Ontologies for Web of Things: A Pragmatic Review

Maxim Kolchin(✉), Nikolay Klimov, Alexey Andreev, Ivan Shilin, Daniil Garayzuev, Dmitry Mouromtsev, and Danil Zakoldaev

ITMO University, Saint-Petersburg, Russia
{kolchinmax,nikolay.klimov}@niuitmo.ru,
{a_andreev,shilinivan,garayzuev}@corp.ifmo.ru,
mouromtsev@mail.ifmo.ru, d.zakoldaev@mics.spb.ru

Abstract. Web of Things (WoT) is another area where Semantic Web technologies provides a foundation for effective data access through a unified data model that in its turn realises interoperability among all components of WoT landscape. There exists significant amount of research focusing on applying RDF data model, OWL ontologies and Reasoning in different WoT scenarios, such as home automation, Industry 4.0 and etc. But so far this approach didn't get wide adoption beyond research community. In this paper we attempt to answer the question: Are existing ontologies ready to form an ontology framework for annotating real-world devices? By the example of three real-world devices, we review existing ontologies which can be used to describe their facilities, location and etc. And in the end, we present an instrument to generate semantic descriptions for such devices.

Keywords: OWL · Ontology · Web of things · Knowledge engineering

1 Introduction

Physical *(or virtual)* devices that are able to communicate their states between each other form a network of connected devices. These devices are sensors and actuators that can be wearable devices for health monitoring, geospatial and environmental monitoring sensors and other devices from different fields such as automation and industrial manufacturing, logistics, intelligent transportation of people and goods. Technologies transforming ordinary devices to connected ones and the networks of these devices constitute the concept of Internet of Things (IoT) which has gathered significant attention from industry and academia [1, 14, 20]. The Web of Things was proposed [6] as a next evolutionary step for Internet of Things concept where the devices "are fully integrated in the Web by reusing and adapting technologies and patterns commonly used for traditional Web content" [7].

Data or service providers face several problems when they want to expose data of the physical devices on the Web. One of them is the heterogeneity of

P. Klinov and D. Mouromtsev (Eds.): KESW 2015, CCIS 518, pp. 102–116, 2015.
DOI: 10.1007/978-3-319-24543-0_8

the devices at the communication and data levels. At the communication level, it can be mitigated by a middleware which has a modular architecture allowing to implement specific modules providing support for particular technologies and protocols. In this paper we don't aim to review existing middleware for WoT, therefore we refer readers to [2] paper which does it and also classifies them based on proposed fundamental functional blocks. At the data level, the heterogeneity is caused by different and sometimes substandard data models and formats supported by various device manufacturers. The same things (observations, observed properties, units of measurement and etc.) can be described in different ways without a possibility for integration. At the data level this problem can be solved using the ontology-based approach which is based on using semantically rich models (ontologies that can be extended for a particular use-case). Several works already have shown how this approach can be applied to easy integration of diverse data sources [11,15]. Ontologies and vocabularies such as the SSN (Semantic Sensor Network) Ontology [4] have been created and adopted in a number of research projects [5,10,13,17,19].

Although in the ontology based approach has got significant adoption in research projects, it still hasn't got similar adoption in industry and among application developers. This situation can be explained by different reasons: (a) lack of standardisation, (b) high complexity of existing ontologies, (c) even with three reasons provided by Lanthaler and Gult for what they call *semaphobia* [12]. Whatever reason it is, in this paper we aim to answer the following question: *Are existing ontologies ready to form an ontology framework to annotate real-world devices?*

To answer the given question we take three examples of real-world devices, based on these examples we define several high-level conceptual groups that include concepts to describe these devices and their measurements or observations, review existing ontologies which can provide concepts that fall down at least in one of the conceptual groups. Also using the reviewed ontologies we define an integrated ontology framework and present a tool that provides a user interface to rapidly build semantic descriptions of WoT devices, making complexity of formal specification transparent to the user. We argue that such tools play a significant role in ricing adoption of the approach, because writing semantic descriptions by hand is time consuming, tedious and a error-prone task.

Limitations. This work has two limitations which are based on the fact that we take in a account only three examples of real-world devices which maybe don't cover all of the concepts of WoT:

- We don't aim to provide a comprehensive review of existing ontologies, but only ones that are related to the given examples of real-world devices,
- We don't aim to outline all possible conceptual groups, but only the ones that are related to the given examples.

For a comprehensive review of existing ontologies and use cases we refer readers to the review done by W3C Semantic Sensor Network Incubator[1] Group and published in their final report [3].

Structure. The remainder of the paper is organised as follows. In Section 2 we introduce three examples of real-world devices. In Section 3, we introduce the conceptual groups that include concepts required to describe the given devices. In Section 4 we review existing ontologies which, from our point of view, provides concepts falling down at least in one of the conceptual groups. Section 5 introduces a tool providing a user interface to rapidly build semantic descriptions for WoT devices. Section 6 describes the current states and issues of the reviewed ontologies. And the last section we conclude the paper.

2 Examples of Real-World Devices

To derive conceptual groups and concepts which constitute these groups, we suggest examples of three real-world devices that will help us later to review existing ontologies. The first devices is an Arduino[2]-based weather station that may seem a toy device, but such devices actually actively used by enthusiasts to create a crowd-sourced weather portals such as *NarodMon Project*[3] where people share air temperature, humidity and other readings of their sensors with the community. The second device is a wall/ceiling mount exhaust bath fan with a humidity sensor that switches on/off the fan if humidity at high or normal levels respectively. The third device is an electric meter which is installed in a residential building and measuring energy consumption by all consumers in this building.

RW1. An Arduino-based Weather Station. The weather station is called "EnvTH-0.0.1", it's a research prototype developed in ITMO University and capable to measure air temperature and humidity. It's equipped with DHT-22[4] sensor which measures air temperature and humidity. Detailed characteristics of the sensor, such operating range, accuracy and etc., listed in Table 1. The station was deployed on the window of room 380 at the main campus of ITMO University. The station publishes its measurements on the Internet through CoAP protocol. A photo of this stations is shown in Figure 1a.

RW2. A Wall/Ceiling Mounted Exhaust Bath Fan. The model of the fan is called "Soler & Palau DECOR-100 CHZ"[5]. It's a commercial product of

[1] Cf. http://www.w3.org/2005/Incubator/ssn/
[2] Cf. http://www.arduino.cc
[3] Cf. http://narodmon.ru
[4] Cf. https://www.sparkfun.com/datasheets/Sensors/Temperature/DHT22.pdf
[5] Cf. http://www.solerandpalau.co.uk/product.jsp?PRODUCTID=157&CATEGORYID=41

Table 1. Characteristics of an Arduino-based weather station

Measuring property	**Air temperature**	**Humidity**
Operating range	0–100% RH	-40–80 C^o
Accuracy	±2% RH	±0.5 C^o
Sensitivity	0.1% RH	0.1 C^o
Measurement range	0–100% RH	-40–80 C^o
Frequency	2s	
Resolution	0.1% RH	0.1 C^o

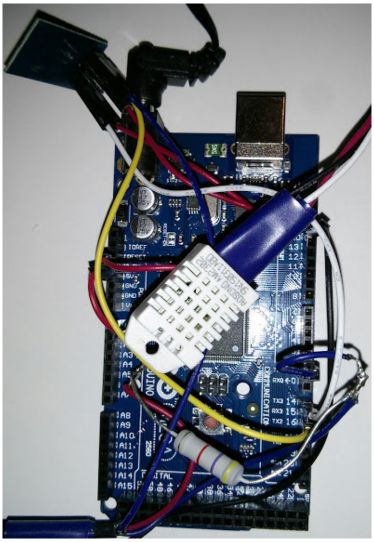
"Soler & Palau" company and capable to exhaust a room only if the humidity is higher than a threshold and then switch off automatically if the humidity is back to normal. The fan has a humidity sensor and an actuator which allows the user to switch on/off the fan manually. A photo of the fan is shown in Figure 1b.

RW3. An Electric Meter in a Residential Building. The model of the electric meter is called "Mercury 230 ART"[6], it's a three phase electric meter and a commercial product of Incotex, LLC company, see Fig. 1c. The meter was deployed on 29th April 2015 in a residential building at Kotelnikova alley 5/1 (60.013456, 30.288267) and is maintained by WingHouse company. The measurements taken by the meter are transmitted by a gateway (Fig. 1d) to a server in a single packet by a specified interval. The packet contains the following information: (i) serial number, (ii) current date and time, (iii) sampling date and time, (iv) voltage on each phase, (v) amperage on each phase, (vi) total active power on all phases, (vii) total reactive power on all phases.

3 Conceptual Groups

In this section high-level concepts and their relations that describes the devices are presented. They are grouped in several groups which we call *conceptual groups*. Below each of the conceptual groups is explained. In Section 4, we review existing ontologies which provide enough expressiveness in terms of concepts they allow to represent to fall in one of the groups.

[6] Cf. http://www.incotexcom.ru/m230art_en.htm



(a) An Arduino-based weather station

(b) A wall/ceiling mount exhaust bath fan

(c) An electric meter in a residential building

(d) A gateway transmitting measurements from the electric meter in Fig. 1c

Fig. 1. Photos of devices used in this work as examples of real-world devices

CG1. Actuator, Sensor, System. Each of the example devices is a composite device, consisting of one or more sensors and/or actuators. So it's needed to have an ontology representing a hierarchy of parts of a composite device. In this group we define the following concepts:

- *Sensor*s are “physical objects that perform observations, i.e. they transform an incoming stimulus into another, often digital, representation”[8]. They have several characteristics such as measuring capabilities, accuracy, measuring frequency, observed property (e.g. wind, air temperature) and etc.,
- *Actuator*s are physical objects that modify (e.g. rotate, switch on/off and etc.) the physical state of another physical object. Actuators characterised by the physical object whose state they change, operating range and etc.
- *System*s are composite devices consisting of one or several sensors or actuators. A system can be also a subsystem of a large device.

CG2. Global and Local Coordinates. Since the *devices* are often physical objects (e.g. in environmental monitoring, advanced meter management, etc.) their location is important. The location can be *global* represented with the geo-coordinates such as latitude and longitude, and *local* (e.g in a building) represented with the geo-coordinates of the place, relative coordinates within this place and moreover the place may have a number of levels (e.g. floors).

CG3. Communication Endpoint. This conceptual group referes to a fundamental requirement for Web of Things is a notion of physical objects which are able to communicate their states over the Internet by itself or using intermediate gateways. Therefore the applications accessing the sensor data need to know how to communicate with the objects, e.g. which *protocol* and *version* to use.

CG4. Observations, Features of Interest, Units, and Dimensions. The sensor *observation* is another core concept in the field which is a result of a stimulus observed by a sensor. It’s characterised by sampling time, feature of interest (e.g. electricity, air, water), observed property (e.g. current strength, air temperature). Also in this group we include *units of measure* and *dimensions*.

CG5. Vendor, Version, Deployment Time. *Sensor*s and *actuator*s are devices which were manufactured by a *vendor* and usually have the *version* of hardware and software. Also it may be important for some use cases to know the date and time when a particular device was deployed. So this conceptual group focus on the following information:

- about device vendor and manufacturer which may contain the name of the organisation, web site, or some other information that can identify it,
- about device deployment such as time, place (see CG2) and so on,
- about the organisation which responsible for maintenance and support of the device such as the name of the organisation, contact information, responsible person, etc.

4 Ontologies

After we defined the conceptual groups in the previous section, in this section we review existing ontologies which allow to represent concepts falling into another the conceptual groups. Also we take in account the *rating* of the ontologies accroding to [9] rating defined by Janowicz et al. There is an option to found them and count popularity, richness and other properties in Linked Open Vocabularies[7] catalogue. In Table 2 we summarise the ontologies we selected to represent the concept and their relations from the defined groups.

Table 2. Matrix with conceptual groups and corresponding ontologies

Conceptual group	**Ontology**
CG1 Actuator, sensor, system	Semantic Sensor Network (ssn)[8], DogOnt[9]
CG2 Global and local coordinates	WGS84 Geo Positioning (geo)[10], LIMAP[11], OGC GeoSPARQL[12], DUL[13]
CG3 Communication endpoint	OSGi DAL[14], SAREF[15], FIEMSER[16], FIPA[17]
CG4 Observations, features of interest, units and dimensions	OGC OM[18], QUDT[19], OM[20], MUO[21], AWS[22]
CG5 Vendor, versions, deployment time	MMI Device[23], FOAF[24], linkingyou[25]

[7] Cf. http://lov.okfn.org
[8] Cf. http://purl.oclc.org/NET/ssnx/ssn#
[9] Cf. http://lov.okfn.org/dataset/lov/vocabs/dogont
[10] Cf. http://www.w3.org/2003/01/geo/wgs84_pos#
[11] Cf. http://data.uni-muenster.de/php/vocab/limap
[12] Cf. http://www.opengis.net/ont/geosparql#
[13] Cf. http://www.loa-cnr.it/ontologies/DUL.owl#
[14] Cf. https://sites.google.com/site/smartappliancesproject/ontologies/osgi_dal-ontology
[15] Cf. http://ontology.tno.nl/saref
[16] Cf. https://sites.google.com/site/smartappliancesproject/ontologies/fiemser-ontology
[17] Cf. http://sites.google.com/site/smartappliancesproject/ontologies/fipa#
[18] Cf. http://www.opengeospatial.org/standards/om
[19] Cf. http://qudt.org/
[20] Cf. http://www.wurvoc.org/vocabularies/om-1.6/
[21] Cf. http://idi.fundacionctic.org/muo/muo-vocab.html
[22] Cf. http://www.w3.org/2005/Incubator/ssn/ssnx/meteo/aws
[23] Cf. http://mmisw.org/ont/mmi/device
[24] Cf. http://xmlns.com/foaf/spec/
[25] Cf. http://purl.org/linkingyou/

4.1 CG1: Actuator, Sensor, System

There are several ontologies including concepts from this group. One of them is Semantic Sensor Network (SSN) Ontology[4] that was developed by W3C Semantic Sensor Network Incubator Group[26] in 2011. The concept of *Sensor*s is represented based on the Stimulus-Sensor-Observation Ontology Design Pattern [8] and also allows to represented an hierarchy of *System*s using *ssn:hasSubSystem* object property, see Listing 1.1. But the ontology doesn't have representations for the concept of *Actuator*s, this fact is mentioned in [18] paper where the authors suggest several extensions to the SSN ontology, but unfortunately the developed ontology is not available any more, so we don't consider it.

*Actuator*s can be represented by another ontology called DogOnt[5] which has class *dogont:Actuator* and several properties such as *dogont:actuatorOf*, *dogont:hasActuator*, *dogont:controlledObject* and etc.

```
:system-0 a ssn:System ;
    ssn:hasSubsystem [
        a ssn:Sensor ;
        ssn:observes :Temperature .
    ];
    ssn:hasSubsystem [
        a ssn:Sensor
        ssn:observes :Heat .
    ];
```

Listing 1.1. An example of a *System* with two *Sensor*s (temperature and heat)

The concept of *Sensor*s more popular in existing ontologies, than *Actuator*s. According to the LOV [3] catalogue, 19 ontologies has a class with "sensor" in its name and only 2 ontologies for "actuator". The SSN is a "5 star" ontology which follows all the rating requirements and DogOnt is only a "4 star" ontology, because according to the LOV [7] catalogue it doesn't have incoming links.

4.2 CG2: Global and Local Coordinates

In this group we cover concepts and relations related to the spatial nature of *things*. As stated in CG2, the spatial information can be *global* and *local*.

The global location of the *things* is described with geocoordinates such as latitude and longitude which can be represented by well known WSG84 ontology[6] which has class *geo:Point* and properties *geo:latitude*, *geo:longitude*, *geo:altitude*. By combining these properties with *dul:hasLocation* from DUL[9] ontology is possible to represent the sensor location, see Listing 1.2.

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

```
:system-0 a ssn:Sensor ;
    dul:hasLocation [
        a geo:Point ;
        geo:latitude "59.956438" ;
        geo:longitude "30.3095818"
    ] .
```

Listing 1.2. An example of a *Sensor* with geo-coordinates

The *local* coordinates are relative to the *global* and used took locate something in a building, e.g. an electric meter in an apartment. In Listing 1.3, you can find an example of a *System* located in a room at the 4th floor of some building which has global coordinates expressed in geo-coordinates of a polygon. For this example we used LIMAP[7], OGC GeoSPARQL[8], DUL[9] and WSG84[6] ontologies.

```
:system-0 a ssn:System ;
    limap:isOccupantOf [
        a limap:Room ;
        limap:hasLocalCoordinates [
            a limap:LocalCoordinates ;
            geosparql:hasGeometry "POLYGON((
                    3.976 0,
                    6.765 0,
                    6.765 2.273,
                    3.976 2.273))"^^geo:wktLiteral .
        ] ;
        limap:isLocated :plan-4 .
    ] .
:plan-4 a limap:EscapePlan ;
    limap:hasSourceImage <...image url...> ;
    limap:isEscapePlanOf [ a limap:Floor ;
        dul:hasLocation [ geo:floor "4"^^xsd:int ] ;
        limap:isFloorIn [ a limap:Building ;
            limap:hasGlobalCoordinates [
                a limap:GlobalCoordinates ;
                geosparql:hasGeometry
                    "POLYGON((
                        -81.587 45.336,
                        -81.148 39.774,
                        -69.964 39.300,
                        -70.403 45.583,
                        -81.587 45.336))"^^geo:wktLiteral
            ] .
        ] .
    ] .
```

Listing 1.3. An example of a *Sensor* located in a room of a building

Although the LIMAP ontology provides enough expressiveness, it's mainly focused on people and their locations in buildings, so the ontology requires minor customisation particularly in *limap:isOccupantOf* object property which has *rdfs:domain* referring to a person.

4.3 CG3: Communication Endpoint

The concepts from this group are needed to represent the way to communicate with the *things* which at least are communication *protocol* and its *version*. For that purpose we suggest to look at FIPA[13] and FIEMSER[12] ontologies which comply with our requirements. Listing 1.4 shows an example of using FIPA ontology and the similar example, but using FIEMSER ontology in Listing 1.5.

```
:sensor-0 a ssn:Sensor, fipa:Device ;
    fipa:hasHwProperties [ a fipa:HwDescription ;
        fipa:hasConnection [
            a fipa:ConnectionDescription ;
            fipa:hasConnectionInfo [
                a fipa:InfoDescription ;
                fipa:hasName "CoAP" ;
                fipa:hasVersion "1.0" .
            ]
        ]
    ] .
```

Listing 1.4. An example of sensor description with information about the *protocol* and *version* described with FIPA ontology

```
:sensor-0 a ssn:Sensor, fiemser:CommDevice ;
    fiemser:uses :CoAP .

:CoAP a fiemser:NetProtocol ;
    fiemser:hasName "CoAP" ;
    fiemser:hasVersion "1.0" .
```

Listing 1.5. An example of sensor description with information about the *protocol* and *version* described with FIEMSER ontology

Both ontologies comply with the requirements, but only FIEMSER ontology has a separate class for the protocol which means it's more unambiguous.

4.4 CG4: Observations, Features of Interest, Units and Dimensions

The concept of *observation* can be represented by the SSN ontology that also covers other related concepts mentioned in CG4. Listing 1.6 shows an example of a temperature observation described with the SSN[4] and QUDT[15] ontologies.

```
:obs-0 a ssn:Observation ;
    ssn:observationResultTime
        "2015-05-18T10:00:00"^^xsd:dateTime ;
    ssn:observedBy :sensor-0 ;
    ssn:observationResult :obs-0-result .

:obs-0-result a ssn:SensorOutput ;
    ssn:isProducedBy :sensor-0 ;
    ssn:hasValue :obs-0-resultvalue .

:obs-0-resultvalue a ssn:ObservationValue,
                        qud:QuantityValue ;
    qud:numbericValue "15"^^xsd:double ;
    qud:unit qud:DegreeCelsius .
```

Listing 1.6. An *observation* represented using the SSN and QUDT ontologies

The QUDT ontology allows to represent a comprehensive list of quantities, units and dimensions. We refer readers to [16] for a more detailed survey of existing ontologies for quantities, units, and dimensions.

4.5 CG5: Vendor, Version, Deployment Time

Information about *vendor*, *version* of the device and other information are relevant to many domains, not only to IoT. Therefore there exists a lot of ontologies focusing on this conceptual group. Probably the most popular one is FOAF[20] ontology which allows to represent organisations, people and most of required information such as name, address, web-site and etc. Regardless of whether information is in people's heads, in physical or digital documents, or in the form of factual data, it can be linked. Also there exists other more focused ontologies allowing to describe people and organizations such as:

- Ontology for public services and organizations (OSP)[27]. It is mostly for government organizations and not completely translated into English.
- Linking-you vocabulary[21]. Vocabulary for describing common web pages provided by an organisation. It is possible to describe the type of the web page such as contact page, about page, etc.

[27] http://data.lirmm.fr/ontologies/osp

The MMI Device Ontology[19] developed by the Marine Metadata Interoperability Project[28] provides abstractions for representing a *device*, *manufacturer*, *model id*, *owner of a device* and its *serial number* and so on.

5 Tool

Using the ontologies we reviewed in the previous section, we created a tool to generate semantic description of WoT devices. Currently it supports on the concepts and relations suitable for the examples devices described in Section 2, but we plan to extend it further. The tool is called Web of Things Semantic Description Helper and can be found online on https://github.com/semiotproject/wot-semdesc-helper. On Fig. 2, you can find a screenshot of the user interface which is used to constructed the semantic descriptions.

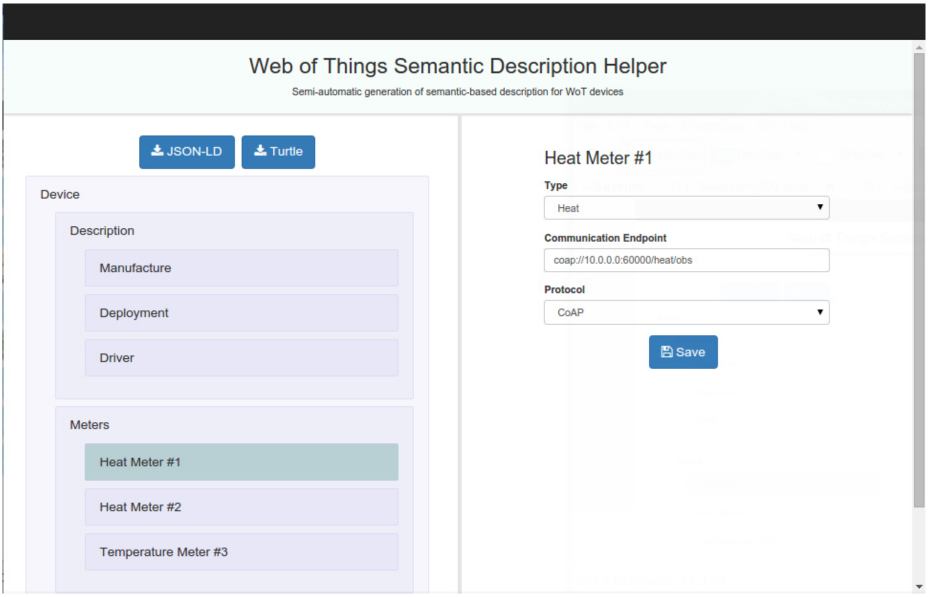


Fig. 2. A screenshot of Web of Things Semantic Description Helper

6 Discussion

There exist a lot of ontologies and vocabularies providing primitives for representation of all the conceptual groups we outlined, but they have different issues which are actually relevant to most of the ontologies in any field:

[28] http://marinemetadata.org

– poor documentation and lack of examples of the correct use of the ontology,
– some ontologies are only described in papers and are not implemented.
– lack of modularity so that more time is spent on reasoning than needed.

The ontologies and vocabularies should be improved following the 5-star Linked Data Vocabularies principles [9]. Also, to lower the barrier to start using ontologies, the ontologies for WoT should be standardised by a community, the similar way it was done in Schema.org project. More general concepts and relations are sufficiently covered by existing ontologies, the next step could be ontologies that are very focused on a particular domain such as different kinds of meters, specific sensors and so on. Also instruments providing all needed functionalities for managing the life-cycle of the *devices* representations are needed.

7 Conclusion

In this paper we provided a pragmatic review of existing ontologies and vocabularies in the field of Internet of Things which comply with at least the 2-star requirements from the 5-star rating [9] and therefore can be applied in real-world projects. We divided the ontologies and vocabularies into several conceptual groups which focus on a set of high-level concepts and relations from IoT. And for each such a group we selected and described existing works. Then at the end of the paper we discussed our findings and issues of the vocabularies and suggest possible solutions.

Acknowledgments. This work has been funded by the Ministry of Education and Science of the Russian Federation (Grant #RFMEFI57514X0101).

References

1. Atzori, L., Iera, A., Morabito, G.: The Internet of Things: A survey. Computer Networks **54**(15), 2787–2805 (2010). http://www.sciencedirect.com/science/article/pii/S1389128610001568
2. Bandyopadhyay, S., Sengupta, M., Maiti, S., Dutta, S.: Role of middleware for internet of things: A study. International Journal of Computer Science and Engineering Survey **2**(3), 94–105 (2011). http://dx.doi.org/10.5121/ijcses.2011.2307
3. Barnaghi, P., Compton, M., Corcho, O., Castro, R.G., Graybeal, J., Herzog, A., Janowicz, K., Neuhaus, H., Nikolov, A., Page, K.: Semantic Sensor Network XG Final Report. Tech. rep., The World Wide Web Consortium (W3C), June 2011. http://www.w3.org/2005/Incubator/ssn/XGR-ssn/
4. Compton, M., Barnaghi, P., Bermudez, L., García-Castro, R., Corcho, O., Cox, S., Graybeal, J., Hauswirth, M., Henson, C., Herzog, A., Huang, V., Janowicz, K., Kelsey, W.D., Phuoc, D.L., Lefort, L., Leggieri, M., Neuhaus, H., Nikolov, A., Page, K., Passant, A., Sheth, A., Taylor, K.: The SSN ontology of the W3C semantic sensor network incubator group. Web Semantics: Science, Services and Agents on the World Wide Web **17**, 25–32 (2012). http://www.sciencedirect.com/science/article/pii/S1570826812000571

5. Corcho, O., Calbimonte, J.P., Jeung, H., Aberer, K.: Enabling Query Technologies for the Semantic Sensor Web. Int. J. Semant. Web Inf. Syst. **8**(1), 43–63 (2012). http://dx.doi.org/10.4018/jswis.2012010103
6. Guinard, D., Trifa, V.: Towards the web of things: web mashups for embedded devices. In: Workshop on Mashups, Enterprise Mashups and Lightweight Composition on the Web (MEM 2009), in proceedings of WWW (International World Wide Web Conferences), Madrid, Spain, April 2009
7. Guinard, D., Trifa, V., Mattern, F., Wilde, E.: From the internet of things to the web of things: resource-oriented architecture and best practices. In: Architecting the Internet of Things, pp. 97–129. Springer, Heidelberg (2011). http://dx.doi.org/10.1007/978-3-642-19157-2_5
8. Janowicz, K., Compton, M.: The stimulus-sensor-observation ontology design pattern and its integration into the semantic sensor network ontology. In: Proceedings of the 3d International Workshop on Semantic Sensor Networks (2010). http://ceur-ws.org/Vol-668/paper12.pdf
9. Janowicz, K., Hitzler, P., Adams, B., Kolas, D., Vardeman II, C.: Five stars of Linked Data vocabulary use **5**(3). http://dx.doi.org/10.3233/SW-140135
10. Kolchin, M., Mouromtsev, D., Arustamov, S.: Demonstration: web-based Visualisation and Monitoring of Smart Meters using CQELS. In: Proceedings of the 7th International Workshop on Semantic Sensor Networks (2014). http://knoesis.org/ssn2014/paper_3.pdf
11. Kotis, K., Katasonov, A.: Semantic interoperability on the web of things: the semantic smart gateway framework. In: 2012 Sixth International Conference on Complex, Intelligent and Software Intensive Systems (CISIS), pp. 630–635, July 2012
12. Lanthaler, M., Gutl, C.: A semantic description language for restful data services to combat semaphobia. In: 2011 Proceedings of the 5th IEEE International Conference on Digital Ecosystems and Technologies Conference (DEST), pp. 47–53, May 2011
13. Le-Phuoc, D., Nguyen-Mau, H.Q., Parreira, J.X., Hauswirth, M.: A middleware framework for scalable management of linked streams. Web Semantics: Science, Services and Agents on the World Wide Web **16**, 42–51 (2012). http://www.sciencedirect.com/science/article/pii/S1570826812000728. The Semantic Web Challenge 2011
14. Perera, C., Zaslavsky, A., Christen, P., Georgakopoulos, D.: Context Aware Computing for The Internet of Things: A Survey. IEEE Communications Surveys Tutorials **16**(1), 414–454 (2014)
15. Pfisterer, D., Romer, K., Bimschas, D., Kleine, O., Mietz, R., Truong, C., Hasemann, H., Kröller, A., Pagel, M., Hauswirth, M., Karnstedt, M., Leggieri, M., Passant, A., Richardson, R.: Spitfire: toward a semantic web of things. IEEE Communications Magazine **49**(11), 40–48 (2011)
16. Simons, B., Yu, J., Cox, S.: Defining a water quality vocabulary using QUDT and ChEBI. In: Proceedings of the 20th International Congress on Modelling and Simulation, December 2013. http://www.mssanz.org.au/modsim2013/L6/simons.pdf
17. Taylor, K., Griffith, C., Lefort, L., Gaire, R., Compton, M., Wark, T., Lamb, D., Falzon, G., Trotter, M.: Farming the Web of Things. IEEE Intelligent Systems **28**(6), 12–19 (2013). http://dx.doi.org/10.1109/MIS.2013.102

18. Wang, W., De, S., Toenjes, R., Reetz, E., Moessner, K.: A comprehensive ontology for knowledge representation in the internet of things. In: 2012 IEEE 11th International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom), pp. 1793–1798, June 2012
19. Wetz, P., Trinh, T.D., Do, B.L., Anjomshoaa, A., Kiesling, E., Tjoa, A.M.: Towards an environmental information system for semantic stream data. In: Proceedings of the 28th Conference on Environmental Informatics - Informatics for Environmental Protection, Sustainable Development and Risk Management, pp. 637–644. BIS-Verlag (2014). http://publik.tuwien.ac.at/files/PubDat_230174.pdf
20. Whitmore, A., Agarwal, A., Da Xu, L.: The Internet of Things - A survey of topics and trends. Information Systems Frontiers **17**(2), 261–274 (2015). http://dx.doi.org/10.1007/s10796-014-9489-2