SCIENCE CHINA
Information Sciences

• **REVIEW** •
Special Focus on Intelligent City and Big Data

October 2015, Vol. 58 100102:1–100102:18
doi: 10.1007/s11432-015-5397-4

A literature survey on smart cities

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Received April 3, 2015; accepted May 27, 2015; published online August 25, 2015

Abstract Rapid urbanization creates new challenges and issues, and the smart city concept offers opportunities to rise to these challenges, solve urban problems and provide citizens with a better living environment. This paper presents an exhaustive literature survey of smart cities. First, it introduces the origin and main issues facing the smart city concept, and then presents the fundamentals of a smart city by analyzing its definition and application domains. Second, a data-centric view of smart city architectures and key enabling technologies is provided. Finally, a survey of recent smart city research is presented. This paper provides a reference to researchers who intend to contribute to smart city research and implementation.

Keywords smart city, architecture, data-centric, data vitalization, urban data

Citation Yin C T, Xiong Z, Chen H, et al. A literature survey on smart cities. Sci China Inf Sci, 2015, 58: 100102(18), doi: 10.1007/s11432-015-5397-4

1 Introduction

The urbanization of the world's population has become a key issue that needs to be addressed. In the 1950s, only 30% of the world's population lived in cities; by 2014, the urbanization level had reached 54%, and the United Nations predicts that by 2050, the figure will be 66% [1]. Developing countries in Asia and Africa are urbanizing even more rapidly than other regions of the world. In the past 10 years, China's urbanization has increased from 40.53% to 53.73% [2]. With the irreversible process of urbanization, cities and megacities (cities with a population greater than 10 million) are emerging with increasing frequency [3]. Since cities are not only hubs of human activity, but also the places where economic, environmental and societal demands are magnified, urbanization causes many important and significant economic, social and demographic transformations [4].

The urbanization process has greatly improved people's standard of living, providing water supplies and sewerage systems, residential and office buildings, education and health services and convenient transportation [5]. Cities are commonly regional economic centers that are helpful in improving regional economic prosperity and creating more jobs. The concentration of educated people in cities helps to improve the industrial structure and promote production efficiency [6]. However, urbanization also creates

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new challenges and problems. The growing population and maximal use of natural resources in cities cause ecological and environmental problems, and increase public disorder problems [7]. As a representative developing country, the economic advantages of China's cities are being offset by the perennial urban curses of overcrowding, air and water pollution, environmental degradation, contagious diseases and crime; the urban issues of reducing air pollution and providing clean water, safe neighborhoods and efficient infrastructure desperately need to be addressed [8]. In Mexico, Mexico City has encountered a serious increase in emissions of gases and particulate matter that have affected its air quality [9]. In a 2011 study, 493 city areas in the USA had high traffic congestion, which causes Americans to spend 4.8 billion hours longer travelling and to purchase an extra 1.9 billion gallons of fuel for a congestion cost of US $101 billion [10]. A recent study of crime statistics in Japan indicated that urbanization can be considered the leading factor in the cause of crime [11]. All these challenges and problems force citizens, governments and stakeholders to pay attention to the environment and sustainable development of cities, and to try to find a set of technical solutions to reduce these urban problems.

The Information and Communication Technology (ICT) revolution has offered people the opportunity to reduce the scale of and/or solve urbanization issues. During the past 10 years, city systems have become more digital and information-based, and there has been a fundamental change in the living environment of citizens and the governing mode of cities. The economy, culture, transport, entertainment and all other aspects of cities have become closely combined with ICT, and the Internet has become a major part of citizens' daily lives. The abundant accomplishments of digitizing a city's information not only introduce daily convenience to the population, but also establish an infrastructure and conglomeration of data as a basis for further evolution of modern cities. Over the last 10 years, innovative information technologies such as cloud computing, 'big data', data vitalization, the 'Internet of Things' and mobile computing have become widely adopted in a variety of different areas. Cloud computing enables developers to provide Internet services without the need for a large capital outlay on hardware for deployment, or the staff to operate it [12]. The amount of information published and processed both on- and offline has given rise to an information explosion, and a new field dedicated to dealing with it—big data—which has spawned the need for new, more scalable, techniques to derive answers from huge sets of data [13]. The emergence of the Internet of Things makes it possible to access remote sensor data and to control the physical world from a distance, meaning that cities can effectively sense and manage essential elements such as the water supply, building operations, and road and transport networks [14]. Data vitalization proposes a new paradigm for large-scale dataset analysis and offers ubiquitous data support for top-level applications for smart cities [15]. With the help of mobile computing, users can access and process information anywhere, and anytime, on all aspects of life [16].

The urbanization, growth and associated problems of modern cities, coupled with the rapid development of new ICT, has enabled us to first envisage the 'smart cities' concept, and now to begin to build smart cities, which is seen as the future form for cities.

The concept of the smart city has attracted world interest, including governments, companies, universities and institutes. Different stakeholders have tried to understand and explain the smart city from their different viewpoints. The term 'smart city' appeared for the first time in the early 1990s, and researchers have emphasized technology, innovation and globalization in the process of urbanization [17]. Smart cities have attracted great attention since 2008, with the launch of IBM's Smarter Planet project [18]. Since then, the concept of smart cities has continued to grow and evolve. Harrison et al. defined a smart city as an instrumented, interconnected and intelligent city [19]. Another definition, by Giffinger and Gudrun, provided six smart characteristics to be considered: economy, governance, environment, people, mobility and living [20]. A common definition for a smart city is using ICT to make a city (administration, education, transportation, etc.) more intelligent and efficient [21–23]. The definitions and concepts of smart cities are still emerging, and there is currently no clear and consistent definition of a smart city among the different stakeholders. In order to implement and assess smart cities in practice, a deeper understanding of the 'smart city' still needs to be defined [24]. Many countries and cities have launched their own smart city projects to resolve urbanization issues and challenges. The USA was one of the first countries to launch a smart city project with a high compliment of smarter planet notions from President Barack

Obama [25]. The Digital Agenda initiative of the European Commission promotes smart cities in Europe, and a corresponding Smart Cities and Communities initiative, focusing on energy efficient cities, has also been launched and has achieved a great deal to date (2015) [26]. Japan launched the i-Japan Strategy 2015, striving to create a citizen-driven, reassuring and vibrant digital society [27]. Singapore announced its Intelligent Nation 2015 plan, and launched many projects to build a smarter future city [28]. Not only have developed countries shown much enthusiasm, but developing countries have also taken practical action to follow the trend to smart cities. In particular, for developing countries, the speed of urbanization is considerably faster and, as a consequence, the infrastructure problems faced are much greater. With more than 200 pilot smart cities, China has invested heavily more than 2 trillion RMB in smart cities (both research and implementation) in 2015 alone, to sustain its largely urban population [29]. In 2014, India declared an intention to build more than 100 smart cities, with high-technology communication capabilities, throughout the country [30]. At the city and application level, more smart city initiatives can be found in the literature [31].

ICT plays an important role in smart city construction. Top-level architecture research plays a considerable role in guiding technology development in every domain of a smart city and improving research into resource configuration. The earliest architecture research was conducted by IBM [19]. It gave a detailed introduction to the technology functions, centered on infrastructure and services, without too much emphasis on the importance of city data. Chourabi et al. proposed a smart city architecture, considering the need to combine the government, citizens, community, economy and basic infrastructure from the perspectives of policy, organization and technology [32], but without much discussion of the technology. Paroutis et al. considered data processing technologies to be fundamental for all smart city applications [33]. An increasing number of researchers have begun to define smart city architectures from the viewpoint of data [34–36]. Smart city architecture research has led to a systematic understanding of the technologies needed to implement a smart city. Due to the variety of definitions proposed by different stakeholders, smart city architectures in the literature are still very diverse. Most architectures show that a smart city is driven and enabled by multidisciplinary technology [37], in particular, data processing technologies. A variety of innovative information technologies, such as cloud computing, big data, data vitalization, the Internet of Things and mobile computing, have been widely deployed in the smart city concept [38]. In these, data-centric enabling technologies play an important role in smart city implementation.

As introduced above, driven and supported by today's advanced ICT, the concept of the smart city arose from the challenges and issues caused by the rapid urbanization of the world. Although there is a large body of research into smart cities, producing great innovation and implementations by many countries and cities, there remain several key issues that need to be addressed. These unresolved issues are included in the following questions:

- How can we better understand the concept of a smart city?
- What are the main enabling technologies in a smart city?
- What are the main research issues for smart cities?

In this paper, we give synthesized answers according to recent implementation projects and research into smart cities. Section 2 presents an understanding of smart cities by analyzing definition and application domains. Section 3 illustrates smart city architectures and key enabling technologies from a data-centric viewpoint. Section 4 presents some research issues through recent related work. Finally, Section 5 concludes the paper.

2 Understanding smart cities

2.1 From digital city and intelligent city to smart city

Several different terms have been coined that all refer to the use of ICT to improve the capabilities and performance of a modern city. Digital city, intelligent city and smart city are all subtly different concepts used to describe ICT-driven city research and development issues. The change in terms used to describe ICT-driven cities reflects a natural evolution of strategy to improve the quality of city life.

A digital city refers to the digitization of a city, involving networking, visualization and information technologies to access population, resource, environment, economic and social data [39]. A digital city combines communication and computing infrastructure to meet the needs of the government, citizens and businesses [40]. The aim of a digital city is the sharing of information and networks [41]. A prime example of existing digital cities is Chicago, which built its digital metropolis with large networks [42].

An intelligent city is defined as a city equipped with the infrastructure of ICTs [43]. An intelligent city can be considered to be a cross between a digital city and a knowledge society [44]. An intelligent city is a place in which the local system of innovation is enhanced by digital collaboration spaces, interactive tools and embedded systems, and the aim of an intelligent city is to transform life and work within its region in significant and fundamental, rather than incremental, ways [45].

From a technical standpoint, a digital city describes the city's characteristics; but, from a more complex standpoint, a smart city includes the human and governmental aspects, among others, as well as the technology. Hence, a digital city is not necessarily smart, but a smart city must, first of all, be digital. A digital city is more focused on the technological basis and has clearer boundaries, whereas a smart city relates to both technology and sustainability.

An intelligent city is often considered as a synonym for a smart city by some researchers and practitioners. People usually do not understand differences between a smart city and an intelligent city. Nam and Pardo explain why the term smart city is becoming more widespread and accepted in solving new urbanization challenges [24]. 'Smartness' is centered on a user perspective, and is better than the more elitist term 'intelligent'. 'Smart' means to be able to self-adapt and provide customized interfaces and services to user needs, which is more user-friendly than 'intelligent', which implies having a quick mind and being responsive to feedback.

To summarize, we use the following simplification as our way to distinguish between the terms. A digital city is one whose procedures, communication and information have all been digitalized. An intelligent city is a digital city that has a layer of intelligence that can make high-level decisions based on a level of artificial intelligence. A smart city is an intelligent city where application is focused on practical use and user experience.

2.2 Definitions of a smart city

An understanding of the definition of a smart city is vital to be able to understand its scope and content. As was demonstrated in Section 1, a concrete definition of a smart city is still emerging, and various definitions have been given by stakeholders from several different standpoints.

It is difficult to formalize the definition, because the smartness of a city can be as simple as a single function provided to a certain group of citizens, or as complicated as an entire administration process representing the restructuring efforts of a government procedure [37].

2.2.1 *Review of definitions*

Several surveys of smart city definitions have been made [24,25,37,38]. However, most of these surveys only collect and explain different definitions, and lack an explicit taxonomy for smart city definitions from different perspectives. In this section, we study and analyze the definitions of a smart city from the following four perspectives:

- Technical infrastructure.
- Application domain.
- System integration.
- Data processing.

Technical infrastructure One of the earliest definitions proposed by Harrison et al. describes a smart city as an instrumented, interconnected and intelligent city [19]. This definition emphasizes the connecting of the physical, ICT, social and business infrastructures of a city. Washburn et al. considered a smart

Table 1 Taxonomy of smart city definitions

Literature	Technical infrastructure	Application domain	System integration	Data processing
Harrison et al. [19]	×			×
Giffinger et al. [20]		×		
Washburn et al. [21]	×	×		
Bowerman et al. [46]	×			
Al-Hader et al. [47]	×			×
Lazaroiu and Roscia [48]		×		
Dirks and Keeling [49]			×	
Moss Kanter and Litow [50]			×	
Javidroozi et al. [51]			×	×
Yamamoto et al. [52]		×		×

city to be a collection of smart computing technologies applied to infrastructure components, in which hardware, software and network technologies are integrated [21]. Bowerman et al. argued that, in a smart city, all structures should be designed, constructed and maintained, making use of advanced, integrated materials, sensors, electronics and networks that are interfaced with computerized systems comprising databases and tracking and decision-making algorithms [46]; they make this case for all infrastructure: power, water, transportation, etc. Al-Hader et al. defined the smart city as representing the transmission and receipt of data using communication protocols on network elements [47].

Domain application Giffinger et al. gave a representative definition of a smart city from a domain application perspective [20]. They identified six smart characteristics with which to define and assess smart cities: economy, people, governance, mobility, environment and living. Washburn et al. stated that a smart city should use smart computing technologies and infrastructures to make city services more intelligent, interconnected and efficient, including city administration, education, healthcare, public safety, real estate, transportation and utilities [21]. Lazaroiu and Roscia defined a smart city as a solution that considers electricity, water and gas consumption, as well as heating and cooling systems, public safety, waste management and mobility [48].

System integration The technical infrastructure and field application of a smart city can be considered as a set of interconnected and integrated systems and subsystems. Some researchers have tried to define a smart city from this perspective. Dirks and Keeling defined a smart city as the organic integration of systems and their interrelationship to make the system of systems smarter [49]. Moss Kanter and Litow defined a smart city as an organic whole: a network and a linked city system [50]. Javidroozi et al. considered that for a city to be smart, the integration of city systems is essential, in order to provide flexibility and access to real-time information for the creation and delivery of efficient services [51].

Data processing In their definition, Al-Hader et al. emphasized that sending and receiving data is the basis of monitoring and controlling the functional operational framework needed for smart management of network assets [47]. Harrison et al. described a smart city from a data processing perspective [19]: instrumentation enables the capture and integration of live real-world data through sensors; interconnection allows the data obtained from instrumentation to be integrated across multiple processes, systems, organizations, industries or value chains; and finally, intelligence means that data processing must yield new insights that drive decisions and actions which can demonstrate a tangible added value. Yamamoto et al. discussed data that were collected and analyzed with advanced data processing technologies to achieve smart services in a smart city [52].

2.2.2 *Discussion and proposition*

After identifying the representative definitions of a smart city from different perspectives, we provide a taxonomy of definitions in Table 1.

As shown in Table 1, the definitions of a smart city are from different perspectives for different researchers. Several researchers have defined the smart city from multiple perspectives, while others do so from only one. In our work, we consider only the four perspectives, although, because the concept is still evolving, some new perspectives may yet emerge for defining smart cities.

We cannot give a universal definition for a smart city today, but we can define smart cities from a wider perspective, considering these four perspectives: a smart city is a system integration of technological infrastructure that relies on advanced data processing with the goals of making city governance more efficient, citizens happier, businesses more prosperous and the environment more sustainable.

2.3 Application domains of smart cities

The objective of a smart city is to improve the city's sustainability from the aspects of governance, citizens, businesses and the environment. Smart applications are developed to fulfill the information and decision-making requirements of government, citizens, companies and the environment. A great number of different applications for smart city emerge every day, and researchers try to include the application domains in the literature.

2.3.1 *Review of application domains*

Liu and Peng have surveyed pilot smart cities in China. They identified three main application domains and their sub-domains [29]: (1) life enrichment: home, community, healthcare and education; (2) public administration and services: public safety supervision, food safety supervision, smart traffic, smart tourism and environmental protection; (3) wide-scale resource management: water, electricity and agriculture. Giffinger and Gudrun used six characteristics, 31 factors and 74 indicators to evaluate a city's smartness: the six top characteristics can be considered to be general smart city application domains: smart economy, smart people, smart governance, smart mobility, smart environment and smart living [20]. Washburn et al. listed seven critical infrastructure components and services for a smart city: city administration, education, healthcare, public safety, real estate, transportation and utilities [21].

Neirotti et al. first listed all the application domains relevant to the topic of urban development, then divided these application domains into hard and soft domains, according to the importance that ICT systems have as key enabling technologies [53]. Hard domains are the city settings in which an improvement in sustainability relies on the deployment of ICT systems, along with the appropriate policy interventions and urban planning, such as buildings, energy grids, natural resources, the environment and transport. Soft domains are the areas in which ICT systems have a limited role and are not necessarily aimed at processing and integrating real-time information, and where citizens are freer to use smart services; areas such as education, culture and innovation. Finally, they proposed seven smart city domains: natural resources and energy, transport and mobility, buildings, living, government, economy, and people.

2.3.2 *Discussion and proposition*

With the rising wave of smart city implementations and smart application development, the application domain definitions are tending to become more specific, in-depth and extensive. In order to guide general smart city planning, especially for particular systems or applications, it is necessary to let the designers know clearly in which areas their projects are situated, and what aspects are to be considered and covered. In our work, after identifying the application domains, sub-domains and classifications, we continue to use the four perspectives cited in our smart city definition as a basis for analyzing application domains. Our classification of smart city application domains is shown in Table 2.

As shown in Table 2, different applications and projects can be situated in a domain or sub-domain according to the classification. Some applications or projects may involve two or more domains, such as smart grid projects [54], in which government monitoring, citizen consumption, environmental effects and business operations are all included in the operation process. The objective of this classification is to avoid the positioning of an application or project into a subclass that may cause the isolation of an integrated system or application. The classification helps investors and designers of smart cities to better understand their project's domain coverage and potential benefits.

Table 2 Classification of smart city application domains

Domain	Sub-domain	Description
Government (more efficient)	E-government Transparent government Public service Public safety City monitoring Emergency response	Improving the internal and external efficiency of the government; enabling citizens and other relevant organizations to access official documents and policies; ensuring that public services work efficiently; monitoring and managing public safety; responding quickly and effectively in emergency situations.
Citizen (happier)	Public transport Smart traffic Tourism Entertainment Healthcare Education Consumption Social cohesion	Traveling and moving more efficiently; accessing contextualized, precise, real-time information in daily life; high-quality essential public services such as education, healthcare and sport; enriching spare time activities, communicating and sharing more with others.
Business (more prosperous)	Enterprise management Logistics Supply chain Transaction Advertisement Innovation Entrepreneurship Agriculture	Improving inter management efficiency and quality; using more efficient logistics and supply chain platforms and methods; advertising more widely and accurately; expanding trade partners and customers; facilitating entrepreneurship and investment; upgrading the business activity in a city, such as production, commerce, agriculture and consulting; fostering innovation.
Environment (more sustainable)	Smart grid Renewable energy Water management Waste management Pollution control Building Housing Community Public space	Delivering more sustainable, economic and secure energy and water supplies by taking into account citizens' behavior; using more green or renewable energy; recycling and treating waste efficiently and safely; reducing and preventing pollution in the city; offering mobility, telecommunication, information and all other facilities in different city spaces.

3 Smart city technologies

3.1 Smart city architecture

Smart city architecture provides guidelines on how to use the technologies to conceive and implement a smart city project. Researchers have proposed many different smart city architectures. The earliest smart city architecture was proposed by IBM [19]. In this architecture, IBM introduced the technological functionalities of a smart city and emphasized that a smart city is based on an ICT infrastructure and information services, but no mention was made of the importance of city data. Chourabi et al. proposed an initial framework explaining the integration of technology, organization and policy within a smart city [25]; the built infrastructure, natural environment, governance, human communities and economy share a two-way interaction with the smart city, but more detailed technologies and structure were not discussed. A variety of architecture definitions help people to better understand the core components and key enabling technologies of smart cities. In this section, we introduce several representative smart city architectures and analyze their technical characteristics.

3.1.1 *Review of architectures*

Liu and Peng summarized the smart city architecture of China's pilot smart cities. Their architecture is composed of four layers: sensing, transmission, processing and application. City data are sensed and collected via cameras, RFID (Radiofrequency Identification) tags, GPSs (Global Positioning Systems), etc., in the sensing layer, where the IoT (Internet of Things) is the core component. The transmission layer is responsible for exchanging and transmitting data via networks. The processing layer has many processing platforms, where virtual technologies and middleware work together to process and control data and offer services and functions to upper layers. The application layer offers solution sets for widely intelligent applications.

Al-Hader et al.'s smart city architecture is a pyramid of five layers [47]. The first layer is all the infrastructure of the smart city, including the natural environment, sensors and networks. The second layer is a data storage layer that contains various databases and resources. The third layer is a smart building management system. The fourth layer is an interface layer that contains the common operations platform and integrated web services. The top layer of the pyramid is an integration and combination of the systems layer. The architecture illustrates the development vison of smart cities, but lacks concrete technology sets and the interconnection of layers.

Cimmino et al. proposed a smart city architecture of three domains from the telecommunications viewpoint [55]. The overall architecture supports easy provisioning of smart city applications and services. Cloud technologies are applied to the traditional telecommunication stack. Virtual machines can be provided as a service to any smart city application.

Balakrishna proposed three basic building blocks as an architecture for smart city applications [56]. The author considers that the most fundamental requirements, and thus the first building block, to enabling smart cities is the large-scale instrumentation of the city's infrastructure, including structural, utility, transport and environmental infrastructure, with various sensors. The second building block is the large-scale deployment of a high-speed network infrastructure that facilitates the mobility, connectivity and transmission of information across various levels, and distribution of services and products to end users. The third building block is the efficient management of the aggregated smart data coming from a variety of sources. The access to smart data enables information to be transformed into 'smartness'.

Anthopoulos and Fitsilis proposed a physical architecture that contains five layers [57]. The infrastructure layer contains all network and location-based service systems. The information layer is an information storage layer. The service layer offers location-based services to users. The business layer vertically transacts with all the other layers, applying its rules and blueprints to all unique applications and systems. This architecture, inspired by the digital city, follows a Service Oriented Architecture (SOA), and mainly supports mobile applications and services.

Theodoridis et al. used the IoT concept in smart cities and described an architecture of three tiers and three planes [58]. Their architecture was applied in the Smart Santander project. The three tiers are the device, gateway and server tiers. The device tier consists of deployed IoT devices such as sensors, RFID readers and tags, and smartphones, thus supporting a wide range of communication capabilities. The gateway tier interconnects the devices with a core network infrastructure and the Internet. The server tier provides large processing and storage capabilities, supporting various smart application servers. The three planes consist of infrastructure management, IoT experimentation and the smart city service. The infrastructure management plane includes software components and APIs (Application Programming Interface) that are responsible for the overall operation and performance of the infrastructure. The IoT experimentation plane consists of modules that are responsible for managing an experiment using components from different tiers. Finally, the smart city service plane consists of software components and APIs that guarantee the continuous flow of data to smart city services.

Zygiaris et al. defined a smart city reference model from smart innovation ecosystem characteristics [59]. Their model can be used to define smart innovation characteristics. The seven layers of this model denote the city's smartness level, from low to high. The layers are: 0, city; 1, green city; 2, interconnection; 3, instrumentation; 4, open integration; 5, application; 6, innovation. Layers 2 to 5, (interconnection, instrumentation, open integration and application) are the distinguishing parameters used to estimate a city's smartness.

Rong et al. considered a smart city as a data-oriented problem [37]. Six layers are proposed in their logical architecture of a smart city. The first layer is a data acquisition layer, which comprises sensor systems and data sources. The data transmission layer is the second layer, and contains advanced communication hardware, network technologies and transmission control. The third layer, data vitalization and storage, is the core layer in this architecture. Data vitalization is a major technology set for smart city data processing issues [60]. The main process of data vitalization is data cleaning, data evolution, data association and data maintenance. In the fourth layer, the support service layer, the stored and vitalized data are processed and used as common services and platforms. SOA, cloud computing, intelligent information retrieval and virtual reality, etc., are the basic technologies in this layer. The fifth layer, the domain service layer, provides domain specialized services, such as smart transportation and smart healthcare. These domain services can support and drive various domain applications. The top layer is an event-driven smart application layer. In this layer, event-driven applications are directly provided to end users in the smart city. In this architecture, standards and evaluation, security and maintenance are emphasized for the implementation of the smart city.

3.1.2 *Discussion and proposition*

In the above literature survey, there are divergent visions of smart city architectures. Through these different expressions, we can still find some common characteristics.

Data-centric smart city Almost all the architectures consider data sensing and data transmission as the fundamental start point for a smart city. Data storage, data mining and data processing are considered as core factors for the realization of smartness. Smart applications in various domains are supported by the utilization of data services. That is to say, the future of smart city concepts will concentrate on data. Researchers have reached a consensus on this point from the perspective of architecture design.

The challenge for smart city data is to understand the interactions between the city and its people [61]. From the perspective of computers and systems, the city is defined by its sensed data. Therefore, to understand the city, it is necessary to understand the interactions of the city, the data and the citizens. This is why the basic infrastructure of different sensors is an essential element in a smart city architecture.

Solving urban problems such as traffic congestion can be thought of as similar to that of a doctor diagnosing a disease and prescribing a treatment for a patient. We need to build up associations between large-scale city data and the dynamic characteristics of the city. In this process, abundant data sources can greatly reduce the difficulty for solving problems, but the reliability of the final results will still depend on data analysis and processing technologies. Data vitalization might be a good set of solutions in a data-centric smart city.

The multidisciplinary smart city The data-centric smart city is a multidisciplinary concept. The different architecture layers of a smart city range from the basic physical infrastructure to very specific domains. Not only do various ICTs, such as big data, IoT, data vitalization, SOA, etc., play an important role in smart cities, but also other sciences and technologies, such as transportation, environment, energy and sociology are essentially involved. These sciences and technologies can be considered a strong supplement to information science in building data analysis and processing models. A smart city is a systematic concept, in which a variety of ICTs provide the common technical platform that support and take advantage of other disciplines' sciences and technology.

Therefore, in a smart city, we need to fully consider its multidisciplinary features and pay attention to the knowledge, experience and technology of other disciplines. On the one hand, we should apply various ICTs for different specific domains from the information science perspective, in order to solve information and communication problems. On the other hand, we also need to use the technologies of other disciplines for reference, in order to understand various urban characteristics and solve urban domain problems.

Smart city architecture proposition After considering the two characteristics of smart city architectures above, we give our proposition for smart city architecture, shown in Figure 1.

Since data and data management play a core role in smart cities, the logical hierarchical architecture consists of four general layers and two planes: the data acquisition layer, the data vitalization layer, the common data and service layer, and the domain application layer; the standard and evaluation plane, and the security and authentication plane.

The first layer is composed of the data acquisition and data transmission infrastructure and systems. Like all other architecture propositions, the acquisition of divergent urban data is the basis of all smart city concepts, as well as the first step of a data-centric strategy [62]. The advanced equipment, sensors, GPS, and RFID readers and tags, are deployed in specific domains to acquire data. This layer allows

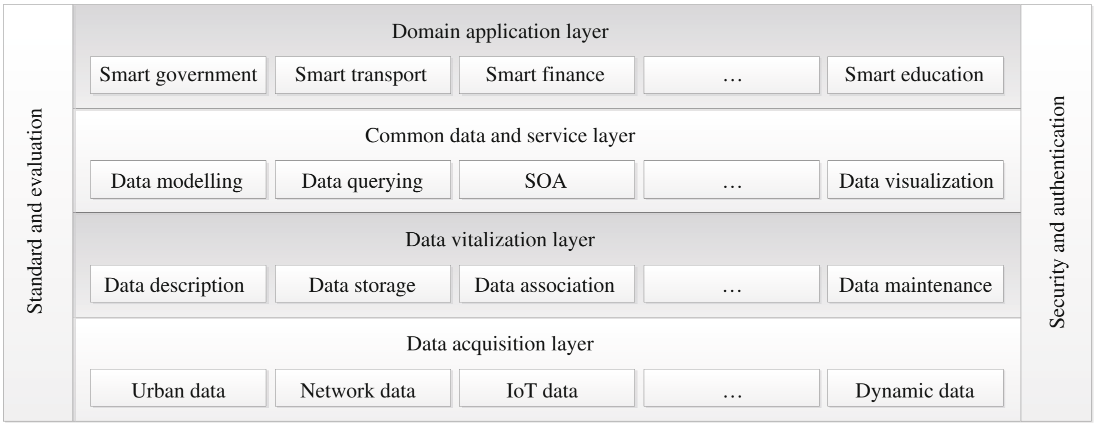

Figure 1 Smart city architecture proposition.

the connection to other data networks such as IoT, ad hoc networks and GISs (Geographic Information Systems). Data aggregation systems ensure that various data formats (such as unstructured data) are able to meet the requirements of the system [63]. This layer also provides data transmission with large-scale networks [64]. Advanced communication network equipment, software systems and transmission control protocols allow reliable high-speed data transmission from terminal devices to systems.

The second layer is the data vitalization layer. This layer possesses large-scale data storage functionality, so as to support the data collected from the data acquisition layer with high reliability and scalability [65]. Data vitalization technologies support data cleaning, data evolution, data association and data maintenance. Data cleaning technologies reduce data errors and inconsistencies. Data evolution supports data semantics and virtual data tags, proposed for the Internet of Data. Data association technologies help to find interconnection between data and generate association rules. Data maintenance ensures data robustness after access and processing. When all these processes have been applied, we say that the data has been vitalized.

The common data and service layer provides vitalized data as a common service or platform for the upper level. SOA methodologies are usually applied in this layer to package all required functionality into services [66]. Cloud computing technologies can offer the large-scale storage and computing capacities required by applications [12]. Data query and retrieval technology provides upper layer applications with contextualized and accurate data. All the data requested can be demonstrated to upper layer applications by using data visualization technologies [67] as services.

The top layer is the domain application layer. This layer provides smart city users with concrete domain applications, such as smart transport and smart education. Specific domain applications are requested and designed in this layer, to satisfy a smart city's end users, and realize the smartness of the whole city or one of its specific domains. User experience is very important for domain applications, and even determines the success or failure of smartness [68]. The lower-layer elements in the architecture, infrastructure, networks, systems, platforms, services, technology and data improve support for the domain applications and their integration.

3.2 Enabling technologies

The architecture we proposed in Subsection 3.1.2 combines a systematic set of technologies to implement smart cities. In this subsection, we avoid repeating the technologies that are already well described and studied in the literature, and only refer to some key enabling technologies to promote the importance of the data-centric characteristics of the smart city.

3.2.1 *Data sensing*

Data-centric smart city technology is mainly supported by large quantities of urban data, from a top-level design to low-level implementation details; therefore, the sensing and acquisition of urban data are fundamental to smart cities [69]. Traditional urban sensing technologies directly or indirectly collect sufficient dynamic urban data while providing different domain application services [70].

Beside traditional sensing technologies, people often record and share what they see and hear, anytime and anywhere, using their mobile phones, which is referred to as mobile phone sensing [71]. Privately owned sensors, such as cameras, GPS devices and mobile phones, are plentiful, and there are even some home weather stations; the data from a large population of such private sensors can be harnessed to provide valuable services in a smart city. This is called community sensing [72,73]. Community sensing in smart city applications can be considered to be a supplement to traditional data acquisition methods.

3.2.2 *Data vitalization*

The concept of data vitalization is a set of new data management technologies and data application modes, proposed by Xiong et al. [60,74,75]. Data vitalization means giving data life. The core idea of data vitalization technology is to reflect the associations between the physical world's generated data and the digital world of data storage and management, transforming the isolated data in storage space into an organic entirety, and recreating associations between data in information systems in order to break through the limitation of data use in information systems.

Data is organized into vitalized cells in data vitalization. A vitalized cell is the fundamental unit for data management of an organization. A vitalized cell both stores data and reflects data associations and interactions. When a vitalized cell stores data, it continuously learns user behaviors and reorganizes the data in the cell in order to better adapt the data to user requests. When objects change in the physical world, the vitalized cells are also able to change the data structure and content via data evolution technologies, thus realizing evolution of the stored data.

Data vitalization provides the possibility of tracking the evolution process of physical objects in information systems, which can be considered as a powerful technology set to manage massive urban data in smart cities. Mei et al. proposed a surveillance video data structuring method with data vitalization techniques [76]. The smart city architectures proposed by Rong et al. [37] and Subsection 3.1.2 are all based on data vitalization core functionalities. Data vitalization technology has shown its potential technical advantages in many fields of data management. Using data vitalization technology to rebuild urban data organization, realizing smartness from the bottom structure of data, will be an important trend of the data-centric smart city concept in the future.

3.2.3 *Data mining*

Data mining is another important technology for data application and knowledge discovery from big data [77]. A data-centric smart city must make use of data mining to reveal hidden, unknown, potentially valuable information and knowledge from data storage, especially from big data [78]. Pan et al. proposed data mining survey research in a smart city in which human and vehicle trace data mining can be used in various application domains, namely smart traffic, smart urban planning, smart public health, smart public safety and smart commerce [79].

One of the main challenges in this domain is how to find appropriate data sets from massive urban data to fit with concrete domain applications. For example, urban dynamic measuring research often requires that the urban data set should cover as many urban dynamic features as possible. At the same time, concrete domain applications demand that the data be as uniform as possible. Data set requests create significant challenges for the collection, management and mining of urban data. Solving the problem of data set selection and data combination is very important for smart city data mining.

3.2.4 *Data visualization*

Data visualization is closely associated with the end users of a smart city. It is an approach proposed to provide friendly presentation of data and services to smart city application users [80]. Data visualization can show complex urban data to users in a direct and simple way, and so can establish an interaction between data and users. Current work on data visualization is mainly focused on GIS visualization, such as that described by Ferreira et al. [81], translating New York City taxi trip data into urban visualizations, and Anwar et al. [82], presenting a visualization technique to support traffic incident analysis.

One important challenge is that in data-centric smart city applications, the data are often big data. Finding a user-friendly visualization method to present urban big data is difficult, and new techniques and frameworks for expressing city data are needed. Motivated by domain applications, data visualization must be an essential part of future smart city technology.

4 Smart city research challenges

Urban data from different specific domains are collected as a basic start point for smart cities. Through integration, analysis and vitalization of this data, researchers can study and design more efficient and smarter city applications or systems from an overall city viewpoint. The technologies applied in this research work, including the key enabling technologies listed in Section 3, are the essential support for realizing city smartness. Research on city smartness is very broad because of its multidisciplinary characteristics. ICT issues, social issues, environmental issues, economic issues, administrative issues, etc., are all included in smart city research. Due to the limitations of space, it is difficult to list all research issues in this paper. In this section, we review some representative data-driven research issues mainly in three domains: city traffic, citizen behavior and city planning.

4.1 Related work

4.1.1 *City traffic*

Urban traffic is an important issue in smart cities. Traffic systems are often the most important of a city's existing systems. Public transportation smartcards, vehicle GPSs, traffic cameras and other sensors can record a great deal of traffic behavior and provide a significant amount of data. Because of the advantage of massive traffic data, smart city technologies are often first applied in the traffic domain. The urban data used by smart traffic technologies include: GIS data, GPS data, POI (Point of Interest) data, passenger flow data, etc. [83–85]. Researchers use different data processing methods and algorithms to understand and analyze the collected data and perceive city traffic conditions so as to provide navigation, traffic control, itinerary recommendation and other smart applications.

Some research targets the perception and analysis of city traffic conditions. A general approach is to perceive the general traffic conditions, analyze the traffic behavior statistics and build analysis models. Real-time traffic reports based on monitoring data have been applied [86]. In addition, the detection and monitoring of particular road sections [87] and average commuting time evaluation [88] have already improved significantly traffic control efficiency. Through analyzing and mining vehicle GPS data [89], it is possible to understand the traffic patterns in a city, and thus evaluate and predict traffic conditions [90].

Other research has focused on specific traffic applications and services. A representative application is a navigation service based on GPS. A detailed digital map and real-time traffic analysis results can provide users with high-quality navigation services [91]. GPS data traces of human movement can optimize the navigation path for the driver [92]. Another typical application is in understanding the behavioral patterns of taxis and passengers, and their interrelation. Li et al. [93] analyzed and compared the effectiveness of different passenger searching strategies for 5350 taxis. Sun et al. investigated ways to increase taxi driver income by improving the passenger search strategy [94].

The analysis and mining of city traffic data can also play an important role in the optimization of public traffic systems. Ceapa et al. [95] systematically analyzed passenger congestion patterns on the London Underground, and proposed a technical solution for passenger congestion. Yousaf et al. [96] proposed a planning model for ride-sharing systems that could effectively reduce traffic load. Leng et al. [97] proposed a method to predict passenger flows in the subway using historic passenger origindestination information.

4.1.2 *Citizen behavior*

A study of the statistical mechanics of human behavior aims to reveal the interior laws of human behavior by using statistical methods. In an urban environment, the statistical mechanics of urban human behavior aims to combine information science and techniques to understand citizen behavior through huge urban data, and to resolve urban problems. Barabasi [98] showed that human behavior does not follow a Poisson process in its temporal distribution. He also proposed a priority queuing model which shows that the temporal distribution of human mobility approaches a power law. Examining the long-distance travel patterns of citizens, Brochmann et al. [99] found that the human spatial distribution is very different from the random walking process, as well as the Levy flying process. Since these results attracted a lot of research interest, urban human behavior research is becoming more and more popular in the smart city concept.

Mobile phone data was the earliest data used to analyze temporal and spatial activities of the public. In 2009, a temporal analysis of human activities using volunteers' records of SMS data over 36 months discovered that their behavior followed a power law distribution with a power exponent between 1.2 and 1.7 [100]. About 1.5 million SMS records of 140 thousand users were analyzed by Wu et al. [101] to show that these records follow a two-mode distribution, starting with a power law distribution and with the tail end following an exponential distribution. The spatial features of human behavior have also been studied. By studying 100,000 mobile phone users' communication records over 6 months, Gonzalez et al. [102] discovered that user journey distances are distributed according to a power law with a caudal index. Song et al. [103] analyzed the predictability of human spatial activity patterns by using mobile communication record data. They found that users' spatial activity in the sampled data had a prediction probability of 93%, and there was no obvious difference among individuals.

GPS data is also an important research source for analyzing human behavior. The GPS trace data of 50 taxis in four cities in Sweden over 6 months were analyzed by Jiang et al. [104] to investigate taxi passengers' travel statistics. It was found that passenger travel distance follows a two-mode power law distribution. However, Liang et al. [105] disagreed with this result, and showed that the passenger's travel time and distance both follow an exponential distribution, which was also confirmed by the research of Rambaldi et al. [106] and Bazzani et al. [107] on individual cars travel records. Li et al. [108] used citizens' GPS data to predict potential co-occurrence when people check-in at places of interest with their location-based social network service, and Yu et al. [109] used the contextual features of subway passengers, like GSM radio, to precisely predict the arrival of trains.

4.1.3 *City planning*

City planning is a key issue in urbanization. The concept of a data-centric smart city includes using data sensing and data computing technology to help understand different urban characteristics, so as to guide urban construction and development. Research focuses on the identification of urban area function based on dynamic urban data. The urban area includes commercial areas, residential areas, industrial areas, administrative areas, etc., according to its function. There are two principle research challenges. First, different functional urban areas often overlap, so it is very difficult to accurately define the actual function of a specific urban area by any means. Second, the urban area function depends on deep-level semantic characteristics, and there are no urban data that can directly reflect these characteristics, so it is a challenge for researchers to retrieve urban semantic characteristics from urban dynamic data.

Despite the difficulties, much tentative research has been initialized. Some early research work realized simple identification. In the research work of Puissant et al. [110] and Deng et al. [111], only residential and non-residential areas can be distinguished. Herold et al. [112] developed three area function identifications: residential area, industrial area and administrative area. The research of Vna de Voorde et al. [113] identified four areas: commercial, industrial, service and residential. This research work on coarse granularity identification can perform very well in some new, simply structured and well-planned cities.

However, the above methods cannot satisfy the demands of large cities. It is necessary to achieve finer granularity in urban area function identification technologies. In the work by Peng et al. [114], the urban area was divided into residential, working and other function areas. The area commuting pattern was defined as a linear combination of the three function coefficients, according to its own situation. The coefficients in the linear combination can indicate the different characteristic of each function. For example, if an area's commuting pattern is higher on its working function coefficient than the other two, it can be identified as a working area. Chen et al. [115] gave a method to estimate the commercial density level of the whole city, and urban areas can use this to estimate the probability of commercial functions.

Mobile phone data are also used to identify area function [116], as well as to identify the function of urban streets [117] and points of interest [118]. In the work of Bram and McKay [119], subway passengers flow data was used to identify the features of New York City subway stations, which provides useful guidance for subway station planning in the city.

4.2 Discussion

The above research issues reflect the potential smartness in city traffic, citizen behavior and city planning domains through data processing technologies. Although the research reviewed here is very diverse in its application domain, as well as in its technology and method, we can still summarize the common characteristics and challenges.

First, the surveyed work does not intend to analyze concrete applications in a specific smart city domain, but rather attempts to provide fundamental support methods and theories. Each urban application domain has its own inherent operating rules. The surveyed research work aims to reveal and model these inherent rules, through analyzing and mining urban data acquired by a variety of digital sensors. These rules will play a very important role in smart city implementation. In the process of modelling, more data usually create more accurate models, but more data also increase the computing cost. The challenge is the trade-off between accuracy and computing cost.

Second, the data in a specific domain can support smart applications not only in that domain, but also, potentially, in other domains. Public mobility data can be used to identify urban area functions; smartphone GPS data can also help to recommend commercial services. As described by the data vitalization concept, there are inner associations between data. Sometimes, it is difficult to obtain data in a target domain due to infrastructure limitations. In such a case, researchers try to build association models between the target domain and other domains where data can be acquired more easily. Finally, information about the target domain can be deduced by association models and obtained data. The challenge is how to reduce the coupling between obtained data and irrelevant features, and build a strong correlation with the target domain.

5 Conclusion

Researchers often understand a smart city from different perspectives. In this paper, we provide a gateway to better understanding the concept of a smart city through the analysis of its definition and application domains. We propose that any smart city definition should consider four key perspectives: technical infrastructure, the application domain, system integration and data processing. We classified smart city application domains into four essential domains: government, citizens, business and environment. We define a smart city as a systematic integration of technological infrastructures that relies on advanced data processing, with the goals of making city governance more efficient, citizens happier, businesses more prosperous and the environment more sustainable.

By reviewing the literature, we have shown that smart city architectures are considered to have data-centric and multidisciplinary characteristics. We have proposed a new smart city architecture composed of four layers of: data acquisition, data vitalization, common data and services, and domain application. We have summarized several key enabling technologies for smart cities from a data-centric viewpoint. Among them, data vitalization is considered to be a core technology, which can transform isolated data into an organic entirety, and recreate associations among data in information systems.

Urban data are collected, analyzed, vitalized and used to realize smartness in urban domains. We have presented some recent research progress in smart city domains, such as city traffic, citizen behavior and city planning. The surveyed related research work tries to provide fundamental support techniques and theories for different smart application domains through massive urban data. Throughout the literature, we found two challenges in urban data processing research: first, there is a contradiction between accuracy and computing cost for urban rules modelling; second, for building associations among different domain data, we need to reduce the coupling between obtained data and irrelevant features, and build strong correlations with the target domain. Our survey offers a reference to researchers who are contributing to smart city research and implementation work.

Acknowledgements
The work was supported by National Natural Science Foundation of China (Grants Nos. 61402028, 61204426) and China's National Key Technology R&D Program (Grant No. 2014BAF07B03).

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