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An Application Domain-Based Taxonomy for IoT Sensors

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Abstract. If we look at the Internet of Things (IoT) from a viewpoint that comprises higher levels of abstraction, we will see that the IoT generated data can actually be transformed into more complex information, which would in turn facilitate the lives of human users. Because sensors have different purposes and measure different phenomena, it is necessary to know them and their different areas and domains of application so we can make a better use of their potential. This paper presents the identification and categorization of the main sensors used these days to build IoT applications, arranged in a taxonomy of application domains and sensor measurement types. To this purpose, we review the literature in order to identify IoT solutions, areas and domains of application and the main sensor types employed in these solutions. We hope this taxonomy can provide IoT designers, developers, and researchers with a snapshot of how sensors are currently used in the IoT application domains. Knowing the source devices is a key strategy to provide publication, discovery, sharing, reuse and integration of data/information within the IoT. We believe identifying and categorizing those sensors could be the first step to creating in the future a common communication model, which could be instantiated from each environmental context on the IoT.

Keywords. Internet of Things, IoT, Application Domain, Sensors, Taxonomy

Introduction

Internet of Things (IoT) is the term used to describe the vision in which "things" are interconnected and are capable of transmitting and receiving data through the Internet. The IoT allows "things", i.e., everyday objects, to perceive and to interact with the world, performing tasks and communicating with each other to share information and coordinate decisions [1]. Physical phenomena information is perceived by sensors, transmitted, aggregated, analyzed and used in the digital world, and as well as in the physical world by means of actuators that generate actions over the environment [2].

The integration of objects in the Internet allows new forms of management of the "moving parts" of businesses, since the state of vehicles, people, equipment and products is available in real-time for monitoring and controlling. IoT objects could

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embed sensors and actuators in order to be able to autonomously respond to situations according to defined rules [3], under various scenarios. Thereby, we can envisage the IoT potential through the variety of applications and services that it enables and the sectors that can be exploited.

A major element that produces inputs used by IoT applications are sensors, which provide measures of people, objects and the environment, in real-time or within certain time intervals, according to the application. A report generated by IDC [4] states that in the first half of 2014 the world had about 20 billion objects which contained embedded sensors and communicated to each other through the Internet. It also estimated that in circa 2020 this number would be of approximately 30 billion devices.

Sensors have different purposes since they provide different types of measures of: (i) objects, such as speed, fuel level and tire pressure of vehicles; (ii) the environment, as the temperature of a room and the amount of CO2 on a busy street; and (iii) people, as the amount of oxygen and glucose present in a blood sample. The combination of sensors serving different purposes allows the creation of complex services [5], for example, a system for agriculture, which combines position and humidity sensors to control the level of water in the fields [6]. However, the wide variety of existing sensors and its constant growth can hamper the discovery and selection of the most appropriate sensor type for each application domain.

In this paper, we propose a taxonomy to categorize the types of sensors used nowadays in different IoT application domains. To this end, we analyzed several IoT-based initiatives in order to identify the main IoT application domains and the sensor types currently used in each one of them. First, we present a table of summarized information on sensors and finally, the proposed IoT-based taxonomy for sensors.

The remainder of this paper is organized as follows. In section 1, we review the IoT application domains. In section 2, we present a survey on the IoT sensor types. In section 3, we present the related works. In section 4, we present the proposed taxonomy; finally, in section 5 we provide the closing remarks of this work.

1. IoT Application Domains

The IoT is becoming more and more used in several areas of activity since it enables the creation of a myriad of applications and services. By means of the use of large volume and variety of data produced by networked devices, the IoT fosters the generation of new applications [7] which can, for example, monitor the environment and climate, trigger actions and events, provide subsidies for making decisions and improve the quality of life by automating everyday tasks. Some of the IoT application domains are Smart City, Industry, and Health and Welfare [8].

The Smart City domain comprises IoT-based services applied to different areas of urban settings. Smart City applications envisage the best use of public resources, improvement of the quality of services provided to people, and reduction of operating costs of public administration [7]. Combining Smart City applications with IoT-based services allow the establishment and improvement of services focused on: (i) mobility and intelligent tourism, providing, for example, information about the state of roads, occupation of parking lots and the history of tourist attractions; (ii) smart grids, allowing better management of the network through new information on energy consumption; (iii) intelligent building, allowing new forms of residential automation, and infrastructures for monitoring and controlling; and (iv) public safety and environmental monitoring, facilitating the management of environmental disasters and strengthening the security of buildings open to the public [8].

IoT-based services are also used in the industry domain, such as in agricultural activities, factories and issues of logistics of resources and products. In agriculture, IoT applications are used to perform the monitoring of soil moisture [6] and the conditions of the plants, control microclimate conditions and monitor weather conditions that can damage the crops [9]. In the factories, we can find applications for monitoring of pollutant gases [10], locating employees [11] and improving the manufacturing process [12]. Moreover, in logistics issues, IoT-based services can be applied to the improvement of the processes involved in supply chains [13].

In the domain of Health and Wellness, we find IoT applications used for monitoring and diagnosing of patients, and for managing of people and medical resources. IoT-based services applied to the health domain enable the creation of applications to remotely and continuously monitor the vital signs of patients in order to improve medical care [14]. Besides, they ease the diagnosis by providing health indicators for patients, and enable the identification and tracking of equipment in a medical institution [9].

The diversity of applications and services based on the use, sharing and combination of data generated on the IoT shows us the need to know and classify the sources of data and information on the IoT. Since sensors are the main data generating devices in the IoT, we present in the next section a review of them in such a context.

2. IoT Sensor Types

Sensors are largely responsible for the generation of data consumed by applications in the IoT. In general, sensors are devices composed of components that are responsible for the perception and conversion of collected data, being able to obtain measurements on several phenomena, providing new inputs to be combined and analyzed by IoT applications [16]. One of the most important aspects when choosing a sensor is the kind of phenomenon that it is able to measure [5], and the target phenomenon is closely connected with the service the solution designer wants to provide.

Displacement and position sensors are present in diverse applications in the IoT. Measures related to movement, such as vibration, inertia, acceleration, rotation and speed are useful in applications related to traffic management [2], indoor location [11], and tracking of transport fleets to industry [9]. Moreover, sensors that provide measurements related to positioning of objects and people, such as presence, proximity, orientation and location are present in applications related to vehicle location [17], indoor location [18], intelligent parking system [19], and management of laboratories in educational institutions [20].

Other types of sensors are those that monitor the environment. For example, temperature sensors are used in homes for heating systems [21], ventilation and air conditioning (HVAC) [22] or, when coupled with gas sensors, in fire detection systems and in intelligent agriculture [23, 24]. Gas sensors may be used for gas detection in smart city applications to measure urban pollution [2]. Acoustic sensors are used for environmental conservation in applications for monitoring bird populations and illegal logging [2]. Weather sensors are used in applications related to irrigation and intelligent agriculture [2, 6, 24]. Applications for the medical domain also make use of sensors for measuring temperature, humidity and for detection of toxic agents (gas) in services for monitoring of well-being and health of a patient in their own home [25]. In industry, radiation sensors are used to detect levels of radiation in nuclear power plants, gas sensors are used to identify leaks in industrial environments, and fluid sensors are used to detect leaks in data centers and data warehouses, preventing damage and losses resulting from these leaks [9].

We can also find sensors that measure the mass of a body or the effects of phenomena on that body. These types of sensors assist in the formation of smart cities. There are, for example, applications to monitor the flow of water in water pumps or rivers [2] and to measure the mass of an athlete by the pressure exerted on a scale, in the smart health domain [26]. Furthermore, there are also sensors that measure the force, load and tension being used in monitoring of infrastructures, such as buildings and bridges [2].

Focused on health and medical care, we can also find sensors to measure chemical and physical phenomena of the human body. These sensors are used to measure heart rate (electrocardiogram), muscle electrical activity (electromyography), blood pressure, cholesterol level, amount of oxygen and sugar in the blood, body temperature and SpO_2, in services for local or remote monitoring of patients [27-29, 14, 9]. In addition to monitoring the health of patients, there are sensors applied to medical domain used to diagnose the health condition of patients [9] and in the management of medical institutions, by monitoring and tracking of patients, staff and medical equipment [30].

Some technologies commonly used by IoT applications and services, in a complementary way or as the main data sources, are the Radio Frequency Identification (RFID) and the Global Positioning System (GPS). RFID provides identification of people and objects, and is used for various purposes such as tracking packages [17] or access control in a building. Besides, RFID is part of the first definition of the IoT, in which "things" were simple identifiable RFID objects [31]. GPS has the purpose of identifying the current location of an object. Various applications use GPS, such as the ones that track transport facilities [32] or identify suitable routes to a given destination.

It is important to remark that the choice of sensor does not rely only on the types of measures provided by them. Features like accuracy, repeatability, operating range relative to the input signal, reading fluctuations (generated by internal or external noise), resolution, and selectivity also affect the choice of which sensors to use [5]. Since this work focuses on the relation between sensor types and IoT application domains, no further discussion will be taken about these other sensor features. We have chosen to let this matter to be addressed in future works.

As we can notice, this short overview of sensors and the relation between them and their possible fields of application becomes a key aspect for discovery, sharing, reuse and integration of data in the current IoT.

3. Related Works

At this moment, in the literature, we can find works that classify and provide descriptions and examples of applications related to a particular sensor type [2, 5, 15, 33] or propose taxonomies related to general and specific aspects of the IoT. Referring to the general aspects of the IoT, there are taxonomies related to concepts of connected objects [34], deployment scenarios [35] and base and architectural technologies [8]. In relation to the specific aspects, we can find taxonomies for use cases focused on the health domain [36], security and privacy [37, 38, 39], and sensor measurement [40].

The works in [2, 5, 15, 33] present summarized classifications of sensors by giving, in general, practical examples and applications, and providing overviews of the sensors used in the IoT. We consider these works as a first step in creating a more elaborate categorization of sensors, which provides information about possible areas of use and application domains for sensors.

In contrast to [40], which provides a taxonomy for categorizing sensors using a specific set of measures, in this work we propose a taxonomy for IoT sensors based on the analysis of works and applications identified in the literature, in order to explain and characterize sensors and application domains as they are used now into the IoT.

4. Proposed Taxonomy

A taxonomic classification allows the organization of a knowledge domain, in order to improve the access and understanding of information. A taxonomy for IoT sensors helps us understand how certain types of sensors are combined and used in different application domains. To develop a taxonomy for IoT sensors, we have conducted a survey on studies related to the IoT into the following databases: Web of Science, IEEE Xplore, ACM, ScienceDirect, and Scopus. From the data collected, we have detected the following classification of sensors identified by type and subtype, as shown in Table 1.

Table 1. IoT sensor types and subtypes.

Type	**Motion**	**Position**	**Environment**	**Mass Measurement**	**Biosensor**
Subtype	Movement	Orientation	Temperature	Volume	Blood
	Velocity	Inclination	Humidity	Pressure	Organ
	Inertia	Proximity	Luminance	Density	Mental
	Vibration	Presence	Acoustic	Deformation	Tissue
	Acceleration	Location	Radiation	Viscosity	
	Rotation		Gas	Flow	
			Magnetic Field	Load	
			Weather	Moisture	
			Chemical	Shock	
			Electrical	Contact	
			Color	Strain	
			EMF[2]	Corrosion	
				Electrical Conductivity	
				Oxygen	

We undertook a three-step bottom-up strategy to organize this classification: (i) the discovery of sensor instances, i.e., the identification of sensors used in certain scenarios; (ii) the grouping of sensors instances with similar measures, allowing the creation of subtypes; and, (iii) the definition of general terms or "types", for grouping the identified subtypes. The identified sensors types were:

- **Motion** – groups the measures related to the movement of a body[3];
- **Position** – groups the measures related to the positioning of a body;
- **Environment** – groups the measures obtained from an environment;
- **Mass Measurement** – groups the measures obtained from the measurement of a body or a physical interaction force with a body;

[2] Electromagnetic Field (EMF).
[3] We understand by the term "body" any mass (solid, liquid or gaseous), animate or inanimate.

- **Biosensor** – groups the sensors used for obtaining measures from organisms.

We emphasize that the sensors were grouped by types of measurements they provide, regardless of the technology used to obtain this measurement. For example, a device that produces readings on the temperature of an environment by means of an infrared sensor is fitted in the temperature category, even if the sensor working principle is based on the detection of infrared light. However, variations of infrared sensor are used, for example, for motion detection in security systems, thus put in the motion category.

This sensor grouping is a generic-specific relationship, in which the subtypes of a group have common characteristics; the proposed taxonomy for IoT sensors contains whole-part relationships. From the identified areas and application domains, and from the relation of these with the sensors by means of applications and services, we propose a taxonomy for IoT sensors with three levels: domain, area, and sensors. Thus, a domain is composed of areas, and the areas, in turn, are composed of applications and sensors. The taxonomy does not contain applications, so the sensors are directly related to the application areas. The proposed taxonomy is shown in Figure 1.

Domain	Industrial			Smart Cities			Healthcare	
Area	**Agriculture**	**Logistic**	**Plant Floor**	**Transport**	**Buildings**	**Environment**	**Monitoring**	**Management**
Sensor (subtype)	Chemical	Gas	Acoustic	Acceleration	Acceleration	Acoustic	Acceleration	Acceleration
	Conductivity	Humidity	Chemical	Acoustic	Acoustic	Chemical	Blood	Location
	Gas	Inclination	Contact	Contact	Color	Conductivity	Emotion	Luminance
	Humidity	Location	Gas	Gas	Deformation	Corrosion	Gas	Pressure
	Location	Luminance	Humidity	Inclination	Flow	Density	Humidity	Temperature
	Luminance	Pressure	Inclination	Load	Gas	EMF	Inclination	
	Moisture	Shock	Inertial	Luminance	Humidity	Flow	Movement	
	Pressure	Temperature	Location	Magnetic Field	Inclination	Gas	Organ	
	Temperature	Vibration	Luminance	Moisture	Luminance	Humidity	Orientation	
	Weather		Moisture	Movement	Magnetic Field	Load	Presence	
			Movement	Oxygen	Movement	Location	Pressure	
			Orientation	Presence	Orientation	Luminance	Radiation	
			Presence	Pressure	Presence	Moisture	Temperature	
			Temperature	Proximity	Pressure	Movement	Tissue	
			Vibration	Shock	Proximity	Pressure	Vibration	
			Volume	Temperature	Temperature	Proximity		
			Weather	Velocity	Vibration	Strain		
				Volume		Temperature		
						Volume		
						Weather		

Figure 1. Taxonomy of IoT sensors.

The domain level of the taxonomy consists of three domains that encompass all areas and sensors. These domains are Industrial, Smart Cities and Healthcare, and were adapted from Borgia's work in [8]. We assume in this work that they represent the main application domains of the IoT. The terms contained in the area level were defined based on terms commonly found in the literature [2, 8, 9, 15] and used by the authors to describe their applications. Thus, eight areas of application have been identified. The areas of agriculture, logistics and plant floor are related to the industry domain. Transport, buildings and the environment areas are related to the smart cities domain. Finally, monitoring and management areas are related to the healthcare domain.

In the industrial domain, the agriculture area involves all applications focused on agricultural activities such as planting, monitoring, irrigating, and harvesting. The logistics area involves applications related to the distribution chain and product lifecycle management. The plant floor area involves all activities related to security, monitoring, controlling and manufacturing in the industrial sector. The works in which we identified applications for the areas of the industrial domain were [6, 10-12, 13, 17, 24, 41-53].

In the smart cities domain, the transport area involves applications focused on cars, traffic flow, finding better routes and smart parking. The buildings area is focused on applications for the automation of services related to buildings, such as security and home automation, security in public buildings and infrastructure monitoring. Moreover, the environmental area is composed of all services focused on monitoring and acting on the environment, such as monitoring of air pollution and noise, wildlife preservation, and climate monitoring, for the detection of natural disasters and subsequent actions to mitigate their effects. The works in which we identified applications for the areas of the smart cities domain were [7, 19-23, 49, 51, 52, 54-73].

In the healthcare domain, the monitoring area involves services used to monitor vital signs and diagnose patients. The management area involves services to improve management in health institutions, enabling monitoring of patients, staff and equipment, and environmental conditions. The works in which we identified applications for the areas of the healthcare domain were [8, 14, 18, 25, 27-30, 38, 49, 51, 74-79].

The IoT application scenarios were used to define the areas and identify the sensor subtypes present in each area. The terms used in sensor level were obtained from the subtypes found in Table 1. Thus, we built the third level by binding subtypes of sensors with the area in which they can be applied. In addition, it is worth noticing that due to the whole-part nature of the taxonomy, the same sensor subtype can appear several times for different areas. However, this is an expected behavior, since the use of sensors depends on the purpose of the IoT applications. These, in turn, depend on the ability of the IoT designers to generate creative solutions and make use of available resources (sensors, other devices and technologies) in the context of the problem they intend to solve. Moreover, new contexts that emerge daily in consequence to the dynamics of the real world eventually demand the development of new sensor types.

The most used sensors on IoT applications and services are the temperature, humidity and gas sensors, appearing in a large part of the works analyzed and in almost all areas defined in the taxonomy. For the industrial sector, we identified that the most commonly used sensors are the temperature, humidity and gas sensors. For the smart cities domain, the most commonly used sensors are the temperature, humidity and luminance sensors. In addition, for the healthcare domain, the most commonly used sensors are biosensors for organs and blood, and temperature sensors. The widespread use of temperature, humidity, gas and luminance sensors can be attributed to the universal phenomena they observe and the availability and variety of prices in which they can be obtained [2]. As for the biosensors, the emphasis in their use is in the healthcare domain, which is focused on health and quality of life of patients and uses several types of biosensors.

Finally, it is possible to notice that a wide set of solutions combine the use of conventional sensors with RFID and GPS technologies. This is understandable since RFID is present in the IoT since its first steps, and GPS is a well-established technology that provides useful information about the location of things and people.

5. Conclusion

In this work, we have analyzed several solutions to identify areas and domains of application of IoT and the types of sensors employed in these solutions. We have identified various sensors types, according to their collected data type. We have summarized the existing IoT sensors by their type and subtype, and built a taxonomy for IoT sensors by relating areas and application domains with the types of sensors found in current IoT initiatives.

Since this is a work still in progress, we consider as limitations of it the non-exhaustive list of documents analyzed during the first step, mostly of academic nature. As future work, we intend to extend the proposed taxonomy by investigating new IoT applications, and by using data from IoT solutions provided by companies. Furthermore, we could identify more areas and subareas within the application domains, and evaluate and explore some other characteristics of the sensors, apart from those already used in this work.

The taxonomy proposed here can be used as a resource to aid IoT designers, developers and researchers in the process of identification and selection of sensors, as well as in the categorization and recognition of the main sensors used nowadays in the main IoT application areas. Although this taxonomy is a snapshot of the moment, we believe it can be used as a reference for further IoT application development.

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