The Semantic Sensor Network Ontology, Revamped

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Abstract. The Semantic Sensor Network Ontology, popularly known as *SSN*, was developed by an Incubator Group of the World Wide Web Consortium (W3C) over 2009 to 2011. Subsequently, the W3C and the Open Geospatial Consortium (OGC) joined forces to update the SSN as informed by experience, to harmonize it with OGC's O&M, and to publish a new version to be endorsed as both a W3C Recommendation and an OGC standard in late 2017. The major contribution of the new SSN is a modular structure designed to be more convenient for ontology engineers and data custodians. It also slightly extends the coverage of the previous SSN with new terms for sampling and actuation. SSN retains the ability to comprehensively represent: *sensors* in terms of what they can sense, and what and how they do sense; *observations* in terms of what they measure and what values they find; *systems* (or networks) of sensors in terms of sensor components and how they are deployed; and *real-world objects* (called *features of interest*, OGC-style) in terms of their physical properties, what can sense them, and what observations of them have been made. A few little-used SSN terms have been deprecated, and several others have been renamed. For a comprehensive description of new SSN the reader is referred to the specification [10]. A full description of the scope, design rationale and additions, with examples of its application are presented in [11].

Keywords: sensor · ontology · OGC standard · W3C recommendation

1 Introduction

The Semantic Sensor Network Ontology, popularly known as *SSN*, was developed by an Incubator Group of the World Wide Web Consortium (W3C) over the period 2009 to 2011. It was well-timed for the rapid growth of industrial interest in the *Internet of Things* that ramped up around 2012, when the concept was expanded beyond RFID alone to include arbitrary sensors and actuators. The original SSN, hereafter referred to as SSNX, was largely an experimental design. It was influenced in part by the by the Observations and Measurements (O&M) model (issued in 2007 [6] and later standardised by ISO[13] and the Open Geospatial Consortium (OGC) [8]). It was intended to serve research projects in, for example, agriculture [30], smart campus [26], environmental modelling [29,16], IoT [4], streaming [22], and climate modelling [18]. These projects developed or exploited semantic technologies, and were seen to benefit from a quality, shared ontology for describing sensors, networks of sensors, sensor capability, and the phenomena they sense. Arguably, it was designed for an ontology-expert audience and not for the emerging cohort of professional software engineers developing linked data infrastructures. Indeed, it was linked to the OGC's SensorML standards [5] through patterns showing how SSNX terms could be used to annotate entities and relations expressed SensorML's XML [19], but to the knowledge of the authors this design was seldom employed.

In 2014 the W3C and the OGC decided to work together to jointly progress the application of linked data techniques to spatial data, recognising the relatively low uptake of traditional spatial data infrastructure standards based on XML schemas and SOAP or REST interaction protocols. The *Linking Geospatial Data* workshop [1] was convened in 2014 to gauge the demand and scope for a joint standards activity. Later that year the Spatial Data on the Web Working Group was established, chaired by the first author, with Ed Parsons of Google [31]. Amongst many other goals, the Working Group was to bring SSN forward as a formal recommendation of the W3C and a standard of the OGC. The key requirement for the new standard was to address the perceived complexity of the SSNX, considering modularisation as a possible approach to facilitate ease of use.

In this paper, written 18 months after the standard was published, we highlight the significant features of the new SSN, particularly aiming to provide insight into the rationale behind its design. We also take a look at how the new SSN is being used through a very brief survey of the literature.

2 Disentangling the upper ontology

Firstly, and most significantly, it was readily agreed that the reliance of SSNX on the Dolce Ultralite (DUL) upper ontology [24] through an `owl:import` statement added more confusion than clarification, both through the introduction of very abstract terms and also through the dependency for representation of concrete measurement values. While it was recognised that the upper ontology gave some valuable structure and coherence to the design of SSNX, it was widely believed to get in the way of learning and using the SSNX. The first step of redesign was to move axioms relating SSN terms to DUL terms away from the SSN ontology to a new *Dolce Ultralite Alignment module*, called SSN-DUL that itself imports SSN and DUL. We were able to update the DUL URL at the same time, as DUL had moved in the intervening years and this frequently annoyed SSN users. By this simple redesign SSN could be readily used either with or without DUL.

3 Re-thinking the O&M relationship

For the SSNX it was determined very early that an ontology of sensors needs to be able to talk about the observations sensors make. In O&M, arguably the central concept is an `Observation`, and this was conceived as an *act* [7]. In common language, as well as in related OCG documentation (such as https://www.opengeospatial.org/standards/om), while we may use the verb *to observe*, we usually talk about *making* an `observation`, and the `Observation` itself is the artefact or record of the act of observing. The SSNX conceived the concept `Observation` as an information construct or social construct, more precisely, as a DUL `situation` that conveniently groups together the things you need to know about the what the `Sensor` did when it took a measurement. However, by the time of the SSN development in the context of a joint working group with the OGC, the conception of an observation as an *event* was entirely familiar. Furthermore, in the near aftermath of the long-running debate about the signifiers of URIs (http range 14 debate [32]), and declining interest in upper ontologies, there was little will for distinguishing physical world concepts from a social or digital interpretation of them. Consequently, SSN reverted to the O&M conception of an `Observation` as an event in explanatory annotations. On the other hand, the SSN has retained the property `madeObservation` and its inverse `madeBySensor` (previously `observedBy`) that connects `Sensor` to `Observation`. Unfortunately by this SSN has inherited the ontological confusion of O&M, stating that a `Sensor` *makes* an event `Observation`. In any case, in SSN the distinction is not significant as the relationship of `Observation` to other SSN concepts is unaffected; but it does make a difference to its integration with other ontologies including PROV [17] (where it is a `Prov:Activity`) and DUL (where it is now a `dul:Event`) [11].

4 Modularity

The working group began with a starting point for modularity developed by Michael Compton, where parts of the ontology, with the topic-specific focus as identified in the original SSN design, were separated into OWL ontologies with `owl:imports` relationships amongst them. However, this was found to be difficult to work with as the dependency between the terms from different modules typically led to an import of all modules, which increased the difficulty instead of a simplification.

Modularity in DLs has been well-researched. The research has focused on extracting *modules* with a selected focus from pre-existing non-modular ontologies to satisfy various desirable coherence properties. For example, [15] extracts modules in EL and ALC, whereby a *signature* of terms define the focus of a module and the module is populated with axioms from the source ontology such that well-defined *dependencies* of the signature terms are maintained. Alternatively, [3] develops *package-based description logics* that redefine the semantics of interpretation of standard description logic together with a signature focus to extract terms from multiple independent ontologies, aiming to satisfy desirable coherence properties. Neither of these style of approaches was considered appropriate for SSN where we had the opportunity to designing modularity from scratch, and where a key requirement was always to make use of SSN easier by ontology engineers and data custodians.

One way to make it easier would be to reduce the signature, and another would be to reduce the expressivity of the ontology language and thereby reduce the burden of understanding the intent and consequence of complex axioms. The modular architecture of SSN does both these things. Furthermore, we wanted SSN modules to satisfy linked-data engineering practices that are not addressed by established modularity designs. These included

- That each ontology module is retrievable from the module URI;
- That the namespace for each module is the same as its URI; and
- That each term is defined in a unique module that is referenced using `rdfs:isDefinedBy` whenever it is used in an ontology

Our SSN design satisfies the desiderata of packaged description logics [3] by design, without requiring its non-standard inference.

As published, SSN has been designed with a central core ontology of terms considered to be most in-demand for use of the ontology, called SOSA for *Sensor, Observation, Sample and Actuator* which are its key concepts. The axioms of SOSA are simple in two respects. The signature is minimised by avoiding terms considered of only specialist use. The language of expression is minimised by using only the ALI(D) DL language. This language is convenient for performance of reasoning, and while OWL classes and object properties are declared, the only constructs that require OWL reasoning services (or RDF(S), for that matter) are inverse roles and concrete XML Schema datatypes. There is no subclass nor subproperty hierarchy. Intended domains and ranges of object properties are documented by way of `schema.org`'s `schema:domainIncludes` and `schema:rangeIncludes` and these are explicitly declared to be annotation properties, not object properties in SOSA, hence cannot be reasoned with.

On the other hand, the interpretation of basic terms introduced in the SOSA core is constrained by more expressive ALRIN axioms in the SSN module which `owl:imports` SOSA. SSN also extends SOSA with further terms: 6 classes and 15 object properties to enrich the relationships amongst SOSA classes and to extend the modelling to aspects of `Systems` of `Sensors` and `Deployment`.

While SSN is consistent with SOSA, it cannot guarantee consistency with arbitrary other ontologies that also extend SOSA, under the usual semantics. Nor can it guarantee consistency with ABox assertions that are made in the SOSA context, with, for example, no formal domain, range or cardinality axioms. This is unfortunate, as it would be very convenient for data integration to have the property that any consistent SOSA ABox also forms a consistent ontology when combined with the SSN TBox. On the other hand, any consistent SSN ABox *is* a consistent ontology when combined with the SOSA TBox when instances of terms not present in SOSA are removed, so a data integration strategy of resorting to the lowest-common-denominator *is* simple to execute.

Figure 1 is adapted from the figures presented in [10,11] and shows the import relationships between the SSN, SSN-DUL and SOSA modules, together with some other modules introduced in the following.

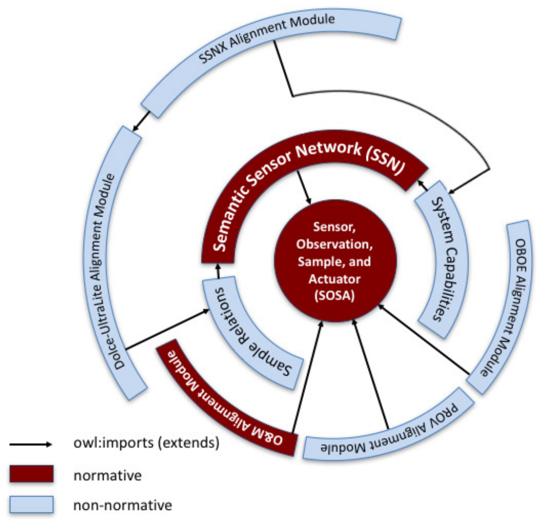

Fig. 1. The SSN family of ontologies showing import relations and normative or informative status in the SSN standard. Note that the *sample relations* module in the standard incorrectly imports SOSA at time of writing; instead the working group's *intended* relationship to SOSA and SSN is depicted in the figure. An improved version, that also removes the SKOS import in the standard version, is available on the working group's repository at github.com/w3c/sdw/blob/gh-pages/ssn/rdf/sample-relations.ttl

5 How a sensor works

In the early days of the development of SSNX, there was an ontologically elegant effort to structure the ontology around a *skeleton* fragment that explained what `Sensors` do. In particular, this skeleton represented `Sensors` as things that `detect(s)` a `Stimulus` in the physical world and that `implement` a `Sensing` process to produce (that is, inverse `isProducedBy`) a `SensorOutput`. However, ontology users have shown to be little interested in what sensors do when they capture data, so this was determined to be overly-complex. In the SSN this part of the skeleton was excised from the core SOSA where `Observation` has become of more central importance.

6 New terms

SSN has been extended very little from SSNX. While several new capabilities were derived from proposed use cases or directly proposed by Working Group members, these were largely eschewed in the interests of simplicity and generality.

However, partly in SOSA and partly in the greater SSN, the pattern for description of `Observation` has been cloned (with term changes) to describe the acts of `Actuation` and `Sampling`. An `Actuation` is made by an `Actuator` on a `Feature of Interest`, and a `Sampling` is made by a `Sampler` on a `Feature of Interest`.

In addition, in what may well be the most widely appreciated simple extension to SSNX, SOSA `Observation` has been extended by a simple datatype property `hasSimpleResult` that can be used to directly assert the literal values of an `Observation`, `Actuation` or `Sampling`, without further reference to external ontologies or via property chains or paths.

About a dozen SSNX terms have been renamed.

7 Other SSN modules

In addition to ssn-dul, several small alignment ontologies to popular external ontologies have also been released with SSN. One, the SSNX alignment module, is intended to ease the transition of existing SSNX applications to SSN by providing, as far as possible, subclass and subproperty relations that, interpreted by a reasoner, can infer SSN instances from SSNX instances. Similarly, PROV-O[17] and OBOE [23] alignments are provided.

A *System capabilities* module extends SSN by the terms and axioms from SSNX that are designed for modelling the capabilities of sensors and systems of sensors to measure particular physical properties, and identifying their measurement limitations. In this case they were separated from SSN as a separate module due to an analysis of use that showed they were used less often than the remaining SSN terms and so could be treated as specialist terms for a limited audience that are better not clogging up SSN.

Finally, the *sample relations* extends the basic structures for SOSA terms for the sampling process, designed for asserting relationships amongst different sampling individuals. Please refer to figure 1 for advice on using this module.

8 Presentation

The presentation of the new SSN is improved over the original SSNX by taking advantage of improved tools and practices developed by the linked data community. This new presentation should, itself, improve the usability of the new SSN. In comparison with the presentation of SSNX, the new ontologies consistently use `rdfs:comment` and `skos:definition` to annotate terms with descriptive explanations, and `skos:example` for an example for how it might be applied, expressed in English. The ontologies are documented with the *Vocabulary for Annotations* (`vann`) and *Vocabulary of a Friend* (`voaf`) terms for use with linked data tools.

Further, updated examples are used in the specification to support understanding. A section on *Common Modelling Questions* has been included as a response to the lessons learnt over the years of experience with SSNX.

9 SSN in the Wild

SOSA has been experimentally evaluated in the OGC [25] and some datasets and ontologies using SSNX have been updated. For example, measurements made by a meteorological station at an experimental farm in 2017 [27] are now published and queryable via SOSA [12]. The new sampling terms have been applied to describe a collection comprising millions of geological samples at Geoscience Australia [2]. Additional applications in research are published in the SSN workshop held at ISWC in 2018 [20].

10 Conclusion

One-and-a-half years after the publication of the new SSN standard, and a half-year since its publication in the academic literature[11,14], we find that the 2011 SSN Incubator Group Report [19] and 2012 journal paper [10] are being cited at a greater rate than SSN. This may well be due to the time lag to create awareness of the update, but it would seem plausible that the added visibility due to its status as a standard of two standards organisations should have overcome the lag by now. It is hoped that this paper will encourage the shift to the new SSN.

While the simple core SOSA has not yet been taken up by `schema.org` [9], there are some clear equivalence mappings to relevant schema.org terms including `sdo:variableMeasured` with `sosa:observedProperty`; `sdo:measurementTechnique` with `sosa:procedure`; and `sdo:object` with `sosa:featureOfInterest`. Work will be undertaken to harmonise these vocabulary fragments in the near future.

Meanwhile, the complementary emerging *W3C Web of Things* standard [28], that is protocol and security-focussed, offers a context extension method by which SSN can be employed for data description. The comparable OGC *SensorThings* standard, that addresses both an interaction protocol (like *Web of Things*), and a small vocabulary, has been published. It refers to part of the prior O&M which is mirrored in SOSA[21].

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