Environmental Modelling & Software 70 (2015) 65–79

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Capability representation model for heterogeneous remote sensing sensors: Case study on soil moisture monitoring

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A R T I C L E I N F O

Article history:
Received 9 September 2014
Received in revised form
3 April 2015
Accepted 10 April 2015
Available online

Keywords:
Sensor capability representation model
Geospatial sensor web
Sensor interoperability
Cooperative observation
Soil moisture monitoring

A B S T R A C T

Sensor capability information can be used as a basis for the integrated management of vast and heterogeneous remote sensing sensors in Global Earth Observation System of Systems environment. However, the existing representation of this information shows an inconsistent pattern, incomplete capability aspects, and casual expression forms, resulting in information silos among different systems. A sensor capability representation model (SCRM) is proposed in this study. Based on the Meta Object Facility architecture, a five-tuple hierarchical SCRM framework is formulated. Five specific representation element collections for typical remote sensing sensor types are developed to satisfy the requirements of detailed capability expression. The Open Geospatial Consortium Sensor Model Language is used as the expression form of the proposed SCRM. A prototype system is developed and a case study is conducted for a soil moisture monitoring application in Baoxie Town. The SCRM can also be extensively utilised for other environmental monitoring and modelling situations.

1. Introduction

A sensor is a type of device that consists of sensing, data processing, and communicating components. A sensor network is composed of a large number of interconnected sensor nodes that are densely deployed inside or very close to target phenomena (Akyildiz et al., 2002). Sensors and sensor networks are fundamental instruments for environmental scientists, providing them with a wealth of data needed to produce models and studies of ever-increasing value (Schimak et al., 2010). However, the vastness and heterogeneity of sensors make the access and integration of sensor data into forms that are usable for environmental analysis and modelling highly time consuming and challenging, particularly in real-time (Hill et al., 2011). Sensor capability information refers to sensor information related to the comprehensive performance of a sensor for live data acquisition processes. Such capability is mainly determined on the basis of the performance of the sensor observation system itself. Accessing and integrating various sensors to obtain live data streams for specific environmental analysis and modelling applications is considerably important.

Remote sensing sensors are important for environmental monitoring and modelling tasks, such as soil salinity mapping (Quinn et al., 2010) and land surface temperature modelling (Sheng et al., 2009), among others. The capability information of such sensors can be derived from the capability elements reflected during the whole observation process when performing environmental monitoring missions. These elements include spatial resolution, revisit cycle, and spectral resolution. Capability information collection is critical for observation mission planning, evaluating observed data, and providing important support for the dynamic real-time monitoring of environmental parameters. With an increasing trend towards using integrated modelling environments, sensor capability information provides an important data source for complex and dynamic integration environment modelling (Laniak et al., 2013a) and delivers sufficient information for the quality evaluation of model input parameters (such as soil humidity) in real-time environment monitoring (Laniak et al., 2013b). This information can provide a unified framework for sensor management and resource utilisation, thus facilitating decision making and policy development.

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http://dx.doi.org/10.1016/j.envsoft.2015.04.005
1364-8152/

In the Global Earth Observation System of Systems (GEOSS) scope, an international public interoperability infrastructure using land, sea, air and space-based Earth observation systems has been formed to provide comprehensive environmental data, information and analyses (Butterfield et al., 2008). Linking major infrastructures from separate domains together will require adequate and additional metadata information about each system component in terms of different sensor types, observation mechanisms, and intended applications (Nativi et al., 2009). The metadata related to sensor capability information plays an important role in the context of GEOSS. The abundant sensor capability information functions as a vital information base under the GEOSS context in the process observation planning and quality control, as well as in satisfying multi-scale real-time dynamic monitoring demands.

A good representation of sensor capability benefits the management of distributed, massive, and heterogeneous sensor resources, and also facilitates further data exchange and data fusion. The diversity of remote sensing sensor types, observation mechanisms, and intended applications hinder a unified, sufficient and fine-grained capability information representation method. An example of this diversity can be found in remote sensing soil moisture monitoring applications, in which hundreds of remote sensing devices with visible, infrared, thermal infrared, and active or passive microwave sensors may be used, and various spatial-temporal observation capabilities and other operational capabilities should be taken into consideration. The effects of sensor diversity and poor capability representation will result in incomplete and inefficient discovery and low utilisation of these sensor resources when facing a complex and collaborative observation task.

In dealing with remote sensing monitoring tasks of regional or global soil moisture, particularly for soil moisture-related crop monitoring (precision agriculture), geologic hazards (landslide and mud–rock flow), and early warning and response for meteorological disasters (such as floods and droughts), a unified observation-capability encapsulated information model is necessary to represent the capabilities of heterogeneous remote sensing sensors, with other operating capabilities considered to facilitate comprehensive discovery and cooperative observation. The framework of the main capability facets of the capability-encapsulated information base for heterogeneous remote sensing sensors in the soil moisture monitoring application must be provided, with an emphasis on observation capability and considering the thematic application. Capability element collections should also be provided to represent the detailed multi-level capability information of heterogeneous sensors.

In regard to the description information model of sensors, the Open Geospatial Consortium (OGC) Sensor Model Language (SensorML) (Botts and Robin, 2014), one of the Sensor Web Enablement (Botts et al., 2008) information model standards, provides a flexible and general framework for describing the sensor information used for determining appropriate sensors for specific tasks, planning sensor observations for special needs, and exploring a variety of properties associated with the tasks. SensorML can meet the basic needs of the sensor web. However, SensorML only provides a framework without considering specific sensor types and without focussing on detailed capability representation. This condition results in missing or insufficient detailed capability representation, especially on the observation quality and thematic information for sourcing the observed data, as well as evaluating the capability and cooperative observation capabilities of sensors. Meanwhile, even for the same type of sensor, different users may obtain totally different model descriptions in numerous ways, which indicates that no systematic and consistent representation mechanism exists for a specific sensor type.

Because the SensorML data model specifies a majority of its elements as optional, and as it allows expressing the same information in several, differently structured ways, a SensorML profile for discovery has been developed (Houbie et al., 2010). This profile ensures that a minimum set of metadata is provided for every sensor in a common structure. In the Heterogeneous Missions Accessibility (HMA) initiative that aims to harmonise ground segment interface activities for Earth observation (EO) missions, Usländer et al. (2012) utilised the SensorML component as the metadata model of EO instruments and the SensorML profile for discovery. However, this profile is only a minimum collection of the sensor information for a basic query. Considering system interoperability, collective optimisation of observation strategies, cooperative gap filling, observational continuity and other high-level applications, abundant and well-organised sensor capabilities are of vital importance.

Chen and Hu (2012) have discussed the composition of a unified meta-model for atmospheric satellite observation systems. The Atmospheric Satellite Sensor Observation Information Model (A-SSOIM) is developed by reusing or expanding existing metadata standards, and the SensorML is used to formalise the A-SSOIM. The contents of the A-SSOIM have more detailed elements, which target atmospheric satellite sensors, than the general framework of the SensorML. However, for the sensor capability, the description of the A-SSOIM is limited to some basic information of the specific atmospheric satellite sensor. A sensor web node meta-model proposed by Chen et al. (2014) provides a unified node description method for heterogeneous sensor web resources including sensing, processing and application nodes, to achieve the goal of integrated management. This model has a hierarchical structure and mostly focuses on node information sharing; for the sensing node, the model urgently needs well-represented sensor capability information for the performance component to fulfil its evaluation and management functions.

The W3C Semantic Sensor Network Incubator group (the SSN-XG) has produced an OWL 2 ontology to describe sensors and observations (Compton et al., 2012), known as the SSN ontology. Other related works include sensor networks data ontology (Eid et al., 2007), semantic data modelling (Barnaghi et al., 2013), and semantic sensor network (Lefort et al., 2011). These sensor or sensor-related ontologies can describe sensors in terms of sensor capabilities, measurement processes, observations, and deployments. The capabilities described in the SSN mainly include measurement properties (e.g., accuracy, range, and precision) and the environmental conditions that hold those properties, thus representing a specification of sensor capability under such conditions. For complex remote sensing sensors and specific thematic applications, such as soil moisture monitoring, the aspects and depth of capability description remain lacking.

StarFL (Malewski et al., 2014) is a metadata language for sensor descriptions. It follows a more restrictive approach and incorporates concepts from the recently published Semantic Sensor Network Ontology (Compton et al., 2012) to serve as an application profile of the SensorML. StarFL defines a restricted vocabulary and model for sensor metadata, to achieve a high level of interoperability and a straightforward reusability of sensor descriptions. The language covers enhanced details of a sensor system. However, StarFL only defines the accuracy, detection limit, drift, frequency, latency, precision, range, resolution, response time, selectivity, and sensitivity of the measure capability towards general sensor types. As for complex sensor systems such as remote sensing satellite sensors, sensor capability information is lacking.

In terms of a comfortable search, order, delivery or even combination of EO products, Usländer (2012) gives an overview of the use cases and the architectural solutions that aim at an open and