Smart Cities Architectures
A Systematic Review

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Abstract: The smart cities concept arises from the necessity of managing several problems caused by the unbridled population growth at urban centers. To make a city become "smart" it is needed to employ Information and Communication Technologies (ICT) to access, process and deliver information according to the urban context. This information can be employed to mitigate several urban issues, such as traffic jams, high natural resource consumption, epidemias, sustainability, waste management, low quality and life expectancy of citizens, among others. Thus, the increasing need to create architectures that are able to interact with the Internet of Things, i.e., several built-in devices, appliances, sensors and actuators embedded in each urban context. This work is a systematic review regarding proposals for such architectures. After selecting the relevant approaches, we have identified a set of issues that these approaches aim to solve and some architectural patterns employed.

1 INTRODUCTION

The most accepted definition for the term City is described in Kuper (Kuper, 1995): a relatively large and permanent settlement. Usually, big cities have high population density, with its citizens living in constant interaction with industries, business and services.

According to a UNESCO report released in 1950 (Nations, 2007), 30% of world population lived in urban areas. This number grew to 50% in 2010 and it is estimated that in 2050 the percentage of people living in large urban centers will be around 70%. Consequently, several issues are easily identified in urban centers, such as traffic jams, high natural resource consumption, epidemias, sustainability, waste management, low life expectancy of citizens, among others.

This unbridled populational growth sets a challenge of combining city services with Information and Communication Technologies (ICT) in order to mitigate these urban issues and promote better living conditions for citizens. In other words, the challenge is how to turn a city into a Smart City and it has been widely discussed both in academic and industry, from projects and initiatives considering several viewpoints.

To achieve this goal, it is needed the utilize of some sort of sensing capability in the targeted objects (vehicles, people, home, etc.) and ensuring connectivity. It is from this unitary monitoring mechanism that a holistic view of the city is built, dedicated to efficient maintenance of its services. This vision can be specialized to a scenario, where each object is equipped with enough technology and intelligence to transform it in a data supplier/consumer. It is reasonable to picture this distribution and integration with each object owning part of the needed data to some computation executed in a centralizing entity, responsible for the processing and management. This set of objects acting collaboratively in pursuit of a well defined common purpose is called *Internet of Things*(IoT) (Atzori et al., 2010), and it constitutes the essential technological foundation for implementing smart cities.

Smart Cities offer a new approach to optimize services, reducing costs and improving citizens life quality. This way, it is needed that sensors become smart, since they represent the peripheral elements of a complex future ICT world. However, due to the specific application field, smart sensors are very heterogeneous in terms of communication technologies, sensing features and elaboration capabilities(Fazio et al.,

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2012).

Thus, it arises the need of establishing a smart city architecture able to store, combine, process and delivery contextualized information for the Internet of Things (Sanchez et al., 2011) (Fazio et al., 2012). These architectures must enable the integration between different urban contexts, e.g., using smart city architecture is possible to analyze the impact of every city event in different contexts.

In this context, this Systematic Literature Review (SLR) aims to analyze the main approaches that describe the architectures of smart cities based on the Internet of Things. According to Kitchenham's guidelines (Kitchenham and Charters, 2007), the aim of an SLR is intended to support the development of evidence-based guidelines through selection and synthesize the most relevant research. Many architectural approaches have been proposed in the literature, and this paper will focus on architectures that combine internet of things with smart city. This way, this literature review will be based on three questions:

Q1. What architectures have been proposed combining the internet of things with smart cities?

Q2. What are the main goals and issues addressed by these architectures?

Q3. What are the patterns used by the existing proposals?

The remainder of this paper is structured as follows. Section 2 describes the applied research methodology. Section 3 presents and analyzes the results related to review questions, while Section 4 closes the paper by describing the main conclusions.

2 RESEARCH METHODOLOGY

The systematic review is a means of identifying, evaluating, interpreting and comparing all available that is research relevant to a particular question (Kitchenham and Charters, 2007). Thus, for review purposes, only approaches that combine smart cities with the internet of things were considered.

This way, this section aims to describe the search strategy and all steps followed to filter and extract relevant data from approaches found. Our research methodology followed all the stages and steps recommended in Kitchenham's guidelines (Kitchenham and Charters, 2007).

2.1 Search Strategy and Data Sources

The strategy used to construct the search terms followed the same approach used in (Kitchenham and Charters, 2007) (Chen et al., 2009) (Khurum and Gorschek, 2009):

- Derive main terms based on the research question and the topics being researched;
- Determine and include synonyms, related terms, and alternative spelling for major terms;
- Incorporate alternative spellings and synonyms using boolean operator "OR";
- Link main terms using boolean operator "AND".

Following this strategy, we constructed the search string as bellow:

(smart city OR intelligent city OR digital city OR urban environment) AND (internet of things OR heterogeneous sensors) AND (architecture OR middleware OR platform)

Due to the variation of the search features provided by the main digital sources of literature (such as IEEExplore, Springer Link, and ACM Digital Library), it was not possible to use a single search string for all the digital sources (Chen et al., 2009). Thus, we made a significant effort to ensure that the search strings used were logically and semantically equivalent.

After the search string definition, we searched the primary studies in these digital sources (1. IEEExplore; 2. Science Direct; 3. ACM Digital Library; 4. Springer Link; 5. CiteSeerX; 6. Academia.edu; and 7. ISI Web of Science). Furthermore, considering that smart city involves business concepts, we also searched patents on the *World Intellectual Property Organization* (WIPO)[1].

About the manual search, we performed it in these conferences (1. International Conference on Computational Intelligence, Modeling and Simulation (IJCCI); 2. International Conference on Intelligent Environments (IE); 3. Multimedia Information Networking and Security (MINES); 4. Emerging Technologies for a Smarter World (CEWIT); 5. International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS)).

The quality of search engines may have influenced the completeness of the identified primary studies. That means our search may have missed those studies whose authors would have used other terms to specify smart cities architectures associated to internet of things.

2.2 Study Selection

We selected only works that propose architectures or frameworks to centralize the several contexts and

[1] www.wipo.int

technologies involving the urban environment. Thus, aiming to increase analysis reliability, all the authors were involved in source selection process.

After defining the search string and data sources, the filters to refine the work found were defined. Figure 1 illustrates the results of each step with the corresponding filters.

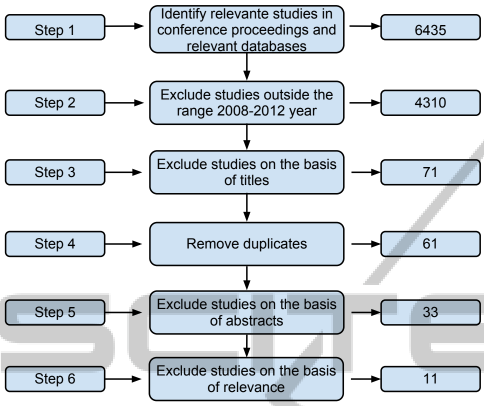

Figure 1: Steps of the search strategy.

The goals of the filters were to select the main approaches that describe architecture of smart cities based on the internet of things. Thus, the first filter matches all work found in relevant databases, previously described, obtained from the search string.

The second filter was applied to exclude the work in which the publication year is outside the range 2008-2012. This interval was chosen after analysis and verification that the work published before 2008 dealt with the internet of things applied to smart city in isolation, i.e., the work proposed to solve problems in a specific scenario using only a technology, without analyzing the connection between different urban contexts.

Regarding the inclusion criteria, the work was included if:

- it proposed an architecture or framework to centralize the information from several urban contexts or;
- it described an IoT middleware design that met more than one technology and context and;
- the approach has not been addressed in earlier studies analysed;

During the review several papers were found describing the same architecture. In this case, only the most complete work was included. After this stage, there were 11 approaches left.

This high discrepancy between the initial amount of approaches and the amount of resulting primary studies is discussed and explained in Kitchenham et al. (Kitchenham et al., 2009).

Regarding patents, we did not find any patent related to integration of different city contexts. Usually, the patents that are closer to the context of this systematic review generally describe a specific algorithm or technique optimization in a controlled environment.

3 RESULTS AND ANALYSIS

After performing the search on relevant databases, and filtering them according to the criteria described in the previous section, 11 approaches remained. These approaches were read and discussed among the authors, aiming to highlight the topics related to the review questions. This section aims to discuss these approaches, starting with an approach review, describing addressed issues, applied patterns, and finally, analyzing all the results.

If an approach had a name, we used that name. Otherwise, we created a name using the first authors surname followed by the publication year. Table 1 lists each of the 11 approaches in chronological order.

Table 1: List of approaches reviewed.

ID	Approach	Year	Reference
1	Al-Hader'2009	2009	(Al-Hader et al., 2009)
2	Anthopoulos'2010	2010	(Anthopoulos and Fitsilis, 2010)
3	SOFIA	2010	(Filipponi et al., 2010)
4	EcoCity/ISMP-UC	2011	(Lee et al., 2011)
5	CPAF	2011	(Mostashari et al., 2011)
6	SmartSantander	2011	(Sanchez et al., 2011)
7	IMS	2011	(Shao, 2011)
8	USN	2011	(Hernández-Muñoz et al., 2011)
9	Wu'2011	2011	(Wu et al., 2011)
10	Fazio'2012	2012	(Fazio et al., 2012)
11	S^{3}OiA	2012	(Vega-Barbas et al., 2012)

3.1 What Architectures have been proposed Combining the Internet of Things with Smart Cities?

Architectures for smart cities can be designed starting from different areas of scientific knowledge. This subsection aims to briefly discuss architectures found, ordered by the publication date, highlighting its goals and features proposed to solve the issues they address.

Starting with Al-Hader'2009 (Al-Hader et al., 2009), it proposes an architecture supported by four principles: applications, business, process management and network infrastructure. The first principle corresponds to applications which uses different technologies for monitoring sensors, such as Global Positioning System (GPS). The vast majority of these applications meet cities operational demand, however, using the rules defined in the second principle - business - they can aggregate economically viable solutions. The third principle is the processes management in which relationships, rules, strategies and policies between smart cities applications and business units are defined. Finally, the last principle is a network infrastructure, responsible for connecting the other three principles.

Anthopoulos et al. (Anthopoulos and Fitsilis, 2010) proposed an architecture based on the analysis of different initiatives already implemented, modeled applying the principles of Enterprise Architecture, which sets up a mission, information, technologies, specific processes and framework required to implement it. Anthopoulos et al. highlight that the construction of a smart city must forecast legacy systems integration to the new infrastructure, migration and reuse of existing data, simplification of urban processes through participatory performance, resource utilization optimization, systems and equipment interoperability, and providing tools for monitoring, management and analysis.

The SOFIA (Filipponi et al., 2010) project is centered on the concept of smart environment as an ecosystem of interacting objects, such as sensors, devices, appliances and embedded systems in general, self-organized, providing services and custom processing. The SOFIA architecture is event driven, in which an event is an observable change in the state of an Information Technology (IT) system; it can be triggered by real world events, such as presence detection, timeouts etc., by internal events like the reception of a message (e.g., a command) or the completion of a task.

Sensors monitoring and management are also the goal of the ISMP-UC (Lee et al., 2011) project. The EcoCity architecture has three basic layers. The bottom layer consists of different types of sensors, actuators, and other devices distributed accross the city. On the top layer there is a range of U-eco City Services. Above these layers lies the middleware which collects and processes data and contextual information. Its service-oriented architecture enables services to be developed independently and invoked through standardized Web services interfaces.

Moreover, Mostashari et al. (Mostashari et al., 2011) proposes a framework, called *Cognitive Process Architecture Framework* (CPAF), which allows different urban processes to be designed with cognitive abilities. In this context, cognition is the ability of a system to learn from previous experiences and adapt its behavior based on them. A cognitive system is able to sense, perceive and respond to changes in the environment, and can therefore improve a systems performance by increasing its adaptive capacity.

Another approach with several sensors embedded in an urban environment is SmartSantander (Sanchez et al., 2011). The number of devices to be deployed in Santander and its surroundings is foreseen to climb up to 12,000 devices, thus creating the basis for development of a future Smart City. The SmartSantander aims to produce the following key outcomes: i) An architectural reference model for open real-world Internet of Things (IoT) experimentation facilities; ii) A scalable, heterogeneous and trustable large-scale real-world experimental facility; iii) A representative set of implemented use cases for the experimental facility; and iv) A large set of Future Internet experiments and results.

As SmartSantander focuses on interoperability of objects, the IMS (Shao, 2011) proposes an approach that combine IoT with citizens. According to the authors, the development of ICT is related to the proximity with people. For this, IMS is based on three layers: access, session and application. The access layer is the lowest layer and provides capability to access IMS network from different terminals. The session layer provides session establishment, modification, and termination; providing session management to the upper layer. Finally, the application layer, the highest one of IMS network, allows application deployment.

The interoperability of objects also is explored by Hernandez et al. (Hernández-Muñoz et al., 2011), that proposed an architecture called *Ubiquitous Sensor Network* (USN). The goal was to provide an infrastructure that enabled the integration of heterogeneous and geographically dispersed sensors in a centralized technological base, in which services could be developed at minimal cost; to this end, the project based itself on the integration of Internet of Things and Internet of Services. Additionally, the architecture included a module known as *USN-Gateway* that enabled interoperability between sensor and the IP network.

Like the USN, Wu'2011 (Wu et al., 2011) proposes a middleware to manage the spatial information from multiple sources always has different formats, structures, and spatial database engines. The middleware builds a bridge to heterogeneous spatial and application by the support of Multi-Agent and Web Service. This platform follows the Service-Oriented Architecture (SOA), and it is consisted of two main parts: Contract-First model and message conversion agent model.

Fazio'2012 (Fazio et al., 2012) proposes an architecture which allows the aggregation of different information types from several sensors embedded on different urban contexts. The main goal of this architecture is to provide contextualized data, combining several data sources. To this end, the architecture consists of four levels: I) REST APIs, which allow on-demand interactions with clients, applications and/or other services; II) The *Sensor Observation Service Agent* (SOS Agent), which supports all functionalities for describing sensors and observations; III) Sensor Manager, able to interact with sensors, it coordinates their activities and collect data for the upper layers. It provides a uniform management of heterogeneous sensors; IV) the Sensing Infrastructure (SI), which is composed of several different sensors and sensing devices.

The architecture called S^3OiA, described in (Vega-Barbas et al., 2012), also manage the different information types and interoperability issues among such a large number of heterogeneous actors. The S^3OiA architecture is syntactic and semantic Service-Oriented Architecture that allows the integration of any type of object or device on the Internet of Things. It allows an ad-hoc dynamic application composition in cooperating and distributed environments which are uniformly described. To such extent it has been defined within the architecture design a set of semantic dependency management modules which track services and resources allowing the already created applications to continue running despite changes of the context.

3.2 What are the Main Goal and Issues Addressed by these Architectures?

These architectural approaches are proposed to meet several issues on urban systems. As the analysis approaches were not proposed for specific purposes, the techniques used to solve these issues are easily adapted to different urban contexts. Table 2 summarizes the architectures IDs with the issues addressed.

One of the most discussed and studied issue on IoT projects is the **interoperability of objects**, where the object is an abstraction of a sensor, actuator or any device able to perform some sort of computation (Atzori et al., 2010). In fact, this is a critical requirement to the consolidation of any platform that uses a range of objects with different technical specifications and communication protocols. The majority of architectures explicitly designate a module or layer to meet this requirement, as in SOFIA (Filipponi et al., 2010), USN (Hernández-Muñoz et al., 2011), Wu'2011 (Wu et al., 2011) and S^3OiA (Vega-Barbas et al., 2012). In particular, the SOFIA project developed an interoperable platform and select a set of vertical applications to compose this smart environment based on embedded systems. Regarding to USN (Hernández-Muñoz et al., 2011), this module - known as *USN-Gateway* - besides being responsible for the interoperability of objects on the platform, it also implements mechanisms that allow interoperability between sensors network and the IP network. In case of Wu'2011, the interoperability is implemented by two main parts: Contract-First model and message conversion agent model. i) Contract-First agent model integrates distributed and heterogeneous spatial information. ii) Message conversion agent model resolves the protocol conflict between different applications problem. Finally, in S^3OiA the integration of heterogeneous objects (legacy and future created) is made from extensible mechanism using OSGi[2] platforms.

Another important feature inherent to the smart cities context is **continuous real-time monitoring**. The real-time monitoring is an important requirement for keeping city services constantly updated, due to an event triggered in a city domain can influence the decisions-making of others. Furthermore, the real-time monitoring is the most valuable instrument to provide relevant information that will be used to predict phenomena. In this context, the main architectures which implement this feature built into the structure are Al-Hader'2009 (Al-Hader et al., 2009), SOFIA (Filipponi et al., 2010), SmartSantander (Sanchez et al., 2011) and USN (Hernández-Muñoz et al., 2011).

This diversity of objects capturing data and operating over several city domains combined with real-time monitoring raises a great opportunity for employing **sustainable policies** on the data analysis process. Due to the high coverage of all city areas, architectures must include, since its conception, sustainable policies. These policies are related to environmental, economic and social aspects of each domain. The architectures that seek to integrate sustainability are EcoCity/ISMP-UC (Lee et al., 2011) and SmartSantander (Sanchez et al., 2011), however they only address the environment issue.

Aiming to adopt these sustainable policies, a smart city architecture must provide mechanisms to improve **social aspects** for citizens to be involved effectively; otherwise the entire investment will not be effective. One example is the Digital City of Trikala, Greece, after five million euro spent on infrastructure maintenance and 6 years of operation, the population did not use it and was not even aware of the digital services availability (Anthopoulos and Fitsilis, 2010). The only architecture that contains a citizen's involvement principle is IMS (Shao, 2011), in which the architecture provides apparatus for citizens to interact

[2] www.osgi.org

with the things anywhere.

This proximity between devices and people, usually with access to the Internet, originated the term **ubiquity** (Spínola and Travassos, 2012). Ubiquity comprehends any mobile technology feat capture information about the environment and citizens or act over the same (Sanchez et al., 2011). Ubiquity is another key requirement that must be explored in smart cities. The ubiquity concept is an essential key for the implementation of real-time monitoring requirement, that was explored on SmartSantander (Sanchez et al., 2011) and USN (Hernández-Muñoz et al., 2011) approaches.

This ubiquity eventually produces a large amount of data (Filipponi et al., 2010), generating the phenomenon known as Big Data (Gopalkrishnan et al., 2012). The smart city space can be considered an ubiquitous computing environment where sensors are installed in many different areas and provide information about the environment to interested devices, applications and users (Sanchez et al., 2011). All these high data volumes need to be protected, in compliance with **security policies**, both in relation to the availability and storage. These goals are discussed in SmartSantander (Sanchez et al., 2011) and Fazio'2012 (Fazio et al., 2012).

Besides, to improve the data analysis process, **sensors location** is needed (Shao, 2011) (Hernández-Muñoz et al., 2011) (Vega-Barbas et al., 2012). From the geographic location of the sensors it is possible to perform actions according to the environment (Jauregui-Ortiz et al., 2012). This feature is addressed by the approaches IMS (Shao, 2011), USN (Hernández-Muñoz et al., 2011) and S^3OiA (Vega-Barbas et al., 2012). In IMS, location is an important information in the investigation the citizens behavior; in USN, the location discovery is considered as a essential requirement of architecture. S^3OiA aims to unify the countless device discovery protocols that are currently used. One of the ideas issued to overcome it aims to create a new standardized IoT common protocol or interoperable architectures that abstract these inconsistencies.

Finally, urban environments are essentially a set of complex systems available to meet the needs of its citizens. Architectures that are willing to give support to these systems should consider them as complementary in the search for effective urban management, rather than treating them isolated. For this end, the Anthopoulos'2010 (Anthopoulos and Fitsilis, 2010), CPAF (Mostashari et al., 2011), IMS (Shao, 2011) and Fazio'2012 (Fazio et al., 2012) approaches implemented some **service composition** techniques.

3.3 What are the Patterns used by the Existing Proposals?

Regarding the addressed patterns it was difficult to identify which patterns each architecture used due to the lack of design and implementation details. Nevertheless, some patterns were identified, specially the patterns regarding to communication and messaging between components.

Among these communication patterns, the most employed is the **publisher-subscriber** pattern (Buschmann et al., 1996). In the publisher-subscriber pattern, publishers send messages to a specific channel; the subscriber listening to that specific channel receives all messages. Among the analyzed approaches, four of them explicitly described the use of this pattern: SOFIA (Filipponi et al., 2010), USN (Hernández-Muñoz et al., 2011), SmartSantander (Sanchez et al., 2011), Wu'2011 (Wu et al., 2011) and Fazio'2012 (Fazio et al., 2012).

The main reason is the real world natural modeling (Filipponi et al., 2010), since several events can be triggered simultaneously and can be interpreted by the same component. Additionally, this pattern enables service composition since each service can receive information from other services and combine them appropriately. Moreover, in USN this pattern is used to constantly monitor the sensors, appliances and devices.

Besides the publisher-subscriber pattern, Fazio'2012 (Fazio et al., 2012) employs another two patterns: **facade** and **abstract factory** (Gamma et al., 2001).

By analyzing the approaches, we noticed that the **architectural model based on layers** (Buschmann et al., 1996) is more employed, due to the facility in compose and expand components (Hernández-Muñoz et al., 2011) (Fazio et al., 2012) (Vega-Barbas et al., 2012), being used by 8 studied approaches. However, two approaches are not arranged in layers: Al-Hader'2009 (Al-Hader et al., 2009) and SOFIA (Filipponi et al., 2010). The SOFIA architecture is based on event driven and Al-Hader'2009 is based on principles.

Due to the difficulty of identifying information concerning to the architectural patterns of each approach, it was not possible to identify the patterns used in Al-Hader'2009, CPAF and IMS.

3.4 Analysis

After answering the questions, others factors were analyzed. The first factor is the adhesion to the layered model for most of the studied approaches, primarily

Table 2: Approaches reviewed summary.

Architecture ID	1	2	3	4	5	6	7	8	9	10	11
Issue											
Object interoperability			■					■	■		■
Real-time monitoring	■		■			■		■			
Sustainability				■		■					
Social aspects							■				
Ubiquity						■		■			
Security						■					
Sensor discovery							■	■			■
Service composition		■			■		■			■	
Pattern											
Publisher-Subscriber			■			■		■	■	■	
Facade										■	
Abstract factory										■	
Layers		■		■	■	■	■	■		■	■

due to the simple composition and expansion of the components.

Regarding the issues from this systematic review may be noted that no architecture met all the issues surrounding smart city architecture. We believe that usually the architectures are proposed for specific purposes, to solve problems of small niches in the smart city context.

It may also be noted that for implementation of these smart city architecture heterogeneity is essential, due to factors, such as the high range of devices and proximity to citizens.

Another relevant point is the proximity with the citizens. To turn a city into smart city is a social rather than a technological challenge. So, all technological mechanism should be developed based on the citizens needs, so that they feel involved in the process.

Furthermore, a smart city should monitor events and take preventive decisions in real time. This prevention must be done examining several urban contexts. Thus, the architectures are focusing on the composition and aggregation of services, data, information and contexts.

Finally, the approaches analyzed are in different stages of validation. Some approaches, such as SmartSantander and SOFIA, already have some statistical data and case studies that demonstrate the architecture behavior in some contexts. Moreover, some approaches, such as CPAF, have not presented any practical validation to the proposed design.

4 CONCLUSIONS

Throughout this systematic review several smart city architectures based on the internet of things were analyzed. The section 2 described the research methodology used and the results were analyzed on section 3 related to the reviewed questions.

At the end of this review, we identified a set of issues that these architectures aim to solve and that can be considered as minimum requirements for implementing a smart city architecture. Each issue represents a core set of features that are critical for the deployment and adoption of a smart city.

Regarding the patterns, we conclude that the layered model seems to be the most promising, since several approaches have successfully implemented it. Moreover, this pattern provides some interesting benefits in relation to the smart city context.

Furthermore, the analyzed approaches are in different validation stages. Some approaches, such as Smart Santander and SOFIA, have already presented some statistical data and case studies that demonstrate the architecture behavior in some contexts. Moreover, some approaches, such as CPAF, were designed without practical validations.

From the analyzed studies we noted that no architectures meets all the issues of a smart city. Thus, for future work, we will design and implement a IoT-based smart city architecture. As a case study, it will be considered essential services in Brazilian context as a means to validate the architecture in a real scenario.

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