Industrial Internet of Things: A Systematic Literature Review and Insights

Yongxin Liao, Eduardo de Freitas Rocha Loures, and Fernando Deschamps

***Abstract*—The connection of embedded computing devices via the Internet has dramatically changed the way people live. This concept has also been extended to the industrial sector. It not only provides a more reliable, real-time and secure communications, but also enables the smart factory concept in the fourth industrial revolution to be realized. However, in the current literature, there is still a lack of a formal and objective review that specifically focuses on this topic. This paper aims to address this gap. First, the applied systematic literature review method is explained. Findings and insights are then illustrated through the analysis of the collected data related to the four research questions. Finally, the strengths and limitations of the work are summarized.**

***Index Terms*—Implementations, Industrial Internet of Things (IIoT), standards, systematic literature review (SLR), technologies.**

I. Introduction

The coming of the fourth industrial revolution, with the emergence of the smart factory concept, has brought many challenges to traditional manufacturing organizations. As part of a "smart, networked world," smart factories should be able to manage the growing complexity of their environments, be less prone to disruption, and also be capable of carrying out production more efficiently [1]. This is a paradigm shift from the existing centrally controlled manufacturing to decentralized manufacturing that has already started to take place through the enabling of barrier-free communication between manufacturing resources, people, and even individual products [2], [3]. The supporting backbone of this transformation is the integration of the Internet of Things (IoT) standards and technologies into the industrial processes [4]. Smart electronics are embedded into the production systems along the life cycle of a product, to dynamically build up a global or an internal information network [5], in what has come to be known as the Industrial IoT (IIoT).

IIoT enables manufacturing organizations to extend their existing applications and even conceive new ways of operating. As an example, besides performing data mining in traditional areas, such as machine health analysis or predictive maintenance, some manufacturing industries have already begun to apply big data and analytics on the years of data collected from processes and products through IIoT to solve critical problems (e.g., the root cause for the low quality of products [6]). Moreover, as it is pointed out in the report from the International Data Corporation [7], the worldwide spending on IoT is forecast to reach nearly $1.4 trillion in 2021. The manufacturing operation spending in IoT is poised to remain the highest in Asia/Pacific (excluding Japan), the United States, and Western Europe. These driving forces have made the Industry 4.0 vison, namely "a fully describable, manageable, context-sensitive, and controllable or self-regulating manufacturing systems" [1], become closer to the reality.

Going beyond reviews that focus on other research efforts, such as the review about the fourth industrial revolution [8], the analysis of cyber-physical systems and emerging IT trends [9], the review of technologies, trends and challenges in 5G IoT [10] and the algorithmic historiography of extant literature on IoT [11], the main objective of this paper is to perform a literature review focused on the IIoT academic achievements in a systematic manner. More specifically, four research questions of interest are listed, as follows.

1) Who is working on IIoT, when and where?
2) What are the main standards and technologies in IIoT to support communications?
3) What are the main IIoT research efforts?
4) What are the main IIoT implementations?

The remaining of this paper is structured as follows. The systematic literature review (SLR) method is introduced in Section II. Section III presents the main SLR findings from both a more general perspective (the analysis of keywords and source journals) and a more specific perspective (the analysis of the data corresponding to each research question). Based on these results, Section IV provides insights obtained from the SLR and identifies future IIoT research directions. Finally, Section V concludes this paper and discusses its limitations and future perspectives.

II. SLR Method

In this SLR, both qualitative and quantitative analysis methods were integrated and applied [12], [13]. This approach is better described next.

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TABLE I
INCLUSION AND EXCLUSION CRITERIA WITH THEIR EXPLANATIONS

I/E	Criterion	Explanations
Exclusion	Duplicate Articles (DA)	The same article that appears multiple times in one or more databases.
	Without Full-text (WF)	The authors of this work are without access to the full-text of the article.
	Wrong Categorization (WC)	The source of an article is misclassified. For example, the <Procedia Engineering> is a collection of conference proceedings but not a peer-reviewed journal.
	Non-English Article (NEA)	The article is not written in English.
	Non-Research Article (NRA)	The article is not a research article, e.g., an editorial note.
	Non-Related (NR)	The definition of IIoT is out of the research context of this work, namely, the concern of IIoT is outside manufacturing context.
	Wrongly Related (WR)	The characters in an article is miss matched during the text conversion (in case of old articles). For example, recognizing the image "Hot" or "not" as the "iiot".
	Implicitly Related (IR)	The article doesn't explicitly express its research focus on IIoT. Instead, IIoT **only** appears **once** in the article Highlights or its Authors' Biographies.
Inclusion	Review or Survey (RS)	The article presents a review or a survey related to IIoT.
	Theoretical Solution (TS)	The article aims to solve some specific IIoT research problems, and gives **only** some theoretical propositions.
	Experimental Solution (ES)	The article aims to solve some specific IIoT research problems, gives some solutions, and provides laboratory experiments.
	Practical Solution (PS)	The article aims to solve some specific IIoT research problems, gives some solutions, and provides industrial implementations.

A. Article Collection, Inclusion and Exclusion

The collection of articles started by defining a search string. This string is composed of three search terms: "Industrial Internet of Things," "Industrial IoT," and "IIoT," with the logic operator "OR" in between them. Three reference databases were used: the *Scopus* abstract and citation database, the *IEEE Xplore* digital library, and the *Science Direct* platform. Those articles should satisfy the following conditions: they must be published online before August 2017; search terms must appear in their titles, abstracts, and keywords; and they must be published in peer-reviewed journals. To be more objective, as can be seen from Table I, eight exclusion criteria and four inclusion criteria were defined.

A fast filtering process was carried out to exclude those articles that fulfill the exclusion criteria DA, WF, WC, NEA, and NRA in Table I. The remaining articles that entered the first round of the review process had their titles, abstracts, and keywords examined. Articles that fulfill the exclusion criteria NR, WR, and IR in Table I were excluded. The remaining articles after the first round went through the second round of the review process and had their full-texts analyzed. They were classified according to the four inclusion criteria (RS, TS, ES, and PS in Table I), and had, in parallel, data of interest collected.

B. Data Collection

For each included article, two kinds of data were collected. The first kind is the basic data related to the articles themselves: *titles, keywords*, and *journals* in which articles were published. The second kind is the specific data that can be used to answer each research question listed in Section I.

For *Q*1 "Who is working on IIoT, when and where?" the data of interest are: the *authors* and *publication years* of the articles; the *institutions* of the *authors* (only taking into account the institutions that are explicitly written in the title page of the articles); and the *geographical locations* of the *institutions*.

For *Q*2 "What are the main standards and technologies in IIoT to support communications?" the data of interest are the *communication standards* and *technologies* that are enumerated, discussed, or improved. In most instances, the collected data can be used to represent both the standard and the technology, such as, ZigBee and ISA 100.11.a. In other instances, they should be distinguished—e.g., WiFi is a technology based on the IEEE 802.11 standard. Furthermore, the limitations of the standards and technologies were also collected.

For *Q*3 "What are the main IIoT research efforts?" the data of interest are: the summarized *research questions* that each included article addresses; the summarized *solutions* for each *research question*; and the related *features* that the *solutions* intend to provide. These data were collected from the articles that are classified as TS, ES and PS.

For *Q*4 "What are the main IIoT implementations?" the data of interest are: the *industries* that participated in the IIoT implementations; the *geographical locations* of these *industries*; and the *main functions* of the IIoT implementations. These data were collected from the articles that are classified as PS.

C. Data Analysis

The collected data were processed by qualitative research methods, and then quantitatively illustrated. More specifically, four qualitative data analysis methods were applied: data denoising, data confirmation, data enrichment, and data categorization.

Data denoising was performed to unify data expressions due to the fact that: *keywords* (collected for the general data analysis); *authors*, *institutions*, and *geographical locations* (collected for *Q*1); and *standards* and *technologies* (collected for *Q*2) might be expressed in different languages, in the form of abbreviations, or using synonyms.

Data confirmation was carried out to increase the reliability of the *standards* and *technologies* (collected for *Q*2). Because of the large amount of data that was manually extracted by studying the full-texts, a qualitative analysis tool, named ATLAS.ti [14], was employed in a double-check for guaranteeing the correctness of this data collection.

Data enrichment was performed to enhance the original data of interest with additional information. For the general data analysis, *subject areas and categories* (based on the Scimago Journal and Country Rank [15]) of the journals that published the articles in this paper were supplemented. For *Q*2,

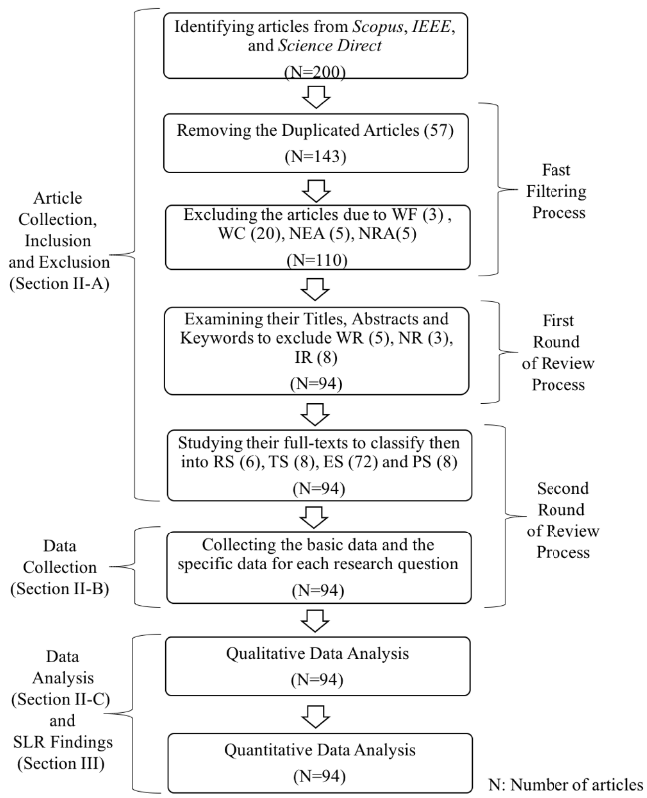

Fig. 1. SLR flowchart.

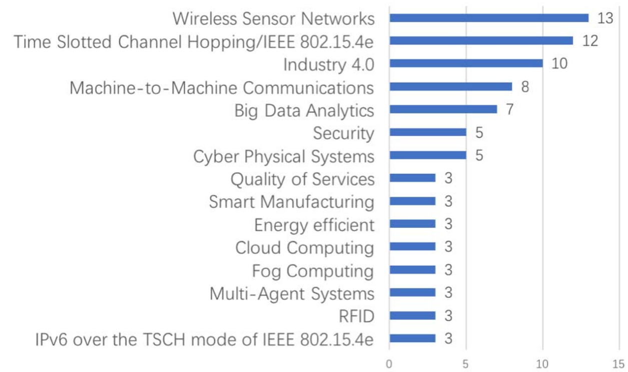

Fig. 2. List of the most frequent keywords.

to better understand every collected *standard* and *technology*, their scientific background was supplemented and studied.

Data categorization was used to improve statistical and graphical data descriptions through classification of the collected data into corresponding categories. For *Q*1, the ontological class hierarchy [16] approach was applied to group the *keywords* that shared similar natures. For *Q*2, related *standards* and *technologies* were organized according to the industrial Internet connectivity framework (IICF) proposed by the industrial Internet consortium [17]. For *Q*3, the research efforts were first positioned into the reference architecture model for industry 4.0 (RAMI 4.0) [18], and then analyzed based on their main features. For Q4, the participating industries were classified according to the North American industry classification system (NAICS) [19].

III. SLR Findings

Fig. 1 shows the steps of the SLR and the number of included and excluded articles. Section III-A presents the general analysis of the collected *keywords* and *journals*. Section III-B provides a more specific data analysis for each research question (from *Q*1 to *Q*4).

A. General Data Analysis

1) Analysis of Keywords: Among the 94 included articles, 85.1% of them (80 articles) have explicitly provided keywords in their full-texts, in a total of 439. The data categorization process followed the notion of the subclass axioms in ontology (all the members of a class are the members of its super class), but not the composition (a compound is made up of several elements). Therefore, the "is a kind of" rule was employed to verify the correctness of the categorization. For example, "Green Cloud Computing" can be considered a subclass of "Cloud Computing." However, "Smart Warehouse" is just a part of "Smart Manufacturing," but not a subclass of it.

As can be seen from Fig. 2, besides the two keywords present in the search terms (IoT, which appears 28 times, and IIoT, which appears 46 times), the most frequent keywords are listed in descending order. An overview of the current IIoT academic research can be summarized into the four points discussed next.

First, "Wireless Sensor Networks," "Industry 4.0," "Machine-to-Machine Communications," "Cyber Physical Systems," and "Multi-Agent Systems" turn out to be the five main IIoT application fields.

Second, many research efforts related to IIoT have been dedicated to guarantee "Security," to maintain "Quality of Services," to enable "Smart Manufacturing," and to improve "Energy efficient."

Third, advanced computing technologies (such as "Big Data Analytics," "Cloud Computing," and "Fog Computing") and emerging connectivity standards (such as "Time Slotted Channel Hopping/IEEE 802.15.4e," and "IPv6 over the TSCH mode of IEEE 802.15.4e") have either been adopted or enhanced by IIoT.

Finally, as one of the key enablers of IoT, from the perspective of localization and communication [20], "RFID" also finds its own way to contribute to IIoT.

2) Analysis of Journals: The included articles were published by 55 different journals. Among these journals, 67.3% (37) have published only one article that is explicitly related to IIoT. From the other 18 journals (32.7%) that published two or more articles related to IIoT, as illustrated in Fig. 3(a), both the IEEE Systems Journal and *IEEE Communication Magazine* have five articles each and appear to be the most relevant IIoT journals.

Furthermore, based on the subject areas and categories of the identified journals, except from 3.6% (two journals) that do not provide this information, 14 major thematic categories were identified, as can be seen in Fig. 3(b). "Computer Science" is covered by 37 journals and "Engineering" is

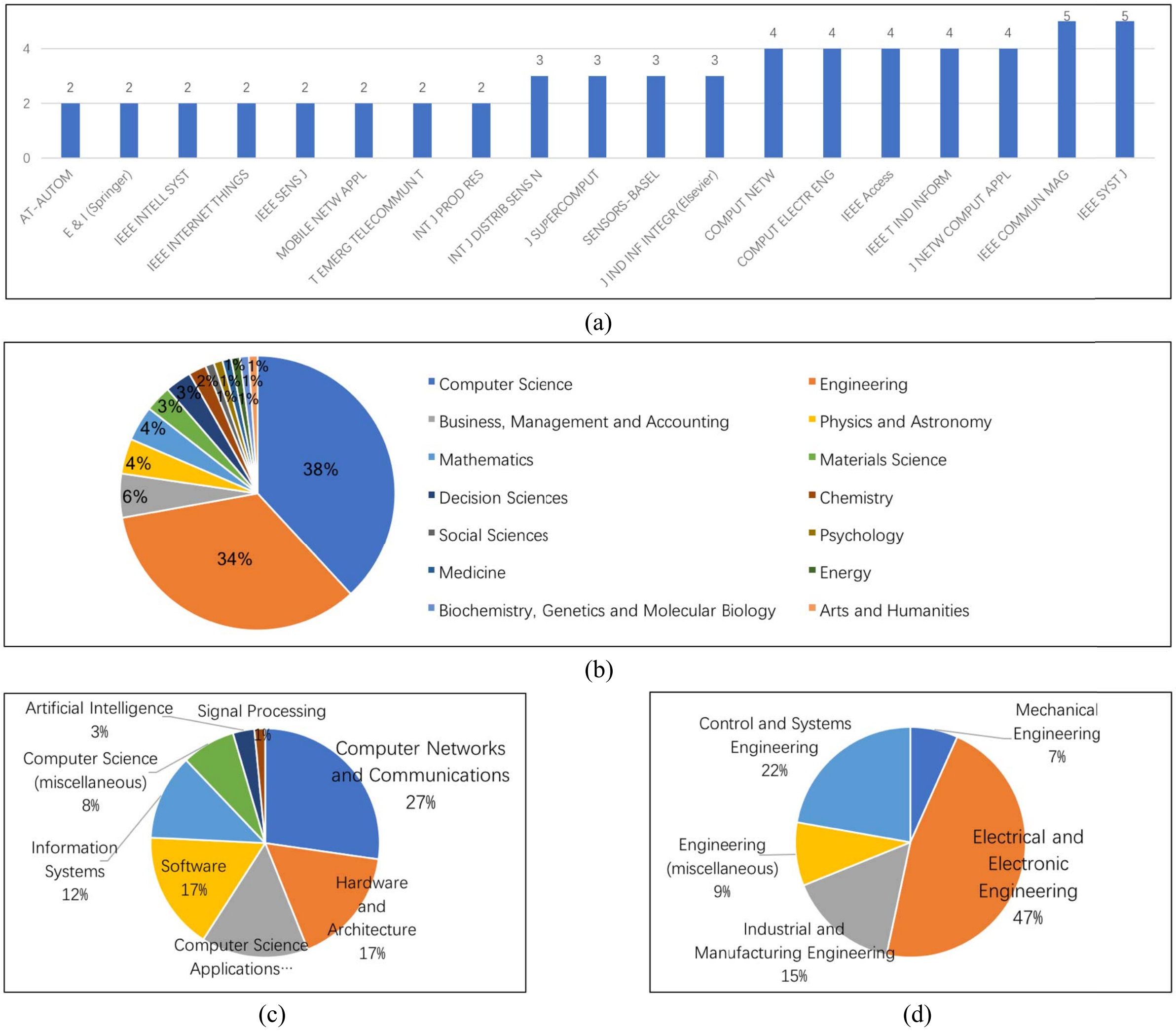

Fig. 3. Analysis of relevant journals: number of included articles, subject areas, and categories. (a) List of journals that contain more than one included IIoT article. (b) Major thematic categories. (c) Relevant subject categories of computer science. (d) Relevant subject categories of engineering.

covered by 33 journals. These are the two most relevant subject areas for IIoT. More precisely, "Computer Networks and Communication" is covered by 18 journals [see Fig. 3(c)] and "Electrical and Electronic Engineering" is covered by 21 journals [see Fig. 3(d)]. These are the two major IIoT relevant subject categories.

B. Specific Data Analysis

1) Data Analysis for Q1: As shown in Fig. 4(a), in 2013 and 2014, the number of IIoT academic contributions remains at two articles per year. Then, from 2015, a rapid upward trend appears. The number continues to grow from 11 articles in 2015 to 50 articles in 2017.

These articles are the contributions of 355 authors. On the one hand, the vast majority of authors have only participated in one (91.5%, 325 authors) or two articles (7.1%, 25 authors). On the other hand, there exist five authors (1.4%) that have participated in three or more articles [21]–[32]. Based on articles co-authorship, as illustrated in Fig. 4(b), it can be seen that *Thomas Watteyne*, who took part in six IIoT articles [21]–[26], has a close collaboration with two other authors: *Xavier Vilajosana* (four co-authored articles) and *Tengfei Chang* (three co-authored articles). Additionally, as shown in Fig. 4(c), the subject categories of the journals, where those six articles come from, indicate one promising combination of domains for IIoT research: "Electrical and Electronic Engineering", "Computer Networks and Communication", "Computer Science Application", and "Modeling and Simulation."

Article authors are from 157 different institutions that can be divided into three main categories: 125 universities, which account for 79.6% of the total institutions; 22 companies or corporate research centers that make up 14.0%; and the remainder are ten national or independent research centers (6.4%). Moreover, as can be seen from Fig. 4(d), the "University of Science and Technology Beijing" (five articles), the "ABB Corporate Research Centers" (three articles from the Swedish division and 1 from the German division), and the "Chinese Academy of Sciences" (three articles from the Beijing division, one from the Wuhan division, and one from the Changchun division) published the largest number

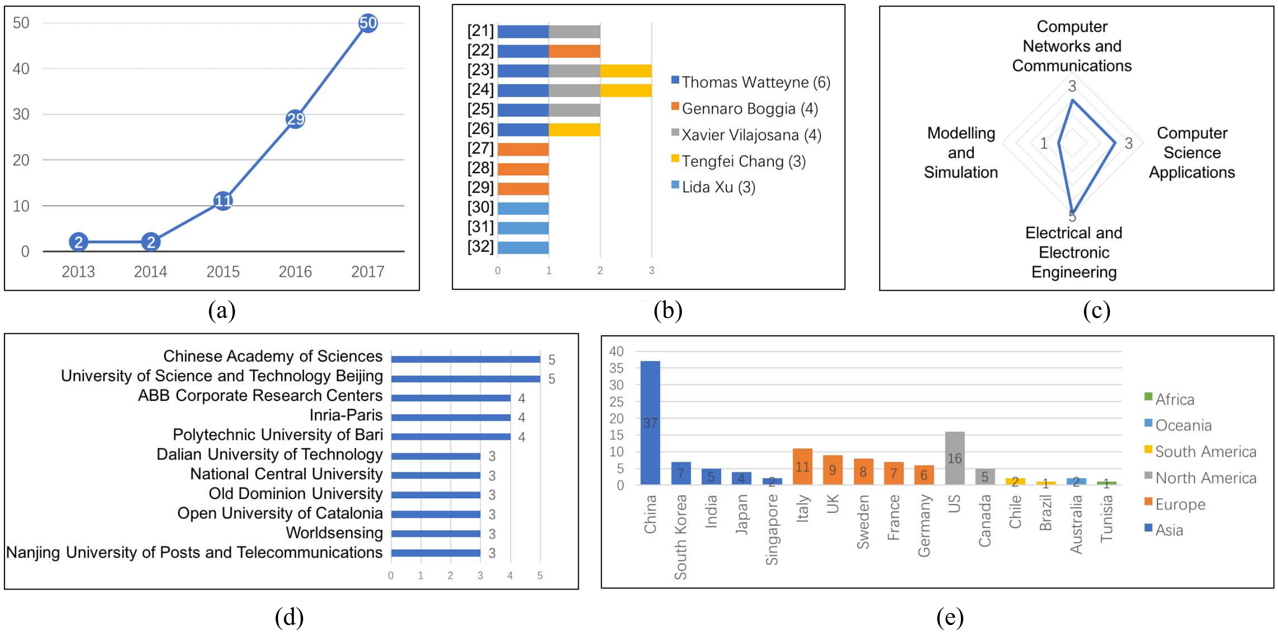

Fig. 4. Data analysis for Q1: years, authors, institutions, and countries. (a) Number of included articles by publication year. (b) Authors with more than 2 IIoT journal articles. (c) Relevant subject categories of [21]–[26]. (d) Institutions with more than 2 IIoT journal articles. (e) Countries with the largest number of IIoT journal articles in each continent.

of IIoT articles in the three above-mentioned categories, respectively.

Those institutions are located in 31 different countries. In particular, 69.1% of the included IIoT journal articles (65) have the participation of European institutions. Asian institutions take part in 58 articles (61.7%), North American institutions participate in 21 articles (22.3%), and South American, Oceania, and African institutions only appear in five articles (5.3%). Furthermore, Fig. 4(e) enumerates the five countries with the largest number of IIoT journal articles in each continent (in case of less than five countries with articles published in a continent, all are listed). It can be noted that, although Germany has been the initiator of Industry 4.0, German institutions have contributed less than other countries with journal articles that are explicitly related to IIoT. Instead, as one of the largest world manufacturing hubs, the institutions in China have already shown their importance.

2) Data Analysis for Q2: In total, 123 communication standards and technologies were collected from the 94 included IIoT articles. More than half of them (53.7%) appeared in less than three articles. The rest of them (47.3%) were more frequently mentioned. To better illustrate and analyze them, the five-layer connectivity Stack Model in the IICF [17], which is specifically proposed for capturing all industrial Internet connectivity requirements, is employed.

The definitions of the IICF layers are briefly introduced as follows: the *Physical Layer* refers to the exchange of the digital signals between participants over a shared substratum, which can be either wired or wireless physical medias; the *Link Layer* refers to the exchange of digital frames between participants; the *Network Layer* refers to the exchange of packets between participants; the *Transport Layer* refers to the exchange of information (bits and bytes) between participants through using an unambiguously defined communication protocols; the *Framework Layer* refers to the exchange of information in a shared data structure between participants. In this layer, common protocols are used to unambiguously define the data structure and to exchange data.

As can be seen from Fig. 5, the communication standards and technologies identified in this paper are shown in the corresponding layers with the numbers of included articles that enumerate, discuss, or propose improvements to them. They can be classified into six main groups: 1) wireless personal area network (WPAN); 2) wireless local area network (WLAN); 3) cellular network; 4) low power wide-area network (LPWAN); 5) satellite network; and 6) traditional industrial computer network (Fieldbus).

First, there exist three popular *Wireless Sensor Network* Technologies: ZigBee, ISA 100.11a, and WirelessHART. They are all based on the low-rate wireless personal area networks standard, namely, IEEE 802.15.4.

Second, compared to wired communication (e.g., IEEE 802.3 Ethernet, which only appears in one of the included articles), wireless technologies (such as IEEE 802.14.5, Wi-Fi and Bluetooth) turn out to be the mainstream in IIoT. Moreover, as the successor of IPv4, IPv6 is frequently mentioned in IIoT studies.

Third, taking advantage of the wide coverage and appropriate bandwidth, standards and technologies in the *Cellular Network* group, especially the upcoming 5G, have already become one important research branch of IIoT. A more detailed review about the state of the art of 5G IoT can be found in the work of Li *et al.* [10].

Fourth, even if the LPWAN standards and technologies (such as, LoRa, Sigfox, and NB-IoT) have only been mentioned by five of the included articles, there is a rapidly

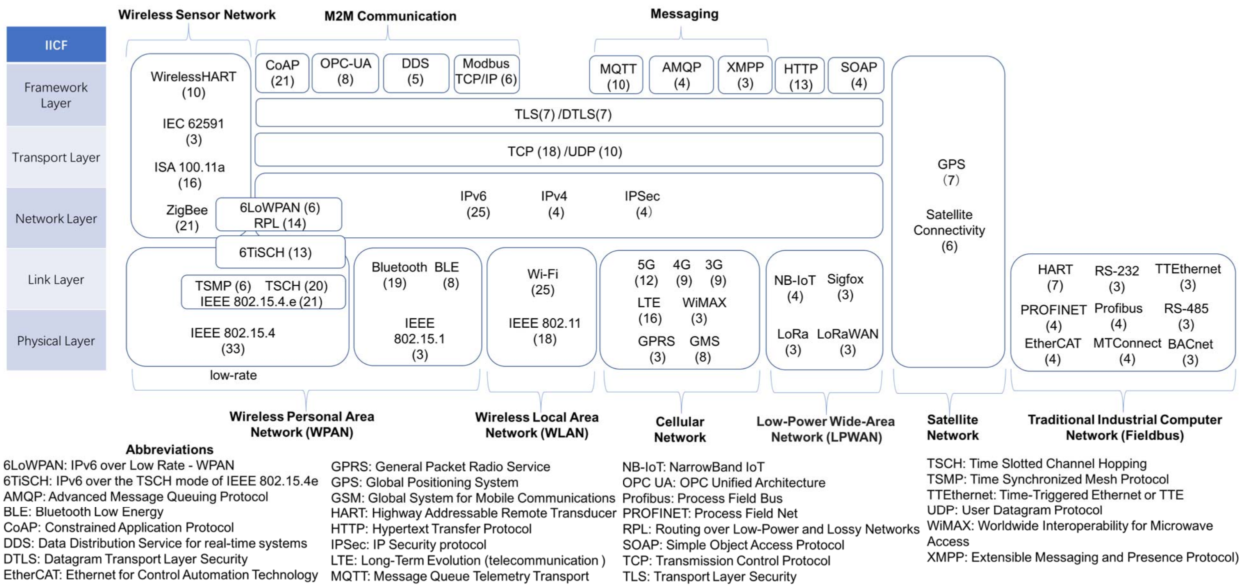

Fig. 5. Data analysis for Q2: the IIoT communication standard and technology stack.

growing research interest in this area, with only one article published in 2016 and four articles published in 2017.

Fifth, compared to the other groups, the standards and technologies in the *Satellite Connectivity* group, that includes GPS, are usually used as enumeration terms that are listed together with others. There are few IIoT articles that specifically focus on them.

Finally, because the standards and technologies in the *Fieldbus* group, such as *HART* and *PROFINET*, are still employed by many legacy manufacturing systems, the effective and efficient integration of IIoT with them remains a challenging task.

3) Data Analysis for Q3: The analysis of the *research questions* and the corresponding *solutions* from the articles that were classified as TS, ES, and PS in Table I (88 articles in total), is used to summarize the state of the art of IIoT research.

Nearly one-fifth of the articles (19.3%, 17 articles) propose general approaches [33]–[35], frameworks [36]–[40], or architectures [41]–[49] that cover most or all of the Product life cycle phases, hierarchy levels, and layers in RAMI 4.0 [18]. Therefore, to better highlight and compare current IIoT research efforts, only the remaining 71 articles (80.7%) are classified and illustrated in Fig. 6 according to these three RAMI 4.0 perspectives.

First, almost three quarters (73.8%) of the articles raise *research questions* whose issues are either related to industrial Internet networks (47.7%, 42 articles) or manufacturing data (26.1%, 23 articles). From the product life cycle perspective of RAMI 4.0 (the horizontal axis of the cube in Fig. 6), these concerns are associated with the *Production* phase, in which, products are manufactured on the basis of a more general type.

Second, based on the hierarchy levels perspective of RAMI 4.0 (the diagonal axis of the cube in Fig. 6), 41 articles (46.6%) propose *solutions* to optimize industrial Internet networks, which turn out to be the most important type of IIoT propositions at the shop floor execution level (including the *Field Device*, *Control Device*, *Station*, and *Work Center* levels). Moreover, at the supervisory management level (including the *Enterprise* and *Connected World* levels), *solutions* are predominantly about data analysis method (19.3%, 17 articles) and data protection strategies (4.5%, four articles).

Third, according to the Layers perspective of RAMI 4.0 (the vertical axis of the cube in Fig. 6), the majority of contributions are in the *Communication* and *Information* layers, accounting for 46.6% of contributions (41 articles). The *Function* and *Business* layers rank second, with 26 articles having dedicated their research efforts to them (29.5%).

Finally, analyzing the main features that these articles intend to provide, it can be noted that higher *Network Reliability*, lower *Energy Consumption*, and *Real-Time* data exchange are the major motivations at the *Communication* and *Information* layers. In comparison, shorter *Computational Time* and robust *Security* strategies receive more attention than other features at the *Function* and *Business* layers.

4) Data Analysis for Q4: The transformation of academic achievements into industrial applications is one of the most important purposes of IIoT research. In this SLR, as can be seen from Table II, there are eight articles (8.5%) that are either applying their propositions in real-world industrial environments [36], [40], [41], [50]–[52] or directly using data collected from real-world production lines [6], [53]. Ten organizations from seven countries (three from Europe, two from Asia, one from North America, and one from South America) participated in these studies. The NAICS [19] is used to classify them based on the main products that they manufacture.

According to this classification, the “221 Utilities” appears to be the most popular subsector, with applications in four organizations. Three articles [36], [41], [51] propose wireless sensor network solutions to improve the real-time and reliability of data collection for industries that belong to

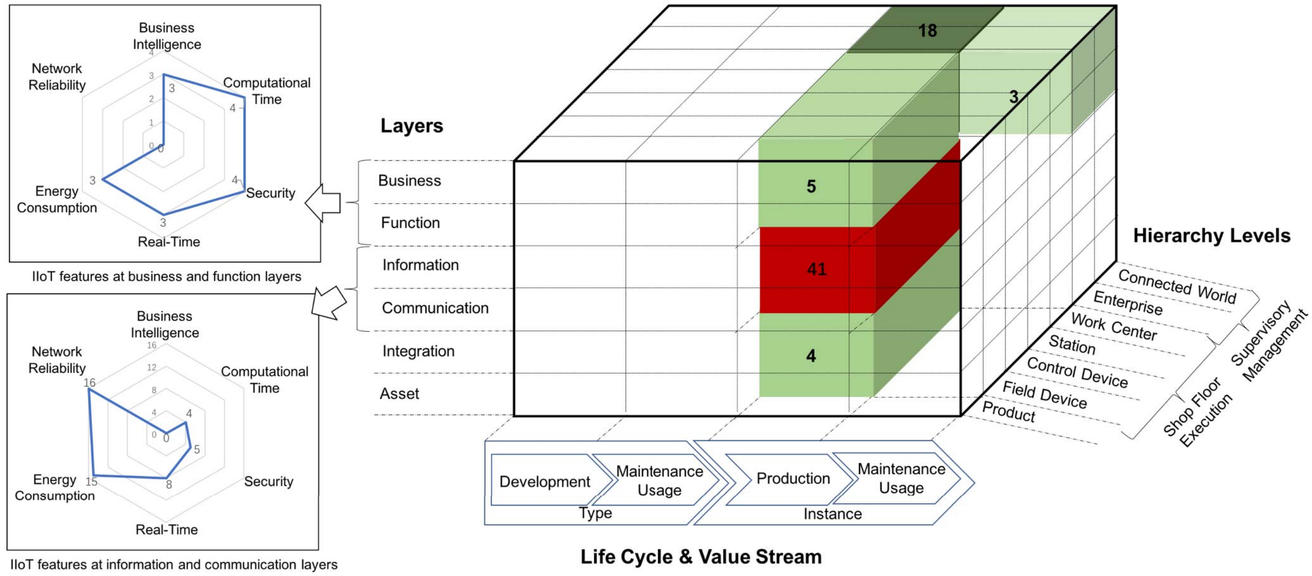

Fig. 6. Data analysis for Q3: state of the art IIoT research efforts in RAMI 4.0.

TABLE II
IIoT Research With Industrial Applications

Ref.	Year	Industry Name	Country	Main Product
[50]	2017	N/A (Confidential)	Belgium	Car and Truck
[6]	2017	Robert Bosch LLC	USA	Car Parts
[41]	2017	IdroLab plant	Italy	Electric Power
		Petro Ecuador Esmeraldas Refinery	Ecuador	Oil & Gas
[36]	2017	General Electric Power Manufacturing	USA	Electric Power
[51]	2017	N/A	N/A	Electric Power
[52]	2016	Mercedes-Benz	Germany	Car
[53]	2016	Longda Foodstuff Group Co., Ltd	China	Foodstuff
		Jinan District Heating Limited Company	China	Heating
[40]	2015	NEC	Japan	Electronics

"2211 Electric Power Generation". One article [53] presents a heterogeneous device data ingestion model to unify collected data from multiple sources in a heating water provider ("2213 Water, Sewage, and Other Systems").

The second most popular subsector is "336 Transportation Equipment Manufacturing", with applications in three organizations that either produce Motor Vehicles (3361) or Motor Vehicle Parts (3363). One work [50] develops an intelligent scheduler to plan the individual packets of the different streams by taking into account physical layer interference. Another work [6] presents a manufacturing analytics method to identify the root causes for the low quality of products. Finally, there is a work [52] that provides a model for the implementation of a smart assembly line, with the use of IIoT, in car manufacturing.

Moreover, IIoT applications also can be found in organizations from subsector "334, Computer and Electronic Product Manufacturing" (to provide IIoT technologies and solutions [40]), "211, Oil and Gas Extraction" [41] (to allow critical data publishing and distributed sensing), and "311, Food Manufacturing" [53] (to collect, analyze, and store data from multiple sources).

IV. Discussion

A. Related Works

Among the 94 included articles, six articles (6.4%) are classified as RS in Table I (three review articles [32], [54], [55] and three survey articles [56]–[58]).

The first review article [32] was published in 2014. It presents a review about IoT, its key enabling technologies, IoT applications in industry, and discusses research trends and challenges. However, though it claims its main contribution is the systematical summarization of the state-of-the-art of IoT in industry, two major limitations should be noted. One is the content that is specifically related to IIoT, which only covers around 10% of its overall content of this review article. Moreover, differently from a regular systematic review, its review method is implicit, similar to a subjective narrative review [59], which decreases the reliability and makes reproduction of results by others difficult [60].

The second review article [54] was published in 2016. It takes an IIoT communication technology perspective, and presents an opposite opinion in relation to the previous review article [32]. It declares that technologies employed so far (such as, ZigBee, WiFi, and GPRS) are not able to fully cover the strict requirements of industrial networks (e.g., energy efficiency). Thus, it dedicates its research effort on the review and comparison of current LPWAN-based solutions and the discussion of their key challenges.

The third review article [55] was published in 2017. It envisions that the advent of fifth-generation (5G) networks will

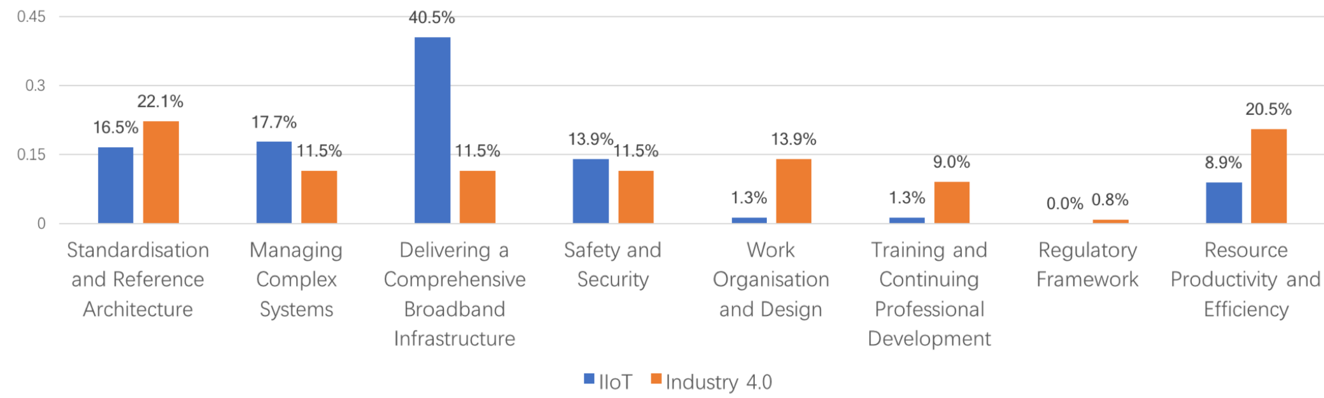

Fig. 7. Comparison of IIoT and industry 4.0 based on the eight priority areas for action.

bring together all the common standards and communication requirements by integrating multiple heterogeneous access technologies. The article also overviews several recent wireless power and data transfer solutions and technologies, both near-field and far-field.

The first survey article [56] was published in 2016. Its main objective is to answer how does IIoT influence business models of established manufacturing companies with respect to different industrial segments. The expert interviews were carried out in 69 manufacturing companies from the five most important German industries to address that research gap.

The second survey article [57] was also published in 2016. It focuses on giving an answer to how a smart city production system can change future supply chain design. Hence, an integrated framework was developed, first, to understand the interplay between smart cities production systems and supply chains, and then to support interview construction and data analysis in its study.

The third survey article [58] was published in 2017. It presents a survey to analyze and compare the effects of digitalization on future processes of manufacturing companies in a highly industrialized country (Germany) and a major emerging industrial economy (China). Questions raised in this survey article address two main dimensions: 1) environment and 2) social sustainability.

Therefore, to the authors' knowledge, in the present literature, there is still a lack of a more formal and objective systematic review that is specifically focused on IIoT and analyses it from multiple perspectives. The contributions that are made in this paper, as mentioned in Section I, can be used to address this issue.

B. *Industry 4.0 Versus IIoT: Academic Comparison*

Among the 94 included IIoT articles, 35 (37.2%) contain the term "Industry 4.0" (or "Industrie 4.0") in their full-texts. In more than half of those articles, these terms either appear only in the titles of their references (six articles) or do not provide an explicit description of their relationship with IIoT (12 articles). In the remaining articles, there are 16 articles that consider IIoT as another name (four articles), as a similar approach (three articles), as a component (five articles) or as a supporting technology (four articles) of Industry 4.0. Furthermore, there also exists one article that introduces Industry 4.0 as one of the research and standardization groups (like the Industrial Internet Consortium [61], [62]) that develops IIoT technologies. Thus, to avoid this kind of confusion in future IIoT research, an unambiguous explanation of this relationship is indispensable.

First, from a geographical location perspective, Industrie 4.0 is a term that was created in Germany and first appeared at the Hannover Fair in 2011 [4]. Since then, it started to attract increasing attention all around the world [73]. Therefore, the participation of German institutions can be found in most of the Industry 4.0 publications [8]. However, based on the data analysis for Q1 (Section III-B1), in IIoT research, the Chinese institutions have shown their prominence.

Second, from a publication time perspective, academic research on IIoT and Industry 4.0 both have just started within the last decade. In particular, according to the *Scopus* abstract and citation database, the earliest conference papers and journal articles that contain the term IIoT in their full-texts (2010, e.g., [63]) is two years earlier than the ones containing Industry 4.0 (2012, e.g., [64]).

Third, from a journal categorization perspective, even though the major thematic categories of the relevant journals in both of them are consistent ("Computer Science" and "Engineering"), the detailed subject categories suggest some differences. More precisely, IIoT journals turn out to be more focused on "Computer Networks and Communications" and "Control and System Engineering" (based on the general data analysis in Section III-A). By contrast, journals that publish Industry 4.0-related research are more closely associated with "Software" and "Industrial and Manufacturing Engineering" [8].

Fourth, to better highlight the differences from a research efforts perspective, the collected *research questions*, *solutions* and *features* for Q3 (Section III-B3) are also used to classify the included IIoT articles into the eight priority areas for action recommended by the National Academy of Science and Engineering [1]. As illustrated in Fig. 7, in Industry 4.0 research, besides "Standardization and Reference Architecture" and "Resource Productivity and Efficiency," which attract the majority of its research efforts, most of the other areas receive a more balanced attention [8]. In contrast to this, on the one hand, IIoT research dedicates nearly

TABLE III
MAIN LIMITATIONS OF EACH NETWORK GROUP

Network Group	Main Limitations from Included IIoT Articles
WLAN	1) Not low power consumption [21][70][34][54] 2) Difficult to guarantee the latency [50][36][71] 3) Do not provide the determinism and robustness levels required by industrial applications [21][54][66]
WPAN	1) Routing algorithms or channel hopping mechanisms may increase overall network power consumption [54][66] 2) Complexity and interference issues caused by the increment of the network size [54] 3) Low data rate but longer battery life [54]
Cellular Network	1) High cost [54][36] 2) High level of power consumption [36]
LPWAN	1) Low data rate [54]
Satellite Network	1) High level of power consumption [54][65] 2) High cost [54] 3) Not suitable for the indoor positioning [65]
Fieldbus	1) Interoperability issues [36][72] 2) Ongoing cable reduction trend: from analog to digital communication over bus networks [66] 3) The number of available data are limited [36]

a half of its research efforts to "Delivering a Comprehensive Broadband Infrastructure." On the other hand, compared to Industry 4.0, the areas of "Work Organization" and "Training and Continuing Professional Development" are much less prominent in IIoT.

According to this data-based comparison just presented, a conclusion can be drawn: IIoT is neither simply equivalent to nor just a part of Industry 4.0. It is an emerging approach that focuses on the "Computer Networks and Communications" area, to deliver "a Comprehensive Broadband Infrastructure," which is one of the mandatory requirements for Industry 4.0.

C. Network Coexistence in IIoT

To transform existing production equipment along the life cycle of a product into a smart and networked manufacturing system, the integration of IIoT communication standards and technologies is indispensable. However, due to the fact that there are different groups of networks (as illustrated in Section III-B2), choosing which network standards and technologies are more appropriate for a given application becomes a critical issue. In the current literature, different opinions have been given. Based on the collected limitations of those standards and technologies and the grouping of Section III-B, Table III illustrates the main limitations for each network group. They are mainly associated with energy consumption, cost, signal range, and data rate, which are analyzed next.

First, energy consumption has become one of the most important criteria for IIoT. Among the listed network groups, half of them (WLAN, Cellular Network, and Satellite Network) have the drawbacks of not being of low power consumption or being of high power consumption. However, these three network groups could provide a higher data rate if compared to the others (such as Low-Rate WPAN and LPWAN).

Second, even though both Cellular Network and Satellite Network groups are considered as high cost alternatives, they could provide a wider signal range than other network groups (such as WLAN and WPAN).

Lastly, LPWAN is the only group that can be considered as a candidate to satisfy both the low cost and the long signal range criteria.

To summarize, none of the existing network groups can provide the best performance from all perspectives. Namely, lower energy consumption, higher data rate, lower cost, and wider signal range. Therefore, the coexistence of multiple types of networks, to deal with different requirements in different situations, will appear in most of the IIoT industrial applications.

D. Research Trends

IIoT has been attracting increasing attention from different universities, companies, corporate research centers, and national or independent research centers from all around the world [see Fig. 4(d) and (e)]. A fast-growing number of academic contributions and industrial applications was seen between 2015 and 2017: the number of IIoT articles grew by 354% [see Fig. 4(a)] and the number of reported IIoT implementations grew by 400% (see Table II). Nevertheless, according to this SLR, several future IIoT research directions can be suggested.

The data analysis for Q2 (Section III-B2) illustrates the multiple standards and technologies in IIoT that support communication in each IICF layer. Furthermore, the coexistence of networks to fulfill different needs is also appearing to be unavoidable in smart and networked factories (Section IV-C). This situation, in some cases (e.g., the coexistence of WLAN and WPAN technologies that compete for the same radio resource), might cause interference and lead to undesirable effects, like high package loss rate. Even though, this critical issue is possible to be addressed by channel hopping technologies [65], tradeoffs exist: the procedure is time consuming and reduces network throughput [66]. Therefore, the efficiency improvement of the methods that address interference problems and the proposition of a more mature network selection strategy will become two IIoT research hotspots.

The data analysis for Q3 (Section III-B3) not only shows that current IIoT research efforts are mainly focusing on the issues during the *Production* phase of a product's life cycle (from the Life Cycle and Value Stream perspective of RAMI 4.0) but also indicates two other missing puzzle pieces. More specifically, from the hierarchy level perspective, although the shop floor execution level and the supervisory management level have both received a great deal of attention, there is still a lack of IIoT research that is specifically dedicated to the product level. Additionally, from the layers perspective, the integration and asset layers, compared with the other four upper layers, are the most neglected ones. Hence, more research efforts, especially for these two missing parts, are required to make the IIoT puzzle more complete.

The data analysis for Q4 (Section-III-B4) identified eight articles that present IIoT industrial applications, which only account for 8.5% of the total included articles. Moreover, among the 20 main economic activity sectors from NAICS, participating organizations in these studies belong to only three sectors (namely "Sector 21 Mining, Quarrying, and Oil and Gas Extraction," "Sector 22 Utilities," and "Sector 31-33 Manufacturing"). Additionally, for those organizations which are in the manufacturing sector, the "311, Food Manufacturing," the "334, Computer and Electronic Product Manufacturing" and the "336 Transportation Equipment Manufacturing" subsectors are the only 3 out of 21 subsectors that have IIoT implementations described in the literature. Thus, because this proportion in the manufacturing sector is very low (14.3%), more practice-oriented research is needed to transform academic achievements into industrial applications in other subsectors.

V. Conclusion

This paper provided an unambiguous literature review that specifically focused on IIoT in a systematic manner. Data were collected from the screening of the full-texts of 94 journal articles (Section II) selected according to well-defined inclusion and exclusion criteria. The contents of these articles were used for both a general data analysis about keywords and journals (Section III-A), and a specific data analysis related to four research questions of interest (Section III-B). Furthermore, four main insights were obtained through this SLR. The importance of this paper was highlighted based on the discussion about its related works (Section IV-A). The key differences between Industry 4.0 and IIoT were pointed out to avoid further confusions (Section IV-B). The coexistence and limitations of multiple IIoT standards and technologies in one application were investigated (Section IV-C). In the end, several research directions were outlined for the future of IIoT research (Section IV-D).

In addition to the above contributions, two main limitations of this paper should also be noted. First, this SLR only considered journal articles, not conference papers. It could be more comprehensive if all types of scientific contributions were taken into account. However, in such case, the number of relevant original research papers would become much higher than the ideal paper number (<300) for an appropriate SLR [13]. Second, the SLR could be more accurate (e.g., with the possibility to track the earliest year of IIoT journal articles back to 2011) and more complete (e.g., to give all aspects of information related to IIoT industrial applications) if the missing data (such as, the three articles that are classified as WF in Table I [67]–[69] and the confidential information in Table II) were available, although this only accounts for a very small proportion of missing information.

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