A Survey and Analysis of Ontology-Based Software Tools for Semantic Interoperability in IoT and WoT Landscapes

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***Abstract*—The current Internet of Things (IoT) ecosystem consists of non-interoperable products and services. The Web of Things (WoT) advances the IoT by allowing consumers to interact with the IoT ecosystem through the open and standard web technologies. But the Web alone does not solve the interoperability issues. It is widely acknowledged that Semantic Web Technologies hold the potential of achieving data and platform interoperability in both the IoT and WoT landscapes. In this context, the paper attempts to review and analyze the current state of ontology-based software tools for semantic interoperability.**

***Keywords*—Internet of Things; Semantic Web of Things; Semantic Web Technologies; Semantic Interoperability; Ontology Validation; Ontology Engineering.**

I. Introduction

Data generated by the Internet of Things (IoT) devices is communicated, processed and stored in many different and sometimes non-standardized formats. As a result, there is a lack of a uniform way to describe IoT data meaning and context. IoT data interpretation is often challenged by inconsistencies, non-standard naming conventions and vocabularies. Current software tools provide very limited descriptors to enable us to understand any high-level meaning of data. A time-consuming normalization effort is required before the collected IoT data can be effectively used to generate business value. For this reason, **semantic interoperability** has recently gained attention in academia and industry. The concept is well studied within the current Semantic Web landscape. Researchers have started to study the application of semantic interoperability principles applicable to the IoT and Web of Things (WoT) landscapes.

There are four levels of interoperability: (1) technical, (2) syntactic, (3) semantic, and (4) organizational according to IERC AC4 (European Research Cluster on the Internet of Things) [1], [2], [3]. Technical and syntactical interoperability were the main concerns in research and development the recent years. AIOTI Working Group 3 is dedicated to IoT standardization and has confirmed that one of the most important topic is on the semantic interoperability[1]. **Semantic Interoperability for the Web of Things** has been recently published highlighting the main interoperability issues [4]. However, **cross-industry semantic interoperability**[2] does not mention the *organizational interoperability* as introduced by IERC AC4 [2], [3]. They follow the Conceptual Interoperability Model (CIM) which is less detailed compared to IERC AC4.

From the given landscape, we aim to perform an analysis of the current literature regarding semantics-based projects for the IoT, WoT and Smart City. From the study, the key challenge appears to be on how to ensure semantic interoperability among the existing IoT projects, platforms and ecosystems given that more than 380 ontology-based (IoT) projects already exist [5], [6].

In this paper, we are mainly focused on surveying tools that - (i) aim to achieve semantic interoperability and (ii) are easy to integrate on IoT application development. These tools typically have following requirements.

- Minimal software setup effort is required. The tools are based on web APIs which avoid any versioning issues and interoperability issues.
- Tools to improve ontologies to encourage their reuse to ensure semantic interoperability.

The paper is structure as follows: Section II reviews software tools and ontologies to ensure semantic interoperability. Section III introduces ontology catalogues relevant for smart cities, IoT and WoT. Section IV presents the related work. Section V provides a set of criteria to classify and compare software tools. Section VI explains the implementation of the integration of the tools explained previously. Section VII evaluates our contribution by applying software tools on IoT ontology. Finally, the research contribution is concluded in Section VIII.

II. Semantic Interoperability Software Tools

This section introduces software tools to ensure semantic interoperability: (i) data validation tools for IoT in sub-section II-A and (ii) the need of ontologies in sub-section II-B.

A. Data Validation Tools for IoT

To the best of our knowledge, we have only found two software tools to validate RDF datasets compliant with a specific ontology designed for IoT:

[1] https://ec.europa.eu/digital-single-market/en/alliance-internet-things-innovation-aioti

[2] http://www.embedded-computing.com/semantic-interop/cross-industry-semantic-interoperability-part-one#

978-1-4673-9944-9/18/$31.00

- **SSN Ontology Validation Service**[3] has been designed in the context of the CityPulse FP7 EU project to validate RDF dataset designed according to the SSN V1 ontology [7].
- **FIESTA-IoT Ontology Validation Tool**[4] has been designed in the context of the FIESTA-IoT H2020 EU project to validate RDF dataset designed according to the FIESTA-IoT ontology [8] [9]. This tool is an extension of the previous one.

There are other such validation tools having the same functionality of checking semantic annotation compliant with a specific ontology such as GoodRelations Validator, SKOS Validator but they are out of the scope of this paper since they do not validate IoT-related datasets.

B. Ontologies and Semantic Modeling Tools

Several research projects including the EU Inter-IoT project[5] have investigated semantic technologies and consider ontologies as the basis of providing interoperability [10]. An adaptive ontology based model for interoperability for resource discovery in IoT is described in [11] while a unified IoT ontology for interoperability and federation of testbed is presented in [12].

Including Semantic Web Technologies (SWT) in the IoT systems increase processing time and code complexity. To address these concerns of software developers, IoT-Lite is proposed in [13]. It is a lightweight instantiation of W3C SSN ontology. IoT-Lite provides a compact mechanism to represent key IoT concepts for quick resource discovery and promotes interoperability. An experiment on sensor query RTT time using IoT-Lite and IoT-A model shows that - (i) the former outperforms the latter significantly and (ii) IoT-Lite is highly scalable and works well with high volume of sensors.

III. Semantic Interoperability with Ontology Catalogs relevant for IoT

This section is dedicated to existing ontology catalogs relevant for IoT and WoT. Ontology catalogs are concrete tools that encourage the reuse of ontologies. We have found four ontologies catalogs: **Ready4SmartCities, OpenSensingCity, LOV, and LOV4IoT**. We briefly describe and compare them. Our criteria to compare ontology catalogs are as follows:

- The *number of ontologies* referenced within the catalog.
- The *maintenance* of the ontology catalog: automatically, semi automatic or manually.
- *Quality* of the ontologies as explained in [14].
- *Ontology Collection*: the way new ontologies are being integrated within the catalog.
- *Ontology Metrics* to provide some statistics about ontologies (e.g., number of concepts or properties within the ontology).
- *Dataset* designed according to an ontology.
- *Integration with tools to improve the re-usability*. For instance, automatic documentation encourage the reuse of the ontology.

We mainly selected ontology catalogs based on OWL ontologies since OWL is a W3C recommendation and we focused on ontology catalogs supporting the activity of ontology reuse. Before comparing the catalogs, we give a brief description of each of them that we included in our survey.

A. Ready4SmartCities

Read4SmartCities is a project providing a catalog of ontologies relevant for building smart cities [15] [16]. The project is working on the alignment of such ontologies. The project does not seem maintained anymore, since it is written on the web site: latest revision July 2015. The project classifies ontologies according to the following criteria: (i) Ontology name, (ii) Online availability (RDF, HTML), (iii) Open License, (iv) Ontology language, (v) Syntax, (vi) Domain, and (vii) Natural Language (e.g., English). The Read4SmartCities catalog is focused on the following seven domains - energy, climate, weather, environment, building, occupancy, user behavior and characteristics. The catalog also covers five cross domain ontologies - temporal, organizational, statistical, spacial and measurement. Read4SmartCities catalog also checks ontology quality since is integrated with the Oops ontology validation tool [17].

The ontology collection has been done by reviewing the literature, the standardization, lookup ontology catalogues (LOV, Watson, and Swoogle), dataset investigation and stakeholders (contributors though an on-line form, populators to include new ontologies within the catalogue and metadata curators to review ontologies and improve them).

B. OpenSensingCity

Smart City Artifacts (SCA) provides a web portal[6] which collects information about the Smart Cities and provide web applications to visualize the list of existing projects, ontologies and datasets. This web portal is designed in the context of a French National ANR project, called OpenSensingCity. The SCA ontology has been designed to describe Smart City projects and artifacts [18]. A SPARQL endpoint is provided to query the RDF dataset designed according to the SCA ontology and which reuse ontologies (DC, doap, prov, foaf, sc, muto, fabio, dbowl, omv).

OpenSensingCity catalogue has been designed for the ANR-funded OpenSensingCity project which aims at fostering the usage of real time open data in the context of smart cities by providing operating tools including an ontology catalog for smart cities[7]. OpenSensingCity aims at helping application developers to take advantage of open data streams as easily as possible. The catalog references about 124 ontologies. Ontologies are classified by fifty-nine domains (e.g., energy, geography, sensors, transportation, tourism) and tags[8]. When clicking

[3] http://iot.ee.surrey.ac.uk/SSNValidation/about.html
[4] http://certificate.fiesta-iot.eu/#/home
[5] http://www.inter-iot-project.eu/
[6] http://opensensingcity.emse.fr/scans/
[7] http://opensensingcity.emse.fr/scans/ontologies
[8] http://opensensingcity.emse.fr/scans/domainstags

on an ontology, statistics are provided (number of classes and properties, etc.), ontologies can be automatically visualized with WebVOWL [19], syntax validation with Triplechecker and ontology validation with OOPs.

C. Linked Open Vocabularies (LOV)

Linked Open Vocabularies (LOV) is a huge ontology catalog. We are focused on the *IoT tag*[9] which has been added to the LOV catalog [20] upon request by the LOV4IoT catalog. Recently, eighteen more ontologies have been referenced. A tag such as smart cities would be relevant to retrieve more easily relevant ontologies. For instance, by looking for the *city keyword* in LOV[10], only 4 ontologies have been found: km4city, gci, turismo and iso37120.

LOV provides an interface for contributors to suggest their own ontologies or other ontologies that might be aware of. To suggest the ontology and then being inserted within the catalog, a bot is checking some best practices such as ontology metadata description [21].

D. Linked Open Vocabularies for Internet of Things (LOV4IoT)

Linked Open Vocabularies for Internet of Things (LOV4IoT) references **391 ontologies**, most of the projects are referenced when they are related to an IoT applicative domain exploiting sensors and/or semantic web technologies. In this paper, we are focused on IoT ontologies and smart cities ontologies. LOV4IoT classifies ontologies according to the best practices as well. It provides a keyword search (browser search functionality) and a navigation mechanism (by domain) in a manually gathered collection of ontologies. Web services are also provided to select ontologies per domain which query the LOV4IoT RDF dataset. More information can be found on the LOV4IoT project[11].

The target audience is people involved in designing IoT and smart city applications or any domains already referenced within the catalog (e.g., building automation, health-care). The main difference with other ontology catalogs is that it provides the ontology best practices status and reference research articles introducing or explaining the ontology. LOV4IoT is innovative in the way that it provides the structured state of the art as a tool for ontology practitioners. Numerous ontologies cannot be automatically suggested to the LOV catalog due to the lack of ontology metadata for instance.

According to the ontology library survey from d'Aquin et. al. "*the libraries where administrators are the only ones making decisions on what to include, usually do not have well defined requirements*"; within LOV4IoT, ontologies are included since they are related to IoT topic, but ontologies have also been classified according to their best practices learnt from the LOV community.

The LOV4IoT has an impact in encouraging best practices in various communities not familiar yet with ontology best practices. For this reason, a set of concrete tools have been studied in Section V to later automatically improve any ontologies referenced within ontology catalogs.

[9]http://lov.okfn.org/dataset/lov/vocabs?tag=IoT

[10]http://lov.okfn.org/dataset/lov/vocabs?q=city

[11]htpp://lov4iot.appspot.com

IV. Related Work

The **EGM White paper** [22] introduces several relevant validation tools including Fluent Editor, Infovore, MoKI, QSKOS, Eyeball, OWL Validator, RDF Validator, RDF Distiller and Good relations validator. Further, the paper explains a tool to validate RDF datasets designed according to specific ontologies. The tool checks lexical validation, syntactic validation and semantic validation.

A survey about semantic interoperability from Ganzha et. al. [23] discusses about the most popular ontologies by focusing on IoT, sensor, (e/m) Health and transportation or logistics ontologies. The main shortcoming of the paper is that the authors do not introduce at all the existing ontology catalogs for IoT and smart cities. The authors claim that more work is needed to achieve semantic interoperability. From our point of view, there is a need to define a set of best practices for ontologies to later automatically improve ontologies. No tools have been provided to facilitate the access to all ontologies mentioned in the paper. What is also missing in the paper, is a set of tables to compare ontologies within the same domain according to the concepts covered.

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 [3] [2]. They mention the need to overcome the following challenges: (i) a unified model to semantically annotate IoT data, (ii) reasoning mechanisms, (iii) linked data approach, (iv) horizontal integration with existing applications, (v) design lightweight versions for constrained environments, and (vi) alignment between different vocabularies. IERC AC4 does not reference concrete tools encouraging - (i) semantic web best practices, (ii) the use of methodologies to ensure interoperability among ontology-based IoT applications, and (iii) reuse of the domain knowledge already designed. For this reason, a set of concrete tools to encourage semantic interoperability, reuse and ontology improvement is provided in Section V.

Serrano et al. [24] provide a set of validation tools or relevant work regarding semantic interoperability - Hyperthing, Neon, OWL validator, OQuare, OntoClean, OnToology, vapour, oops, W3C RDF validator, jena eyeball, ontoCheck, OntoAPI, OntoMetric, Prefix. However, there is a lack of guidance to pick the tool fitting our needs.

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: (i) any methodologies to reuse exiting ontologies, (ii) concrete tools to validate ontologies, (iii) explain how to evaluate an ontology, and (iv) how to develop a well-designed ontology.

V. Studies on Validation Tools to evaluate ontologies

To validate ontologies, we define the following criteria, and some software tools satisfying the criteria, the synthesis table I is also available. The criteria are as follows:

1) **Serialization**. The current ontology format supported is OWL since it is a W3C recommendation.

2) **Syntactic validation** is necessary during the compilation and the execution of ontologies with libraries to be proceed by the ontology validation workflow. Tools such as OWL Manchester and Triple Checker can be used.
3) **Interlinking** enhances interoperability, integration and browsing among ontologies. Ontology matching tools can be employed such as LogMap[12].
4) **Documentation** encourages the re-usability of the ontology. Parrot and LODE have been chosen since it provides a web service to provide an automatic documentation. More and more tools are being designed to provide such criteria to ease the task of developers (e.g., Widoco) [25].
5) **Visualization** eases the learning phase by providing a fast understanding of the ontology which encourages the re-usability of the ontology. WebVOWL tool is integrated to provide an automatic ontology graph visualization.
6) **Discoverability** can be ensured when following LOV ontology metadata. It is required to suggest the ontologies on the LOV catalog or being referenced by semantic search engines. Deferenceable URI can be tested with Vapour.
7) **Improve Ontology Design** can be done with Oops which detects numerous ontology pitfalls.

We classify in Table I tools that we have already tested to evaluate ontologies. For instance, the WebVOWL tool can be used to provide automatic ontology graph visualization. The Parrot tool can be used for automatic documentation, etc. In the table I, the first column is dedicated to the tool name, the second column to the criteria satisfied, the third column to explain if the tool is maintained or not and the last column is dedicated to the research publication. We have considered the tools reusable when they are providing Web services, APIs or code and documentation. The web services are easier to integrate when developing the workflow, but the implementation depends on the web reliability and on the maintenance of the web services. Sometimes the servers hosting the web services are down or when new versions are released, it might have an impact on the implementation. When the tools are open-source, we can avoid such dependencies, but it is more time-consuming to get into the code based on heterogeneous languages and technologies. This is another reason demonstrating the need to help non experts in the validation process. In Table I, within the maintained column: *High* means that the community behind the tools is reactive when issues arise such as server down, fixing bugs, answering questions or adding new functionalities and *Medium* means that the tool might be frequently down, due to server issues.

To ease the ontology improvement of ontologies with the set of tools introduced above, Table II provides all GUIs URL for each tool. This table is convenient for ontology engineers willing to improve their ontologies.

To automatically improve ontologies with the set of tools introduced above, Table III provides all APIs and web services URL for each tool. This table is convenient for developers willing to atutomatically integrate the tools within projects. For instance, this table has been used by the PerfectO project which integrate the tools [13] to automatically evaluate and or improve all ontologies from the LOV4IoT catalogue.

Table IV is convenient for developers willing to extend and/or improve the validation tools to add more functionalities. To achieve this, developers need to be familiar with the language (e.g., Java, PHP) used to develop the software and go deeply into the code to be able to improve the software. The programming language used to develop the software is given in the second column in Table IV. Most of the code is hosted on GitHub and Bitbucket collaborative environment development, the URL of the code is given in the third column in Table IV.

The tools presented in those tables have been integrated within the PerfectO project explained in the next section VI.

VI. Implementation: Testing Availability of Tools

We have implemented a Javascript-based tool accessible online[14] which automatically checks the status of validation tools since we realized that frequently some tools are down. For instance, in December 2016, three tools were down: Oops, Vapour and OWL Manchester. This tool encourages the maintenance of current tools to achieve semantic interoperability. The tools is also relevant for developers when they are integrated the tools within their project.

The web service `http://perfectsemanticweb.appspot.com/perfecto/statusTool/?url={url}` has been implemented in Java and with the Jersey web service library. The web service returns the result OK or NOT OK. For instance, the web service URL is tested with Vapour tool[15]. Using AJAX technology, the web service is queried and the result returned by the web service is parsed in JavaScript and displayed in the HTML web page as depicted in Figure 1.

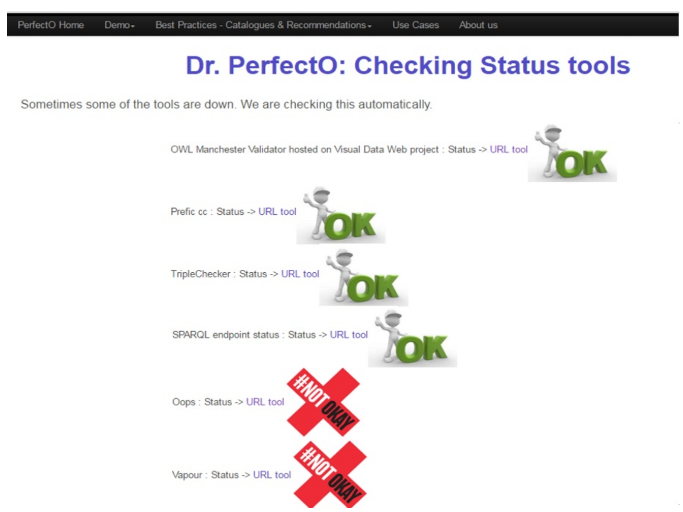

Fig. 1. Automatically checking the accessibility of validation tools

[12] https://www.cs.ox.ac.uk/isg/projects/LogMap/

[13] http://perfectsemanticweb.appspot.com/?p=ontologyValidationLOV4IoT

[14] http://perfectsemanticweb.appspot.com/?p=availability_tools

[15] http://perfectsemanticweb.appspot.com/perfecto/statusTool/?url=http://linkeddata.uriburner.com:8000/vapour

Tools	Validation Criteria	Maintained	Paper
Jena	Serialization - Syntactic	Yes - High	Yes [26]
Oops	Ontology Design	Yes - High	Yes [17]
Triple Checker	Syntactic	Yes - High	Not found
LOV	Discoverability	Yes - High	Yes [20]
Parrot	Documentation	Yes	Yes [27]
LODE	Documentation	Yes	Yes [28]
WebVOWL	Visualization	Yes - High	Yes [19]
Vapour	Discoverability	Yes - Medium	Yes [29]
OWL Manchester	Syntactic	Medium	Not found

TABLE I. REUSED TOOLS FOR THE IMPLEMENTATION OF PERFECTO

Tools	GUI URL
Jena	https://jena.apache.org/
Oops	http://oops.linkeddata.es/
Triple Checker	http://graphite.ecs.soton.ac.uk/checker/
LOV	http://lov.okfn.org/dataset/lov/
Parrot	http://ontorule-project.eu/parrot/parrot
LODE	http://www.essepuntato.it/lode
WebVOWL	http://vowl.visualdataweb.org/webvowl.html
Vapour	http://linkeddata.uriburner.com:8000/vapour
OWL Manchester	http://visualdataweb.de/validator/

TABLE II. TOOLS AND GUIS USED TO IMPROVE ONTOLOGIES

Tools	Web Service/API URL
Jena	Jena librarieshttps://jena.apache.org/download/index.cgi
Oops	Web service: http://oops.linkeddata.es/response.jsp?uri=
Oops	RESTful Web Service documentation: http://oops-ws.oeg-upm.net/
Triple Checker	Web Service: http://graphite.ecs.soton.ac.uk/checker/?uri=
LOV	Web Service API Documentation http://lov.okfn.org/dataset/lov/api
Parrot	Web Service: http://www.ontorule-project.eu/parrot/parrot?documentUri=
LODE	Documentation: http://www.essepuntato.it/lode/
WebVOWL	Web service: http://vowl.visualdataweb.org/webvowl/#iri=
Vapour	Web service: http://linkeddata.uriburner.com:8000/vapour?uri=
OWL Manchester	Not found yet

TABLE III. TOOLS AND WEB SERVICE TO AUTOMATICALLY IMPROVE ONTOLOGIES

Tools	Programming Language	Code Available
Jena	Java	GitHub: https://github.com/apache/jena
Oops	Not found yet	Not found yet
Triple Checker	PHP	GitHub: https://github.com/cgutteridge/TripleChecker
LOV	GUI with Javascript	GitHub:https://github.com/pyvandenbussche/lov
LOV	Back end with Java	GitHub:https://github.com/pyvandenbussche/lovScripts
Parrot	Java	Bitbucket: https://bitbucket.org/fundacionctic/parrot/wiki/Home)
LODE	Java	GitHub:https://github.com/essepuntato/LODE
WebVOWL	JavaScript	GitHub: https://github.com/VisualDataWeb/WebVOWL
Vapour	Java	BitBucket: https://bitbucket.org/fundacionctic/vapour/wiki/Home
OWL Manchester	PHP	GitHub: https://github.com/rollxx/OWL

TABLE IV. REUSED TOOLS FOR THE IMPLEMENTATION

The next Section VII evaluates the ontologies referenced within the LOV4IoT ontology catalog (introduced in Section III) with the tools presented in Section V.

VII. EVALUATION: APPLYING TOOLS ON IOT ONTOLOGIES

An evaluation has been thoroughly done with **27 IoT or smart cities ontologies** from LOV4IoT which have been tested with **6 validation tools** mentioned in the table (Parrot, WebVOWL, Oops, TripleChecker, LODE and Vapour). The evaluation is accessible online[16]. The evaluation demonstrates that there are no ontologies which can be successfully loaded with all of the tools and shows that numerous errors are encountered. LODE is preferred compared to Parrot since more ontologies can be automatically documented.

We have firstly validating ontologies that have been developed within projects that we have been involved in such as SEAS, OpenSensingCity and FIESTA-IoT, then the evaluation has been extended to smart cities and IoT ontologies (e.g., VITAL, KM4city).

Lessons Learnt: We shared the lessons learnt to fix the issues in a "guide for dummies" accessible online[17]. We are highly encouraging validation tools to provide web services but they need to be highly maintained to ease the development and the automatic ontology improvement. Otherwise, the main issue is that the PerfectO demonstrators rely on web services which can be down.

VIII. CONCLUSION

In this paper, we have been mainly focused on investigating software tools to achieve semantic interoperability with a focus on tools to improve or evaluate ontologies. We have in mind to improve the design of the PerfectO [18] project and e-learning

[16]http://perfectsemanticweb.appspot.com/?p=evaluation_lov4iot_perfecto

[17]http://perfectsemanticweb.appspot.com/?p=documentation

[18]http://perfectsemanticweb.appspot.com/

platform to support semantic interoperability additional concrete software tools. Semantic Web best practices are mainly known by the semantic web community, but not yet by other communities (e.g., IoT and WoT). For this reason, as a first step, PerfectO classifies and references tools that can be reused to encourage semantic interoperability. For instance, we share this knowledge in an innovative way through mindmaps and guide for dummies, and a set of interactive tools to improve and evaluate ontologies.

The main benefit is to reduce the learning curve of discovering all available tools and to ease the task of the developers to achieve semantic interoperability. The PerfectO platform is available and constantly updated. All of the tool URLs and publications referenced are also available on the platform in a more interactive manner.

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