Tools for the Confluence of Semantic Web and IoT: A Survey

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Abstract: The last decade has meant a whole revolution in the context of Internet of Things (IoT), becoming one of the most important areas of research nowadays. The Semantic Web emerged as a way to add semantics to data to enable advanced reasoning. Due to this, the integration of both areas represents a beneficial convergence for more ”semantic-aware” devices and services. In this paper we present a review to analyze the state of the art of the confluence of the Semantic Web and IoT: extracting an overview of the ad-hoc implemented tools, their categorization, and the supported sub-domains on which they exert their influence.

1 INTRODUCTION

Internet of Things (IoT) represent the convergence of devices with sensors, remote sensing and analysis capabilities supported by heterogeneous networks (Dorsemaine et al., 2015; Atzori et al., 2017). However, the definition and view of IoT has not been static, rather it has changed over time: from pure device-to-device communication to a more ”social network-oriented” view enabled by technologies such as cloud computing, big data and the emergence of social networks (Atzori et al., 2017). In this context, the importance of semantic reasoning and the Semantic Web has run in parallel with the goal of supplementing the IoT domain with more knowledge about semantic-enabled operations to support the provision of smart services to final users (Jara et al., 2014).

The goal of this paper is to review the proposed ad-hoc tools based on the Semantic Web in the context of the IoT domain. The final aim is to gather an overview of the domains of application, the type of tools implemented and the main research results.

To run the research review, we followed the Systematic Literature Review (SLR) modality (Kitchenham and Charters, 2007), in which the review follows a formalized approach from the identification of the research goals, to the definition of the search queries, to the filtering by researchers of the gathered articles based of pre-set criteria, followed by data synthesis and knowledge representation. Such method allows to summarize all the reviewed research with more formalized final results.

The article is structured as follows. In Section 2 we provide the background about IoT and the Semantic Web, together with the summary of previous reviews that were conducted in the area. In Section 3, we summarize the method adopted to conduct the review, together with setting the research questions and the main annotations when performing the review process. In Section 4 we summarize the main results from the review, by answering each research question. In Section 5 we close the article with the main conclusions.

2 BACKGROUND

Created for specific use cases, each IoT device is meant to solve a specific task with the protocols provided by the manufacturer to allow the connection of sensors and different networks (Jara et al., 2014). As such, their connectivity is limited to a single domain – the concept of Web of Things (WoT)[1] was introduced for the integration of IoT with the Web architecture, making IoT devices connectable in general to the Web to allow some form of data reasoning. Such integration makes IoT inter-connectable to other instances that have their own schema of Web connection, abstracting to a higher layer. The biggest advantage that WoT offers is not just the connection to the Web architecture, but the fact that all the capabilities of Seman-

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[1] https://www.w3.org/WoT/

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Table 1: Previous Surveys about Ontologies & IoT.

Year	Survey	Domain
2021	(Krishnamoorthy et al., 2021)	Healthcare
2020	(Rhayem et al., 2020)	General
2020	(Sobin, 2020)	Agriculture
2019	(Balaji et al., 2019)	WoT
2019	(Balakrishna et al., 2019)	Smart Cities
2019	(Li et al., 2019)	WoT
2019	(Zgheib et al., 2019)	Healthcare
2018	(Gyrard et al., 2018)	Smart Cities
2018	(Zaidan et al., 2018)	Smart Home
2017	(Bajaj et al., 2017)	Sensors
2017	(Goudos et al., 2017)	Smart Cities
2017	(Marques et al., 2017)	Smart Homes
2016	(Jahan et al., 2016)	General
2016	(Szilagyi and Wira, 2016)	General

tic Web are set to be used, supporting the concept of Semantic Web of Things, allowing to share ”things” and compose services built on top of IoT devices (Jara et al., 2014).

Furthermore, the integration of IoT with Semantic Web enables the use of ontologies, which allow the data to be processed by machines, while making it more understandable for humans. This further expands the capabilities of IoT giving access to semantic reasoners and certain databases built around Semantic Web notions such as RDF[2] or OWL2[3], enhancing the possibilities of the provision of composed services.

It is easy to see how the confluence of Semantic Web and IoT can be beneficial for the provision of smart services to users, building on top of low-level layers. Therefore, a new breed of tools and instruments have been born from the confluence of IoT and Semantic Web to bring a higher interoperability for all of IoT devices as well as new and enhanced features for end-users.

2.1 Previous Surveys

There are several existing studies that discussed IoT, ontologies, Semantic Web and their interactions in different domains (Table 1). We summarize in this section the main reviews identified.

There are some reviews that focus generally on the aspects of integration of ontologies and IoT. For example, (Bajaj et al., 2017) review focuses on sensor and general ontologies and the technologies and challenges that come along with them, such as interoperability. (Balaji et al., 2019) focuses on an overview of IoT technology in general terms focusing more on the communication aspects (such as RFID and Wireless Sensor Network). Also (Zaidan et al., 2018) centers more on aspects related to communication in the context of IoT and integration of semantics. (Balakrishna et al., 2019) reports about the semantic interoperability in Smart Cities, covering aspects such as RDF, RDF schema, OWL, SPARQL, semantic annotations, and semantic reasoning. (Goudos et al., 2017) focuses on Smart Cities integration of IoT devices covering aspects such as transportation and logistics, discussing the implication of usage of Semantic Web for IoT. (Rhayem et al., 2020) provides a Systematic Literature Review focusing on Semantic Web Technologies applied in IoT covering many aspects such as semantic technologies, reuse of ontologies, modularity, context, methodology, and evaluation techniques. (Sobin, 2020) covers challenges such as security or scalability, classifying the findings according to the domain, like healthcare or smart agriculture, providing a new taxonomy in terms of communication protocols and architectures.

Some reviews focus specifically on tools support, like (Gyrard et al., 2018) that centers the interest on analyzing ontology-software tools for interoperability. Some catalogs of ontologies are reviewed by domain, and offer a tool for evaluating the different ontologies and approaches investigated. Also (Jahan et al., 2016) focuses on different frameworks for the Web of Things. (Krishnamoorthy et al., 2021) puts the emphasis on different architectures for Healthcare IoT differentiating up to 19 different critical applications. Also (Marques et al., 2017) has the central point on different IoT projects in the context of IoT architectures with applications such as smart homes, or healthcare. Overall, 10 different IoT platforms are included. (Szilagyi and Wira, 2016) focuses more on technologies and ontologies that have a commercial use, organized according to their position in the IoT Stack. (Zgheib et al., 2019) focuses more on middleware architectures for healthcare IoT, determining up to 7 different middleware approaches going towards semantic middleware approaches. (Li et al., 2019) centers on standardized IoT ontologies and how they cover one of the different WoT layers – looking at six different ontologies and their integration within IoT and WoT.

This review is different than the aforementioned ones as we specifically focus on the classification of implementations that were considered for the conver-

[2]https://www.w3.org/RDF/
[3]https://www.w3.org/TR/owl2-overview/

Table 2: Queries run on the digital repositories.

Repository	Query	# Articles Found
IEEEXplore	("Abstract":"IoT" OR "Abstract":"Internet of Things") AND ("Abstract":"ontology" OR "Abstract":"semantic web" OR "Abstract":"WoT") AND ("Abstract":"tool" OR "Abstract":"technology")	76
ACM DL	(Abstract:"IoT" OR Abstract:"Internet of Things") AND (Abstract:"Semantic Web" OR Abstract:"ontology" OR Abstract:"WoT") AND (Abstract:"technology" OR Abstract:"tool")	14
Elsevier	("Abstract":"IoT" OR "Abstract":"Internet of Things") AND ("Abstract":"ontology" OR "Abstract":"semantic web" OR "Abstract":"WoT") AND ("Abstract":"tool" OR "Abstract":"technology")	114
SpringerLink	((Abstract:"IoT") OR (Abstract:"Internet of Things")) AND ((Abstract:"Technology") OR (Abstract:"Tools")) AND ((Abstract:"Semantic Web") OR (Abstract:"WoT") OR (Abstract:"Ontology")) AND (Language:"English")	368

gence of Semantic Web and IoT (framework, environment, platform, ontology, architecture, middleware) linking to the different domains (e.g., Smart Cities, Healthcare). Overall, we provide the distinguishing characteristics of the tools that were implemented as enablers for the confluence of Semantic Web and IoT.

3 METHOD

To look into ad-hoc tools implemented for the confluence of Semantic Web and IoT, we adopted the Systematic Literature Review (SLR) research approach. A SLR is a formalized review process to collect, synthesize, and report previous research in a domain (Kitchenham and Charters, 2007). The process starts with the definition of the survey needs, the definition of the research questions and derived queries. Afterwards, researchers go trough a series of steps to review the collected articles taking into account inclusion / exclusion criteria. After a collaborative process about the final decision to include the papers, all the research is synthesized in the final presentation of the results, answering the research questions.

The goal of the current review was to investigate the tools for the confluence of Semantic Web and IoT. Since a large and recent number of papers have focused on the IoT domain, we wanted to look into the availability of tools to support the IoT context with capabilities related to reasoning and the Semantic Web. To run the review, we selected four main digital repositories:

DR1. IEEEXplore (ieeexplore.ieee.org)

DR2. ACM Digital library (dl.acm.org)

DR3. Elsevier ScienceDirect (sciencedirect.com)

DR4. SpringerLink (link.springer.com)

For each repository we run the queries on the abstracts as it can be seen in Table 2. Inclusion and exclusion criteria were the following:

Inclusion Criteria: i) there is a tool for Semantic Web - IoT confluence described in the paper; ii) the tool is applied to a concrete case in a specific domain; iii) only papers written in English; iv) only articles from the range of years 2011-2021;

Exclusion Criteria: i) other reviews (secondary / tertiary studies); ii) vision / position / challenges / editorials / posters;

To reach the main goal of the review, we set-up the following Research Questions (RQs):

RQ1. What are the **domains** on which the different tools are applied/developed for?

RQ2. What are the different **designs of tools** that are being developed for the confluence of the Semantic Web and IoT?

RQ3. Is there a more prevalent **type of tool** that is used to cover the topic?

RQ4. What is the main **focus of** this kind of **tools** and how do they relate to the different types that can be found in the literature?

RQ5. Is there any specific **secondary tool** (e.g., software library / framework) that was mentioned more in the proposals of the reviewed tools?

Overall, 572 papers were found from the digital repositories divided into 334 journal articles and 238 found in proceedings. These were filtered based on inclusion and exclusion criteria by two authors of the paper. After agreement on the inclusion consulting the abstracts (and in case of indecision the full paper), 60 papers were used to answer the research questions. These papers, as well as the characteristics of the tools that appear in them, have been collected and assigned a key for easier referencing in Table 3.

4 REVIEW RESULTS

We present the results from the review divided by RQs, with a classification of the tools by domain, type, category and focus, as well as a domain tree. Furthermore, let it be noted that all the different divisions that we have created to classify the papers are

Table 3: References Index.

Reference	Key	Design	Type	Domain	Focus
(Kim et al., 2018)	K01	Modelled Tool	Architecture	Smart Grids	Security
(Muppavarapu et al., 2021)	K02	Semantic System	Framework	Smart Homes Smart Buildings	Interoperability User-friendliness
(Ibaseta et al., 2021)	K03	Semantic System	Architecture	Smart Buildings	Interoperability
(Turchet et al., 2020)	K04	N\A	Ontology	Music	N\A
(Awad et al., 2019)	K05	Modelled Tool	Environment	WoT	Interoperability
(Provoost et al., 2020)	K06	Modelled Tool	Platform	Smart Cities	User-friendliness
(Janowicz et al., 2019)	K07	N\A	Ontology	Sensors	N\A
(Baldassarre et al., 2019)	K08	Semantic System	Environment	Social IoT	Interoperability
(Loseto et al., 2016)	K09	Semantic System	Framework	WoT	Interoperability
(Silva et al., 2020)	K10	Semantic System	Architecture Platform	Smart Cities Smart Buildings	Interoperability
(Platenius-Mohr et al., 2020)	K11	Modelled Tool	Environment	Industry	Interoperability
(Charpenay et al., 2015)	K12	Semantic System	Framework	Building Automation	Interoperability
(Xu et al., 2017)	K13	Modelled Tool	Environment	Security	Interoperability
(Yu et al., 2018)	K14	Semantic System	Framework	IoEverything	Interoperability
(Koorapati et al., 2018)	K15	Semantic System	Framework	General	Security
(Lian et al., 2020a)	K16	Modelled Tool	Middleware Ontology	General	Interoperability
(Sciullo et al., 2019)	K17	End-user Tool	Platform	Industry Smart Home	User-friendliness
(Zeng et al., 2019)	K18	Semantic System	Framework Ontology	Cloud\Edge Computing	Interoperability
(Hwang et al., 2016)	K19	Modelled Tool	Environment Ontology	Virtual Agent	Interoperability
(Ming and Yan, 2013)	K20	Semantic System	Middleware Ontology	General	Interoperability
(Al Sunny et al., 2017)	K21	Semantic System	Architecture Ontology	Industry	User-friendliness
(Tomičić and Grd, 2020)	K22	N\A	Ontology	Security	N\A
(Burns et al., 2018)	K23	Semantic System	Framework	Smart Cities	Security Reasoning
(Zhou et al., 2018)	K24	Modelled Tool	Platform	Social IoT	Security
(Willner et al., 2017)	K25	Semantic System	Platform	Smart Factories	Interoperability
(Liang et al., 2019)	K26	Semantic System	Framework	General	Security
(Shimoda et al., 2020)	K27	Semantic System	Environment	Sensors	Interoperability
(Reda et al., 2021)	K28	Semantic System	Environment	Healthcare	Interoperability Reasoning
(Fensel et al., 2013)	K29	Semantic System	Environment	Energy Consumption Smart Grids	Interoperability
(Su et al., 2017)	K30	Semantic System	Framework Ontology	Cloud\Edge Computing	Interoperability Reasoning
(Kotis et al., 2012)	K31	Semantic System	Framework	Sensors	Interoperability

Table 3: References Index. (cont.).

(Dolan et al., 2020)	K32	Semantic System	Framework	Smart Homes	User-friendliness
(Sanctorum et al., 2021)	K33	End-user Tool	Platform	Toxicology	User-friendliness
(Kyriazakos et al., 2015)	K34	Modelled Tool	Platform Architecture	General	Interoperability
(Govoni et al., 2017)	K35	Modelled Tool	Middleware	Smart Cities	User-friendliness
(Hashemian et al., 2019)	K36	End-user Tool	Framework	WoT	Interoperability
(Durand et al., 2017)	K37	Modelled Tool	Framework	WoT	Security
(Seok et al., 2019)	K38	Semantic System	Environment	Sensors	Interoperability
(Sciullo et al., 2020)	K39	End-user Tool	Platform	WoT Sensors	User-friendliness
(Negash et al., 2019)	K40	Modelled Tool	Architecture	WoT	Interoperability
(Khodadadi and Sinnott, 2017)	K41	Semantic System	Framework	Energy Consumption	Interoperability
(Teixeira et al., 2020)	K42	Semantic System	Architecture Framework	General	User-friendliness
(García Mangas and Suárez Alonso, 2019)	K43	Modelled Tool	Framework	WoT	Interoperability
(De et al., 2014)	K44	Semantic System	Architecture	General	Interoperability
(Thramboulidis et al., 2019)	K45	Modelled Tool	Framework	Industry Automation	Interoperability
(Khan et al., 2016)	K46	End-user Tool	Architecture Environment	Smart Home Healthcare	Interoperability
(Elsayed and Elgamel, 2020)	K47	Semantic System	Platform	Smart Cars	Interoperability User-friendliness
(Duy et al., 2019)	K48	Semantic System	Framework	Sensors	Interoperability
(Lian et al., 2020b)	K49	Modelled Tool	Middleware	General	Interoperability Reasoning
(Hu et al., 2020)	K50	Modelled Tool	Framework	General	Interoperability
(Luecking et al., 2020)	K51	Semantic System	Framework	General	Security
(Sun et al., 2018)	K52	Semantic System Modelled Tool	Environment	General	Interoperability Reasoning
(Steinmetz et al., 2017)	K53	Modelled Tool End-user Tool	Environment	Industry	Interoperability
(Xu et al., 2018)	K54	Semantic System	Middleware Framework	Smart Home	User-friendliness Reasoning
(Berat Sezer et al., 2016)	K55	Semantic System	Framework	General	Interoperability
(Khattab et al., 2018)	K56	End-user Tool	Environment	General	User-friendliness
(Miori and Russo, 2012)	K57	Semantic System	Environment	Smart Home Healthcare	Reasoning
(Mavrogiorgou et al., 2020)	K58	Semantic System End-user Tool	Platform	Healthcare	User-friendliness
(Machorro-Cano et al., 2019)	K59	End-user Tool	Platform	Smart Home	User-friendliness
(Nakatani et al., 2019)	K60	Modelled Tool	Environment Ontology	Virtual Agent	User-friendliness

non-exclusive, meaning that the same paper could fall under two different classes.

4.1 RQ1 — Domain of the Tools

We classified the provided tools by the domain of application (Table 4). There are 21 domains described with most of them having an occurrence of about a 3% of the total. The General domain comprises a 21.6% of the articles and describes those articles that focus in IoT as a whole, without describing or introducing any further specific topics. This is due to the high heterogeneity of the research. To answer the question about the possible relation between different domains, we have included a representation of a domain tree (Fig. 1) where we classified the domains from the more general to the more specific concepts.

The confluence of Semantic Web with IoT has covered many diverse fields each supported by different tools and implementations. This is to be expected as IoT represents a central concept of many emerging smart domains, and at the same time it also comes to show how cross-cutting the IoT concept is — being applied to many different domains: from industry and automation, smart cities, smart grids to the healthcare domain.

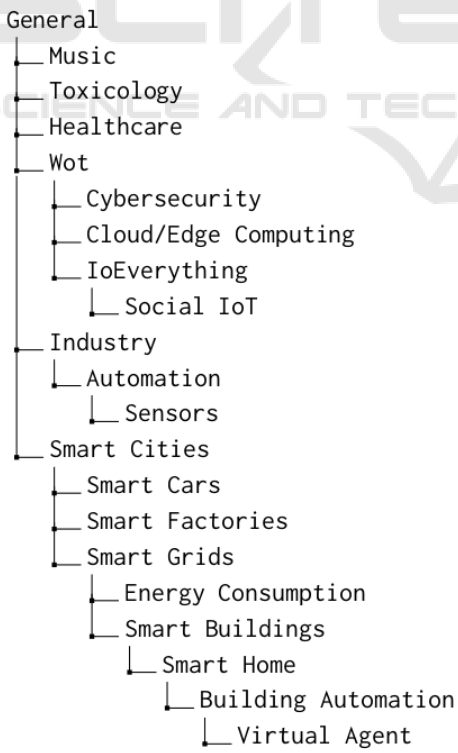

Figure 1: Domain Tree.

Table 4: Domain of Tools.

Domain	Count	Percentage	Items
Smart Grids	2	3.3%	K01, K29
Smart Home	7	11.6%	K02, K17, K32 K46, K54, K57 K59
Smart Buildings	3	5%	K02, K03, K10
Music	1	1.6%	K04
WoT	5	8.3%	K05, K09, K36 K37, K43
Smart Cities	5	8.3%	K06, K10, K23 K35, K39
Sensors	7	11.6%	K07, K27, K31 K38, K39, K40 K48
Industry	5	8.3%	K11, K17, K21 K45, K53
Building Automation	1	1.6%	K12
Cybersecurity	2	3.3%	K13, K22
IoEverything	1	1.6%	K14
General	13	21.6%	K15, K16, K20 K26, K34, K42 K44, K49, K50 K51, K52, K55 K56
Cloud/Edge Computing	2	3.3%	K18, K30
Virtual Agent	2	3.3%	K19, K60
Social IoT	2	3.3%	K08, K24
Smart Factories	1	1.6%	K25
Healthcare	4	6.6%	K28, K46, K57 K58
Energy Consumption	2	3.3%	K29, K41
Toxicology	1	1.6%	K33
Automation	1	1.6%	K45
Smart Cars	1	1.6%	K47

4.2 RQ2 — Design of Tools

As shown in Table 5 we have divided the tools found in three non-exclusive categories as high-level goals of the tools: i) End-user Tools, ii) Semantic Systems and iii) Modelled Tools. This categorization helps to provide a perspective on the type of each tool. The first category, End-user Tool, refers to any tool that has been developed with an end-user in mind; i. e.: a tool that has been designed to be used by a non-specialist in the IoT/Semantic Web topic. These tools only represent about a 15% of the total, showing the relative low number of tools specifically designed for end-user integrating IoT and the Semantic Web. Some of the End-user Tools are considerably different from each other. As an example we have K17 where *WoT Store* is enabled in such a way that a non-expert could include new functions in the pre-existing devices. On the other hand, K33, presents *DIY-KR-KIT*, that while still being an End-user Tool, it is intended to help developers work faster and with greater ease in the domain of ontologies, providing a GUI in which the components of the ontology behave as pieces from a jigsaw thanks to the Blockly technology[4].

Table 5: Categorization of the Tools.

Category	Count	Percentage	References
Semantic System	32	53.3%	K02, K03, K08, K09, K10 K12, K14, K15, K18, K20 K21, K23, K25, K26, K27 K28, K29, K30, K31, K32 K38, K41, K42, K44, K47 K48, K51, K52, K54, K55 K57, K58
Modelled Tool	19	31.6%	K01, K05, K06, K11, K13 K16, K19, K24, K34, K35 K37, K40, K43, K45, K49 K50, K52, K53, K60
End-user Tool	9	15%	K17, K33, K36, K39, K46 K53, K56, K58, K59

With the term Semantic System we are referring to any tool that is built upon semantic technologies, i. e.: that uses the support provided by the main semantic standards to create its functionalities. These tools represent the 53.3% of the total. These tools rely on the core semantic technologies (e.g., OWL, SPARQL, RDF) and are building full support based on the most common standards. It is interesting to see how these technologies have been applied in research related to IoT. For example K14 develops an unnamed framework that uses standards such as OWL or RDF to retrieve sensors information, while K23 uses the *NIST CPS Framework* and the same standards to propose a better understanding of the trustworthiness of the different devices thanks to reasoning.

Finally, by Modelled Tools we are referring to tools that are based and implemented from a previously introduced model that provides theoretical support. These tools, a 31.6% of the total, show how the confluence can be based on the support of previous models that need emerging tools for the application in the specific context. Between these tools we can find an important heterogeneity — K34 provides *BETaaS Platform* for integrating IoT devices from a context-aware perspective, but on the other end K49 solves the same problem with the use of a middleware approach, such as *I2oTegrator*, through the use of multiple operations geared towards the use of reasoning.

4.3 RQ3 — Types of Tools

When pondering the question about the type of tool used in the confluence, we categorized the tools in 6 different types, as it can be seen in Table 6. These 6 types are: platform, environment, framework, middleware, architecture, and ontology. Even though ontologies can be considered a more cross-cutting concept than the other categories, we preferred to include it in the classification, as it can give a more detailed view of the representation of ontologies among the reviewed software implementations. Furthermore, it could be argued that ontologies are not tools, but we are considering them as so as they supply a critical role when addressing IoT data.

- Platform. We refer by the definition given by IGI[5]: *"specific platforms on which technical architecture is laid out and is made to run. This type of platform mostly consists of mixture of hardware and software services"*.
- Environment. The term environment denotes a higher level than platform: ecosystems that allow the implementation of new capabilities of IoT taking into account the integration of platforms, services, and business functionality (Messerschmitt and Szyperski, 2003).
- Framework. Represents a layered structure on which functions are developed and interrelate with some developed software platform – in other terms, *"a software structure with facilities for software development, such as language translators, debugging facilities, libraries"*[6].
- Middleware. Formed by software components that enable connection between different layers often through network connectivity (Etzkorn, 2017).
- Architecture. The building blocks of software systems and the design of the different functionalities and capabilities (Bass et al., 2003).

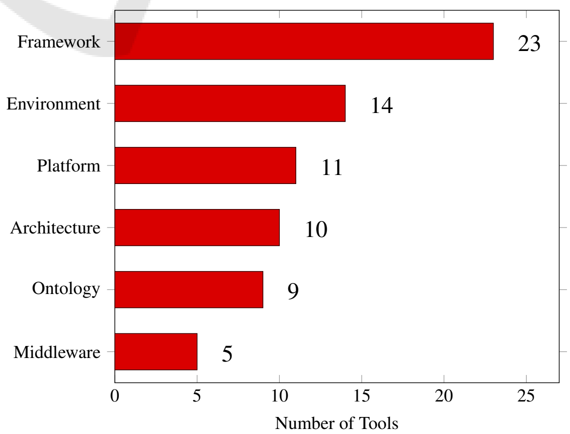

Figure 2: Different Types of Tools.

[4]https://developers.google.com/blockly

[5]https://www.igi-global.com/dictionary/technology-platforms/29539

[6]https://www.igi-global.com/dictionary/software-framework/27680

Table 6: Types of Tools.

Platform (15.28%)	Environment (19.44%)	Framework (31.94%)	Middleware (6.94%)	Architecture (12.50%)	Ontology (13.89%)
K10, K17, K24, K25, K33 K34, K39, K47, K58, K59 K06	K05, K08, K11, K13, K19 K27, K28, K29, K46, K52 K53, K56, K57, K60	K02, K09, K12, K14, K15 K18, K23, K26, K30, K31 K31, K32, K36, K37, K41 K42, K43, K45, K48, K50 K51, K54, K55	K16, K20, K35, K49, K54	K01, K03, K10, K21, K34 K40, K42, K44, K46, K60	K04, K07, K16, K18, K19 K20, K21, K22, K30

- Ontology. We are referring to the vocabularies that *"define the concepts and relationships used to describe and represent an area of concern"*[7]. There are many ontologies available in different domains — e.g., in the energy domain (Blanco. et al., 2021).

The classification (Fig. 2 and Table 6) shows the diversity of the IoT implementations that were categorized, where multiple types of tools can be used to implement solutions in the confluence with the Semantic Web. We discuss next the main findings.

The less represented type of tools are those that fall under the label of middleware. While there have been some interesting tools such as *SPF* of K35, which supports IoT deployment and distributed computing for Smart Cities, the representation of this type of tools is relatively low (6.94%).

Architecture (architectural descriptions), Ontology and Platform are distributed similarly, in the range 12-16%. In particular, the case of ontology type tools is interesting as they are usually provided alongside other type of tools, such as frameworks as *OntModel* in K30 for the transference of ontologies, or such as architectural descriptions as *MTComm* in K21 for Cyber-Physical Manufacturing Cloud. This is mostly due to the fact that ontologies are introduced not as a standalone tool, but rather as a complement to empower other parts of the infrastructure. For example, the case of K19, in which unnamed ontology models are defined to facilitate the work of an environment focused on providing rules for installing new functionalities based on virtual agents.

The two most relevant categories were Environments and Frameworks, with a 19.44% and 31.94% of the cases respectively. This gives us two different perspectives, as on the one hand, environments are more catered towards the integration and usage of IoT technologies, while frameworks focus on the development of the IoT technology itself. This can be easily appreciated in K57 where an environment developed with *DomoNet* and *DomoML* is described to prevent health hazards in a Smart Home thanks to the use of IoT devices. On the other hand, in K36 a framework named *WoTbench* for measuring the performance of different IoT devices is introduced, and thus offering a new tool for the development of new IoT technologies.

All in all we can take as a conclusion that the work currently done in the confluence of IoT and Semantic Web is focused on a variety of software platforms, environments, frameworks with ontologies playing an important role to support the different implementations. We also found relatively low number of articles that were applying machine learning, despite the current interest for it. One example of this is K06 in which sensors and WoT were used to predict the parking occupancy comparing the results obtained by Neural Networks and Random Forests methods.

4.4 RQ4 — Focus of Tools

As for the different focus of the tools we extracted four main categories that were represented in the articles: i) Security, ii) User-friendliness, iii) Reasoning, and iv) Interoperability (Fig. 3 and Table 7). By "focus on security" we are referring to tools that try to improve the integrity and resistance to attacks of IoT devices. By "user-friendliness" we refer to those tools whose focus is offering a better experience of the IoT environment for the user, trying to relieve the need for technical expertise. By "reasoning" we are strictly referring to those tools whose main objective is to enhance the semantic reasoning offered by the so-called Semantic Web reasoners with IoT integration. And, finally, by "interoperability" we are including the work done to overcome the heterogeneity that defines IoT devices enhancing the integration process.

Both reasoning and security cover each a 11.6%. An example of security can be found in K01 where we can see the intention of modelling ontologies to prevent Advanced Persistent Threat (APT) attacks – one of the most common kind of attacks in IoT. In the same sense, reasoning is a really advanced tool for processing data that requires a well-established domain. For now, reasoning is used as a complement as in K52, where it is used to enable the interoperability of IoT devices connected to a data stream.

User-friendliness represents a 25% and the second one focus in terms of size. This focus represents the intention of making the domain more amicable for users that adopt new services based on semantic IoT.

[7] https://www.w3.org/standards/semanticweb/ontology.html

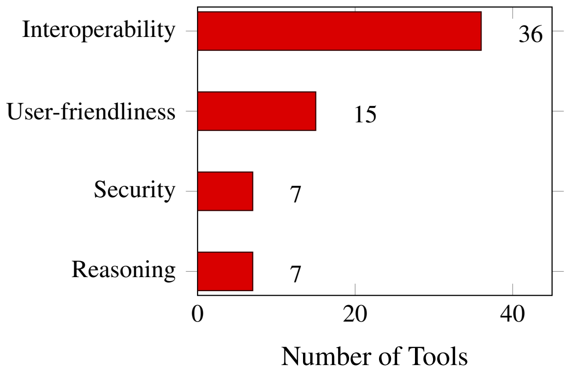

Figure 3: Focus of Tools.

A substantial part of the community cares for growing further away from its frontier and proposes tools that are able to bring the IoT/Semantic Web to most non-expert users. Probably the best example of this is K17, where the *WoT Store*, akin to most common app stores, is set up so the end-user is able to integrate new functionalities in pre-existing devices.

Table 7: Focus of Tools.

Focus	Count	Percentage	References
Security	7	11.6%	K01, K15, K23, K24, K26 K37, K51
Interoperability	36	60.0%	K02, K03, K05, K08, K09 K10, K11, K12, K13, K14 K16, K18, K19, K20, K25 K27, K28, K29, K30, K31 K34, K36, K38, K40, K41 K43, K44, K45, K46, K47 K48, K49, K50, K52, K53 K55
User-friendliness	15	25.0%	K02, K06, K17, K21, K32 K33, K35, K39, K42, K47 K54, K56, K58, K59, K60
Reasoning	7	11.6%	K23, K28, K30, K49, K52 K54, K57

Finally, interoperability is by far the biggest focus of all the reviewed papers with a count of 60%. This is due to the nature of IoT and how heterogeneous the field can be. It also points out how it is an open problem that is yet to be solved by an all-integrating solution. One of the papers that is best at showing how the work is done in interoperability is K50, where the framework *Things2Vec* is implemented for using generated graphs to model the function sequence relationships between IoT devices.

4.5 RQ5 — Secondary Tools

Answering this RQ has been more challenging, as third party tools used in the research might not have been mentioned in the articles. We have noted up to 54 different secondary tools without a specific one being used generally enough that it could be considered as a key one. On this regard, the most used secondary tool is Protégé with a total of 7 instances, which is far from having significance given the number of reviewed articles. Other articles cite common secondary tools such as Pellet, Apache Jena, HermiT. As highlighted when answering other RQs, the majority of the papers mention OWL and SPARQL — which are more than expected standards for the convergence of IoT and the Semantic Web.

5 CONCLUSION

We have proposed a review about tools that were built to support the confluence of Semantic Web and IoT, offering a comprehensive perspective on the current state of the art. We have defined five different research questions that range from the domains the tools are developed for, to the focus of the tools – including questions about the design, the type of tools and about any other secondary tools that might have been used. We have been able to identify 6 different types of tools, 3 different types of categories for the tools, and 4 different types of focus. The classification has been analyzed from the perspective of the 21 different domains that we have been able to identify (e.g., Industry 4.0, Smart Cities). When answering the research questions, we have provided some interpretations about the current state of the art and the research directions. Overall, we found out that the tools for the convergence have focused more on interoperability aspects, and generally more on the application of modelling and building semantic systems, rather than on the provision of end-user tools. As well, there is a variety of heterogeneous domains that are covered by the tools: from the energy domain, to the healthcare.

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REFERENCES

Al Sunny, S. N., Liu, X. F., and Shahriar, M. R. (2017). MT-Comm: A Semantic Ontology Based Internet Scale Communication Method of Manufacturing Services in a Cyber-Physical Manufacturing Cloud. In *2017 IEEE International Congress on Internet of Things (ICIOT)*.

Atzori, L., Iera, A., and Morabito, G. (2017). Understanding the internet of things: definition, potentials, and societal role of a fast evolving paradigm. *Ad Hoc Networks*, 56.

Awad, S., Malki, A., Malki, M., Barhamgi, M., and Benslimane, D. (2019). Composing WoT services with uncertain data. *Future Generation Computer Systems*, 101.

Bajaj, G., Agarwal, R., Singh, P., Georgantas, N., and Issarny, V. (2017). A study of existing ontologies in the iot-domain. *arXiv preprint arXiv:1707.00112*.

Balaji, S., Nathani, K., and Santhakumar, R. (2019). Iot technology, applications and challenges: a contemporary survey. *Wireless personal communications*, 108(1).

Balakrishna, S., Solanki, V. K., Gunjan, V. K., and Thirumaran, M. (2019). A survey on semantic approaches for iot data integration in smart cities. In *International Conference on Intelligent Computing and Communication Technologies*. Springer.

Baldassarre, G., Lo Giudice, P., Musarella, L., and Ursino, D. (2019). The MIoT paradigm: Main features and an "ad-hoc" crawler. *Future Generation Computer Systems*, 92.

Bass, L., Clements, P., and Kazman, R. (2003). *Software architecture in practice*. Addison-Wesley Professional.

Berat Sezer, O., Dogdu, E., Ozbayoglu, M., and Onal, A. (2016). An extended IoT framework with semantics, big data, and analytics. In *2016 IEEE International Conference on Big Data (Big Data)*.

Blanco., J., Rossi., B., and Pitner., T. (2021). A comparison of smart grids domain ontologies. In *17th Int. Conference on Web Information Systems and Technologies - WEBIST,*, pages 115–123. INSTICC, SciTePress.

Burns, M., Griffor, E., Balduccini, M., Vishik, C., Huth, M., and Wollman, D. (2018). Reasoning about Smart City. In *2018 IEEE International Conference on Smart Computing (SMARTCOMP)*.

Charpenay, V., Käbisch, S., Anicic, D., and Kosch, H. (2015). An ontology design pattern for IoT device tagging systems. In *2015 5th International Conference on the Internet of Things (IOT)*.

De, S., Christophe, B., and Moessner, K. (2014). Semantic enablers for dynamic digital–physical object associations in a federated node architecture for the Internet of Things. *Ad Hoc Networks*, 18.

Dolan, A., Ray, I., and Majumdar, S. (2020). Proactively Extracting IoT Device Capabilities: An Application to Smart Homes. In *Data and Applications Security and Privacy XXXIV*, Lecture Notes in Computer Science, Cham. Springer International Publishing.

Dorsemaine, B., Gaulier, J.-P., Wary, J.-P., Kheir, N., and Urien, P. (2015). Internet of things: a definition & taxonomy. In *2015 9th International Conference on Next Generation Mobile Applications, Services and Technologies*. IEEE.

Durand, A., Gremaud, P., and Pasquier, J. (2017). Decentralized web of trust and authentication for the internet of things. In *Seventh International Conference on the Internet of Things*, IoT '17, New York, NY, USA. Association for Computing Machinery.

Duy, T. K., Huu Hanh, H., Tjoa, A. M., and Quirchmayr, G. (2019). SemIDEA: Towards a Semantic IoT Data Analytic Framework for Facilitating Environmental Protection. In *2019 19th International Symposium on Communications and Information Technologies (ISCIT)*. ISSN: 2643-6175.

Elsayed, K. I. and Elgamel, M. S. (2020). Web of Things Interoperability Using JSON-LD. In *2020 30th International Conference on Computer Theory and Applications (ICCTA)*.

Etzkorn, L. H. (2017). *Introduction to Middleware: Web Services, Object Components, and Cloud Computing*. Chapman and Hall/CRC.

Fensel, A., Tomic, S., Kumar, V., Stefanovic, M., Aleshin, S. V., and Novikov, D. O. (2013). SESAME-S: Semantic Smart Home System for Energy Efficiency. *Informatik-Spektrum*, 36(1).

García Mangas, A. and Suárez Alonso, F. J. (2019). WOTPY: A framework for web of things applications. *Computer Communications*, 147.

Goudos, S. K., Dallas, P. I., Chatziefthymiou, S., and Kyriazakos, S. (2017). A survey of iot key enabling and future technologies: 5g, mobile iot, sematic web and applications. *Wireless Personal Communications*, 97(2).

Govoni, M., Michaelis, J., Morelli, A., Suri, N., and Tortonesi, M. (2017). Enabling Social- and Location-Aware IoT Applications in Smart Cities. In *Smart Objects and Technologies for Social Good*, Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Cham. Springer International Publishing.

Gyrard, A., Datta, S. K., and Bonnet, C. (2018). A survey and analysis of ontology-based software tools for semantic interoperability in iot and wot landscapes. In *2018 IEEE 4th World Forum on Internet of Things (WF-IoT)*. IEEE.

Hashemian, R., Carlsson, N., Krishnamurthy, D., and Arlitt, M. (2019). WoTbench: A Benchmarking Framework for the Web of Things. In *9th International Conference on the Internet of Things*, IoT 2019, New York, NY, USA. Association for Computing Machinery.

Hu, L., Wu, G., Xing, Y., and Wang, F. (2020). Things2Vec: Semantic Modeling in the Internet of Things With Graph Representation Learning. *IEEE Internet of Things Journal*, 7(3). Conference Name: IEEE Internet of Things Journal.

Hwang, I., Kim, M., and Ahn, H. J. (2016). Data Pipeline for Generation and Recommendation of the IoT Rules Based on Open Text Data. In *2016 30th International Conference on Advanced Information Networking and Applications Workshops (WAINA)*.

Ibaseta, D., García, A., Álvarez, M., Garzón, B., Díez, F., Coca, P., Pero, C. D., and Molleda, J. (2021). Monitoring and control of energy consumption in buildings using WoT: A novel approach for smart retrofit. *Sustainable Cities and Society*, 65.

Jahan, F., Fruitwala, P., and Vyas, T. (2016). Towards the next generation of web of things: a survey on semantic web of things' framework. In *Proceedings of First International Conference on Information and Communication Technology for Intelligent Systems: Volume 1*. Springer.

Janowicz, K., Haller, A., Cox, S. J. D., Le Phuoc, D., and Lefrançois, M. (2019). SOSA: A lightweight ontology for sensors, observations, samples, and actuators. *Journal of Web Semantics*, 56.

Jara, A. J., Olivieri, A. C., Bocchi, Y., Jung, M., Kastner, W., and Skarmeta, A. F. (2014). Semantic web of things: an analysis of the application semantics for the iot moving towards the iot convergence. *International Journal of Web and Grid Services*, 10(2-3):244–272.

Khan, M., Din, S., Jabbar, S., Gohar, M., Ghayvat, H., and Mukhopadhyay, S. C. (2016). Context-aware low power intelligent SmartHome based on the Internet of things. *Computers & Electrical Engineering*, 52.

Khattab, A., Hamza, H. S., and Khattab, S. M. (2018). Enhancing User Experience in IoT Mashup Using Semantic Technology. In *2018 IEEE Global Conference on Internet of Things (GCIoT)*.

Khodadadi, F. and Sinnott, R. O. (2017). A Semantic-aware Framework for Service Definition and Discovery in the Internet of Things Using CoAP. *Procedia Computer Science*, 113.

Kim, G., Choi, C., and Choi, J. (2018). Ontology modeling for APT attack detection in an IoT-based power system. In *Proceedings of the 2018 Conference on Research in Adaptive and Convergent Systems*, RACS '18, New York, NY, USA. Association for Computing Machinery.

Kitchenham, B. and Charters, S. (2007). Guidelines for performing systematic literature reviews in software engineering.

Koorapati, K., Ramesh, P. K., and Veeraswamy, S. (2018). Ontology Based Resource Management for IoT Deployed with SDDC. In *2018 IEEE International Conference on Cloud Computing in Emerging Markets (CCEM)*.

Kotis, K., Katasonov, A., and Leino, J. (2012). Aligning Smart and Control Entities in the IoT. In *Internet of Things, Smart Spaces, and Next Generation Networking*, Lecture Notes in Computer Science, Berlin, Heidelberg. Springer.

Krishnamoorthy, S., Dua, A., and Gupta, S. (2021). Role of emerging technologies in future iot-driven healthcare 4.0 technologies: a survey, current challenges and future directions. *Journal of Ambient Intelligence and Humanized Computing*.

Kyriazakos, S., Anggorojati, B., Prasad, N., Vallati, C., Mingozzi, E., Tanganelli, G., Buonaccorsi, N., Valdambrini, N., Zonidis, N., Labropoulous, G., Rodriguez, B. M., Mamelli, A., and Sommacampagna, D. (2015). BETaaS Platform – A Things as a Service Environment for Future M2M Marketplaces. In *Internet of Things. User-Centric IoT*, Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Cham. Springer International Publishing.

Li, W., Tropea, G., Abid, A., Detti, A., and Le Gall, F. (2019). Review of standard ontologies for the web of things. In *2019 Global IoT Summit (GIoTS)*. IEEE.

Lian, M., Yang, D., Yin, Z., Liu, J., Li, M., and Chai, A. (2020a). Research and Design of Semantic Model of IoT Entity Based on Ontology. In *2020 IEEE 6th Int. Conf on Computer and Communications (ICCC)*.

Lian, M., Yang, D., Yin, Z., Liu, J., Li, M., and Chai, A. (2020b). A Semantic Web Service Oriented Middleware Framework for Internet of Things. In *2020 13th International Conference on Intelligent Computation Technology and Automation (ICICTA)*.

Liang, X., Ma, L., An, N., Jiang, D., Li, C., Chen, X., and Zhao, L. (2019). Ontology Based Security Risk Model for Power Terminal Equipment. In *2019 12th International Symposium on Computational Intelligence and Design (ISCID)*, volume 2. ISSN: 2473-3547.

Loseto, G., Ieva, S., Gramegna, F., Ruta, M., Scioscia, F., and Di Sciascio, E. (2016). Linking the Web of Things: LDP-CoAP Mapping. *Procedia Computer Science*, 83.

Luecking, M., Fries, C., Lamberti, R., and Stork, W. (2020). Decentralized Identity and Trust Management Framework for Internet of Things. In *2020 IEEE International Conference on Blockchain and Cryptocurrency (ICBC)*.

Machorro-Cano, I., Paredes-Valverde, M. A., Alor-Hernandez, G., del Pilar Salas-Zárate, M., Segura-Ozuna, M. G., and Sánchez-Cervantes, J. L. (2019). PESSHIoT: Smart Platform for Monitoring and Controlling Smart Home Devices and Sensors. In *Technologies and Innovation*, Communications in Computer and Information Science, Cham. Springer International Publishing.

Marques, G., Garcia, N., and Pombo, N. (2017). A survey on iot: architectures, elements, applications, qos, platforms and security concepts. In *Advances in mobile cloud computing and big data in the 5G era*. Springer.

Mavrogiorgou, A., Kiourtis, A., and Kyriazis, D. (2020). A plug 'n' play approach for dynamic data acquisition from heterogeneous IoT medical devices of unknown nature. *Evolving Systems*, 11(2).

Messerschmitt, D. G. and Szyperski, C. (2003). *Software ecosystem: understanding an indispensable technology and industry*. MIT press.

Ming, Z. and Yan, M. (2013). Study on the ontology-base context-aware and reasoning model of IOT. In *IEEE Conference Anthology*.

Miori, V. and Russo, D. (2012). Anticipating Health Hazards through an Ontology-Based, IoT Domotic Environment. In *2012 Sixth International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing*.

Muppavarapu, V., Ramesh, G., Gyrard, A., and Noura, M. (2021). Knowledge extraction using semantic similarity of concepts from Web of Things knowledge bases. *Data & Knowledge Engineering*, 135.

Nakatani, S., Saiki, S., Nakamura, M., and Yasuda, K. (2019). Implementation and Evaluation of Personal Ontology Building System with Virtual Agent. In *Digital Human Modeling and Applications in Health, Safety, Ergonomics and Risk Management. Healthcare Applications*, Lecture Notes in Computer Science, Cham. Springer International Publishing.

Negash, B., Westerlund, T., and Tenhunen, H. (2019). Towards an interoperable Internet of Things through a web of virtual things at the Fog layer. *Future Generation Computer Systems*, 91.

Platenius-Mohr, M., Malakuti, S., Grüner, S., Schmitt, J., and Goldschmidt, T. (2020). File- and API-based interoperability of digital twins by model transformation: An IIoT case study using asset administration shell. *Future Generation Computer Systems*, 113.

Provoost, J. C., Kamilaris, A., Wismans, L. J. J., van der Drift, S. J., and van Keulen, M. (2020). Predicting parking occupancy via machine learning in the web of things. *Internet of Things*, 12.

Reda, R., Piccinini, F., Martinelli, G., and Carbonaro, A. (2021). Heterogeneous self-tracked health and fitness data integration and sharing according to a linked open data approach. *Computing*.

Rhayem, A., Mhiri, M. B. A., and Gargouri, F. (2020). Semantic web technologies for the internet of things: Systematic literature review. *Internet of Things*, 11.

Sanctorum, A., Riggio, J., Sepehri, S., Arnesdotter, E., Vanhaecke, T., and De Troyer, O. (2021). A Jigsaw-Based End-User Tool for the Development of Ontology-Based Knowledge Bases. In *End-User Development*, Lecture Notes in Computer Science, Cham. Springer International Publishing.

Sciullo, L., Aguzzi, C., Di Felice, M., and Cinotti, T. S. (2019). WoT Store: Enabling Things and Applications Discovery for the W3C Web of Things. In *2019 16th IEEE Annual Consumer Communications Networking Conference (CCNC)*. ISSN: 2331-9860.

Sciullo, L., Gigli, L., Trotta, A., and Felice, M. D. (2020). WoT Store: Managing resources and applications on the web of things. *Internet of Things*, 9.

Seok, H., Nam, S., and Lee, Y. (2019). Implementing A Semantic-based loT Mashup Service. In *Proceedings of the 2019 2nd Artificial Intelligence and Cloud Computing Conference*, AICCC 2019, New York, NY, USA. Association for Computing Machinery.

Shimoda, K., Diefenbach, D., Singh, K., Taya, A., Tobe, Y., and Maret, P. (2020). RW-QAnswer: an assisting system for intelligent environments using semantic technology. *Journal of Reliable Intelligent Environments*, 6(4).

Silva, B. N., Khan, M., and Han, K. (2020). Integration of Big Data analytics embedded smart city architecture with RESTful web of things for efficient service provision and energy management. *Future Generation Computer Systems*, 107.

Sobin, C. (2020). A survey on architecture, protocols and challenges in iot. *Wireless Personal Communications*, 112(3).

Steinmetz, C., Schroeder, G., dos Santos Roque, A., Pereira, C. E., Wagner, C., Saalmann, P., and Hellingrath, B. (2017). Ontology-driven IoT code generation for FIWARE. In *2017 IEEE 15th International Conference on Industrial Informatics (INDIN)*. ISSN: 2378-363X.

Su, X., Li, P., Flores, H., Riekki, J., Liu, X., Li, Y., and Prehofer, C. (2017). Transferring Remote Ontologies to the Edge of Internet of Things Systems. In *Green, Pervasive, and Cloud Computing*, Lecture Notes in Computer Science, Cham. Springer International Publishing.

Sun, J., Kamiya, M., and Takeuchi, S. (2018). Introducing Hierarchical Clustering with Real Time Stream Reasoning into Semantic-Enabled IoT. In *2018 IEEE 42nd Annual Computer Software and Applications Conference (COMPSAC)*, volume 02. ISSN: 0730-3157.

Szilagyi, I. and Wira, P. (2016). Ontologies and semantic web for the internet of things-a survey. In *IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society*. IEEE.

Teixeira, S., Agrizzi, B. A., Filho, J. G. P., Rossetto, S., Pereira, I. S. A., Costa, P. D., Branco, A. F., and Martinelli, R. R. (2020). LAURA architecture: Towards a simpler way of building situation-aware and business-aware IoT applications. *Journal of Systems and Software*, 161.

Thramboulidis, K., Vachtsevanou, D. C., and Kontou, I. (2019). CPuS-IoT: A cyber-physical microservice and IoT-based framework for manufacturing assembly systems. *Annual Reviews in Control*, 47.

Tomičić, I. and Grd, P. (2020). Towards the Open Ontology for IoT Ecosystem's Security. In *2020 43rd International Convention on Information, Communication and Electronic Technology (MIPRO)*. ISSN: 2623-8764.

Turchet, L., Antoniazzi, F., Viola, F., Giunchiglia, F., and Fazekas, G. (2020). The Internet of Musical Things Ontology. *Journal of Web Semantics*, 60.

Willner, A., Diedrich, C., Ben Younes, R., Hohmann, S., and Kraft, A. (2017). Semantic communication between components for smart factories based on oneM2M. In *2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*. ISSN: 1946-0759.

Xu, G., Cao, Y., Ren, Y., Li, X., and Feng, Z. (2017). Network Security Situation Awareness Based on Semantic Ontology and User-Defined Rules for Internet of Things. *IEEE Access*, 5. Conference Name: IEEE Access.

Xu, Y., Hu, P., and Ning, H. (2018). An Ontology-Based Domain Modeling and Device Search in Smart Home. In *2018 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData)*.

Yu, J., Kwon, S., Kang, H., Kim, S.-J., Bae, J.-H., and Pyo, C.-S. (2018). A Framework on Semantic Thing Retrieval Method in IoT and IoE Environment. In *2018 International Conference on Platform Technology and Service (PlatCon)*.

Zaidan, A. A., Zaidan, B. B., Qahtan, M., Albahri, O. S., Albahri, A. S., Alaa, M., Jumaah, F. M., Talal, M., Tan, K. L., Shir, W., et al. (2018). A survey on communication components for iot-based technologies in smart homes. *Telecommunication Systems*, 69(1).

Zeng, W., Zhang, S., Yen, I.-L., and Bastani, F. (2019). Semantic IoT Data Description and Discovery in the IoT-Edge-Fog-Cloud Infrastructure. In *2019 IEEE International Conference on Service-Oriented System Engineering (SOSE)*. ISSN: 2642-6587.

Zgheib, R., Conchon, E., and Bastide, R. (2019). Semantic middleware architectures for iot healthcare applications. In *Enhanced Living Environments*. Springer.

Zhou, B., Maines, C., Tang, S., Shi, Q., Yang, P., Yang, Q., and Qi, J. (2018). A 3-D Security Modeling Platform for Social IoT Environments. *IEEE Transactions on Computational Social Systems*, 5(4). Conference Name: IEEE Transactions on Computational Social Systems.