Ontologies and Semantic Web for the Internet of Things – A Survey

Ioan Szilagyi, Patrice Wira
MIPS Laboratory, University of Haute-Alsace, Mulhouse, France
{ioan.szilagyi; patrice.wira}@uha.fr

***Abstract*—The reality of Internet of Things (IoT), with its growing number of devices and their diversity is challenging current approaches and technologies for a smarter integration of their data, applications and services. While the Web is seen as a convenient platform for integrating *things*, the Semantic Web can further improve its capacity to *understand* things' data and facilitate their interoperability. In this paper we present an overview of some of the Semantic Web technologies used in IoT systems, as well as some of the well accepted ontologies used to develop applications and services for the IoT. We finally present the Semantic Web Stack for the Internet of Things pointing out some of its shortcomings in the development of an IoT application or service.**

Keywords—semantic web; internet of things; ontology; schema IoT; OWL

I. INTRODUCTION

The Internet of Things (IoT) is a technological evolution that, by interconnecting *things*, provides the basic structure for the development of next generation everyday services and applications. Cisco states that the IoT was born sometime between 2008 and 2009 when the number of connected devices on the Internet exceeded the number of world population. They estimate that by 2020 the IoT will feature around 50 billion connected devices [1]. With the penetration and the convergence of the Internet, the IoT will eventually evolve onto the Internet of Everything [2].

An Internet of Things' adapted Metcalf Law [3, p. 184] would state that the value of a network is proportional to the square of the number of connected *things* (e.g. compatible communicating devices, users). The value of the network will determine its capacity to understand a situation or a context and this understanding will "potentially enable services and application to make intelligent decisions and to respond to the dynamics of their environment" [4].

The capacity of the IoT to understand its environment is given by its interdisciplinary nature. Services in sectors like buildings, energy, consumers and homes, healthcare and life science, industry, transportation, retail, security/public safety and, of course, IT and networks are represented in the IoT through a variety of applications and over "300 different device types" [5]. However, the variety of devices that covers different aspects of the environment has direct consequences on the data that they produce and can limit the capacity of higher level systems to interpret and process the generated data. The integration of data generated by the large diversity of things is one of the most important task in an IoT system [6]. Providing interoperability among the things is "one of the most fundamental requirements to support object addressing, tracking and discovery as well as information representation, storage, and exchange" [4].

There is consensus that Semantic Technologies is the appropriate tool to address the diversity of Things [4], [7]–[9]. "*Formal semantics enable the knowledge management and data exchange in a machine-interpretable way. This makes semantic technologies a key to overcome common modelling, model-exchange and interoperability problems that need to be solved across the life cycle of systems"* [9].

Without the objective of being exhaustive in our presentation, we outline some of the works in the domain and provide a survey on existing ontologies. We finally propose a Semantic Web Stack for the IoT.

II. INTERNET OF THINGS

Defining the IoT is not an easy task. IEEE launched an invitation intended to establish a baseline definition for IoT, and in May 2015 they published a document that provides an overview of current definitions and concepts used in the domain of IoT. Depending on the *environment scenario*, which can be small or large, the IoT is defined as follow: (1) for the small environment scenario the IoT is "*a network that connects* ***uniquely identifiable 'Things'*** *to the Internet.* ***The 'Things' have sensing/actuation and potential programmability capabilities.*** *Through the exploitation of unique identification and sensing,* ***information about the 'Thing'*** *can be collected and the* ***state of the 'Thing' can be changed from anywhere, anytime, by anything.***", and (2) for the large environment scenario, the IoT is : "*a self-configuring, adaptive, complex network that interconnects 'things' to the Internet through the use of standard communication protocols.* ***The interconnected things have physical or virtual representation in the digital world, sensing/actuation capability, a programmability feature and are uniquely identifiable. The representation contains information including the thing's identity, status, location or any other business, social or privately relevant information. The things offer services, with or without human intervention, through the exploitation of unique identification, data capture and communication, and actuation capability.*** *The service is exploited through the use of intelligent interfaces and is made available anywhere, anytime and for anything taking security into consideration*" [10]. The difference between a small and a

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large environment is given by its complexity defined in terms of number of connected things and the thing's ownership/management capabilities. The IERC (European Research Cluster on the Internet of Things) definition states that IoT is "*a dynamic global network infrastructure with self-configuring capabilities based on standards and interoperable communication protocols where physical and virtual 'things' have identities, **physical attributes**, and **virtual personalities** and user intelligent interfaces, and are seamlessly integrated into the information network*" [11]. The ITU (International Telecommunication Union) defines IoT as "a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" [12]. According to these definitions IoT is primarily a network.

While an IoT system can become very complex, we present in Fig. 1 a simple and basic architecture based on an IoT system. The Thing, which has computational and communication capabilities can exchange information with other things on the network in order to coordinate their actions and/or they can simply produce data that will be used at a higher level of the service or application (e.g. analytics, business decisions).

Without re-considering here all the aspects and characteristics defining an IoT system, we will emphasize on some of its elements' characteristics. While the network aspect is a core component and tight related to Internet standards and protocols, we will focus our attention to the "Thing" that forms the IoT system.

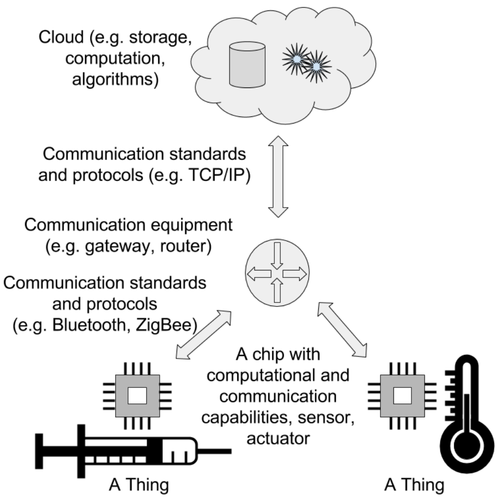

Fig. 1. Basic architecture of the Internet of Things

A. The Thing and its capabilities

What kind of things can form the IoT? Can any-*'Thing'* be integrated in an IoT system? What are the requirements for the *Thing*? These are some questions that may come when trying to define the *Thing* in an IoT system.

While the definition given by IEEE gives programmability capabilities to the Thing, this is seen in a context where the technology has already merged with the Thing. The Thing itself does not necessarily possess computational and communication capabilities. These capabilities are given by a *chip* that is attached and deeply integrated into the Thing. The things that form the IoT were not necessarily created with the purpose of connecting them to the Internet (the first IoT thing was a toaster [13]). Generally, all kind of things can be connected to an IoT system. However, a Thing must possess some interest for a service or an application; it must do something useful in order to be considered for integration in an IoT system. These things can be: Tags (e.g. QR Code, RFID); Devices (e.g. Arduino, Raspberry Pi), Machines (e.g. Smart Bulb, Smart Car), or even entire Environments (e.g. Smart Building, Smart City)[14, p. 4].

When integrated into an IoT system, the Thing can be characterized by three main capabilities: (1) communication; (2) programmability (data processing and storage); and (3) sensing and/or actuating capabilities. ITU defines the "device" as a "piece of equipment with mandatory capabilities of communication and the optional capabilities of sensing, actuation, data capture, data storage and data processing" [12]. Sensing and/or actuating capabilities allow the Thing to interact with its environment. A Thing may dispose of sensing (e.g. thermometer), actuating (e.g. motors) or both capabilities (e.g. thermostat). While the actuating capabilities are usually restricted and would require in most cases authorizations, sensing capabilities can be shared to multiple services and applications, and so contributing to the overall value of the IoT.

The programmable capability gives some autonomy to the Thing so it can simulate some locally limited level of intelligence. The communication capability allows the Thing to be part of a network, contribute to the value of the network and augment the value (e.g. decisions accuracy, intelligence) of the applications and/or services that consumes its data. However, the higher-level applications and services must be able to interpret and exploit the data produced by the Thing.

B. The Thing on the Web

The ubiquity of Web technologies (e.g. browsers, languages) makes them a convenient choice for visualizing the data produced by the Things or for managing it.

One of the first steps towards the *Web of Things* was proposed by Guinard and Trifa in [15]. The variety of protocols (e.g ZigBee, Bluetooth, X10) implemented in devices can cumber the ability of the device to integrate an IoT system [16]. In order to eliminate this shortcoming, they define the *Web Thing* as *"a digital representation of a physical object accessible via a RESTful Web API"* [17]. The *Web Thing Model* imposes technical implementations that allow the Thing to easily integrate the Web (e.g. JSON payload). The Web Thing necessarily communicates over HTTP and implements an API using the REST architectural style.

Fig. 2 illustrates the hierarchy of Thing concepts from Guinard and Trifa's perspective. We notice the concept of *Semantic Web Thing* at the top of the hierarchy. It features semantic annotation of the Thing that already implements the *Web Thing Model* and other specific requirements (e.g. GET, POST, PUT, DELETE; JSON representation).

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The semantic annotation leverages the human-consumption oriented Web to a machine-interpretable Web. It provides technologies (e.g. languages, frameworks, tools) to annotate data so that software agents are provided with the ability to interpret and infer about things on the Web. This is a key answer to the volume, variety and velocity of data produced on the Web.

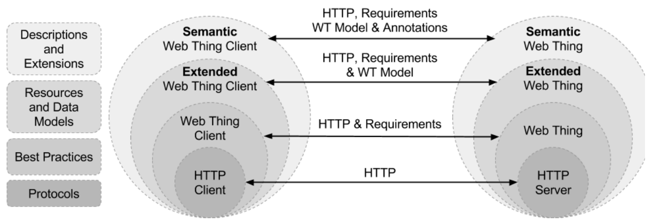

Fig. 2. The Web Thing hierarchy (source: [17])

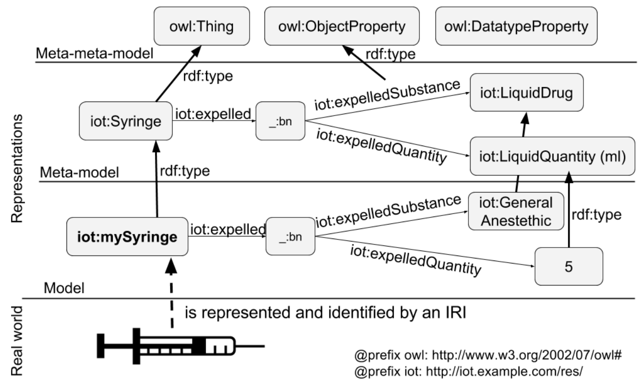

Fig. 3. The representation of the Thing on the Semantic Web

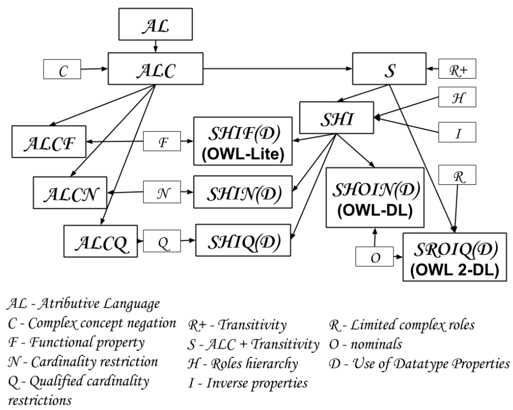

Fig. 4. Description logics on OWL

III. The Semantic Web of Things

The objective of the Semantic Web is to provide a new form of content that is meaningful and processable by both humans and computers, and we can add from an IoT perspective, by Things connected to the Web. How IoT systems can benefit from this vision is already presented in several works. The most cited and relevant areas are interoperability, data storage, data integration, data abstraction and access, semantic reasoning and interpretation, resource/service search and discovery, scalability [4], [6], [7]. In [6], the challenge of *"interoperating and integrating data and information is the more important and demanding task"*. In [8], a model is presented that annotates data generated by the Thing in order to integrate it in a knowledge base and according to [18] the semantic vision is part of the IoT evolutionary process.

The two main areas of an IoT system that benefit the most from the integration of semantic technologies are: (1) the representation and description of the Thing, its capabilities and environment; and (2) semantic annotation of the data that the Thing produces.

A. Thing representation on the Semantic Web

One of the requirements of the Web Thing Model is the implementation of a "root resource accessible via an HTTP URL". This serves as the entry point for the Web Thing and enables interaction with it. However, this is not an URI (Uniform Resource Identifier or IRI – Internationalized Resource Identifier). An IRI provides two functions: (1) assign *uniquely* identifiable names to things (resources) and (2) specifies the location of the resource (an URL provides only the second functionality). On the Semantic Web, the Thing is identified and represented by an IRI, as seen in Fig. 3.

Once represented on the Semantic Web, the Thing is described using relations between its identifier and other resources. The RDF (Resource Description Framework) provides a mechanism for describing things on the Web using *RDF triples.* Multiple interconnected triples form an RDF Graph, which represents the RDF Model of the described Thing.

B. Understanding Things' data: Metadata, schemas and ontologies

For machines, data do not stand for themselves; they must be interpreted using other data. Literally data about data, this other data is called metadata. While metadata can share the same level of abstraction as the described data, schemas and ontologies provides a higher level of abstraction. The `rdf:type` property specifies an "is a" relation and it is used between different levels of abstraction (see Fig. 3).

RDFS (RDF Schema) and OWL (Web Ontology Language) are used to define domain specific schemas and ontologies: The meta-models. Semantic Web ontologies and schemas are core concepts of the Semantic Web. An ontology is defined as a "formal specification of a shared conceptualization" [19]. We notice the two main aspects for ontology: (1) the *formal specification* and (2) the *shared conceptualization*.

The formal aspect of ontologies is defined by *description logic* semantics and constructs, see Fig. 4. The OWL language comes in three sublanguages called species: OWL Lite, OWL DL and OWL Full, which provides different levels of expressiveness.

They correspond to different description logics: OWL Lite implements $\mathcal{SHIF}(\mathcal{D})$ logic, while OWL DL implements $\mathcal{SHOIN}(\mathcal{D})$ logic. The formal aspect of ontologies enables

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reasoners to infer on described data based on the implemented logic. In OWL2, the second version of the OWL language, OWL2 DL, which implements $\mathcal{SHROIQ}(\mathcal{D})$ logic comes in three sublanguages: OWL2 QL, OWL2 EL, OWL2 RL. The difference consists in their expressivity level.

When conceiving an ontology, one must balance between the implemented level of expressiveness and the desired complexity class (see [20]). Reasoners and smart software agents can benefit from the knowledge encoded in the ontology. A software agent can exploit that knowledge and take decision based not only on data, but also on the knowledge provided by the ontology.

The shared conceptualization aspect is aimed at providing a common understanding of the described domain. This allows software agents to interpret data based on commonly defined and accepted concepts and relations in the ontology. IoT systems can and should benefit from both these aspects of the Semantic Web technologies.

IV. Ontologies for the Internet of Things

There are already several projects that index ontologies and vocabularies on the Web. One of the most used schemas on the Web is provided by *Schema.org* and is defined as "a collaborative, community activity with a mission to create, maintain, and promote schemas for structured data on the Internet, on Web pages, in email messages, and beyond". This schema is used on more than 10 million sites and at the time of writing consists of 642 Types, 992 Properties and 210 Enumeration values [21]. It describes general and commonly used types like Person, Place, Product, Action, etc., which can be integrated in a Semantic Web of Things system at a higher level of abstraction. However, it does not provide specific IoT domain concepts (e.g. Sensor or Actuator concept).

Open Knowledge Foundation provides a gateway to reusable semantic vocabularies on the web [22]. Called LOV (Linked Open Vocabularies) [23], the online catalogue facilitates searching of any kind of vocabularies used for data description on the Web.

A collection of Linked Open Vocabularies for the IoT is maintained at [24]. At the time of writing, 299 IoT specific vocabularies were presented on the catalogue. This catalogue does not offer the search functionality through collected ontologies, but organize the ontologies in 19 categories (e.g. Smart Home, Healthcare, Transportation). Evaluating and comparing these almost 300 ontologies is beyond the scope of this paper and will be reserved for a future work. However, there are already several works in the literature that provide good insights on IoT ontologies. We will resume our survey on some of the most prominent and well referenced in other works or by the Open Knowledge Foundation catalogue.

Attempting to answer the question of how ready are today's ontologies to form a framework for annotating real-world devices, [25] presents a review of some of the most popular ontologies that they use in order to implement an IoT system, and categorize them in 5 "conceptual groups": (1) Actuator, sensor, system – used to describe intrinsic characteristics of the device; (2) Global and local coordinates – used to represent the physical location of the device; (3) Communication endpoint – used to describe the communication capabilities of the device; (4) Observations, features of interest, units and dimensions – used to describe the data produced by the device; and (5) vendor, version, deployment time – used to describe data in relation with the manufacturer, the owner or other maintenance specific tasks. From the 5 enumerated groups, the *Observation, features of interest, units and dimensions* group describes the data that the Thing *produces*, while the other 4 groups describe data about the Thing.

The Web Thing Model characterizes Things by their static and dynamic properties. Static properties are related to the Thing (e.g. product, services), while dynamic properties are related to the context of the Thing (e.g. location, Quality of Service) [26, p. 34].

The type of a device can be described in relation with the function it performs [27]. Many situations may require multiple sources of data in order to take an action, so the sensors are more popular than actuators [28, p. 109]. A simple search for the Sensor concept produced 797 results, while the Actuator concept produced only 41 results.

One of the most popular ontology is the Semantic Sensor Network Ontology (SSN) [29] developed by the W3C Semantic Sensor Network Incubator Group. While this ontology describes the Sensor concept, it does not provide representations for the Actuator concept. Multiple ontologies construct and expand this ontology.

The Ontology for Meteorological sensors [30] and SPITFIRE Ontology describes sensors, observations and related concepts and it is based on the alignments among Dolce+DnS Ultralite (DOLCE Lite-Plus and Descriptions and Situations ontology) [31], W3C SSN ontology and the Event Model-F ontology [32].

The IoT ontology [33] [34] describes knowledge about things. They describe concepts like *Smart Entity*, *Physical Entity, Control Entity, Electronic Device, Smart Network etc.* It builds on SSN Ontology, DOLCE Ultralite Upper ontology (DUL), Quantities, Units, Dimensions and Data Types Ontologies (QUDT) [35].

The Semantic Actuator Network (SAN) [36] provides a wide range of concepts and properties for actuators: some concepts are *Acting, Actuating Device, Actuating Property, Actuating Range, etc.* DogOnt ontology is aimed at home automation systems. It provides description for the *actuator* concept as a sub-concept of an controllable electric system [37]. IoT-O ontology, a core domain IoT ontology, is intended to model horizontal knowledge about IoT systems and applications, and to be extended with vertical, application specific knowledge. It is built on different modules: SSN, SAN, etc. [38]. A comprehensive ontology for knowledge representation in the IoT is presented in [39], it describes IoT Services, Observation and Measurement, Entity of Interest, etc. A review of 17 sensor observation ontologies is presented in [40]. Some other general ontologies that are integrated into IoT systems are Time ontology [41] GeoNames Ontology [42], FOAF [43].

V. THE SEMANTIC WEB STACK FOR THE IOT

Fig. 5 shows the Semantic Web Technologies Stack for the IoT, an adaptation from “Semantics at different levels in IoT” in [4, p. 7] and “IoT Layered Architecture” in [2, p. 14]. It presents the core Semantic Web Technologies used at different levels of an IoT system. The integration of Semantic Web technologies into IoT systems can be identified at three different levels. The “modeling level” provides a common understanding of Things’ characteristics and capabilities. It uses shared and common accepted vocabularies and ontologies to facilitate the integration of data generated by different systems (e.g. sensor ontologies). The “data processing level” uses description logics and OWL semantics in order to enable reasoning and inference over the data. Finally, the “IoT Services and Application” level uses specialized description and ontologies that enables service publication, discovery, composition and adaptation.

Fig. 5. Semantic Web Stack for IoT

A. *Models and meta-models : knowledge bases*

The overall quality of the final service or application depends of the quality of every involved layer. In this context, the first layer is concerned with data preparation. Interpreting and understanding the data is the first prerequisite in this process. This layer manages the semantic integration and aggregation of data from a variety of sources. Semantically annotated data can be transformed and modeled according to specific needs. In Fig. 5 the Model *represents* the Thing and forms the Assertions Box (ABox), while the Meta-model describes *the vocabulary* used to describe the Thing and forms the Terminological Box (TBox). A Knowledge Base is composed by these two components. Finally, the meta-meta-model provides the construct vocabulary for the TBox.

B. *Data processing*

An IoT system is, by its nature, a distributed system and processing its data can be done at different levels. While the limited local information can provide some basic interpretation and processing in its domain of interest, further insight on the data is obtained at higher levels, when data from multiple sources are gathered, processed and correlated. We emphasize two different approaches for processing this data: (1) using semantic reasoners and (2) using Big Data specific algorithms (e.g. machine learning).

1) *Reasoning and Inferences*. Rules and semantic alignments (e.g. `owl:equivalentClass`, `owl:subClassOf`, `owl:sameAs`) can be used to transform and adapt the data to the declared ontologies. Depending on the expressiveness of the ontologies, reasoning engines can further infer associations and links into the data. For data transmission and storing in a Semantic Web context, JSON-LD, a W3C recommendation from 2014, provides a convenient way to serialize RDF data. XML format is also available. Triplestores (e.g. Fuseki, StarDog) are used to store RDF triples. The query language for the Semantic Web is SPARQL (SPARQL Protocol And RDF Query Language). It provides a convenient way to interrogate multiple triplestores over HTTP.

2) *Big Data and machine learning algorithms*. Semantic Technologies are an excellent choice for IoT systems for two reasons: (1) it allows sharing the data description through schemas and ontologies and (2) it allows knowledge encoding in ontologies via description logic constructs. However large quantity of data combined with high expressive ontologies, can limit reasoners’ performance in their inferences. IoT systems are generally used to monitor, diagnose, predict and recommend actions. In ontology based systems, the knowledge is described a priori, this makes them less adapted to systems where the objective is to predict and analyze behaviors of different environments and users. From this point of view, the integration of machine learning algorithms with well described data could provide better value services and applications. An example using both statistical learning and ontologies to extract residential user activity is presented in [44].

C. *IoT Services and Applications*

Ontologies and semantic annotations can also enhance the description of the provided services. OWL-S provides semantic markup for web services [45]. The Semantic Sensor Observation Service (SemSOS) [46] and the use of ontologies for automated deployment [47] are some examples of semantic technologies based applications and services in IoT environments [48].

VI. CONCLUSION

In this paper we presented some of the core concepts of IoT systems and Semantic Web technologies. We presented the evolution of the Thing to the Web Thing Model and finally to its representation using Semantic Web technologies. We reviewed the most popular ontologies used in IoT systems. We presented a Semantic Web Stack for the IoT and how Semantic Technologies can improve the overall value of an IoT system. This paper surveys certain aspects of semantic technologies used for IoT systems, but it does not provide an in-depth analysis of existing ontologies and schemas. Given the purpose of ontology – to formally conceptualize and describe the knowledge of a domain – we reserve that task to a further work. The IoT is supposed to be *smart.* This cannot be done without an accurate data interpretation (semantic models), putting data in context (knowledge bases), analyzing multiple sources of data (aggregation, reasoning and inference), behavior processing (machine learning algorithms) and intelligent services and applications. We think that the integration of semantic technologies (interpretation layer, processing layer and services/applications layer) with adapted machine learning algorithms will produce a smarter IoT.

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