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Smart Cities as Cyber-Physical Social Systems

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ABSTRACT

The emerging prototype for a Smart City is one of an urban environment with a new generation of innovative services for transportation, energy distribution, healthcare, environmental monitoring, business, commerce, emergency response, and social activities. Enabling the technology for such a setting requires a viewpoint of Smart Cities as cyber-physical systems (CPSs) that include new software platforms and strict requirements for mobility, security, safety, privacy, and the processing of massive amounts of information. This paper identifies some key defining characteristics of a Smart City, discusses some lessons learned from viewing them as CPSs, and outlines some fundamental research issues that remain largely open.

1. Introduction

As of 2014, 54% of the earth's population resides in urban areas, a percentage expected to reach 66% by 2050. This increase would amount to 2.5 billion people added to urban populations [1]. At the same time, there are now 28 megacities (each with 10 million people or more) worldwide, home to 453 million people or about 12% of the world's urban population. Projections indicate more than 41 megacities by 2030. It stands to reason that the management and sustainability of urban areas have become one of the most critical challenges our society faces today. Consequently, cities are looking for ways that ensure a sustainable, comfortable, and economically viable future for their citizens by becoming "smart."

The emerging prototype for a Smart City is one of an urban environment with a new generation of innovative services for transportation, energy distribution, healthcare, environmental monitoring, business, commerce, emergency response, and social activities [2]. The term Smart City is broadly used to capture the overall vision outlined above, as well as the intellectual content that supports it. The technological infrastructure of a Smart City is based on a network of sensors and actuators embedded through-out the urban terrain, interacting with wireless mobile devices (e.g., smartphones) and having an Internet-based backbone with cloud service. The data collected and flowing through such a cyber-physical system (CPS) may involve traffic conditions, the occupancy of parking spaces, air/water quality information, the structural health of bridges, roads, or buildings, and the location and status of city resources including transportation vehicles, police officers, or healthcare facilities. The applications stemming from this environment are virtually endless and are being invented and deployed on a daily basis, paving the way for tremendous new business and commercial opportunities targeting select user groups as much as the totality of urban dwellers.

Enabling such a Smart City setting requires a cyber-physical infrastructure combined with new software platforms and strict requirements for mobility, security, safety, privacy, and the processing of massive amounts of information (so-called "big data"). The prevailing paradigm is one of a "cloud" in which most data reside and drive a variety of novel and continuously evolving applications with real-time response and stringent security expectations. It is worth emphasizing that the ultimate value of a Smart City's infrastructure lies in "closing the loop" that consists of sensing, communicating, decision making, and actuating—rath-

er than simply collecting and sharing data (Fig. 1). This requires a balanced understanding of both "physical" and "cyber" components that takes into account the important issues of privacy, security, safety, and proper energy management necessitated by the wireless nature of most data collection and actuation mechanisms involved.

A major challenge for this paradigm is the need to integrate heterogeneous widely distributed devices into a common software environment. For example, cameras and different types of sensors embedded in power lines or in a building's heating, ventilation, and air conditioning (HVAC) components must be able to communicate with each other, as well as with smartphones, tablets, laptops, and servers. This process may be seen as parallel to the process that occurred in the 1980s and early 1990s, as the Internet evolved to integrate data, voice, video, and specialized applications into a unified environment, and as software platforms emerged for various industry and business sectors. Similarly, in the CPS domain that the Internet is rapidly evolving toward, one expects new platforms to emerge, defined by mobility and the secure and safe processing of massive amounts of data.

In this new reality, referred to as the Internet of Things, the Internet as we know it is likely to be but one component of a much larger network. Whereas the Internet is ultimately no more than a structure for transporting packets from one computer to another, in a Smart City, data flow from heterogeneous sensing devices to servers and, conversely, commands flow to actuating devices performing useful real-time operations (e.g., controlling traffic lights or HVAC components and dispatching resources for critical healthcare or emergency needs). In the current setting, each new Smart City application created requires its own unique way to fit in and become accessible to its users. What is lacking—and what defines the future—is an underlying common platform allowing such applications to become plug-and-play components in this environment.

2. Defining a Smart City

There is no single generally acceptable definition for a Smart City, but several efforts are emerging to try and capture the multidimensional and multidisciplinary nature of what a Smart City represents. In what follows, a few such definitions are given, originating from different sources: government agencies, industrial organizations, technology leaders, and academia.

(1) "A city well performing in a forward-looking way in [economy, people, governance, mobility, environment, and living] built on the smart combination of endowments and activities of self-decisive, independent and aware citizens." [3]

(2) "Smart Sustainable Cities use information and communication technologies (ICT) to be more intelligent and efficient in the use of resources, resulting in cost and energy savings, improved service delivery and quality of life, and reduced environmental footprint—all supporting innovation and the low-carbon economy." [3]

(3) "Hitachi's vision for the Smart Sustainable City seeks to achieve concern for the global environment and lifestyle safety and convenience through the coordination of infrastructure. Smart Sustainable Cities realized through the coordination of infrastructures consist of two infrastructure layers that support consumers' lifestyles together with the urban management infrastructure that links these together using information technology (IT)." [4]

(4) "We believe a city to be smart when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural re-
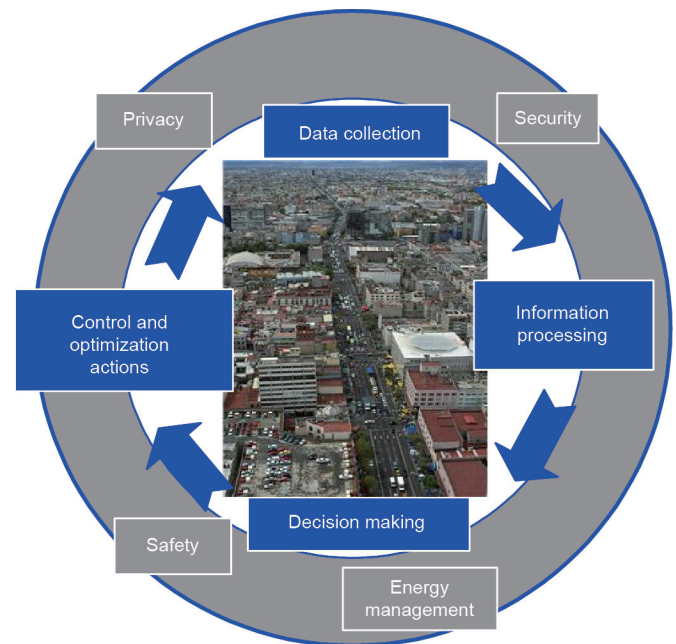

Fig. 1. The cyber-physical infrastructure for a Smart City.

sources, through participatory governance." [5]

All these attempts at defining Smart Cities share a number of common elements. In summary, Smart Cities are [6]: ① sensible (sensors sense the environment), ② connectable (networked devices bring the sensed information to the Web), ③ accessible (information on our environment is published and is accessible by users on the Web), ④ ubiquitous (users can access information at any time and in any place, while moving), ⑤ sociable (users acquiring information can publish it though their social network), ⑥ sharable (sharing is not limited to data, but also to physical objects that may be used when they are in free status), and ⑦ visible/augmented (the physical environment is retrofitted and information is seen not only by individuals through mobile devices, but also in physical places such as street signs).

It is worth noting that absent from these definitions is the point made earlier about "closing the loop" in a Smart City. This aspect is not yet widely recognized as the ultimate value of a CPS.

3. Lessons learned from viewing Smart Cities as CPSs

Our work at Boston University toward establishing a cyber-physical infrastructure for Smart Cities has helped us identify several issues that offer a number of guiding principles for research. In addition, efforts to deploy Smart City applications in the City of Boston have provided valuable feedback from both the city administrators responsible for orchestrating such deployments and the end users themselves. Some key observations are summarized below.

(1) "Smart" is not just collecting and disseminating data. As illustrated in Fig. 1, viewing the CPS that is a Smart City as a closed-loop system is extremely important and, in some cases, critical. Simply collecting and disseminating data to a user group can in fact be more harmful than helpful. As an example, today's "smart parking" technology essentially informs drivers where parking spaces are available; as a result, it is often the case that multiple drivers converge to where a few spaces are available, thus creating additional traffic congestion from drivers attracted to the area who cannot find a space [7].

(2) The "law of unintended consequences" finds fertile ground

in smart cities. When people are provided with an abundance of new data and services, they exhibit an amazing capacity to use services developed for specific purposes in innovative ways that were never envisioned in the first place. This principle of beneficial "unintended consequences" appears to be at work when one continuously develops new capabilities and makes them widely available in simple, intuitive, easy-to-use ways. Thus, creating a few apps and establishing a user-friendly platform for accumulating and disseminating data has a remarkable amplification capability in promoting innovation.

(3) The role of humans in Smart Cities. Technology alone cannot transform a city or a community; necessary mechanisms must be included to create incentives for using the technology and for accommodating the "human in the loop." When it comes to the efficient management of sharable resources, there is a fundamental conflict between the individual and social optima. The control of traffic in an urban setting is a prime example of this fact, as individual drivers seek to achieve what they perceive to be their own goal, which is often not aligned with what benefits the entire group of drivers at a given point in time [8]. While technology offers the means to achieve a social (or global) optimum, one cannot impose it in a vacuum. Understanding and respecting human behavior is a key component of a CPS; in fact, a CPS should be more accurately referred to as a Cyber-Physical Social System. This wording also implies the importance of municipal governments in developing and implementing the policies necessary to provide incentives and deliver the ultimate value of CPS technologies to smart cities.

4. Fundamental research issues for Smart Sities

From the point of view of systems and control theory, a Smart City is a highly dynamic stochastic hybrid system [9] with a multitude of issues that can only be successfully addressed through a multidisciplinary approach, bringing together researchers from engineering, computer science, and the social sciences. The following provides an outline of some of the major research areas that are clearly involved in the effort to transform the Smart City vision described above into a reality.

(1) Sensing and cooperative data collection. Clearly, this is the starting point for a Smart City and, in fact, for any CPS. A key challenge here is the highly inhomogeneous and distributed nature of the data sources we are interested in, as well as of the sensing devices charged to interact with them and with each other in a cooperative manner. A sensor network may be viewed as a control system encompassing three main tasks: coverage control, data source detection, and data collection. The interactions among these three tasks are important and define significant tradeoffs.

(2) Security, safety, privacy, and energy management in the collection and processing of data. As illustrated in Fig. 1, the entire process of data collection and processing is subject to constraints—some strictly physical (such as limited energy, mostly in wireless network settings), and some imposed by legal, cultural, and economic principles and regulations.

(3) Dynamic resource allocation. Ultimately, most of the Smart City functionality boils down to managing limited sharable resources, such as transportation capacity, services, or energy. The highly dynamic nature of the urban environment calls for novel resource allocation mechanisms beyond conventional algorithms. For example, it makes little sense to commit a resource such as a parking space to a vehicle located many minutes or hours away, when a better resource may become available while the vehicle is

in transit [7]. The conventional notion of "response time" or "latency" in classical performance optimization problems no longer applies and new performance metrics are necessary. The same is true for many energy-aware resources, such as Electric Vehicles (EVs): Their presence in a transportation network has opened up a new generation of routing and scheduling problems [8].

(4) Data-driven control and optimization. In part due to the availability of enormous amounts of data (big data) in a Smart City setting, there is an opportunity to develop new schemes for control and optimization that are driven by real-time data as much as by sophisticated off-line models. In addition, the complexity of the stochastic processes involved in traffic or in the demand for certain resources arguably makes such data-driven mechanisms an absolute necessity, and motivates the need for a software platform that breaks technological and institutional silos existing today and enables the efficient accumulation, storage, and dissemination of data to anyone with the potential to innovate.

(5) Connected Automated Vehicles (CAVs). The advent of this new generation of vehicles is a game-changing development whose impact will be profound, not only in terms of transportation system performance, but also in terms of broad economic, environmental, and social effects. CAVs have the potential to reduce energy costs, along with unwanted emissions, and to alter the behavior of a typical driver and the overall attitude of urban dwellers toward driving in ways that are largely unpredictable. Thus, there is an urgent need to quantify the improvement in transportation efficiency resulting from CAVs, along with their impact on other components of the cyber-physical infrastructure.

(6) Interdisciplinary research. As mentioned earlier, technology alone cannot transform a city without the participation and cooperation of its citizens. A Smart City is in fact a sociotechnical ecosystem of people, technology, organizations, and information. As such, the proper design and management of this ecosystem needs to bring together engineers, ecologists, economists, and social scientists, providing a wealth of interdisciplinary research opportunities.

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