Semantic Web Methodologies, Best Practices and Ontology Engineering Applied to Internet of Things

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***Abstract*—We discuss in this paper, semantic web methodologies, best practices and recommendations beyond the IERC Cluster Semantic Interoperability Best Practices and Recommendations (IERC AC4). The semantic web community designed best practices and methodologies which are unknown from the IoT community. In this paper, we synthesize and highlight the most relevant work regarding ontology methodologies, engineering, best practices and tools that could be applied to Internet of Things (IoT). To the best of our knowledge, this is the first work aiming at bridging such methodologies to the IoT community and go beyond the IERC AC4 cluster. This research is being applied to three uses cases: (1) the M3 framework assisting IoT developers in designing interoperable ontology-based IoT applications, (2) the FIESTA-IoT EU project encouraging semantic interoperability within IoT, and (3) a collaborative publication of legacy ontologies.**

***Keywords*—Semantic Web of Things; Internet of Things; Semantic Web Technologies; Best Practices; Methodologies; Ontology Engineering.**

I. Introduction

Semantic web technologies are getting more used to enhance semantic interoperability within project. Recently, semantic web technologies are integrating to Internet of Things [1]. Designing an ontology [2] is getting more and more popular to ease the interoperability among applications, services, softwares and platforms and for describing the domain knowledge. The main benefits of using ontologies are: (1) exchanging data among systems, (2) providing interoperability among systems, (3) designing knowledge, (4) sharing knowledge, and (5) simplifying operations.

However, within the Internet of Things (IoT) community, each project or platform develops its own ontology which still hinders interoperability. A major challenge would be to reuse as much as possible the existing ontologies within the Internet of Things community to ease interoperability among EU and international projects, platforms, systems, services, etc.

On the other side, the semantic web community recommends to reuse existing domain knowledge [3] [4]. For non-semantic web experts, this is a real challenge. The Linked Open Vocabulary for Internet of Things (LOV4IoT) is a first step to overcome the challenge of reusing domain ontologies [5]. LOV4IoT references almost 300 ontology-based projects relevant for IoT; when available, the ontologies, the datasets and/or the reasoning mechanism is shared online [6]. According to the semantic web experts (e.g., Linked Open Vocabulary (LOV) catalogue [7]), such ontologies are not compliant with the semantic web best practices and not reliable.

Moreover, the IERC Cluster Semantic Interoperability Best Practices and Recommendations (IERC AC4) [8] [9] proposes a set of best practices and recommendations. In this paper, we propose to go beyond their recommendations by referencing a set of tools or semantic web methodologies to easily design interoperable semantic-based IoT applications. IERC AC4 defines four interoperability issues as depicted in Figure 1:

- *Technical interoperability* that concerns heterogeneous software and hardware (e.g., communication protocol heterogeneity).
- *Syntactical interoperability* that concerns data formats (e.g., JSON or XML). Syntactical interoperability is also an issue for combining and reusing ontologies or semantic datasets developed with different software dealing with different syntaxes (e.g., RDF/XML, N3).
- *Semantic interoperability* that concerns (1) ontology heterogeneity (e.g., ontology designed by different persons differ in the structure), (2) terms used to describe data (e.g., t, temp and temperature are several terms to describe temperature), and (3) the meaning of data exchanged according to the context (e.g., body temperature differs from room temperature). This is important to later interpret IoT data and build smarter and interoperable semantic-based IoT applications. IERC AC4 underlines the need to be agreed on common vocabularies to describe data.
- *Organizational interoperability* that concerns heterogeneity of the different infrastructures.

In this paper, we are mostly focused on semantic interoperability challenges.

The main novelty of this paper is studying ontology methodologies, semantic web best practices and applying them within the IoT community. Moreover, we address the following research challenges to ease interoperability among semantic-based IoT applications:

- How to reuse the existing ontologies and domain knowledge?
- Is the ontology and domain knowledge reliable (e.g, maintained)?

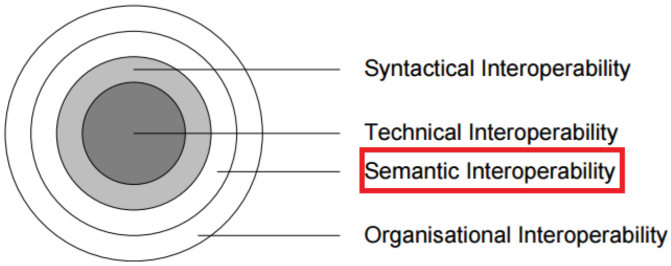

Fig. 1. Interoperability challenges according to IERC AC4 [8] [9]

- Which methodology should be followed to build an ontology?
- How to evaluate an ontology?
- How to check that ontologies are interoperable?
- How to ease the reuse of already designed domain knowledge (e.g, providing documentation)?

The rest of the paper is structured as follows: section II presents the state of the art and clearly explains the limitations. Section III describes our proposed Recommendations and Best Practices beyond the IERC AC4 Cluster. Section IV is focused on the uses cases. Finally, we conclude the paper in section V.

II. Related Work

In this section, we describe work encouraging the reuse of existing ontologies and datasets: (1) ontology methodologies, (2) semantic search engines, (3) ontology and dataset repositories, (4) IERC AC4 cluster for best practices within IoT.

A. Ontology Methodology

Noy et al. explain in the second step of their **ontology development 101 methodology** that ontology designers should consider reusing existing domain knowledge (e.g., ontologies) [3].

Corcho et al. survey the existing ontology methodologies [10] and answer the following questions: (1) Which methods and methodologies can I use for building ontologies?, (2) Which tools give support to the ontology development process, and (3) Which languages should I use to implement my ontology?

The **Neon** project[1] recommends reusing available knowledge and proposes a set of methodologies [11] [12]. The Neon project focuses on nine scenarios [11]: (1) from specification to implementation, (2) reusing and re-engineering non-ontological resources, (3) reusing ontological resources, (4) reusing and re-engineering ontological resources, (5) reusing and merging ontological resources: ontology matching tools enable ontology aligning or merging, (6) reusing merging, and re-engineering ontological resources, (7) reusing ontology design pattern (ODPs), (8) restructuring ontological resources, and (9) localizing ontological resources to translate of all the ontology terms into another natural language. We are mainly interested in the scenario 3 to help IoT developers in reusing ontologies relevant for IoT. The others future steps are interesting for re-designing ontologies in an interoperable manner and 'not reinventing the wheel at each ontology development' to speed up the ontology development process.

[1] http://www.neon-project.org/

On-to-Knowledge is another methodology for designing ontologies comprised of four steps: (1) kick-off, (2) refinement, (3) evaluation, and (4) ontology maintenance [13].

Such methodologies should be followed to reuse or design ontologies and datasets. The methodologies provided by the NeON project [12] and Noy et al. are the most popular ones [3].

B. Semantic Search Engines

In the Neon project, they suggest to use semantic web search engines, but we have seen the limitations of such tools. Indeed, these tools do not take into account at all ontologies that are explained and described in research articles. Semantic search engines such as **Sindice**[2] [14], **Watson**[3] [15] and **Swoogle**[4] are not enough mature for finding domain ontologies relevant for IoT because of a lack of best practices to publish, share and reuse IoT ontologies.

Semantic search engines can be employed when looking for specific ontologies or datasets.

C. Ontology and Dataset Repository

Datalift[5] [16] is a project to assist people in semantically annotating and linking data, but they are not focused on IoT and do not provide vocabularies related to IoT. Datalift provides the **Linked Open Vocabularies (LOV)**[6] [7], a catalogue for ontologies, mainly known by semantic web experts. LOV lacks of ontologies relevant for IoT, and does not accept new ontologies if they do not follow their best practices. Unfortunately, such best practices are not known outside the semantic web community. The **DataHub**[7] is a catalogue for datasets and does not provide quality checking when submitting a new dataset.

Linked Open Vocabularies for Internet of Things (LOV4IoT) is a dataset referencing almost 300 ontology-based domain-specific projects in various domains relevant for IoT such as agriculture, smart home healthcare, weather, etc. [5]. Further, domain ontologies are classified according to their status such as not available, online, following best practices, etc. In [5], a set of recommendations and tools are provided to follow semantic web best practices. In this paper, we enrich our previous work regarding best practices.

Oyster is a Peer-to-Peer system for exchanging ontology metadata among communities in the Semantic Web and an online solution for sharing ontologies to assist research in reusing existing ontologies [17].

Ontology and dataset repositories can be employed when looking for specific ontologies or datasets.

[2] http://sindice.com/
[3] http://watson.kmi.open.ac.uk/WatsonWUI/
[4] http://swoogle.umbc.edu/
[5] http://datalift.org/
[6] http://lov.okfn.org/dataset/lov/
[7] http://datahub.io/

D. IERC AC4 Cluster for best practices

The European Research Cluster on the Internet of Things (IERC) AC4 released in March 2015 a set of best practices and recommendations for semantic interoperability [8] [9]. They mention the need to overcome the following challenges: (1) a unified model to semantically annotate IoT data, (2) reasoning mechanisms, (3) linked data approach, (4) horizontal integration with existing applications, (5) design lightweight versions for constrained environments, and (6) alignment between different vocabularies.

IERC AC4 does not reference concrete tools encouraging: (1) semantic web best practices, (2) the use of methodologies to ensure interoperability among ontology-based IoT applications, and (3) reuse of the domain knowledge already designed.

E. Limitations of current approaches

Besides the IERC AC4, we did not find any approaches applying semantic web methodologies and best practices to IoT. The IERC AC4 proposes a set of best practices, but do not provide: (1) any methodologies to reuse exiting ontologies, (2) concrete tools to validate our ontologies, (3) explain how to evaluate an ontology, and (4) how to develop a well-designed ontology.

III. Our proposed Recommendations and Best Practices beyond the IERC AC4 Cluster

We propose a list of best practices that can further improve the publication and discovery of ontologies in the IoT domain. Those best practices can be grouped into five categories: (1) ontology & dataset publication (formats, serialization), (2) metadata for vocabulary, (3) ontology quality, (4) ontology & dataset reuse, and (5) namespace management.

A. Ontology & dataset publication (formats, serialization)

In this section, we are focused on ontology and dataset publication (formats, serialization) best practices:

Best Practice 1. *The format used to represent IoT data should be unified and we should provide wrappers/translators to deal with heterogeneous formats (e.g., SenML/XML, SenML/JSON, CSV, Excel).*

Best Practice 2. *The format used to represent semantic IoT data (e.g., RDF/XML, JSON-LD, Turtle, Ntriples) should be unified to ease the interlinking of datasets.*

Best Practice 3. *The terms used to describe IoT data should be unified. For instance, computers have to deal with synonyms such as precipitation and rain having the same meaning. A first step dealing with this challenge is the M3 language/nomenclature to describe sensor data in a unified way [18].*

Best Practice 4. *Checking the syntax of semantic documents (e.g., RDF or OWL) will facilitate interoperability. It can be done with the RDF Validator[8] and the OWL validator[9]. TripleChecker[10] is a tool which can detect a property used but not declared in the ontology or a wrong format date.*

[8]http://www.w3.org/RDF/Validator/

[9]http://mowl-power.cs.man.ac.uk:8080/validator/

[10]http://graphite.ecs.soton.ac.uk/checker/

B. Metadata for vocabulary

In this section, we are focused on metadata for vocabulary best practices:

Best Practice 5. *An ontology should contain minimal annotations on labels and comments, as well as metadata to capture the authors, different versions dates, provenance information, etc. as preconized by LOV [19]. Adding label is important when using ontology matching tools, since most of them are based on comparing labels. We have in mind to extend the ProtegeLOV plugin[11] to encourage people follow such best practices. Further, adding ontology metadata eases the tasks of semantic search engines and ontology repository. The Ontology Metadata Vocabulary (OMV) ontology [20] could be reused within the LOV catalogue.*

Best Practice 6. *Sharing datasets on the Web is becoming popular, it would be even better to share at the same time the dataset, the ontology used to model the dataset or even the reasoning employed to enrich the dataset with additional knowledge. It is essential to link datasets to ontologies and can be done by using the VoID ontology [21].*

C. Ontology quality

In this section, we are focused on ontology quality best practices:

Best Practice 7. *A dereferenceable ontology eases the lookup of the terms. Checking that your ontology or dataset are deferenceable is essential to automate tasks. It can be done with Vapour[12] [22].*

Best Practice 8. *Checking and fixing popular and common ontology pitfalls (e.g., merging different concepts in the same class) can be done with the Oops[13] tool [23].*

Best Practice 9. *Following methodologies and tutorials will encourage the reusability of the ontologies: Noy et al. [3] and NeON[11].*

D. Ontology & dataset reuse

In this section, we are focused on ontology and dataset reuse best practices:

Best Practice 10. *Sharing your ontology on the Web for reuse and discovery and referencing it on ontology catalogue (LOV[14], LOV4IoT [24] or Ready4Smartcities catalogue) or semantic search engines (e.g., Watson [15], Swoogle [25]) benefits both in increasing the reusability of the terms in the vocabulary as well as improving the quality of the vocabulary. Linked Open Data (LOD) provides tools such as the CKAN DataHub[15] to share and reuse datasets.*

Best Practice 11. *Enriching you domain knowledge with documentation to encourage and ease the re-usability of the*

[11]http://labs.mondeca.com/protolov/

[12]http://validator.linkeddata.org/vapour

[13]http://oops.linkeddata.es/

[14]http://lov.okfn.org/dataset/lov/

[15]http://datahub.io/

ontology or dataset. Some tools such as SpecGen[16], *Neologism*[17] *and Parrot*[18] *could be used to achieve such tasks.*

Best Practice 12. *Aligning and reusing ontologies is challenging [4]. When the ontology is reliable (e.g, maintained, standardized or popular), we should directly reuse the concepts or properties for existing ontologies (e.g.,* `ssn:device`*). Otherwise, re-defining the same concept or property can be done and add* `owl:equivalentClass`*,* `owl:equivalentProperty`*.*

Best Practice 13. *Checking that the IoT ontology is aligned with the W3C SSN ontology [26] which is popular, maintained and under standardization. Further, the extended ontology can be checked with W3C SSN validator*[19] *[27]?*

E. Namespace management

In this section, we are focused on namespace management best practices:

Best Practice 14. *Choosing a good namespace which is still available. It can be done with the Prefix.cc tool.*

Best Practice 15. *Unifying namespaces for ontologies and datasets. To automate tasks, it would be easier to unify namespaces. Frequently, we do not have labels or comments attached to the concepts and properties. We have to automatically parse the URI to get the label hidden in the URI. Having unified namespace will be easier to get the hidden labels. For instance, some namespaces ends with the character tilde or backslash.*

Best Practice 16. *Ensuring the sustainability of the ontology namespace. Frequently, the namespace of the ontology depends on the server where it is hosted. When the server is not available anymore, accessing the namespace of the ontology will provide the error page not found. To avoid this issue, PURL enables to maintain the same namespace while changing the host server.*

We summarize in Table I our proposed set of recommendations to follow semantic web best practices and ease interoperability among ontology-based projects, platforms, services and applications. The first column indicates our proposed requirements, the second column provides the description, and the third column indicates tools helping to fulfilling such requirements. For instance, the documentation is essential to easily reuse ontologies. Indexation of the domain knowledge on semantic tools is required to later automatize tasks or automatically update knowledge bases. Syntax is essential to easily load ontologies under whatever the software without having any syntaxes.

IV. USE CASES

This work has been applied to three use cases: (1) the FIESTA-IoT EU project, (2) the Machine-to-Machine Measurement (M3) framework, and (3) re-publishing the existing ontologies that we explain below.

[16]https://github.com/specgen/specgen
[17]http://neologism.deri.ie/
[18]http://ontorule-project.eu/parrot/parrot
[19]http://iot.ee.surrey.ac.uk/SSNValidation/

A. FIESTA-IoT EU project

The LOV4IoT catalogue of ontology-based projects reusable for Internet of Things can be exploited to automatically re-design domain knowledge compliant with our proposed best practices. This is a necessary step required in the FIESTA-IoT project, where an entire work package is focused on best practices, validations and certifications.

B. Machine-to-Machine Measurement (M3) framework

Our proposed recommendations and best practices have been applied within the Machine-to-Machine Measurement (M3) framework framework to build interoperable Semantic Web of Things (SWoT) templates to ease the task of IoT developers to design semantic-based IoT applications without having to learn semantic web technologies [28]. Such templates are based on a set of interoperable ontologies, datasets and rules. The process has been done manually. An extension of this work would be to automatize the process to automatically generate and combine such interoperable SWoT templates to ensure interoperability among applications.

Moreover, the M3 framework deals with the challenges provided by IERC AC4 explained in section II-D:

- Challenge 1: A unified model to semantically annotate IoT data is addressed with the M3 framework component called M3 language [6] implemented as an extension of the W3C Semantic Sensor Networks ontology .
- Challenge 2: Reasoning mechanism is addressed with the M3 framework component called Sensor-based Linked Open Rules (S-LOR), a dataset of interoperable rules to deduce new knowledge from IoT data [29].
- Challenge 3: Linked data approach is addressed with the M3 interoperable domain knowledge [28].
- Challenge 4: Horizontal integration with existing applications with the M3 framework component called Semantic Web of Things (SWoT) generator which enables combining applicative domains [6].
- Challenge 5: Design lightweight versions for constrained environments is addressed with the M3 framework. Instead of using the Jena semantic web framework, the AndroJena library has been used [30].
- Challenge 6: Alignment between different vocabularies is addressed with the M3 interoperable domain knowledge extracted from the Linked Open Vocabularies for Internet of Things (LOV4IoT) dataset [6].

C. Towards a collaborative Publication of Legacy Ontologies

Some ontologies very relevant for IoT are kept in silos by the owners and do not follow some best practices in their design. LOV4IOT platform references almost 300 ontologies that fall into that category. To overcome the issue, we propose to use a collaborative approach using Github for modeling the ontologies and publish them using PURL system under the URI `http://purl.org/iot/vocab/{name_ontology}`. For instance, name_ontology is m3-lite with the

Requirement	Description	Tools
Ontology publication (formats, serialization)	Did you validate the syntax of your ontology? Does your ontology follow an unified language/nomenclature to describe and semantically sensor data Did you correctly use the W3C Semantic Sensor Network (SSN) ontology?	Oops, TripleChecker, RDF Validator, OWL validator M3 language/ nomenclature M3 ontology? W3C SSN validator
Metadata for vocabulary	Is your ontology referenced on LOV? Does your ontology follow LOV recommendation? Did you add ontology metadata to explain the purpose of the ontologies?	LOV recommendations, OMV vocabulary
Ontology quality	Did you provide documentation attached to your ontology? Is your ontology deferenceable? Did you follow tutorials and methodologies to design ontologies?	SpecGen, Neologism and Parrot Vapour Noy et al. [3], NeON [11]
Ontology and dataset reuse	Did you try to reuse the existing ontologies or datasets catalogues? or from semantic search engines? Are your ontology and dataset referenced on such tools? Is your ontology shared online?	LOV, LOV4IoT, Ready4Smartcities, LOD, CKAN Watson, Swoogle
Namespace	Did you choose a good namespace? Did you check that your namespace is available? Do you ensure the sustainability of the namespace?	Prefix.cc PURL

TABLE I. BEST PRACTICES RECOMMENDATIONS FOR IOT

following namespace http://purl.org/iot/vocab/m3-lite#. PURL enables keeping always the same namespace whatever where the ontology is hosted.

The work has already started at https://github.com/LOV4IoT/vocabs. The goal is to republish all the legacy ontologies under the PURL.org namespace using redirection to the Github location.

V. CONCLUSION AND FUTURE WORK

In this paper, we applied semantic web methodologies and best practices to the Internet of Things. To the best of our knowledge, we are the first work bringing together the semantic web methodologies to IoT and going beyond the IERC AC4 by proposing requirements, best practices and referencing concrete methodologies and tools. Moreover, we applied such best practices to three use cases: M3 framework, FIESTA-IoT EU project and a collaborative publication of legacy ontologies.

Designing such methodologies is an essential step to reuse existing domain knowledge and ease the interoperability of semantic-based IoT projects, testbeds, experiments, services and applications which is the main purpose of the FIESTA-IoT EU project. As a future work we will provide a validator to check that ontologies are compliant with FIESTA-IoT requirements. Another challenging step would be to automatically extract the domain knowledge available in ontologies, datasets and rules and make it interoperable.

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