Cyber-physical systems and smart cities

Learn how smart devices, sensors, and actuators are advancing Internet of Things implementations

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Today’s urban environments present many challenges for cyber-physical systems (CPSs) and smart cities. This article introduces CPSs and provides real-world use cases for this technology. This article also describes the social and technical challenges that smart cities will face in the near future.

Synergy of cyber and physical worlds

Smart devices are becoming more sophisticated with increased capabilities while they remain a relatively low-cost technology. Also, many of these smart devices rely on the prevalence of high-speed wireless networks, including 4G cellular networks. With the Internet of Things, every object can retrieve information from the environment and then manage and share that information with other devices or users.

Internet of Things is a dynamic and distributed environment that is composed of numerous smart devices that sense their environment and that are able to act in that environment. Because of these devices, it is possible to monitor the external environment, gather information about the real world, and create a type of ubiquitous computing, which enables every device to communicate with any other device in the world, from everywhere. The IoT aims to make the Internet more pervasive by allowing devices to be connected and collaborate among themselves as singular sensors or as a swarm of sensors that create macro endpoints and act as entire systems.

The synergy of computational and physical components, specifically the use of cyber-physical systems (CPSs), led to the advancement of Internet of Things implementations. CPSs introduce cooperation among elements of the cyber and physical space, by integrating computational resources. CPSs often support real life processes and provide operational control of Internet of Things objects, which allow physical devices to sense the environment and modify it.

Internet of Things (IoT) is a disruptive technology that provides the potential for innovations and significant improvements to societal and business environments. With IoT technologies, you can create adaptive and intelligent applications that can better manage resources and provide more efficient systems. IoT and CPSs are designed to support applications that can manage enormous
amounts of data and a wide variety of data from the environment. Thus, CPSs can boost the smart city vision by using information and communication technologies for more efficient and effective resource management. Smart cities focus on providing innovative and better quality services to its citizens by improving the infrastructure of the city while reducing the overall costs.

**Cyber-physical systems**

In a cyber-physical system (CPS), computing elements coordinate and communicate with sensors, which monitor cyber and physical indicators, and actuators, which modify the cyber and physical environment where they are run. CPSs often seek to control the environment in some way. CPSs use sensors to connect all distributed intelligence in the environment to gain a deeper knowledge of the environment, which enables a more accurate actuation.

In a physical context, actuators act and modify the environment where users live. In a virtual context, CPSs are used to collect data from the virtual activities of users, such as their involvement on social networks, blogs, or e-commerce sites. Then, CPSs react in some way to that data to predict actions or needs of users as a whole. With software solutions such as IBM WebSphere Sensor Events you can connect to and analyze sensor-based, real-time data and events, and integrate those events into smarter solutions.

**Figure 1. CPS architecture**

Some practical applications of cyber-physical systems include:

- In the manufacturing environment, CPSs can improve processes by sharing real-time information among the industrial machines, manufacturing supply chain, suppliers, business systems, and customers. Also, CPSs can improve these processes by self-monitoring and controlling the entire production processes and then adapting production to satisfy
customers' preferences. CPSs provide a higher degree of visibility and control on supply chains, improving the traceability and security of goods.

- In the healthcare environment, CPSs are used for real-time and remote monitoring of the physical conditions of patients to limit patient hospitalization (for example, for patients who suffer from Alzheimer’s disease) or to improve treatments for disabled and elderly patients. Moreover, CPSs are used in research in the neuroscience field to better understand human functions with the support of brain-machine interfaces and therapeutic robotics.
- In the renewable energy environment, smart grids are CPSs where sensors and other devices monitor the grid to control it and provide better reliability and improve the energy efficiency.
- In smart building environments, smart devices and CPSs interact to reduce energy consumption, to increase safety and security, and to improve inhabitants’ comfort. For example, with CPSs you can enable energy monitoring and control systems usage, which help you achieve zero-energy buildings, or you can determine the extent of damage that buildings suffer after unexpected events and help prevent structural failures.
- In the transportation environment, individual vehicles and the infrastructure can communicate with each other, sharing real-time information about traffic, location, or issues, in order to prevent accidents or congestion, improve safety, and ultimately save money and time.
- In the agriculture environment, CPSs can be used to create more modern and precise agriculture. CPSs can collect fundamental information about the climate, the ground, and other data, in order to realize more accurate systems of agricultural management. CPSs can constantly monitor different resources, such as watering, humidity, plant health and others, through sensors and, thus, keep the ideal environmental values.
- In computer networks, CPSs can boost cyber environments to better understand systems and users' behaviors, which can help improve performances and resource management. For example, applications can be optimized to work in relation to the contexts and to the users' actions, or to monitor available resources. Moreover, popular social networks and e-commerce websites store users' navigation information and users' web content, analyzes that information, and then tries to predict interests and make recommendation for friends, posts, links, pages, events, or products.

**Smart cities**

Smart cities can be seen as wide-scale cyber-physical systems, with sensors monitoring cyber and physical indicators and with actuators dynamically changing the complex urban environment in some way. Governments, organizations, and technology industries are rising to the challenges of increased urbanization, working to improve urban life by offering improved efficiencies with energy utilizations or services, for example.

According to the *United Nations Population Prospects, 2014 Revision* report, the urban population of the world is growing rapidly, and it is continuing to increase. In 2014, 54% of the world's population resides in urban areas, and the coming decades will bring further profound changes to the size and spatial distribution of the global population. In 1950, 30% of the world’s population was urban; by 2050, 66% of the world’s population is projected to be urban. Figure 2 is captured from Figure 2 in the *United Nations Population Prospects, 2014 Revision* report.
Figure 2. This figure is from the United Nations Population Prospects, 2014 Revision report that shows urban and rural population of the world, from 1950 to 2050

With the stress that urbanization and an aging population puts on a city, urban areas must rethink their organizational structures and infrastructures as they face new challenges. These challenges include how to responsibly use (and not waste) key resources, such as energy, water, food, and other raw materials. Rapid and unplanned urban growth threatens sustainable development if the necessary infrastructure is not developed. In this context, improving efficiencies is crucial to a city’s success. Thus, smart cities (large-scale CPSs) are cropping up, such as Santander, Singapore, Boston, and many others (review the IBM case studies).

The map in Figure 3 illustrates the distribution of smart (and not smart) cities with a population of more than 100,000 people in Europe. Smart cities are those cities that meet criteria based on characteristics such as smart governance, smart living, smart mobility, smart people, smart economy, and smart environment. Figure 3 is captured from Figure 10 in the EU Parliament report, Mapping Smart Cities in the EU, published in 2014.
**Figure 3.** Mapping Smart Cities in the EU, 2014, figure from report that shows the location of cities with a population of more than 100,000 that are not smart cities and smart cities in Europe

SmartSantander is a large-scale research project that spreads thousands of sensors around the city of Santander in Spain. Its purpose is to build a smart solution and improve various aspects of the city life, such as reducing traffic, reducing energy consumption, improving the quality of the environment, and encouraging citizens’ participation. Also, the project hopes to share this environmental information and develop other useful applications. The research is also testing to see whether it is possible to reduce distances between theoretical designs of smart infrastructures and the adoption of practical applications in a real-world environment. The results of this test will help increase the spread of Internet of Things (IoT) and CPSs in real scenarios in the future.

Singapore, which was named as the world's smartest city for many years, is becoming a leading nation in implementing smart infrastructures and providing quality services (see "What's the Second Act for the World's First Intelligent Community"). Singapore is one of the world's most important business centers, has one of the busiest ports, and is home to Asia's fifth largest airport. Singapore expects to create the first smart nation in the world to boost economic growth, to meet population needs, and to be an example for other nations. The insights of this smart nation are grouped as:

- Better policies to manage different contexts
• Development of novel business models and revenue streams that can strengthen the economic growth
• An increase in active citizens' participation towards the creation of quality services that can improve everyday life of the community

**Boston** received the IBM Smarter Cities Challenge 2012 Grant, based on its innovations and existing ecosystem. In fact, the presence of many universities and startup companies in the area drives the city towards cutting-edge technology research and gets the city accustomed to adopting new models frequently. Moreover, Boston invests heavily in research and development and technology innovation. Its citizens are considered some of the most intelligent people in the world. Boston was one of the first urban areas to use crowdsourcing to collect data from their environment. Boston introduced a pilot experiment to promote citizens' collaborations and to encourage citizens' participation with the goal to improve services quality.

**Future challenges**

For cyber-physical systems and smart cities to be successful, people need to think and act differently and get more involved in city life. Active communities that can aggregate the distributed knowledge of each individual and can complete synergistic actions to improve the city services are essential.

Technology today allows for distributed computing and crowdsourcing, sharing information among users, and building a collective intelligence. Collective intelligence is one of the keys for the success of CPSs and smart cities. Collective intelligence uses the crowdsensing for the cooperative monitoring of the urban environment. It also targets cooperative actuation of operations to perform tasks of general interest in an efficient way.

From the technical perspective, many hard challenges must still be solved, at least in an efficient and industrially applicable way. Some of the challenges are:

- **Data heterogeneity.** Data heterogeneity is a significant issue that can affect communication performance and the design of communication protocols. Systems need to be able to support a great number of different applications and devices.
- **Reliability.** CPSs are suitable to use in critical contexts like healthcare, infrastructure, transportation, and many others. Reliability and safety are basic requirements because of how actuators affect the environment. In fact, the impact of actuators can also be irreversible, and therefore the presence of unexpected behavior must be minimized. Moreover, the environment is not predictable so CPSs must continue to work under unexpected circumstances and adapt themselves in case of failures.
- **Data management.** It is necessary to store and analyze big data from different connected devices, process them, and show real-time results. Data can be managed by using offline or online stream processing in relation to the goals of the system. In particular with an online stream, information can change frequently with real-time conditions and are based on adaptive and continuous queries.
- **Privacy.** The challenge is to balance privacy concerns and personal data control, with the possibility to access data to provide better services. Because CPSs manage large amounts of
data, including sensitive information like health, gender, religion, and many others, significant issues about data privacy are raised. CPSs require privacy policies in order to address privacy issues, thus a data anonymization management tool is required to have anonymized information before the system processes it.

- **Security.** CPSs must ensure security during communications because all actions among devices are coordinated in real time. As CPSs expand and increase interactions between physical and cyber systems, security problems affect more CPSs. Traditional security infrastructures are not enough to address the issue and new solutions must be found. Security issues are critical on new data and stored data that was collected for future use. Lastly, CPSs are based on heterogeneous applications and wireless communications, which often raise critical security issues.

- **Real-time.** CPSs manage large amounts of data that is derived from sensors. The computations need to work efficiently and be timely, because physical processes keep going independently from the results of the computations. To satisfy this requirement, CPSs must ensure that they have the bandwidth or system capacity needed to meet time-critical functions because failures on time of actions can cause permanent damages.

## Conclusion

We must embrace the technological evolution that the Internet of Things, and CPSs in particular, bring to our every day lives. These technologies will increase the quality of services and ultimately benefit the environment as they are implemented in smart cities throughout the world.

CPSs, as a driver of innovation, involve many different disciplines. Industries as a whole have the opportunity to turn CPSs into an industrially applicable field. Moreover, CPSs require a highly skilled workforce, promoting collaborations and iterations between industries and universities. Finally, CPSs have a huge potential to change and improve every aspect of peoples' lives, addressing critical challenges for our society and exceeding today's distributed systems in security, performance, efficiency, reliability, usability, and many others.
Related topics

- Read the IBM WebSphere Developer Technical Journal series on "Smarter Planet solutions with Sensor Monitoring"
  - Part 1: Building solutions using WebSphere Sensor Events
  - Part 2: Sensor solutions for a smarter supply chain
  - Part 3: Building a smarter medical device monitoring solution
  - Part 4: Asset tracking for process optimization
- Review this developerWorks article, "Smarter city data model standards landscape, Part 1: Core."
- Review the IBM Smarter Cities case studies.
- Read the IBM Redpaper "The Interconnecting of Everything" to learn more about the Internet of Things.
- Review the following websites on Smarter Cities:
  - Smarter Cities (from A Smarter Planet)
  - Smarter Cities for smarter growth

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