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Internet of Things-enabled smart cities: State-of-the-art and future trends

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ABSTRACT

The dramatic spread of urbanization in modern cities requires smart solutions to address critical issues such as mobility, healthcare, energy, and civil infrastructure. The Internet of Things (IoT) is one of the most promising enabling technologies for tackling these challenges by creating a massive world-wide network of interconnected physical objects embedded with electronics, software, sensors, and network connectivity. Arguably, IoT is becoming the building block for next generation smart cities owing to its potential in exploiting sustainable information and communication technologies. The rapid development of the IoT is impacting several scientific and engineering application domains. This paper presents a comprehensive literature review of key features and applications of the IoT paradigm to support sustainable development of smart cities. An emphasis is placed on concomitance of the IoT solutions with other enabling technologies such as cloud computing, robotics, microelectromechanical systems (MEMS), wireless communications, and radio-frequency identification (RFID). Furthermore, a case study is presented to demonstrate how an affordable and suitable IoT-based working prototype can be designed for real-time monitoring of civil infrastructure. Finally, challenges and future directions for IoT-based smart city applications are discussed.

1. Introduction

The phrase "Internet of Things (IoT)" was first reported in 1999 following the advent of Internet-based techniques in the 1990s [1]. IoT can be defined as a global infrastructure enabling advanced services by interconnecting physical and virtual things using interoperable information and communication technologies (ICTs) [24]. IoT-induced networks [2–5] and cloud technology [6–12] have been extensively investigated in many studies. Unlike many other services, IoT is mainly driven by Internet-based technologies, rather than user needs or applications [13,14]. IoT allows devices to "talk" together using various methods such as pervasive and ubiquitous computing, embedded devices, and sensor networks [15–19]. In fact, IoT is the key to make many of the traditional communication approaches "smart" [20]. Thanks to the rapid development of cloud technology, increasing storage capacity and processing efficiency, and decreasing fabrication and deployment expenses, sensor use has grown significantly in the last several decades. Using various ICTs, 50–100 billion devices will be connected to the Internet by the end of 2020 [21]. Fig. 1 illustrates the projected increase in world population alongside the projected growth of smart devices connected to the Internet from 2015 to 2025. The number of smart devices is projected to reach 75.44 billion while the world population is estimated to reach 7.99 billion by the end of 2025 [22,23]. More importantly, the per capita smart devices will likely increase from approximately 2 in 2015 to nearly 10 in 2025.

Previous studies have categorized IoT into application and technology domains [20]. In the technology domain, significant literature has been devoted to describing IoT-enabled technologies, protocols, and the associated challenges and advantages [8,25–42,151,157,162,164,166,168,170–177]. In this domain, real-time history data is taken into account using various sensory mechanisms [43]. IoT network architectures are characterized with corresponding network Quality of Service (QoS) [44]. Furthermore, integration approaches have been used in automation systems using IPv6 enabled architecture [45], flexible IoT hierarchical architecture models and smart grid IoT systems for energy conservation [46–48], IoT-based systems combining different types of sensor deployments [49], web servers [50], IoT platforms collecting data from environments [51,153,167], and dynamic priority scheduling systems [52]. In the application domain, the rapid growth in different IoT applications has been widely studied [12,155,193]. In particular, IoT has been applied in modern cities for different operations, e.g., cyberville, digital city, electronic city, flexicity, information city, smart city, telicity, wired city, etc. [35]. In addition, various applications have been developed

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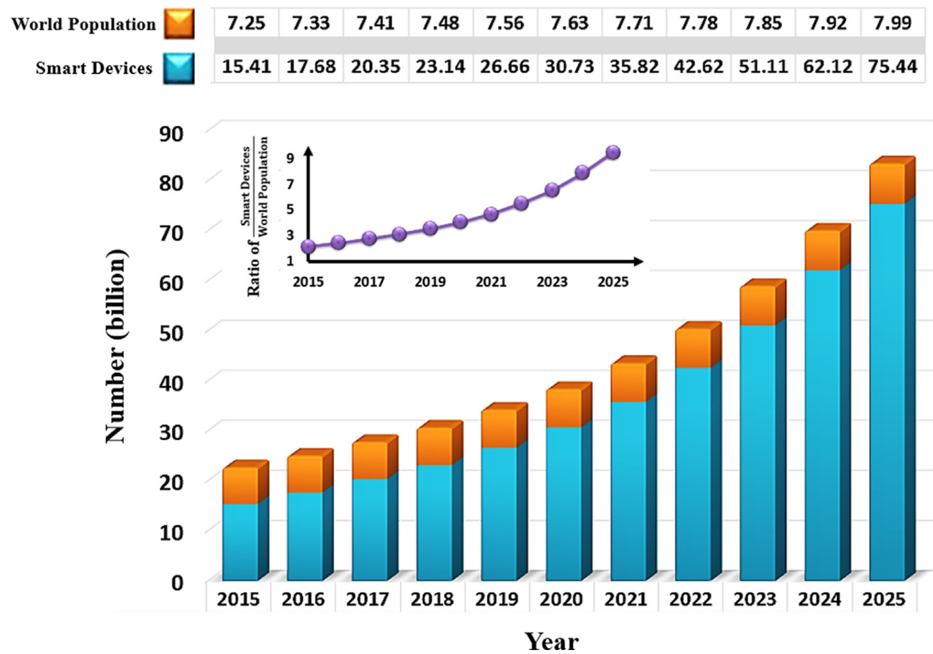

Fig. 1. Comparison between the estimated world population and the projected number of smart devices connected to the Internet: 2015–2025 [22,23].

based on IoT technologies, such as IP cameras [53], smart wheelchairs [54], Web of Things (WoT) – to combine IoT with existing web standards [55,160], scheduling models that optimize the quality of collected information [56], smart city Platform as a Service (PaaS) systems based on IoT hubs [57], routing protocols based on routing-by-energy and link quality (REL) [58], IoT-enabled observation, orientation, decision and action (OODA) [59], integrated information systems that combine IoT, building information management, early warning systems, and cloud services [60], low-power structural health monitoring (SHM) [61–67,149,150,169], sensors and sensing technologies [68–74], health monitoring systems for environments [75–78], damage prediction model [79,80], energy harvesters [81–85,190] buckling-induced energy harvesting mechanisms [86–94], WiFi-based Wireless Sensor Network (WSN) and industrial networks in IoT [95,156], and healthcare community [96].

Given the rapidly growing capabilities of the IoT, it is poised to serve as a central feature of smart cities. In the last few years, there has been a surge of research aimed at exploring the potential of the IoT in the sustainable development of smart cities. This paper aims to: 1) provide a state-of-the-art overview of IoT in terms of smart city-related applications and technology domains, 2) discuss current achievements, research gaps and future trends of the IoT-enabled smart cities, and 3) present a case study on developing a cost-effective IoT-based real-time monitoring system. The remainder of the paper is outlined as follows: Section 2 presents the state-of-the-art of IoT in application domains; Section 3 focuses on IoT in the technology domain; Section 4 evaluates the existing IoT-induced smart city projects; Section 5 presents a simple case study on cost-efficiency real-time monitoring systems for smart cities based on IoT technology, and; section 6 summarizes the main findings of this review.

2. IoT in the application domain

Modern cities have been facing critical management efficiency and other urban quality of life issues due to their rapid growth [42]. Smart city technologies appear to provide many viable solutions for these and other modern challenges in urban centers [29]. A smart city can be defined as a modern city that is functionalized in an intelligent and sustainable way to ensure sustainability and efficiency. This goal can be achieved by integrating varied infrastructures and services into cohesive units such that they can be monitored and controlled by intelligent devices. Smart cities mainly aim to address both critical and everyday issues such as crime management, education, energy, environment, healthcare, public transportation, employment, waste management, and the strategic and shared use of buildings and other city spaces, vehicles, and even pets. Using IoT-based data management and cloud technologies, different urban information systems can be developed to encompass sensory level data and networking support structures [98,182]. The benefits and major challenges of the IoT technologies in smart cities have been examined by many researchers [99–103]. Smart transportation and mobility based on IoT platforms are the most widely studied topics in this domain. Some examples are smart parking [104], smart velomobility [105], roadmap framework [106], and IoT-enabled multiagent systems with sensors distributed along roadways [107]. Also, sensing technology [13,108] and security challenges [13,109–115,187] are of significance to the applications of the IoT in smart cities. Recent attention has been particularly paid to combining smart city physical infrastructure and human stakeholders [101]. Atzori et al. [116] investigated a possible architecture for IoT where various devices are integrated into a social network. To improve the resilience level of infrastructures in IoT, a novel architecture was also reported by Abreu et al. [117]. Many studies have focused on the IoT architectures for applications in smart cities [2,118,119]. Smart city projects have been reported in the context of various case studies [120–129,131,154]. Recently, IBM smart city projects featured interesting empirical tests combining IoT with the Open Innovation (OI) model in smart cities [130]. IoT technologies were also deployed in smart tourism projects in many cities [132–134,147]. The following section describes the components and characteristics of smart cities in the application domain of IoT, and attempts to motivate the need to develop modern cities into smart cities.

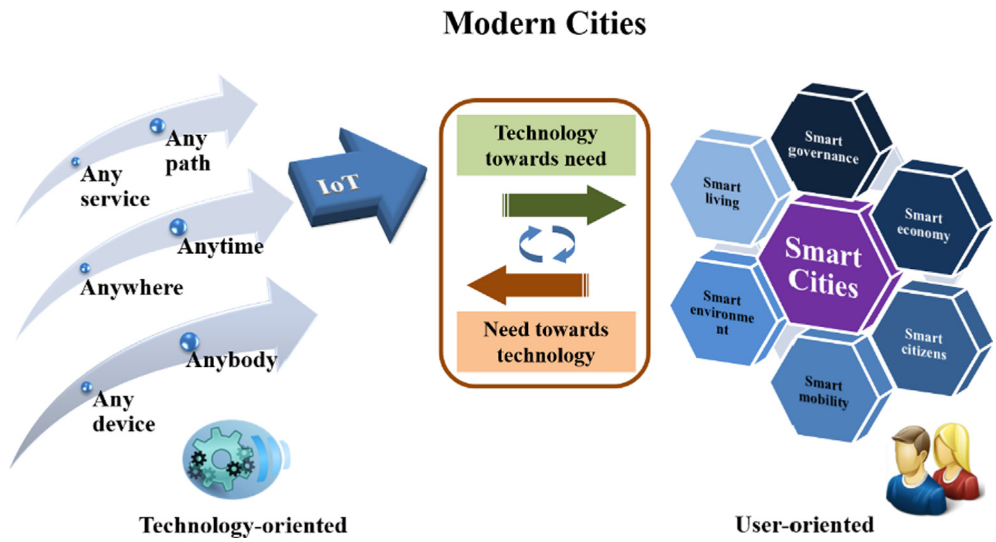

Fig. 2. Relationship between IoT and smart cities.

2.1. IoT-enabled smart cities: overview

Smart cities are a primary driver of the IoT application development. A smart city may be defined in one of several ways, depending on one's perspective. One of the well-accepted definitions denotes it as a city that connects "*the physical infrastructure, the information-technology infrastructure, the social infrastructure, and the business infrastructure to leverage the collective intelligence of the city*" [97]. A smart city can also be understood as an urban center with technologies that use digital data to deliver better public services and more effective uses of resources. A smart city consists of six major components, including smart governance, smart economy, smart citizens, smart mobility, smart environment, and smart living. In general, IoT is technology-oriented while smart cities are user-oriented. Each are moving towards one other with a common goal of providing better services for modern cities [14]. Fig. 2 shows the relationship between the IoT and key smart city components.

According to a report by the United Nations, the worldwide urban population is estimated to reach as much as 70% of the world's population by 2050 [12]. The rapid growth in population and urbanization has caused many issues in modern cities, e.g., global environmental changes, energy consumption, traffic congestion, etc. While global urban regions occupy less than 2% of the earth's surface, they account for up to 75% of the world's energy use and approximately 80% of the greenhouse gas emissions worldwide. Given the critical issues associated with modern cities, sustainable development and "smart" approaches are arguably a societal *imperative* [25,102,143]. IoT and smart cities have been extensively investigated in recent years. Many applications involving IoT platforms and smart city projects have been reported in the last decade. Fig. 3 presents the search interest trends of IoT and smart cities, and the distribution of smart city projects worldwide during 05/2013–06/2018 [135]. Fig. 3(a) displays the variations of weekly Google search popularities of the two terms. A sustained, steady interest in smart cities has been observed, while interest in IoT has significantly increased during the last five years. Fig. 3(b) illustrates the search interest of IoT and smart cities with respect to geographic location [135]. As expected, higher search interest has come from more developed areas. Fig. 3(c) shows the distribution of smart city projects,

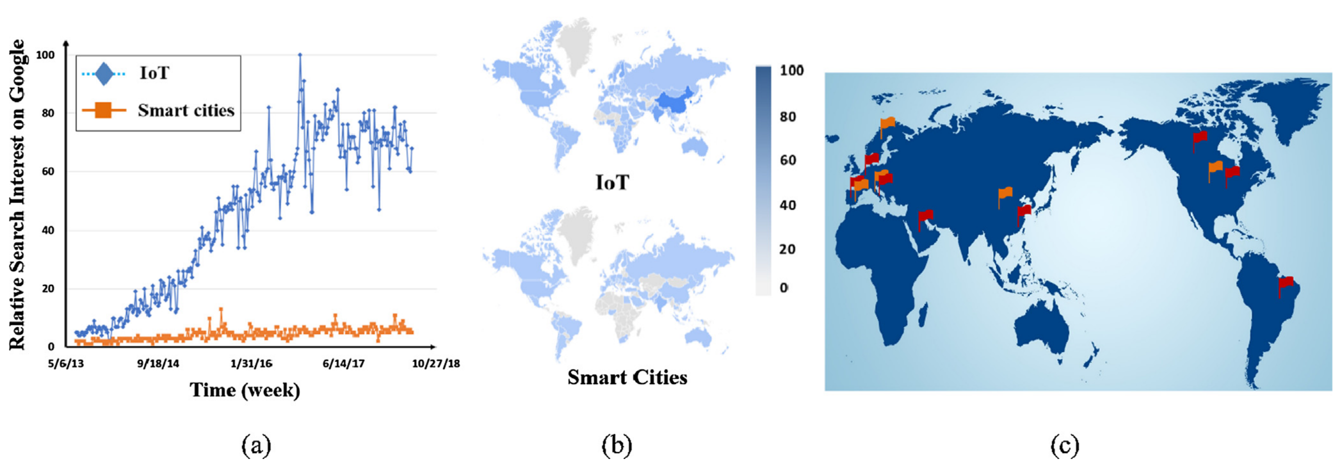

Fig. 3. (a) Search interest trends of IoT and smart cities on Google during 05/2013–06/2018 [135]. (b) Search interests of the IoT and smart cities with respect to country on Google during 07/2012–06/2017. (c) Distribution of smart city projects worldwide (Drawn based on the articles in Smart City Projects in Table 2).

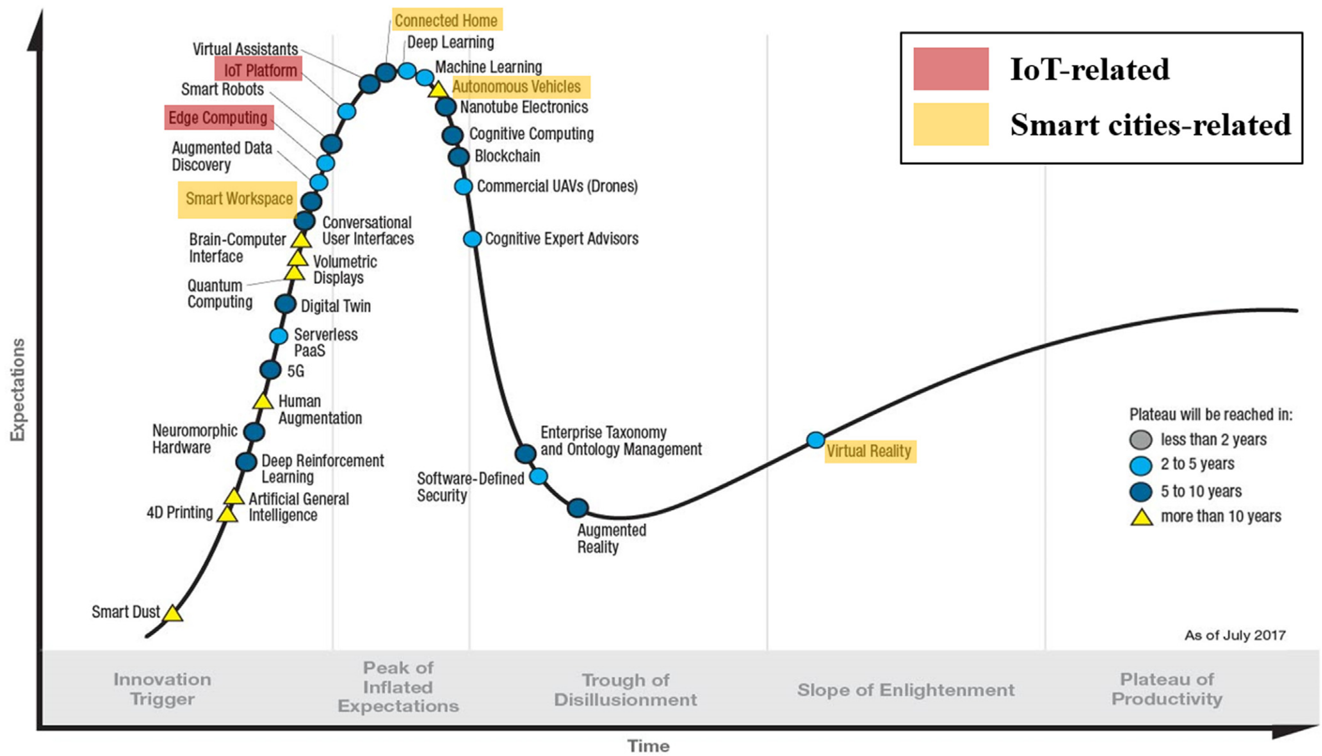

Fig. 4. Gartner's 2017 hype cycle of emerging technologies [136].

Table 1
Main layers of IoT-based services in smart cities.

Layer	Name	Purpose
I	Device	Identification of objects and collection of specific information by sensor devices
II	Network	Sending the data collected by the device layer to information processing systems
III	Middleware	Information processes and ubiquitous computations
IV	Application	Global management of applications based on the information processed by the middleware layer
V	Business	Management of the overall performance of IoT systems

which aligns with the aforementioned search interests of Fig. 3(b). IoT and smart cities can be considered as one of the most important and fast-growing emerging technologies.

Fig. 4 shows the hype cycle of emerging technologies in 2017 as reported by Gartner [136]. It is forecasted that the IoT and smart cities-related technologies will take 5–10 years to achieve mainstream adoption. For the deployment of IoT platforms in smart cities, IoT-based services can be categorized into five layers [12], as summarized in Table 1. To technologically support smart cities, IoT technologies can be economically employed to provide many of the required communication and network devices. Table 2 summarizes studies focused on the IoT and smart cities during the period 2010–2017. Appendix A presents further details on the reviewed publications with respect to scholarly domain, article scope, type of article and publisher.

2.2. IoT applications in smart cities

The IoT has attracted significant interest from both the research and practice communities during the last decade. To achieve key functionalities in IoT, certain operating systems and communication protocols are needed to enable interactions between users and devices [48]. A broad overview of the IoT in the application domain is presented in Fig. 5. Modern cities have become "smarter" and more efficient in many respects because of developments in information and communications technology (ICT). On the other hand, it is not necessary, and moreover not possible, to render every component in smart cities as "smart". The deployment of the smart components shown in Fig. 5 are significantly correlated with the cost and availability of the required technologies [35]. Several projects in Europe, under the 7th Framework Program for Research and Technological Development (FP7), e.g., Advancing Identification Matters (AIM), District Information Modeling and Management for Energy Reduction (DIMMER), Intelligent Use of Building Energy Information (IntUBE), and Smart Energy Efficient Middleware for Public Spaces (SEEMPubS), have focused on the deployment of IoT in varied application domains [138–141]. Smart cities to date have applied communication and network technologies to address modern urban issues such as population growth, crowding, and traffic congestion [42].

2.2.1. Smart mobility and transportation

In smart cities, the concept of mobility is often simply equated with transportation. However, effective urban mobility can be understood in an even more general sense. Intelligent transportation, or Intelligent Transport Systems (ITS), primarily focuses on deploying IoT networks to address transportation with respect to varied functionalities and applications [180,181]. For instance, Fig. 6(a) displays a data parser for smart parking in smart cities [180]. Smart mobility is also defined as the features of new services or products related to smart software. In general, however, smart mobility and smart transportation tend to refer to the same services, i.e., applying IoT networks to increase personal mobility within smart cities. Mobility and transportation consist of public transportation, daily commutes using private vehicles, leisure travel, etc., which are all sources of pollution, although varying in

Table 2
Summary of the studies on IoT and smart cities during 2010–2017.

Internet of Things (IoT)				
Application Domain			Technology Domain	
Smart Cities	Overall	[1,3,4,13,21,25,28,34,35,40,43,44,49,53,57,59,98,99,10-0,101,102,103,108,110,122,137,143,151,157,162,164,16-6,168,170,171,172,173,174,175,176,177,185,186]	Cognitive Management, Machine-to-Machine (M2M), Structural Health Monitoring (SHM), Communication & Sensing	[2,41,52,62,63,64,65,66,67,71,72,145,149,150,1-55,160,163,169,178,179,182,184]
	Home & Civil Infrastructure	[5,45,47,60,61,116,117,118,119,129,142,158]	Data Mining & Cloud-related Technologies	[6,7,8,9,10,11,12,20,26,30,32,36,37,56,111,152,-153,165,191]
	Mobility & Tourism	[24,54,104,105,106,107,133,134,144,180,181]	Privacy & Security	[96,109,112,113,114,115,187]
	Energy Consumption	[42,48,58,81,83]	Sensor and Sensing Technology, Energy Harvesting, & Others	[14,15,16,17,18,19,25,28,29,31,33,38,50,55,68,-69,70,73,74,76,77,78,79,80,82,84,85,86,87,88,8-9,90,91,92,93,94,95,131,156,159,161,167,183,1-89]. [190,192,193]
Industry, Agriculture & Environment		[39,46,51,75,95]		
Smart City Projects		[27,97,120,121,123,124,125,126,127,128,130,132,138,139,140,141,147,154,188]		

Note: Italicization refers to review articles.

degree. Based on IoT platforms, smart mobility and transportation aim to provide wide accessibility and efficiency to citizens of smart cities, regardless of any physical, sensorial or cognitive limitations.

In addition, public spaces, such as community gardens and neighborhood parks, play critical roles in modern city life and help fuel the accelerating pace of urbanization. Open spaces, however, have been lost (re-purposed) in some rapidly developing cities over the past ten years [134]. Smart mobility can help citizens effectively utilize, share and manage open spaces, especially when they become scarcer.

Demand-responsive, smart parking lots have been developed for plug-in electric vehicles (PEVs) in the energy and reserve markets [144]. The operational behavior of PEV parking lots has been investigated to obtain incentive-based and price-based demand response programs. Fig. 6(b) presents a concept of *smart velomobility* in smart E-bike monitoring systems (SEMS) [105]. The platform in SEMS obtains real-time history data from the E-bike using the sensors attached to the bike. The system can then monitor the E-bike's battery without rider intervention.

2.2.2. Smart homes and civil infrastructure

The major functionalities of smart homes and civil infrastructure can be realized to a large extent through the analysis of data recorded by wireless sensors. One of the main objectives in a smart home is to efficiently control the devices and applications in a modern home, e.g., electronic devices, home indoor/outdoor security systems, climate control, light controls, room temperature monitoring, appliance use and maintenance/health monitoring, etc. [158]. Fig. 6(c) schematically shows an IoT-enabled smart home [42]. Sensors are installed to monitor different parameters, and data are sent back to the IoT platforms for analysis. Information are used such that homeowners can remotely monitor the status and environment of their smart home, and also for real-time control of connected objects (temperature settings, door locks, security camera and two-way audio feeds, appliance control, etc.). In a similar way, smart civil infrastructure systems can be developed. Sensors distributed over civil infrastructure systems allow for continuous condition assessment and, in some cases, system or device control. Infrastructure IoT developments are currently receiving remarkable attention [178]. Research efforts have resulted in developing new paradigms such as cognitive IoT (CIoT) that incorporates cognitive capabilities into conventional IoT frameworks [179], or cognitive dynamic systems (CDS) that provide guidelines for systematically implementing cognition into the IoT [145]. Recently, a "sense now, retrieve later" paradigm has been proposed, which combines wireless self-powered sensors with low-cost passive RFID-based data interrogation technique [142]. This method is based on detecting sub-microwatt signals generated by mechanical strain/deformation in structures using self-powered sensors, and sending the RFID-scanned data to the cloud via IoT. Fig. 6(d) provides an illustration of how this system can be used to monitor pavements [142].

2.2.3. Smart retail and healthcare

In smart cities, online retail and healthcare can be supported by IoT advances [33]. Remote retail and healthcare can be effectively enabled by visualizing sensor data retrieved from smart devices carried by or worn by citizens. Fig. 6(f) shows a conceptual diagram of an IoT-based remote monitoring in wearables and personalized healthcare [33]. Visualization is particularly important to online shopping, given that customers typically desire to see the items before making any purchases. Research efforts are being devoted to improving the accessibility of critical services for people with disabilities using visualizing sensors [54,134]. Users with disabilities have been increasing in the US and other regions around the world during the past several decades and hence, studies have been conducted to achieve healthy and balanced societies by enabling wider and more equitable access to health services though technology advances. In smart cities, the status of patients can be monitored to provide faster and more reliable work-flows in

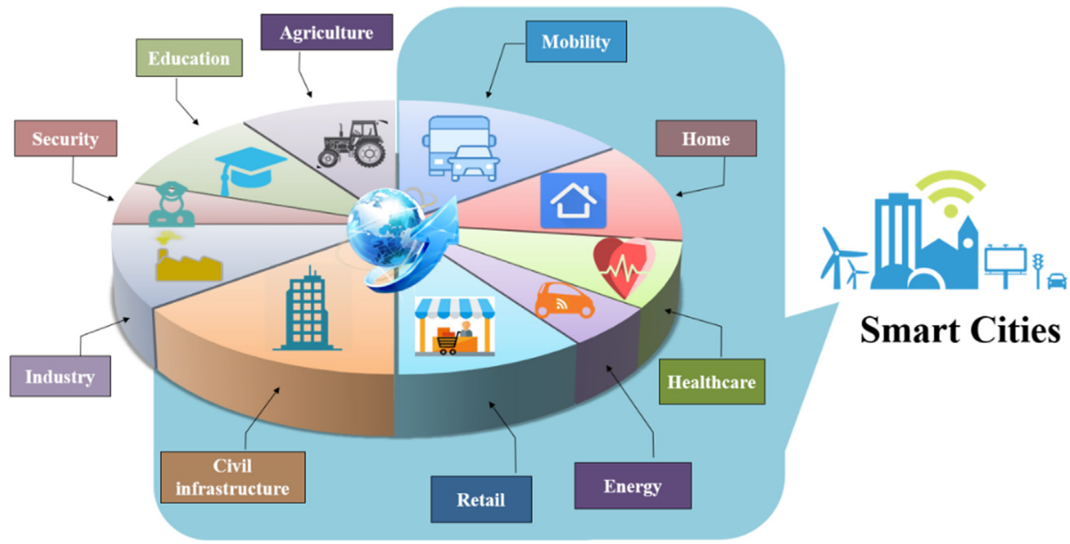

Fig. 5. Smart cities in the application domain of IoT.

hospitals. The location of ambulances is continuously monitored and intelligently routed. In support of improving access, comfort and independence of people with disabilities in modern cities, smart healthcare systems have led to recent improvements [54]. Connecting wheelchair users with the Internet, research efforts have been devoted to increase social inclusion in terms of online shopping and communication. A project involving the assistance of the blind with a smart 'E-cane' system has been documented [134]. To integrate cane users with smart cities, the authors proposed a hardware-software integrated system that enables the users to access the Internet to obtain updated street and traffic information. Fig. 6(e) summarizes healthcare projects that have been carried out in smart cities [54,134].

2.2.4. Smart energy

Energy is related to almost every aspect of modern cities. In an IoT-enabled smart home, residential units can be monitored and managed to reduce energy consumption [42]. Smart (remote) education is obtained in smart cities by remotely connecting through IoT, which ensures that people access online sources without physically attending educational events. Distance education assists in reducing the use of public and private transportation and hence, may decrease energy consumption. In addition, smart energy in transportation primarily aims to provide efficient energy management, e.g., congestion control, smart parking, and traffic management [42]. Energy efficiency in smart cities is now the focus of many studies. Many IoT networks have been developed to sufficiently manage energy consumption in smart cities. Mobile phone-based apps are typical examples of remotely controlling electrical devices, especially in smart homes [103]. IoT networks have been applied to Service-oriented Architecture (SoA) in the Smart Energy Efficient Middleware for Public Spaces (SEEMPubS) project [48]. The author implemented a heating, ventilation and air conditioning (HVAC) system in the project to remotely control the cooling and heating systems in the SoA. To carry out the SEEMPubS project, specifically designed mobile phone apps are connected to a database. The status of the SoA (e.g., occupancy, residual space temperature, outdoor temperature, equipment capacity) are regularly uploaded to the database, such that the users can easily control the building temperature [48].

3. IoT in the technology domain

IoT technologies in smart cities can be characterized into three typical layers with respect to the architecture or function block [20]: IoT service, IoT middleware, and IoT infrastructure. The data operation process in current IoT technologies consists of four phases, including collecting, delivering, analyzing, and implementing data [117,159]. In an IoT architecture, the service layer refers to the applications and services that are used to support smart cities. Urban analytics operates on data from collection and diffusion, create usable information for smart services. The middleware layer involves technologies that are applied to seamlessly integrated data and devices. The infrastructure layer addresses the physical devices located throughout smart cities. The devices effectively gather data and can react to different situations, for instance smart streetlights for intelligent and weather adaptive lighting in streets, or noise pollution sensors for real-time monitoring of noise in centric zones [20].

The data operation process in the collection of IoT data mainly consists of two aspects, identification and sensing. The former is critical to IoT in naming and matching services with respect to specific demands, while the latter refers to the process of gathering data from correlated objects in sensing networks and sending it to a database, cloud, or other data warehouse. Data delivery is achieved using IoT communication technologies to connect separate smart services together. In general, IoT nodes in data delivery are operated using low power noisy and lossy communication links. Another commonly used communication approach is WiFi, which uses radio waves to transform data between objects, generally within a 100 m range. Analyzing data refers to software applications and processing units such as Field-Programmable Gate Arrays (FPGAs), microcontrollers, microprocessors, and/or Service Organization Controls (SOCs). Note that the analysis of the sensing data is considered as the core, i.e., computational capability, of the IoT. The implementation of IoT data is typically categorized into collaborative-aware services, identity-related services, information aggregation services, and ubiquitous services. Identity-related services are the most fundamental and significant services in implementing data in IoT [117]. Fig. 7 presents the technologies in IoT-enabled smart cities with respect to typical IoT architecture and the data operation process [20,117].

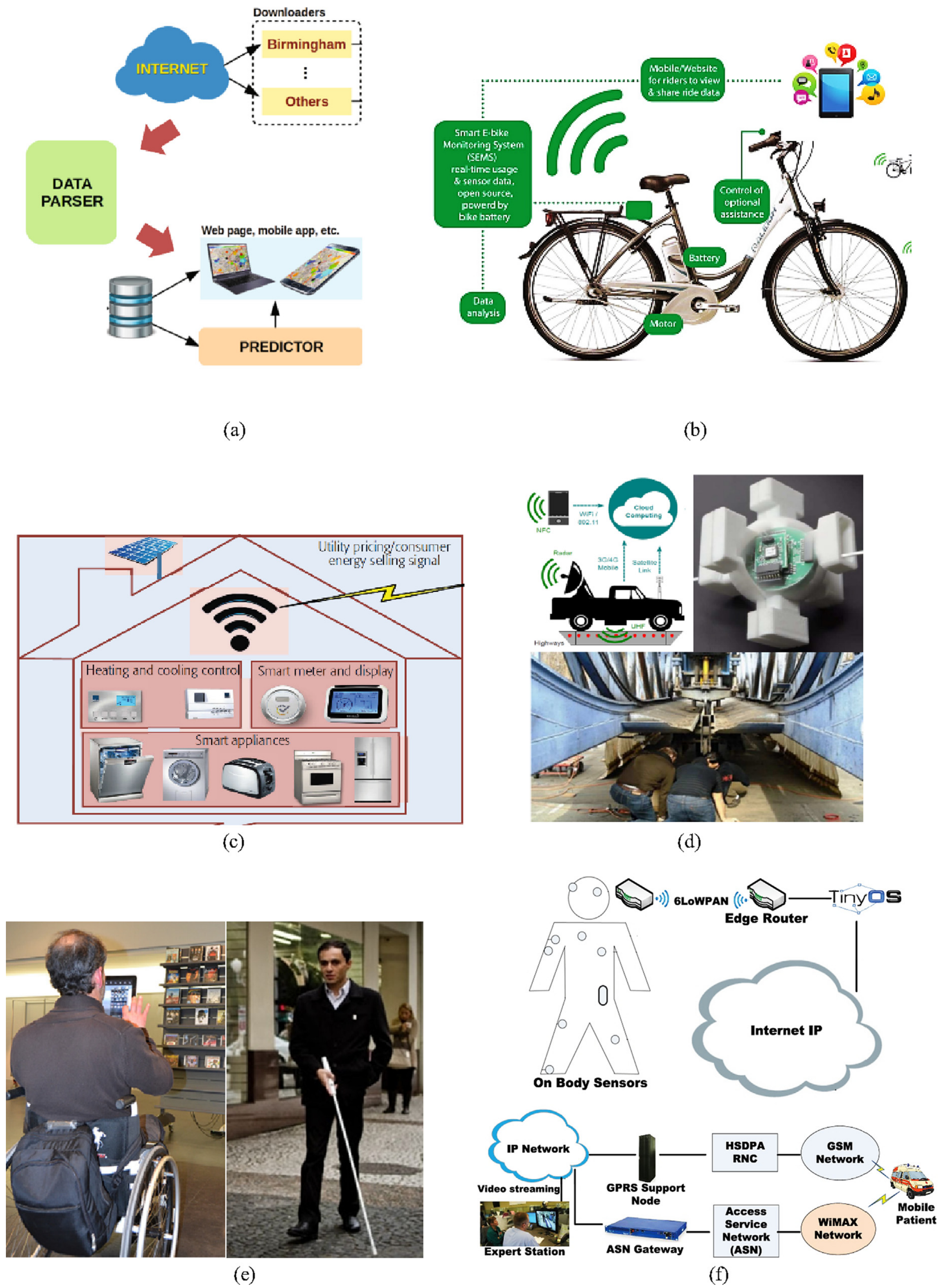

Fig. 6. (a) Data parser for smart parking (Redrawn from [180]), (b) Smart E-bike monitoring system (SEMS) [105], (c) Illustration of IoT-induced smart home [42], (d) Illustration of smart civil infrastructure with self-powered wireless sensing technology that can be integrated with IoT [142], (e) A wheelchair user interacting with self-through AR app [54] and demonstration of a smart electronic walking stick (cane) [134], (f) Remote monitoring in wearables and personalized healthcare [33].

3.1. IoT architecture

IoT architecture has been frequently investigated with respect to the process of conducting smart functionalities in recent years [161,185,186]. Fig. 8 presents a typical design. Note that the middleware layers play an important role in the architecture. Middleware combines typical abstraction mechanisms and functionalities, packaging IoT infrastructure for users. Recent studies aim to offer an IoT middleware layer with particular focus on the enhanced resilience of the IoT architecture. Many middleware components have been developed to facilitate communication and to exchange information between devices. Integration layers are of significance in integrating information between devices while delivering information to users. Linked sensor middleware (LSM) is carried out as a platform combining real world data and semantic web to provide different services [146]. Other architecture design mechanisms have also been reported in recent studies. Cloud-based middleware infrastructure has been studied to deliver access to IoT services over various platforms. To collect and filter data from the objects connected to the Internet, new algorithms and cloud techniques have been developed [148,152,184]. For example, two network architecture design approaches have been developed: an evolutionary approach and clean-slate approach [137]. The former leads to incremental changes in smart architectures in current networks to optimize the reuse of existing networking solutions, while the latter advocates re-design of networks without taking into account the current structures. Many IoT architectures have been reported for different functional applications. A cloud computing and IoT-based cloud manufacturing (CCIoT-CMfg) system has been developed, which consists of four layers: IoT layer, service layer, application layer, and bottom supporting layer [182]. Fig. 8(a) displays the architecture of this system. Four types of IoT architectures are proposed with respect to the characteristics of IoT networks including: 1) autonomous architecture, 2) ubiquitous architecture; 3) application-layer overlay architecture; and 4) service-oriented architecture [137]. A general IoT structure is demonstrated in Fig. 8(b) [48].

3.2. Data operation process in IoT

Many data mining and processing techniques have been proposed to enable functionalities in IoT [163,165]. The data operation process is typically categorized into collecting data, delivering data, analyzing data, and implementing data. Fig. 8(c) presents a semantic engine for the data operation process in IoT [159]. The semantic engine contains six components: 1) unifying IoT data, 2) model/vocabulary ontology to semantically annotate data, 3) interpreting IoT data, 4) architecture, 5) services, and 6) real-time and scalable data analytics.

3.2.1. Data collection

The collection of IoT data can be characterized into identification and sensing. The identification process is focused on identifying the address and ID of objects in a network. Two widely-used data identification approaches in IoT are Electronic Product Codes (EPC) and Ubiquitous Codes (uCode). The ID of an object might not be unique in a network. In this case, an address is used to accurately identify that object. Also, a network might contain public and private Internet Protocols (IPs), e.g. IPv4 and IPv6. The sensing process involves collection of data using sensing devices such as actuators, smart sensors, wearable sensors, smartphones, etc. Arguably, one of most meaningful breakthroughs happening in this area is the emergence of single board computers (SBCs). SBCs are equipped with an applications processor capable of running an advanced operating system like Linux, Windows, or Android [20]. They are generally ready for deployment with minimal setup and can be integrated with sensors, built-in TCP/IP and security firewalls. Some of the popular SBCs in the market are Arduino Yun, BeagleBone Black, Intel Galileo, Adafruit Feather, and Raspberry PI.

3.2.2. Data delivery

The delivery of IoT data is significantly related to communication protocols in IoT-based networks. Many communication protocols with varied characteristics are currently used, e.g., IEEE 802.15.4, WiFi, Bluetooth, LTE-Advanced, and Z-wave. IEEE 802.15.4 is one of the most commonly-used IoT data link protocols. This protocol is based on defining frame formats, defining headers that include source and destination addresses, and defining how nodes communicate with each other. WiFi is another major data delivery method applied to communicate information between smart devices without using routers in *ad-hoc* configurations. Bluetooth represents a communication approach for exchanging data between smart devices in relatively short distances using short-wavelength radio. Long-Term Evolution (LTE) is a standard wireless communication protocol for high-speed data transfer between smart devices, and LTE-Advanced (LTE-A) is as an advanced version of LTE. LTE-A has a bandwidth extension to reach 100 MHz, and has extended coverage, high throughput, low latencies, and uplink and downlink spatial multiplexing [20]. Near Field Communication (NFC), RFID and Ultra-Wide Bandwidth (UWB) are other popular communication technologies. NFC is mainly used when the support data rate is approximately 424 kbps and the high frequency band is 13.56 MHz. The applicability range of NFC is nearly 10 cm. RFID is one of the first technologies used for the M2M communication such as tags. UWB technology has been developed to support communications between

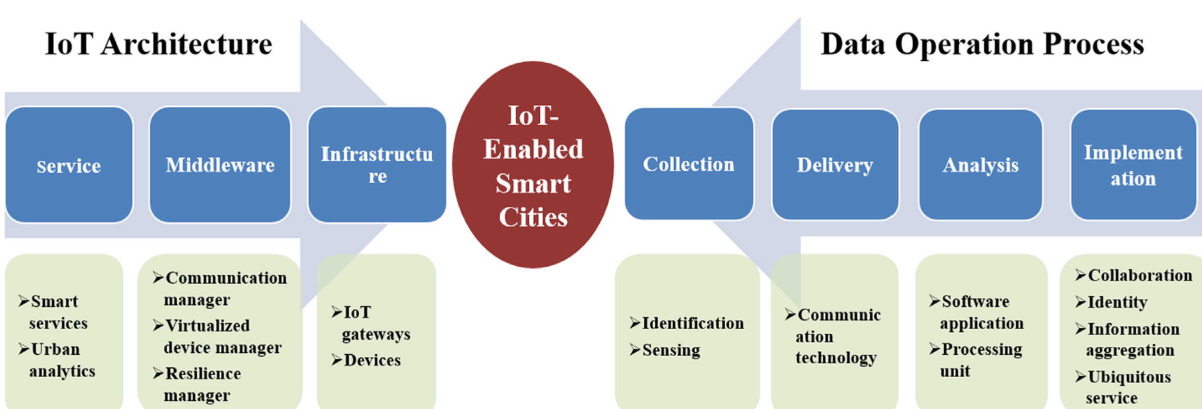

Fig. 7. Characterization of the technologies in IoT-enabled smart cities with respect to typical IoT architecture (redrawn from [20]) and data operation process (redrawn from [117]).

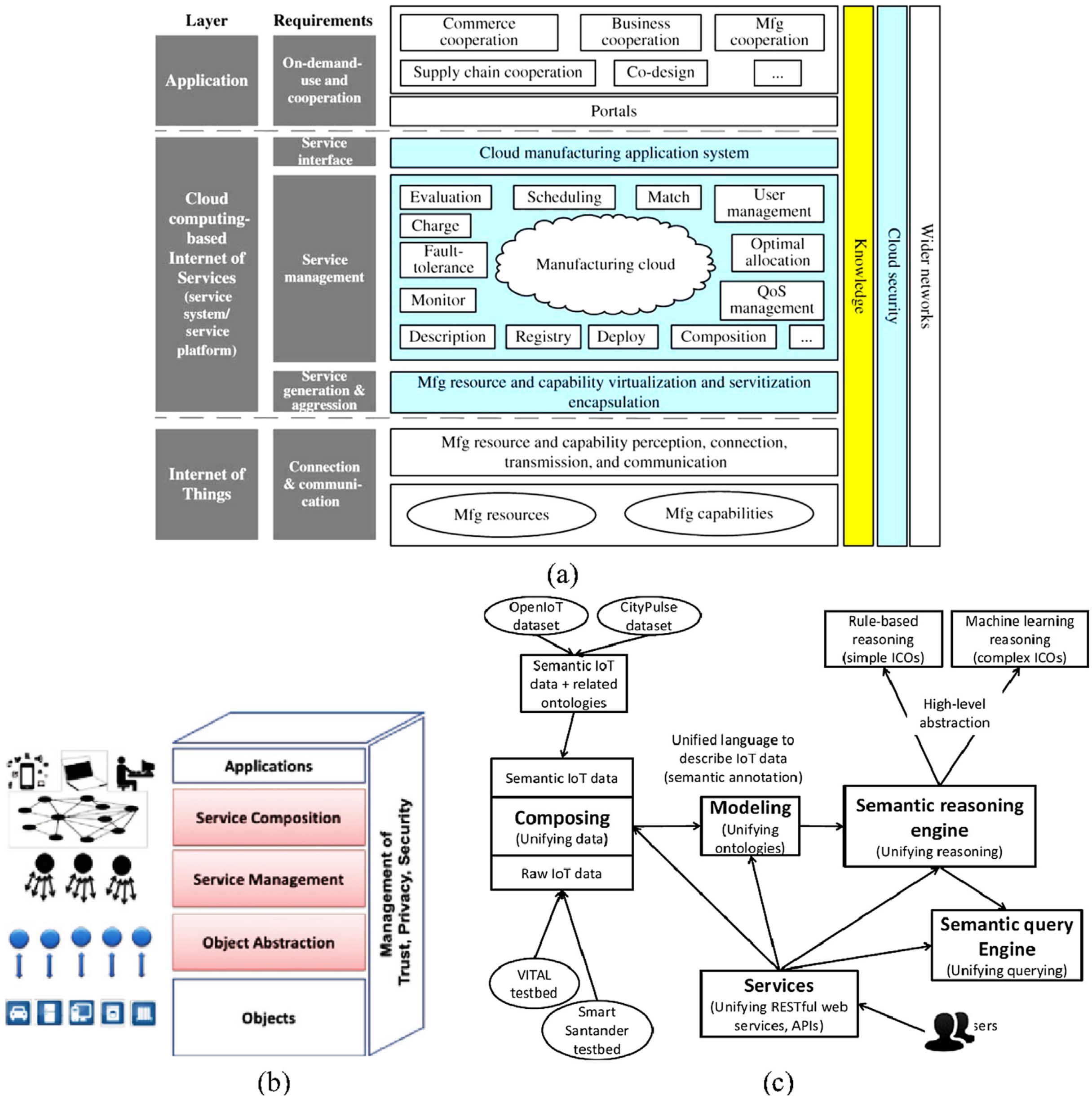

Fig. 8. (a) Architecture of the CCIoT-CMfg system [182]. (b) Service-oriented architecture (SoA) for an IoT middleware system [48]. (c) Semantic engine for the data processing in IoT [159].

objects within a smaller radius, but with high bandwidth and low energy.

3.2.3. Data analysis

A number of software platforms and operating systems (OSs) have been built to enable IoT data analysis. Unlike PCs and mobile devices, there are many commercial and open source OSs powering the IoT. Real-time Operating Systems (RTOSs) are widely used to manage hardware resources, host applications, and process data on real-time basis. An RTOS generally contains a real-time kernel and other higher-level services such as file management, protocol stacks, and Graphical User Interfaces (GUIs). RTOSs such as Contiki RTOS, LiteOS, Riot OS, and TinyOS are critical components to build reliable IoT solutions in various areas, e.g., transportation, automotive, healthcare, and telecommunications. Cloud platforms are also crucial computational components of IoT. They provide valuable, application-specific services in a number of application domains. Many commercial and free cloud frameworks and platforms are currently available to leverage specific IoT-based services [20].

4. Existing projects in IoT-enabled smart cities

The rapid development of modern cities has created serious issues in areas such as public healthcare [27], public services [128], air quality [125,127], and energy consumption [127,139]. The enormous amount of data generated by smart IoT-enabled objects in these cities can be

Table 3
Smart city projects worldwide.

Project	Location		Description
	Country	City	
AIM [138]	Germany	–	The AIM is focused on harmonizing IoT technologies to manage energy consumption.
SGIM [188]	USA	Chicago	The City Digital SGIM project aims to create new, real-time sensing capabilities and cloud-based analytics to evaluate the performance of storm water management techniques.
IBM Smart City Projects [130]	Belgium, Brazil, Italy, Saudi Arabia, Spain, USA, etc.	–	The IBM smart city projects aim to create a clear vision of smart cities and IoT, while adopting a worldwide OI approach; delineating specific strategies, and creating OI units ad hoc for smart cities' projects.
SmartSantander [121,124]	Germany, Serbia, Spain, UK, etc.	–	The SmartSantander aims to develop an IoT/FI platform and implement it in a smart city.
Barcelona Intelligent City (BCI) [120]	Spain	Barcelona	The BCI aims to define, design and develop a reference model of a network management platform and sensor data.
WHO Healthy City Project [27]			The WHO health city project aims to harness the power of IoT to improve the health and well-being of the local citizens in smart cities.
Smart Parking [128]		Santander	The smart parking project aims to manage the limited parking space in the smart city, with particular emphases on the control of load and unload areas, traffic prediction, and citizens with disabilities,
DIMMER [139],	UK Italy	Manchester Turin	The DIMMER aims to reduce climate changes by controlling energy chain and improving energy efficiency using the sensors and actuators implemented in the smart city.
Padova Smart City [125]	Italy	Padova	The Padova smart city project aims to monitor the public street lighting and air pollution in the city using wireless sensors.
IntUBE [140]	Finland	–	IntUBE aims to increase life-cycle energy efficiency of the buildings in smart cities without compromising the comfort or performance of the buildings.
GreenIoT [127]	Sweden	Uppsala	The GreenIoT aims to monitor the air pollution and traffic planning in the smart city, to reduce air pollution through active monitoring, traffic management, and better city planning.
Smart City Projects [132]	China	Beijing, Shanghai, Guangzhou, etc.	The Smart City Projects aim to strengthen city management, while improving city services and ameliorating city functions.

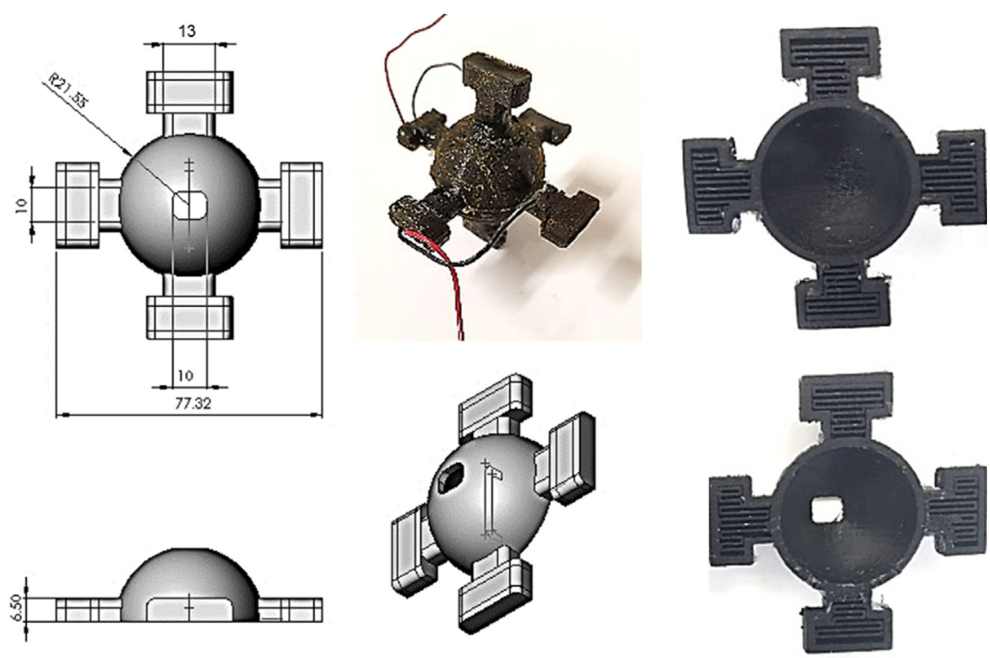

Fig. 9. The designed sensing system embedded in a spherical casing.

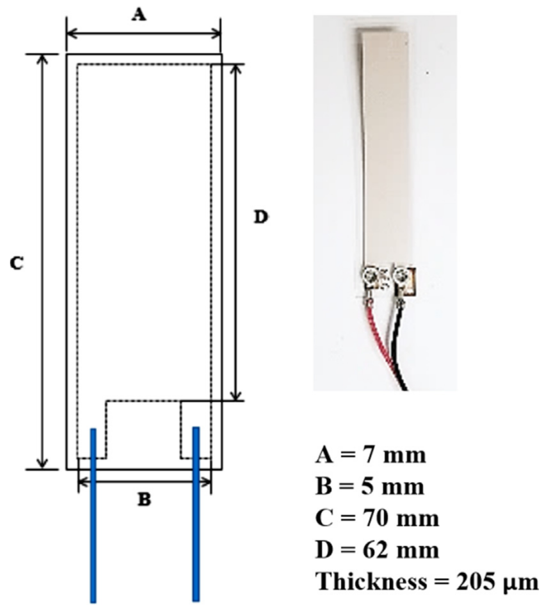

Fig. 10. Dimension of the PVDF sensor.

used to create safer, more livable communities for their citizens. During the last decade, several IoT-enabled smart city projects have been launched. These projects have resulted not only to a better quality of life but also a remarkable reduction of the operational costs of public administration [125]. Table 3 summarizes the existing smart cities projects worldwide.

5. Case study of a low-cost, real-time monitoring system based on IoT

IoT technology can be used to develop cost-effective, real-time infrastructure monitoring systems in a smart city. In this section, a simple case study is presented to demonstrate how an affordable and robust IoT-based working prototype can be designed for real-time monitoring of civil infrastructure. To this aim, a technical procedure is described to monitor the response of piezoelectric transducers using an inexpensive IoT device. For this case study, embedded polyvinylidene fluoride (PVDF) piezoelectric films are used. Built upon previous work at Michigan State University for smart health monitoring of pavement systems [66], a new miniaturized spherical packaging system is manufactured to encase the sensors. The size of the designed spherical packaging system is of the same order of a coarse aggregate (crushed rock) particle. The spherical packaging system was designed using SolidWorks software and was built by 3D printing. Fig. 9 shows the manufacturing process of the packaging system with embedded piezoelectric transducers. The top part has an opening to cast epoxy into the mold. When the epoxy is strained, an induced axial loading is transferred to the piezo sensor. Fig. 10 displays the dimensions the PVDF film which is adhered to the anchor legs of the spherical packaging. Additional details regarding the PVDF films, epoxy properties, calibration, and other technical items have been reported elsewhere [66].

In order to monitor the piezo sensor response in real-time using an IoT device, different communication protocol standards can be used

Table 4
List and costs of the components used in the IoT prototype (based on prices in October 2017).

Part	Commercial Name	Price
Main board	Adafruit Feather M0 WiFi - ATSAMD21 + ATWINC1500	$34.95
Power supply	Lithium Ion Polymer Battery - 3.7v 500mAh	$7.95
USB cable	Standard A to micro-B USB cable	$2.95
Cloud/Data Visualization	Plotly public hosting	Free
Total price per node	–	$45.85

*The total price does not include the investment in time for building the working prototype.

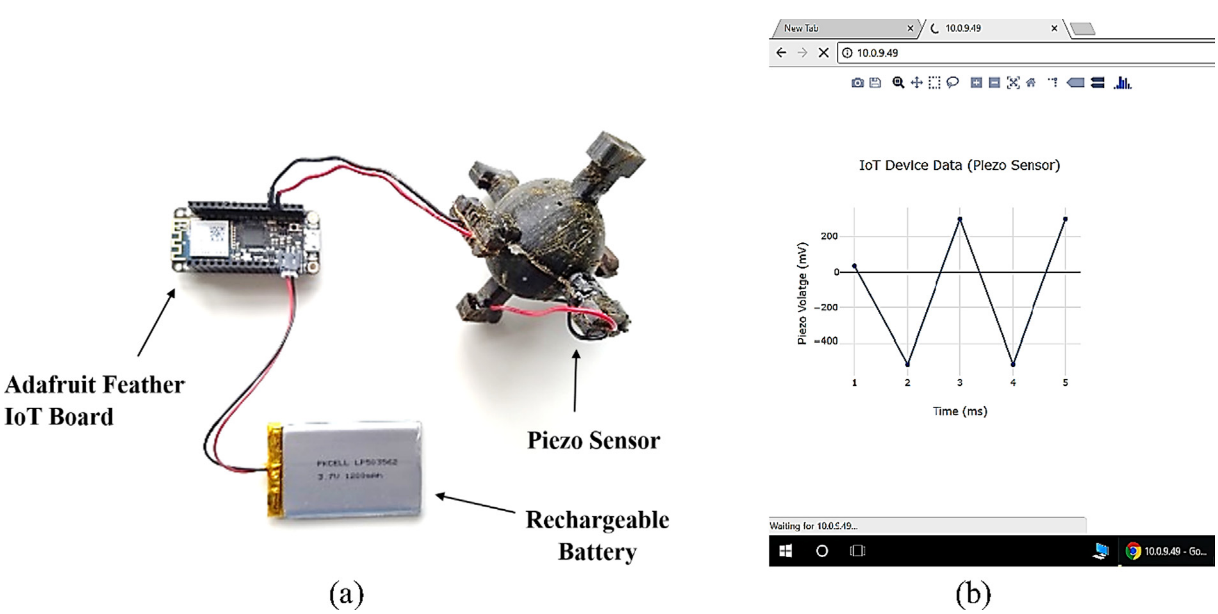

Fig. 11. (a) Sample response of the piezo sensor in rea-time using Adafruit Feather board, and (b) Plotly data visualization platform.

(e.g., Bluetooth, UWB, ZigBee, 4G, Wi-Fi). In this study, an IoT with a built-in webserver device and Wi-Fi connection are used to simplify deployment of the prototype unit. In this manner, the sensor data can be easily accessed and illustrated with a web browser. Recently, new microcontrollers known as SBC have emerged [189]. These economical and affordable devices are smaller than classic computers and offer computing power and scalability for big projects. There are different SBCs in the marketplace, with distinctive features regarding connectivity, computing power, size or energy usage (e.g., Raspberry Pi, BeagleBone, ODroid) [191,192]. Herein, a widely-used open-source platform Arduino was used for building the electronic prototype. Arduino consists of a microcontroller and Integrated Development Environment (IDE). The microcontroller serves as the physical programmable circuit board and IDE is the software used to write and upload codes to the microcontroller. An Arduino can be turned into a simple web server using an Ethernet shield. The sensor data can then be read by accessing that server with a browser running on any computer connected to the network. An Arduino compatible board (Adafruit Feather M0 WiFi - ATSAMD21 + ATWINC1500) with FCC-certified WiFi module is used to act as a webserver with JavaScript to show the piezo sensor data. The WiFiWebServer Arduino sketch is used to serve a webpage from the Adafruit Feather M0 WiFi shield. This sketch is modified to visualize the piezo sensor readings (see Appendix B).

The next step is to add the WiFi101 library to Arduino to use the WiFi board. The SSID and the password are required to connect the Adafruit Feather board to a WiFi network. It can serve as either a server accepting incoming connections or a client making outgoing ones. The library supports WEP and WPA2 Personal encryption. The board communicates with the WiFi shield 101 compatible using the SPI bus. Each board has a unique a MAC and IP address. Validity of IP addresses depends on the configuration of the network. The networks may dynamically assign an IP to the board (e.g. for DHCP network protocol). For such networks, network scanning apps (e.g. Fing) can be used to find the assigned IP address. Once the IP is known, the piezo sensor response can be monitored by opening a browser and navigating to the shield's IP address. In this example, the piezo sensor is connected to the analog pins 0 and ground. Different platforms can be used to visualize the sensor data in real-time (e.g., eThingSpeak, Plotly, Azure, etc). In this study, Plotly's JavaScript charting library is used for the real-time data visualization. Plotly is an online data analytics and visualization tool that provides web-service for hosting graphs. It also offers free public hosting and users with a free account can retain one private plot. This is an attractive feature for lowering the cost of developing prototype systems, as in the current example.

Fig. 11 shows the designed IoT system with sample response of the piezo sensor in real-time. As the piezo sensor is excited, it harvests the strain energy from the deformations and converts it into electric signals. As soon as the programmed Adafruit Feather IoT board is connected to a power supply, it automatically starts searching for the Wi-Fi network and tries to connect to it. The assigned IP address is then found using the Fing scanning app. When the IP address assigned to the IoT board is accessed on a Web browser, the voltage generated by the piezo sensor will be shown on Plotly hosting graph in real-time. The plot is updated in a predefined delay time, which is taken as 0.3 s in this study in order to give the browser time to receive the data.

Arguably, one of the key issues for successful deployment of monitoring systems is their economic cost. Table 4 shows the approximate price of the components used for building the proposed monitoring platform. The price of sensing equipment (piezo sensors, epoxy, etc.) is not included in the cost analysis. As seen in Table 4, developing such IoT prototype for civil infrastructure monitoring can be inexpensive. However, for advanced applications, this low-cost system should meet some other major criteria such as reliability for long-term measurements, enough computing power to do on-board calculations, and different connectivity options.

6. Conclusions

Urbanization has driven many of the major societal challenges that have arisen in recent history. The resulting issues and challenges have created a market for smart city technologies. Among many of the enabling technologies, IoT plays a key role in shaping the future of smart cities as a networking paradigm. Smart cities and IoT are poised to create a new age in urban living, enhancing the safety, livability, and comfort of citizens, and providing a backbone for high-tech businesses and enabling more efficient and smart city services and administrations. Extensive studies have been recently carried out to explore the unique features of the IoT in both technology and application domains. The literature in the technology domain has been focused on introducing IoT-enabled technologies, protocols, challenges and advantages. The application domain projects have been conducted on different city operation aspects such as cyberville, digital city, electronic city, flexicity, information city, and wired city. In this paper, we have surveyed the state-of-the-art of IoT research as it relates to the sustainable development of smart cities. Integration of the IoT with other enabling technologies to create a system of systems has been further studied. A case study is also presented to explore the development challenges of the IoT-based monitoring systems. Based on the analysis of the publications, a great deal of research is still necessary to address IoT challenges such as privacy, participatory sensing, energy efficiency, visualization, cloud computing, and edge computing. This requires continuing collaboration between public authorities, private companies and academia. More focus should also be placed on developing smart city infrastructures to support the IoT. The other area that IoT will profoundly change in the near future is human habits and physical well-being. Therefore, it is vitally important to consider the social impacts of IoT-based technologies on individuals and communities as part of planning, design, and deployment.

Appendix A

Table A1 presents the classification of the reviewed publications with respect to scholarly domain, article scope, type of article and publisher.

Table A1
Classification of the reviewed publications with respect to the domain, scope, type and publisher.

Domain	Scope		Journal			Conference		Book Chapter, Website, and Project Report
			IEEE	Elsevier	Springer, Sage, Wiley, IOP and Others	IEEE	SPIE and Others	
IoT in Application Domain	Smart Cities	Overall	[13,35,98,100,151,172,173,174]	[1,25,28,49,53,137,143,168,170,171]	[34,40,101,102,122,162,164]	[43,44,57,59,99,110,177,186]	[3,4,103,157,176]	[21,108,166,175,185]
		Home & Civil Infrastructure	[118,119,158]	[5,116]	[60,117]	[45,47,129,142]	[61]	–
		Mobility & Tourism	[144]	[54,104,105]	[107,133,134]	–	[106]	[24,180,181]
		Energy Consumption	[42]	[48]	[58]	–	[81,83]	–
	Industry, Agriculture & Environment		–	[39]	[51]	[46,95]	[75],	–
IoT in Technology Domain	Cognitive Management, M2M, SHM, Communication & Sensing		[2,41,71,145,178,182]	[62,63,64,65,66]	[72,149]	[52,150,169,179]	[67,160]	[155,163,184]
	Data Mining & Cloud-related Technologies		[12,20]	[8,9,26,36,37,152]	[30,32]	[7,56,111]	[6,191]	[10,11,153,165]
	Privacy & Security		–	–	[96,114,115,187]	[109],	–	[112,113],
	Sensor and Sensing Technology, Energy Harvesting, & Others		[14,31,33,161,183]	[15,19,25,28,76,78,79,80,82,87,88,89,91,92,167,190,193]	[29,70,73,74,84,90,93,94,192]	[17,18,38,50,55,68,69,95,159]	[16,77,85,86,131]	[156]
Smart City Projects			[97,127]	[154]	[27,128,130]	[120,121,125,126,132]	[123,124]	[138,139,140,141,188]

Note: Italicization refers to review articles.

Appendix B

The Arduino sketch modified to visualize the piezo sensor response in real-time.

```
//
#include < SPI.h >
#include < WiFi101.h >
#include < Wire.h >
char ssid[] = "network SSID";
char pass[] = " network password ";
int keyIndex = 0;
int status = WL_IDLE_STATUS;
WiFiServer server(80);
float Gain_A = 0.154 ;
int analogPin0 = A0 ;
const int numReadings = 1000;
int readsens2 = 0;
int readsens3 = 0;
int readsens4 = 0;
int readsens5 = 0;

int readsens = 0;
void setup() {
WiFi.setPins(8,7,4,2);
Serial.begin(9600);
analogReadResolution(12);
analogReference(AR_INTERNAL);
if (WiFi.status() = = WL_NO_SHIELD)
{
while (true);
}

while (status != WL_CONNECTED) {
Serial.print("Attempting to connect to
SSID: ");
Serial.println(ssid);
status = WiFi.begin(ssid, pass);
delay(10000);
}
server.begin();
printWifiStatus();
}

void loop() {
WiFiClient client = server.available();
if (client) {
Serial.println("new client");
boolean currentLineIsBlank = true;
while (client.connected()) {
if (client.available()) {
char c = client.read();
Serial.write(c);
if (c = = '\n' && currentLineIsBlank) {
char messagesp[] = " < !DOCTYPE html > "
"\n < html > "
"\n < head > "
"\n "
"\n < script
src='https://cdn.plot.ly/plotly-latest.min.js' > < /script > "
"\n < /head > "
"\n "
"\n < body > "
"\n < div id='myDiv' style='width: 480px; height:
400px;' > < /div > "
"\n < script > "
"\nvar trace1 = {"
"\n x: [1,2,3,4,5],";

char messagesp3[] =
"\n mode: 'lines + markers',"
"\n name: 'Piezo Volatge'"
"\n};"
"\n "
"\nvar data = [trace1];"
"\n "
"\nvar layout = {"
"\n title: 'IoT Device Data (Piezo Sensor)',"
"\n xaxis: {"
"\n title: 'Time (ms)'"
"\n },"
"\n yaxis: {"
"\n title: 'Piezo Volatge (mV)'"
"\n }"
"\n};"
"\n "
"\nPlotly.newPlot('myDiv', data, layout);"
"\n < /script > "
"\n < /body > "
"\n < /html > ";

client.println("HTTP/1.1 200 OK");
client.println("Content-Type: text/html");
client.println("Refresh: 0.3″); // refresh the page automatically
every 0.3 sec
client.println();
client.println();
client.write(messagesp);

int readsens = analogRead(analogPin0)*Gain_A;
client.print("\n y: [");
client.print(readsens5);
client.print(", ");
client.print(readsens4);
client.print(", ");
client.print(readsens3);
client.print(", ");
client.print(readsens2);
client.print(", ");
client.print(readsens);
readsens5 = readsens4;
client.print("],");
readsens4 = readsens3;
readsens3 = readsens2;
readsens2 = readsens;
client.write(messagesp3);
client.println();

break;
}
if (c = = '\n') {
// you're starting a new line
currentLineIsBlank = true;
}
else if (c != '\r') {
// you've gotten a character on the
current line
currentLineIsBlank = false;
}
}
}
delay(0.3);
client.stop();
Serial.println("client
disonnected");
}
}
void printWifiStatus() {
Serial.print("SSID: ");
Serial.println(WiFi.SSID());
IPAddress ip = WiFi.localIP();
Serial.print("IP Address: ");
Serial.println(ip);
long rssi = WiFi.RSSI();
Serial.print("signal strength
(RSSI):");
Serial.print(rssi);
Serial.println(" dBm");
}
//
```

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