IoT Semantic Interoperability: A Systematic Mapping Study

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Abstract: The Internet of Things (IoT) is a paradigm in which the Internet connects people and the environment using devices and services that are spread in the user daily routine. In this scenario, different agents, devices and services are able to exchange data and knowledge using a common vocabulary or mappings that represent and integrate heterogeneous sources. This semantic interoperability is facilitated by the Semantic Web that provides consolidated technologies, languages and standards, offering data and platforms interoperability. In this context, this work reviews and analyzes the state-of-the-art of IoT semantic interoperability, investigating and presenting not only which Semantic Web technologies are employed but also the challenges that support the studies in this area of research.

1 INTRODUCTION

The Internet of the Things (IoT) emerged as a paradigm in which people and things exchange information anytime, anywhere, with any device. In the IoT environment, sensors are able to monitor people and the environment, generating a large volume of data that can be consumed by different applications in different domains, e.g., cardiac monitoring, smart homes, and smart cities management.

Almost a hundred new IoT platforms entered the global market in 2016, increasing the total number to about 450 (Ganzha et al., 2017b). It is forecasted that about 50 billion devices will be connected to the Internet by 2020 (Evans, 2011). In this scenario of increasing number of distributed and heterogeneous devices, there is a demand for technologies that support interoperability, providing means of representation, discovery and integration.

The use of higher-level abstractions, i.e., semantic information extracted from data, is considered an attractive solution to minimize heterogeneity employing common and shared representations. In this context, semantic interoperability can be defined as the ability of different agents, services, and applications to exchange information, data and knowledge both on and off the Web (W3C, 2018).

Within IoT environments, where data are heterogeneous, dynamic and distributed, mechanisms of semantic interoperability are necessary to provide interoperability in a flexible way, allowing systems to understand the collected data. Through Semantic Web standards, semantic interoperability agents can use shared vocabularies to exchange information between platforms (W3C, 2018).

The European Research Cluster on the Internet of Things (IERC) released a set of best practices and recommendations for semantic interoperability (Serrano et al., 2015). However, this study examines the challenges encountered in IoT semantic interoperability, but does not show which Semantic Web technologies have been adopted and what are the limitations of current approaches.

Rigorous research that collect and present the technologies and challenges related to semantic interoperability in the context of IoT has not been found in the literature so far. In this perspective, this paper presents a systematic mapping study (Kitchenham et al., 2010) about semantic interoperability in the context of IoT with the purpose of defining the state-of-the-art, emphasizing which and how Semantic Web technologies have been used and what are the current limitations and challenges faced in the field.

The remainder of this paper is structured as follows: Section 2 provides the background for the paper with a brief explanation about Semantic Interoperability and IoT Semantic Interoperability; in Section 3, the process of systematic mapping study applied to this work is described; in Section 4, the results obtained from the systematic mapping study are presented and analyzed based on the research questions; Section 5 addresses the study limitations; and, in Section 6, we discuss the findings that emerged from the results and present our final considerations.

2 IOT SEMANTIC INTEROPERABILITY

Semantic Interoperability refers to the ability of two or more computational systems to exchange information through a shared meaning that can be interpreted automatically and correctly. Thus, interoperability at the semantic level requires a common understanding of the meaning of the content being exchanged, preserving the semantics of the original message.

Despite the adoption of shared ontologies and vocabularies that allow the representation and sharing of meaning, there is still a need to maintain the intrinsic information from data sources, preserving domain knowledge and facilitating data maintenance. Another issue of semantic interoperability is related to the maintenance of shared ontologies, which requires a centralized and periodic updating mechanism. Finally, the software infrastructure based on shared ontologies still has problems related to scalability, a well-known open question of the Semantic Web.

The data generated by IoT devices in different formats hinders the interoperability of applications and platforms that can not interpret the data, acting inconsistently on the received information. In this context, there is a need for using common vocabularies capable of describing the meaning of data in this environment. Semantic interoperability is a concept only recently studied in the context of the Semantic Web. It has gained prominence in both academia and industry, that have been applying its principles to IoT scenarios (Gyrard et al., 2018). In order to implement solutions that minimize the interoperability problems found in the IoT environment, the community began to adopt Semantic Web technologies, standards, languages, and approaches for modeling (Serrano et al., 2015) and integrating ontologies.

Semantic Web technologies provide the technical and operational structure as well as the means to facilitate semantic interoperability. This can be achieved by either modeling new ontologies or reusing existing ontologies by semantically integrating (aligning) different vocabularies with equivalences between their classes and properties (W3C, 2018).

However, the use of these technologies still faces challenges in terms of sharing the published ontologies and correct and consistent reuse. More specifically, there are several requirements and challenges for semantic interoperability in IoT that should be addressed by other tools, for instance: integration of distributed data sources, a unified semantic annotation model of IoT data, management of sensors based on composition and fusion of streams from various data sources, discovery of sensors and data sources for application requests according to their capabilities, analysis and reasoning on semantic level resources through reasoners and visualization tools (Serrano et al., 2015).

In spite of this effort to elicit the limitations of semantic interoperability approaches and to describe auxiliary tools, IERC does not recommended Semantic Web approaches, tools or methodologies to: (i) Semantic Web methodologies to model IoT ontologies, (ii) reuse of existing ontologies and (iii) validation tools for ontologies (Gyrard et al., 2018).

Gyrard and Serrano (2015) proposed a unified semantic mechanism, presenting technologies for the construction of interoperable systems in the domain of IoT and Smart Cities. One of the main challenges highlighted by the authors is to unify models, vocabularies and ontologies to semantically annotate the data. The authors cite the LOV4IoT[1] catalog of ontologies and the need for approaches and tools that provide a unified semantic model aligned with the existing vocabularies provided by IoT platforms. The authors extend the M3 ontology (Gyrard et al., 2015a), which is already aligned with ontologies provided by IoT platforms, to address the weaknesses related to ontologies (Gyrard and Serrano, 2015). However, their work does not discuss limitations related to best practices for ontology modeling, reuse and matching.

These and other limitations of current approaches encourage work in this area to develop studies that address these gaps, pointing out tools and solutions that drive the adoption of semantic interoperability mechanisms in the IoT scenario.

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[1] http://lov4iot.appspot.com

3 THE RESEARCH METHOD: SYSTEMATIC MAPPING STUDY

A systematic mapping study (Kitchenham et al., 2010) is a means to identify, evaluate and interpret relevant work concerning a research question or a phenomenon of particular interest. It is assumed that the results of using a controlled process and a formal bibliographic research benefit the research community by listing topics of interest, gaps, and challenges. Associated to our systematic mapping study, we also performed snowballing procedures (Wohlin, 2014), a systematic research approach that uses backward (i.e., checking the references of the studies) and forward (i.e., checking papers that cited the studies) to identify additional papers, in order to expand the set of works considered in our research.

The research questions for a systematic mapping study are more general, including questions of which sub topics were addressed and which sub topics have sufficient studies for detailed review.

We have followed a process based on guidelines for performing systematic literature reviews by Kitchenham and Charters (2007) that is shown in Fig 1. The process consists of three main activities that are detailed in the following sections: planning (Section 3.1), conducting (Section 3.2), and reporting (Section 4) . The planning activity aims to define the protocol, organizing the research steps. In our work, the conducting activity was executed in two distinct phases. First, we selected the primary studies using the digital libraries. After, we complemented the set of articles with the snowballing procedure (Wohlin, 2014).

3.1 Planning: Protocol Definition

The aim of the planning phase is the definition of a review protocol. The systematic review protocol (Kitchenham, 2004) defines the research questions to be answered, the sources, and how papers are selected. Thus, for the execution of this work, a protocol was developed. Its main topics are described in the following.

3.1.1 Research Questions

The objective of our study was to identify the Semantic Web technologies and the challenges to ensure semantic interoperability in the context of IoT. Therefore, we have established the following research questions:

RQ1: What Semantic Web technologies have been proposed to ensure semantic interoperability in the context of IoT?

RQ2: What limitations and challenges to ensure semantic interoperability in the context of IoT have been described by these proposals?

3.1.2 Search String

Based on the PICO (P - patient, problem or population; I - intervention; C - comparison, control or comparator; O - outcome) approach (Pai et al., 2004) and on the key terms of the research field, the following search string was elaborated: *((“internet of things” OR “iot” OR “web of things” OR “wot”) AND (“semantic interoperability” OR “semantic integration” OR “ontology integration”) AND (“state of the art” OR survey OR problem OR “lessons learned” OR middleware OR challenge OR application)).*

The term *semantic integration* was added as part of a broader view of semantic interoperability as, driven by semantic integration, services and tools can become interoperable (W3C, 2018).

3.1.3 Research Sources

To obtain the primary studies, we have used two methods: database search and snowballing. For the database search, we selected the most relevant digital libraries in Computer Science and Engineering (Chen et al., 2010): (a) ACM Digital Library[2]; (b) IEEE Xplore Digital Library[3]; and (c) Science Direct[4]. Regarding the snowballing approach, we used both the backward and forward procedures (Wohlin, 2014).

3.1.4 Study Selection Criteria

We have defined the following selection criteria in order to select the most suitable studies:

SC1: The study must be written in English;

SC2: The selected article must be available on the Web;

SC3: The study should present initiatives related to semantic interoperability in the IoT domain, covering at least one of the research questions.

No restriction was defined based on the type of works, which means that all kinds of studies, such as conference and journal papers, short and full papers, were chosen. They were processed in the same way considering the above selection criteria. There is also no restriction on the publication years of the papers.

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[2] http://dl.acm.org

[3] https://ieeexplore.ieee.org

[4] https://www.sciencedirect.com

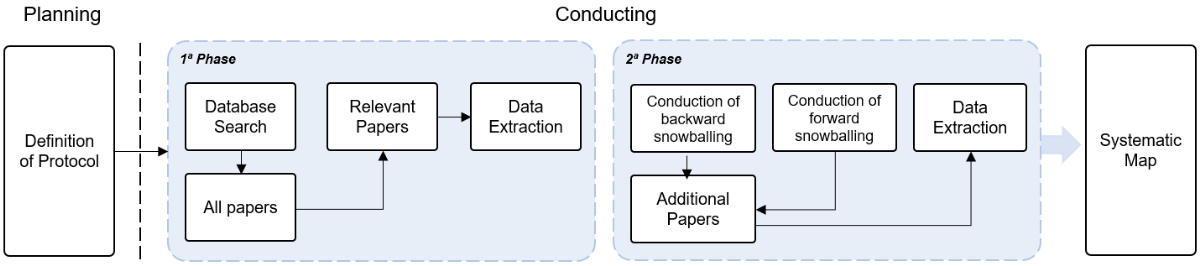

Figure 1: The systematic mapping process.

Table 1: Number of papers eliminated by selection criteria

Selection criteria	Number of papers
SC1	0
SC2	13
SC3 - research question (RQ1)	134
SC3 - research question (RQ2)	10

3.2 Conducting

This activity was performed in two phases. The first phase is related to the conduction of database search, which aims to find relevant papers in digital libraries using well-defined search strings. The second phase is related to the conduction of backward snowballing, i.e., seeking papers from reference lists of the papers identified during the first phase, and the conduction of forward snowballing, i.e., seeking papers that had cited the papers found during the first phase of the activity. The outcome of the conducting activity phases are described in the following.

3.2.1 Conducting: first phase

In this step, we searched for articles based on the defined protocol. The set of search strings was applied to the search engines: ACM, IEEE and Science Direct. This stage retrieved 169 papers, 36 from the IEEE, 13 from the ACM and 120 from Science Direct. After the application of the selection criteria, we rejected 157 papers (shown in Tab. 1) and 12 papers remained. Finally, we performed data extraction for each selected paper, extracting approaches, technologies and tools aimed at the modeling, reuse and validation of ontologies and the challenges in their adoption.

3.2.2 Conducting: second phase

The snowballing procedure is usually performed with a starting set of papers. In our study, the starting set corresponded to the 12 papers selected in the first phase of the conducting activity. Moreover, we performed backward and forward snowballing to find additional papers. In the end, we obtained four more articles for data extraction.

4 RESULTS OF THE SYSTEMATIC MAPPING STUDY

This systematic mapping study was performed in December, 2018. We have found 16 papers (shown in Tab. 2) that answer the defined research questions. All of them present approaches that use Semantic Web technologies and discuss limitations and challenges to ensure IoT Semantic Interoperability. Only two papers (Ganzha et al., 2017b,c) propose semantic integration approaches, presenting steps such as a mapping among ontologies.

Moreover, these papers cover different domains of application such as health, transport and logistics (Ganzha et al., 2016), geospatial data (Ganzha et al., 2017c) and water management (Howell et al., 2018). The results of this systematic study are discussed in details in Section 4.1, which discusses the results related to the Semantic Web technologies proposed for IoT Semantic Interoperability and proposes a list of methods and tools suitable for IoT Semantic Interoperability, and Section 4.2, which presents the limitations and challenges to ensure IoT Semantic Interoperability found in the proposed approaches.

4.1 Semantic Web technologies proposed for IoT Semantic Interoperability

Semantic Web technologies provide knowledge sharing and reuse mechanisms (Simperl, 2009), which facilitate semantic interoperability. However, the use of Semantic Web technologies for semantic interoperability approaches needs to follow the Semantic Web community recommendations in order to boost the

Table 2: IoT Semantic Interoperability approaches

Aspects	Approaches
Model ontologies	Gyrard et al. (2015b), Agarwal et al. (2016), Gyrard and Serrano (2016), Strassner and Diab (2016), Gyrard and Serrano (2015), Ganzha et al. (2017a) , Howell et al. (2018)
Reuse ontologies	Gyrard et al. (2018), Gyrard et al. (2015b), Gyrard and Serrano (2016), Gyrard et al. (2018), Strassner and Diab (2016), Rhayem et al. (2017), Ganzha et al. (2016), Barnaghi et al. (2012), Ganzha et al. (2017b), Ganzha et al. (2017c),Gyrard and Serrano (2015),Chindenga et al. (2016) Nagib and Hamza (2016)
Ontology validation tools	Gyrard et al. (2018)

reuse of existing knowledge, avoiding the construction of heterogeneous models that hinder interoperability. Semantic interoperability also refers to other levels and tasks, such as semantic mappings and reasoning. However, these issues were not raised by the articles found during this study.

In order to reply RQ1, during the data extraction process, we identified approaches and tools that: (i) Semantic Web methodologies to model IoT ontologies, (ii) reuse existing ontologies, and (iii) ontology validation tools.

4.1.1 Semantic Web methodologies to model IoT ontologies

Following the best practices discussed by Gyrard et al. (2015b), we found methodologies that encourage the modeling and reuse of ontologies, for example, the ones by Noy et al. (2001) and Suárez-Figueroa (2010), called NeON, which provide tutorials with guidelines for developing well-designed ontologies. The work of Noy et al. (2001) is also used as a methodology for ontology construction by Agarwal et al. (2016), which also proposes an ontology available online, through a open source ontology documentation tool called Live OWL Documentation Environment (LODE)[5].

The proposal of Gyrard and Serrano (2016) presents a methodology for semantic interoperability applied to IoT and smart cities that adapts the NeON methodology to specific characteristics of IoT. Howell et al. (2018) applied the NeON methodology and adapted the existing semantic resources to the application of IoT aimed at the domain of water management. One of the goals of their work is to develop a reference ontology in the field.

There is a need to encourage best practices by developing ontologies (Gyrard et al., 2018), reusing existing ontologies as much as possible and aligning ontologies to increase interoperability, reducing heterogeneity between models and development time.

As discussed by Gyrard and Serrano (2015), limitations such as the lack of adoption of best practices can be solved with approaches presented here, such as the one of Noy et al. (2001) and NeON (Suárez-Figueroa, 2010), in order to define a unified model for modeling ontologies in IoT, see Fig 2.

4.1.2 Reuse existing ontologies

The first step in the reuse of existing ontologies is through catalogs (Gyrard et al., 2018) such as the Linked Open Vocabulary for Internet of Things (LOV4IoT), which referenced 448 ontologies relevant to IoT in May 2018 (Gyrard et al., 2015b; Gyrard et al., 2018). It includes a status field that indicates whether the ontology is shared online or follows the best practices, which is the main difference to other catalogs. As a catalog of ontology sharing and reuse, proposal (Gyrard and Serrano, 2016) also adopts the LOV4IoT.

There are other catalogs that aimed at the context of smart cities, for instance, Ready4Smartcities (Poveda-Villalón et al., 2014a), a catalog that integrates the OOPS (Poveda-Villalón et al., 2014b) ontology validation tool and the OpenSensingCity[6] catalog, which also provides ontologies in the context of smart cities, including the WebVOWL (Lohmann et al., 2014) visualization tool, OOPS and the TripleChecker[7] tool for ontology syntax validation (Gyrard et al., 2018).

The proposals of Gyrard et al. (2018); Gyrard et al. (2018) investigated relevants IoT catalogs, i.e., Ready4Smartcities, OpenSensingCity and LOV4IoT, presenting a methodology for enhancing catalogs of ontologies, supporting their maintenance.

Among the ontologies found in these catalogs the W3C Semantic Sensor Network (SSN) ontology is recognized as the standard for generically describing

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[5] http://www.essepuntato.it/lode

[6] http://opensensingcity.emse.fr

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

information in the IoT environment and some works have extended this ontology to applications of specific domains (Gyrard et al., 2015b; Rhayem et al., 2017). Any project that uses semantic technologies in IoT should extend the SSN ontology, adding the concepts needed to handle the application in the intended domain (Ganzha et al., 2016; Barnaghi et al., 2012). The choice of a consolidated ontology like SSN avoids the use of a set of ontologies that describe the same concepts (Strassner and Diab, 2016).

To facilitate the exchange of information between two or more IoT artifacts, ontological alignments (Ganzha et al., 2017b) can be used to translate messages between entities with different semantic representations of the domain of interest. Alignment of ontologies refers to the process of finding matches between two or more ontologies. To represent this alignment the INTER-IoT project develops its own INTER-IoT Alignment Format (Ganzha et al., 2017b,c), an XML representation inspired by the API Alignment (David et al., 2011) and to some extent by EDOAL[8].

Gyrard and Serrano (2015) have shown the importance of a catalog of ontologies (LOV4IoT in this case) to support the proposed unified semantic mechanism. Other catalogs for smart cities, described in this section, are important in this approach, such as Ready4Smartcities and OpenSensingCity. In addition, the authors cite the lack of ontology matching or alignment tools adapted for IoT ontologies. In this section, we described an approach that promises to overcome this limitation, called INTER-IoT Alignment Format, see Fig 2.

4.1.3 Ontology validation tools

To ensure that ontologies comply with best practices, it is necessary to introduce tools that validate its syntax, detecting undeclared elements or made available in an incorrect format (Gyrard et al., 2015b). The work of Gyrard et al. (2018) performed an evaluation of 27 ontologies for IoT and smart cities, available in the LOV4IoT catalog, using six validation tools, namely: Parrot[9], WebVOWL, Oops, TripleChecker, LODE and Vapour[10]. This evaluation concluded that there are ontologies that can not be loaded in all tools, revealing errors, suggesting LODE as preferred tool in comparison to Parrot due to the possibility of automatic documentation of more ontologies.

4.2 Limitations and Challenges

In order to answer RQ2, during the data extraction process, we extracted the limitations and challenges that the existing proposals face in order to ensure semantic interoperability in the context of IoT.

4.2.1 Semantic Web methodologies to model IoT ontologies

Initially, IoT data and knowledge engineering efforts focused on developing IoT data infrastructure by means of publication and data access, giving less attention to data processing and integration with existing applications (Barnaghi et al., 2012).

Inside the IoT community, each project, platform or application usually develops its own ontology (Gyrard and Serrano, 2015). Few studies use a methodology for ontology modeling (Agarwal et al., 2016; Gyrard and Serrano, 2016), making interoperability difficult and reducing the possibility of reuse (Gyrard et al., 2015b).

The Semantic Web community uses practices (Gyrard et al., 2014) that have not been followed in the IoT scenario (Gyrard and Serrano, 2015). It is noticed the absence of Semantic Web experts in the modeling of the ontologies found for this scenario. According to Ganzha et al. (2017a) the organizations that develop ontologies modeling approaches do not seek consensus, which is a social aspect that limits interoperability in the IoT environment and becomes a challenge.

Another aspect is related to the language and formalism in which the developed ontologies have been made available. The approach presented by Ganzha et al. (2017a) in the context of healthcare and logistics and transport does not have an ontology represented by Semantic Web languages such as RDF(S)[11] or OWL[12], impairing the sharing of ontologies and the ability to exchange information between agents and platforms. Nevertheless, ontologies can be written in different formalisms, some more expressive than others (Strassner and Diab, 2016). In domains like the ones described by Strassner and Diab (2016), data integration from a common vocabulary is difficult, because most available ontologies are either defined in UML artifacts or described in markup languages. It is required to normalize concepts between formal ontologies and implicit ontologies, making it a challenge for non-specialist users.

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[8] http://alignapi.gforge.inria.fr/edoal.html

[9] http://ontorule-project.eu/parrot/parrot

[10] http://linkeddata.uriburner.com:8000/vapour

[11] https://www.w3.org/RDF

[12] http://www.w3.org/OWL

4.2.2 Reuse existing ontologies

Some approaches present the use of ontologies in the IoT scenario (Agarwal et al., 2016), but they miss or have insufficient concepts for the measurements provided by the sensors, and many of these ontologies do not follow the best practices, thus, it is difficult to correctly interpret the concepts.

The reuse of existing standard domain ontologies and higher ontologies is suitable to unify high-level concepts in various applications and should be extended according to the intended application logic (Nagib and Hamza, 2016). The SSN ontology [13] presents itself as a good example of a higher ontology that contains classes focused on the concepts of sensors and observations.

However, one of the problems of semantic interoperability (Amato et al., 2011) is related to the adoption by many systems and approaches (Strassner and Diab, 2016) of a collection of ontologies or a set of data models to prototype an ontology that shares the meaning of context in a common vocabulary, resulting in the loss of intrinsic information of the data sources.

In the Semantic Web, this problem can be mitigated by using matching or alignment tools. However, according to Gyrard and Serrano (2015), the semantic level of class-to-class mapping used by ontology matching or alignment tools is not enough to describe the data in the IoT scenario, making it an open challenge.

Another aspect pointed out in Amato et al. (2011) concerns the maintenance of shared ontologies. In the IoT scenario, the catalogs of ontologies are used to minimize this problem, however, the maintenance of these catalogs is still a problem that deserves investigation (Gyrard et al., 2018; Gyrard et al., 2018). Finally, scavenging is also a key issue in this environment, where, according to Chindenga et al. (2016), practical mechanisms and implementations are needed to provide independent interoperability of manufacturers and suppliers of devices and services, ensuring efficient scalability of IoT.

5 THREATS TO VALIDITY

When conducting secondary studies, the findings made by the researchers, both in the selection of the studies and in the conclusions influence the result (Wohlin et al., 2012). Thus, in this section we present the threats to the validity of our study.

As threats to the validity of the results of the systematic mapping study carried out are: (i) bias in the selection of the studies analyzed; (ii) imprecision in the data extraction and (iii) how to classify and interpret data.

The selection of the analyzed studies followed the selection procedure of the primary studies, in which the search of the sources was applied, an initial set of studies was selected from the titles and abstracts of all papers. We also performed the snowballing process from the initial set of selected studies. After comparing the papers using the inclusion and exclusion criteria (Section 3.1), the selected papers were fully read and, again, faced with the criteria. The included articles were selected for data extraction.

In order to minimize the loss in data extraction, the advanced mode of search engines was used in all search sources. Papers that did not use the keywords defined in our search string in the title or abstract were not selected. Hence, papers that did not mention IoT were not listed in this paper. Finally, the data extraction was performed in pairs and, in the case of impass, the discussions were done with a third reviewer until a consensus was reached.

Regarding the data classification, it was based on limitations previously proposed in the literature, i.e., Semantic Web methodologies to model IoT ontologies, reuse of existing ontologies and validation tools for ontologies. Data extraction and classification were performed by the first author and reviewed by the third author.

6 FINAL CONSIDERATIONS

This paper presented a systematic mapping study that found 16 publications related to IoT Semantic Interoperability. These publications were analysed and we discussed their limitations and challenges, and how the existing technologies are relevant to the current state-of-the-art.

Before performing the systematic mapping study, we investigated the literature in search for secondary studies on IoT semantic interoperability. Since no secondary study was found on this research topic, we performed the systematic mapping study. The mapping results provided an overview of the research related to the investigated topic.

Regarding Semantic Web technologies proposed for IoT semantic interoperability, few approaches were found for ontology modeling. The works that adopted some approach needed to adapt some stages of the process to IoT characteristics. We observed that the lack of selection of the best practices rec-

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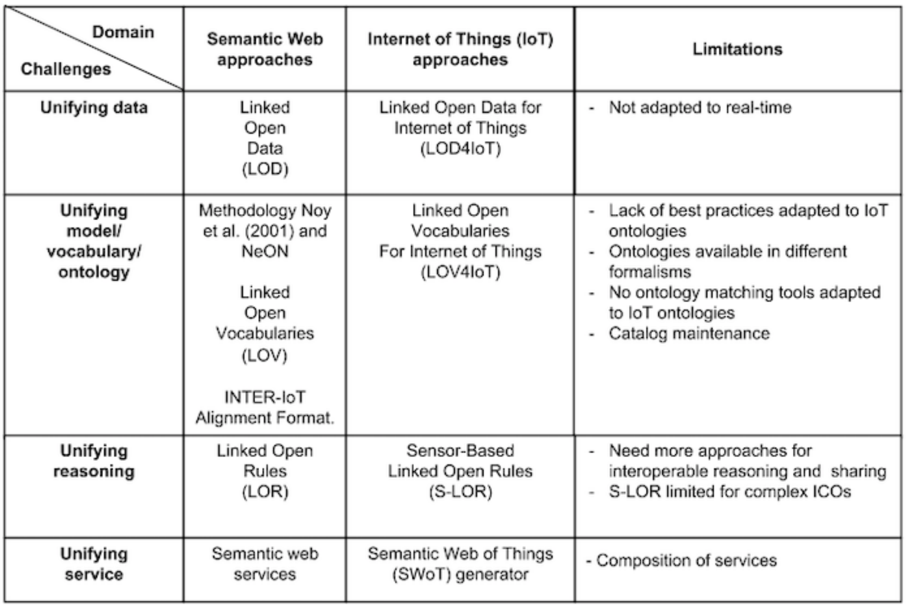
[13] https://www.w3.org/TR/vocab-ssn/



Domain Challenges	Semantic Web approaches	Internet of Things (IoT) approaches	Limitations
Unifying data	Linked Open Data (LOD)	Linked Open Data for Internet of Things (LOD4IoT)	- Not adapted to real-time
Unifying model/ vocabulary/ ontology	Methodology Noy et al. (2001) and NeON Linked Open Vocabularies (LOV) INTER-IoT Alignment Format.	Linked Open Vocabularies For Internet of Things (LOV4IoT)	- Lack of best practices adapted to IoT ontologies - Ontologies available in different formalisms - No ontology matching tools adapted to IoT ontologies - Catalog maintenance
Unifying reasoning	Linked Open Rules (LOR)	Sensor-Based Linked Open Rules (S-LOR)	- Need more approaches for interoperable reasoning and sharing - S-LOR limited for complex ICOs
Unifying service	Semantic web services	Semantic Web of Things (SWoT) generator	- Composition of services

Figure 2: Approaches and limitations for a unified semantic engine for Internet of Things. Based on the work of Gyrard and Serrano (2015).

ommended by the Semantic Web community is still a gap that was not totally fulfilled by the existing approaches. With respect to the reuse of existing ontologies, there was a concern on the part of the IoT community to build catalogs of ontologies aimed at the domain of their applications as well as to adopt ontology validation tools within the cataloging environment, providing verification of the ontology syntax.

The approach of Gyrard and Serrano (2015) presented an aspect not yet explored by the IoT community, which is the semantic level used by the current matching or alignment tools, which, according to the authors, are not enough to describe the data in the IoT scenario. However, to minimize this problem, the only approach that proposes a solution by developing its own alignment format is the INTER-IoT Alignment Format (Ganzha et al., 2017b,c). Thus, we conclude that this is an unexplored research subject, as it is important to maintain semantic interoperability in this scenario.

As another result, we also find approaches that address other known semantic interoperability issues, as the maintenance of intrinsic information the data sources (Amato et al., 2011). The adoption of shared ontologies solves the problem of single interpretation of meaning, but may lead to the loss of relevant domain information from data sources.

Therefore, semantic interoperability in the context of IoT has requirements that can be supported by Semantic Web technologies, but there are limitations in this context, especially due to formal representation and correspondence of ontologies. Unfortunately, these aspects, in general, can not be solved automatically and, when we consider the literature in this aspect, it is not clear how good the tools are in order facilitate the work that must be performed.

In summary, these results indicate gaps in the context of IoT semantic interoperability (i) need for adopting best practices recommended by the Semantic Web community; (ii) absence of methodologies in modeling ontologies that meet the needs of applications in the domain of IoT; (iii) unavailability of maintenance of ontology catalogs in IoT domains; and (iv) lack of matching or alignment tools to describe the data in the IoT context. These gaps provide a roadmap of issues to be explored in future research.

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