A Survey of the
Semantic Specification of Sensors

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Abstract. Semantic sensor networks have been proposed as part of the solution to the difficulties of installing, querying and maintaining complex, heterogeneous sensor networks. However, semantics and semantic sensor networks are complicated technologies themselves and, ultimately, the quality and generality of this technology and its components, at least as much as the quality of the vision, will decide their usefulness. This paper reviews the state of the art for the semantic specification of sensors, one of the key fundamental technologies in the semantic sensor network vision. Eleven sensor ontologies are reviewed and analysed for the range and expressive power of their concepts. The reasoning and search technology developed in conjunction with these ontologies is also reviewed, as is technology for annotating OGC standards with links to ontologies. This review paper demonstrates that while a range of semantic capabilities have been developed, the state of the art is some way from the vision for semantic sensor networks.

1   Introduction

The Semantic Web promises a Web of annotated and linked data, a Web populated by autonomous and semi-autonomous software agents, agents that interpret, reason about and act on the annotations, links and data [12]. While the vision is someway from being realised, useful technologies have emerged [48]. Applications, and associated technologies, have been envisaged and developed not only for the Web and Web services [22] but also for other networked, though not necessarily Internet-connected, devices, such as the Device Context Ontology [8].

Semantic Web technologies, both those envisaged and those already realised, have the potential to benefit domains where issues such as volume, complexity and heterogeneity can overcome traditional techniques. Sensor networks are one such area where scale, complexity and the need to integrate across heterogeneous standards, sensors and systems all indicate the application of semantics.

Sensors and Sensor Networks: Digital sensors have begun to pervade much of the modern world: for example, phones, computers and even fridges are now equipped with various sensors, as are roadways, traffic lights, buildings and even

some otherwise natural landscapes. Increasingly, sensor networks, that is, networks of connected sensors and associated devices, are being used in such diverse applications as environmental monitoring (for example, in ecological monitoring, agriculture, and wildfire and flood detection), security and surveillance (for example, in traffic, building, city, and airport monitoring and anti-terrorism), and health (for example, in-home monitoring).

Sensor networks, range from single-purpose sensing units through to large networks of devices, while the sensors themselves range from single-feature sensors to more complicated systems, such as weather stations and satellites. The sensors may be powered or harvest power from their environment and may internally, or in concert with other sensors, process, aggregate and interpret observations. The network itself may be constructed from a heterogeneous collection of sensors and other devices. Though each unit potentially collects and transmits a small amount of data, sensor networks typically deal with large volumes of data.

Sugihara and Gupta's review [52] further outlines the broad scope of sensor networks, the devices they can contain and how they are programmed. Yick et al. [55] review wireless sensor networks and applications.

Nodes (devices with attached sensors) interact to form a sensor network, and deliver data, through a gateway, to a base station. The base state and associated services then offer live and historical data, analysis, interpretation and prediction. The identifiable entity a sensor is attached to is called a platform, which may be another sensor, a node, or even a fish. Sensors are said to observe a physical quality (temperature, depth, etc) of a feature (a lake) and report observations. Specifications of sensors' responses to stimuli under various conditions are called response models. Generally a network is organised such that data flows from low-powered devices to higher-powered devices for further aggregation and processing.

In this review, sensor refers to a range of instruments, including transducers, sensor devices and computations: for example, wind chill, calculated from wind speed and ambient temperature, could be sensed by an in situ device or computed from co-located measurements. A sensor is defined as a source that produces a value representing a quality of a phenomenon. Sensors and scientific or other computational models form a continuum of sensing that is not easy to partition; there is some aspect of prediction or inference that is perhaps stronger in a model, but is, in any case, still present in any transducer or sensing device. Hence, sensor in this review refers to physical devices that measure and computations that measure: though, much of the material reviewed does view sensors as devices.

Standardisation can remove some of the difficulties of device incompatibility, and there are a number of standards for sensor networks [17]. However, standardisation is typically more successful in removing interface heterogeneity than solving data and concept incompatibilities. The Open Geospatial Consortium's (OGC) Sensor Web Enablement (SWE) suite of standards [13], including SensorML [14] and Observations and Measurements (O&M) [19, 20], for example, standardise interfaces for services and description languages for sensors and their processes Quite deliberately, the OGC's SWE working groups have not at-

tempted to provide standards for interoperability beyond describing a standard set of functions or a standard syntax: domain semantics, for example, have been left for the relevant communities.

The OGC's choice is prudent for, and a key feature of, a suite of domain independent standards. It does, however, mean that, without external agreement, SWE cannot provide more than syntactic interoperability. Using vocabularies of concepts, relationships between those concepts and various reasoning techniques, semantics can, with largely domain independent techniques, provide more than syntactic interoperability.

Semantics: The semantic approach to information systems design uses declarative descriptions of information and processing units, allowing (semi-)automatic satisfaction of declaratively described requirements. Declarative descriptions enable both domain-independent and domain-specific reasoning of various forms (logic-based or otherwise) to be applied in processes such as entity identification, search, and query and workflow generation.

Metadata serves a spectrum of data, and service, enrichment functions from documentation, to explicitly and implicitly linking data and services, to composition.

$$\text{elicitation} \rightarrow \text{linking} \rightarrow \text{composition}$$

Semantics enables reasoning, including search, logical reasoning and domain reasoning, throughout this spectrum. Reasoning can of course be reflective using, for example elicitation to infer further linkages.

This review views semantic descriptions as OWL ontologies — for which purpose, both the original W3C OWL recommendation [4], based on the $\mathcal{SHOIN}$ Description Logic (DL), and the almost finalised OWL 2 [9], based on $\mathcal{SROIQ}$, are included. Semantics does, however, serve a dual role: it is part mark-up and elicitation of information and part logic for reasoning. Ding et al. [22], for example, argue out that an ontology language for semantics requires a model for defining entities and relationships, a syntax in which to write down the entities and relationships and a semantics for inference and constraints. However, this view is limiting in that it implies that semantics is OWL-encoded information and Description Logic reasoning. But, as Sheth et al. [50] point out, any number of inference mechanisms can be applied to semantic descriptions.

A semantic sensor networks requires declarative specifications of sensing devices, the network, services, and the domain and its relation to the observations and measurements of the sensors and services. Processing tools, logical and otherwise, can then be used to answer queries, infer further information, search for and identify particular resources or generate workflows, all of which might require reasoning and inference in analysing the specifications, links between entities and data, allowing users to develop, use and adapt sensor networks, while abstracting away the the low-level details and difficulties of the network and its multiple devices.

Review Topics and Outline: This review evaluates the state of the art in the semantics for describing and reasoning about sensors. Almost any semantic

technology for sensor networks requires semantic descriptions of sensors or the process of making observations as a fundament component.

Section 2 further defines semantic sensor networks. It outlines a reference model of capabilities as a basis for comparison against the state of the art.

Section 3 reviews eleven ontologies for sensors — including published and unpublished material: as this is a technology review, not a publication review, unpublished, publicly available material is equally relevant to peer-reviewed articles. Section 3.2 analyses the range of concepts that each ontology can describe, and Section 3.3 complements this by discussing the relative expressive power and completeness of the concepts.

Section 4 discusses methods that have been used to relate SWE documents to semantic descriptions.

Section 5 reviews the technological setting of the eleven ontologies (and other relevant published material on semantic sensor networks). It shows the capability that current semantic sensor specifications enable.

Section 6 concludes the paper, evaluating the state of the art against the semantic sensor networks vision and outlining required future work.

2 Semantic Sensor Networks

A uses declarative descriptions of sensors, networks and domain concepts to aid in searching, querying and managing the network and data. A semantic sensor web is an OGC-style sensor web enriched with semantic annotation, querying and inference [49]. The important distinctions are that semantic sensor webs rely on OGC standards and focus on issues external to the network, although the use of semantics inside the network isn't precluded, while the term semantic sensor network includes semantic sensor webs, semantic sensor networks that aren't reliant on OGC standards and explicitly allows the use of semantics to manage the network as well as its resulting data.

Proposed semantic sensor network architectures [35, 41, 32, 56, 39], on which the discussion in this section is based, use multiple layers of semantics and technology to provide infrastructure and services. The three layers of the architecture in this review, Figure 1, data, processing and application, support network-internal processing, inference and integration, and services respectively. Knowledge inferred at the processing layer is made available to the application layer and may also be used to manage the network. The stack of semantic specifications is based on node-level semantics that includes sensor (also device and node) and observation semantics, both of which rely on domain semantics for describing the link between the abstract and technical properties of the sensors and observations and their real-world interactions and placements. Network-level semantics allows the description of network wide properties, while semantics at the integration level allows for mappings between distinct, but related, concepts to be established and also for the concepts needed for composition, inference and, for example, scientific models and prediction. The levels of awareness enabled by the architecture roughly equate to perception (sensed and aggregated
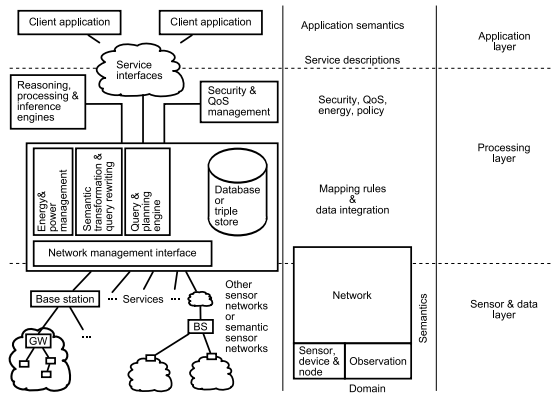
Fig. 1. Semantic Sensor Network Architecture.

data), comprehension (base station processing) and projection (scientific or other analysis) in Endsley's [26] model of situation awareness.

Semantics in the architecture takes the form of vocabularies of concepts and relations defined in OWL, first-order mappings for integration, and logic programming rules (and other forms of inference) for defining further reasoning power. These technologies allow a semantic sensor network to integrate multiple sensor networks, other data sources and services in ways that can cross organisational and domain boundaries.

The following list of use cases (compiled from material in the Marine Metadata Interoperability (MMI) Device use cases,[4] Sheth et al. [49], Ni et al. [41] and Huang and Javed [32]) are referenced in the remaining sections.

1. Classify sensors according to functionality, output, or measurement method.
   Requires machine interpretable specifications of sensors, their output types and the domains in which they operate.
2. Find sensors that can perform a particular measurement, or can supply a particular measurement in a particular format.
   Requires the same specifications as use case 1; however, the technology required to fulfil this case can be complex. An advanced system could do more than search existing sensors, it could compose existing sensors and data streams to create virtual sensors. Data format incompatibilities could also be removed by composing suitable transformation functions.
3. Collate data spatially, temporally, or by accuracy.
   Requires specifications of sensors that include locations, accuracy and modelling of observation data.
4. Infer domain knowledge from low-level data.
   Inference requires a reasoning mechanism, domain and sensor specifications and annotated data.

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[4] http://marinemetadata.org/community/teams/ontdevices/usecases

5. Produce an event when a particular condition is reached within a period. Such an advanced use case requires everything in the previous use cases, as well as query processing, energy management and configuration management. This would require sensor specifications about energy, sensor operating conditions and lifetimes. Related use cases could include finding sensors to satisfy particular tasks, and using reasoning to help plan a deployment.

3   Sensor Ontologies

First, the eleven ontologies studied in depth in this review are introduced (§3.1). Then, the concepts that each ontology can describe are outlined (§3.2) with reference to the discussion in the previous two sections. Since indicating that ontologies have concepts for particular aspects of sensors does not indicate the relative expressive power or quality of those concepts, this section concludes by discussing qualitative aspects of the ontologies (§3.3).

3.1   Ontologies

Table 1 summaries the ontologies studied in this review.

Avancha, Patel and Joshi [10] describe an ontology for adaptive sensor networks, where nodes react to available power and environmental factors, calibrating for accuracy and determining suitable operating states. Matheus et al. [37] include sensor types in an ontology developed for recording provenance, or pedigree, information in naval operations.

The OntoSensor [47, 46] ontology was intended as a general, knowledge base of sensors for query and inference. It was based on SensorML and also includes concepts from IEEE SUMO and ISO 19115. Kim et al. [33] extend OntoSensor for Web services, though the ontology isn't available and the details are not clear.

Eid et al. [24, 25] propose a two-tier framework for a sensor ontology. In their framework the sensor hierarchy, data and extension ontologies (lower tier) all reference SUMO (upper tier).

The ISTAR [43, 27] ontology was developed as part of a system to automatically select sensors for tasks based on their fitness for the task description. The system can select suitable sensors, aid in deployment, decide at runtime on the sensors to use from those selected as candidates and configure deployed sensors.

The Coastal Environmental Sensing Networks (CESN) project[5] at the University of Massachusetts Boston is developing technology for sensor networks for coastal observing. Calder et al. [16] have built an ontology of sensor types and a DL and rules reasoner for making inferences about data and anomalies in measurements.

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[5] `http://www.cesn.org`

[6] `http://www.memphis.edu/eece/cas/onto_sensor/OntoSensor.txt`

[7] `http://www.cesn.org/resources/cesn.owl`

reference	date	active	purpose
Avancha et al. [10]	2004	✗	adaptive sensor networks
Matheus et al. [37]	2005	✗	pedigree (provenance)
OntoSensor [47, 46][6]	2006	✗	knowledge base and inference
Eid et al. [24, 25]	2007	?	searching heterogeneous sensor network data
Kim et al. [33]	2008	?	services
CESN [16][7]	2008	✓	inferring domain knowledge from data
SWAMO [54][8]	2008	✓	intelligent agents
ISTAR [43, 27][9]	2009	✓	task assignment
OOSTethys [2][10]	2009	✓	integrating standards-compliant Web services
MMI [1][11]	2009	✓	interoperability
CSIRO [40][12]	2009	✓	data integration, search, classification and workflows

Table 1. Ontologies studied in this review: references, year of last known update or publication, active if known, main stated purpose, and url if ontology is publicly available.

SWAMO [54] ...FIXME

The OOSTethys community[13] are developing open-source resources to help install, integrate and update standards-compliant Web services for oceanographic observing, with a particular emphasis on OGC standards.[14] The sensor ontology focuses on system structure and the proceedure and result of an observation.

The Marine Metadata Interoperability (MMI) Device Ontologies Working Group[15] is developing an ontology of oceanographic devices, sensors and samplers. The resulting ontology is likely to be applicable in domains other than oceanographic sensing.

The CSIRO sensor ontology [40, 18] is a generic ontology for describing sensors and deployments. It is intended to be used in data integration, search, classification and workflows.

The OntoSensor ontology has (FIXME count ontosensor properly) X class definitions and Y individuals of CrossBow sensors.[16] The CESN ontology has ten concept definitions for sensor instances and six individuals. There two example sensors available for the CSIRO ontology.

Hu, Wu and Guo [31] develop two layers of ontology with the intention of using rules to deduce high-level, contextual information from low-level data, but don't provide enough detail to be included in the analysis here. Horan [30] uses

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[8] FIXME ... should I remove / is it OWL??

[9] http://www.csd.abdn.ac.uk/research/ita/sam/downloads/ontology/ISTAR.owl

[10] http://mmisw.org/ont/mmi/20090519T125341/general

[11] http://mmisw.org/ont/mmi/device

[12] http://www.w3.org/2005/Incubator/ssn/wiki/images/4/42/
SensorOntology20090320.owl.xml

[13] http://www.oostethys.org/

[14] http://www.oostethys.org/ogc-oceans-interoperability-experiment

[15] http://marinemetadata.org/community/teams/ontdevices

[16] http://www.xbow.com/

the OWL-S [42] Web services ontology as a basis for a sensor ontology, but also don't provide enough detail for inclusion. As it is based on services, processes, inputs and outputs, and grounding (which is interpretable as access, communication and physical information) OWL-S seems an appropriate basis for a sensor ontology; however, it would need to be extended with sensor specific concepts — many of OWL-S's capabilities are, in any case, covered by the CSIRO, OntoSesnor, MMI, OOTethys and SWAMO ontologies.

3.2 Concepts

Section 2 discussed node-level, network-level and integration-level uses of semantics in sensor networks and outlined how a sensor ontology is used at each level. For the sensor ontology, or managers of a sensor network, the choice of what functionality to expose to each level is application dependant. Hence, the discussion in this section covers the whole range of functionality and description of the sensor, rather than the uses inside, or outside, the network.

Table 2 shows the aspects of sensors that the ontologies can describe. A tick indicates the capability to describe the stated aspect in some form. The absence of a tick indicates either no ability to describe this aspect, or insufficient information. Absence of some aspect from the table indicates that none of the studied ontologies can describe those concepts.

The table shows that the Avancha, Eid and Kim ontologies focus mainly on data and measurements, with little capacity to describe sensors, systems or how measurements are taken. The CESN ontology, and to some extent Matheus's ontology as well, lie at another extreme, being almost entirely a description of sensor types.

The SWAMO, MMI and OOSTethys ontologies extend the analysis along a third dimension, from measurements and sensor types to systems and structure. Each focuses on systems, the components of a system and how those components are organised — the structure of systems. They can be seen, in some sense, as ontologies for describing the structure and process of measurement taking systems, as each also includes concepts for describing measurements. Both MMI and OOSTethys are work-in-progress and it's likely that their scope will be extended; the MMI Device Ontologies Working Group, for example, intend to add concepts ranging from physical properties and limits of the sensor to communication information and software.[17]

The CSIRO and OntoSensor ontologies cover a wider range of concepts than the other ontologies. Each being able to describe most of the spectrum of sensor concepts, though the OntoSensor ontology includes more on data and sensor types than the CSIRO ontology. The CSIRO ontology can, however, describe composition and structure, while OntoSensor can only describe part-of relations — the difference between an assembly plan and a parts list. These expressivity differences are the subject of the next section.

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[17] http://marinemetadata.org/community/teams/ontdevices/facetoutline

ontology	base concepts	sensor								physical					observation					domain			
		sensor hierarchy	identity & manufacturing	contacting & software	deployment	configuration	history	components	action & process	location	power supply	platform	dimension, weight, etc.	operating conditions	data/observation	accuracy	frequency	response model	field of view/sensing	units of measurement	feature/quality	sampled medium	time
MMI	sensor (system) & process		✓		✓	✓		✓	✓			✓	✓	✓		✓	✓	✓			✓	✓	
CSIRO	sensor & process	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		
OOSTethys	component, system & process							✓	✓			✓			✓						✓	✓	
CESN	sensor	✓			✓					✓					✓						✓		✓
SWAMO	agent, process & sensor			✓				✓	✓	✓		✓			✓				✓	✓	✓		✓
Kim	sensor					✓				✓					✓	✓	✓		✓		✓		
OntoSensor	component & sensor	✓				✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓
Eid	sensor		✓			✓				✓	✓				✓	✓	✓	✓	✓				
Matheus	system & sensor	✓		✓					✓	✓					✓		✓						
Avancha	sensor			✓						✓	✓				✓	✓	✓	✓	✓	✓	✓	✓	
ISTAR																							

Table 2. Sensor Concepts

3.3 Expressive Power

This section discusses the relative expressive power of the ontologies for a number of important points. The OntoSesnor, SWAMO, OOSTethys, CSIRO and MMI ontologies, for example, can each describe the platform a sensor is attached to; however, only OntoSensor and OOSTethys can describe the components of platforms. Further, OntoSensor can describe part-of relations, while OOSTethys, through the MMI platform ontology [36], can describe their structure. In other words, the SWAMO, CSIRO and MMI ontologies can say a sensor is attached to something (a platform), OntoSensor can list the parts of the platform if they are independently interesting, while OOSTethys can show how the parts of the platform are made into the whole — how the parts are composed.

Similarly, the same five ontologies can describe the components of a sensor system and its processes. Again, OntoSensor describes only part-of relations, as do the MMI and OOTethys ontologies. SWAMO can describe part-of relations for systems and a form of process chaining. While the CSIRO ontology can describe more sophisticated forms of structural and sequencing composition, with, for example, sequence, conditional and repetition for process composition.

Sophisticated forms of composition are important in describing sensors, as SensorML recognises. Without structural composition it is not possible to describe sensors accurately, nor is it possible to search for and automatically compose and execute virtual sensors.

Interestingly, in the OntoSensor and CSIRO ontologies, sensors and processes are in different parts of the concept hierarchy, whereas the OOTethys and MMI ontologies are organised such that a process is-a system — and to such an extent in OOTethys that a sensor is-a system and a system is-a process. The organisation in the OntoSensor and CSIRO ontologies allows sensors as sub-processes and vice versa, but the explicit hierarchical organisation of the MMI and OOTethys ontologies may allow some interesting modelling options.

The OntoSensor, Matheus, CESN and CSIRO ontologies each provide some capacity for organising sensors into a hierarchy of sensing concepts, of which OntoSensor has the most concepts and sub-concepts. The OntoSensor ontology also has the greatest expressive capacity for data.

Observations and data, which are needed in describing capabilities of sensors, require care in modelling, for example, accuracy can be a fine point because it is often condition dependent. The Vaisala WM30 wind sensor,[18] for example, has an accuracy of $\pm 0.3 m/s$ for wind speeds below $10 m/s$, accuracy of $\pm 2\%$ for wind speeds up to $60 m/s$ and isn't rated for wind speeds over $60 m/s$. These finer aspects of the response model can be represented in the CSIRO ontology, and to some extent in the SWAMO and OntoSensor ontologies. However, none of the ontologies can fully describe response models, configurations, history, or operating conditions to the level required to satisfy all use cases in Section 2.

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[18] `http://www.vaisala.com/files/WM30_Brochure_in_English.pdf`

4   Semantic Annotation

Semantic annotations link data to more expressive ontological representations through model references [5]. As large amounts of sensor data are being made available on the web, semantic descriptions of sensors and sensor data provide a means to make such data discoverable, accessible, and queryable, and semantic annotation of sensor data provides a means of relating the data to the semantic description. Assuming sensor data is encoded in SWE format, there are currently two approaches for annotation: RDFa [6] and XLink [3].

RDFa, Resource Description Framework-in-attributes, enables the layering of RDF information on any XHTML or XML document. RDFa provides a set of attributes that can represent semantic metadata within an XML language and a simple mapping to RDF triples. These attributes can be added to SensorML and O&M documents to provide semantic annotations for the sensor data [49, 11], but require additional syntax.

XLink, the XML Linking Language, is an XML markup language for creating hyperlinks in XML documents. The XLink recommendation outlines methods of describing links between resources in XML documents, whether internal or external to the original document. XLink attributes can be added to SensorML and O&M documents (see Figure 2(a)) to provide semantic annotations for the sensor data [29, 38].

```
<om:observedProperty>
 <swe:CompositePhenomenon dimension="5" gml:id="WEATHER_OBSERVABLES">
 <gml:name>Weather Measurements</gml:name>
  <swe:base xlink:href="http://www.w3.org/2009/Incubator/ssn/ontologies/SensorOntology.owl"/>
   <swe:component xlink:href="http://www.w3.org/2009/Incubator/ssn/ontologies/SensorOntology.owl#AirTemperature"/>
   <swe:component xlink:href="http://www.w3.org/2009/Incubator/ssn/ontologies/SensorOntology.owl#DewPoint"/>
   <swe:component xlink:href="http://www.w3.org/2009/Incubator/ssn/ontologies/SensorOntology.owl#RelativeHumidity"/>
   <swe:component xlink:href="http://www.w3.org/2009/Incubator/ssn/ontologies/SensorOntology.owl#WindSpeed"/>
   <swe:component xlink:href="http://www.w3.org/2009/Incubator/ssn/ontologies/SensorOntology.owl#WindDirection"/>
 </om:observedProperty>
```

(a) XLink annotation of O&M

```
<swe:field name="AirTemperature">
 <swe:Quantity definition="http://www.w3.org/2009/Incubator/ssn/ontologies/SensorOntology.owl#AirTemperature">
  <swe:uom xlink:href="http://www.w3.org/2009/Incubator/ssn/ontologies/SensorOntology.owl#fahrenheit"/>
 </swe:Quantity>
</swe:field>
```

(b) XLink and *definition* attribute in O&M annotation

Fig. 2. semantic annotation of O&M

XLink is already used in SWE documents, thus, no syntactic or structural changes are required. However, this approach does require the development of translation tools since, unlike RDFa, XLink has no predefined mapping to RDF. In addition to using XLink, SWE also provides a definition attribute that provides a link to a registry definition, but these may also link to an ontological description (see Figure 2(b)) [29, 38].

SWING [23], Semantic Web-Service Interoperability for Geospatial Decision Making, describes sensor annotation of OGC documents at three distinct levels: (1) at the document level using keyword metadata, (2) at the schema level using

SAWSDL [5], and (3) at the data level using XLink and definition attributes within SensorML and O&M documents as described above.

5   Technologies

The section discusses how the technology developed alongside the sensor ontologies enables parts of the SSN architecture outlined in Section 2. There are three generic reasoning mechanisms that have been used to enable the technology discussed in this section: OWL reasoning (DL inference), logic programming rules and SPARQL queries.

By virtue of being metadata expressed in OWL, each of the ontologies is a language for cataloguing sensors, with various levels of completeness and expressive power (§ 3.2 and § 3.3), and thus come with DL inference for validation, categorisation and some search capability.

SPARQL [7] gives greater search potential than DL querying, and can be combined with DL inference [51]. Kim et al. [33] and Eid et al. [25] give examples of using SPARQL to query a sensor ontology.

Logic programming rules give a further inference resource for classifying instances or adding new instances to an ontology. Logic programming, in conjunction with DL inference, can be used to derive high-level information (say, inference about weather conditions) from low-level data (temperature and wind speed). It is used by Calder, Morris and Peri [16] to deriver further inferences about data, in ISTAR to derive further capabilities of sensors [43, 27, 21], and by a number of other related technologies [53, 15, 56, 11, 32, 31]. Henson et al. [29] annotate SWE services to reason over sensor data and query high-level knowledge of the environment as well as low-level sensor data.

OWL reasoning and logic programming is used with the ISTAR ontology to suggest sensors that match parts of tasks and a set covering algorithm is used to find simple combinations of these that could form a complete solution to the information needs of the task [21, 43, 27]. The CSIRO ontology can be used for more complex automated composition and potentially similar technology to that used for Web service composition [18].

6   Conclusion

This paper has reviewed the state of the art in semantic descriptions of sensors: eleven OWL ontologies were reviewed, with a focus on sensor ontologies as a key enabling component of semantic sensor networks.

A combination of OntoSensor and the CSIRO ontology represents the current level of expressive capability for semantic sensors. However, questions remain about the correct structure and scope of a sensor ontology, including how best to express composition of processes and systems, how to express response model details such as accuracy and how to delineate between and integrate sensors, services and scientific (and other predictive) models. Units of measurement, location and time, for example, are perhaps best deferred to authorities (O&M

defers to external authorities). Until such authorities and ontologies exist, however, these aspects must be handled in conjunction with a sensor ontology; for example, building on either OWL-Time[19] or Henson et al.'s [28] model for time series information, which is not currently covered adequately in sensor ontologies.

No current ontology, nor a combination of the available ontologies, is able to express all the properties required for Section 2's semantic sensor network use cases. However, the current state of the art can enable classification, and linking of data and sensors, and the technology exists to construct virtual sensors as compositions of existing components. In short, sensor ontologies have enabled a range of semantic technologies for semantic sensor networks, but the state of the art is some way from enabling the full range of features envisaged by a semantic sensor network in either this document or the SENSI reviews.

DL inference and logic programming rules are the main forms of inference the have been used with semantics for sensors [16, 43, 27, 21, 53, 15, 56, 11, 32, 31, 29]. However, as advocated by Sheth, Ramakrishnan and Thomas [50], the importance of domain reasoning, abductive, fuzzy and probabilistic reasoning is beginning to be realised. Search using DL and SPARQL has been applied for sensor descriptions. More advanced Semantic Web technologies such as mixtures of DL, structural similarity and information retrieval techniques, as in Klusch et al. [34], have not yet been applied to sensors.

If large amounts of data can be annotated using the techniques outlined in Section 4 — either post processed or tagged at point of observation — then semantic reasoning and linking can be applied to a wider range of data than that emanating from semantic sensor webs and networks.

Sensors and observations are complementary and for some aspects intersecting. This review has seen sensors and measurements from a sensors perspective; however, the observation perspective is equally important and should be reviewed to complement the review begun by this review. Among other O&M ontologies, Probst [44, 45] gives an ontological grounding for O&M aligned to the DOLCE upper ontology.

The W3C Semantic Sensor Networks Incubator Group (SSN-XG),[20] which includes developers from the CSIRO, MMI and OOTethys ontologies, aims to build a general and expressive ontology for sensors, addressing the coverage, structural and expressivity issues discussed in this review.

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[19] http://www.w3.org/TR/owl-time/

[20] http://www.w3.org/2005/Incubator/ssn/

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