



Physical-Cyber-Social Computing: Looking Back, Looking Forward

In the last 30 years, the vision to connect all computers and devices over a global network and the idea of sharing and connecting various contents and types of data using hyperlinks, as promulgated by Tim Berners Lee, profoundly impacted our lives. Building on this premise, in the last 15 years we connected different humans and their information to this Web to yield a composite Cyber-Social Web. Emerging trends in the Internet of Things (IoT) and mobile technologies show the value of connecting these cyber and social webs with *physical world objects* and embedding them into various applications and daily life activities. The interconnection of physical, cyber, and social data and services lets us break free of the realms of the cyberworld, and augment or interact with physical and social phenomena and real-world objects. Opportunities abound for combining and augmenting data into useful applications that help with our surroundings. For example, in a hurricane scenario, someone might wonder,

Are my family members in safe locations? What is the safest route to pick them all up and go to a shelter location? And in more of a day-to-day scenario that same person might wonder, Which is the nearest restaurant rated with four stars by my friends?

These applications need an awareness of the *physical world*, such as the location or current outside weather condition, the *cyber* information sources publicly available (for example, Wikipedia), and the surrounding *social* context or record of interactions on social media. To support these applications, physical-cyber-social (PCS) computing is defined as a framework that “takes a human centric and holistic view of computing by analyzing observations, knowledge, and experiences from physical, cyber, and social worlds” (<http://wiki.knoesis.org/index.php/PCS>).¹ Essentially, PCS computing provides multiple applications in domains spanning from emergency response to healthcare, security, tourism, and everyday living. Examples of PCS applications

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that drive societal growth range from finding the nearest available emergency services, to recommending the best pizza parlor in the city, to determining the most suitable vacation spot. This special issue highlights additional PCS applications, such as smart firefighting, intelligent infrastructure, and user guidance in an airport.

The IoT and Web of Things are among recent terms referring to the general concept of communication and interaction between devices, people, and physical objects. Complementing this communication and interaction is the growth of facts and knowledge on the Web, which includes

- outcomes of collective intelligence – human-authored and curated high-quality descriptive and factual information (such as *Wikipedia*);
- high-quality structured data and knowledge, such as open government data repositories and Linked Data on the Web and freebase; and
- the ability to extract high-quality facts and knowledge from unstructured and semistructured sources, as demonstrated by systems such as Yago (www.mpi-inf.mpg.de/departments/databases-and-information-systems/research/yago-naga/yago), and Never-Ending Language Learning (NELL; <http://rtw.ml.cmu.edu/rtw/kbbrowser>).

By integrating physical, cyber, and social computing into one unified holistic framework, PCS applications are at an intersection that wouldn't be possible in siloed forms of computing that only focus on one or two of these facets. This unified perspective brings multiple research and design concepts to the fore. The early work in the IoT domain started with RFID and wireless sensor networks and projects and initiatives that targeted building the underlying protocols, hardware, and software components, and extending and enhancing existing communication networks to enable interaction and communication between physical and cyber worlds. The work in the IoT domain has gained great momentum and interest from industry and academia, with several initiatives such as the European Research Cluster on the Internet of Things (www.internet-of-things-research.eu) and Industrial Internet Consortium (www.industrialinternetconsortium.org); and the social and human aspects of the IoT and cyber-physical systems also are becoming more perceptible. Although this area of work still needs more R&D and standardization, the underlying hardware, software, and communication

networks in the IoT are advancing to provide industry and real-world services and applications. The human-centric aspects of IoT and cyber-physical systems utilize social and crowd intelligence as well as data and service computation, providing scalable PCS computing solutions that can deal with volume, variety, velocity, and dynamicity of the data and service. These are key components in generating the next wave of IoT developments.

IoT and Social Systems

With billions of deployed sensors, mobile phones (which can also function as real-time, personal, location-aware sensors), wireless devices, and satellites, today's systems can observe signals from almost every person and place on planet Earth. Building upon observations and interpretations of data, occurrences, and events related to different real-world phenomena and using cyber-social information, it's possible for cyber-physical systems to respond to individual applications and users' needs while still balancing societal context in real time. However, we also must take into account the issue of privacy, security, and trust (and the risk of infrastructure failure) to design reliable and dependable solutions for business, public, and personal services and applications.

Building such PCS systems requires two fundamental capabilities. First is the ability to combine heterogeneous data and services provided by devices via various communication networks and Internet/Web services – satellite data, weather maps, traffic systems, healthcare records, and financial networks – to obtain geotemporal situations. Second is the ability to integrate real-world data/services, crowd intelligence, and existing knowledge on the Web into actionable-knowledge that the system uses for automated decision making or that it gives directly to individual users and applications. Then control mechanisms can use this personalized information to respond in (near) real time to users' various needs in various domains.

The proliferation of sensing and actuation devices means that computing systems need not restrict themselves to the cyber trails/partial reports of people's actions (for example, tweets, surveys, or yearly medical check-ups) but actually work with real signals, coming in (near) real time, from the real world via the user's mobile and other devices. These signals coming from all parts of the world can be "reality mined"¹ to build an accurate understanding of the "pulse of the planet,"² as well as social structures to undertake (near)

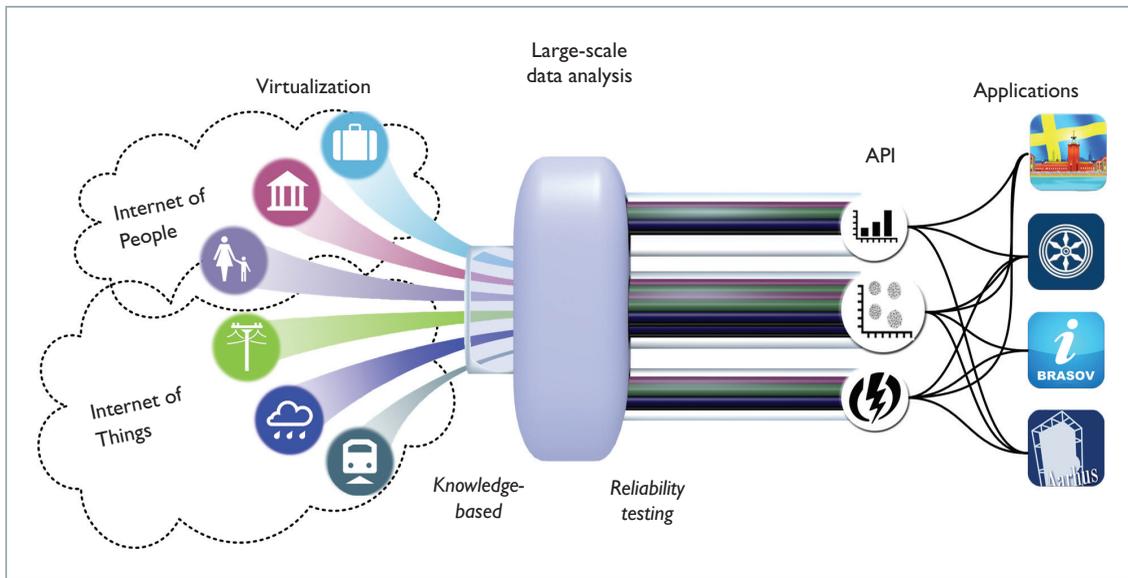


Figure 1. Using physical-cyber-social data for smart city applications in the European Union Seventh Framework Programme’s CityPulse project. (Copyright for this image belongs to the CityPulse consortium.)

real-time control actions. Thus, emerging PCS systems will interpret the social structure surrounding each user, be aware of upcoming situations, and combine them to provide (near) real-time actionable information and services to the user or end device. For example, the European Union Seventh Framework Programme’s (EU FP7’s) CityPulse project (www.ict-citypulse.eu) uses the IoT data (collected by sensory devices) and social data (collected from social media, such as Twitter) to provide actionable information for various smart city applications. Figure 1 provides an overall view of the project’s concepts.

Challenges and Opportunities

Clearly, realizing the vision of PCS systems relies heavily on the existence of emerging “Big Data.” Such large amounts of information have been encountered by humans in other contexts. The human eye has millions of receptor cells that are organized in several layers over the retina.³ These cells can capture a massive amount of information – but if the cells send all this data to the brain, the human brain is unable to process all of it. Thus the eye uses complex selective attention and filtering processes to decide which part of the data should be sent back to the brain at a time. This is then followed by our brain’s perception capabilities. Biological systems seem to have better mechanisms to deal with Big Data compared to technologies in the digital world.

In the digital era, the more advanced that devices, sensors, and observation and data collection tools become, the more data are gathered and made available. Data overload is becoming a key problem in our daily lives in terms of handling, processing, and making use of Big Data. New advancements in nanoelectronics, sensor- and device-manufacturing technologies, and communication networks provide a unique opportunity to create digital representations of objects and various phenomena in the physical world. Utilizing various sensing, actuation, and computing technologies allows integration of physical and cyber systems. Network-enabled sensing and actuation devices can connect to the Internet and send data or interact with different users, applications, and services, or with other devices. Sometimes these interactions and data exchanges are autonomous or controlled by a human user. The Internet and Web and the rapid growth of mobile technologies and smartphones have also enabled the creation of various social networking technologies that allow people and devices to connect and interact with each other in the cyberworld.

Hence, in the coming era, selecting appropriate data sources, filtering information, and reducing the cognitive load will become critical components of the process to build smart PCS systems. Semantic technologies and automated approaches towards integrating multiple modalities are essential for solving practical research challenges. Current

research is making excellent progress in biology- and neuroscience-inspired computing that make raw data more meaningful to machines, and also to humans without overloading their cognitive and decision-making capabilities.

Emerging PCS systems need coordination and interaction between different communication, network, and computation components; this won't be like conventional processing and computation on the Internet, which isn't dependent on how and where data are collected. Instead, now the data costs energy and network bandwidth to be collected, and multiple sources can provide similar data but with various qualities, granularities, and trust. The data providers' and communication networks' latency and reliability, as well as computational complexity and efficiency, will have a direct impact on real-time PCS services and applications. We need selective attention (like the human eye) and smart collection mechanisms to effectively use the data and services in the PCS systems.

Smartphones' and ubiquitous devices' growing computational capabilities help us handle many processes, such as aggregating and abstracting raw data on-device or in-network before transmitting and sharing over the cloud. Computing at the edge and dynamic balancing between on-device, in-network, and cloud computing processes are among key challenges to develop efficient solutions for PCS computing. Developing adaptive methods and solutions to deal with the dynamicity of the environments and providing adequate data and service qualities are also among the challenges in PCS systems.

In dealing with volumes of data, so far most of the focus has been on high-performance computing and large-scale data handling solutions; however, PCS systems will need better machine learning and processing solutions for dynamic and streaming data that are provided by multiple heterogeneous sources.⁴ They'll also need a combination of textual, multimedia, and numerical data and solutions such as deep learning, adaptive algorithms, and multiview learning, to observe the same phenomena from multiple perspectives and interpret situations holistically. Creating common (semantic) description frameworks for the data and underlying resources in PCS systems (for example, the Semantic Sensor Network [SSN] ontology⁵), and also providing and sharing use-case scenarios and reference datasets and common practices will help the research and developer community build upon existing solutions and

ideas, implement interoperable solutions, and test and evaluate solutions' effectiveness based on common key performance indicators (KPIs). For example, the CityPulse project identifies a number of common use cases for smart city applications (101 smart city use cases: www.ict-citypulse.eu/scenarios) and the project provides a collection of large datasets (CityPulse dataset collection: <http://iot.ee.surrey.ac.uk:8080>) that researchers and developers can use in the smart city domain and other areas for developing and testing applications that rely on cyber-physical and social data.

In This Issue

We see several of the themes that we discussed reflected in the three articles in this special issue. These articles clearly convey the impact that combined physical, cyber, and social data and services can create in cross-domain applications, ranging from smart firefighting to airport guidance. They also point to the early but crucial steps towards tackling some of the aforementioned research challenges, including sensor selection, semantic integration of data sources, and limited computational resources.

The first article in this special issue, "Dynamic Social Structure of Things: A Contextual Approach in CPSS," focuses on defining an adaptive smart services framework that hides heterogeneity in the infrastructure and supports service visibility based on the seamless integration among physical, cyber, and social worlds. Essentially, Dina Hussein and her colleagues propose a novel smart services framework in CPSS to boost sociality and narrow down the contextual complexity based on situational awareness. In their proposed Dynamic Social Structure of Things (DSSoT) approach, within a given spatiotemporal situation and based on the individual goals and various other social aspects of users, the framework induces and structures relevant social objects and smart services in a temporal network of interactions. The authors provide a use-case scenario of guiding a "lost user" in an airport as a concrete example of the approach's utility.

Next, in "Matching Over Linked Data Streams in the Internet of Things," Yongrui Qin and his colleagues focus on the important problem of disseminating data to relevant data consumers efficiently. Their work leverages semantic technologies, such as Linked Data, which can facilitate machine-to-machine communications to build an efficient information dissemination system for Semantic IoT. Defining a new data structure, they ground the

system implementation and experiments in a Smart Building IoT Project. The proposed system can disseminate Linked Data at the speed of 1 million triples per second with 100,000 registered user queries, which is several orders of magnitude faster than existing techniques.

Finally, in the third article, “Humans’ Critical Role in Smart Systems: A Smart Firefighting Example,” Albert Jones and his colleagues question the foundation of the notion that “smart” somehow requires autonomy to overcome troublesome human errors. The authors believe that humans will play critical roles in such smart systems – particularly when it comes to such systems’ resilience. All existing smart systems have interacting autonomous, human, and organizational control agents – all with predefined boundaries. This means that each agent’s cognitive abilities are both finite in terms of computational resources and constrained by the model of the system that they control. Using the smart firefighting application as a grounding example, the authors discuss how humans will play critical roles as active agents in the operation and evolution of PCS systems.

Overall, this special issue provides concrete evidence of this field’s progress, as well as real-world applications in this nascent research area. A report from the Dagstuhl seminar held on this topic provides complementary information.⁶ It’s apparent that IoT and PCS systems will have significant impact on multiple areas of human lives – ranging from healthcare, entertainment, retail, urban living, and day-to-day activities to industry applications and emergency relief. ☐

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