The SSN Ontology of the Semantic Sensor Networks Incubator Group

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Abstract

The W3C Semantic Sensor Networks Incubator group (the SSN-XG), as one of its activities, produced an ontology to describe sensors and observations — the SSN ontology, available at `http://purl.oclc.org/NET/ssnx/ssn`. This article describes the development of the SSN ontology, the SSN ontology itself and its alignment to the DOLCE-UltraLite foundational ontology. The SSN ontology can describe the capabilities of sensors, the measurement processes used and the resultant observations.

Keywords:

1. Introduction

The W3C Semantic Sensor Networks Incubator group (the SSN-XG), which ran from March 2009 to September 2010, worked on an OWL ontology to describe the capabilities and properties of sensors, the act of sensing and the resulting observations. This article describes the ontology and its development.

As the prevalence of sensing devices and systems grows, semantic technologies are increasingly seen as a way to manage the large volume of generated data as well as the sensors themselves. Sensors are now used in applications ranging from meteorology to medial care to environmental monitoring to security and surveillance. The growth in number of applications and sensors is accompanied by growth in the volume of data and the heterogeneity of devices and data formats.

Semantics can play a role in assisting users to manage and query sensors and data. Indeed as the scale and complexity of sensing networks increases, machine interpretable semantics may allow autonomous or semi-autonomous agents to assist in collecting, processing, reasoning about and acting on sensors and data. For their own part, users generally want to operate at levels above the technical details of format and integration, and rather work with domain concepts and restrictions on quality, allowing technology to handle the details.

The current suit of standards relevant to sensors [1], such as SensorML [2] and O&M [3, 4] from the Open Geospatial Consortium's (OGC) Sensor Web Enablement standards [5], provide syntactic interoperability [6]; a further, or alternate, layer is required to address semantic compatibility.

1.1. The SSN-XG — The W3C Semantic Sensor Networks Incubator Group

W3C incubator groups are one-year (plus possible extensions) exploratory activities on emerging web related concepts, guidelines or activities. They can lead to further W3C activities, member submissions or recommendations. The SSN-XG was initiated by the CSIRO and Wright State University as a forum for the development of an OWL ontology for sensors and to further investigate annotation of and links to existing standards.

The SSN-XG ran from March 2009 to September 2010. Some 41 people, from 16 organisations, joined the group, with 20 members attending more than 10 meetings. The group meet via weekly phone conference and once face-to-face in Washington, October 2009, aligning with SSN09 — the Semantic Sensor Networks Workshop [7] — which was held in conjunction with ISWC 2009.

The complete activities of the group where recorded on the group's wiki `http://www.w3.org/2005/Incubator/ssn/wiki/Main_Page`, where the group's final report `http://www.w3.org/2005/Incubator/ssn/wiki/Incubator_Report` can also be found. Along with the

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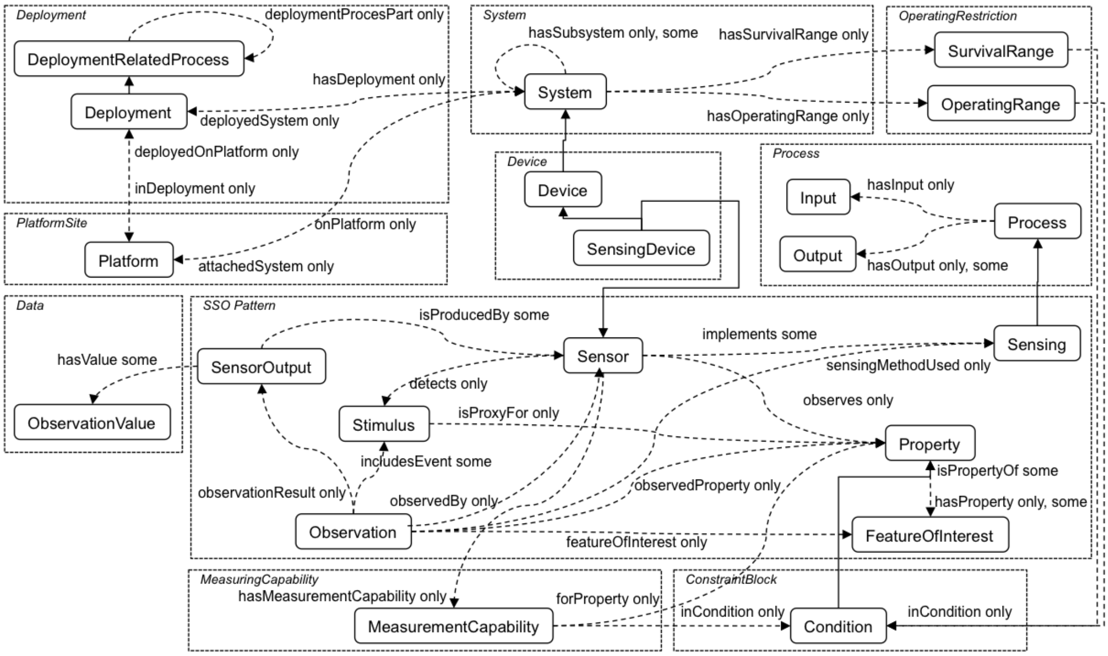

Figure 1: The SSN Ontology, key concepts and relations, split by conceptual modules. The concepts not depicted are largely properties for measurement capabilities, and survival and operating ranges: accuracy, precision, resolution and the like. Note the central importance of sensors, observations and properties, brought out by the SSO pattern.

ontology, the final report includes sections on the group's review of existing sensor and observation related ontologies, mappings of terms from the ontology to other standards and vocabularies, and material on the group's other main deliverable on semantic annotation of OGC Sensor Web Enablement standards.

The section of the final report on the ontology, `http://www.w3.org/2005/Incubator/ssn/wiki/Incubator_Report#SSN_ontology`, contains a full explanation of the ontology with examples and notes on how to use the ontology in many common scenarios. This article omits the examples and concentrates on the broad structure and main concepts and relations of the ontology.

1.2. Development of the SSN Ontology

The SSN ontology was developed by group consensus over a period of some eleven months. First the core concepts and relations were developed (sensors, features and properties, observations, and systems), then measuring capabilities, operating and survival restrictions, and deployments were added in turn and finally the alignment to DOLCE-Ultralite and the realisation of the core Stimulus-Sensor-Observation pattern were added.

For each addition, a group member developed a proposal, including ontology extension and, often, examples, that was taken to the group, debated in meetings, and on the group's mailing list, and, when ready, voted on as an addition to the SSN ontology. Discussions focused on, and improved, structural aspects as well as names, intended scope and meaning, and relevant properties and restrictions. The decision to align to DUL was made by group vote, and alignment choices were discussed at meetings, but each alignment choice wasn't made by group vote, rather by consensus amongst group members involved in the alignment. In general, concepts and object properties found natural alignments in DUL, given the already developed definitions and intentions. The group choose not to place domain and range restrictions on object properties, choosing instead to restrict concepts in terms of defined properties.

In developing final documentation, the group further organised the ontology into ten conceptual modules of related concepts. At this point, final English definitions and mappings to sources and similar definitions were added to the ontology, and scripts were developed to derive navigable documentation for the wiki. Members of the group also developed and documented examples using the ontology in their projects.

A review of existing ontologies and standards (see also Compton et al. [8]), development of use cases and the participants' projects, experience and expectations guided the group in first deciding what would and would not be in the ontology and then in developing each part of the ontology.

1.3. The SSN Ontology

The ten conceptual modules and key concepts and relations of the SSN ontology are shown in Figure 1. The full ontology consists of 41 concepts and 39 object properties: that is, 117 concepts and 142 object properties in total, including those from DUL.

The group decided that the ontology should contain concepts and relations relevant only to sensors, leaving concepts related to other, or multiple, domains to be included from other ontologies when the ontology is used. Doing so makes the ontology single subject and so aims for modularity and reusability.

Thus the ontology can describe sensors, the accuracy etc of such sensors, obsevations and methods used for sensing. Also concepts for operating and survival ranges are included, as these are often part of a given specification for a sensor, along with its performance within those ranges. Finally, a structure for field deployments is included to describe deployment lifetime and sensing purpose of the deployed macro instrument.

Clearly related, but not sensor only, material such as units of measurement, locations, hierarchies of sensor types, and feature and property hierarchies are left to other ontologies. Where appropriate, concepts are included to allow linking the ontology to these external ontologies: for example, an observation is of a particular property of a feature, where observations are fully described by the ontology, while feature and property are left as place holder concepts. The intention is that in building an ontology based on the SSN ontology, one would include the SSN ontology, suitable units, location and feature ontologies and link these with, for example, OWL subClassOf to specify that the properties in the property ontology are properties of the SSN ontology; this combination can then be used to describe a hierarchy of sensors relevant to the particular application. The SSN-XG wiki pages contain a number of such examples.

The SSN ontology, available with the uri

`http://purl.oclc.org/NET/ssnx/ssn`,

is built around a central pattern describing the relationships between sensors, stimulus and observations, the Stimulus-Sensor-Observation (SSO) pattern [9]. The ontology can be seen from four main perspectives:

- A sensor perspective, with a focus on what senses, how it senses, and what is sensed;
- A data or observation perspective, with a focus on observations and related metadata;
- A system perspective, with a focus on systems of sensors and deployments; and,
- A feature and property perspective, focussing on what senses a particular property or what observations have been made about a property.

The ontology takes a liberally inclusive view of what a sensor is: anything that observes. And allows such sensors to be described at any level of detail, for example, allowing sensors to be seen simply as objects that play a role of sensing, and, also, allowing sensors to be described in terms of their components and method of operation.

Terms and relations in the ontology are commented with rdfs:comment, rdfs:isDefinedBy, rdfs:label, rdfs:seeAlso and dc:source. The latter using skos to relate the ontology to existing standards and vocabularies, while some of the former link to further explanation on the group's wiki.

The ontology is aligned to the DOLCE-Ultralite foundational ontology (DUL),[1] thus further explaining concepts and relations and restricting possible interpretations of the ontology.

[1]DUL uri: `http://www.loa-cnr.it/ontologies/DUL.owl`

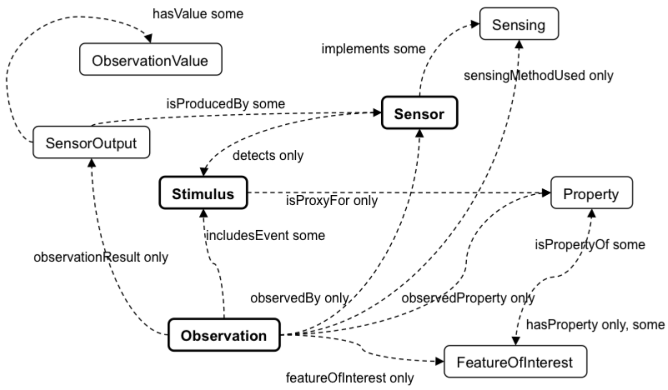

Figure 2: The Stimulus-Sensor-Observation Pattern.

1.4. Paper Organisation

This paper is organised around the core SSO pattern (§2) and the sensor (§3), observation (§4) and system (§5) perspectives introduced above. The feature and property perspective is already covered by the relations introduced in the other sections, and so, isn't given a section of its own. Pertinent points of the DUL alignment are discussed along with the ontology. Namespaces for the sensor and DUL ontologies are written prefixing concepts and properties as ssn: and dul: respectively.

2. The Stimulus-Sensor-Observation (SSO) Pattern

Central to the ontology is the Stimulus-Sensor-Observation pattern (Figure 2). The pattern links sensors, what they sense and the observations that result, encompassing three of the four perspectives — the missing system perspective is more about system organisation and deployments than sensing, but clearly links to the SSO pattern.

2.1. Stimuli

Stimuli are changes or states (dul:Event) in an environment that a sensor can detect and use to measure a property. A stimulus (ssn:Stimulus) is thus a proxy (ssn:isProxyfor) for an observable property (ssn:Property), or a number of observable properties. For example, changes in electrical resistance as a proxy for temperature in a thermistor, or current generated by spinning wind cups for wind speed.

Properties themselves are observable characteristics of (ssn:isPropertyOf) real-world entities (ssn:FeatureOfInterest). In the DOLCE alignment we specify ssn:FeatureOfInterest $\sqsubseteq$ dul:Event $\sqcup$ dul:Object, rather than using dul:Entity for features, since one cannot sense properties of abstract entities, such as sets and regions.

2.2. Sensors

Sensors (ssn:Sensor) are physical objects (dul:PhysicalObject) that observe, transforming incoming stimuli (ssn:detects) into another, often digital, representation (ssn:SensorOutput). Sensors may be hardware devices, sensing systems, human run laboratory setups — anything that senses.

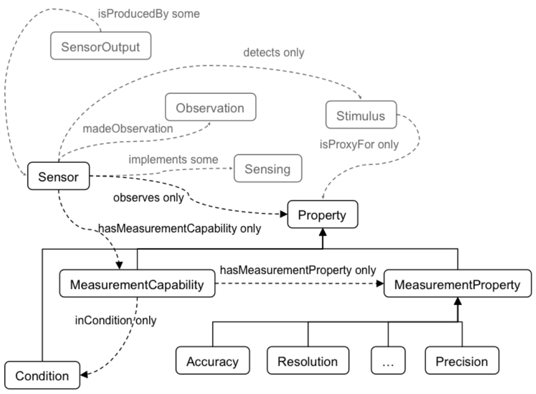

Figure 3: Ontology view concentrating on measurement capabilities of sensors. A sensor may be linked to any number of capability descriptions, each specifying, for example, how the sensor's accuracy and resolution are affected by prevailing environmental conditions.

A sensor follows (ssn:implements) a method (ssn:Sensing ⊑ dul:Method ⊑ dul:Description) describing how the sensor observes: this may be for example a description of the scientific method implemented by the sensor.

The sensing method, though, is distinct from a process or workflow description of how the sensor operates (not described by the SSN ontology, workflow and process descriptions being more widely applicable and expected to be imported from a suitable ontology). A method is an abstract description; there may be any number of ways to concretely realise one.

2.3. Observations

Observations (ssn:Observation) are the nexus of the SSO pattern. For a sensing event, an observation can link the act of sensing (dul:includesEvent, not in pattern), the event that is the stimulus (dul:includesEvent), the sensor (ssn:observedBy), a method (ssn:sensingMethodUsed), a result (ssn:observationResult), and an observed feature (ssn:featureOfInterest) and property (ssn:observedProperty), placing all in an interpretative context.

Since an observation is an explanatory context of the stimulus event and result of sensing, given the description of the sensing method used, we regarded observations as social constructs (ssn:Observation ⊑ dul:Situation). That is, observations are contexts for interpreting incoming stimuli, rather than being events themselves.

A sensing method can both describe the principle underlying a sensor and describe how observations where made: that is, the principle underlying the observation, describing, for example, how a sensor was positioned and used. In some cases, this allows a modelling choice, where, for example, sensing devices used in a particular way could be best modelled as sensors used as per an observation method, whereas, a more intricate setup may be be more appropriately modelled as a sensor than observation method.

3. Sensor Perspective

The SSO pattern describes a sensor in terms of its stimulus, sensing method and the observations it makes. The complete sensor perspective enriches this picture to include the capabilities of sensors. For each property a sensor is capable of observing (ssn:observes), the performance (accuracy, etc) of the sensor might be affected by prevailing environmental conditions, related or not to the property under observation.

3.1. Measuring Capability

That the accuracy of a sensor is affected by prevailing conditions is an observable property of the sensor. Indeed, sensing devices, are often described by a data sheet that lists properties observed of the sensor in various conditions. That is, accuracy, measurement range, precision, resolution and the like are all properties that one might observe of a sensor.

The ontology models ssn:Accuracy, ssn:DetectionLimit, ssn:Drift, ssn:Frequency, ssn:Latency, ssn:MeasurementRange, ssn:Precision, ssn:ResponseTime, ssn:Resolution, ssn:Sensitivity and ssn:Selectivity as measurement properties (ssn:MeasurementProperty ⊑ ssn:Property). A sensor may have (ssn:hasMeasurementCapability) a number of measurement capabilities (ssn:MeasurementCapability ⊑ ssn:Property), describing the capability of the sensor in (ssn:inCondition) various conditions (ssn:Condition), which are in turn observable properties of the sensor's environment.

A measurement capability instance collects together observed properties of a sensor in the conditions specified. A sensor may have links, through ssn:hasMeasurementCapability, to any number of ssn:MeasurementCapability instances: for example, multiple instances with the same property, but different conditions, specify the capability of the sensor in a range of conditions, while, for sensors that observe multiple properties, multiple instances with different properties, perhaps each with different conditions, specify the capability of the various sensing functions.

4. Observation Perspective

Complementing the sensor perspective is the observation perspective, which completes the description of an observation introduced in the SSO pattern. Observations are contexts for interpreting incoming stimuli and so place the observing event and stimulus in an interpreting context. The context includes observed feature (ssn:featureOfInterest), property (ssn:observedProperty), observing sensor (ssn:observedBy), result (ssn:observationResult) and method (ssn:sensingMethodUsed) from the SSO pattern and can also record an adjudged quality, in complement to a sensor's capabilities, of the observation (ssn:qualityOfObservation), a time the result became available (ssn:observationResultTime) and a time at which the sampling took place (ssn:observationSamplingTime) - time being an aspect the SSN ontology does not describe and is left for an imported time ontology.

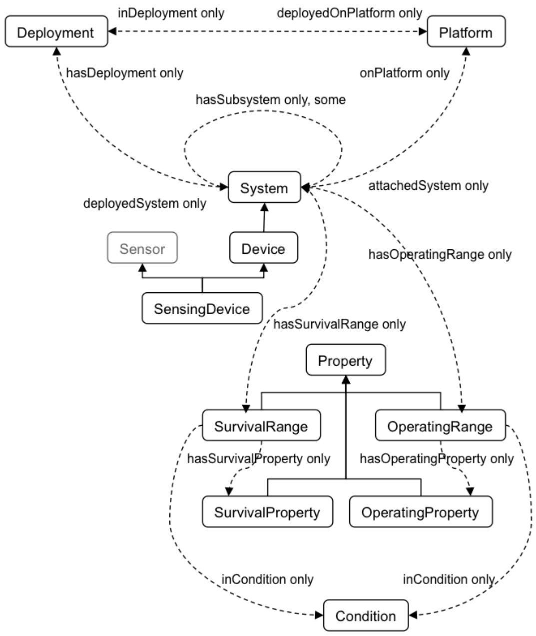

Figure 4: Ontology view showing systems, deployments, platforms and operating and survival conditions.

The treatment of an observation as a social construct, interpreting events, participants and associated result, differs from O&M, in which observations are seen as the observing events themselves. The treatment here has the benefit that it separates a stimulus event from potential multiple interpretations of it and that it signifies the interpretative nature of observing. Despite the different ontological classifications of observation, the associated data remains the same.

5. System Perspective

The system perspective is constructed around a system (ssn:System) concept representing parts of sensing infrastructure. A system has components (ssn:hasSubSystem) which are systems. Systems, of which devices and sensing devices are sub concepts (ssn:SensingDevice ⊑ ssn:Device ⊑ ssn:System), have operating and survival ranges (ssn:hasOperatingRange and ssn:hasSurvivalRange), may be mounted on platforms (ssn:onPlatform) and may be deployed (ssn:hasDeployment).

5.1. Operating and Survival Restrictions

Similarly to how prevailing environmental conditions may affect the performance of a sensor, a system or device may have a defined operating environment, and environmental extremes may exceed the capacity of a system to survive and make further observations. The general structure for describing operating and survival ranges is the same as for sensors and measurement capabilities, indeed they are observable properties of systems. The operating range (ssn:OperatingRange), describing characteristic of the environmental and other conditions in which the system is intended to operate, includes features such as power ranges, power sources, standard configurations, and attachments. The survival range (ssn:SurvivalRange) describes environmental conditions to which a sensor can be exposed without causing lasting damage: i.e., the sensor continues to operate as per defined measurement capabilities. If, however, the survival range is exceeded, the sensor is considered damaged such that measurement capability specifications may no longer hold.

5.2. Deployment

A deployment (ssn:Deployment ⊑ dul:Process ⊑ dul:Event) is a process that encompasses all phases in the lifetime of a deployed system: such as, installation, maintenance and decommissioning. A system is deployed on (ssn:deployedOnPlatform) a platform (ssn:Platform - a role an entity plays whilst a system is attached).

Locations of platforms, systems or sensors and temporal properties of deployments are areas where other ontologies are required to fill in the details. Broadly, location can be represented as either abstractions of real-world locations or as absolute or relative locations. For example, relating (dul:hasLocation) a sensor to a place (dul:PhysicalPlace), as in the sensor/platform is on the eastern edge of the lake, indeed the relation between a sensor and a platform can be specified in this way (ssn:onPlatform ⊑ dul:hasLocation); while absolute and relative locations acknowledge that location is an observable aspect of an entity, which thus may have a property (ssn:hasProperty) stating location using, for example, absolute or relative latitude and longitude.

Temporal properties could be included by specifying a date for deployment processes (dul:hasEventDate) or by including a time ontology, perhaps treating time as observable and classifying time concepts into the DUL hierarchy (using dul:TimeInterval).

6. Discussion

6.1. Using the SSN Ontology

The group's main use cases — entitled: data discovery and linking, device discovery and selection, provenance, and device operation, tasking and programming — cover a range of applications from data and linked open data (LOD) to selection and deployment and mission planning.

Examples on the group's wiki are used in explaining each conceptual module of the ontology and thus there are examples for each group of concepts in the ontology. These examples include two LOD examples, from the SENSEI[2] project (see also, Barnaghi and Presser [10]) and the Kno.e.sis Center,[3] where it is used to semantically annotate and assist in analysing streaming sensor data; a smart products (sensor embedded products) example from the SmartProducts project;[4] specifications drawn from commercial sensor data sheets and

[2] `http://www.sensei-project.eu/`
[3] `http://knoesis.wright.edu/`
[4] `http://www.smartproducts-project.eu/`

an agriculture and meteorology example. These examples combine the SSN ontology with units of measurement, feature and quality, and domain ontologies.

The ontology is used as a fundamental ontology in the SemsorGrid4Env project,[5] which aims to build large semantic sensor network applications for environmental management. It is used in the SPITFIRE project[6] to enable network and protocol-agnostic end-to-end service communication in sensor networks (see also Leggieri et al. [11]). It is also used in the Exalted project[7] to enable query management, event processing and communication. Projects at 52 North[8] are using the ontology to develop plug & play infrastructure and to provide linked sensor data. At CSIRO[9][10] the ontology is used in research on sensor network installation, querying and programming and provenance. The ontology is also used in publishing data from the Spanish Meteorological Agency.[11]

and ....????

The ontology allows a division between TBox definitions of sensor classes and ABox definitions of sensor instances. For example, particular makes of sensor defined as TBox definitions, including measurement capabilities and survival and operating ranges from data sheets, and ABox individuals which need not repeat the general information for the sensor, which is inferred to be present, specifying instead specific information such as location, deployment, etc. This is an advantage over SensorML which has no such class/instance division. The SSN ontology thus allows class and instance definitions to be managed in separate ontologies, perhaps by separate authorities.

6.2. Conclusion

The W3C Semantic Sensor Networks Incubator Group, the SSN-XG, developed an OWL ontology — the SSN ontology — for describing sensors, sensing, the measurement capabilities of sensors, the observations that result from sensing and deployments in which sensors are used. The ontology covers large parts of the SensorML and O&M standards from the OGC, omitting calibrations as well as process descriptions and data types, which were deemed not sensor specific and if required can be included from other ontologies.

The development of the ontology was informed largely by the incubator group participants' use cases, existing OWL ontologies, OGC standards, and vocabularies such as the International Vocabulary of Metrology [12, also ISO/IEC Guide 99:2007].

The SSN ontology is currently used in a number of research projects. Continued use of the SSN ontology by its development community and others will expose design flaws or required additions, and may encourage a community to reform for agreed enhancements, either informally or as part of a development or even standards group.

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