electronics

Review

Applications of Ontology in the Internet of Things: A Systematic Analysis

Fahad Qaswar [1], M. Rahmah [1], Muhammad Ahsan Raza [2,*], A. Noraziah [1,3], Basem Alkazemi [4], Z. Fauziah [1], Mohd. Khairul Azmi Hassan [5] and Ahmed Sharaf [6]

1 Faculty of Computing, College of Computing and Applied Sciences, University Malaysia Pahang, Pekan 26600, Malaysia
2 Department of Information Technology, Bahauddin Zakariya University, Multan 60000, Pakistan
3 Center for Software Development & Integrated Computing, Pekan 26600, Malaysia
4 Department of Computer Science, College of Computer and Information Systems, Umm Al-Qura University, Makkah 21955, Saudi Arabia
5 Department of Information Systems, Faculty of Information and Communication Technology, International Islamic University, Kuala Lumpur 50728, Malaysia
6 Deanship of Scientific Research, Umm Al-Qura University, Makkah 21955, Saudi Arabia
* Correspondence: ahsanraza@bzu.edu.pk

Abstract: Ontology has been increasingly implemented to facilitate the Internet of Things (IoT) activities, such as tracking and information discovery, storage, information exchange, and object addressing. However, a complete understanding of using ontology in the IoT mechanism remains lacking. The main goal of this research is to recognize the use of ontology in the IoT process and investigate the services of ontology in IoT activities. A systematic literature review (SLR) is conducted using predefined protocols to analyze the literature about the usage of ontologies in IoT. The following conclusions are obtained from the SLR. (1) Primary studies (i.e., selected 115 articles) have addressed the need to use ontologies in IoT for industries and the academe, especially to minimize interoperability and integration of IoT devices. (2) About 31.30% of extant literature discussed ontology development concerning the IoT interoperability issue, while IoT privacy and integration issues are partially discussed in the literature. (3) IoT styles of modeling ontologies are diverse, whereas 35.65% of total studies adopted the OWL style. (4) The 32 articles (i.e., 27.83% of the total studies) reused IoT ontologies to handle diverse IoT methodologies. (5) A total of 45 IoT ontologies are well acknowledged, but the IoT community has widely utilized none. An in-depth analysis of different IoT ontologies suggests that the existing ontologies are beneficial in designing new IoT ontology or achieving three main requirements of the IoT field: interoperability, integration, and privacy. This SLR is finalized by identifying numerous validity threats and future directions.

Keywords: internet of things; ontology; semantic; web of things

check for updates

Citation: Qaswar, F.; Rahmah, M.; Raza, M.A.; Noraziah, A.; Alkazemi, B.; Fauziah, Z.; Hassan, M.K.A.; Sharaf, A. Applications of Ontology in the Internet of Things: A Systematic Analysis. *Electronics* **2023**, *12*, 111. https://doi.org/10.3390/electronics12010111

Academic Editors: Hosung Park and Soochang Park

Received: 24 November 2022
Revised: 18 December 2022
Accepted: 20 December 2022
Published: 27 December 2022

1. Introduction

The interest in ontology for the Internet of Things (IoT) scenario is growing rapidly. Ontology is formally defined as the "explicit specification of a conceptualization" [1]. Phrase explicit specification explains the classes and specifications of a domain. Conceptualization refers to an abstract and simplified view of the domain that needs to be represented. Every information-base or database mediator supports conceptualization indirectly but unambiguously [2]. Ontology provides a typical method of interpreting field simulations or system insights to allow automatic interpretation by machines. Ontology is utilized in IoT to reduce or solve problems that may occur during the communication of IoT devices. It helps solve various issues in IoT, such as interoperability, security, scale, profound heterogeneity, unknown topology, unknown data point availability, incomplete or inaccurate metadata, and conflict resolution [3,4]. The following questions need to be understood. (1) What are the main points of the ontologies helpful for IoT? (2) What languages are required in IoT-motivated ontology development? (3) Under the assumption that IoT ontologies are reused, how does such reuse proceed? The purpose of this current review is to determine how ontologies support IoT. Notably, no systematic investigation of the benefits of ontologies in IoT has been conducted in extant literature.

The review method is used here to classify, estimate, and infer IoT ontologies to solve IoT problems and provide suggestions through a detailed examination of ontologies in the IoT domain. Our main goal is to analyze how ontologies support IoT and classify the traditions that have been functional for this ground. Furthermore, we perform a thorough and numerical breakdown of the papers' grades to reduce repetitiveness and provide a general analysis of the use of ontologies in IoT.

1.1. IoT

The phrase "Internet of Things" was coined by Massachusetts Institute of Technology's Kevin Ashton in 1999 in a presentation [5]. According to Ashton, embedding radio frequency identification (RFID) into ordinary objects helps in the identification of objects (i.e., keys), resulting in the formation of IoT. The term "Internet of Things" was developed from the words "Internet" and "things" [3]. The Internet is a universal system of integrated computer networks that consume the typical Internet protocol suite (TCP/IP) to help billions of consumers communicate with one another. Presently, countries associate with one another via interactions of their data, news, and thoughts on the Internet. According to [4], about 4,422,494,622 Internet users worldwide existed as of 2 February 2019. This figure indicates that 57.3% of the world's population uses the Internet. The second IoT word, things, includes not only automated devices but also food, clothing, furniture, materials, parts and equipment, landmarks, shrines, and artworks, and the collection of trade, culture, and convolution. This condition means that things can be divided into living and non-living things. Things represent real objects in this physical or material world. We are physical beings, and so is our environment. Our budget, civilization, and existence are not based on concepts or information but on things. Ideas and information have value, but physical things have much more value.

Today, information technology relies more on data devised by people than on data from computers. If we had devices that knew everything about things that use data (i.e., gathered without help from human beings), then we could track and count things. This capability greatly reduces surplus, damage, and costs; for instance, we can know everything about things to be replaced, repaired, or recalled [6]. From being a concept to reality, IoT is now utilized in industrial products and smart home appliances [7–9]. It involves RFID and other hardware products under the IoT umbrella, such as sensors, actuators, and mobile devices. Modern vision considers these to be things that can act upon, measure, or provide amenities based on real-world objects [10].

1.2. Ontology

The term ontology, which was borrowed from the domain of philosophy, describes the nature of being [11]. The ontology concept was initially utilized by artificial intelligence researchers who created simulations with the help of computers using automated reasoning. From the IT perspective, ontology describes a set of depictive primitives in an explicit knowledge area [12]. Commonly adopted primitives include classes, qualities, and relationships together with their effects and boundaries. Ontology can be represented using a wide range of programming languages and schemes, such as description logic (DL), first-order logic, relational model, and UML [13]. The most commonly used ontology language in the information stack of the semantic web is web ontology language (OWL) [14]. OWL originated from description logic to provide correct semantics of perceptions and associations.

RDF ontology is also a part of the W3C technology information stack. It represents the semantics of a domain in triple form (i.e., subject–predicate–object). The semantics denoted in RDF or OWL can be extracted by means of a query language known as SPARQL [15], which mostly resembles the SQL-like query language. Semantic web rule language (SWRL), another ontology language, extends the set of OWL axioms to consider Horn-like instructions and deliver further explanations [16].

1.3. Ontologies in IoT

This section presents several of the popular and most used ontologies in IoT. First, the semantic sensor network (SSN) ontology [17] is based on the ontology design pattern, which describes the relations among sensors, stimuli, and observations. It also includes elements from the stimulus sensor observation (SSO) design. SSN ontology can be understood from four major perspectives. (a) The sensor perspective describes what a sensor senses, how it senses, and what is being sensed. (b) The observation perspective refers to the data under observation and the associated metadata. (c) The system perspective discusses how a sensor system is made up and deployed. (d) The feature and property perspective discusses what sensors sense about a property.

Second, the suggested upper-merged ontology (SUMO) integrates a number of current upper-level ontologies [18]. It contains different sections to describe ontology overall. The first section is identified as the structural ontology that comprises descriptions of relations that help the framework describe the ontology properly. The second section is identified as the base ontology that includes essential ontological concepts, such as abstract objects and the division between objects and methods. The set/class principle section of SUMO (i.e., the third section) contains simple set abstract knowledge. The numeric section describes basic arithmetic tasks, and the temporal section builds relationships based on Allen's temporal relations. The graph theory section offers general graph theoretic views. The unit of measure section provides explanations of SI and other unit systems. The other sections of the ontology provide sub-hierarchies and axioms linked to process, object, and attribute types.

Third, the sensor, observation, sample, and actuator (SOSA) ontology offers a lightweight common goal description of showing the collaboration among things as a part of performing sampling, observation, and actuation [19]. SOSA is created by reusing the W3C SSN ontology while considering user choice, specific audience, and technical requirements. SOSA can be used as an alternative to the SSN-based SSO principle. Fourth, the DogOnt ontology has particular importance in the interoperation between home automation systems [20]. The basic concepts of DogOnt are from real-world case studies and focus on device, state, and functionality modeling. This ontology can be described along five main hierarchy trees: (a) building things, which demonstrates presented things that are either manageable or not; (b) building environment, which indicates where objects are situated; (c) state, which demonstrates the stable configurations that manageable things can accept; (d) functionality, which reveals what manageable things can perform the action; and (e) home automation network component, which provides the specifications of each home automation network.

Fifth, IoT-Lite is an extension of the SSN ontology to define important IoT concepts and permit the interoperability and encounter of sensory data in mixed IoT environments via lightweight semantics [21]. The authors of IoT-Lite defined 10 rules for achieving worthy and scalable semantic model design. The rules include the following: (1) the design should support large-scale ontology, (2) think of users who will use the semantics and plan for their prerequisites, (3) offer ways to update and modify the semantic notes, (4) make tools for validation and interoperability analysis, (5) produce taxonomies and dictionaries, (6) reuse current models, (7) associate data and explanations to other present assets, (8) define guidelines or best practices for giving worth for each thing, (9) make the design simple, and (10) construct actual methods, tools, and APIs to take control of and process the semantics.

The rest of this review article has the following sections. Section 2 outlines the methodology used to conduct this literature review. Section 3 presents the results with regard to the research questions. Section 4 discusses the scope, related work, and threats to the validity of the literature review, and the last section addresses the conclusion.

2. Literature Review Methodology

Figure 1 presents the methodology used in this work to describe the layout of identifying literature and the latest ontology trends in the IoT field. Our methodology is simple; it starts with the objectives that define the main goals to be accomplished in this research. Research questions are set to describe how the use of ontology supports the IoT field. The search method is the third step; it includes search term identification and inclusion and exclusion criteria. The fourth step discusses various data sources, including online electronic databases, and how relevant papers are carefully selected during the selection procedure. The fifth step shows how data are extracted from each article selected in the previous step. The last step explains the criteria used to assess all selected papers in Step 4 and eventually meet quality demands.

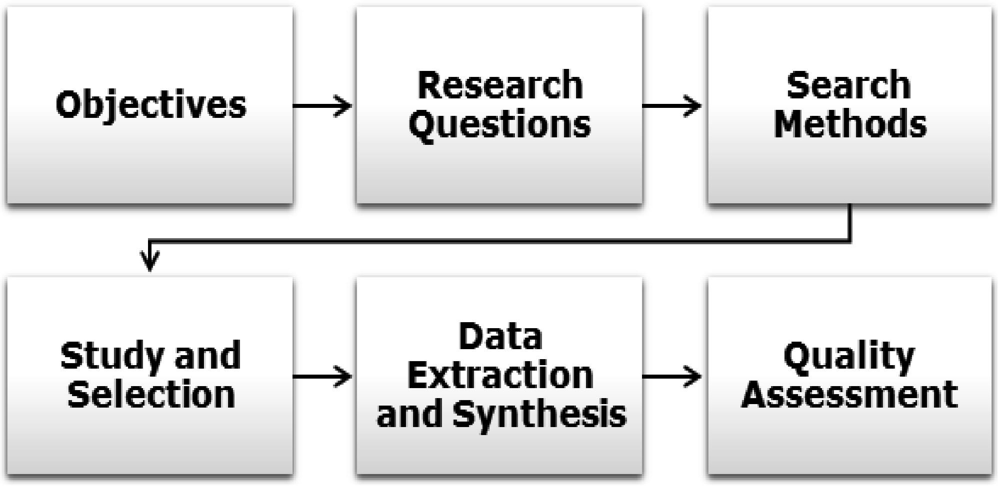

Figure 1. Steps of the literature review methodology.

2.1. Objectives

This paper describes how ontologies are created and utilized in the IoT field. The objectives of the proposed research are listed below.

1. To determine the popular ontologies in IoT
2. To identify the drawbacks of existing IoT ontologies
3. To recognize the applications of ontology in different IoT platforms and ensure the requirement of ontology development doctrines.

2.2. Research Questions

Several of the research questions in our proposed study are presented below.

RQ1. What are the different kinds of ontologies in the IoT environment?
RQ2. Why does IoT require ontology?
RQ3. What kind of languages are used for IoT ontologies?
RQ4. What are the limitations of existing IoT ontologies?
RQ5. Which studies have reclaimed IoT ontologies?

2.3. Search Method

This step of our methodology identifies the search process and the criteria for the inclusion and exclusion of literature. The following search terms are used for the retrieval of relevant literature.

2.3.1. Search Terms

1. "Ontology Engineering"
2. "Ontology Development"
3. "Ontology Construction"

4. “Ontology Techniques”
5. “Ontology Creation”
6. “Internet of Things”

These search terms are derived from different data sources, such as keywords provided by selected articles and alternative words of primary keywords. Boolean variables (OR and AND) are used to construct a search query from the already identified search terms. An example of a search query is given below.

(ontology) AND (techniques/OR engineering/OR development/OR construction/OR creation) AND (internet of things/OR IoT)

2.3.2. Inclusion and Exclusion Criteria

The goal of describing inclusion and exclusion rules is to organize major papers with the intent to deliver a clear suggestion of the research questions and reduce the possibility of bias.

(A) Inclusion Rules

- Year: 2014–2020
- Paper description: English language paper, research articles, review articles
- Paper focus: ontology engineering for IoT
- Should at least fulfill the requirement of one research question
- Should satisfy the minimum quality threshold

(B) Exclusion Rules

- Studies that do not meet the inclusion criteria, such as literature not related to ontology engineering for IoT, are excluded.
- Gray studies that pertain to articles without bibliographic facts: journal date, type, volume and topic numbers, observation, perspective, keynote, considerations, editorials, remarks, lectures, introductions, narrative papers, and presentations in slide format without any related articles are excluded.
- Duplicate papers in electronic databases are excluded.
- Studies that aim for general frameworks and methodologies and talk little about ontology development in IoT are excluded.

2.4. Study and Source Selection

Studies are selected from specific electronic databases that professionals in ontology and IoT confirm. Through the search terms, the following electronic databases are investigated: Emerald Insight, Taylor and Francis, Science Direct, IEEE Explorer, ACM Digital Library, and Scopus. Figure 2 illustrates the review procedure of studies from the selected sources and the number of studies selected at each phase. The selection of articles on IoT ontology consists of five phases. Phase 1 identifies and organizes the studies obtained from the diverse electronic databases. Phase 2 is implemented to identify duplicate studies by checking the title and author name. Phase 3 determines the studies that meet the inclusion criteria by reviewing the titles, keywords, and publication dates. Phase 4 utilizes the abstract to exclude papers that do not satisfy the inclusion criteria. The last phase is used to study the complete text of the selected papers (i.e., the output of Phase 4) and further determine whether a paper meets the inclusion criteria completely or not. After a detailed review, 115 primary articles satisfying the research questions are selected (listed in Section 2.6).

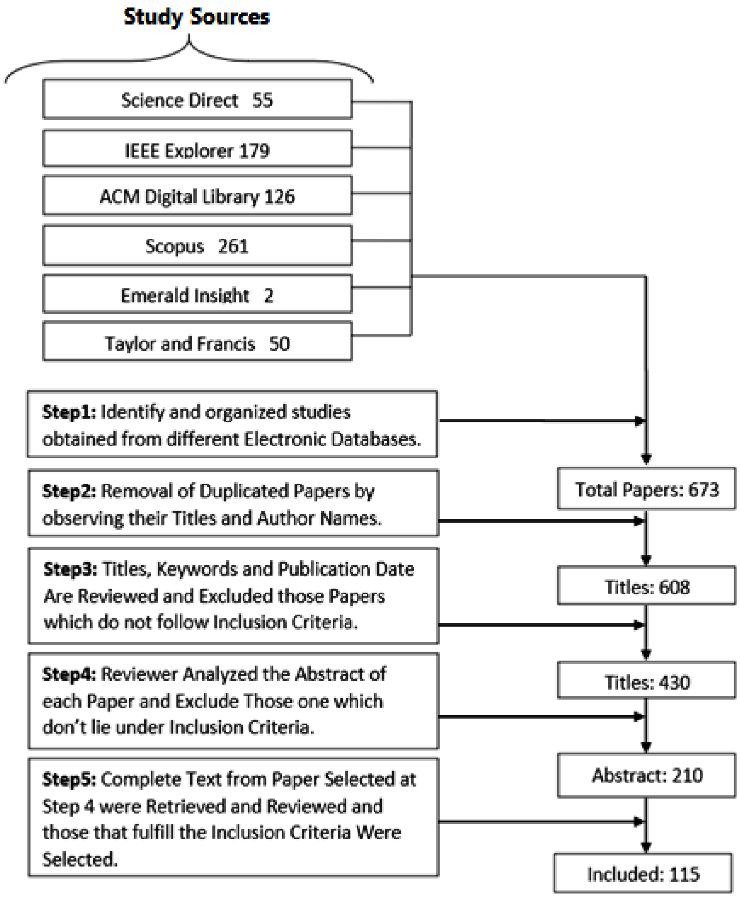

Figure 2. Flowchart representing the process of paper search and selection.

2.5. Data Extraction and Synthesis

This systematic literature review (SLR) follows the procedure in [22] as a guideline for data extraction. Data extraction entails finding data from the 115 primary articles related to our research questions. The data collected from each article include the following: (i) article title; (ii) author name; (iii) journal and its database; (iv) date of assessment; (v) data scrutiny; (vi) importance in terms of IoT ontology problems, challenges, practices, simulations, and procedures; (vii) approach used (i.e., discussion, a study of industry-specific issues, testimony, and review); (viii) methods used for justification; (ix) study drawbacks; (x) location of research; (xi) given reference; (xii) future work; and (xiii) year of publication. After completing data extraction, we examine the content of each article to understand the emphasis of every paper. As a final point, an inter-rater arrangement [23] among scholars is established to evaluate the information extraction results. A statistical measure known as the kappa coefficient [24] is applied. Kappa values smaller than 0 denote the absence of agreement, and values between 0 and 0.20 depict insignificant agreement. Kappa values between 0.21 and 0.40 show reasonable agreement, values between 0.41 and 0.60 indicate adequate agreement, values in the range of 0.61–0.80 mean substantial agreement, and values within 0.81–1 denote almost flawless agreement.

2.6. Quality Assessment Criteria and Score

Quality assessment results help increase the precision of data outcomes [25]. A quality assessment of particular studies (i.e., selected 115 papers) is performed using the simple marking method to assess the studies' reliability, completeness, and importance. The studies are assessed using four quality assessment questions shown in Table 1. When a study satisfies the defined question, it receives 1 point (i.e., Y = 1) for the given question; otherwise, it receives a mark of 0 (i.e., N = 0). When a study's influence is not sufficiently eloquent, the study receives a mark of 0.5 (i.e., P = 0.5). The first quality assessment question (i.e., Q1) has a 1 mark for a study appropriate in business/industrial processes and a 0.5 mark for educational determination. The total score is calculated by adding the obtained marks for the assessment questions. Table 2 lists the quality assessment results of the selected studies. A total of 79.13% of the studies are above 50%, with an average total score of 2.94. As indicated in Table 2, the overall minimum quality score is 62.5%, which is the overall minimum acceptable quality score. In the individual quality assessment criteria, Q1 and Q2 have high individual quality assessment scores of 78.5% and 77.5%, respectively. Q3 and Q4 have the lowest individual quality assessment scores of 73.5% and 69%, respectively. Overall, the quality of the selected studies is good. All four quality criteria are acceptable as far as the authors are concerned.

Table 1. Four basic quality assessment criteria.

	Criteria	Probable Solutions
(i).	Were the ambitions of the research expressed explicitly?	Y = 1, P = 0.5, N = 0
(ii).	Was the planned procedure described in detail?	Y = 1, P = 0.5, N = 0
(iii).	Whether the trial strategy is applicable or not?	Y = 1, P = 0.5, N = 0
(iv).	Was the investigation useful on appropriate datasets or case studies?	Y = 1, P = 0.5, N = 0

The meanings of acronyms are: Y = Yes, N = No, P = Partial.

Table 2. Quality scores of the selected papers for the four assessment questions.

ID#	Author	Year	Q1	Q2	Q3	Q4	Total Score	Quality%
1	Wei Wang et al. [26]	2012	1	1	1	1	4	100
2	Kevin Lee et al. [27]	2017	0.5	0	0.5	0.5	1.5	37.5
3	Thomas Fruhwirth et al. [28]	2018	1	1	1	0.5	3.5	87.5
4	Huijuan Zhang et al. [29]	2014	1	0.5	1	0	2.5	62.5
5	Ahmed Abatal et al. [30]	2018	0.5	1	0	1	2.5	62.5
6	Amelie Gyrard et al. [31]	2018	1	0	0.5	0.5	2	50
7	Muhammad Ghulam Kibria et al. [32]	2015	0.5	0.5	0.5	1	2.5	62.5
8	Henrique Brittes Potter et al. [33]	2016	0.5	1	0.5	1	3	75
9	Xiaoming Zhang et al. [34]	2015	0.5	0	0.5	0	1	25
10	Lyazid Sabri et al. [35]	2017	1	1	0.5	0.5	3	75
11	Fabiano B Ruy et al. [36]	2015	0	0.5	0.5	0	1	25
12	Hisham Kanaan et al. [37]	2017	1	1	0.5	1	3.5	87.5
13	Yuqing Yan et al. [38]	2018	0	0.5	0.5	0	1	25
14	Bruno A. Mozzaquatro et al. [39]	2016	1	1	0.5	0.5	3	75
15	Ahmed Sameh et al. [40]	2018	0.5	0.5	1	0.5	2.5	62.5
16	Yajuan Guan et al. [41]	2017	0.5	0.5	1	1	3	75
17	Amelie Gyrard et al. [42]	2015	0	0	0.5	1	1.5	37.5
18	Eliot Bytyci et al. [43]	2016	0.5	1	1	0.5	3	75
19	Marie Kim et al. [44]	2017	0	0.5	0	0.5	1	25
20	Feng Gao et al. [45]	2017	0	0.5	0.5	0	1	25
21	Zubeida C Khan et al. [46]	2017	0	0.5	0	0	0.5	12.5
22	Alexey Kashevnik et al. [47]	2018	0.5	0.5	1	0.5	2.5	62.5
23	Melinda Kingsun et al. [48]	2018	0	1	0.5	0.5	2	50
24	Panagiotis Kasnesis et al. [49]	2015	1	1	1	0.5	3.5	87.5
25	Amelie Gyrard et al. [50]	2016	0.5	1	1	0.5	3	75
26	Hoan-Suk Choi et al. [51]	2016	0.5	0.5	0	1	2	50
27	David Perez Abreu et al. [52]	2017	1	1	1	0.5	3.5	87.5
28	Mohit Mittal et al. [53]	2017	0.5	1	0.5	0.5	2.5	62.5
29	Charilaos Akasiadis et al. [54]	2015	0.5	0.5	0.5	1	2.5	62.5

Table 2. *Cont.*

ID#	Author	Year	Q1	Q2	Q3	Q4	Total Score	Quality%
30	Omer Berat Sezer et al. [55]	2015	1	0.5	1	0.5	3	75
31	Alfred Zimmermann et al. [56]	2015	0	0.5	0.5	0.5	1.5	37.5
32	Laszlo Kovacs et al. [57]	2018	0.5	0	1	0.5	2	50
33	Mahmud Al-Osta et al. [58]	2018	0.5	0.5	0.5	1	2.5	62.5
34	Hyun Jung La et al. [59]	2015	1	1	1	1	4	100
35	Alexander Willner et al. [60]	2015	0	0	0	0.5	0.5	12.5
36	Na-Ri Yang et al. [61]	2014	1	1	1	1	4	100
37	Yulia Evchina et al. [62]	2016	0	0	0.5	1	1.5	37.5
38	Sajjad Ali et al. [63]	2016	0.5	1	0	0.5	2	50
39	Agung Prasetio et al. [64]	2017	0	1	0.5	0.5	2	50
40	Shaun Howell et al. [65]	2017	0.5	1	0.5	1	3	75
41	C. Alexakos et al. [66]	2015	0.5	1	1	0.5	3	75
42	Mengru Tu et al. [67]	2018	0.5	0.5	0	0.5	1.5	37.5
43	Hoan-Suk Choi et al. [68]	2014	0.5	1	1	0.5	3	75
44	Mujahid Mohsin et al. [69]	2017	1	1	1	0.5	3.5	87.5
45	Maria Bermudez-Edo et al. [21]	2017	1	1	1	0.5	3.5	87.5
46	Muhammad Ghulam Kibria et al. [70]	2015	1	1	1	1	4	100
47	Muhammad Ghulam Kibria et al. [71]	2016	0.5	0.5	0.5	1	2.5	62.5
48	Amelie Gyrard et al. [72]	2016	1	0	0.5	1	2.5	62.5
49	Sajjad Ali et al. [73]	2017	0.5	0.5	0.5	1	2.5	62.5
50	Charbel El Kaed et al. [74]	2017	0.5	0.5	0	1	2	50
51	Xiaoliang Meng et al. [75]	2014	0.5	0.5	0	0	1	25
52	S M Nahian Al Sunny et al. [76]	2017	1	1	0.5	0.5	3	75
53	Guangquan Xu et al. [77]	2017	1	1	1	0.5	3.5	87.5
54	Ioan Szilagyi et al. [78]	2016	1	0	1	0.5	2.5	62.5
55	Anupama Mallik et al. [79]	2015	1	0.5	0.5	1	3	75
56	Yasir Imtiaz Khan et al. [80]	2018	1	0.5	0.5	0	2	50
57	Elaheh Maleki et al. [81]	2018	1	0.5	0.5	1	3	75
58	Charles Steinmetz et al. [82]	2017	1	1	1	0	3	75
59	Cleo Sgouropoulou et al. [83]	2015	0	0	0	0	0	0
60	Youngjun Kim et al. [84]	2014	0.5	0	0.5	0	1	25
61	I-Ling Yen et al. [85]	2016	0.5	1	0.5	0.5	2.5	62.5
62	Inna Sosunova et al. [86]	2017	0.5	0	0	1	1.5	37.5
63	Michael Compton et al. [17]	2012	0	1	0	0	1	25
64	Kunal Suri et al. [87]	2017	1	0.5	1	0.5	3	75
65	Min-Jung Yoo et al. [88]	2016	0.5	0.5	0.5	1	2.5	62.5
66	Amelie Gyrard et al. [89]	2015	0.5	0.5	0.5	0.5	2	50
67	Christoph Legat et al. [90]	2014	0	0.5	0.5	0	1	25
68	Maxim Kolchin et al. [91]	2016	1	0.5	0.5	0.5	2.5	62.5
69	Xingchao Wang et al. [92]	2015	1	1	0.5	0.5	3	75
70	I-Ling Yen et al. [93]	2018	0	1	0.5	0.5	2	50
71	Sang Hum Lee et al. [94]	2014	1	1	0.5	0.5	3	75
72	Bruno A. Mozzaquatro et al. [95]	2017	0.5	1	0.5	0.5	2.5	62.5
73	Krzysztof Janowicz et al. [19]	2018	0.5	1	1	0.5	3	75
74	An Ngoc Lam et al. [96]	2018	1	1	1	0.5	3.5	87.5
75	Ambreen Hussain et al. [97]	2017	0.5	1	0.5	0.5	2.5	62.5
76	Mahdi Ben Alaya et al. [98]	2015	0.5	0.5	1	0.5	2.5	62.5
77	Archana Chougule et al. [99]	2016	1	1	1	1	4	100
78	Sajjad Ali et al. [100]	2017	0.5	0.5	1	0.5	2.5	62.5
79	Lina Lam et al. [101]	2019	0.5	0.5	0	0.5	1.5	37.5
80	Ahlem Rhayem et al. [102]	2017	1	0.5	1	1	3.5	87.5
81	T. Elsaleh et al. [103]	2019	1	1	1	1	4	100
82	Varun M Tayur et al. [104]	2019	1	1	0.5	1	3.5	87.5
83	Marc-Oliver Pahl et al. [105]	2019	0	0.5	1	0	1.5	37.5
84	Rose Yemson et al. [106]	2019	1	0.5	0.5	1	3	75
85	Roberto Yus et al. [107]	2019	1	1	1	1	4	100
86	Vusi Sithole et al. [108]	2019	1	1	0	0.5	2.5	62.5
87	Soulakshmee Devi Nagowah et al. [109]	2019	1	1	1	1	4	100
88	Yue Xu et al. [110]	2018	1	1	0.5	0.5	3	75
89	Sondes TITI et al. [111]	2019	1	1	1	1	4	100

Table 2. *Cont.*

ID#	Author	Year	Q1	Q2	Q3	Q4	Total Score	Quality%
90	Adrian Taboada Orozco et al. [112]	2019	1	1	1	0.5	3.5	87.5
91	Shuai Zhang et al. [113]	2019	0.5	1	1	1	3	75
92	Pablo C. Calcina-Ccori et al. [114]	2019	1	0.5	1	0.5	3	75
93	Anderson Soares Costa et al. [115]	2019	1	1	1	0.5	3.5	87.5
94	Milankumar Patel et al. [116]	2019	1	0.5	0.5	1	3	75
95	Michalis Georgiou et al. [117]	2019	0.5	0	0.5	0	1	25
96	Wenxi Zeng et al. [118]	2019	1	1	1	0.5	3.5	87.5
97	Kamal Uddin Sarker et al. [119]	2019	1	1	0	0.5	2.5	62.5
98	Valerie Issarny et al. [120]	2019	1	0.5	0.5	1	3	75
99	Pablo C. Calcina-Ccori et al. [121]	2019	1	1	1	0.5	3.5	87.5
100	Sara Bonfitto et al. [122]	2019	0.5	0.5	0	0.5	1.5	37.5
101	Abdelkader Magdy Shaaban et al. [123]	2019	1	1	0.5	0.5	3	75
102	Lidia Bajenaru et al. [124]	2019	1	0.5	1	0.5	3	75
103	Santiago Gil et al. [125]	2019	1	0.5	0.5	0.5	2.5	62.5
104	Daoqu Geng et al. [126]	2019	1	1	1	0.5	3.5	87.5
105	Matthew Weber et al. [127]	2019	0.5	0	0.5	0	1	25
106	Angelos Chatzimichail et al. [128]	2019	0.5	0	1	0	1.5	37.5
107	Mayke Ferreira Arruda et al. [129]	2019	1	0.5	0.5	1	3	75
108	Pedro Gonzalez et al. [130]	2019	1	0.5	0.5	0.5	2.5	62.5
109	Mahda Noura et al. [131]	2019	1	0.5	0.5	1	3	75
110	Hoan Le et al. [132]	2020	1	1	1	0.5	3.5	87.5
111	Vatsala Nundloll et al. [133]	2020	0.5	1	1	0.5	3	75
112	Amri Toumia et al. [134]	2020	1	1	0.5	1	3.5	87.5
113	Luca Turchet et al. [135]	2020	1	1	1	1	4	100
114	JongGwan An et al. [136]	2020	1	1	1	1	4	100
115	Igor Tomicic et al. [137]	2020	1	1	1	1	4	100

3. Results and Analysis

3.1. Overview of Selected Articles

In this SLR, 115 studies are selected. From these studies, 85 appeared in conferences, 20 were published in journals, 5 were reported in a symposium, 1 was from a workshop, 1 was from a newsletter, 1 was from a book chapter, 1 was from a proceeding, and 1 was derived from a magazine (see details in Appendix A Table A1). Figure 3 shows the respective percentages of the studies selected for SLR from different publication sources. Figure 4 depicts the number of articles in terms of the year of publication. From a chronological point of view, publications have been increasing since 2012. 2019 is the year with the maximum publications (i.e., 26.09%), followed by 2017 (20.87%), 2015 (14.78%), 2018 (13.04%), 2016 (12.17%), 2014 (6.09%), 2020 (5.22%), and 2012 (1.74%). The obvious rise in the number of studies on semantic interoperability in IoT using ontology indicates that the subject is trending.

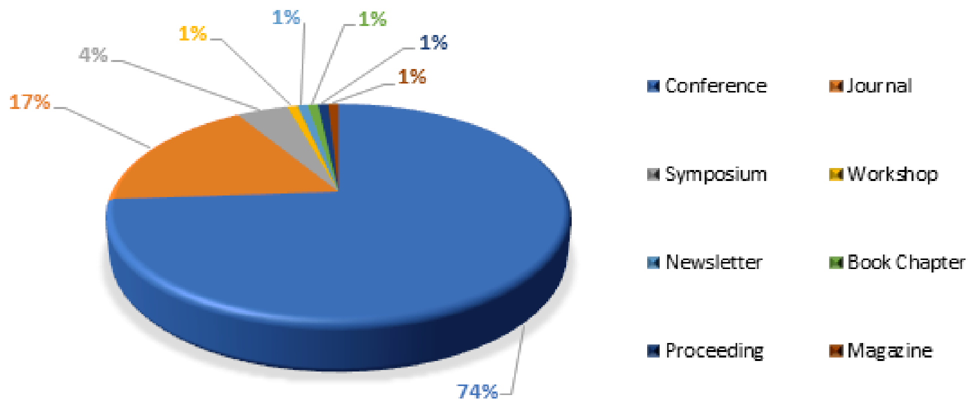

Figure 3. Percentage of selected papers in different publication sources.

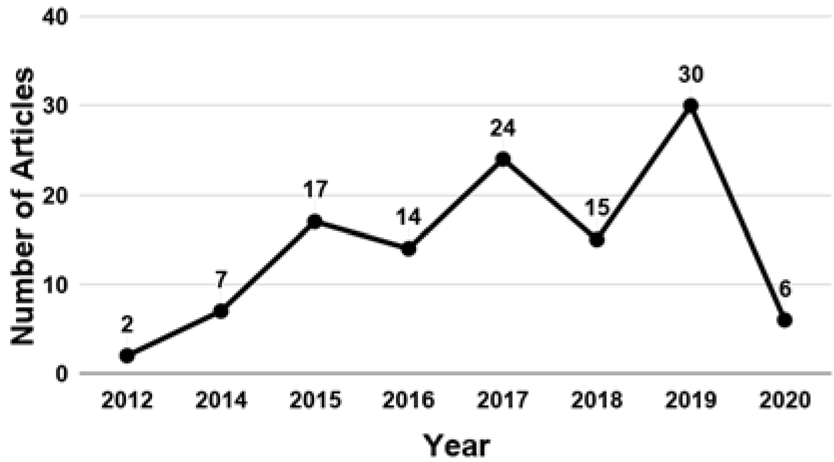

Figure 4. The selected number of studies per year for the review.

3.2. Different Kinds of IoT Ontologies (RQ 1)

Different ontologies have been used to solve IoT problems, and the most used ontology is the web of objects (WoO) semantic ontology (10% of the total studies discussed it). SSN ontology is also used by three studies, which constitute 6% of the total articles. The other ontologies used are description ontology, IoT-O ontology, IoT-Lite ontology, and IoT-Sec ontology; each is used two times in the selected papers, that is, 4% of the total papers. The selected studies identified a total of 45 ontologies in different IoT scenarios. Figure 5 depicts the most cited and applied ontologies in the IoT environment.

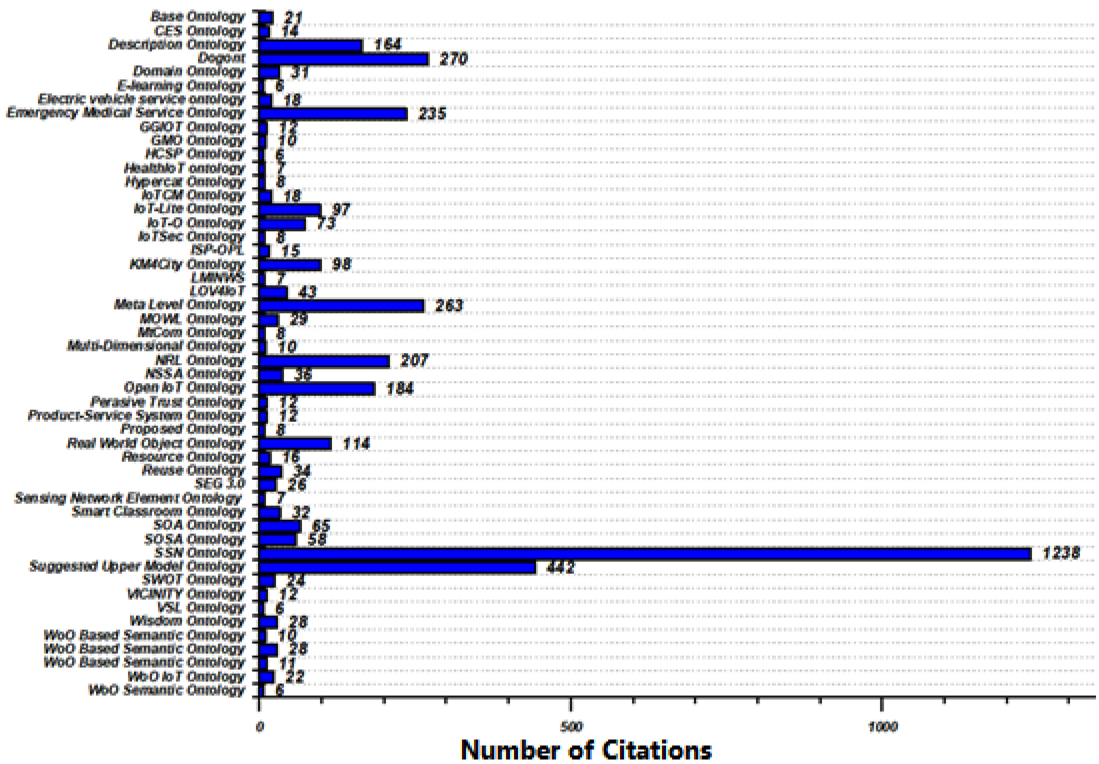

Figure 5. Existing ontologies in IoT.

For instance, the authors in [98] introduced IoT-O ontology that consists of five main components: sensor, observation, actuator, actuation, and service models. SSN ontology was established over a period of one year by group agreement [17]. The creators of the ontology decided that only concepts and relations applicable to sensors should be included, which led to the SSN being selected in multiple domains and third-party ontologies. Moreover, this ontology is flexible and supports reusability. According to [17], the SSN ontology can be viewed from four major viewpoints. The sensor viewpoint focuses on sensors, including what a sensor is sensing, how it is being sensed, and what is actually sensed. The data viewpoint focuses on observations and their associated metadata. The system viewpoint focuses on what kind of sensor systems are to be deployed. The property viewpoint concentrates on what interpretations have been made about a property or senses a specific property.

The DogOnt ontology emphasizes interoperation between home automation sensors or devices [20]. DogOnt has five main components: building thing, building environment, state, functionality, and home automation network component. The NRL ontology is formed by combining seven security ontologies [69], where each ontology has its special security field, such as authorizations, algorithms, assertions, and observations. It also includes instructions, mechanisms, policies, and a specific ontology (i.e., OWL-S service ontology) for questioning and related services. The GAIA-MAS ontology (GMO) [66] describes the multi-agent system used in the GAIA approach. It works as a meta-model to represent different objects of GAIA based on MAS, which means GMO is built on top of the GAIA conceptual model. It comprises super classes, such as agent system, agent system entity, and abstract concept. The primary purpose of GMO is to demonstrate how the multi-agent system can be easily unified with IoT tools, such as sensors and RFID. This union, in turn, can be utilized to integrate all of the systems involved in the manufacturing process of an industrial or enterprise environment. POR's main aim is to create a new "ontology repository" atmosphere that is different from other former repositories [40]. The goal of the suggested new repository environment is to provide a form of ontology guidance service to help non-domain software developer experts obtain the knowledge required to build their software. IoT-A [54] consists of two main classes called Resource and Service. The resource gives information about hardware modules, such as wireless sensors and devices. Service explains the working of its related Resource to the world. Services can be in the form of software and web services describing what a service can do and how much the service affects the physical world area, which may be a smart home, agricultural area, or manufacturing area.

To improve the alliance between business and IT societies, the SOA ontology [56] defines the fundamental concepts, vocabulary, and semantics of a service-oriented architecture. Architecture ontologies share information based on explicitly defined concepts, so a shared dictionary for enterprise architects is required. To this end, SOA provides the opportunity to deduce transitive knowledge automatically. The main purpose of IoT-Lite ontology [57] is to define the essential ontology modules necessary for an IoT agent. This definition allows the interoperability and detection of sensory data in various IoT platforms. The main concepts of the IoT-Lite ontology consist of objects (i.e., features and position), devices (e.g., sensors, actuators, and RFID tags), and services that are delivered by a device.

Smart home ontology (SHO) [55] entails a simulation that uses home devices, such as computers, home appliances, security, and lighting. All of these devices are modeled separately. Simulation is implemented by applying a master/slave model. All demonstrated devices are linked to each other by a message queue. The master node acts in the form of the main computer, and all connected devices act as slaves that receive commands from the main computer. WoO explains data, information, and knowledge [84]. Data are collected through devices, but data are useless without performing any operation. Information grants meanings to data (i.e., metadata), and knowledge delivers the most appropriate information from different sources to fulfill user, service, and environment requirements. The multimedia web ontology language (MOWL) is used for illustration and as a cognitive approach [79]. Diverse sensors and other devices, such as motion sensors, cameras, temperature sensors, and photo sensors, produce outputs in different media layouts, including audio, video, and text. Therefore, the IoT field needs ontology to represent multimedia. MOWL provides the simple groundwork for converting information on an IoT field with multimedia inputs from multi-model devices, thus supporting full-time data interpretations.

3.3. IoT Requirements of Ontology (RQ 2)

The requirements for ontology in the IoT domain are discussed in this section to answer the second research question. The selected studies help analyze the IoT ontology requirements. Table 3 depicts the IoT ontology requirements, which are divided into three: interoperability, integration, and privacy. Interoperability requirements were discussed extensively in the existing studies; 36 studies (31.30% of the total articles) discussed them. Privacy and security requirements were discussed in 13.04% of the studies, and 10.43% of the studies illustrated the integration requirement. Notably, an article can fulfill more than one IoT requirement.

Table 3. Requirements of Ontology in IoT.

Serial No.	Ontology Requirements for IoT	Count	Paper ID	%
R1	Interoperability	36	1, 3, 6, 16, 17, 22, 25, 35, 38, 40, 45, 46, 48, 49, 50, 54, 56, 59, 65, 69, 74, 75, 76, 78, 81, 82, 85, 86, 87, 89, 93, 95, 110, 111, 113, 114	31.30
R2	Integration	12	8, 9, 10, 19, 20, 26, 29, 31, 41, 68, 92, 105	10.43
R3	Privacy and Security	15	12, 14, 28, 44, 52, 53, 72, 79,94, 101, 106, 107, 108, 112, 115	13.04

3.3.1. R1: Interoperability Requirement

With regard to the IoT interoperability requirement, ontology was used in 36 of the studies. The ID 1 study described the strategy of a complete ontology for knowledge depiction in IoT. It also talked about how it can be used to support responsibilities such as analysis, service finding, and dynamic configuration. ID 3 proposed reutilizing the existing ontologies on one side and developing reusable ontologies on the other. In this study, a multi-agent system was presented for performing optimization in the smart energy field. In addition, the application-specific ontologies in the domain of IoT were utilized to support the agent system. ID 6 attempted to assess and examine the existing state of ontology-based software tools for semantic interoperability. The study proposed constructing a platform that connects several ecosystems exhibiting "interoperability as a service" for infrastructures in IoT. The methodology is bottom–up, distributed, user-centric, and standards-based without depending on a single standard.

ID 17 discussed the proposal about the semantic web of things (SWoT) ontology to support IoT developments, such as (i) constructing an interoperable SWoT product describing interoperable semantic-based IoT application outlines, (ii) simply deducing high-level concepts from sensor readings under the directions of a given template, (iii) planning domain-oriented or inter-domain IoT applications by using the SWoT model, and (iv) advocating for reutilizing ontology as much as possible to anticipate contextual data. ID 22 recommended an approach based on ontology-based context administration, published semantic interoperability support, and used block-chain techniques. ID 25 recommended SEG 3.0 and used it in IoT, specifically for the smart city scenario, as evidence of conception. First, features that were necessary for the methodology were identified. Second, various formal phases and techniques for the approach were also defined. Lastly, evidence of applying this approach was made available. ID 35 introduced a model for semantic information exchange. The study described approaches to formally define coalitions, including their infrastructures and the life cycle of the offered resources and services. The work contributes to upper-level ontology and the primary integration of its concepts. These previous offerings have become a base for future work in the field of distributed semantic source management. ID 38 described the IoT service execution model established on the WoO platform to support the living ecosystem.

ID 40 revealed a use case of smart home application interoperability. The study recommended that semantic web technologies and IoT can be combined to form big data models with dynamic data streams. ID 45 suggested using IoT-Lite, an extension of the SSN ontology, to define important IoT concepts and allow the interoperability and detection of sensory data in various IoT platforms by using lightweight semantics. ID 46 presented a method for collaboration between a physical device, a smartphone, and a WoO application server. An abstract semantic ontology model was presented for data reusability and interoperability among virtual objects (VOs). In ID 48, the linked open vocabularies for IoT (LOV4IoT) dataset were created, focusing on referencing and categorizing semantics-based tasks related to IoT. The dataset was established to support interoperable domain instructions for deducing high-level generalizations based on sensor data using scheming sensor-based linked open rules (S-LOR). In ID 49, a microservices model built on the WoO IoT platform was presented to facilitate interoperability in gloomy conditions. ID 50 suggested a model-driven approach that adopts current ontology collections and frameworks to speed up the implementation of ontology-based IoT application development. ID 54 presented a semantic web stack for IoT that highlights the limitations in the creation of an IoT application or service. ID 56 indicated the need for security rules for the interoperability of smart home entities. To this end, a context-based ontology was created to support diverse perspectives, such as user and physical perspectives. ID 59 talked about the deployment method for the AgRes ontology. The method defines the ontology and interoperability stages of the AgRes online application. ID 64 concluded that ontologies act as assisting and semantic interoperability technologies for the establishment of services, such as device charging, location discovery, and traffic management.

In ID 69, semantics and ontology technologies were used in the process of detecting devices in the IoT environment. First, a common sensing network ontology structure was constructed for the device detection process. Second, the main classes and their hierarchy were defined. Third, the components and relationships that were openly associated with the sensor component were constructed. The authors argued that the proposed ontology offers semantics by which sensing network elements in IoT can be inevitably discovered and worked together. ID 74 presented a methodology, namely, automatic computing, to assist the progress of interoperable IoT elements at the semantic level. The methodology was assessed via different performance criteria in a smart home scenario. ID 75 utilized an IoT-centered healthcare scheme, which appears useful in water information systems. ID 76 proposed an ontology for IoT called IoT-O. IoT-O was developed using previously distinct ontologies to justify the concepts that apply to the IoT environment, such as device, node, actuator, and actuation. ID 81 proposed a lightweight semantic ontology model to interpret IoT data streams. Data search and discovery were performed using data types (i.e., metadata descriptions) of ontology. ID 82 presented a model for data interoperability between different sensors. The model transforms raw sensor data into knowledge. The input consists of raw sensor observations that are annotated using ontologies. In ID 85, interoperability of heterogeneous data was achieved by designing semantic and data exchange layers. An extensible and general metamodel for the semantic layer was presented by utilizing the popular SOSA and SSN ontologies. This layer helps describe fixed and dynamic features depending on the field (spatial aspects and users). To accomplish interoperability, the data exchange layer summarizes the machine-level communication. ID 86 reported that the interoperability of different devices needs to be considered in the design of IoT reference architectures. Such interoperability can be achieved by establishing a lightweight ontology that can be used to organize the data of different devices. ID 87 described an ontology for smart classrooms in a university campus to deal with semantic interoperability problems in an IoT-supported campus situation. ID 89 suggested a healthcare-IoT-based model where an ontology is responsible for semantic interoperability between various devices and users in the healthcare field. ID 95 recommended a semantic enhancement of the Hypercat descriptions that increases interoperability using a JSON-LD-based directory.

3.3.2. R2: Integration Requirement

ID 08 presented a method to incorporate dynamic devices into IoT-based situation-aware structures. The method (known as ContQuest) proposes a number of middleware facilities for situation-aware applications, which offer adaptative capabilities for complex data. A device is reflected as a resource in the ContQuest method; therefore, it is known as a resource agent. Every resource agent follows the proposed design that intends to simplify the integration and utilization of various devices. ContQuest also contains design solutions to adjust devices that have dissimilar communication rules. ID 09 and ID 10 presented methods that offer visual data facilities for various sensor data in the RDF form to support integration. Each method produces SPARQL query statements dynamically and automatically according to the situations selected by end users. The method can also perform semantic deduction based on personalized instructions given by users. ID 19 put forward a unique idea of machine integration via semantic technology. The presented model consists of ontology modeling and a set of machine-learning rules for the suggested concept of semantic filtering. ID 20 presented a middleware known as an automated complex event implementation system (ACEIS) among sensor data streams and smart city applications. The ACEIS performs two major tasks: identifying and putting together IoT device-generated data in a city environment and creating IoT-generated stream queries for observing the requested complex events. ID 26 presented cross-domain situations in which the heterogeneity of the data format can be removed and integrated via common meta-data descriptions. ID 29 explored the integration issue from a developer's viewpoint. The authors designed an ontology for smart meeting rooms. They emphasized real-world cases, such as applications for calculating the persons inside a smart meeting room using ontology expertise to support IoT. ID 31 provided a new meta-model for incorporating IoT objects, wherein the objects are semi-automatically merged into a complete digital enterprise architecture. ID 41 increased the independence and elasticity in the manufacturing atmosphere. This achievement ultimately changed the interoperability and the way industrial products and ecosystems are integrated. ID 68 defined a middleware called SemIoT Platform. The SemIoT utilizes semantic web technologies, current ontologies, and the REST architectural style to fulfill the needs of an IoT environment. The authors also assessed SemIoT's characteristics through a use case. ID 92 planned a semantic illustration of geolocation to be integrated into the Swarm structure (i.e., a middleware for distributed assistance of devices in IoT).

3.3.3. R3: Security/Privacy Requirement

ID 12 suggested a distributed ontology-based system to satisfy healthcare institute privacy requirements regarding advanced IoT and electronic health records. ID 14 proposed an ontology-centered security framework for decision-making to improve the protected information of industrialized systems. The IoTSec ontology was proposed to enhance system security utilizing queries gathered from the surroundings. ID 28 reported that the major problem faced by current IoT systems is security. Different attacks on IoT systems were discussed in this article, and it emphasized the ontology-based model as a solution for different attacks. The IoTChecker tool, which is used to capture anomalies spontaneously in IoT security configurations, was presented in ID 44. The tool utilizes multiple IoT ontologies to recognize the threats to the IoT environment. Overall, the tool is easily adjustable and scalable. It performs significantly better in finding faults than the manual analysis of IoT configuration. ID 52 described the design of an agent–adapter structure for exchanging engineering services across the Internet. ID 72 discussed situation-aware cybersecurity in IoT by utilizing a reference ontology. The ontology was used to deal with various situational models and security problems. ID 79 illustrated IoT applications on the cloud platform. An ontology-based resource depiction model was proposed to deliver reliable assessments of various detecting devices. The proposed model offers integrated access, mechanism, and privacy for IoT devices. ID 94 suggested the need for trust between IoT devices and created a well-expressed trust ontology. ID 101 presented an ontology-centered security tool that can be useful in the early phases of developing critical systems. The tool uses ontology to confirm that the intended security requirements are achieved. ID 106 recommended a method for merging devices effectively. The method adopts ontology and offers safe and secure alerts to people. ID 107 incorporated a lightweight privacy layer (IoT-Priv) into simple IoT concepts, such as device, measuring device, and service. The IoT-Priv ontology proposal matches IoT requirements to particular privacy terms and expresses actions under different consequences.

3.4. Ontology Languages Used in IoT (RQ 3)

The most important ontology languages that have been used to support IoT ontology development activities are identified to answer this research question. These languages are represented as semantic web knowledge stacks [15], such as extensible markup language (XML), resource description framework (RDF), SWRL, and OWL (the latest). However, other languages are identified from the articles and considered in the classifications to answer the research question. Table 4 depicts how much each language is utilized in the articles. W3C-recommended languages were used widely in the selected articles. Most of the studies used OWL, which includes 41 articles accounting for 35.65% of the total articles. The second most used ontology language is RDF, which was used in 16 articles, that is, 13.91% of the total articles. The SPARQL query language was utilized in 12 articles and accounted for 10.43% of the total studies. The SWRL rule language was used in 10 articles (8.7% of the total articles). XML was used in five articles and accounted for 4.35% of the total articles. PHP, HTML, CSS, JS, and JSON were used only in two articles, which is 1.74% of the total studies. The least used ontology languages were OPL, Protégé, Jena, Java, and MOWL, which were adopted in only one study. In addition, several articles did not use any ontology language. These papers were placed under the non-specific category at the end of Table 4. The non-specific articles are 21 in total and included in the analysis because they give answers to the other research questions, except for RQ3.

Table 4. Popular Languages of Ontology in IoT.

Ontology Languages	Count	Paper ID	%
OWL/OWL-S	41	1, 3, 4, 7, 8, 15, 16, 17, 22, 33, 35, 36, 41, 42, 44, 45, 46, 47, 51, 53, 55, 57, 58, 59, 62, 70, 71, 73, 74, 75, 76, 77, 84, 107, 109, 110, 111, 112, 113, 114, 115	35.65
RDF	16	10, 19, 23, 26, 31, 34, 40, 48, 65, 68, 78, 79, 85, 93, 104, 105	13.91
SPARQL	12	5, 21, 29, 30, 37, 38, 39, 49, 50, 82, 92, 99	10.43
SWRL	10	11, 13, 25, 45, 63, 64, 80, 88, 89, 90	8.70
XML	5	2, 9, 52, 60, 61	4.35
SOSA	2	72, 81	1.74
PHP, HTML, CSS, JS	2	6, 18	1.74
JSON	2	95, 100	1.74
OPL	1	12	0.87
Protégé/Jena	1	27	0.87
MOWL	1	56	0.87
Java	1	94	0.87
Non-specific	21	20, 24, 28, 32, 43, 54, 66, 67, 69, 83, 86, 87, 91, 96, 97, 98, 101, 102, 103, 106, 108	18.26

OWL, RDF, SPARQL, SWRL, and XML languages are recommended semantic web technologies by W3C. SOSA (PHP, HTML, CSS, and JS), OPL (Protégé/Jena), Java, JSON, and MOWL are not part of W3C but are also popular ontology languages. With regard to the usage of ontology languages, Table 4 shows that 73.04% of the total studies (i.e., 78 articles) used W3C-suggested languages for IoT ontologies rather than other languages. Only 10 studies used W3C non-recommended languages. Therefore, we can posit that W3C-mentioned languages are popular for building ontologies. Although OWL is the most widely acknowledged ontology language, half of the studies used it as an ontology-building language. We can also conclude that many studies that put forward the use of ontologies in the IoT procedure are still not ensuring the appropriate action of using standard languages to form formal ontologies.

3.5. Limitation of Existing IoT Ontologies (RQ 4)

Many ontologies have been defined explicitly for IoT platforms, but none is complete and contains all principal concepts. Therefore, ontology engineers should reuse existing ontologies and build a new ontology by combining new knowledge with existing ontologies depending on the domain requirements. Furthermore, several ontological languages, such as RDF, RDF Schema, OIL, DAML+OIL, and OWL, are available for classifying or editing ontologies. These languages enable the exchange of data between different applications associated with ontologies. Still, it is impossible to swap or reuse data among IoT ontologies that do not have the same language. Another problem with IoT ontology is that it may contain inconsistencies, which cause difficulties in describing concepts. Another disadvantage is the synonyms and illustrations in IoT ontologies. Demonstrating synonyms can be performed via two techniques. The first method deals with any two synonyms by using a new relationship because both are well-thought-out ideas and are thus included in the IoT ontology. In the second method, both synonym items are regarded as a single concept with two or more related terms, which means there are two graphical illustrations at the terminological level but only one at the abstract level. These two methods represent the lack of agreement about synonyms and introduce distortion in knowledge. These issues limit the reusability and interchangeability of IoT ontologies. Another limitation is the availability of tools for creating IoT ontologies. However, most of the studies depicted two main choices of ontology tools: standard ontology editing tools (e.g., Protégé) and an ontology-centered terminological resource editor (e.g., Ontoterm) [138].

Security in IoT ontology is necessary to ensure the privacy of the owner's sensitive data. Researchers from the International Data Space Association [139,140] conducted a study and identified over 200 companies facing the problem of losing control over data by using an IoT ontology. Most of the companies were in distress because of losing data autonomy. In this context, we need to understand the data owner. For instance, an IoT vendor (who installs sensors in public transport) can be considered a data owner [139]. By contrast, the owner of the data is the public. For instance, passengers using public transport are things, and they are the actual owners of the data. Maintaining data privacy in IoT ontology is an open challenge. However, existing privacy security approaches for IoT ontology consist of encrypted and anonymized methods, which are mostly available for particular services. Therefore, novel privacy protection techniques for independent services, such as encrypted searching techniques, usage control, and end-to-end encryption for things, automated devices, handlers, and subsystems, are needed.

3.6. Reuse of Ontologies (RQ 5)

This research question is answered by determining which articles reused ontologies from the perspective of IoT. All articles are shown in Table 5 according to whether they reused ontology. According to the table, most of the reviewed articles (i.e., 83 articles or 72.17% of the total) did not reuse ontology. This finding implies that these articles designed their ontology for a specific study area, such as home automation, smart city, and smart agriculture. Meanwhile, 32 articles

(27.83% of the total) reused ontologies in constructing their IoT ontology. The yes classification in Table 5 denotes the ontology reused by the studies.

Table 5. Reuse of Ontologies in Different Publications.

Reuse of Ontology	Count	Paper ID	%Age
Yes	32	1, 3, 6, 7, 11, 15, 16, 20, 28, 38, 42, 43, 44, 45, 46, 47, 57, 65, 67, 68, 73, 76, 82, 85, 87, 89, 90, 107, 109, 110, 112, 115	27.83
No	83	2, 4, 5, 8, 9, 10, 12, 13, 14, 17, 18, 19, 21, 22, 23, 24, 25, 26, 27, 29, 30, 31, 32, 33, 34, 35, 36, 37, 39, 40, 41, 48, 49, 50, 51, 52, 53, 54, 55, 56, 58, 59, 60, 61, 62, 63, 64, 66, 69, 70, 71, 72, 74, 75, 77, 78, 79, 80, 81, 83, 84, 86, 88, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 108, 111, 113, 114	72.17

To describe the data collected from the physical world by IoT devices, ID 1 defined ontology and reused the concepts of the SSN ontology. Concepts like observation and measurement were reused from the SSN ontology. ID 3 introduced a split-and-conquer method for reusing existing ontologies. The method consists of three major stages: (i) dividing an ontology into small chunks, (ii) modeling the ontology vocabulary to derive an application-oriented ontology, and (iii) selecting specific fragments from the chunks of existing ontologies according to application requirements. The selected fragments are combined to create an application-oriented ontology. ID 3 reported that ontology patterns in an existing ontology framework could help improve the performance of approaches for new ontology learning. ID 15 reused cinema and security management ontologies to describe terms and features, add restrictions, and construct instances to produce an improved ontology description. ID 16 believed that one of the core requirements of the VICINITY project is to reuse existing ontologies to increase interoperability among systems. The complex event service (CES) ontology reuses existing ontologies using Jena 3.0 to validate complex service requirements [45].

To facilitate the interoperability of IoT data (features such as common vocabulary, machine readability, and reusability), JADE agents were deployed in [53] using IoT ontologies. WoO can simulate real-world things using ontology semantics, thereby supporting data reusability, extensibility, and interoperability [63]. In another study, WoO objects were correlated with VOs by using ontology to form composite VOs [70]. The authors believed that composite VOs offer reusability, extensibility, and interoperability for knowledge-based IoT services. ID 44 adopted a top–down methodology to create five distinct ontologies focusing on the characteristics of the IoT environment. The ontologies were established with features such as compatibility with recent IoT ontologies, reuse of ontologies, modularity, and online distribution of established ontologies. In [22], rules were proposed for the IoT-Lite ontology to create a scalable and reusable semantic model for IoT. In ID 57, the authors proposed an ontology where the sub-classes can be reused due to their modular structure. Furthermore, the ontology can be integrated with IoT ontologies via context-specific classes and relationships. ID 65 constructed the DOLCE Ultra Lite (DUL) ontology using the core classes of the SSN ontology. A novel methodology was proposed in [89], in which existing ontologies can be reused in new domain knowledge (i.e., ontology) to simplify the interoperability of IoT devices, investigations, and services. The new ontology was used as the core of the FIESTA-IoT EU mission. The authors in [90] provided a list of fundamental requirements, which, if followed, improve the reusability of ontologies in the procedure of application development. The SOSA ontology reuses the concepts and attributes that are previously well described in the novel SSN ontology, along with extra-identified properties [19]. ID 76 argued that the DUL ontology describes common concepts similar in all knowledge domains, thus enabling reuse and interoperability. DUL is a lightweight basic model that demonstrates the physical and social perspectives of different domains.

The reuse of current ontologies can support the creation of an interoperable semantic IoT scheme. To this end, the Comprehensive Ontology for IoT (COIoT) reuses fundamental concepts from previous ontologies, such as SSN, IoT-lifecycle, PowerOnt, OWL-S, GeoNames, and DUL. It offers new concepts such as policy, context, services, and monitoring [104]. The SemIoTic framework in [107] reuses the QoS ontology, in which the metrics, such as reply time, latency, error rate, consistency, and cost (i.e., dollars per observation), are connected to IoT devices. The authors in [109] proposed an ontology by reusing concepts from existing ontologies, such as context ontology, ontology of next-generation smart classrooms, semantic sensor network ontology (SSN), and friend of a friend (FOAF). Multiple ontologies related to the IoT and the health domain were reused to construct a new ontology [111]. One of the main purposes behind the design and development of the IoT-Priv ontology in [129] was to maintain the lightweight feature provided by the IoT-Lite vocabulary and the reusability of its concepts.

4. Discussion

The discussion begins by describing the scope of this SLR. The next section presents related works, followed by a discussion of threats to the validity of SLR.

4.1. Opportunity for Organized Literature Evaluation

The terms ontology and IoT are used mutually as search terms to retrieve and analyze literature. An organized literature review procedure is adopted to ensure that all studies discuss the use of ontologies in IoT activities. In the computer science domain, an ontology conveys complete semantics of domain knowledge (e.g., a conceptual model); therefore, the synonyms for the term ontology are not considered in this literature review. This SLR highlights several key facets, as follows: (i) how ontologies are affiliated with IoT; (ii) their usage in IoT activities, such as tracking and information discovery, storage, information exchange, and object addressing; (iii) the ontology technologies (e.g., languages) exploited in the IoT environment; and (iv) reuse and integration of existing IoT ontologies.

4.2. Applications of Ontology for IoT Design and Development

After a detailed demonstration of ontology support for the IoT domain along with the classification of IoT ontologies, we can summarize that the adaptation of the IoT ontology depends on an assessment of the following facets:

– Most studies have exploited IoT ontologies as a solution for semantic interoperability in IoT. Existing studies (i.e., 31.30% of the selected articles) discussed ontologies as a measure for interoperability issues. Only 15 articles among the selected studies used IoT ontologies to minimize privacy issues, while integration issues are discussed least in terms of IoT ontologies (i.e., 12 papers). This percentage ratio indicates that ontology is an effective means for achieving interoperability requirements in the IoT field.
– An IoT ontology enables the global sharing and accessibility of data; hence, issues related to the security of sensitive data emerge. Currently, no active IoT ontology security model is available for assisting mission-critical applications (such as autonomous vehicle control).
– Most of the selected studies (i.e., 73.04%) depicted W3C-suggested languages for describing IoT ontologies. However, OWL is considered the main choice by the researchers.
– A total of 27.83% of selected studies reused existing ontologies to facilitate the interoperability of IoT data. This finding implies that current ontologies are helpful in designing new IoT ontologies or integrating IoT ontologies.
– The majority of Studies depict Protégé ontology editor as the main choice of ontology tool to construct the IoT ontology.

– Accurate identification and validation capabilities for making opinions associated with IoT ontology development are presently unavailable. Furthermore, strict government policies regarding IoT ontology standardization also limit innovations.

4.3. Related Work

W3C recommended a specific ontology, namely, SSN, in 2012 [17]. SSN is used to describe the sensor, which is a main hardware component of IoT. The properties (i.e., relations) are associated with the sensors in the SSN ontology. These relations help in solving heterogeneity problems regarding sensor detection and data collection. However, the SSN has several drawbacks, such as vague concepts to reveal the subsequent relationship of the sensor with other things in the IoT infrastructure. The next disadvantage is that SSN uses only one concept for sensor description, so SSN cannot model the entire system of IoT. The authors in [141] proposed an IoT ontology for data transmission in sensor systems, and sensor supervision was performed. However, the proposed ontology supports a limited number of sensor types; thus, only a few sensors can intelligently sense the environment. Moreover, the ontology is specific to building rooms and their floors, which ultimately restricts the usage of this ontology to interior locations only. A novel IoT architecture was illustrated in [142]; it integrates M3 ontology, domain knowledge, rules to define the sensors and their measurements, and entities uniformly. The architecture also performs reasoning for each of the items. However, the sensors face problems, such as mobility, data heterogeneity, and sensor locating issues. The authors in [143] suggested a context-aware ontology to facilitate different actions in diverse situations. The ontology was designed to support peripheral (physical) or internal (logical) contexts. Peripheral situations can be measured by means of physical sensors, and the relationships among concepts within the ontology provide the internal context (e.g., the employer's objective or response). The relationships between contextual knowledge and user positions were examined in an ontology format in [144]. To assess and recognize user positions, a reasoner was also proposed for the new ontology. The end result indicated that the proposed reasoner and ontology identify positions with higher precision than traditional GPS positions.

4.4. Threats to Validity

This section organizes the threats to validity into the following categories: construct, internal, external, and conclusion validity.

4.4.1. Construct Validity

This validity is related to two concepts: ontology and IoT. The first concept makes sure that all studies are related to ontology methodologies. The second concept includes the terms WoT and IoT to ensure that possibly related studies on IoT processes from the electronic database are covered. The search is moderated by considering both concepts in the six reliable search databases.

4.4.2. Internal Validity

This validity includes several partial verdicts that might have occurred during paper collection and data analysis, given that several vital articles failed to deliver a straightforward narrative or correct goals and outcomes. This situation makes the inclusion/exclusion benchmarks challenging and independent of the data extraction. The selection procedure is performed via an iterative approach to minimize collection and abstraction errors. Furthermore, the reviewers perform data extraction and argue over all major conflicts. Using this method, we point out the threats that can occur due to individual bias in article interpretation. Notably, the first two reviewers are Ph.D. and master scholars in the field of IoT, and the rest of the reviewers are experts with knowledge of ontology in the IoT domain.

4.4.3. External Validity

This validity pertains to the establishment of the generalizability of the SLR outcomes, which are associated with the main studies representing the assessment issue. The search process is defined by applying numerous test settings and being approved by all reviewers to moderate exterior threats.

4.4.4. Conclusion Validity

One possibility is that this SLR might have excluded a few articles that should have been part of the review. To minimize this type of threat, all of the reviewers of this SLR carefully designed the article selection method and the exclusion and inclusion policies. The definite period of the distributed studies for this SLR is from January 2014 to December 2020 (when we began this SLR). We started in January 2014 to capture all recently published articles and moderate the repetitive search effort.

5. Future Trends for IoT Ontologies

All efforts towards IoT ontologies analysis, as summarized in the Literature review methodology in Section 2, aim at recognizing ontologies support in the IoT field. In this section, we focus on and explore two emerging IoT domains where ontology can be beneficial: Unmanned Aerial Vehicles (UAV) and 6G Networks.

5.1. Ontology for Unmanned Aerial Vehicles

A key aspect of IoT devices toward seamless interoperability is the use of ontology describing the IoT domain uniformly. An IoT ontology describes devices, properties, data streams, relationships, and reasoning [145]. In the field of UAV, ontology provides vocabulary, including concepts, properties of a concept, and the relationships among the concepts. Ontology semantics allow UAVs (i.e., Robots) to understand environmental and space aspects and to advance reasoning and knowledge. However, IoT ontologies (particularly for the UAV field) are not enough.

Recently, the literature has witnessed interoperability improvement in UAV using ontology [145,146]. Authors in [147] exploited SSN ontology to describe data generated by robots. Similarly, Rusdi et al. [148] used the ontology concepts in tourist tracking systems via drones.

5.2. Ontology for 6G Networks

There is an extreme need to solve issues, including interoperability and suitable protocols for wireless applications, integration of artificial intelligence and 5G, and adaptation of dynamic facets [149]. The 5G networks do not address these issues [149]. Sixth-generation (6G) network emerges as fast and low latency communication technology to support missing-critical applications, services, and integration of networks [150]. The technology aims to solve 5G network issues and smooth communication between diverse devices of networks such as IoT. For instance, FANET IoT-based communication needs 6G support to interoperate with devices in undersea networks [151]. The 6G can provide an interoperable environment for communication between UAV and terrestrial networks. Ontology enhances 6G technology by linking devices, networks, services, or network applications at a semantic level, thereby resolving heterogeneity problems (including heterogeneous IoT devices, data rate, network protocols, and wireless systems) between IoT and emerging 6G networks. For instance, li et al. [152] conceptualized cognitive service architecture to enhance the 6G core network. Cognitive service is a key module of the architecture. This module performs real-time perception and reasoning tasks using an IoT ontology knowledge graph to upgrade the 6G core. The new architecture is flexible and can adapt to changing requirements in complex IoT scenarios. Authors in [153] exploited the transdisciplinary domain ontology to discover the R&D requirements for satellite communication within 6G. A smart text mining analysis was applied to identify the innovations and trends in satellite technologies based on the discovered R&D requirements.

6. Conclusions

This study aims to identify and observe the current scenarios of IoT ontologies. The main objective of this review is to determine the core areas of development and improvement in IoT ontology methods (as stated in the literature) by using a systematic assessment of related and contemporary articles. The method used in this review is SLR. SLR begins by articulating research questions following the SLR's objective of identifying and classifying recent ontology management methodologies in the IoT domain. Afterward, potentially related articles are recognized and evaluated based on the established research questions. Furthermore, the review rules, quality assessment questions, and assessment procedures are established to ensure the significance and accuracy of the review. Following the established procedure, article selection, abstraction, quality evaluation, and harmonization procedures are implemented to acknowledge the key articles. Information from the key articles is extracted and synthesized to fulfill the research aims and address the research questions. The SLR reveals that many techniques related to the use of ontology in IoT exist, but improvements in these techniques are still required. Technique scalability, complexity, ease of implementation, result consistency in different scenarios, justification in terms of industry, and adoption to changing environments are among the required improvements. These improvements should be addressed and resolved in future studies on IoT ontology development and management. In addition, this SLR points out validity threats, most of which have been handled in the early phases of the review. In the future, IoT ontologies in UAV and 6G networks need to be investigated to minimize interoperability and heterogeneity issues.

Author Contributions: Conceptualization, F.Q. and M.A.R.; methodology, F.Q.; formal analysis, M.R. and M.A.R.; investigation, M.A.R.; resources, A.N.; data curation, M.R. and M.K.A.H.; writing—original draft preparation, F.Q.; writing—review and editing, M.A.R.; visualization, Z.F. and A.S.; supervision, M.R.; project administration, M.K.A.H. and B.A.; funding acquisition, B.A. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: Special Thanks to Universiti Malaysia Pahang, International Islamic University Malaysia for funding this research under the UMP-UIA collaborative Grant scheme: RDU223217 and the Faculty of Computing for the facilities given to this research. This work was also funded by the Deanship of Scientific Research (DSR) at Umm Al-Qura University through grant number: 22UQU4210132DSR03.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Publication Source Wise Distribution of Studies.

Publication Source	Type	Count	(%)
World Forum on Internet of Things (WF-IoT)	Conference	8	6.96
Global Internet of Things Summit (GIoTS)	Conference	3	2.61
Sensors	Journal	2	1.74
International Conference on Data Science and Data Intensive Systems Assisting (ICDSDISA)	Conference	2	1.74
International Conference on Future Internet of Things and Cloud FiCloud (ICFITCF)	Conference	2	1.74
International Conference on Ubiquitous and Future Networks (ICUFN)	Conference	2	1.74
International Conference on Internet of Things (ICIoT)	Conference	2	1.74
International Congress on Internet of Things (ICIOT)	Conference	2	1.74
International Conference on Trust, Security and Privacy in Computing and Communications(ICTSPCC)	Conference	1	0.87
Service Oriented Computing and Applications (SOCA)	Journal	1	0.87

Table A1. *Cont.*

Publication Source	Type	Count	(%)
International Conference on Industrial Cyber-Physical Systems (ICICPS)	Conference	1	0.87
International Conference on Software Engineering and Service Sciences (ICSESS)	Conference	1	0.87
International Conference on Learning and Optimization Algorithms: Theory and Applications (ICLOATA)	Conference	1	0.87
International Symposium on Software Engineering for Adaptive and Self-Managing Systems (ISSEASMS)	Conference	1	0.87
International Conference on Identification, Information, and Knowledge in the Internet of Things (ICIIKIT)	Conference	1	0.87
Integrated Computer-Aided Engineering	Journal	1	0.87
ACM SIGAPP Applied Computing Review	Newsletter	1	0.87
International Symposium on Autonomous Decentralized Systems (ISADS)	Conference	1	0.87
International Conference on Information System and Data Mining (ICISDM)	Conference	1	0.87
International Conference on Model-Driven Engineering and Software Development (MODELSWARD)	Conference	1	0.87
International Journal of Innovative Computing, Information and Control (IJICIC)	Journal	1	0.87
Communications in Computer and Information Science (CCIS)	Book	1	0.87
International Conference on Advanced Communication Technology (ICACT)	Conference	1	0.87
Future Generation Computer Systems (FGCS)	Journal	1	0.87
South African Institute of Computer Scientists and Information Technologists (SAICSIT)	Proceeding	1	0.87
Electronics	Journal	1	0.87
The Australasian Computer Science Week Multi Conference (TACSWMC)	Conference	1	0.87
International Conference on Communications (ICC)	Conference	1	0.87
International Conference on Advanced Information Networking and Applications Workshops, (ICAINAW)	Conference	1	0.87
International Conference on Wireless Sensors (ICWiSe)	Conference	1	0.87
International Conference on Innovations in Clouds, Internet and Networks (ICIN)	Conference	1	0.87
International Conference on Communication Systems and Network Technologies (ICCSNT)	Conference	1	0.87
International Conference on Collaboration Technologies and Systems (ICCTS)	Conference	1	0.87
International Enterprise Distributed Object Computing Workshop (IEDOCW)	Workshop	1	0.87
International Carpathian Control Conference, ICCC	Conference	1	0.87
Journal of Ambient Intelligence and Humanized Computing	Journal	1	0.87
International Conference on Cloud Engineering (IC2E)	Conference	1	0.87
Annual International Conference, Proceedings/TENCON	Conference	1	0.87
Advanced Engineering Informatics	Journal	1	0.87
International Conference on Sustainable Information Engineering and Technology (SIET)	Conference	1	0.87
Automation in Construction	Journal	1	0.87
Industrial Management and Data System (IMDS)	Journal	1	0.87
Computer and Security (CS)	Journal	1	0.87
International Conferences on Ubiquitous Intelligence & Computing (ICUIC)	Conference	1	0.87
International Conference on Future Internet of Things and Cloud (ICFITC)	Conference	1	0.87
International Conference on Information and Communication Technology Convergence (ICICTC)	Conference	1	0.87

Table A1. *Cont.*

Publication Source	Type	Count	(%)
CEUR Workshop Proceeding	Conference	1	0.87
International Conference on Computational Science and Engineering (ICCSE)	Conference	1	0.87
IEEE Access	Conference	1	0.87
Industrial Electronics Conference (IECON)	Conference	1	0.87
Internet of Things Journal	Journal	1	0.87
International Conference on Industrial Informatics, INDIN	Conference	1	0.87
Proceedings of the 19th Panhellenic Conference on Informatics	Conference	1	0.87
Wireless Personal Communications	Journal	1	0.87
Symposium on Service-Oriented System Engineering, SOSE	Conference	1	0.87
Journal of Material Cycles and Waste Management	Journal	1	0.87
Journal of Web Semantics	Journal	1	0.87
International Conference on Enabling Technologies: Infrastructure for Collaborative Enterprises, WETICE	Conference	1	0.87
IFAC Proceedings Volumes	Conference	1	0.87
International Conference on Information Science and Control Engineering (ICISCE)	Conference	1	0.87
International Symposium on Service-Oriented System Engineering, SOSE	Conference	1	0.87
International Conference on Engineering, Technology, Innovation Management Beyond 2020	Conference	1	0.87
Journal of Web Semantics	Journal	1	0.87
Industrial Cyber-Physical Systems, ICPS	Conference	1	0.87
Communication Magazine Communications Standards Supplement	Magazine	1	0.87
International Conference on Internet of Things and Applications	Conference	1	0.87
IEEE Access	Journal	1	0.87
Procedia Computer Science	Journal	1	0.87
3rd Global IoT Summit (GIoTS 2019)	Journal	1	0.87
International Conference on Information Networking	Conference	1	0.87
International Conference on Advanced Computational and Communication Paradigms (ICACCP)	Conference	1	0.87
IFIP/IEEE International Symposium on Integrated Network Management (IISINM)	Symposium	1	0.87
International Conference on Internet of Things (IOT)	Conference	1	0.87
ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation (AICSEEBCT)	Conference	1	0.87
Open Innovations Conference (OIC)	Conference	1	0.87
International Conference on Computational Intelligence and Knowledge Economy (ICCIKE)	Conference	1	0.87
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)	Conference	1	0.87
International Wireless Communications and Mobile Computing Conference (IWCMC)	Conference	1	0.87
International Conference on Management of Digital EcoSystems (MEDES)	Conference	1	0.87
International Symposium on High Assurance Systems Engineering (ISHASE)	Conference	1	0.87
International Conference on Consumer Electronics (ICCE)	Conference	1	0.87
Brazilian Symposium on Information Systems (BSIS)	Conference	1	0.87
Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON)	Conference	1	0.87

Table A1. *Cont.*

Publication Source	Type	Count	(%)
International Conference on Web Intelligence, Mining and Semantics (ICWIMS)	Conference	1	0.87
International Conference on Service-Oriented System Engineering (SOSE)	Conference	1	0.87
International Conference on Big Data and Smart City (ICBDSC)	Conference	1	0.87
International Conference on Distributed Computing Systems (ICDCS)	Conference	1	0.87
International Systems and Software Product Line Conference (ISSPLC)	Symposium	1	0.87
E-Health and Bioengineering Conference (EHB)	Conference	1	0.87
Colombian Conference on Automatic Control (CCAC)	Conference	1	0.87
International Conference on Electronics Information and Emergency Communication (ICEIEC)	Conference	1	0.87
Intelligent Vehicles Symposium (IV)	Symposium	1	0.87
International Conference on Distributed Computing in Sensor Systems (DCOSS)	Conference	1	0.87
Symposium on Applied Computing (SAC)	Symposium	1	0.87
International Conference on Web Intelligence (ICWI)	Conference	1	0.87
Global Information Infrastructure and Networking Symposium (GIIS)	Symposium	1	0.87
International Conference on Informatics, IoT, and Enabling Technologies, (ICIoT)	Conference	1	0.87
International Conference on Fog and Mobile Edge Computing (FMEC)	Conference	1	0.87
Conference of Open Innovations Association (FRUCT)	Conference	1	0.87
International Convention on Information, Communication and Electronic Technology (MIPRO)	Conference	1	0.87

References

1. Gruber, T.R. A Translation Approach to Portable Ontology Specifications.pdf. *Knowl. Acquis.* **1993**, *5*, 199–220. [CrossRef]
2. Cercone, N.; McCalla, G. What Is Knowledge Representation? *Knowl. Front.* **2011**, *14*, 1–43.
3. Madakam, S.; Ramaswamy, R.; Tripathi, S. Internet of Things (IoT): A Literature Review. *J. Comput. Commun.* **2015**, *3*, 164–173. [CrossRef]
4. Miniwatts Marketing Group. Internet Usage Statistics, The Internet Big Picture: World Internet Users and 2015 Population Stats. *Internet World Stats: Usage and Polulation Statistics.* 2016. Available online: http://www.internetworldstats.com/stats.htm (accessed on 8 February 2019).
5. Ashton, K. That 'Internet of Things' Thing. *RFID J.* **2009**. Available online: https://www.rfidjournal.com/articles/view?4986 (accessed on 10 February 2019).
6. Weiser, M. The computer for the 21st century. ACM SIGMOBILE Mob. *Comput. Commun. Rev.* **1999**, *3*, 3–11. [CrossRef]
7. Reddi, V.J.; Kim, H. On the Internet of Things. *IEEE Micro* **2016**, *36*, 5–7. [CrossRef]
8. Ali, A.; Ahmed, I.A.; Almogren, A.; Raza, M.A.; Shah, S.A.; Khan, A.; Gani, A. Systematic Literature Review on IoT-Based Botnet Attack. *IEEE Access* **2020**, *8*, 212220–212232. [CrossRef]
9. Singh, D.; Tripathi, G.; Jara, A.J. A survey of Internet-of-Things: Future vision, architecture, challenges and services. In Proceedings of the 2014 IEEE World Forum Internet Things, WF-IoT 2014, Seoul, Korea, 6–8 March 2014; pp. 287–292.
10. Hachem, S.; Teixeira, T. Ontologies for the Internet of Things to cite this version: Ontologies for the Internet of Things. In Proceedings of the ACM/IFIP/USENIX 12th International Middleware Conference, Lisbon, Portugal, 12–16 December 2011.
11. Corazzon, R. History of Ontologies. 2019. Available online: https://www.ontology.co (accessed on 10 February 2019).
12. Raza, M.A.; Raza, B.; Jabeen, T.; Raza, S.; Abbas, M. Using Combined List Hierarchy and Headings of HTML Documents for Learning Domain-Specific Ontology. *Int. J. Adv. Comput. Sci. Appl. (IJACSA)* **2020**, *11*, 4. [CrossRef]
13. Van Harmelen, F.; McGuinness, D. OWL Web Ontology Language Overview. *W3C Recomm.* **2004**. Available online: https://www.w3.org/TR/owl-features (accessed on 10 February 2019).
14. Raza, M.A.; Rahmah, M.; Qaswar, F.; Hamid, R.A.; Raza, S. A Novel Approach to Explore Edhi Foundation Knowledge for Ontology Construction. *Int. J. Comput. Sci. Netw. Secur.* **2020**, *20*, 37–45.
15. Pérez, J.; Arenas, M.; Gutierrez, C. Semantics and complexity of SPARQL. *ACM Trans. Database Syst.* **2009**, *34*, 1–45. [CrossRef]
16. Horrocks, I.; Patel-Schneider, P.F.; Boley, H.; Tabet, S.; Grosof, B.; Dean, M. SWRL: A Semantic Web Rule Language Combining OWL and RuleML. *W3C Memb. Submiss.* **2004**, *21*, 1–20.

17. Compton, M.; Barnaghi, P.; Bermudez, L.; Garcia-Castro, R.; Corcho, O.; Cox, S.; Graybeal, J.; Hauswirth, M.; Henson, C.; Herzog, A.; et al. The SSN ontology of the W3C semantic sensor network incubator group. *J. Web Semant.* **2012**, *17*, 25–32. [CrossRef]
18. Pease, I.N.; Li, J. The Suggested Upper Merged Ontology: A Large Ontology for the Semantic Web and its Applications. *Imagine* **2002**, *28*, 7–10.
19. Janowicz, K.; Haller, A.; Cox, S.J.D.; le Phuoc, D.; Lefrançois, M. SOSA: A lightweight ontology for sensors, observations, samples, and actuators. *J. Web Semant.* **2019**, *56*, 1–10. [CrossRef]
20. Bonino, D.; Corno, F. DogOnt—Ontology modeling for intelligent domotic environments. In *Lecture Notes in Computer Science, Proceedings of the ISWC 2008: The Semantic Web—ISWC 2008, Karlsruhe, Germany, 26–30 October 2008*; Springer: Berlin/Heidelberg, Germany, 2008; pp. 790–803.
21. Bermudez-Edo, M.; Elsaleh, T.; Barnaghi, P.; Taylor, K. IoT-Lite: A lightweight semantic model for the internet of things and its use with dynamic semantics. *Pers. Ubiquitous Comput.* **2017**, *21*, 475–487. [CrossRef]
22. Kitchenham, B.; Charters, S. Performing systematic literature reviews in software engineering. In Proceedings of the 28th International Conference on Software Engineering, Shanghai, China, 20–28 May 2006.
23. Fleiss, J.L.; Levin, B.; Paik, M.C. *Statistical Methods for Rates and Proportions*, 3rd ed.; Wiley Series in Probability and Statistics: Hoboken, NJ, USA, 2003.
24. Landis, J.R.; Koch, G.G. The Measurement of Observer Agreement for Categorical Data. *Biometrics* **1977**, *33*, 159–174. [CrossRef]
25. Achimugu, P.; Selamat, A.; Ibrahim, R.; Naz, M. A systematic literature review of software requirements prioritization research. *Inf. Softw. Technol.* **2014**, *56*, 568–585. [CrossRef]
26. Wang, W.; De, S.; Toenjes, R.; Reetz, E.; Moessner, K. A comprehensive ontology for knowledge representation in the internet of things. In Proceedings of the 11th IEEE International Conference on Trust, Security and Privacy in Computing and Communications, Liverpool, UK, 25–27 June 2012; pp. 1793–1798.
27. Wang, W.; Lee, K.; Murray, D. A global generic architecture for the future Internet of Things. *Serv. Oriented Comput. Appl.* **2017**, *11*, 329–344. [CrossRef]
28. Fruhwirth, T.; Kastner, W.; Krammer, L. A methodology for creating reusable ontologies. In Proceedings of the 2018 IEEE Industrial Cyber-Physical Systems, ICPS 2018, St. Petersburg, Russia, 15–18 May 2018; pp. 65–70.
29. Zhang, H.; Meng, C. A multi-dimensional ontology-based IoT resource model. In Proceedings of the IEEE International Conference on Software Engineering and Service Sciences, ICSESS, Beijing, China, 27–29 June 2014; pp. 124–127.
30. Abatal, H.K.; Bahaj, M. A Smart Interconnected Healthcare System using Cloud Computing. In Proceedings of the International Conference on Learning and Optimization Algorithms: Theory and Applications—LOPAL '18, Rabat Morocco, 2–5 May 2018; pp. 1–5.
31. Gyrard, A.; Datta, S.K.; Bonnet, C. A survey and analysis of ontology-based software tools for semantic interoperability in IoT and WoT landscapes. In Proceedings of the IEEE World Forum on Internet of Things, WF-IoT 2018—Proceedings, Singapore, 5–8 February 2018; pp. 86–91.
32. Kibria, M.G.; Fattah, S.M.M.; Jeong, K.; Chong, I.; Jeong, Y.K. A user-centric knowledge creation model in a web of object-enabled Internet of Things environment. *Sensors* **2015**, *15*, 24054–24086. [CrossRef]
33. Pötter, H.B.; Sztajnberg, A. Adapting heterogeneous devices into an IoT context-aware infrastructure. In Proceedings of the 2016 IEEE/ACM 11th International Symposium on Software Engineering for Adaptive and Self-Managing Systems, Austin, TX, USA, 16–17 May 2016; pp. 64–74.
34. Zhang, X.; Zhao, Y.; Wang, X.; Pan, D. An Approach to Provide Visual Data Service for Heterogeneous Sensor Data Based on SSN Ontology. In Proceedings of the 2015 International Conference on Identification, Information, and Knowledge in the Internet of Things, IIKI 2015, Beijing, China, 22–23 October 2016; pp. 254–257.
35. Sabri, L.; Bouznad, S.; Fiorini, S.R.; Chibani, A.; Prestes, E.; Amirat, Y. An integrated semantic framework for designing context-aware Internet of Robotic Things systems. *Integr. Comput. Aided. Eng.* **2018**, *25*, 137–156. [CrossRef]
36. Ruy, F.B.; Falbo, R.A.; Barcellos, M.P.; Guizzardi, G.; Quirino, G.K.S. An ISO-based software process ontology pattern language and its application for harmonizing standards. *ACM SIGAPP Appl. Comput. Rev.* **2015**, *15*, 27–40. [CrossRef]
37. Kanaan, H.; Mahmood, K.; Sathyan, V. An Ontological Model for Privacy in Emerging Decentralized Healthcare Systems. In Proceedings of the 2017 IEEE 13th International Symposium on Autonomous Decentralized Systems, ISADS 2017, Bangkok, Thailand, 22–24 March 2017; pp. 107–113.
38. Yan, Y.; Liao, P.; Zhang, Z. An Ontology Framework of Software Requirements Change Management Process Based on Causality. In Proceedings of the 2nd International Conference on Information System and Data Mining, Lakeland FL, USA, 9–11 April 2018; pp. 107–111.
39. Mozzaquatro, B.A.; Melo, R.; Agostinho, C.; Jardim-Goncalves, R. An Ontology-based Security Framework for Decision-making in Industrial Systems. In Proceedings of the 2016 4th International Conference on Model-Driven Engineering and Software Development (MODELSWARD), Rome, Italy, 19–21 February 2016; pp. 779–788.
40. Sameh, A.; Al-Masri, A.; Al-Mahshouq, N. An open ontology repository at prince sultan university. *Int. J. Innov. Comput. Inf. Control* **2018**, *14*, 197–209.

41. Guan, Y.; Vasquez, J.C.; Guerrero, J.M.; Samovich, N.; Vanya, S.; Oravec, V.; García-Castro, R.; Serena, F.; Poveda-Villalón, M.; Radojicic, C.; et al. An Open Virtual Neighbourhood Network to Connect IoT Infrastructures and Smart Objects—VICINITY. In Proceedings of the2017 Global Internet Things Summit (Giots 2017), Geneva, Switzerland, 6–9 June 2017; pp. 134–139.
42. Gyrard, A.; Bonnet, C.; Boudaoud, K.; Serrano, M. Assisting IoT Projects and Developers in Designing Interoperable Semantic Web of Things Applications. In Proceedings of the 2015 IEEE International Conference on Data Science and Data Intensive Systems Assisting, Sydney, NSW, Australia, 11–13 December 2015; pp. 659–666.
43. Bytyçi, K.E.; Ahmedi, L. Association Rule Mining with Context Ontologies—An Application to Mobile Sensing of Water Quality. *Online Inf. Rev.* **2016**, *30*, 213–216.
44. Kim, M.; Kang, H.; Kwon, S.; Lee, Y.; Kim, K.; Pyo, C.S. Augmented ontology by handshaking with machine learning. In Proceedings of the International Conference on Advanced Communication Technology, ICACT, PyeongChang, Republic of Korea, 19–22 February 2017; pp. 740–743.
45. Gao, F.; Ali, M.I.; Curry, E.; Mileo, A. Automated discovery and integration of semantic urban data streams: The ACEIS middleware. *Futur. Gener. Comput. Syst.* **2017**, *76*, 561–581. [CrossRef]
46. Khan, Z.C.; Keet, C.M. Automatically changing modules in modular ontology development and management. In Proceedings of the SAICSIT '17, Thaba 'Nchu, South Africa, 26–28 September 2017; pp. 1–10.
47. Kashevnik, A.; Teslya, N. Blockchain-Oriented Coalition Formation by CPS Resources: Ontological Approach and Case Study. *Electronics* **2018**, *7*, 66. [CrossRef]
48. Kingsun, M.; Myers, T.; Hardy, D. C-DOM: A structured co-design framework methodology for ontology design and development. In Proceedings of the ACM International Conference Proceeding Series, Brisband Queensland, Australia, 29 January–2 February 2018; pp. 1–10.
49. Kasnesis, P.; Patrikakis, C.Z.; Venieris, I.S. Collective domotic intelligence through dynamic injection of semantic rules. In Proceedings of the IEEE International Conference on Communications, London, UK, 8–12 June 2015; pp. 592–597.
50. Gyrard, A.; Serrano, M. Connected smart cities: Interoperability with SEG 3.0 for the internet of things. In Proceedings of the IEEE 30th International Conference on Advanced Information Networking and Applications Workshops, WAINA 2016, Montana, Switzerland, 23–25 March 2016; pp. 796–802.
51. Service, R.I.; Choi, H.; Kang, D.; Kim, N.; Rhee, W. Cross-domain Metadata Environment for Relative Information-based Service. In Proceedings of the2016 IEEE Conference on Wireless Sensors (ICWiSe), Langkawi, Malaysia, 10–12 October 2016; pp. 15–20.
52. Abreu, P.; Velasquez, K.; Pinto, A.M.; Curado, M.; Monteiro, E. Describing the Internet of Things with an ontology: The SusCity project case study. In Proceedings of the 2017 20th Conference on Innovations in Clouds, Internet and Networks, ICIN 2017, Paris, France, 7–9 March 2017; pp. 294–299.
53. Mittal, M.; Vijayal, S. Detection of attacks in IoT based on ontology using SPARQL. In Proceedings of the 7th International Conference on Communication Systems and Network Technologies, CSNT 2017, Nagpur, India, 11–13 November 2017; pp. 206–211.
54. Akasiadis, C.; Tzortzis, G.; Spyrou, E.; Spyropoulos, C. Developing complex services in an IoT ecosystem. In Proceedings of the IEEE World Forum on Internet of Things, WF-IoT 2015, Milan, Italy, 14–16 December 2015; pp. 52–56.
55. Sezer, O.B.; Can, S.Z.; Dogdu, E. Development of a smart home ontology and the implementation of a semantic sensor network simulator: An Internet of Things approach. In Proceedings of the 2015 International Conference on Collaboration Technologies and Systems, CTS 2015, Atlanta, GA, USA, 1–5 June 2015; pp. 12–18.
56. Zimmermann, A.; Schmidt, R.; Sandkuhl, K.; Wißotzki, M.; Jugel, D.; Möhring, M. Digital enterprise architecture-transformation for the internet of things. In Proceedings of the 2015 IEEE 19th International Enterprise Distributed Object Computing Workshop, Adelaide, SA, Australia, 21–25 September 2015.
57. Kovács, L.; Varga, E.B.; Balla, T. Efficiency analysis of ontology servers. In Proceedings of the 2018 19th International Carpathian Control Conference, ICCC 2018, Szilvasvarad, Hungary, 28–31 May 2018; pp. 353–358.
58. Al-Osta, M.; Bali, A.; Gherbi, A. Event driven and semantic based approach for data processing on IoT gateway devices. *J. Ambient Intell. Humaniz. Comput.* **2018**, *10*, 4663–4678. [CrossRef]
59. La, H.J.; Jung, H.T.; Kim, S.D. Extensible disease diagnosis cloud platform with medical sensors and IoT devices. In Proceedings of the 2015 International Conference on Future Internet of Things and Cloud, FiCloud 2015 and 2015 International Conference on Open and Big Data, OBD 2015, Rome, Italy, 24–26 August 2015; pp. 371–378.
60. Willner, A.; Loughnane, R.; Magedanz, T. FIDDLE: Federated infrastructure discovery and description language. In Proceedings of the 2015 IEEE International Conference on Cloud Engineering, IC2E 2015, Tempe, AZ, USA, 9–13 March 2015; pp. 465–471.
61. Yang, N.R.; Choi, H.S.; Lee, J.Y.; Kim, Y.J.; Rhee, W.S. GOMs: Generic ontology models to process context information in IoT environment. In Proceedings of the IEEE Region 10 Annual International Conference, Proceedings/TENCON, Bangkok, Thailand, 22–25 October 2015.
62. Evchina, Y.; Lastra, J.L.M. Hybrid approach for selective delivery of information streams in data-intensive monitoring systems. *Adv. Eng. Informatics* **2016**, *30*, 537–552. [CrossRef]
63. Ali, S.; Kim, H.; Chong, I. Implementation model of WoO based smart assisted living IoT service. In Proceedings of the 2016 IEEE 3rd World Forum on Internet of Things (WF-IoT), Jeju, Republic of Korea, 19–21 October 2016; pp. 816–818.

64. Prasetio, A.; Akbar, S.R.; Priyambadha, B. Implementation of semantic system in the smart home lights device based on agent. In Proceedings of the 2017 International Conference on Sustainable Information Engineering and Technology, SIET 2017, Malang, Indonesia, 24–25 November 2017; pp. 93–99.
65. Howell, S.; Rezgui, Y.; Beach, T. Integrating building and urban semantics to empower smart water solutions. *Autom. Constr.* **2017**, *81*, 434–448. [CrossRef]
66. Alexakos, C.; Kalogeras, A.P. Internet of Things integration to a Multi Agent System based manufacturing environment. In Proceedings of the 20th IEEE International Conference on Emerging Technologies and Factory Automation, ETFA 2015, Luxembourg, 8–11 September 2015.
67. Tu, M.; Lim, M.K.; Yang, M.-F. IoT-based production logistics and supply chain system—Part 1 modeling IoT-based manufacturing IoT supply chain. *Ind. Manag. Data Syst.* **2018**, *118*, 65–95. [CrossRef]
68. Choi, H.S.; Rhee, W.S. Iot-based user-driven service modeling environment for a smart space management system. *Sensors* **2014**, *14*, 22039–22064. [CrossRef]
69. Mohsin, M.; Anwar, Z.; Zaman, F.; Al-Shaer, E. IoTChecker: A data-driven framework for security analytics of Internet of Things configurations. *Comput. Secur.* **2017**, *70*, 199–223. [CrossRef]
70. Kibria, M.G.; Chong, I. Knowledge based open IoT service provisioning through cooperation between physical web and WoO. In Proceedings of the International Conference on Ubiquitous and Future Networks, ICUFN, Sapporo, Japan, 7–10 July 2015; pp. 395–400.
71. Kibria, M.G.; Chong, I. Knowledge creation model in WoO enabled smart ageing IoT service platform. In Proceedings of the International Conference on Ubiquitous and Future Networks, ICUFN, Vienna, Austria, 5–8 July 2016; pp. 526–531.
72. Gyrard, A.; Bonnet, C.; Boudaoud, K.; Serrano, M. LOV4IoT: A second life for ontology-based domain knowledge to build semantic web of things applications. In Proceedings of the 2016 IEEE 4th International Conference on Future Internet of Things and Cloud, FiCloud 2016, Vienna, Austria, 22–24 August 2016; pp. 254–261.
73. Ali, S.; Kibria, M.G.; Jarwar, M.A.; Kumar, S.; Chong, I. Microservices model in WoO based IoT platform for depressive disorder assistance. In Proceedings of the International Conference on Information and Communication Technology Convergence: ICT Convergence Technologies Leading the Fourth Industrial Revolution, ICTC 2017, Jeju, Republic of Korea, 18–20 October 2017; pp. 864–866.
74. El Kaed, C.; Ponnouradjane, A. Model driven approach accelerating ontology-based IoT applications development. In Proceedings of the CEUR Workshop Proceedings, Amsterdam, The Netherlands, 11–14 September 2017; p. 2063.
75. Meng, X.; Wang, Y.; Wu, Y. Modeling geospatial sensor knowledge under a semantic sensor web environment. In Proceedings of the 17th IEEE International Conference on Computational Science and Engineering, CSE 2014, Jointly with 13th IEEE International Conference on Ubiquitous Computing and Communications, IUCC 2014, 13th International Symposium on Pervasive Systems, Chengdu, China, 19–21 December 2015; pp. 1090–1095.
76. Al Sunny, S.M.N.; Liu, X.F.; Shahriar, M.R. MTComm: A semantic ontology based internet scale communication method of manufacturing services in a cyber-physical manufacturing cloud. In Proceedings of the 2017 IEEE 2nd International Congress on Internet of Things, ICIOT 2017, Honolulu, HI, USA, 25–30 June 2017; pp. 121–128.
77. Xu, G.; Cao, Y.; Ren, Y.; Li, X.; Feng, Z. Network Security Situation Awareness Based on Semantic Ontology and User-Defined Rules for Internet of Things. *IEEE Access* **2017**, *5*, 21046–21056. [CrossRef]
78. Szilagyi, I.; Wira, P. Ontologies and semantic Web for the internet of things—A survey. In Proceedings of the IECON Proceedings (Industrial Electronics Conference), Florence, Italy, 23–26 October 2016; pp. 6949–6954.
79. Mallik, A.; Tripathi, A.; Kumar, R.; Chaudhury, S.; Sinha, K. Ontology based context aware situation tracking. In Proceedings of the IEEE World Forum on Internet of Things, WF-IoT 2015, Milan, Italy, 14–16 December 2015; pp. 687–692.
80. Khan, Y.I.; Ndubuaku, M.U. Ontology-based automation of security guidelines for smart homes. In Proceedings of the IEEE World Forum on Internet of Things, WF-IoT 2018, Singapore, 5–8 February 2018; pp. 35–40.
81. Maleki, E.; Belkadi, F.; Boli, N.; Van Der Zwaag, B.J.; Alexopoulos, K.; Koukas, S.; Marin-Perianu, M.; Bernard, A.; Mourtzis, D. Ontology-Based Framework Enabling Smart Product-Service Systems: Application of Sensing Systems for Machine Health Monitoring. *IEEE Internet Things J.* **2018**, *5*, 4496–4505. [CrossRef]
82. Steinmetz, C.; Schroeder, G.; dos Santos Roque, A.; Pereira, C.E.; Wagner, C.; Saalmann, P.; Hellingrath, B. Ontology-driven IoT code generation for FIWARE. In Proceedings of the 2017 IEEE 15th International Conference on Industrial Informatics, INDIN 2017, Emden, Germany, 24–26 July 2017; pp. 38–43.
83. Sgouropoulou, C.; Koutoumanos, A.; Triperina, E.; Dragoni, M. Ontology-driven linked open (meta-) data services for e-research systems. In Proceedings of the PCI '15—19th Panhellenic Conference on Informatics, Athens Greece, 1–3 October 2015; pp. 363–368.
84. Kim, Y.; Lee, S.; Chong, I. Orchestration in Distributed Web-of-Objects for Creation of User-Centered IoT Service Capability. *Wirel. Pers. Commun.* **2014**, *78*, 1965–1980. [CrossRef]
85. Yen, L.; Zhu, W.; Bastani, F.; Huang, Y.; Zhou, G. Rapid service composition reasoning for agile cyber physical systems. In Proceedings of the 2016 IEEE Symposium on Service-Oriented System Engineering, SOSE 2016, Oxford, UK, 29 March–2 April 2016; pp. 442–449.
86. I Inna, S.; Arkady, Z.; Petr, F. Role-based ontology-driven knowledge representation for IoT-enabled waste management. In Proceedings of the Seventh International Conference on the Internet of Things (IoT'17), Association for Computing Machinery, New York, NY, USA, 22–25 October 2017. [CrossRef]

87. Suri, K.; Gaaloul, W.; Cuccuru, A.; Gerard, S. Semantic framework for internet of things-aware business process development. In Proceedings of the 2017 IEEE 26th International Conference on Enabling Technologies: Infrastructure for Collaborative Enterprises, WETICE 2017, Poznan, Poland, 21–23 June 2017; pp. 214–219.
88. Yoo, M.J.; Kolyvakis, P.; Kiritsis, D.; Werthmann, D.; Hellbach, R. Semantic model for IoT-Enabled electric vehicle services: Puzzling with ontologies. In Proceedings of the 2016 IEEE 4th International Conference on Future Internet of Things and Cloud, FiCloud 2016, Vienna, Austria, 22–24 August 2016; pp. 387–392.
89. Gyrard, A.; Serrano, M.; Atemezing, G.A. Semantic web methodologies, best practices and ontology engineering applied to Internet of Things. In Proceedings of the IEEE World Forum on Internet of Things, WF-IoT 2015, Milan, Italy, 14–16 December 2015; pp. 412–417.
90. Legat, C.; Seitz, C.; Lamparter, S.; Feldmann, S. Semantics to the shop floor: Towards ontology modularization and reuse in the automation domain. *IFAC Proc. Vol.* **2014**, *19*, 3444–3449. [CrossRef]
91. Kolchin, M.; Klimov, N.; Shilin, I.; Garayzuev, D.; Andreev, A.; Mouromtsev, D. SEMIOT: An Architecture of Semantic Internet of Things Middleware. In Proceedings of the 2016 IEEE International Conference on Internet of Things; IEEE Green Computing and Communications; IEEE Cyber, Physical, and Social Computing; IEEE Smart Data, iThings-GreenCom-CPSCom-Smart Data 2016, Chengdu, China, 15–18 December 2016; pp. 416–419.
92. Wang, X.; An, H.; Xu, Y.; Wang, S. Sensing network element ontology description model for internet of things. In Proceedings of the 2015 2nd International Conference on Information Science and Control Engineering, ICISCE 2015, Shanghai, China, 24–26 April 2015; pp. 471–475.
93. Yen, L.I.; Bastani, F.; Zhu, W.; Moeini, H.; Hwang, S.Y.; Zhang, Y. Service-Oriented IoT Modeling and Its Deviation from Software Services. In Proceedings of the 12th IEEE International Symposium on Service-Oriented System Engineering, SOSE 2018 and 9th International Workshop on Joint Cloud Computing, JCC 2018, Bamberg, Germany, 26–29 March 2018; pp. 40–47.
94. Lee, C.S.H. Object Collaboration Model to Create Joint Knowledge in WoO Enviroment. In Proceedings of the IEEE World Forum on Internet of Thing, Seoul, Republic of Korea, 6–8 March 2014; pp. 61–62.
95. Mozzaquatro, B.A.; Jardim-Goncalves, R.; Agostinho, C. Situation awareness in the Internet of Things. In Proceedings of the 2017 International Conference on Engineering, Technology and Innovation: Engineering, Technology and Innovation Management Beyond 2020: New Challenges, New Approaches, ICE/ITMC 2017, Madeira, Portugal, 5 February 2018; pp. 982–990.
96. Lam, N.; Haugen, O. Supporting IoT semantic interoperability with autonomic computing. In Proceedings of the 2018 IEEE Industrial Cyber-Physical Systems, ICPS 2018, St. Petersburg, Russia, 15–18 May 2018; pp. 761–767.
97. Ambreen, H.; Wenyan, W. Sustainable Interoperability and Data Integration for the IoT-Based Information Systems. In Proceedings of the 2017 IEEE International Conference on Internet of Things, Exeter, UK, 21–23 June 2017; pp. 824–829.
98. Alaya, M.B.; Medjiah, S.; Monteil, T.; Drira, K. Toward Semantic Interoperability in one m2m Architecture. In Proceedings of the IEEE Communication Magazine—Communications Standards Supplement, 17 December 2015; pp. 35–41.
99. Chougule, A.; Jha, V.K.; Mukhopadhyay, D. Using IoT for integrated pest management. In Proceedings of the 2016 International Conference on Internet of Things and Applications, IOTA 2016, Pune, India, 22–24 January 2016; pp. 17–22.
100. Ali, S.; Kibria, M.G.; Chong, I. WoO enabled IoT service provisioning based on learning user preferences and situation. In Proceedings of the International Conference on Information Networking, Da Nang, Vietnam, 11–13 January 2017; pp. 474–476.
101. Lan, L.; Shi, R.; Wang, B.; Zhang, L. An IoT Unified Access Platform for Heterogeneity Sensing Devices Based on Edge Computing. *IEEE Access* **2019**, *7*, 44199–44211. [CrossRef]
102. Rhayem, A.; Mhiri, M.B.A.; Salah, M.B.; Gargouri, F. Ontology-based system for patient monitoring with connected objects. *Procedia Comput. Sci.* **2017**, *112*, 683–692. [CrossRef]
103. Elsaleh, T.; Enshaeifar, S.; Acton, S.T.; Rezvani, R.; Barnaghi, P. IoT-Stream: A Lightweight Ontology for Internet of Things Data Streams. In Proceedings of the 3rd Glob. IoT Summit (GIoTS 2019), Aarhus, Denmark, 17–21 June 2019. [CrossRef]
104. Tayur, V.M.; Suchithra, R. A comprehensive ontology for internet of things (COIoT). In Proceedings of the 2019 Second International Conference on Advanced Computational and Communication Paradigms (ICACCP), Gangtok, India, 25–28 February 2019; pp. 1–6.
105. Pahl, M.O.; Liebald, S. A modular distributed IoT service discovery. In Proceedings of the 2019 IFIP/IEEE Symposium on Integrated Network and Service Management (IM), Arlington, VA, USA, 8–12 April 2019; pp. 448–454.
106. Yemson, R.; Thakker, D.; Konur, S. A novel semantic complex event processing framework for streaming processing. In Proceedings of the 9th International Conference on the Internet of Things, Bilbao, Spain, 22–25 October 2019. [CrossRef]
107. Yus, R.; Bouloukakis, G.; Mehrotra, S.; Venkatasubramanian, N. Abstracting interactions with IoT devices towards a semantic vision of smart spaces. In Proceedings of the BuildSys 2019—6th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation, New York, NY, USA, 13–14 November 2019; pp. 91–100.
108. Sithole, V.; Marshall, L. An Exposition of a Lightweight Domain-specific Ontology for the Interoperability of the Internet of Things Patterns. In Proceedings of the 2019 Open Innovations (OI), Cape Town, South Africa, 2–4 October 2019; pp. 8–14.
109. Nagowah, S.D.; Abou, R.; Bayrouni, R. An Ontology for an IoT-enabled Smart Classroom in a University Campus. In Proceedings of the 2019 International Conference on Computational Intelligence and Knowledge Economy (ICCIKE), Dubai, United Arab Emirates, 11–12 December 2019; pp. 626–631.

110. Xu, Y.; Hu, P.; Ning, H. An ontology-based domain modeling and device search in Smart Home. In Proceedings of the 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), Halifax, NS, Canada, 30 July 2018–3 August 2018; pp. 1349–1354.
111. Titi, S.; Elhadj, H.B.; Chaari, L. An ontology-based healthcare monitoring system in the internet of things. In Proceedings of the 2019 15th International Wireless Communications & Mobile Computing Conference (IWCMC), Tangier, Morocco, 24–28 June 2019; pp. 319–324.
112. Orozco, T.; Mouakher, A.; Sassi, I.B.; Nicolle, C. An ontology-based thermal comfort management system in smart buildings. In Proceedings of the 11th International Conference on Management of Digital EcoSystems, Limassol Cyprus, 12–14 November 2019; pp. 300–307.
113. Zhang, S.; Zeng, W.; Yen, I.L.; Bastani, F.B. Semantically enhanced time series databases in IoT-edge-cloud infrastructure. In Proceedings of the 2019 IEEE 19th International Symposium on High Assurance Systems Engineering (HASE), Hangzhou, China, 3–5 January 2019; pp. 25–32.
114. Calcina-Ccori, P.C.; de Biase, L.C.C.; de Oliveira, C.E.L.; Fedrecheski, G.; da Silva, F.C.; Zuffo, M.K. Describing services geolocation in IoT context. In Proceedings of the 2019 IEEE International Conference on Consumer Electronics (ICCE), Las Vegas, NV, USA, 11–13 January 2019; pp. 1–2.
115. Costa, S.; Alves, R.S.; Silva, F.J.d.E.; Endler, M. Dynamic discovery of IoT services based on semantic processing of event flows. In Proceedings of the XV Brazilian Symposium on Information Systems, Aracaju, Brazil, 20–24 May 2019.
116. Patel, M.; Bhattacharyya, S.; Alfageeh, A. Formal Trust Architecture for Assuring Trusted Interactions in the Internet of Things. In Proceedings of the 2019 IEEE 10th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON), New York, NY, USA, 10–12 October 2019; pp. 33–39.
117. Georgiou, M.; Tachmazidis, I.; Antoniou, G. Hypercat JSON-LD: A semantically enriched catalogue format for IoT. In Proceedings of the 9th International Conference on Web Intelligence, Mining and Semantics, Seoul, Republic of Korea, 26–28 June 2019.
118. Zeng, W.; Zhang, S.; Yen, I.L.; Bastani, F. Semantic IoT data description and discovery in the IoT-edge-fog-cloud infrastructure. In Proceedings of the 2019 IEEE International Conference on Service-Oriented System Engineering (SOSE), San Francisco, CA, USA, 4–9 April 2019; pp. 106–115.
119. Sarker, K.U.; Deraman, A.B.; Hasan, R.; Mahmood, S.; Abbas, A.; Sohail, M. Kids' smart campus ontology to retrieve interest. In Proceedings of the 2019 4th Mec International Conference on Big Data and Smart City (ICBDSC), Muscat, Oman, 5–16 January 2019; pp. 1–4.
120. Issarny, V.; Billet, B.; Bouloukakis, G.; Florescu, D.; Toma, C. LATTICE: A framework for optimizing IoT system configurations at the edge. In Proceedings of the 2019 IEEE 39th International Conference on Distributed Computing Systems (ICDCS), Dallas, TX, USA, 7–10 July 2019; pp. 1797–1805.
121. Calcina-Ccori, P.C.; de Biase, L.C.C.; de Oliveira, C.E.L.; Fedrecheski, G.; da Silva, F.C.; Zuffo, M.K. Location-aware discovery of services in the IoT: A swarm approach. In Proceedings of the 2019 Global IoT Summit (GIoTS), Aarhus, Denmark, 17–21 June 2019; pp. 1–6.
122. Bonfitto, S.; Hachem, F.; Belay, E.G.; Valtolina, S.; Mesiti, M. On the bulk ingestion of IoT devices from heterogeneous IoT brokers. In Proceedings of the 2019 IEEE International Congress on Internet of Things (ICIOT), Milan, Italy, 8–13 July 2019; pp. 189–195.
123. Shaaban, M.; Gruber, T.; Schmittner, C. Ontology-based security tool for critical cyber-physical systems. In Proceedings of the 23rd International Systems and Software Product Line Conference-Volume B, Paris France, 9–13 September 2019; pp. 7–10.
124. Bajenaru, L.; Dobre, C.; Ciobanu, R.I.; Balog, A. Patient profile using ontologies in an older adults monitoring IoT-based platform. In Proceedings of the 2019 E-Health and Bioengineering Conference (EHB), Iasi, Romania, 21–23 November 2019; pp. 2–5.
125. Gil, S.; Zapata-Madrigal, G.D. Semantic automation systems, a suitable approach for automation networks in the industry 4.0. In Proceedings of the 2019 IEEE 4th Colombian Conference on Automatic Control (CCAC), Medellin, Colombia, 15–18 October 2019.
126. Geng, D.; Gao, Q. Semantic web technology and prolog reasoning based task planning mechanism and application in smart home for internet of things. In Proceedings of the 2019 IEEE 9th International Conference on Electronics Information and Emergency Communication (ICEIEC), Beijing, China, 12–14 July 2019; pp. 384–387.
127. Weber, M.; Akella, R.; Lee, E.A. Service discovery for the connected car with semantic accessors. In Proceedings of the 2019 IEEE Intelligent Vehicles Symposium (IV), Paris, France, 9–12 June 2019; pp. 2417–2422.
128. Chatzimichail, A.; Chatzigeorgiou, C.; Andritsopoulos, F.; Karaberi, C.; Meditskos, G.; Kasnesis, P.; Kogias, D.G.; Gorgogetas, G.; Tsanousa, A.; Vrochidis, S.; et al. Smart interconnected infrastructure for security and safety in public places. In Proceedings of the 2019 15th International Conference on Distributed Computing in Sensor Systems (DCOSS), Santorini, Greece, 29–31 May 2019; pp. 297–303.
129. Arruda, M.F.; Bulcão-Neto, R.F. Toward a lightweight ontology for privacy protection in IoT. In Proceedings of the 34th ACM/SIGAPP Symposium on Applied Computing, Limassol, Cyprus, 8–12 April 2019; pp. 880–888.
130. Gonzalez-Gil, P.; Skarmeta, A.F.; Martinez, J.A. Towards an ontology for IoT context-based security evaluation. In Proceedings of the 2019 Global IoT Summit (GIoTS), Aarhus, Denmark, 17–21 June 2019; pp. 1–6.
131. Noura, M.; Gaedke, M. WOTDL: Web of things description language for automatic composition. In Proceedings of the 2019 IEEE/WIC/ACM International Conference on Web Intelligence (WI), Thessaloniki, Greece, 14–17 October 2019; pp. 413–417.

132. Le, H.; Boussetta, K.; Achir, N. A unified and semantic data model for fog computing. In Proceedings of the 2020 Global Information Infrastructure and Networking Symposium (GIIS), Tunis, Tunisia, 28–30 October 2020; pp. 1–6.
133. Nundloll, V.; Elkhatib, Y.; Elhabbash, A.; Blair, G.S. An Ontological Framework for Opportunistic Composition of IoT Systems. In Proceedings of the 2020 IEEE International Conference on Informatics, IoT, and Enabling Technologies (ICIoT), Doha, Qatar, 2–5 February 2020; pp. 614–621.
134. Toumia, A.; Szoniecky, S.; Saleh, I. ColPri: Towards a Collaborative Privacy Knowledge Management Ontology for the Internet of Things. In Proceedings of the 2020 Fifth International Conference on Fog and Mobile Edge Computing (FMEC), Paris, France, 20–23 April 2020; pp. 150–157.
135. Turchet, L.; Zhu, G.; Bouquet, P. Populating the Smart Musical Instruments Ontology with Data. In Proceedings of the 2020 27th Conference of Open Innovations Association (FRUCT), Trento, Italy, 7–9 September 2020; pp. 260–267.
136. An, J.; Kumar, S.; Lee, J.; Jeong, S.; Song, J. Synapse: Towards Linked Data for Smart Cities using a Semantic Annotation Framework. In Proceedings of the 2020 IEEE 6th World Forum on Internet of Things (WF-IoT), New Orleans, LA, USA, 2–16 June 2020; pp. 1–6.
137. Tomičić, I.; Grd, P. Towards the Open Ontology for IoT Ecosystem's Security. In Proceedings of the 2020 43rd International Convention on Information, Communication and Electronic Technology (MIPRO), Opatija, Croatia, 28 September–2 October 2020; pp. 1064–1069.
138. Profile, S.E.E.; Profile, S.E.E. Applying Ontologies to Terminology: Advantages and Disadvantages Applying Ontologies to Terminology: Advantages and Disadvantages. *Hermes-J. Lang. Commun. Bus.* **2013**, *51*, 65–77.
139. Space, D. Data Exchange as a First Step towards Data Economy. Available online: https://www.pwc.de/en/digitale-transformation/data-exchange-as-a-first-step-towards-dataeconomy.pdf (accessed on 25 November 2019).
140. International Data Spaces Association. Available online: https://www.internationaldataspaces.org/ (accessed on 25 November 2019).
141. Xue, L.; Liu, Y.; Zeng, P.; Yu, H.; Shi, Z. An Ontology Based Scheme for Sensor Description in Context Awareness System. In Proceedings of the 2015 IEEE International Conference on Information and Automation, Lijiang, China, 8–10 August 2015; pp. 817–820.
142. Gyrard, A.; Datta, S.K.; Bonnet, C.; Boudaoud, K. Standardizing Generic Cross-Domain Applications in Internet of Things. In Proceedings of the 2014 IEEE Globecom Workshops (GC Wkshps), Austin, TX, USA, 8–12 December 2014; pp. 589–594.
143. Baldauf, M. A survey on context-aware systems. *Int. J. Ad Hoc Ubiquitous Comput.* **2007**, *2*, 263–277. [CrossRef]
144. Kim, S.I. Ontology based Location Reasoning Method Using Smart Phone Data. In Proceedings of the 2015 International Conference on Information Networking (ICOIN), Siem Reap, Cambodia, 12–14 January 2015; pp. 509–514.
145. Kamilaris, A.; Botteghi, N. The penetration of Internet of Things in robotics: Towards a web of robotic things. *J. Ambient. Intell. Smart Environ.* **2020**, *12*, 491–512. [CrossRef]
146. Gera, U.K.; Saini, D.K.; Singh, P.; Siddharth, D. IoT-Based UAV Platform Revolutionized in Smart Healthcare. In *Unmanned Aerial Vehicles for Internet of Things (IoT)*; 2021; pp. 277–293. Available online: https://onlinelibrary.wiley.com/doi/10.1002/9781119769170.ch15 (accessed on 25 November 2022).
147. Simoens, P.; Mahieu, C.; Ongenae, F.; de Backere, F.; de Pestel, S.; Nelis, J.; de Turck, F.; Elprama, S.A.; Kilpi, K.; Jewell, C.; et al. Internet of robotic things: Context-aware and personalized interventions of assistive social robots. In Proceedings of the 5th IEEE International Conference on Cloud Networking (Cloudnet), Pisa, Italy, 3–5 October 2016; pp. 204–207.
148. Rusdi, J.F.; Salam, S.; Abu, N.A.; Sahib, S.; Naseer, M.; Abdullah, A.A. Drone Tracking Modelling Ontology for Tourist Behavior. *J. Phys. Conf. Ser.* **2019**, *1201*, 012032. [CrossRef]
149. Yang, W.; Du, H.; Liew, Z.Q.; Lim, W.Y.B.; Xiong, Z.; Niyato, D.; Chi, X.; Shen, X.S.; Miao, C. Semantic Communications for Future Internet: Fundamentals, Applications, and Challenges. *IEEE Commun. Surv. Tutor.* **2022**. [CrossRef]
150. Narsani, H.K.; Ranjha, A.; Dev, K.; Memon, F.H.; Qureshi, N.M.F. Leveraging UAV-assisted communications to improve secrecy for URLLC in 6G systems. *Digit. Commun. Netw.* 2022; *in press*. [CrossRef]
151. Khan, U.; Qureshi, I.M.; Aziz, M.A.; Cheema, T.A.; Shah, S.B.H. Smart IoT Control-Based Nature Inspired Energy Efficient Routing Protocol for Flying Ad Hoc Network (FANET). *IEEE Access* **2020**, *8*, 56371–56378. [CrossRef]
152. Li, Y.; Huang, J.; Sun, Q.; Sun, T.; Wang, S. Cognitive Service Architecture for 6G Core Network. *IEEE Trans. Ind. Inform.* **2021**, *17*, 7193–7203. [CrossRef]
153. Trappey, J.C.; Huang, A.Z.C.; Chen, N.K.T.; Pa, R.J.S.; Trappey, C.V.; Li, K.A.; Huang, L.P. Transdisciplinary Technology Mining of Advanced 6G Satellite Communication Innovations. In *Transdisciplinarity and the Future of Engineering*; IOS Press: Amsterdam, The Netherlands, 2022; Volume 28. Available online: https://www.researchgate.net/publication/365073349_Transdisciplinary_Technology_Mining_of_Advanced_6G_Satellite_Communication_Innovations (accessed on 25 November 2022).