# A Survey of the Semantic Specification of Sensors

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**Abstract.** Semantic sensor networks use declarative descriptions of sensors promote reuse and integration, and to help solve the difficulties of installing, querying and maintaining complex, heterogeneous sensor networks. This paper reviews the state of the art for the semantic specification of sensors, one of the fundamental technologies in the semantic sensor network vision. Twelve 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. Sensor concepts that cannot be expressed accurately by current sensor ontologies are also discussed.

## 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, 49]. Semantic Web technologies 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. While the Open Geospatial Consortium's (OGC) Sensor Web Enablement (SWE) suite of standards provide a syntactic model for sensors, issues such as integration and interpretation of information encoded using the standards have not been resolved.

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

Sugihara and Gupta's [53] and Yick et al.'s [56] reviews demonstrate the broad scope of sensor networks, the devices they can contain and how they are programmed. Sensor networks, which are formed from communicating nodes (devices with attached sensors), range from single-purpose sensing units through to large networks of heterogeneous devices and, with associated services, may offer live and historical data, analysis, interpretation and prediction. Sensors 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. Generally, a network is organised such that data flows from low-powered devices to higher-powered devices for further aggregation and processing. The identifiable entity a sensor is attached to is called a platform. Though each unit potentially collects and transmits a small amount of data, sensor networks typically deal with large volumes of data.

Sensors are said to observe a physical quality (temperature, depth, etc.) of a feature (a lake) and report observations (the term property is used for qualities in SWE standards). Specifications of sensors' responses to stimuli under various conditions are called response models. 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 feature. 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.

While standardisation solves some issues of device incompatibility, and there are a number of standards for sensor networks [18], it is typically more successful in removing interface heterogeneity than solving data and concept incompatibilities. The OGC's SWE suite of standards [13], including SensorML [14] and Observations and Measurements (O&M) [20, 21], for example, standardise interfaces for services and description languages for sensors and their processes. Quite deliberately, the SWE standards to not provide for interoperability beyond describing a standard set of functions or a standard syntax: domain semantics, for example, have been left for the relevant communities. This prudent for, and a key feature of, a suite of domain independent standards; however, it does 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.

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

Semantics enables reasoning, including search, logical reasoning and domain reasoning, throughout this spectrum. Reasoning can of course be recursive, deriving new knowledge from previously inferred knowledge.

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 [8], based on $\mathcal{SROIQ}$, are included. OWL serves a dual role in semantics: it is part mark-up of information and part logic for reasoning. Ding et al. [23] argue 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, as Sheth et al. [51] point out, reasoning need not be limited to DL reasoning and any number of inference mechanisms can be applied to semantic descriptions.

A semantic sensor network 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 OWL semantics for describing and reasoning about sensors.

Section 2 further defines semantic sensor networks. It outlines the capabilities and architecture of a semantic sensor network.

Section 3 reviews twelve ontologies for sensors — including published and unpublished material: as this is a technology review, not a publication review, unpublished, publicly available material is as relevant as 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 reviews the technological setting of the twelve ontologies (and other relevant published material on semantic sensor networks). It shows the capability that current semantic sensor specifications enable.

Section 4.1 reviews methods for relating SWE documents to semantic descriptions.

Section 5 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 semantic sensor network uses declarative descriptions of sensors, networks and domain concepts to aid in searching, querying and managing the network and data. A semantic sensor web, on the other hand, is an OGC-style sensor web enriched with semantic annotation, querying and inference [50]. 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 semantic sensor networks may include semantic sensor webs, semantic sensor networks that aren't reliant on OGC standards and allow the use of semantics to manage the network as well as its resulting data.

Architectures for semantic sensor networks [37, 42, 34, 57, 40] 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, respectively support network-internal processing, inference and integration, and services. 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.

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 [17].

The following list (compiled from material in the Marine Metadata Interoperability (MMI) Device use cases,[4] Sheth et al. [50], Ni et al. [42] and Huang and Javed [34]) demonstrates potential capabilities of semantic sensor networks.

1. Classify sensors according to functionality, output, or measurement method.

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

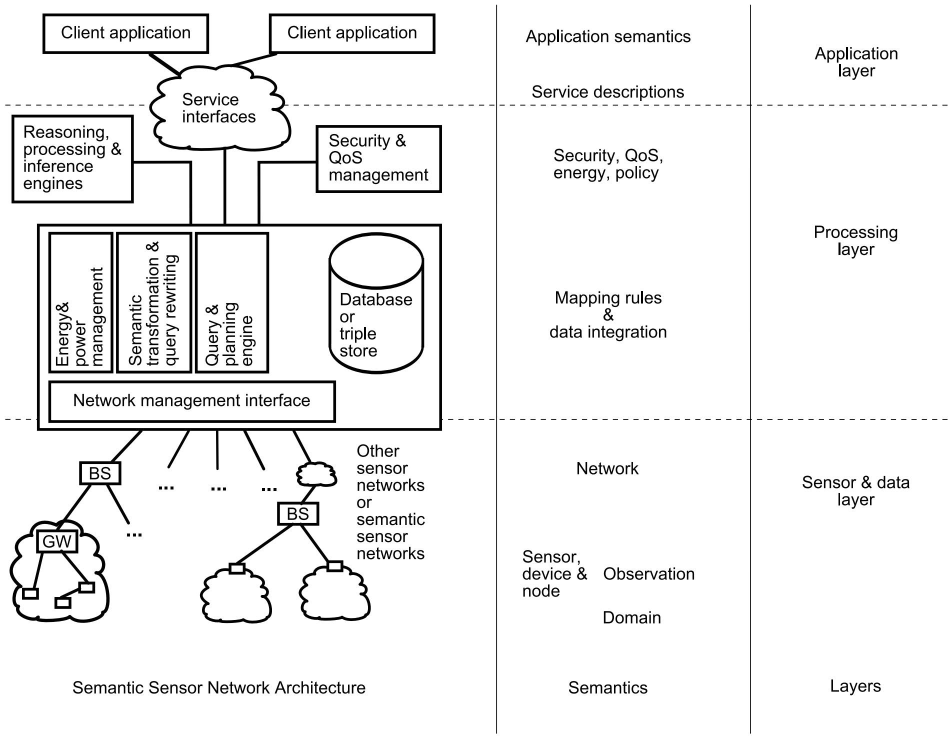


**Fig. 1.** Semantic Sensor Network Architecture. BS = Base Station and GW = GateWay — sensor networks are generally organised around gateways that serve as aggregation and routing points for sub-networks and base stations that collect whole-network data.

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 1 above. However, a 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.
5. Produce an event when a particular condition is reached within a period.
   Requires the specifications in the previous use cases, as well as query processing, energy management and configuration management, and sensor speci-

fications that include energy, sensor operating conditions and lifetimes. Related capabilities could include finding sensors to satisfy particular tasks, and using reasoning to help plan a deployment.

## 3 Sensor Ontologies

First, the twelve ontologies (Table 1) studied in depth in this review are introduced (§3.1). Then, the concepts that each ontology can describe are outlined (§3.2). 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

Avancha, Patel and Joshi [9] 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. [38] include sensor types in an ontology developed for recording provenance, or pedigree, information in naval operations.

The OntoSensor [48, 47] ontology was intended as a general knowledge base of sensors for query and inference, based on SensorML it includes concepts from IEEE SUMO and ISO 19115. The OntoSensor ontology includes concept and individual definitions of CrossBow sensors.[5] Kim et al. [35] extend OntoSensor for Web services, though the ontology or full details are not available.

Eid et al. [25, 26] 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).

Calder et al. [16], as part of the Coastal Environmental Sensing Networks (CESN) project[6] for sensor networks for coastal observing, have built an ontology of sensor types and a DL and logic programming rules reasoner for making inferences about data and anomalies in measurements. The CESN ontology has ten concept definitions for sensor instances and six individuals.

The SWAMO [55] ontology for intelligent software agents describes physical devices and process models and tasks. The ontology was designed to compatible with SensorML.

[5] `http://www.xbow.com/`
[6] `http://www.cesn.org`
[7] `http://www.memphis.edu/eece/cas/onto_sensor/OntoSensor.txt`
[8] `http://www.cesn.org/resources/cesn.owl`
[9] `http://www.dvs.tu-darmstadt.de/staff/aherzog/a3me/a3me.owl`
[10] `http://www.csd.abdn.ac.uk/research/ita/sam/downloads/ontology/ISTAR.owl`
[11] `http://mmisw.org/ont/mmi/20090519T125341/general`
[12] `http://mmisw.org/ont/mmi/device`
[13] `http://www.w3.org/2005/Incubator/ssn/wiki/images/4/42/SensorOntology20090320.owl.xml`

| reference | date | active | purpose |
|---|---|---|---|
| Avancha et al. [9] | 2004 | ✗ | adaptive sensor networks |
| Matheus et al. [38] | 2005 | ✗ | pedigree (provenance) |
| OntoSensor [48, 47][7] | 2006 | ✗ | knowledge base and inference |
| Eid et al. [25, 26] | 2007 | ? | searching heterogeneous sensor network data |
| Kim et al. [35] | 2008 | ? | services |
| CESN [16][8] | 2008 | ✓ | inferring domain knowledge from data |
| SWAMO [55] | 2008 | ✓ | intelligent agents |
| A3ME [30, 31][9] | 2008 | ✓ | resource constrained devices |
| ISTAR [44, 27][10] | 2009 | ✓ | task assignment |
| OOSTethys [2][11] | 2009 | ✓ | integrating standards-compliant Web services |
| MMI [1][12] | 2009 | ✓ | interoperability |
| CSIRO [41][13] | 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.

The A3ME [31, 30] ontology of devices and their capability types was developed to classify devices and their capabilities in a heterogeneous network, with a focus on making the ontology usable on resource constrained devices.

The ISTAR [44, 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 OOSTethys community[14] 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.[15] The sensor ontology focuses on system structure and the proceedure and result of an observation.

The Marine Metadata Interoperability (MMI) Device Ontologies Working Group[16] is developing an ontology of oceanographic devices, sensors and samplers.

The CSIRO sensor ontology [41, 19] is a generic ontology for describing sensors and deployments. It is intended to be used in data integration, search, classification and workflows. There are two example sensor definitions available for the CSIRO ontology.

Hu, Wu and Guo [33] develop two layers of ontology with the intention of using rules to deduce high-level, contextual information from low-level data, but do not provide enough detail to be included in the analysis here. Horan [32] uses the OWL-S [43] Web services ontology as a basis for a sensor ontology, but does not provide enough detail for inclusion. As it is based on services, processes, inputs and outputs, and grounding (which is interpretable as access,

[14] http://www.oostethys.org/
[15] http://www.oostethys.org/ogc-oceans-interoperability-experiment
[16] http://marinemetadata.org/community/teams/ontdevices

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

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 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. Each includes concepts for describing measurements, systems, the components of systems 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. 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 A3ME ontology covers a broad range of concepts, but in a simple way intended for low-power devices that do not have complex reasoning capabilities.

The CSIRO and OntoSensor ontologies are each being able to describe most of the spectrum of sensor concepts and thus cover a wider range of concepts than the other ontologies. 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.

### 3.3 Expressive Power

This section discusses the relative expressive power of the ontologies for a number of important points. The OntoSensor, SWAMO, OOSTethys, CSIRO and MMI ontologies, for example, can each describe the platform a sensor is attached. OntoSensor and OOSTethys, through the MMI platform ontology [11], can describe the components of platforms. The SWAMO, CSIRO, OOSTethys, ISTAR 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.

[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 |
| Avancha | sensor | | | ✓ | | | | | | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Matheus | system & sensor | ✓ | | ✓ | | | | | ✓ | ✓ | | | | | ✓ | | ✓ | | | | | | |
| OntoSensor | component & sensor | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Eid | sensor | | ✓ | | | ✓ | | | | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | |
| Kim | sensor | | | | | ✓ | | | | ✓ | | | | | ✓ | ✓ | ✓ | | ✓ | | ✓ | | |
| CESN | sensor | ✓ | | | ✓ | | | | | ✓ | | | | | ✓ | | | | | | ✓ | | ✓ |
| SWAMO | agent, process & sensor | | | ✓ | | | | ✓ | ✓ | ✓ | | ✓ | | | ✓ | | | | ✓ | ✓ | ✓ | | ✓ |
| A3ME | device & capability | ✓ | ✓ | ✓ | | | | | | | ✓ | | | | ✓ | | | | | | | | |
| ISTAR | system & sensor | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | | ✓ | | | | | | | | | |
| OOSTethys | component, system & process | | | | | | | ✓ | ✓ | | | ✓ | | | ✓ | | | | | | ✓ | ✓ | |
| MMI | sensor (system) & process | | ✓ | | ✓ | ✓ | | ✓ | ✓ | | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | ✓ | ✓ | |
| CSIRO | sensor & process | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | |

**Table 2.** Sensor Concepts

The same five ontologies can describe the components of a sensor system and its processes. OntoSensor, MMI and OOTethys describe part-of relations. 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. These 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.

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 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 the capabilities in Section 2.

## 4 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 support 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 [52]. Kim et al. [35] and Eid et al. [26] give examples of using SPARQL to query a sensor ontology.

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

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 derive further inferences about data, in ISTAR to derive further capabilities of sensors [44, 27, 22], and by a number of other related technologies [54, 15, 57, 10, 34, 33]. 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 [22, 44, 27]. The CSIRO ontology can be used for more complex automated composition and potentially similar technology to that used for Web service composition [19].

### 4.1 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: XLink [3] and RDFa [6].

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. XLink attributes can be added to SensorML and O&M documents (see Figure 2) to provide semantic annotations for the sensor data [29, 39].

```
<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>
```

**Fig. 2.** Semantic annotation of O&M with XLink

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 [50, 10], but require additional syntax.

XLink is already used in SWE documents, thus, no syntactic or structural changes are required. This explains the relative success of XLink-based approaches in earlier attempts to add semantic annotations to SWE documents. Recognizing which XLink attributes correspond to semantic annotations and which correspond to permissible SWE usages could become difficult.

Approaches based on RDFa look more promising at the level of SWE documents since it would be easier to process the annotations independently of the rest of the document. Further work is required to check that the introduction of RDFa would not bring major changes for the implementers of the SWE standards and also to investigate how RDFa-enabled SWE services could be further integrated with other RDFa-based Web mashups.

SWE also provides a definition attribute that provides a link to a registry definition, which may also link to an ontological description [29, 39]. In addition, SWING [24], 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 by semantically annotating SWE documents as described above.

## 5 Conclusion

This paper has reviewed the state of the art in semantic descriptions of sensors: twelve 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 limit 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. 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 the capabilities in Section 2. 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 for semantic sensor networks.

DL inference and logic programming rules are the main forms of inference the have been used with semantics for sensors [16, 44, 27, 22, 54, 15, 57, 10, 34,

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

33, 29]. However, as advocated by Sheth, Ramakrishnan and Thomas [51], 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. [36], have not yet been applied to sensors.

If large amounts of data can be annotated using the techniques outlined in Section 4.1, 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 covered sensors and measurements from a sensor perspective; however, the observation perspective is important and could be reviewed as a complement to this review. Among other O&M ontologies, Probst [45, 46] 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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