

Semantics in the Edge: Sensors and Actuators in the Web of Linked Data and Things

Editorial

Federica Cena^a and Armin Haller^b and Maxime Lefrançois^{c,*}

^a *Dipartimento di Informatica, Università degli Studi di Torino, Turin, Italy*

E-mail: federica.cena@unito.it

^b *Research School of Management & Research School of Computer Science, Australian National University, Canberra, Australia*

E-mail: armin.haller@anu.edu.au

^c *Univ Lyon, MINES Saint-Étienne, CNRS, Laboratoire Hubert Curien UMR 5516, Saint-Étienne, France*

E-mail: maxime.lefrancois@emse.fr

Editors: Pascal Hitzler, Wright State University, USA; Krzysztof Janowicz, University of California, Santa Barbara, USA

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1. Introduction

The rapid advancement and ubiquitous penetration of mobile networks and software-defined networking technology enable us to sense, predict and control the physical world using information technology - the so-called Internet of Things (IoT)¹. Consequently, business models and processes have been redesigned across a broad range of industries where objects are connected over the Web for communication with other objects on the Web, leading to the so-called Web of Things (WoT) on top of the IoT.

Pervasive connectivity, smart personal devices, for example in our homes, and demand for data testify to a WoT that will continue to grow. New devices are being developed and are becoming cheaper, making their integration into everyday objects ever more feasible, and as people buy into WoT technology, economies of scale lend themselves to the creation of ever more data-centric businesses.

The capabilities of these networks of devices presents us with several new and complex challenges

that need to be solved before the Web of Things can deliver its promised potential. While there are, for example, some industry initiatives to achieve interoperability between smart home devices on the communication layer, including a recent collaboration between Google, Amazon, and Apple² to build a specific set of IP-based networking technologies for device certification, the data that these devices generate on the Web is not described uniformly. However, without connecting the data and its semantics that is generated by potentially billions of devices, the users of the WoT will end up in silos of information that require different applications to access and use it. A description of the capabilities of these devices and its context using semantic technologies may help in deciding how to communicate with the device and manage the data that is produced or the actions that can be performed.

At the data level this problem can be solved using an ontology-based approach. Gruber [24] introduced ontologies to Computer Science as an “*explicit specification of a conceptualization*” consisting of a “*set of objects, and the describable relationships among*

*Corresponding author. E-mail: maxime.lefrancois@emse.fr.

¹also referred to as Cyber-Physical Systems (CPS)

²https://zigbeealliance.org/news_and_articles/connectedhomeip/

1 *them*” represented in a declarative formalism. Ontologies
 2 have consequently proven to be a very useful tool
 3 for semantic interoperability between parties that ex-
 4 change data. With the adoption of the Linked Data
 5 movement, as proposed by Berners-Lee [5], machine-
 6 readable connections between data expressed in RDF
 7 in combination with ontologies have since seen a large
 8 uptake on the Web. One such ontology backed by a
 9 consortia of search engine providers including Google,
 10 schema.org, has seen particular success on the Web
 11 and has been used for semantic annotations on 31.3%
 12 of all websites [26] already back in 2015. It is now
 13 responsible for a large portion of the currently available
 14 machine-readable data on the Web.

15 There already exists a significant amount of re-
 16 search focusing on applying the RDF data model and
 17 OWL ontologies in different WoT scenarios, from
 18 home automation to Industry 4.0, by showing how
 19 this approach can be applied to ease integration of di-
 20 verse data sources [39, 55]. Ontologies and vocabu-
 21 laries such as the Semantic Sensor Network Ontology
 22 (SSN) [29] have been adopted in a number of research
 23 projects [7, 63, 69]. Although the ontology-based ap-
 24 proach in WoT has received significant interest and
 25 adoption in research projects, it still lacks similar lev-
 26 els of adoption to schema.org on the Web or adoption
 27 in industry, more generally [38].

28 This lack of adoption can be attributed to several
 29 challenges, the following three of which we consider
 30 as the major open challenges.

- 31 1. Maturity and Coverage of WoT Ontologies
- 32 2. Semantics in the Edge
- 33 3. Distributed and embedded reasoning

34 In the following section, we will detail and discuss
 35 these three challenges in more detail.

36 2. Challenges in deploying a Web of Things

37 2.1. Maturity and Coverage of WoT Ontologies

38 Different standardisation bodies work towards de-
 39 veloping data models and ontologies for the Internet
 40 and Web of Things [18, 28, 34, 35]: the World Wide
 41 Web Consortium (W3C), the Open Geospatial Con-
 42 sortium (OGC), the Internet Engineering Task Force
 43 (IETF), the European Telecommunication Standards
 44 Institute (ETSI), the Open Connectivity Foundation
 45 (OCF), the IPSO Alliance, and the Open Mobile Al-
 46 liance, among them. Many aspects of the data being

1 generated in the WoT need to be described semanti-
 2 cally and the standardisation bodies sometimes adopt
 3 conceptually different modelling perspectives. The di-
 4 agram in Figure 1 shows these aspects and presents the
 5 current state-of-the-art in ontologies available to de-
 6 scribe those.

7 *Real world setting* A central aspect in modeling WoT
 8 applications is the description of the real world setting
 9 in which the Things/Sensors/Actuators are deployed to
 10 observe or act on some features of interest. Many on-
 11 tologies [4, 12, 29, 33, 61] include patterns to describe
 12 such settings. The OGC and W3C joint standard on the
 13 Semantic Sensor Network ontology (SOSA/SSN) [28],
 14 describing networks of sensors and actuators, their ca-
 15 pabilities, their features of interest, and their individ-
 16 ual observations or actuations, serves as a core or as
 17 a source of inspiration to many of these ontologies,
 18 ensuring some form of interoperability between them.
 19 The ETSI SmartM2M technical committee, develops
 20 the Smart Applications REFerence (SAREF) Ontol-
 21 ogy [12]³, to describe devices and their functions.
 22 SAREF is aligned with the oneM2M [52] base ontol-
 23 ogy that describes communication devices and the
 24 messages they exchange, for syntactic and semantic in-
 25 teroperability with external systems.

26 Extensions of SAREF and SSN have been devel-
 27 oped for specific domains, such as CASO for the
 28 Agriculture [51], EEPISA for Buildings [23], and the
 29 SAREF4ABCD series of SAREF extensions⁴ (e.g.,
 30 [13, 56]). The topological organization of features of
 31 interest, which is the focus of [45, 46] is often an im-
 32 portant aspect as properties of related features of in-
 33 terest may be inter-dependent. Specializations such as
 34 BOT [57] are defined for specific domains.

35 In addition, SSN has a separate module, called SSN
 36 System, to model capabilities and operating/survival
 37 ranges of systems/things. Sagar et al. [60] discussed
 38 some remaining modeling issues of SSN in this regard
 39 and proposed the S3N⁵ extension focusing on model-
 40 ing reconfiguration capabilities of sensors and actua-
 41 tors. It is a continuous challenge to make these differ-
 42 ent initiatives progressively converge.

43 *Property qualification or quantification* Sensors and
 44 actuators are deployed to observe and act on spe-
 45 cific properties of features of interest. SOSA/SSN and
 46 SAREF both have the modeling of features of inter-
 47

48 ³SAREF ontology - <https://saref.etsi.org/>

49 ⁴SAREF extensions - <https://saref.etsi.org/extensions.html>

50 ⁵S3N ontology - <https://w3id.org/s3n/>

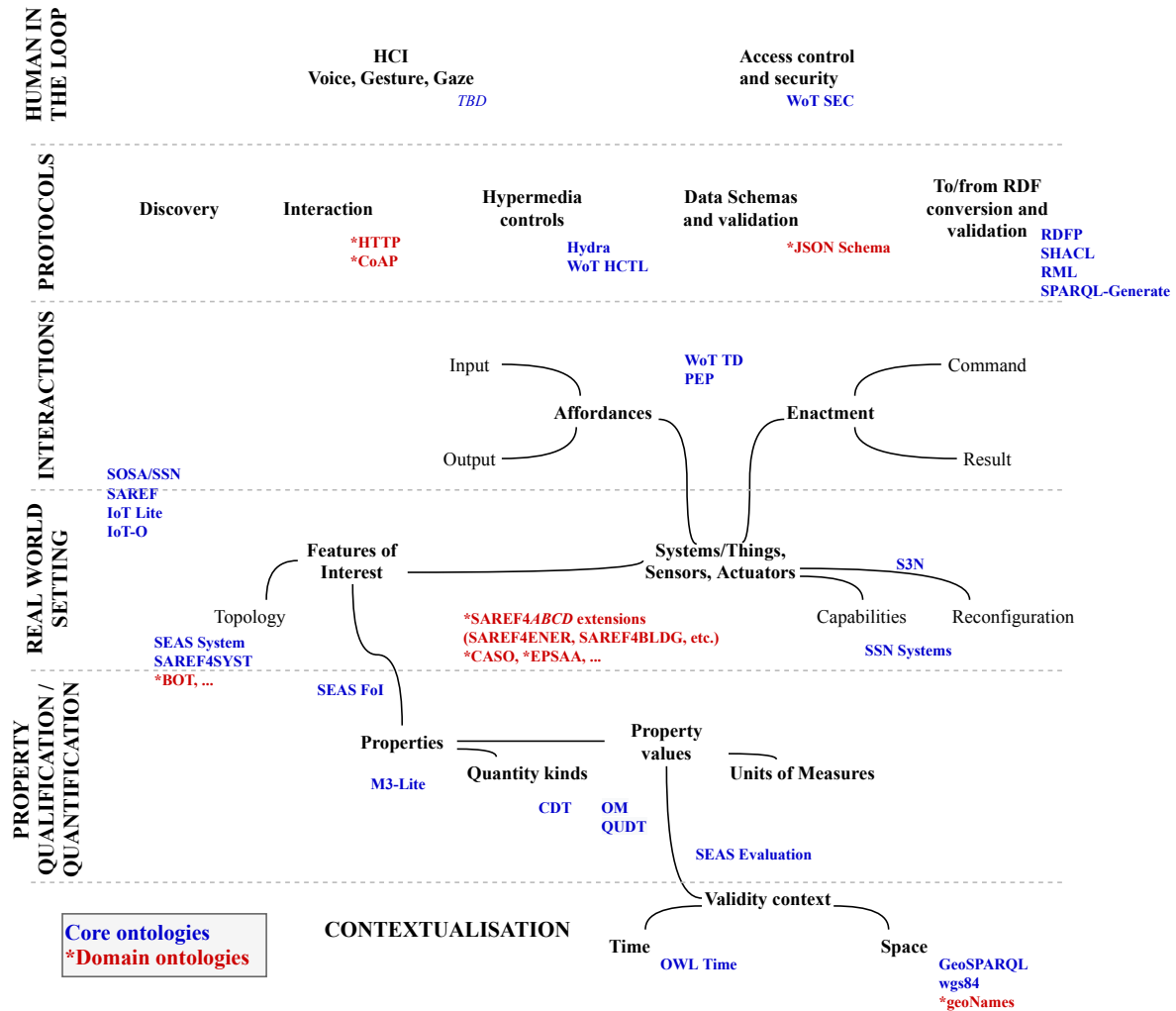


Fig. 1. Data aspects that require semantics in WoT and existing established ontologies

ests and their properties in their core, but do not prescribe whether a property can be reused across features of interest, or should belong to a specific feature of interest⁶, which may lead to interoperability issues across datasets and ontologies. A more strict axiomatization was proposed in SEAS [46]. The work in QUDT [31] on a list of quantity kinds can also help in generically defining properties of features of interest in different domains, e.g. the ontology defines, among many other quantity kinds, a `quantitykind:AreaTemperature` that can be used in many contexts. Taxonomies of properties and

sensors are defined in domain ontologies such as M3-Lite [1], which still need to be adapted to the new version of SSN.

Being able to describe quantity values and their units is a requirement that is almost ubiquitous in any WoT domain. Different ontologies have been developed to describe units, their relations, and quantities with their values. A recent survey [37] compares and evaluates eight well known ontologies for units of measurements, among which QUDT [31], OM [58] and the Units Ontology [22] are the most widely used. The survey also reports on the Wikidata corpus [68] that at the time of research contained over 4.4k measurement units and 4.1k non-prefixed units. While these ontologies are comprehensive in respect

⁶See Footnote 10 in [28] and <https://www.w3.org/TR/vocab-ssn/#SSNProperty-instances> for details on this point.

1 to modelling units of measurements and their rela-
2 tions, a comprehensive model of systems of quantity
3 kinds is still under development, with the QUDT on-
4 tology leading the way (as mentioned above). An alter-
5 native approach relying on RDF 1.1 Datatypes is pro-
6 posed by Lefrançois and Zimmermann [48], and al-
7 lows for more concise representation of quantity val-
8 ues and queries.

9 *Contextualization of value assignment to properties*

10 The OWL time ontology [10], the WGS84⁷, or the
11 GeoSPARQL [54] vocabulary, can be used to describe
12 when and where an actuation or observation is made
13 or valid, or when and where a property has a certain
14 value. These ontologies may also be used to model
15 spatial and temporal properties of devices and fea-
16 tures of interests. GeoNames also provides a dataset
17 of eleven million placenames that can be used for an-
18 notating locations using human-understandable labels.
19 While OWL time fully covers the temporal require-
20 ments in WoT applications, there are still some un-
21 solved issues in modelling spatial aspects [67], i.e.
22 around indoor location relations, authoritative geomet-
23 rical descriptions of place boundaries and relations that
24 define qualitative assertions based on human percep-
25 tions to relate places that are deemed to be the same.
26 However, these are relatively minor issues for mod-
27 elling spatial properties in WoT applications.

28
29 *Device functionality and their APIs* A recent and im-
30 portant core ontology to describe thing affordances in
31 terms of properties, actions, and events, is the Thing
32 description [35] developed by the W3C Web of Things
33 working group. However, the Thing description does
34 not model how the enactment of these affordances is
35 to be modeled. This aspect is covered by SOSA/SSN
36 that describe sensors that implement procedures and
37 make observation. Parallel to this, they describe actu-
38 ators that implement procedures and make actuations.
39 The PEP [46] ontology defines an ontology pattern as a
40 generalization of these two parallel conceptual models.
41 However, the aforementioned models are mainly con-
42 cerned with the flow of information between devices,
43 but there is little integration of device types (sensors,
44 actuators, gateways) themselves. They need to be con-
45 sidered as more than raw data producers, but the data
46 input and output of these devices and the process to
47 execute them needs to undergo harmonisation through
48 ontological models. This has not yet happened other
49 than in some subdomains.

50
51 ⁷W3C Basic Geo ontology - <https://www.w3.org/2003/01/geo/>

1 *Events and Processes* While the PROV Ontology
2 (PROV-O) [42] is an established W3C standard that
3 provides a set of classes, properties, and restrictions
4 that can be used to represent events and activities that
5 happened, i.e. to document a workflow log, an estab-
6 lished process ontology that can be used to describe
7 the execution behaviour of complex functions of WoT
8 devices is missing. PSL [25] and m3po [27] were early
9 examples of process ontologies that could theoretically
10 be used for WoT devices, but neither are described in
11 OWL nor have they found use outside of academia.
12 The WiLD ontology [36] proposed as an execution
13 model for the Linked-Data Fu system is the closest to
14 a process model to describe the execution behaviour of
15 WoT devices, but it has yet to be used in actual im-
16 plementations and it also lacks a mapping to the on-
17 tologies mentioned above for describing device func-
18 tionality and their APIs, in particular the WoT Thing
19 description.

20
21 *WoT protocols* To be part of the WoT, things, sen-
22 sors, and actuators, need to be exposed on the Internet
23 and reachable using Web protocols. This category fo-
24 cuses on ontologies that bind the thing's affordances
25 and their enactments to Web protocols. The architec-
26 ture paradigm for WoT applications is intended to be
27 stateless due to Thing constraints, therefore ontologies
28 such as Hydra [40] are a good fit. More than the clas-
29 sical REST level 2 that is offered by Hydra, the WoT
30 HCTL ontology⁸ intends to further describe hyperme-
31 dia controls (REST level 3), in the form of links and
32 forms. Links are a transposition to RDF of the IETF
33 RFC 8288 Web Links. The WoT HCTL is developed
34 in parallel to a specification effort of the IRTF T2T
35 group called Constrained RESTful Application Lan-
36 guage (CoRAL)⁹.

37 A missing link between the description of affor-
38 dances and the actual messages that will be sent as
39 commands and received as results, is the description
40 of the data model for these messages. The WoT JSON
41 Schema ontology¹⁰ can be used with WoT TD to spec-
42 ify a data schema for these messages if they are us-
43 ing JSON. It remains a challenge to bring semantics in
44 the edge such that WoT devices consume and produce
45 RDF. Section 2.2 provides a general overview of this
46 challenge.

47
48 ⁸WoT HCTL - <https://www.w3.org/2019/wot/hypermedia>

49 ⁹CoRAL - <https://tools.ietf.org/html/draft-ietf-core-coral-03>

50 ¹⁰JSON Schema ontology - [https://www.w3.org/2019/wot/](https://www.w3.org/2019/wot/json-schema)
51 [json-schema](https://www.w3.org/2019/wot/json-schema)

Human in the loop Voice and gesture-controlled interfaces are becoming increasingly popular in the WoT. In particular, in automobiles, smart homes, computer games and Augmented Reality (AR) / Virtual Reality (VR) applications, voice, gestures and sometimes even gaze has become prevalent due to its accessibility to everyone. Designers, producers, and vendors integrating gesture interfaces into their products have also increased in numbers, giving rise to a greater variation of interaction models in utilizing them. However, different modalities that are used to interact with smart environments have not yet been formalized in vocabularies and ontologies, in particular models that formally describe voice commands, gestures and gaze interactions and how they relate to affordances of WoT devices are missing.

Other considerations are of utmost importance for the WoT as it bridges the Web and the real-world where humans need to protect their privacy and integrity. Ontologies to describe access control and security of WoT application will be important for a successful deployment of the semantic WoT. The WoT SEC ontology¹¹ under development is a notable initiative in this line.

2.2. Semantics in the Edge

While RDF has proven to be an effective data model for interoperability on the application layer, its verbose serialisation formats (e.g. RDF/XML, NTriples, or Turtle) present a challenge on the presentation layer. Other than some approaches using the HDT [19] serialisation of RDF [30] or other binary representations of RDF [8], there has been little work and even fewer uptake in industry of providing WoT devices that consume and produce RDF.

Consequently, many data formats and data models exist and they compete with each other for adoption in devices in different WoT domains. Standardisation groups rather try to solve this problem by standardising data formats and service APIs [17, 21, 34]. Some work aim at tackling semantic interoperability despite the heterogeneity of data formats and service API specifications, i.e., across platforms.

The use of semantic Web technologies has been investigated to facilitate semantic interoperability among these platforms [20, 50, 65]. One challenge is to investigate how semantic interoperability can be obtained

on the edge level, i.e. between devices directly, instead of between platforms. The work in Lefrançois [47] is a starting point to investigate how constrained devices that are not natively semantic Web enabled can still be interoperable with one another.

Figure 2a illustrates a typical Web service that consumes and outputs resource representations, that are octet streams typed with internet media types according to the Web architecture principles¹². For some data formats such as JSON or XML, dedicated validation languages such as JSON Schema or XML Schema may be used. Then, the contents of the resource whose representation is given as input or output may be assumed to be an RDF graph. Adopting such an abstraction enables us to assume the service, potentially exposed by a constrained device, consumes and produces RDF. Many languages can be used to specify how an RDF graph can be generated out of octet streams (lifting), or the other way around (lowering). Finally languages such as SHACL or ShEX can be used to specify what form the content RDF graph has. New research challenges stem naturally from this vision. An example is that given a JSON Schema representation validation rule, and a lifting rule, to automatically compute the SHACL shape that the content should validate against.

Figure 2b illustrates a combination of two WoT services that are seemingly incompatible, but that as an abstraction generate and consume RDF, respectively. The output RDF graph, generated using a certain lifting rule, could then be lowered using the second thing's lowering rule. In this setting, the condition for the services to be composable is that the content validation rule of the first thing is more specific than the content validation rule of the second thing. However, SHACL shape containment has not been investigated yet.

2.3. Distributed and embedded reasoning in the Edge

As devices became powerful enough to offer storage and processing, new architectures appeared, based on edge computing. At the same time, it is now often a requirement that the final user is able to configure the intelligent environment. This poses several research questions: (i) how to embed reasoning in edge devices with various capacities; (ii) how to efficiently distribute reasoning tasks among available heterogeneous devices; and (iii) how to allow user to easily write rules for such devices.

¹¹WoT SEC - <https://www.w3.org/2019/wot/security>

¹²<https://www.w3.org/TR/webarch/#internet-media-type>

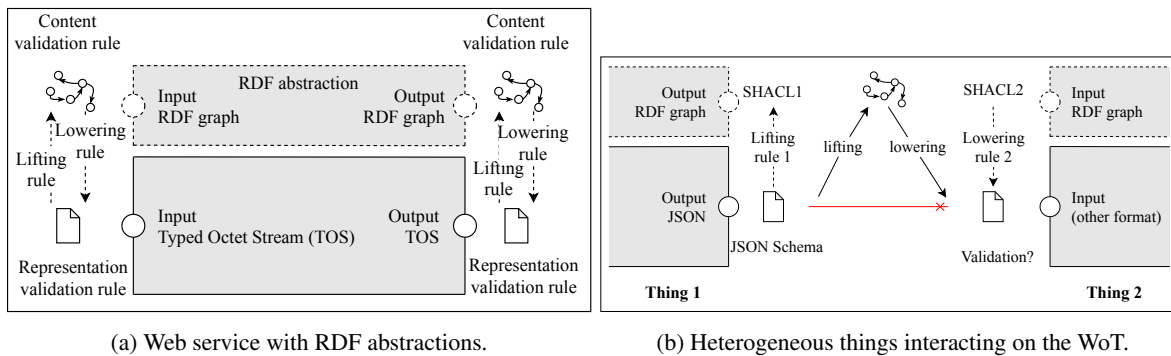


Fig. 2. Semantics in the Edge: using RDF abstractions for the content of Web resource.

How to embed reasoning in devices with various capacities Edge computing allows manipulating data close to sources, saving bandwidth, lowering latency and reducing communication needs. Slider [9] is an incremental reasoner optimised in memory and processing footprint. RDF4LED [41] is a lightweight RDF engine, which comprises of RDF storage and a SPARQL processor, for small query operations in lightweight edge devices. Devices on the WoT generate and consume highly dynamic data. The recent survey on stream reasoning by Dell’aglio et al. [14] discusses several open issues left to tackle in this field.

How to distribute reasoning tasks among devices Reasoning tasks can be distributed among heterogeneous devices: some are powerful computers, some are edge devices with various constraints. One challenge is to develop computationally-efficient reasoning strategies coping with such heterogeneities [62], and as close to the data sources as possible. One such approach is HyLAR that deploys incremental reasoning tasks on both, the server and the client [64]. Assuming that devices may reason with heterogeneous entailment regimes is also a starting point for a new investigation, for example, if a constrained edge node uses a poorer entailment regime than a more powerful gateway.

End-User Development In the scenario offered by such a complex network, the End-User Development (EUD) vision [49] aims at putting customization mechanisms in the hands of end users. Starting from iCAP [16], an early rule-based system for building context-aware applications, several works demonstrated the effective applicability of EUD techniques for the personalization of the functionality of smart devices and online services in different areas, including mobile environments [11] and smart home [6]. Users

can take advantage of visual programming platforms such as IFTTT and Zapier to personalize the joint behaviors of their own connected entities, by adopting the trigger-action programming paradigm, i.e., they allow the definition of IF-THEN rules. Unfortunately, despite its wide adoption, the way it is implemented nowadays presents its own set of open issues: i) low-level of abstraction (current trigger-action programming platforms adopt highly technology-dependent representation models that work with well-known connected entities, previously associated to a specific user, only. Therefore, defining IF-THEN rules becomes a complex task for non-programmers [32]), ii) information overload (contemporary trigger-action programming platforms do not provide users with any discovery support [66], and the explosion of new smart devices and online service results in user interfaces with too much information), iii) and run-time problems (there is the need to provide users with instruments for understanding and debugging their IF-THEN rules, i.e., to avoid possible conflicts [6] and to assess a rules’ correctness [15]).

3. Overview of the Special Issue

The focus of this special issue is to showcase novel approaches of applying semantic technologies to solve the problems of device and data integration mentioned above. We received nine submissions, covering a wide range of points of view related to these topics. The thorough peer-review process selected three of these submissions, of three different submission types (i.e. one full paper, one survey article and one linked dataset description), as mature enough to be published in the Semantic Web journal.

1 The three accepted papers also deal with three popular
2 and important application domains of the WoT [59],
3 *Smart Agriculture*, *Smart Building* and the *Industry of*
4 *the Future*¹³.

5 The paper on *Weather Data Publication on the LOD*
6 *using SOSA/SSN Ontology*¹⁴ by Catherine Roussey,
7 Bernard Stephan, André G eraldine, and Boffety Daniel
8 on *Smart Agriculture* is a typical application domain
9 of WoT architectures, where semantically annotated
10 weather/climate data [2, 44] and the monitoring of cul-
11 tivated fields requires various sensors that push stream-
12 ing data [63] that must be collected and reasoned upon
13 to take decisions executed by actuators. This paper
14 specifically presents an RDF dataset of meteorological
15 measurements that have been obtained by a weather
16 station at an experimental farm located in Montoldre,
17 France and then be converted to Linked Open Data
18 (LOD). The work reuses many of the established on-
19 tologies for WoT that we discuss in Section 2.1. At
20 the core of the dataset sits the new SOSA [33] and
21 SSN [29] ontologies, and extensions of SSN for me-
22 teorological sensors [43]. Further, to model the geo-
23 spatial aspects of the sensors the OGC GeoSPARQL
24 vocabulary [54] and the OWL Time ontology [10] are
25 used, while for weather related measurements such as
26 the temperature, precipitation, wind and solar radiation
27 the QUDT ontology [31] is used.

28 The survey paper *Ontologies for Observations and*
29 *Actuations in Buildings: A Survey*¹⁵ by Iker Esnaola-
30 Gonzalez, Jes us Berm udez, Izaskun Fernandez, and
31 Aitor Arnaiz, discusses another typical application do-
32 main, *smart buildings*, where added-value application
33 services involve information from other verticals such
34 as energy management, e-health, or ageing well. It re-
35 views and compares existing ontologies in the IoT and
36 building domain, using a set of competency questions
37 extracted from a simple situation. Candidate ontolo-
38 gies are filtered based on base quality criteria such as
39 whether the ontology is online, with metadata, docu-
40 mented, designed using principles, and used. Among
41 the ten selected ontologies to model observations and
42 actuations, many are well established and referenced
43 in Figure 1, such as SOSA/SSN [29], SAREF [18],

44 ¹³often also called Industry 4.0, a term originating in 2011 from a
45 project in the high-tech strategy of the German government

46 ¹⁴[http://www.semantic-web-journal.net/content/
47 weather-data-publication-lod-using-sosassn-ontology-0](http://www.semantic-web-journal.net/content/weather-data-publication-lod-using-sosassn-ontology-0)

48 ¹⁵[http://www.semantic-web-journal.net/content/
49 ontologies-observations-and-actuations-buildings-survey-1](http://www.semantic-web-journal.net/content/ontologies-observations-and-actuations-buildings-survey-1)

1 SEAS [46], IoT-O [61], IoT-Lite [4]. The authors then
2 compare available ontologies for expressing time, lo-
3 cation, and units of measurements and quantities, with
4 extended conclusions with respect to Section 2.1. Fi-
5 nally, the authors review ten building domain ontolo-
6 gies, some of which are actively maintained by im-
7 portant consortia: ifcOWL [53] of BuildingSMART,
8 BOT [57] of the W3C Linked Building Data commu-
9 nity group, SAREF4BLDG [56] of ETSI SmartM2M,
10 and Brick [3].

11 *Industry of the Future or Industry 4.0* is a third
12 interesting application domain, where devices, ma-
13 chines, production modules and products are com-
14 prised as Cyber-Physical Systems (CPS) that are au-
15 tonomously exchanging information, triggering ac-
16 tions and controlling each other. Factories are devel-
17 oping into intelligent environments that enable dy-
18 namic re-engineering processes and the ability to
19 respond flexibly to failures. In particular, business-
20 specific knowledge must therefore be modeled as self-
21 contained bundles, and inserted into the system at run-
22 time when needed. To address this issues, the pa-
23 per *EDR: A Generic Approach for the Distribution of*
24 *Rule-Based Reasoning in a Cloud-Fog continuum*¹⁶ by
25 Nicolas Seydoux, Khalil Drira, Nathalie Hernandez,
26 and Thierry Monteil, proposes an original architecture
27 which exploits the complementarity of Cloud and Fog
28 computing. In this model, reasoning rules are used to
29 capture business level logic and are distributed across
30 nodes and executed as close as possible to where the
31 data is produced, in order to enable low-latency deci-
32 sion making. At the same time remote powerful Cloud
33 computation resources are exploited in order to ben-
34 efit from the Cloud stability and permanent availabil-
35 ity. Moreover, as IoT networks are open and evolutive,
36 the computation is dynamically distributed across Fog
37 nodes according to the transformation of the network
38 topology.

41 4. Conclusion and Future Directions

42 Contributions to this special issue have shown that
43 ontologies, linked data, and reasoning, have a wide
44 range of research directions on the Web of Things and
45 can be applied to a wide range of application domains.
46 However, further advances are needed to cover gaps in
47

48 ¹⁶[http://www.semantic-web-journal.net/content/
49 edr-generic-approach-distribution-rule-based-reasoning-cloud-fog-continuum](http://www.semantic-web-journal.net/content/edr-generic-approach-distribution-rule-based-reasoning-cloud-fog-continuum)

existing ontologies, bring semantics in the edge, and develop distributed semantic reasoning approaches.

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