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# The Internet of Things—A survey of topics and trends

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**Abstract** The Internet of Things is a paradigm where everyday objects can be equipped with identifying, sensing, networking and processing capabilities that will allow them to communicate with one another and with other devices and services over the Internet to accomplish some objective. Ultimately, IoT devices will be ubiquitous, context-aware and will enable ambient intelligence. This article reports on the current state of research on the Internet of Things by examining the literature, identifying current trends, describing challenges that threaten IoT diffusion, presenting open research questions and future directions and compiling a comprehensive reference list to assist researchers.

**Keywords** Internet of Things · IoT · Survey · Machine to machine · Ubiquitous · Ambient · Context-aware

## 1 Introduction

Over the last couple of decades, the Internet has been in a constant state of evolution. The early days of the Internet were characterized by the World Wide Web, a network of linked HTML documents that resided on top of the Internet architecture. This network of static HTML pages gradually evolved in to what is referred to as Web 2.0, in which two-way communication became common, which enabled user participation, collaboration and interaction. Web 2.0 technologies include social networking services, blogs, and wikis—technologies that have become essential to modern social interaction as well as for global business. While Web 2.0 currently dominates the Internet, scholars have been working towards another goal, commonly referred to as the Semantic Web and sometimes referred to as Web 3.0. The goal of the Semantic Web is to mark up web content in a way that makes it understandable by machines, allowing machines and search engines to behave more intelligently. Marking up web content in standardized formats would allow machines to process and share data on their own, without the need for human mediation. Alongside developments in the Internet technologies, technologies in Sensor Networks and Near Field Communication using RFID tags have also been evolving. Convergence of these two technologies, i.e. the Internet and Sensor Networks, is leading to new possibilities and visions. The possibility of a framework that would allow direct machine-to-machine communication over the Internet has led researchers to envision the benefits of bringing more machines online and allowing them to participate in the web as a vast network of autonomous, self-organizing devices. This vision has produced a paradigm being referred to as the Internet of Things (IoT).

While there is no universal definition for the IoT, the core concept is that everyday objects can be equipped with identifying, sensing, networking and processing capabilities that will allow them to communicate with one another and with other devices and services over the Internet to achieve some useful objective. The core concepts underlying the IoT are not new. For years, technologies such as RFID and sensor networks have been used in industrial and manufacturing contexts for tracking large-ticket items such as cranes and livestock. The idea of direct machine-to-

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machine communication is also not new, as it is basic to the idea of the Internet in which clients, servers and routers communicate with each other. What the IoT represents is an evolution of the use of these existing technologies in terms of the number and kinds of devices as well as the interconnection of networks of these devices across the Internet. For example, most devices currently on the Internet were originally designed to be part of the Internet and have integrated processing, storage and network capabilities. These devices included servers, desktops, laptops, tablets and smart phones. What the IoT proposes is to attach technology to everyday devices, such as audio/video receivers, smoke detectors, home appliances, etc. and making them online, even if they were not initially designed with this capability in mind. The other major evolutionary change promised by the IoT, is the integration of networks that contain these devices, making each device directly accessible through the Internet. For example, RFID has been used for years to track products through certain parts of the supply chain. However, once the product left the shelf of a retail outlet, the manufacturer's ability to track the object was lost. Likewise, consumers were unable to gain access to the lifecycle information of products they purchased. By giving each product a unique identifier and making its data available through the web, the IoT promises to enable product traceability throughout the entire product lifecycle.

More generally, the IoT holds the promise of creating a global network supporting ubiquitous computing (Bandyopadhyay et al. 2011; Broll et al. 2009; Darianian and Michael 2008) and context-awareness among devices (Dong et al. 2010; Garrido et al. 2010; Jara et al. 2010b). Ubiquitous computing and context-awareness are key requirements of ambient intelligence, one of the key promises of the IoT (Dohr et al. 2010; Jara et al. 2010a). Ambient intelligence would allow everyday objects to understand their environments, interact with people and make decisions. A world full of smart objects holds enormous promise for improving business processes and people's lives, but it also comes with serious threats and technical challenges that must be overcome. The objective of this paper is to provide the reader with an understanding of the current state of IoT, the technologies that support it, the applications of the IoT, its challenges and recent developments through a comprehensive review and classification of the literature.

The rest of the article is structured as follows: Section 2 provides a description of the research process used in this article. Section 3 describes the classification scheme used to summarize the existing research. Section 4 presents an analysis of the trends and coverage of the IoT literature. Section 5 identifies a set of research questions and future directions to guide researchers. Section 6 summarizes the paper and provides some conclusions.

## 2 Research methodology

The objective of this research is to report on the current state of IoT research by examining the literature, identifying current trends, describing the challenges that threaten IoT diffusion, presenting open research questions and future directions, and compiling a comprehensive reference list to assist researchers.

In order to achieve this objective, a comprehensive review of the literature was performed. The reviewed literature included journal articles, conference papers, and edited volumes. Given that the IoT is still in formative stages and not yet been realized, it was necessary to consider a wide range of sources for a comprehensive review of the topic. In particular, cutting edge developments in computer science and engineering are frequently presented in conference proceedings. Given that the IoT is still in a conceptual state and the field is very dynamic at this point, reviewing only journal articles that make a specific theoretical contribution to the IoT would yield a very limited review.

Relevant literature was identified by querying scholarly databases for the terms "Internet of Things" and "IoT". Returned results were downloaded and read. The scholarly databases queried included:

- ABI/INFORM Global
- Academic Search Premier
- ACM Digital Library
- Applied Science & Technology Full Text (EBSCO)
- IEEE Xplore
- ScienceDirect
- Google Scholar

In all, 127 papers were reviewed. Each paper was carefully analyzed and classified into a single category. Classification was performed by the authors who jointly agreed on the classification of each article.

## 3 Classification method

The literature was classified according to its content into the following major categories: technology, applications, challenges, business models, future directions and overview/survey. Some of these top-level categories were further broken down into sub-categories and some of the sub-categories were broken into sub-sub-categories. Table 1 summarizes our proposed classification scheme and the rest of the section elaborates on each of the classification categories.

### 3.1 Technology

At the core of the idea of the Internet of Things is the notion that everyday "things" such as vehicles, refrigerators, medical

**Table 1** The proposed classification scheme

| Major category | Sub-category | Sub-sub-category |
|---|---|---|
| Technology | Hardware | RFID |
| | | NFC |
| | | Sensor Networks |
| | Software | Middleware |
| | | Search/Browsing |
| | Architecture | Hardware/Network Architectures |
| | | Software Architectures |
| | | Process Architectures |
| | | General |
| Applications | Smart Infrastructure | |
| | Healthcare | |
| | Supply Chains/Logistics | |
| | Social Applications | |
| Challenges | Security Challenges | |
| | Privacy Challenges | |
| | Legal/Accountability Challenges | |
| | General Challenges | |
| Business models | | |
| Future directions | | |
| Overview/Survey | | |

equipment, and general consumer goods will be equipped with tracking and sensing capabilities. When this vision is fully actualized, "things" will also contain more sophisticated processing and networking capabilities that will enable these smart objects to understand their environments and interact with people. Like any information system, the IoT will rely on a combination of hardware, software and architectures. Although many of the articles reviewed contained references to the technological components that support the IoT, only the articles that focused specifically on technology were placed in this category. We further classified technology into hardware, software and architecture. These sub-categories are not entirely disjoint as architecture builds upon hardware and software.

### *3.1.1 Hardware*

Much of the hardware upon which the IoT is being built already exists and is currently in wide-spread use. Critical hardware infrastructure includes: RFID, NFC and Sensor Networks.

*RFID* Radio-Frequency Identification (RFID) is a short range communication technology where an RFID tag communicates with an RFID reader via radio-frequency electromagnetic fields. Tags may contain different forms of data, but the data form most commonly used for IoT applications is the Electronic Product Code, or EPC. An EPC is a universally unique identifier for an object. These unique identifiers ensure that objects tracked with RFID tags have individual identities in the IoT.

RFID is not a new technology designed specifically for the IoT. RFID's usefulness in terms of tracking objects has been well established. The technology has applications in the areas of logistics and supply chain management, aviation, food safety, retailing, public utilities and others. The use of RFID has been mandated by organizations such as Wal-Mart, the U.S. Department of Defense, and others. However, the tracking capabilities offered by RFID are generally understood to be a precursor to the Internet of Things (Ngai et al. 2008) and the benefits of RFID can be extended by making their data remotely accessible through the Internet.

*NFC* A newer technology that builds on the RFID standard is Near Field Communication (NFC). NFC is a short-range communication standard where devices are able to engage in radio communication with one another when touched together or brought into close proximity to one another. Each NFC tag contains a Unique Identification (UID) that is associated with the tag. The NFC technology is frequently integrated into smart phones which are able to exchange data with one another when brought together. NFC devices are also able to make connections with passive, unpowered NFC tags that are attached to objects. One common use for NFC is in smart posters. Smart posters contain readable NFC tags that transmit data to the user's smart phone which reads the data from the tag.

*Sensor networks* Sensors are devices that monitor characteristics of the environment or other objects such as temperature, humidity, movement, and quantity. When multiple sensors are used together and interact, they are referred to as a wireless sensor network (WSN). Wireless sensor networks contain the sensors themselves and may also contain gateways that collect data from the sensors and pass it on to a server.

While sensors "sense" the state of an environment or object, actuators perform actions to affect the environment or object in some way. Actuators can affect the environment by emitting sound, light, radio waves or even smells. These capabilities are one way that IoT objects can communicate with people. Actuators are frequently used in combination with sensors to produce sensor-actuator networks. One example of the use of actuators in such a network would be the use of a sensor to detect the presence of carbon monoxide in a room and the use of an actuator to produce a loud noise altering people to the detection of the harmful gas. Thus, the combination of sensors and actuators can enable objects to simultaneously be aware of their environment and interact with people, both goals of the IoT.

### *3.1.2 Software*

While the IoT may rely upon the existing hardware infrastructure to a large extent, new software must be written to support the interoperability between numerous heterogeneous devices and searching the data generated by them.

*Middleware* The IoT will include vast numbers of heterogeneous devices generating enormous quantities of variable data. The IoT middleware sits between the IoT hardware and data and the applications that developers create to exploit the IoT. Thus, IoT middleware helps bring together a multitude of devices and data in a way that enables developers to create and deploy new IoT services without having to write different code for each kind of device or data format.

Many researchers have proposed the use of semantic middleware to interoperate the different classes of devices communicating through different communication formats. The semantic model typically uses XML and ontologies to establish the metadata and meaning necessary to support interoperability (Aberer et al. 2006; Gómez-Goiri and López-de-Ipiña 2010; Huang and Li 2010a; Song et al. 2010). Like the semantic web, semantic middleware seeks to create a common framework that enables data sharing and exchange across distributed devices, applications and locations.

*Searching/Browsing* Current browsers and search engines are designed to display and index relatively stable web content. However, objects in the IoT will be mobile, dynamic, and will generate massive amounts of frequently changing information. Thus, there is the need for an IoT browser that is capable of identifying smart objects, discovering their services and interacting with those objects (Garcia-Macias et al. 2011) as well as an IoT search engine that is capable of searching the rapidly changing information generated by IoT-enabled objects (Ostermaier et al. 2010).

### *3.1.3 Architecture*

Architectures are needed to represent, organize and structure the IoT in a way that enables it to function effectively. In particular, the distributed, heterogeneous nature of the IoT requires the application of hardware/network, software, and process architectures capable of supporting these devices, their services, and the work flows they will affect. We further classify architecture into hardware/network, software, process and general.

*Hardware/network architecture* A number of hardware/network architectures have been proposed to support the distributed computing environments required by the IoT. These architectures include peer-to-peer (Andreini et al. 2010), EPCglobal (Yun and Yuxin 2010), and autonomic (Pujolle 2006). The varying architectures that may be used to support the IoT also highlight the importance of the issue of standardization (Koshizuka and Sakamura 2010).

*Software architecture* Software architectures are necessary to provide access to and enable the sharing of services offered by IoT devices. In particular, service oriented architectures (SOA) (Gronbaek 2008; James et al. 2009; Spiess et al. 2009) and the representational state transfer (REST) model (Castellani et al. 2010, 2011; Guinard et al. 2011) are frequently proposed for IoT use due to their focus on services and flexibility.

*Process architecture* The IoT will certainly affect business processes. Process architectures are necessary to effectively structure the business processes that will incorporate the IoT. In particular, researchers have looked at how to structure workflows (Giner et al. 2010; Kawsar et al. 2010) to support the pervasive computing environments.

*General/requirements* There is no agreement on a single architecture that best fits the IoT. A number of articles proposed various conceptual architecture designs, while others proposed criteria for the assessment of proposed architectures (Främling and Nyman 2008) as well as a conceptual architecture to meet the requirements of smart objects (Kortuem et al. 2010).

## 3.2 Applications

The domain of the application areas for the IoT is limited only by imagination at this point. For a thorough discussion of the common application areas see (Atzori et al. 2010; Miorandi et al. 2012). Based on the review of the literature conducted for this research, the applications category was sub-classified into the following application domains: smart infrastructure, healthcare, supply chains/logistics, and social applications.

### *3.2.1 Smart infrastructure*

Integrating smart objects into physical infrastructure can improve flexibility, reliability and efficiency in infrastructure operation. These benefits can reduce cost and manpower requirements as well as enhance safety.

Smart grids use IoT technology to collect data about energy consumption and make the data available online. The data are typically incorporated into reports showing patterns of use and include recommendations for how to reduce energy consumption and cost (Liu et al. 2011). IoT technologies are also being used inside homes and offices. Homes and buildings are being equipped with sensors and actuators that track utility consumption, monitor and control building infrastructure such as lights and HVAC systems, and conduct surveillance to meet security needs (Darianian and Michael 2008; Li et al. 2011). On a broader scale, IoT technologies can be employed to make cities more efficient. The goal of smart cities is to leverage the IoT to improve the lives of citizens by improving traffic control, monitoring the availability of parking spaces, evaluating air quality and even providing notification when trash containers are full (Schaffers et al. 2011; Vicini et al. 2012).

### *3.2.2 Healthcare*

The IoT is proposed to improve the quality of human life by automating some of the basic tasks that humans must perform. In that sense, monitoring and decision making can be moved from the human side to the machine side. One of the main applications of IoT in healthcare is in assisted living scenarios. Sensors can be placed on health monitoring equipment used by patients. The information collected by these sensors is made available on the Internet to doctors, family members and other interested parties in order to improve treatment and responsiveness (Dohr et al. 2010). Additionally, IoT devices can be used to monitor a patient's current medicines and evaluate the risk of new medications in terms of allergic reactions and adverse interactions (Jara et al. 2010a).

### *3.2.3 Supply chains/logistics*

RFID and sensor networks already have long established roles in supply chains. Sensors have long been used in assembly lines in manufacturing facilities and RFID is frequently used to track products through the part of the supply chain controlled by a specific enterprise. While the use of these technologies in supply chains is not new, the pervasiveness and ubiquity promised by the IoT will enable the use of these technologies across organizational and geographic boundaries. Specifically, the IoT can further improve logistics and supply chain efficiency by providing information that is more detailed and up-to-date (Flügel and Gehrmann 2009) than currently available, mitigating the bullwhip effect (Yan and Huang 2009), reducing counterfeiting (Yan and Huang 2008) and improving product traceability (Zhengxia and Laisheng 2010).

### *3.2.4 Social applications*

Given that IoT devices are likely to be connected to many objects and even to people themselves, examining the potential societal and personal impacts of the IoT is absolutely essential. IoT devices enable a number of functionalities that can promote social interaction and personal needs. One possible application of IoT in a social context is the interaction of IoT devices with existing social networking services such as Facebook or Twitter (Vazquez and Lopez-de-Ipina 2008). Using IoT devices to provide information about an individual's activities and location can save the user time. Further, applications automatically collecting and integrating this information can inform individuals when they are in proximity to friends, social events, or other activities that may interest them (Guo et al. 2011). In addition, IoT-enabled mobile phones may connect directly to other mobile phones and transfer contact information when predefined dating or friendship profiles are compatible (Guo et al. 2012).

## 3.3 Challenges

The challenges facing the emergence of the IoT are numerous. They are both technical and social. These challenges must be overcome in order to ensure IoT adoption and diffusion. We sub-classify challenges into Security, Privacy, Legal/Accountability and General.

### *3.3.1 Security*

IoT devices are typically wireless and may be located in public places. Wireless communication in today's Internet is typically made more secure through encryption. Encryption is also seen as key to ensuring information security in the IoT. However, many IoT devices are not currently powerful enough to support robust encryption. To enable encryption on the IoT, algorithms need to be made more efficient and less energy-consuming, and efficient key distribution schemes are needed (Bandyopadhyay and Sen 2011; Roman et al. 2011b; Yan and Wen 2012).

In addition to encryption, identity management is an important component of any security model and unique identifiers are essential to IoT devices. These identifiers may be used to establish personal identities at financial institutions, identify illegal activity and other functions. Thus, ensuring that smart objects are who they say they are is essential to IoT success (Mahalle et al. 2010; Roman et al. 2011b).

#### *3.3.2 Privacy*

As more and more objects become traceable through IoT, threats to personal privacy become more serious. In addition to securing data to make sure that it doesn't fall into the wrong hands, issues of data ownership need to be addressed in order to ensure that users feel comfortable participating in the IoT.

Thus, the ownership of data collected from smart objects must be clearly established. The data owner must be assured that the data will not be used without his/her consent, particularly when the data will be shared. Privacy policies can be one approach to ensuring the privacy of information. Smart objects and reading devices in the IoT can each be equipped with privacy policies. When the object and reader come into contact, they can each check the other's privacy policy for compatibility before communicating (Roman et al. 2011b).

#### *3.3.3 Legal/accountability*

The IoT will create new legal challenges that must be addressed. In particular, governance of a global resource like the IoT should not be dictated by a single group. Rather, a broad-based stakeholder approach to governance is necessary. Thus, a shared governance structure for the IoT that includes all relevant stakeholders is needed (Weber 2009). In addition to establishing governance, global accountability and enforcement are necessary. Accountability tends to improve the effectiveness of governance through the threat of sanctions (Weber 2011).

#### *3.3.4 General*

A number of articles provide broad overviews of the challenges facing the IoT. These papers cover an array of issues including the challenges of technology and standards (Bandyopadhyay and Sen 2011) as well as social issues (Mattern and Floerkemeier 2010).

### 3.4 Business models

Changes in technology clearly require changes in business models. For example, Web 2.0 technologies have driven new business models such as software as a service, disintermediation, and an increased reliance on online advertising and strategic data aggregation. The IoT will certainly drive the development of new business models that capitalize on its pervasiveness and ubiquity. Researchers have proposed market structures and pricing schemes (Bohli et al. 2009) for the IoT and described how IoT can drive competitive advantage through better information and more localized decision making (Haller et al. 2009).

### 3.5 Future directions

Since the IoT has not yet been realized, it might seem precocious to forecast the future directions of the IoT. However, future visions of the IoT will affect its current development and must therefore be considered.

One future vision for the IoT is the Web of Things. The Web of Things proposes the use of web standards to fully integrate smart objects into the World Wide Web. Using web technologies can make it easier for developers to build applications using smart objects and existing web protocols can more easily enable the interoperability and communication of different devices. A mashup is a Web 2.0 concept where an application uses data and functionality from a variety of web resources. Some researchers proposing the Web of Things model suggest building on the mashup paradigm, except this time applying it to physical devices instead of applications (Guinard and Trifa 2009).

Another future vision that involves integrating even more devices into the IoT is the Internet of Nano-Things. The Internet of Nano-Things can be described as the interconnection of nanoscale devices with communication networks and the Internet. While these devices are proposed to communicate through electromagnetic communication, there are numerous technical challenges (Akyildiz and Jornet 2010) that must be overcome before the idea becomes feasible. The Internet of Nano-Things would be an even more granular approach to ubiquitous computing than the IoT.

### 3.6 Overview/survey

A large number of papers provided overviews of the IoT with varying degrees of depth and coverage. These general papers were classified as overview/survey papers.

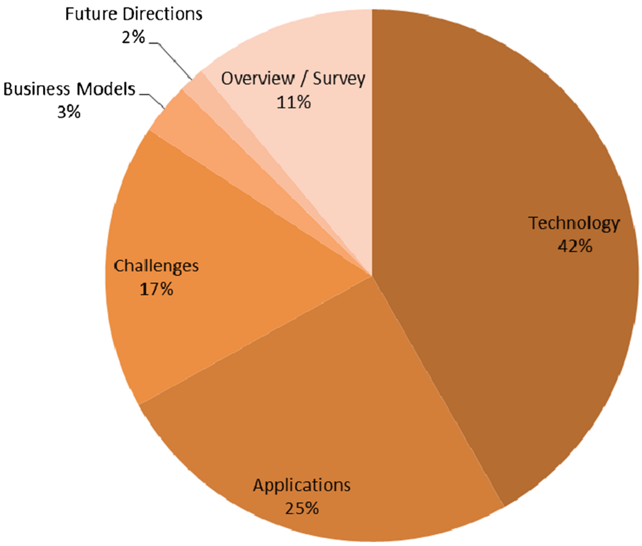


**Fig. 1** Distribution of articles by major category

They touched upon several or most of the classification areas discussed above.

## 4 Classification results

The literature pool of 127 documents was classified according to the scheme overviewed in Section 3. This classification scheme identified important trends in the relative emphasis in the literature being placed on the various classification categories, the types of outlets publishing IoT research, the geographical distribution of the work being done on the IoT, as well as topics that have not yet been given comprehensive treatment by the literature.

### 4.1 Distribution of articles by category

As can be seen from Fig. 1, much of the reviewed literature was focused on IoT technology. This corresponds to the disproportionate representation of engineering conferences and journals that are currently developing the IoT literature.

In particular, the coverage of IoT enabled business models was fairly limited, a fact that also corresponds to the lack of coverage of the IoT in the management literature. Table 2

**Table 2** Distribution of literature by category, sub-category and sub-sub-category

| Major category | Sub-category | Sub-sub-category | Number of articles |
|---|---|---|---|
| Technology | Hardware | RFID | 5 |
| | | NFC | 2 |
| | | Sensor Networks | 4 |
| | | | Total 11 |
| | Software | Middleware | 13 |
| | | Search/Browsing | 2 |
| | | | Total 15 |
| | Architecture | Hardware/Network | 13 |
| | | Software | 8 |
| | | Process | 2 |
| | | General | 4 |
| | | | Total 27 |
| | | | Technology Total 53 |
| Applications | Smart Infrastructure | | 7 |
| | Healthcare | | 7 |
| | Supply Chains/Logistics | | 9 |
| | Social Applications | | 9 |
| | | | Applications Total 32 |
| Challenges | Security | | 9 |
| | Privacy | | 3 |
| | Legal/Accountability | | 2 |
| | General | | 8 |
| | | | Challenges Total 22 |
| Business models | | | 4 |
| Future directions | | | 2 |
| Overview/Survey | | | 14 |
| | | | Grand Total 127 |

**Table 3** Classification of reviewed literature

| Classification | References |
|---|---|
| Technology | |
| Hardware | |
| RFID | (Dominikus et al. 2010; Khoo 2010; Schmidt et al. 2009; Welbourne et al. 2009; Sheng et al. 2010) |
| NFC | (Broll et al. 2009; Garrido et al. 2010) |
| Sensor networks | (Hong et al. 2010; Tozlu 2011; Zhu et al. 2010; Li et al. 2013) |
| Software | |
| Middleware | (Aberer et al. 2006; Bandyopadhyay et al. 2011; Blackstock et al. 2010; De et al. 2011; Dong et al. 2010; Gómez-Goiri and López-de-Ipiña 2010; Huang and Li 2010a; Katasonov et al. 2008; Kiritsis 2011; Puliafito et al. 2010; Roalter et al. 2010; Song et al. 2010; He and Xu 2014) |
| Search/Browsing | (Garcia-Macias et al. 2011; Ostermaier et al. 2010) |
| Architecture | |
| Hardware/Network architectures | (Andreini et al. 2010; Evdokimov et al. 2010; Han et al. 2010; Koshizuka and Sakamura 2010; Ning et al. 2007; Pujolle 2006; Quack et al. 2008; Silverajan and Harju 2009; Uckelmann et al. 2011; Yun and Yuxin 2010; Zhang et al. 2010; Zorzi et al. 2010; Zouganeli and Svinnset 2009) |
| Software architectures | (Castellani et al. 2010, 2011; Gronbaek 2008; Guinard et al. 2011; James et al. 2009; Michael and Darianian 2010; Spiess et al. 2009; Wang et al. 2012) |
| Process architectures | (Giner et al. 2010; Kawsar et al. 2010) |
| General/Requirements | (Främling and Nyman 2008; Kortuem et al. 2010; Ning and Wang 2011; Xiaocong and Jidong 2010) |
| Applications | |
| Smart infrastructure | (Darianian and Michael 2008; Heil et al. 2007; Li et al. 2011; Liu et al. 2011; Schaffers et al. 2011; Vicini et al. 2012; Fang et al. 2013) |
| Healthcare | (Bui and Zorzi 2011; Dohr et al. 2010; Domingo 2012; Jara et al. 2010a, b; Luo et al. 2009; Rohokale et al. 2011) |
| Supply chains/logistics | (Flügel and Gehrmann 2009; Shen and Liu 2010; Yan and Huang 2008, 2009; Zhengxia and Laisheng 2010; Han et al. 2012; Li 2013; Pang et al. 2012; Xu 2011b) |
| Social applications | (Atzori et al. 2011; Guo et al. 2011, 2012; Kranz et al. 2010a, b; Michahelles et al. 2010; Speed 2011; Vazquez and Lopez-de-Ipina 2008; Cao et al. 2013) |
| Challenges | |
| Security | (Alcaraz et al. 2010; Babar et al. 2010; Dlamini et al. 2009; Hancke et al. 2010; Mahalle et al. 2010; Roman et al. 2011a, b; Yan and Wen 2012; Zhou and Chao 2011) |
| Privacy | (Medaglia and Serbanati 2010; Oleshchuk 2009; Sarma and Girão 2009) |
| Legal/Accountability | (Weber 2009, 2011) |
| General | (Bandyopadhyay and Sen 2011; Christin et al. 2009; Coetzee and Eksteen 2011; Ma 2011; Mattern and Floerkemeier 2010; Mayordomo et al. 2011; Shen and Liu 2011; Zhang et al. 2011) |
| Business models | (Bohli et al. 2009; Haller et al. 2009; Fu et al. 2011; Li et al. 2012) |
| Future Directions | (Akyildiz and Jornet 2010; Guinard and Trifa 2009) |
| Overview/Survey | (Aggarwal et al. 2013; Atzori et al. 2010; Chui et al. 2010; Conti 2006; Gluhak et al. 2011; Huang and Li 2010b; Kopetz 2011; Liu and Zhou 2012; Mainetti et al. 2011; Miorandi et al. 2012; Ngai et al. 2008; Stuckmann and Zimmermann 2009; Tan and Wang 2010; Xu 2011a) |

breaks down the major technology category into sub-categories and shows that software and architectures get more emphasis than hardware. This is likely a result of the fact that the IoT makes use of existing hardware technologies, but requires significant innovation in software and architecture development.

In terms of application areas, papers focusing on supply chains and social applications received somewhat greater treatment than the other application areas, perhaps because of the established role of IoT technologies such as RFID in supply chain management and the cultural focus on social

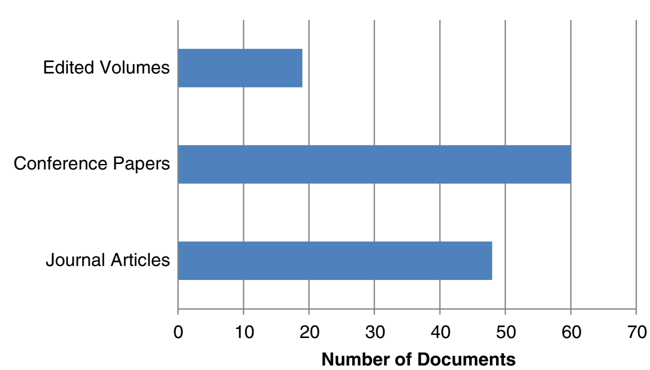


**Fig. 2** Reviewed literature by publication type

**Table 4** Top journals in which articles on the IoT appear

| Journal | Number of articles |
|---|---|
| Information Systems Frontiers | 5 |
| IEEE Internet Computing | 4 |
| IEEE Wireless Communications | 4 |
| IEEE Transactions on Industrial Informatics | 3 |
| IEEE Pervasive Computing | 3 |

media in society. Issues of security and privacy account for over half of the literature focused on challenges. This focus reflects the potential impacts of these issues on IoT adoption and diffusion. Legal and accountability issues received the least coverage in the challenges category, perhaps because these are also unresolved issues in the current Internet. Finally, a significant number of papers presented general overviews of the IoT field. However, this paper makes a contribution to the literature by presenting a systematic classification of the literature which is largely absent in these overview papers. The overall classification scheme for this research and the corresponding literature is presented in Table 3.

### 4.2 Distribution of literature by publication type

As shown in Fig. 2, much of the work being done on the IoT is being disseminated through conference papers. Almost without exception, these papers were presented at technical and engineering conferences that were abstracted by the IEEE Xplore. Disseminating work through conference papers in engineering is much more commonplace and encouraged than it is in other fields. Likewise, almost all of the work appearing in edited volumes was also technical in nature. For example, many of the articles in this category were published in venues like *Lecture Notes in Computer Science*.

The same engineering-oriented focus was identified in the journal articles that were reviewed. Table 4 presents five of the most common journals in which reviewed literature appeared.

### 4.3 Distribution of conference papers by geography

It is extremely difficult to identify the geographic hotspots for academic research in IoT due to issues such as co-authorship, international journals, foreign graduate students, visiting professors, multiple funding sources and other confounding factors. However, as a heuristic only, one can examine the distribution of the physical locations in which the conferences containing IoT related work are held. Figure 3 illustrates that from the literature pool selected in this article, the vast majority of the IoT-focused conference papers were presented at conferences held in Asia and Europe, with very limited representation in North America and Africa, and literally none in South America.

In addition, the majority of the IoT standards are being developed in Europe (Atzori et al. 2010; Miorandi et al. 2012).

## 5 Research questions and future directions

The analysis of the literature revealed that the research being done on the IoT is largely focused on technology at this point. This seems quite reasonable as the IoT has not yet been realized. Once the technology matures, the IoT research will need to broaden into the fields of management, operations, law, economics and sociology, among others. The review of the literature yielded some important findings that can focus the research efforts of scholars. These include:

- The IoT is not well represented in the management literature.
- IoT standards and research are dominated by work done or disseminated in Europe and Asia.
- The IoT literature is dominated by research relating to IoT technology.

**Fig. 3** Distribution of conference locations from literature pool

- The coverage of IoT driven business models is scant.
- Little work has been done on issues related to the legal and governance frameworks that will regulate the IoT.

These findings lead to a set of questions that need to be answered in future research. These research questions include:

- What are the appropriate theories of the IoT for management and operations?
- How does the IoT fit into the “Big Data” movement?
- How will information systems working with IoT data overcome the inherent complexity and data volume in order to provide useful decision support?
- What are the unaddressed applications areas of the IoT (for example, military)?
- What are the IoT business models that will drive global business and commerce?

## 6 Summary and conclusions

This article reported on the current state of IoT research by examining the literature, identifying current trends, describing challenges that threaten IoT diffusion, presenting open research questions and future directions, and compiling a comprehensive reference list to assist researchers. We proposed a classification scheme with six major categories: technology, applications, challenges, business models, future directions and overview/survey. We classified the literature pool of 127 papers according to this scheme.

The IoT holds the promise of improving people’s lives through both automation and augmentation. The capabilities offered by the IoT can save people and organizations time and money as well as help improve decision making and outcomes in a wide range of application areas. The IoT builds on existing technologies such as RFID and Wireless Sensor Networks along with standards and protocols to support machine-to-machine communication such as those envisioned for the semantic web. One question that remains is whether or not the IoT is to be an enduring technology, whether it will fail to materialize, or whether it is a stepping stone to another paradigm. Only time will ultimately answer that question. However, by bringing existing technologies together in a novel way, the IoT has the potential to reshape our world.

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