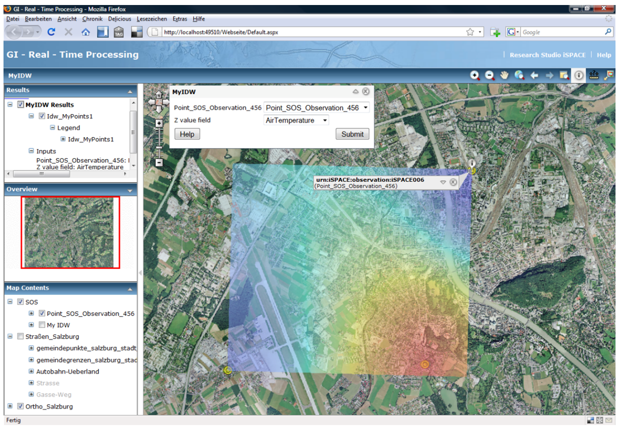

Figure 5. Web-based Live Geo-processing for Environmental Monitoring.

VI. Discussion and Conclusion

With the prerequisites and challenges of real-time monitoring in mind, we developed the Live Geography approach. It suggests the establishment of 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 system 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, 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.

To demonstrate the Live Geography approach's portability, four 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.

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 efforts. This will guarantee optimal data availability for assessing environmental dynamics. However, this implies a shift from developing monolithic single-purpose sensor systems towards creating interoperable measurement infrastructures, which requires 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.

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