Semantic Web and Internet of Things: Challenges, Applications and Perspectives

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Abstract

The apparent growth of the internet of things (IoT) has allowed its deployment in many domains. The IoT devices sense their surroundings and transmit the data via the Web. According to statistics, due to the proliferation of smart devices, the number of active IoT devices is expected to exceed 25.4 billion by 2030.[1] A large number of IoT objects gather an enormous amount of raw data. The data generated by various IoT objects and sensors are heterogeneous, with varying types and formats. Therefore, it is difficult for IoT systems to share and reuse raw IoT data, which causes the problem of lack of interoperability. The lack of interoperability in IoT systems creates a problematic issue that prevents IoT systems from performing well. To address this issue, data modeling and knowledge representation using semantic web technologies may be an appropriate solution to give meaning to raw IoT data and convert it to an enriched data format. The primary goal of this research

[1]https://dataprot.net/statistics/iot-statistics/

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section is to highlight the best outcomes for semantic interoperability among IoT systems, which can serve as a guideline for future studies via the presentation of a literature review on semantic interoperability for Internet of Things systems, including challenges, prospects, and recent work. The paper also provides an overview of the application of semantic web technologies in IoT systems, such as specific ontologies, frameworks, and application domains that use semantic technologies in the IoT areas to solve interoperability and heterogeneity problems.

Keywords: Internet of things, semantic web technologies, semantic interoperability, ontology, heterogeneous data, linked data.

1 Introduction

Connected objects offer greater comfort in our everyday life. They lead to a very appreciable saving of time and energy. Used in various areas, the Internet of Things aims to respond to several significant current and future challenges. They offer the possibility of storing a considerable amount of data on the Web.

Interconnected IoT devices such as sensors and smart objects are heterogeneous. They collect and transmit a large volume of IoT raw data through the Web. The convergence of information and communication technologies has resulted in the exponential proliferation of data which is expected to rise further as the use of IoT devices expands. Hence, a high level of complexity due to a large number of heterogeneous objects, raw datasets, and services, makes heterogeneity unavoidable. The Internet of Things concept implies that all devices are harmoniously connected to communicate and readily accessible from the internet to provide services to applications and end-users [32].

Due to the interest and massive amount of IoT raw data available on the Web, as well as the considerable number of interconnected devices, the scalability, heterogeneity, and several interoperability issues arise [47]. This creates a multitude of problems that are considered a significant obstacle to the vision of IoT and its full implementation and deployment in our daily lives. It is necessary to develop formal semantic representations and technologies to enable interoperability between heterogeneous devices. This implies that providing interoperability between IoT "things" is one of the most fundamental requirements for supporting knowledge representation, discovery, and exchange [13]. These latter are carried out through the use of technologies inherent to the Semantic Web Group [66] such as ontologies, Web services, semantic annotations, and reasoning. The goal of them is to provide a semantic framework that addresses issues of heterogeneity and interoperability in cross-domain applications [40].

Semantic web technologies are well suited to deal with the issue of devices data interoperability. They are an immediate and appropriate solution for providing semantic interoperability throughout the IoT systems. The Semantic Web provides explicit descriptions of things and data collected from various sources in various formats using a set of standards and technologies proposed by the World Wide Web Consortium (W3C). Semantics facilitates data integration by converting heterogeneous data into a reliable and usable knowledge base using the same vocabulary in order to:

- Exchange information unambiguously between IoT systems and IoT applications.
- Integrate easily data that comes from different IoT data sources.
- Publish the IoT data over the internet to permit enriching it and reuse it.
- Development of new innovative IoT applications and systems.

This work aims to present a survey and give a state-of-the-art on the importance of incorporating semantic web technologies into the Internet of Things systems and services to solve different issues related to the lack of semantic interoperability.

The rest of this paper is organized as follows. Section 2 investigates the background of the research area such as IoT evolution, semantic interoperability, and Semantic Web. Motivation and related works are given in Section 3. Section 4 presents the different approaches and frameworks that integrate semantics in IoT. Section 5 surveys the existing ontologies in the IoT domain. Section 6 provides an extensive review of the Semantic Web application in different IoT areas. Finally, we will give a conclusion and future outlook in Section 7.

2 Background

2.1 Internet of Things Evolution

Over the last decade, the Internet of Things has grown drastically. On the one hand, this is primarily due to the advancements in smart technologies. In fact, cloud computing enables low-cost cloud storage, allowing IoT devices to store massive amounts of data generated by IoT systems at fair rates. In addition, Big Data technologies have simplified the organization and interpretation of data generated by IoT systems. Artificial Intelligence and its associated technologies have enabled the generation of insights that aid in the growth of businesses. On the other hand, the advancement of connectivity technologies is critical, with billions of new IoT devices entering each year, such as 5G, which would allow for lightning-fast data transmission to and from cloud servers. Besides that, IPv6 enables IoT devices to be uniquely addressable without working around traditional NAT and firewall issues.

The central elements of the Internet of Things are the sensors, which are increasingly miniaturized electronic compounds that communicate wirelessly through wireless sensor networks (WSN). WSN deploys devices to measure environmental phenomena, playing an essential role in the IoT that has evolved from the WSN in order to integrate them with the internet. The IoT refers to networked physical objects with digital identities, enabling them to connect and communicate over the internet. The network serves as a link between the physical and virtual worlds. The Internet of Things concept envisions a vast number of communicating smart devices complementing the current internet.

IoT was created due to the convergence of the internet and wireless technologies. The technologies behind IoT are expected to enable a wide range of applications and rapidly expand in a range of contexts.

The proposal of the Internet of Underwater Things (IoUT) is a novel class of IoT that emerged from Underwater Wireless Sensor Network (UWSN), a real-world network system. UWSNs have a wide range of applications, including maritime monitoring, security applications, ocean environment monitoring, counting or photographing animals in the ocean, extracting oil and gas resources, military and homeland security applications [12].

The industrial internet of things (IIoT) is the use of Internet of Things (IoT) technologies in manufacturing [1]. The fourth industrial revolution resulted from the Internet and Internet of Things technologies connecting sensors, intelligent industrial equipment, and computer systems. The IIoT includes industrial applications such as robotics, medical devices, and software-defined manufacturing processes.

It should be noted that the Internet of Things is a difficult concept to define precisely. In fact, there is no universal definition of IoT. Perera et al. [54] asserted that the Internet of Things connects people and things Anytime, Anywhere, with Anything, and Anyone, ideally using Any path/network and Any service. According to Nunberg [51], the IoT is defined as "a network of networks made up of millions of private, public, academic, business, and government networks ranging from local to global in scope and linked by a diverse set of electronic, wireless, and optical networking technologies." According to the International Telecommunication Union, the concept of

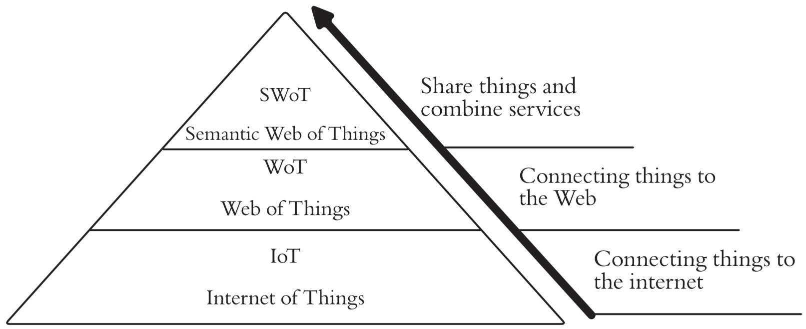

Figure 1 From IoT to SWoT.

IoT is defined as a global infrastructure for the information society that enables advanced services by interconnecting (physical and virtual) things using existing and evolving interoperable information and communication technologies [63].

The integration of any remotely controlled objects into the World Wide Web is referred to as the Web of Things. Construct a link between the physical and digital worlds. It is an Internet of Things innovation that includes smart objects on the internet and the Web. The Web of Things offers an Application Layer that facilitates the building of IoT applications formed of several devices from various platforms and application areas [55]. It has been the central focus of numerous development projects.

The Semantic Web's concepts and technologies are integrated into networks of connected objects to address the interoperability challenges, limiting IoT development. The combination between semantic web technologies and IoT or WoT domains gives rise to the emergence of a new term, known as the Semantic Web of Things (SWoT) [62]. The Semantic Web of things is described as the adoption of semantic web technologies in Internet of Things applications [61]. While the goal of the Semantic Web is to have and create readable content that machines and humans can process, the internet of things can use this vision to reflect, explain, and annotate data. As a result, data can be shared, reused, and combined to create new services and extract real insight from the IoT data sets.

2.2 Semantic Interoperability

In Internet of Things interconnected ecosystems, IoT systems should interact with other systems, understand unambiguous data, and share meaning. The semantic interoperability challenges arise from understanding its content at the semantic level and, as a result, knowing its meaning. Semantic Interoperability (SI), term was first coined in 1995 [37]. The SI can be defined as the ability of different agents, services, and applications to exchange information, data, and knowledge both on and off the Web.

The problem of semantic interoperability has been handled by several organizations that encourage and precipitate the adoption of the Internet of Things:

- ISO/IEC JTC1/SC41 is the focal point and driving force behind JTC 1's standardization program for the Internet of Things and related technologies. It also guides JTC 1, IEC, ISO, and other organizations working on Internet of Things-related applications.[2]
- The Internet Engineering Task Force (IETF)[3] Several IETF Working Groups across multiple Areas are developing protocols and best practices that are directly relevant to IoT communication and security.
- The Alliance for Internet of Things Innovation (AIOTI)[4] was launched in 2015 by the European Commission to strengthen dialogue and interaction among Internet of Things (IoT) stakeholders in Europe, as well as contribute to the creation of a dynamic European IoT ecosystem to accelerate IoT adoption.
- oneM2M[5] is the global standards initiative that includes requirements, architecture, API specifications, security solutions, and interoperability for Machine-to-Machine and IoT technologies.
- W3C[6] is an international community in which member organizations, a full-time staff, and the general public collaborate to create Web standards such as Semantic Web, which represent the pivotal element in our research.

There exist a lot of different standardization initiatives, such as: Dublin Core Metadata Initiative (DCMI),[7] TopicMaps,[8] IEEE (The IEEE1451 family standards) [48] and so on.

[2] https://www.iso.org/committee/6483279.html
[3] https://www.ietf.org/topics/iot/
[4] https://aioti.eu/
[5] www.onem2m.org
[6] www.w3.org
[7] https://www.dublincore.org/specifications/dublin-core/
[8] https://www.topicmaps.org

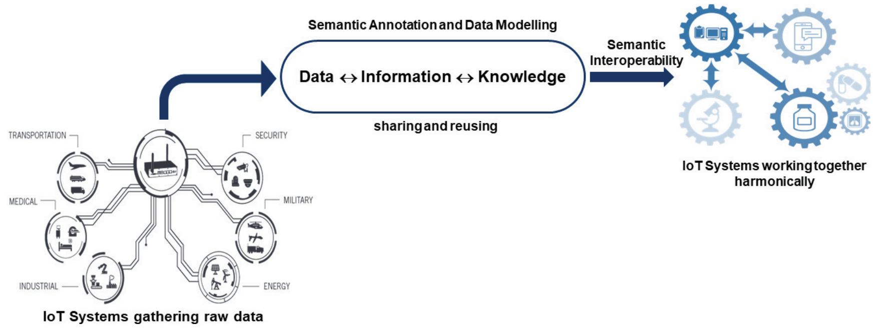

Figure 2 Vision of Semantic Interoperability in IoT.

The Semantic Web provides a common framework that allows data to be shared and reused across applications, enterprises, and community boundaries.[9] The Internet of Things can benefit from interoperability, the primary goal of creating information by annotating data. Semantic annotation is a process that attaches additional data (meta-data) to other data. One of the fundamental principles of the semantic web is that web resources must be associated with the information in order to be used by software agents and to promote their exploitation [33].

A shared and unambiguous interpretation of the information exchanged between the various stakeholders reinforces interoperability aspects. It must be accomplished by allowing applications to share information and view the meaning and values of data transmitted in a homogeneous manner so that it can be reused without errors or data loss. It is critical for the Internet of Things systems to have semantic interoperability. Figure 2 illustrates a vision of Semantic Interoperability in IoT.

2.3 Semantic Web

The Semantic Web aims to make structured data easier to use by giving meaning to Web content so that machines can understand and process it. Coined by Berners-Lee [18] in May 2001 and introduced it as an extension of the current Web in which data has a well-defined meaning for users and machines to collaborate.

Through a set of standards, the World Wide Web Consortium (W3C) transformed the World Wide Web from the “Web of documents” into a

[9] https://www.w3.org/2001/sw/

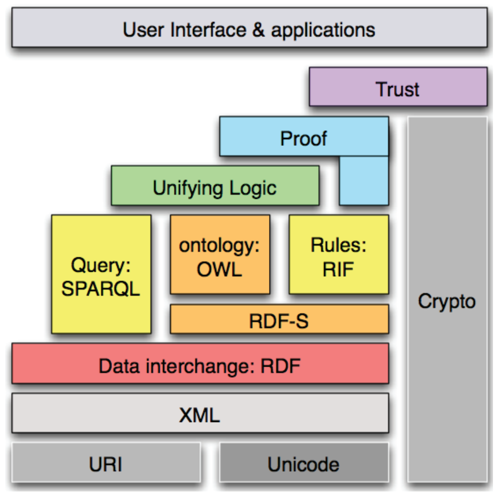

Figure 3 The Semantic Web technology stack. https://www.w3.org/DesignIssues/diagrams/sWeb-stack/2006a.png

"Web of data". The latter, provides a common framework and techniques for manipulating, sharing, reusing, and integrating information across heterogeneous data sources.

2.3.1 Semantic Web Technologies

To achieve the Semantic Web approach, several components, such as languages and knowledge representation formalisms, have been identified through various research works. They were created by the World Wide Web Consortium (W3C) within the Semantic Web framework.

The Semantic Web Stack is an illustration of the language hierarchy. It demonstrates how standardized semantic web technologies are organized to enable the Semantic Web vision (Figure 3).

Data must be uniquely identified, which is accomplished through Uniform Resource Identifier (URI) or Internationalized Resource Identifier (IRI).

1. **Resource Description Framework (RDF) [23]**
   Is the first W3C standard for publishing and linking data to enrich Web resources. It offers a mechanism for describing things using a triple of RDF (subject, predicate, object) that establishes a link between its identifier and other Web resources. Data on the Web must be interpreted in conjunction with other data. RDF is a graph model that uses triples

to describe Web resources formally, and their metadata assists us in defining data about other data. Combining many triples provide what is known as an RDF Graph.

2. **RDF Schema (RDFS) [19]**
   Povides a vocabulary for data modeling with RDF data. It allows for a higher level of abstraction. Its goal is to specify metadata schemas. It defines a set of properties' meaning, characteristics, and relationships. The advantage of RDFS is that it facilitates data inference and strengthens research on that data.
3. **Ontology Web Language (OWL) [22]**
   Allows to represent complex knowledge and interrelationships. It defines resources or objects and their relationships to describe and represent a specific knowledge domain. However, it is also used to determine individuals and assert their properties. OWL defines ontologies by using the RDF/XML syntax to expand the vocabulary and properties of RDF and RDFS. It allows for greater freedom in expressing relationships. OWL has three increasingly-expressive sublanguages: OWL Lite, OWL DL, and OWL Full, which use all OWL language's functionalities and offer varying degrees of expressiveness.
4. **SPARQL Protocol And RDF Query Language (SPARQL) [34]**
   RDF query language is a standardized query language published by the W3C in 2013, which is the equivalent of SQL for RDF graphs and is based on RDF triples to process data on the Web. It is a query language and protocol that uses a set of queries to search, add, modify, or delete IoT data stored in RDF triples.
5. **Semantic Web Rule Language (SWRL) [39]**
   SWRL, combines Ontologies and Rules, is a standard language built on OWL-DL and the Rule Markup Language (RuleML). SWRL expresses rules for reasoning and inferring new knowledge from an existing Web-based IoT data description. The addition of supplementary predicates enhances the RDF triples and allows IoT applications to obtain more precise information and make better decisions.

2.3.2 Linked Data

Linked Data is a W3C initiative that encourages the publication of structured data on the Web through the use of vocabularies empowered by technologies such as RDF, SPARQL, and OWL.

Hyperlinks allow to connect objects or observations and distribute triple-coded declarations across multiple Websites to improve semantic interoperability from IoT data to applications. The concept of linked data was coined in 2006 by Tim Berners-Lee, “the Semantic Web is not only about putting data on the Web. It is about creating links so that a person or a machine can explore the data network. When you have linked data, you can find other linked data” [17].

Like the hypertext Web, the data Web is built with Web documents. In contrast to the hypertext Web, where links are anchors of relationships in hypertext documents written in HTML, links for data connect arbitrary things described by RDF. URIs can be used to identify any type of object or observation. The same expectations apply to HTML and RDF when growing the Web. Linking data related to a given application domain with other existing data on the Web provides more information in different areas [25].

A number of technics for publishing data on the Web was proposed by Berners-Lee [17], namely:

1. Use URIs as names for things.
2. Use HTTP URIs so that people can look up those names.
3. When someone looks up a URI, provide useful information, using the standards (RDF, SPARQL).
4. Include links to other URIs, so that they can discover more things.

It should be noted that are several projects on the Web that index ontologies and vocabularies, among them are:

- **Linked Open Vocabularies (LOV)**[10] is a gateway created by The Open Knowledge Foundation to reuse semantic vocabularies on the Web [72].
- **The Linked Open Vocabularies for the IoT (LOV4IoT)**[11] present a collection of more than 800 specific vocabularies for IoT domains.
- **Schema.org**[12] is a collaborative community activity aimed at creating, maintaining, and promoting structured data schemas on the Internet, Web pages, electronic messages, and elsewhere. It does not, however, include an IoT-specific concept.

3 Motivation and Related works

IoT devices should interact with other systems, understand unambiguous data, exchange meaning, and comprehend its semantic content in the Internet

[10] https://lov.linkeddata.es/dataset/lov/
[11] https://lov4iot.appspot.com
[12] https://schema.org

of Things interconnected ecosystems. Therefore, interoperability challenges arise. The development of IoT systems relies heavily on semantic vision by unifying data, linking it, querying, and reasoning on these data streams. Semantic interoperability constitutes the IoT's kernel. So, the semantic interoperability of Internet of Things systems is essential.

The capacity of different agents, services, and applications to exchange information, data, and knowledge is known as semantic interoperability.[13] It defines the meaning of the material and includes identifying and evaluating data to make the best decision to provide the best service possible [13].

The Semantic Web framework presents knowledge representation formalism that can cope with heterogeneity. It also enables the integration of disparate data inside the same structure and transparent access to applications that might rely on data acquired for a specific purpose. Furthermore, it provides interpretation by delivering a global context of information or the results of deduction rules on existing knowledge.

Our presented survey is concerned with the current state of the art in dealing with semantics in IoT systems and services. This section provides several recent reviews, such as systematic literature reviews on these themes.

Barnaghi et al. [13] discussed the significance of defining and presenting IoT semantics in order to reduce heterogeneity and ambiguity in the massive amounts of data generated via linked things and to assure interoperability amongst IoT systems. In this light, they offered an overview of various current ontologies representing sensors and their data.

Szilagyi et al. [71] explained the significance of using semantic web technologies such as OWL, RDF, and DL at various levels of IoT systems to ensure semantic interoperability between these disparate systems. In addition, they provided an overview of the most frequently cited ontologies proposed for IoT knowledge representation, such as SSN, SAN, and IoT-O.

In [10], Bajaj et al. provided an overview of the most relevant ontologies to consider in the IoT area, such as sensor ontologies, time ontologies, and location ontologies. They categorized current techniques into generic and domain-specific categories.

The work, poroposed by Androcec et al. [8], offered a thorough review of the literature on semantic web technologies applications in the IoT area. The mentioned works are reviewed and categorized based on their publication dates, type of publishing, semantic usages, and citations in other works.

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[13]https://www.w3.org/2001/sw/BestPractices/OEP/SemInt/

Authors of [59] presented a Systematic Literature Review to identify the most relevant techniques based on several research articles. The retrieved papers in this review were classified based on their primary contribution using a categorization method with five factors related to IoT data, IoT services, IoT data and services, IoT Security, and Web of Things.

A primary goal of a research work, realised by Ahamed et al. in [3], was to provide a thorough understanding of semantic interoperability. The latter will aid in the sharing of heterogeneous data via the construction of knowledge-based systems or shared ontologies.

Security standards and interoperability objectives are reviewed by [46] they presented a comprehensive review performing an international standards survey for interoperability and security in the IoT. In addition, they surveyed international standard organizations developing IoT-related standards to guide the investigation of standards. Moreover, they discussed open research problems in IoT interoperability and security.

A survey presented in [58] covers interoperability and energy efficiency issues related to heterogeneous communication of various protocols and standards, resource management, data management, and battery limitation. However, the paper's primary focus is on energy efficiency.

The Haraz et al. [36] review, investigate the conventional and recent developments of relevant state-of-the-art Industrial Internet of Things (IIoT) technologies, frameworks, and solutions for promoting interoperability between different IIoT components. They also discuss several interoperable IIoT standards, protocols, and models for digitizing the industrial revolution.

In [57] Prasad et al. addressed the Semantic Internet of Things interoperability issues of heterogeneous IoT devices in 5G, SDN, and NFV, cloud computing, solutions to overcome those interoperability issues.

4 Internet of Things Framework

The Semantic IoT framework is a collection of layers in charge of data aggregation, persistence, analytics, and serving [52]. Semantic Web Framework enables the integration of heterogeneous data within the same structure and the transparent access to applications that can fall back on the data collected for their specific purpose [7]. In the following, we present existing IoT relevant frameworks that support semantic interoperability in IoT systems, such as BiG-IoT, FIESTA IoT, VICINITY, INTER-IoT, Open-IoT SymbIoTe, and the M3 Framework.

4.1 BiG-IoT

Developing the BiG-IoT API [35, 43] relies on semantic addressing and IoT interoperability issues to realize real Internet of Things (IoT) ecosystems. The project is a Web platform that connects various platforms and middleware systems. It makes use of schema.org as a concept vocabulary. With a well-defined API and a well-defined architecture, it is simple to create applications and services for heterogeneous platforms with an increasing level of semantic interoperability. As presented in [74], the following functions frame the IoT API:

- Identity management for registering resources.
- Discover resources according to user-defined search criteria.
- Access metadata, and data (download data and publish / record feeds).
- Vocabulary management for semantic descriptions of concepts.
- Security, including identity management, authorization, and key management.
- Billing allows you to make money through payment and billing mechanisms.

4.2 FIESTA IoT

Federated Interoperable Semantic IoT Testbeds and Applications. It is a Horizon 2020 research project and an Innovation Action funded by the European Union. It treats the topic of "Future Internet Research and Experimentation." The project consists of large-scale IoT experiments that will use data and resources from disparate IoT platforms [2]. With semantic technologies, the FIESTA project enables researchers and experimenters to share and reuse data from various IoT testbeds. These experiments offer a variety of tools and best practices for enhancing the interoperability of heterogeneous IoT platforms. The FIESTA-IoT architecture is a set of functional blocks allowing [20]:

- Testbed data streams and resources to be plugged into FIESTA-IoT.
- Be discoverable using FIESTA-IoT and be accessible via FIESTA-IoT services.
- Semantic querying both linked data sets (of collected testbed data) and IoT service APIs.
- Secure access to testbed resources by authenticated and authorized experimenters.

4.3 VICINITY

VICINITY project aims to connect cloud-based platforms from various application domains by offering "interoperability as a service" for the Internet of Things [29]. The primary goal is to improve semantic interoperability by utilizing the W3C Web Language Ontology standard. The VICINITY ontology network is made up of cross-domain ontologies that address general concepts such as time, space, and the Web of Things. In addition, they represent the information required for peers to exchange IoT description data. Domain-oriented ontologies seek to cover a wide range of domains, including health, transportation, and so on.

4.4 INTER-IoT

An interoperable and open IoT framework. The main aim of INTER-IoT is to design, implement and test a framework that will allow interoperability among different Internet of Things (IoT) platforms.[14] The INTER-IoT project's ultimate goal is to provide an interoperable system architecture to integrate various IoT architectures across multiple application areas seamlessly. At multiple levels, interoperability will be provided: system, network, middleware, services, and data. It allows the developer to create effective and efficient smart IoT applications on heterogeneous IoT platforms.

The INTER-IoT framework aims to be generic, allowing different approaches to coexist on the platform, such as cloud services that use an IaaS layer to scale their operation as needed [27].

4.5 Open-IoT

ICFOSS promotes a community-enabled knowledge-sharing platform for sharing, discussing, and collaborating on Open Source Hardware and software for the Internet of Things.[15] The Open-IoT project focuses on increasing semantic interoperability [70].

A middleware platform was created to allow semantic integration of applications in the cloud. It uses the semantic sensor network ontology to model the information and semantic integration of various IoT systems. Also, it uses Linked Data to enrich the data and infer it. The Open IoT platform is the middleware and infrastructure that allows end-users to interact with smart objects. They serve as a software interface between the hardware and application layers. The IoT platform orchestrates data flow between IoT devices and IoT applications.

[14] http://www.inter-iot.eu
[15] http://www.openiot.in

4.6 SymbIoTe

Symbiosis of smart objects across IoT environments provides an abstraction layer for a "unified view" on various platforms and their resources, allowing application designers and developers to see platform resources transparent.

SymbIoTe's architecture is based on a hierarchical IoT stack and supports multiple IoT platforms. It deploys interoperability middleware that is both flexible and secure across IoT platforms. The project's primary goal is to develop IoT applications on IoT platforms, as well as dynamic and adaptive smart spaces in which they can collaborate [20, 28]. It offers a semantic Internet of Things search engine for connected smart objects registered by platform providers. Furthermore, an abstraction layer unifies the use of those resources across platforms.

4.7 M3 Framework

Machine-to-Machine Measurement framework enables IoT applications, assists users in interpreting sensor measurements, and combines domains. M2M is used in the project's framework to semantically annotate and reason about M2M data collected from various IoT devices, systems, and domains. The following layers frame the M3 framework to increase the level of interoperability at the syntactic, but especially at the semantic level [31, 32].

- The perception layer is made up of physical IoT devices like sensors, actuators, and smart objects.
- The data acquisition layer collects raw data from IoT devices and converts it into a unified format, such as RDF/XML compliant with the M3 ontology.
- The persistence layer is responsible for storing M3 in a database to store semantic sensor data, which is referred to as the triple store.
- To update M3 domain ontologies, datasets, and rules, the knowledge management layer is responsible for finding, indexing, designing, reusing, and combining domain-specific knowledge, such as ontologies and dataset.
- Reasoning layer that uses reasoning engines and M3 rules to infer new knowledge.
- On inferred sensor data, the knowledge query layer executes SPARQL (an SQL-like language) queries.
- The application layer uses an application (which runs on smart devices) to parse and display the results to end users.

Table 1 Frameworks enhancing interoperability in IoT systems

Framework	Reference	Key Contribution at Semantic Level
Big-IoT	[35, 43, 74]	Expands the standards of the Web of things. Vocabulary management for handling the semantics.
FIESTA IoT	[2]	Reasoning technics and Linking technics.
VICINITY	[29]	VICINITY Ontologies.
INTER-IoT	[27]	DS2DS (Data and Semantics to Data and Semantics).
Open-IoT	[70]	Extend SSN ontology and Linked Data.
SymbIoTe	[20, 28]	Semantic IoT search engine.
M3 Framwork	[31, 32]	Knowledge management layer and Reasoning layer.

Table 1 summarizes the already presented frameworks and their main contributions at the semantic interoperability level. A considerable amount of contributions has developed solutions to improve semantic interoperability. However, they are still in their early stages. The proposed frameworks fail to consider the limitations of IoT systems. Furthermore, the created ontologies are complicated and incompatible with one another, and they focus primarily on the interoperability of specific fields rather than on a general solution. Aside from that, the tools for ontology alignment and ontology merging, which can dramatically improve interoperability levels, have received little attention.

5 Ontology and Internet of Things

To solve the heterogeneity problem, using the core of semantic technology (ontology) to semantic annotation for the information of things can provide machines with more understandable information [49]. The term “ontology” derived from philosophy is defined as a formal description of knowledge in computer science. An ontology offers a unique perspective on the world or its part, and it specifies what concepts to represent and how they are related to producing knowledge artifacts.

The ontology is the most significant component of the Semantic Web, acting as a store for information and knowledge about objects and their kinds and allowing semantic interoperability. Ontologies help with the semantic annotation of raw IoT data. In addition, they provide an abstraction layer that assures compatibility [56].

Ontologies have two fundamental characteristics: they enable a consistent interpretation of information and make explicit domain assumptions. As a result, the model’s interconnection and interoperability make it ideal for tackling the problems of data access and querying in giant IoT data sets.

Several ontologies have been created in the IoT domain, each with a different scope and point of view. In this section, we will take our time to present the most relevant of them.

The most famous developed ontology is the Semantic Sensor Network ontology [21]. SSN ontology developed by the W3C Semantic Sensor Network Incubator Group. Sensors and their observations, the techniques involved, the researched aspects of interest, the samples utilized to do so, and the discovered attributes, as well as actuators, are all described in this ontology. SSN can handle a wide range of technologies and application cases, including the Web of Things. The SSN ontology is extended and built upon by several ontologies.

The Sensor Core Ontology [68] is based on current sensor ontology and sensor domain knowledge. Modules such as the component module, service module, and context module are added to extended the SSN ontology. Space, time, and them are classes introduced within the context module.

Wireless Semantic Sensor Network ontology [15] is an extension of SSN ontology for wireless sensor networks. Enriched the SSN ontology by adding new WSN concepts such as communication, data stream and state. Hence the communication and transformation of sensing data is provided.

IoT Ontology [45] outlines an ontology for representing information about IoT's 'things' such as intelligent entities, physical entities, control entities, electronic devices, and networks and how they should interact. Based on SSN Ontology.

M3 Ontology [30] is an extension of the Semantic Sensor Networks (SSN) ontology. semantic web technologies are used to aggregate cross-domain M2M data and augment it. The M3 ontology describes the M2M architecture's core components and semantically annotates M2M data. It also classifies M2M devices, their data, and domains, as well as linking M3 ideas to domain ontologies to gain further information.

SAREF Ontology [24] focuses on the concept of device. It intended to describe recurring core concepts, their connections, and mappings to other concepts utilized by various assets/standards/models in the smart appliances domain.

OneM2M Ontology [53] explains the meaning of sensors and actuators. Its major goal on the one hand, is to provide compatibility across various IoT systems and on the other hand, to enable semantic interoperability in cross-silo IoT systems.

IoT-O [64] is an ontology for the Internet of Things' core domain. It's designed to represent horizontal information about IoT systems and applications, as well as vertical, application-specific knowledge. IoT-O is made up of many modules: sensing module, acting module, service module, and energy module.

SmartOntoSensor [5] an ontological model aims to create a formal conception of smartphone resources and sensors, including their categories, taxonomy, connections, and information about sensor attributes, performance, and dependability. It includes logical statements that describe associations among components and sensor concepts. Thus, it boost the information value and reusability for application development and sharing by providing a common understanding of data gathered by smartphone sensors. The ontology may be used to define IoT devices and their capabilities in current applications that accept Schema.org annotations.

IoT-Lite [16] is an instantiation of the semantic sensor network ontology. It provides a lightweight core ontology that enables for quick annotation and processing. IoT-Lite can be a fundamental component of a semantic model to which multiple semantic modules can be added, depending on the applications, to give additional domain and application-specific concepts and connections.

Sensor, Observation, Sample, and Actuator (SOSA) ontology [42] built on top of SSN Ontology a light-weight event-centric ontology. The SOSA ontology is a rigorous lightweight general-purpose specification for modeling the interaction of entities involved in observation, actuation, and sampling.

Table 2 presents a resume of the presented ontologies and the fragment of the IoT domain. These ontologies describe general or specific domain.

Table 2 Ontologies for IoT

Ontology	Reference	Year	Area
SSN	[21]	2012	GENERAL
SCO	[68]	2012	SPECIFIC
WSSN	[15]	2012	GENERAL
IoT Ontology	[45]	2012	GENERAL
M3 Onto	[30]	2014	SPECIFIC
SAREF	[24]	2015	SPESIFIC
One M2M	[53]	2016	SPECIFIC
IoT-O	[64]	2016	GENERAL
SmartOntoSensor	[5]	2017	SPECIFIC
IoT Lite	[16]	2017	GENERAL
SOSA	[42]	2019	GENERAL

6 IoT Applications Domains Make Use of Semantic

IoT combines many existing technologies, including communication network technologies, information technologies, sensing/control technologies, software technologies, and hardware/device technologies, to improve operations, lower costs, create new products and business models, and improve engagement and customer experience. Many aspects of our daily lives will be covered by Internet of Things applications and services, including energy management, inventory management, traffic management, home control and automation, industrial automation, healthcare, the battlefield, and many others [14].

An explosion of IoT devices and platforms has been integrated into a wide range of applications, including industry, hospitals, agriculture, infrastructure, electricity, transportation, industrial control, and homes, among others. Thus, a profound upheaval has been produced in all areas. With the addition of semantic notifications, it is possible to achieve deep data analysis and knowledge discovery, especially in the areas of activity recognition, decision-making, and trend discovery [67].

It also provides easy access and interaction with a wide variety of smart physical devices and high-performance objects. Then it facilitates the development of innovative smart applications in many fields, such as smart cities, smart homes, smart health, and smart agriculture. As for now, some applications are being developed that integrate semantics into IoT applications in several areas. We present in this section important application domains of IoT using semantics, in which we take up some examples of recent work in different technology areas and their main contributions.

6.1 Smart Health

Balakrishna et al. [11] recommended employing use-case methodologies to add semantic annotations to achieve semantic interoperability in the IoT health care sectors. Using a use case approach, apply semantic annotations to enable semantic interoperability in big data health care industries. Using the Resource Description Framework (RDF) framework and SPARQL queries to extract and display health care data.

An ontology was constructed for patients with cardiovascular disorders [4]. This technique allows patients in any part of the globe to be diagnosed by heart experts in another part of the world. This system coordinates the integration and interoperability of diverse data into the RDF format.

To combine methods for establishing an integrated platform with knowledge of smart healthcare services, an ontological framework of integrated healthcare services is constructed by [65].

A new scalable semantic framework for Internet of Things (IoT) healthcare applications has been unveiled [73]. In addition, semantic reasoning techniques are given through semantic middleware.

Alti et al. [6] suggested a new semantic contextual that is autonomous and agent-based. A software platform for disease identification and intelligent health monitoring. Semantic Web, Cloud, and Kalimucho middleware are used.

6.2 Smart Industry

In Industry 4.0, the study [50] presents Semantic Web services for AI-based research. They created over 300 Semantic Web services for a physical simulation factory using the Web Ontology Language for Web Services (OWL-S) and Web Service Modeling Ontology (WSMO), which they coupled to an existing domain ontology for intelligent manufacturing control.

Fenza et al. [26] propose the use of Semantic Web models to construct a 5C architecture that is primarily aimed at collecting and processing semantic data streams in order to maximize data yield in a smart manufacturing environment. The SOSA ontology is used to represent the semantic data stream in the solution. Then, C-SPARQL queries are created for running meaningful KPIs (Key Performance Indicators) on a regular basis to address the intended goal.

In [69], to fulfill the goal of smart factories, a manufacturing system framework is supplied with an integration of IoT and semantic technology. An ontological model of the Inclusive Production System was provided, along with a basic example of Nut-Bolt manufacturing.

6.3 Smart Cities and Smart Agriculture

Iatrellis et al. [41] proposed an ontology that incorporates the relevant knowledge and a rule-base for modeling the phases of an employee training process to make up the learning platform's semantic architecture. The semantic model has been translated into a relational database schema, which is then used by the system to execute meaningful queries in order to improve competence management efficiency.

Through the use of semantic web technologies and the construction of an ontology for environmental indicators, this study [60] presents an IoT-based environmental platform for smart cities that allows for interoperability from data gathering through knowledge extraction and display.

Aydin et al. [9] investigated the term "open data" in the context of agriculture, designs an open data processing paradigm, and creates an IoT-based system to collect environmental data from agricultural areas. They also developed an ICT-based solution to demonstrate the viability of the proposed model.

In [44], Khatoon et al. proposed semantically annotating and displaying data collected from various sensors across farms in a user-friendly format. The data is annotated using a simple semantic annotation model. The Resource Description Framework (RDF) is utilized to provide the data semantic functionality. The suggested framework aids in the interoperability of heterogeneous data collected from Internet of Things devices.

7 Conclusion

A large number of Internet of Things (IoT)-related technologies have been increasingly designed and deployed to collect a large amount of heterogeneous data in order to monitor environmental phenomena. Despite its relevance, the IoT's ongoing progress has resulted in an increasingly high level of complexity. This is mainly due to a large number of diverse installed equipment, sensing data, and recommended services. Consequently, interoperability and heterogeneity issues have been raised. To overcome this, semantic web technologies are employed as an appropriate solution for harmonizing data and handling semantic interoperability throughout the IoT systems and services.

The Semantic Web is the web of connections between different forms of data, which are given meaning (semantics) in a standardized language. It allows building a more robust web of data where computers can find, read, and even reason about a unit of content.

After more than 20 years since its first proposal, the Semantic Web has not yet achieved its full vision. According to several prominent authors, the big picture vision of data exchange, discovery, integration, and reuse have yet to be realized [38]. Every aspect of the Semantic Web requires further development. Since there are so many diverse approaches, some application-oriented consolidation is required, along with robust tool interoperability and well-documented processes.

In this paper, we have presented an overview of state of the art on the semantic interoperability issue in the context of the IoT. The main objective of this research part is to showcase the best-of-breed solutions for semantic interoperability amongst IoT systems, which can be used as a guideline for other research works. We have given an overview of semantic web technologies applied in IoT systems, as well as some widely recognized frameworks and ontologies used to construct IoT applications and services. In addition, we have outlined some application domains of the IoT in the context of the Semantic Web.

To achieve full interoperability at the semantic data level, one of the primary challenges to be addressed in the future is full standardization and generalization. It is recommended that each IoT application use standards based on well-known organizations such as IEEE, W3C, OneM2M, DCMI, etc. In addition, contemporary IoT applications necessitate the development of applicable solutions to address the absence of real-time semantic interoperability for streaming raw data. As the Semantic Web of Things is not a real-time framework application, a real-time framework is a very crucial scope to supply for the development of innovative IoT applications or services.

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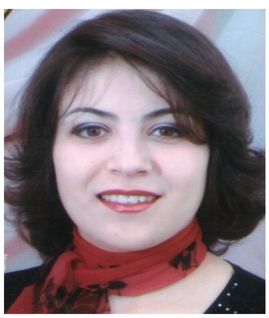

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