Development of a Sensor Web-based Disaster Decision Support System for Integrating Multi-agency Sensor Information

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Key words: Multi-agency, Disaster management, Sensor information integration, In situ sensing, OGC Sensor Web Enablement, Sensor web services

SUMMARY

The required information for managing and responding to rapid-onset disasters such as floods, storms and bushfires needs to be time-sensitive and highly dynamic. It is crucial for frequent updates regarding disaster information, as outdated data would only impair disaster management efforts. Currently, sensors have proven to be very important source of real-time information. A wide range of live data having potential for supporting disaster management can be observed by diverse types of already deployed sensors in an urban area. However, these multi-sourced sensor datasets are produced independently by disconnected sensor data producers. In this study, we investigate the process of integrating multi-agency sensor-derived information for supporting disaster management. The research assesses Australia's activities as the case study in disaster management of a flood by emphasizing on the response phase. Initially, this paper identifies the real-time sensor information flow and the existing issues, and proposes a new approach to overcome these integration issues. Afterwards, on the basis of the designed approach, IDDSS-Sensor is presented, which is a GIS-based disaster decision support system that provides the functions for standard-based access, exchange and usage of multi-vendor sensor information.

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1 INTRODUCTION

Spatial data and related technologies as the engine of disaster management (Donohue 2002, Mansourian, Rajabifard et al. 2006, Degrossi, Albuquerque et al. 2014), coupled with the ability to handle time-sensitivity and dynamism underlying emergency situations (Alamdar, Kalantari et al. 2014, Yulin, Yida et al. 2014) are the need of the time for an effective and efficient disaster management process. Therefore, it is essential that during the management of an emergency, real-time retrieval of dynamic spatial information by disaster responders and government agencies is ensured (Farnaghi and Mansourian 2013).

In situ sensing as an evolving spatial data sourcing technology provides the capability for automated collection of a vast variety of spatial information in real-time (Wang and Yuan 2010, Bonito 2013). The complications surrounding dynamism and time-sensitivity underlying emergency management can be potentially handled by integrating in situ sensing within the disaster management procedures. Nowadays, a significant amount of instantaneous spatial information required in disaster management is regularly obtained from different types of in situ sensors operating under the administration of independent organizations. Weather stations, rainfall and river height gauges, surveillance cameras, traffic and pedestrian monitoring sensors are some of the examples of in situ sensors that supply (near) real-time information from an urban environment.

Currently, despite the growing attention towards employing in situ sensors as a spatial information source for disaster management, actual application of sensor information through real-time integration of multi-agency produced sensor data has been less studied. The principle aim of this research is to improve the process for access, exchange and usage of multi-agency in situ sensor data for supporting disaster management decision making. Various decision-making support functions could be built based on sensing technology in the context of disaster management (e.g., monitoring the situation in the field of the operation, awareness of the status of each operator in the scene, etc.). These functions are required to support different tasks performing at both on-scene and operation centers. From the wide range of disaster decision-making tasks that sensing technology could be incorporated, this research mainly lies in the consideration of in-situ sensing for providing (near) real-time emergency information required at operation centers. Thus, what is needed is a way of making multivendor sensor data easily and immediately identifiable, accessible, usable, and beneficial across the operation centers, which are responsible for providing emergency intelligence to disaster decision-makers and the entire community. Herein, three main underlying stages are taken, as illustrated in Figure 1.

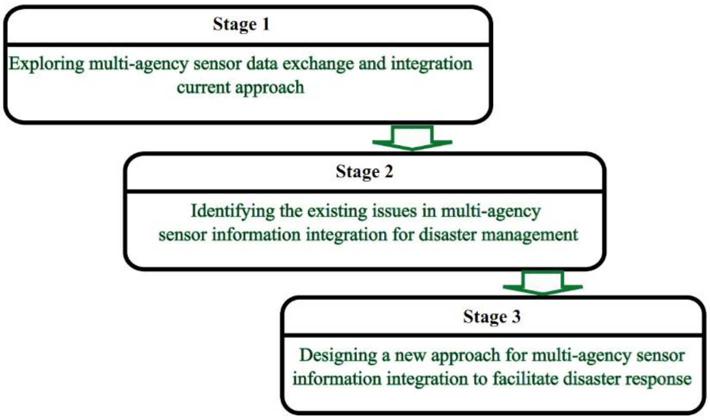

Figure 1: Methodology for designing automatic sensor data integration approach to facilitate disaster response.

In the first stage, to explore the existing issues, challenges and research questions, a case study was conducted on the current practices of multi-agency sensor information integration across emergency management sector, and particularly by the flood management agencies in the state of Victoria, Australia. In the second stage, the key issues in multi-agency sensor data sourcing across emergency management sector were identified. Based on the results of stages 1 and 2, in the third stage a new approach called IDDSS-Sensor was developed to improve access, exchange and usage of multi-agency sensor data in an urban flood response scenario.

The paper starts with a review of associated concepts, theories and related research work. Afterwards, the results of the conducted case study are presented. Finally, a new approach for multi-agency sensor information integration for disaster management and its associated architecture and technologies is presented.

2 BACKGROUND

With an emphasis on the spatial information required for disaster management, an overall review of the disaster domain is presented. Then, in situ sensing and its potential features for expediting multi-agency incident management are described. Finally, the related work on integrating sensory information for disaster management are presented and discussed briefly.

2.1 Disaster domain

Disaster management is the interagency coordination of sum of all the staged activities necessary in preparation, prevention, response, and recovery for disasters such as floods, wildfires and earthquakes (Mansourian, Rajabifard et al. 2006).

Currently, geo-information and related technologies play a pivotal role in all the phases of disaster management (Degrossi, Albuquerque et al. 2014). The spatial information essential for disaster decision-making in Emergency Operation Centers can be classified into static and dynamic datasets. Static spatial datasets are collected and kept up-to-date with a gradual and steady rate. Information about topographic and urban maps, geographic data, road and utility networks are of static type. In contrast, dynamic datasets are acquired and updated in near real-time or real-time. Meteorological observations, traffic and weather data, data about inundated areas and impaired facilities are of dynamic type. Associated stakeholders may obtain and update dynamic datasets prior to a disaster (e.g. traffic data), or afterwards (e.g. casualties health data).

Static and dynamic spatial information are required for supporting decision-making by providing shared situational awareness across multiple responder organizations (NICS 2015). In the context of dynamic information, responding and supporting the agencies currently contribute a variety of sensor resources to aid in awareness of the situation. A crucial challenge is derivation of actionable and useful information from such sensors commensurate with the ability to integrate their data in real-time (Alamdar, Kalantari et al. 2016).

2.2 In situ sensing domain

With the advancement of sensing and communication protocols, attention has been turning towards sourcing and providing disaster information from the sensors deployed in the field. This great variety of sensory information falls under the umbrella of in situ sensing, which is the collection of environmental data inside or in the proximity of a phenomenon (Teillet, Gauthier et al. 2002). A series of computerized devices called in situ sensors, or simply sensors, gather this data. A sensor is an observing or measuring device, which records environmental data such as rainfall, humidity, temperature, or location (Duckham 2013).

Sensors can monitor and provide remote access to many aspects of the disaster area, such as air, temperature, existence of hazardous materials, alongwith human movement during emergency situations (e.g., people and traffic). Integration of sensors and their observed data for disaster management applications has been mainly considered in two research directions, namely sensor network and sensor web. Sensor network research emphasises on the challenges related to deployment of a number of wirelessly communicating sensors in the disaster area, giving due consideration to the constrained energy resources and bandwidth of the network as well as underlying device layers and the network communication details (Werner-Allen, Lorincz et al. 2006, Kajimoto, Yokota et al. 2008, Song, Huang et al. 2009, Narayanan and Ibe 2012). Whereas, in sensor web research, the aim is to enable web-based discovery and usage of multisourced sensor-derived disaster information by hiding the heterogeneous sensor communication and protocol details (Jirka, Bröring et al. 2009, Wang and Yuan 2010, Dìaz, Bröring et al. 2013, Horita, Degrossi et al. 2015).

In most cases, providing raw sensor observations is not particularly beneficial to busy disaster decision-makers. An overwhelming flow of sensor data can, in fact, have negative impact as it increases the potential for data saturation, and consequently results into distraction of disaster responders. Deriving added-value disaster information from raw sensor data could significantly enhance the process of disaster response by providing only valuable and analyzed emergency information to decision-makers.

3 CURRENT PRACTICE

In the first stage of the research, through a case study approach (Yin 2013), the current status of real-time and inter-agency data provision in the state-wide emergency management of Australia was explored. The case study was undertaken in Victoria (a State in the south-east of Australia) with the aim of incorporating sensor datasets as a source of real-time information for supporting disaster decision-making.

In Australia, disaster management is performed based on inter-agency collaboration for various tasks pertaining to emergency command, control and coordination (EMA 1998). Performing these tasks required the shared resources and combined expertise of the emergency services, other government and private organizations, municipal councils and the people of the entire community (EMV 2014). Figure 2 provides an overview of the case study results in terms of real-time sensor-derived information flow across organizations involved in the disaster management of Victoria and their activities with regards to operating sensors.

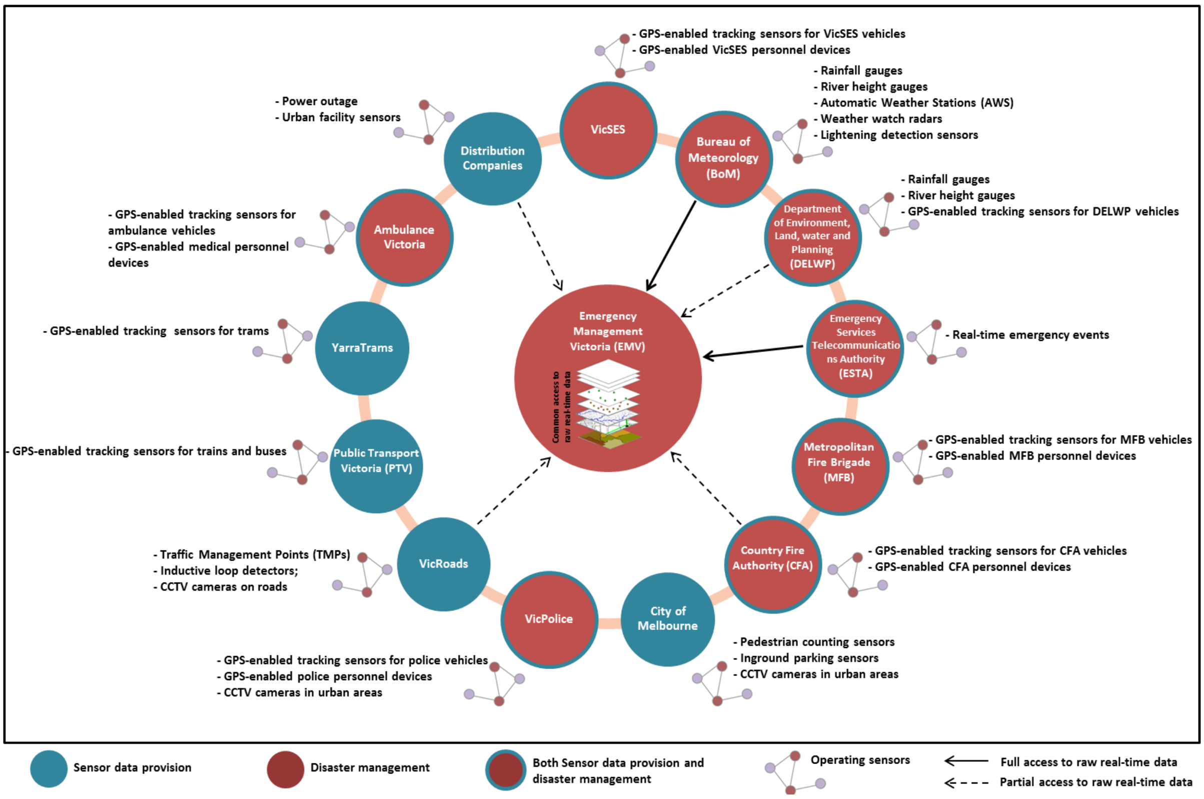

Figure 2: Current approach for multi-agency sensor information integration in emergency management community of Victoria, Australia.

While considering the multi-vendor sensor data provision for disaster management in Victoria, the central organization is Emergency Management Victoria (EMV) (EMV 2014), which is leading with emergency services to gather, store and provide real-time emergency information to stakeholders and community (EMV 2013). Hence, a desired workflow for EMV involves to make the multivendor sensor data easily and immediately identifiable, accessible, usable, and useful, so that value-added information reaches disaster decision-makers in a benefiting manner. Inline with this necessity, EMV has recently established web-based emergency management mapping applications (e.g., EM-COP (EMV 2014)) to provide emergency responders an environment to view multisourced real-time information.

As can be seen in Figure 2 (earlier), currently a number of sensor data producers share a part of their produced data with EMV in near real-time. EMV then provides shared view of the raw sensor data feeds, through visualizing the received data on a base map, based on the location and timestamp of the data sources.

The current approach for sensor information integration for disaster management does not adequately support:

a) on-demand access to multi-agency sensor data;
b) interoperability in multi-agency sensor data exchange;
c) overcoming the existing sources of inconsistency in the exchanged sensor data; and
d) automated usage of multi-agency sensor data.

Firstly, amongst a large number of sensor data producers, only a few made their sensor data to be readily accessible by EMV. As the result, the majority of produced sensor data remains inaccessible for EMO to provide disaster intelligence. Secondly, since sensor data producers mostly rely on proprietary formats and standards (e.g., raw text data, binary, or different XML variants) for storing and sharing their live data, utilization of such data for EMO turns into a non-interoperable and labour-intensive task. The third issue pertains to the lack of mechanisms for on-the-fly harmonization of the sensor data in EMO. Many sources of inconsistencies (e.g., incomplete, noncompliant or faulty sensor data elements) may accompany the multisourced sensor data shared with EMV. Thus, inconsistencies need to be identified and resolved before the data can be integrated and used for incident management. Finally, the live data received at EMV is currently stacked in detached data layers, consequently spatiotemporal queries on sensor data cannot be performed.

From here onward, we will replace the term Emergency Management Victoria (EMV) with Emergency Management Organization (EMO) to refer to an organization with the same roles and responsibilities for disaster management. Hence, EMO refers to an organization which gathers, integrates and combines multi-agency real-time information, and then provides the disaster community the value-added and relevant emergency information.

To overcome the above issues, a new approach called IDDSS-Sensor is developed and presented in the remaining part of the paper. IDDSS-Sensor is a GIS-based disaster decision support system that provides the functions of standard-based access, as well as on-the-fly harmonization and usage of multi-agency sensor data sources.

4 IDDSS-SENSOR: ARCHITECTURAL FRAMEWORK

IDDSS-Sensor was built based on the architectural framework presented in Figure 3. The architecture outlines the overall picture of the involved authorities, the core system components, as well as the relationship between these components. Based on the framework, each agency is responsible for collecting and managing its sensor-derived datasets for everyday activities as well as intra-organizational emergency management.

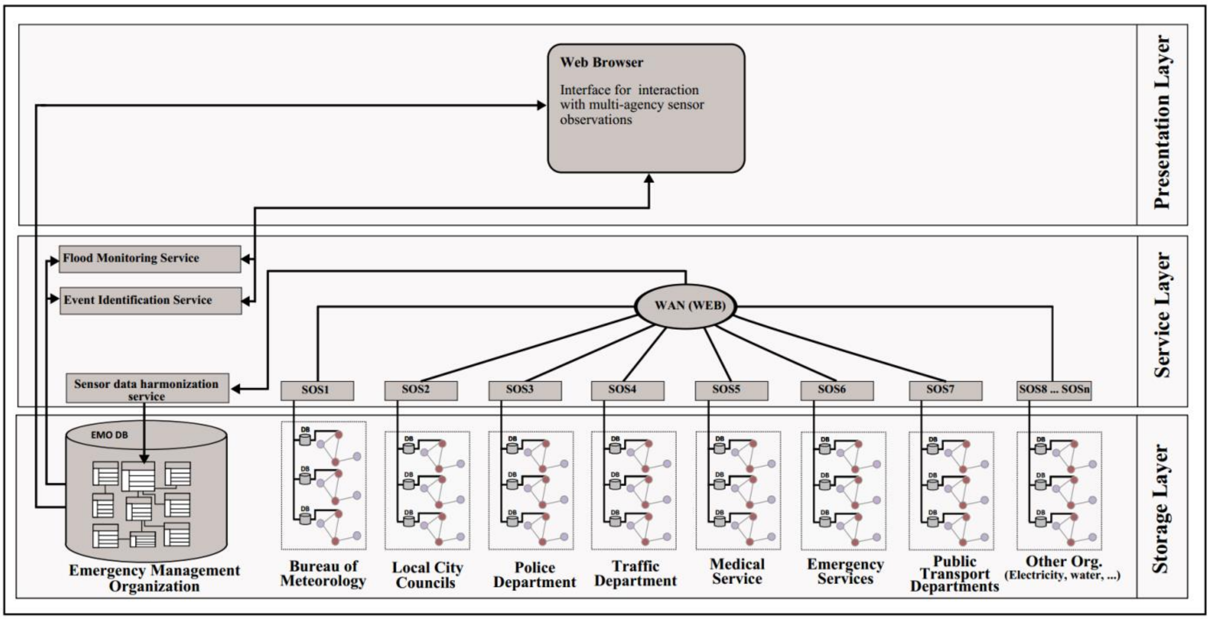

Figure 3: Architectural framework of IDDSS-Sensor

In the context of inter-organizational sensor data exchange, the architecture seeks to enable the homogeneous exchange of sensor data between sensor data producers and EMO. For this purpose, Sensor Web Enablement (SWE) framework of standards is used to standardize sensor data as it provides i) domain independency, ii) producer independency, and iii) openness as well as multi-organizational interoperability (Bröring, Echterhoff et al. 2011). In this way, three parts of SWE standards were employed in this work:

- Observations and Measurements (O&M), which provides the standardized information model for sensor observations (Cox 2011);
- SensorML, which provides the standardized information model for sensor metadata (Botts, Robin et al. 2014); and
- Sensor Observation Service (SOS), which provides the standardized web service interface to access and publish sensor data (Bröring, Stasch et al. 2012).

Herein, for inter-organizational exchange of the data, the metadata of the sensors (e.g., supported outputs, classification and capabilities) is encoded using SensorML. Whereas, the sensor observations (e.g., observed property, result time and result value) are encapsulated using O&M. To convey the sensor metadata and observations to EMO's database, each sensor data producer relies on an SOS server that offers standardized interface for publishing sensor data (i.e., through InsertSensor and InsertObservation operations).

Upon retrieval of sensor data at EMO, the feeds are pre-processed using sensor data harmonization service, prior to their storage in EMO's database. Harmonization process involves two main steps; first step for consistency checking and harmonizing the received metadata (i.e., SensorML files), and the second step for validity checking of the sensor observations (i.e., O&M files). Sensor metadata harmonization includes identification, recognition and if applicable conversion of the elements constituting the SensorML files, including position, featureOfInterest, capabilities, classification, and outputs. The harmonization process for sensor observations consists of regular monitoring and validity checking of observations to detect and alert in case of faulty, delayed and duplicated feeds. The harmonization results for each SensorML and O&M element are added as extra attributes to the original data and are saved in the EMO's database.

Afterwards, the harmonized sensor data is stored in EMO's database. EMO's database consists of the required static spatial data and base maps for disaster management. In addition, the database contains the spatial relation between organizational sensor data together with static spatial data.

The multi-agency sensor data stored in EMO's database can be consumed in two ways. As the first case, the user at EMO can manually interact with the data by performing spatio-temporal queries on sensor data from single or multiple sources. For this purpose, the user builds and stores an SOS query in the client application. Thereby, the client application processes and submits the query to the EMO's database, and consequently retrieves and shows the result in an on-screen table and map.

As the second case, the stored multi-agency sensor data can be automatically consumed by web processing services including event identification service and flood monitoring service. In this regard, the same user-set query parameters (described above) can be passed to the event identification service. The service then uses the user-defined query parameters as event criteria. Also, the service regularly retrieves (latest) SOS observations, processes against stored event queries to identify events, and generates event alerts on-screen. In addition to the event identification service, flood monitoring service also regularly obtains the latest observations and concurrently aggregates the result value of the sensors' observations and show the result in an on-screen table. As a result, the disaster analyst could have an overview of the disaster area in terms of the overall values sensed by the sensors (e.g., overall number of people counts and traffic counts).

4.1 Implementation technologies

To implement the architectural framework explained above, certain sets of software technologies related to SWE are needed to be combined to interactively work together. As illustrated in Figure 3 (earlier), the IDDSS-Sensor architecture is implemented as three layers including the storage, service, and presentation layer.

The storage layer contains the databases to store the sensor and spatial data sources. The service layer includes the deployed web processing services to harvest sensor data in real-time. The presentation layer provides the users a user-friendly graphical user interface for supporting their interaction with multi-agency sensor data. The details of these layers and the implementation technologies used for developing layer components are outlined as follows.

4.1.1 Storage layer

This layer provides the databases to store the sensor and spatial data sources including the followings:

- EMO's database: a database was created on the local machine to store EMO’s spatial data and the harmonized organizational sensor data;
- Sensor data producers' databases: in addition to EMO’ database, a number of databases were created and deployed on the cloud to couple the SOS servers of sensor data producers.

PostgreSQL which is an open-source object-relational database system (PostgreSQL 2015), was employed for the storage layer of the sensor web system. Moreover, PostGIS (PostGIS 2015), which adds spatial capabilities to PostgreSQL, was selected for spatial enablement of this database.

4.1.2 Service layer

The purpose of this layer is to provide SWE complaint web processing services to dynamicaly harvest and then use the sensor data supplied by the storage layer for the following tasks:

- Interoperable publication of sensor data producers’ feeds and retrieving the data at EMO;
- Harmonizing the standardized sensor data feeds reached at EMO;
- Identifying events through harvesting sensors' observations and processing against user-defined event criteria; and
- Monitoring the disaster area by concurrent aggregation of the result value of sensors' observations.

To achieve the first task, the existing open source 52^0North SOS (52North 2015) was hired as SOS implementation.

For the last three tasks new sensor web processing services were developed. Java language was used for the development of these web services. This process was assisted by employing spatial data manipulation tools from an open source platform called Intelligent Decision Support System (IDDSS) (Rajabifard, Thompson et al.). IDDSS is a disaster decision support platform that facilitates the combination and interpretation of multi-sourced geodata and services. IDDSS-Sensor is developed as a module of IDDSS, which brings functionality to the sensor data integration and interpretation into this platform.

4.1.3 Presentation layer

Presentation layer provides the Graphical User Interface (GUI) of IDDSS-Sensor. This web-based client defines flexible tools for enabling the user to interact with and interpret multi-agency sensor information in an effective manner.

JavaScript was used as development language with the aid of CESIUM (AGI 2015), ExtJS (Dong, Pingzeng et al. 2014) and IDDSS that are used for displaying the sensor data, query results and visual indicators.

Table 1 summarizes the described technologies for implementing the layer components. The above three layers work interactively to provide the functions for web-based access and usage of multi-agency sensor data. The layer components are implemented module-based, and are loosely coupled. This separation provides the flexibility to select further amongst different arrangements of deploying the web application on a set of servers, thus bringing more performance and scalability for interacting with highly dynamic sensor-derived data.

Table 1: Implementation technologies used for implementing IDDSS-Sensor.

Implementation Technology	**License**	**Purpose**
52^0North SOS[1]	Open Source	Web-based access to sensor data.
CESIUM[2]	Open Source	To create a 3D globe and to visualize sensor observations and the query results on the globe.
PostgreSQL[3] + PostGIS[4]	Open Source	To store sensor data and spatial datasets.
ExtJS[5]	Open Source	To prepare the GUI of IDDSS-Sensor.
GeoServer[6]	Open Source	Web-based access to static spatial data.
IDDSS[7]	Open Source	To adopt Geodata manipulation features.
Apache Tomcat[8]	Open Source	Web server for deploying the client side of the application.
Jetty[9]	Open Source	Web server for deploying the server side of the application.
Java	Open Source	Developing language for the server side of the software component.
JavaScript	Open Source	JavaScript will be used as the developing language for the client side of the software component.

Figure 4 outlines the overall view of the IDDSS-Sensor client. As can be seen in the figure, three panels are deployed in IDDSS-sensor; one panel for simulating, retrieving and harmonizing SOS data (i.e., Sensor Data Layers panel), and two panels for real-time integration of sensor data sources (i.e., Query Management and Services panels).

[1] http://52north.org/communities/sensorweb/sos/
[2] http://cesiumjs.org/
[3] www.postgresql.org/
[4] postgis.net/
[5] www.sencha.com/products/extjs/
[6] geoserver.org/
[7] http://www.csdila.unimelb.edu.au/projects/IDDSS/About.html
[8] tomcat.apache.org
[9] eclipse.org/jetty/

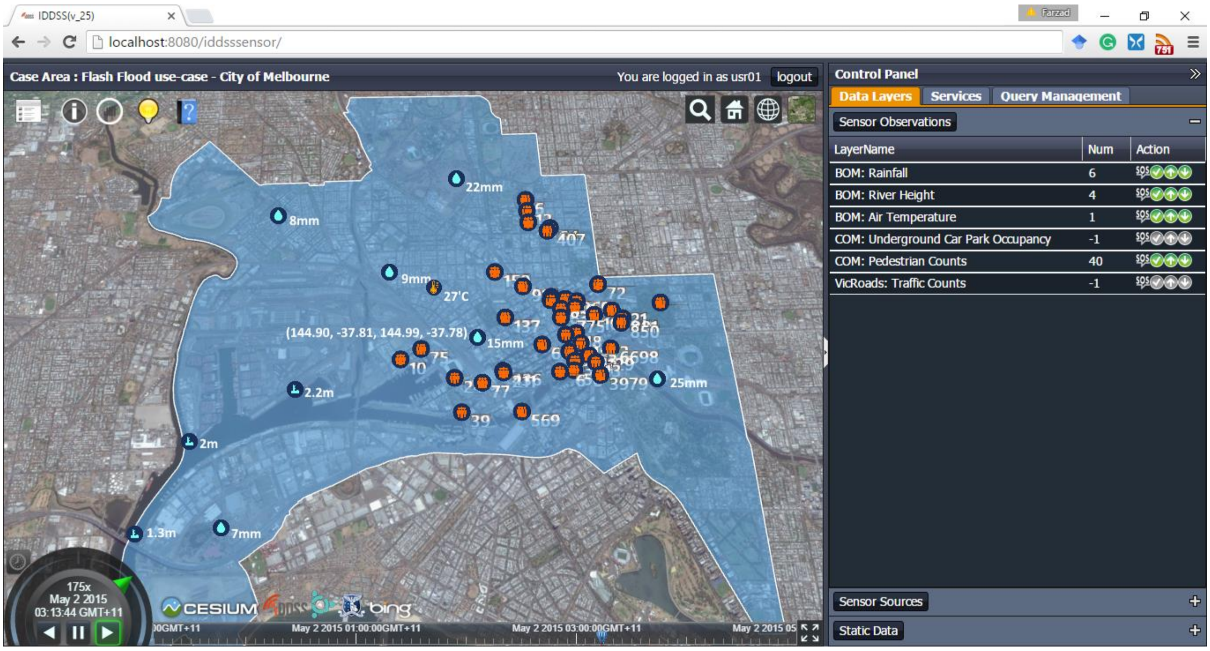

Figure 4: The overall view of the IDDSS-Sensor client.

The data layer panel is the place where the user is able to get access to and harmonize the sensor data served by the SOS servers. The user-system interaction begins by setting a use case area and choosing the desired data source (SOS URL for sensor data and WFS URL for static spatial data). To enhance this, the client provides interactive tools and commands for obtaining user inputs (e.g., temporal and spatial filter for retrieval of sensor observations).

The query management panel is the place, where the user is able to manually interact with organizational sensor datasets. Using this panel, latest SOS observations from single and multiple sources can be concurrently queried by the user. The services panel supports automated interaction with SOS observations by displaying the results of event identification and flood monitoring services.

4.2 IDDSS-Sensor: Deployment results

The implemented IDDSS-Sensor platform was tested in the City of Melbourne (see Figure 4, earlier) as the pilot project area. City of Melbourne is a flood-prone municipality, within the capital city of Melbourne in Victoria. A flash flood scenario was considered as the use-case to test the capabilities and effectiveness of IDDSS-Sensor for integrating multi-agency sensor data.

The goal of the use-case is to provide the disaster analysists at EMO the actionable sensor information that is produced in other agencies. As a result, during the timeline of a flash flood response (i.e., from the time when a flood warning is issued until the time when flood response operations are completed), the analysts could establish situational awareness through interoperable and interactive access to organizational sensor data. In addition, the flood responders could configure event identification service by setting up alerts they want to be notified if something bad happens (e.g., observations of sensors go beyond a threshold).

To proceed with the experiment, a number of sensors with different observed properties, including pedestrian count, traffic count, underground car park occupancy, rainfall, water level and temperature were described based on SensorML encoding and inserted in the deployed SOS servers. Using the panel shown is Figure 5, the measurements of the inserted sensors are then simulated in real-time by configuring the temporal range and rate for simulation.

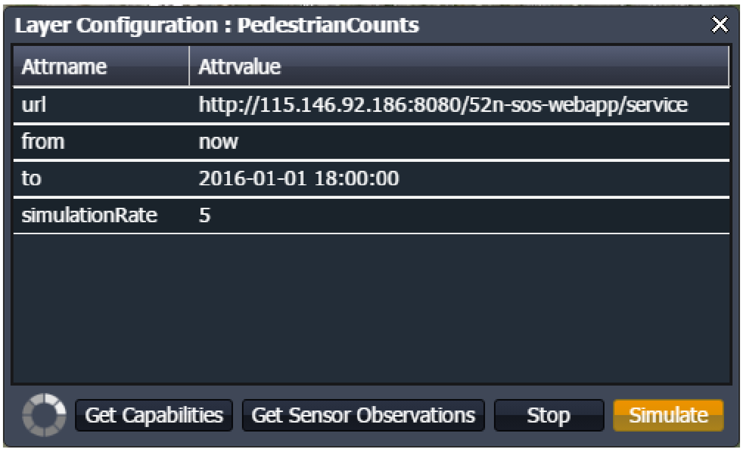

Figure 5: Simulating and getting sensor observation in real-time.

The workflow for simulation includes incremental generation of observations, description of the observations based on O&M encoding and publishing the generated O&M files into the associated SOS server. Furthermore, Get Sensor Observations process includes retrieval of latest observations from the SOS servers and visualizing them on the map. Consequently, the disaster analyst is provided with map-based situational awareness through concurrent and interactive access to observations from multiple sensor sources (Figure 6). The figure shows the case where the user at EMO is provided with live map of people count observations (produced and maintained by the City of Melbourne).

Figure 6: Deployment results: map-based situational awareness provided by IDDSS-Sensor.

In addition to map-based situational awareness, the user can use chart-based situational awareness to examine the timeline of the measurements made by the selected sensor(s), shown in **Error! Reference source not found.**.

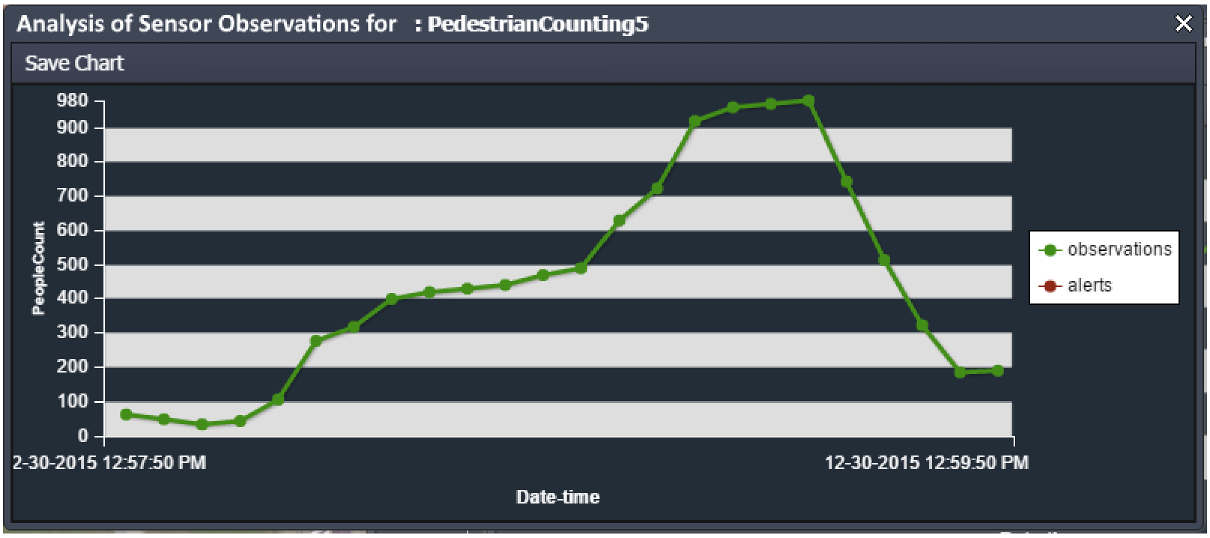

Figure 7: Deployment results: chart-based situational awareness provided by IDDSS-Sensor.

In addition to sensor-based situational awareness, IDDSS-Sensor enables the capability related to event identification. In this case, decision-makers could use the system to subscribe to observation topics of concern and be notified of the alert notifications.

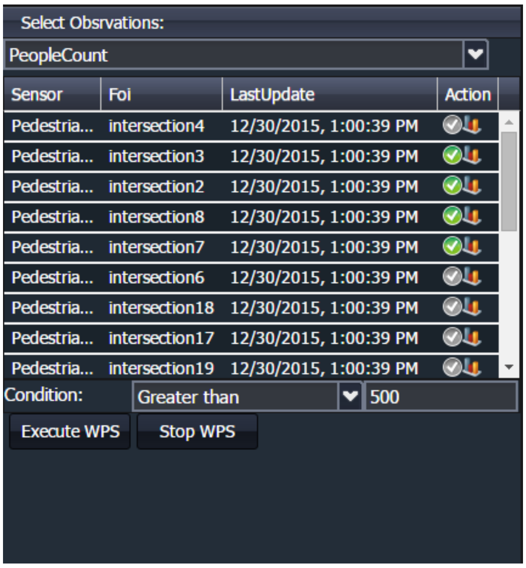

Figure 8: Interface for event identification service.

Figure 8 indicates the interface for query management as well as event subscription. Using the panel the user at operation center can query the observations produced by other organizations and subscribe to observation topics of concern (e.g. critical rainfall observations). For this purpose, the system dynamically retrieves the observed properties that are monitored by the organizational sensor systems. The panel is then populated by the observed properties, so that the user can select a desired observed phenomenon. In doing so, all the sensors that monitor the selected observed property are retrieved and populated in the panel. The user is then able to select one or more sensors and define query condition on the observations. Upon query submission, the results based on latest observations are retrieved from EMO's database and are shown on the screen. In addition, the set of defined parameters is registered in the event identification service and is appeared in the Services panel as a new notification rule. In case the rule is activated by the user, the event identification service regularly retrieves subsequent observations of the selected sensors, processes against stored notification rules to identify events, and generates and publishes event alerts to the client. Finally, the client processes the alert notifications and shows them on the screen. Figure 9 shows the results of event identification service for two different queries. These queries are examples of the interaction that, during flood response operations, disaster analysists at EMO might seek to perform on the accessed cross-organizational sensor data.

a. b.

Figure 9: Deployment results: alerts detected by the event identification service for user-set notification rules. a. Shows the alert for pedestrian counting observations where the result of people count observed property exceeded the 500 counts. b. Shows the alert for rainfall observations where the result of rainfall observed property exceeded the 100mm.

5 CONCLUSION

Disaster management and in particular disaster response are time-sensitive and highly dynamic processes, requiring real-time spatial information to reach government agencies and disaster responders. Currently, disaster management has been widely spatially-enabled through utilization of spatial data sourcing and related technologies. However, spatial information sourcing for disaster management is still facing unique challenges regarding low temporal resolution, inability to source a broad range of data, and limited support for automated operations. Part of any move from current status to real-time spatial data enablement is the need for more effective and efficient disaster management processes.

In this article, we studied the problem of multi-agency sensor information integration for disaster management. In the first part of the paper, we explored the current practice as well as the key issues inhibiting full incorporation of multi-agency sensor data for emergency management. It is demonstrated that the current approach relies on providing common access to raw sensor data that does not support full incorporation and usage of organizational sensor data in disaster management scenarios. In the second part, we designed an architectural framework for improving the integration and usage of multi-agency sensor data in disaster management. The designed architecture includes components for standard-based access, harmonization, and usage of multi-vendor sensor data which together provide interoperability and more automation for incorporating real-time sensor-derived disaster data. In the third part, on the basis of the designed architecture we implemented IDDSS-Sensor, a GIS-based disaster decision support system that is able to make disaster response more effective by combining multi-agency sensor data sources.

We have presented an approach that lowers the barrier to provide real-time disaster information based on sensor data sourcing. Although the emphasis of this paper was on integrating flood-related sensor data, the proposed approach and the presented technology can be reused to manage other large scale natural hazards such as bush-fire or storm, or at smaller scale emergency situations such as responding to a hazmat incident.

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