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Geo CPS: Spatial challenges and opportunities for CPS in the geographic dimension

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ABSTRACT

Recent advances in the Internet of Things (IoT) have brought great opportunities for geographical information systems (GIS) to be integrated with cyber-physical systems (CPS) in urban management. However, the term IoT and CPS are new in the GIS realm. This article reviews the concepts of IoT and CPS from the perspective of geospatial spaces and proposes the concept of Geo CPS to develop the potential of new technology in the geographic dimension. Two forms of Geo CPS are discussed: pseudo-CPS (PCPS), which projects spatial data onto a display without interaction among data sources, and true-CPS (TCPS), which handles data sources deeply and semantically. While PCPS already has wide industrial applications, TCPS is still in its infancy. The spatial challenge for CPS in geo space involves operating conditions in an open environment, and here, the human-machine system interface will be key. A transformation of our mindset relating to GIS can lead to the creation of new value-added geographical information services. This will require new schemes and platforms for data sharing, processing, security, and privacy, etc.

1. Introduction

Geographical information is essentially an integration of information on position with attributes as often expressed by *position + attributes* where the symbolic “+” denotes the relational connector in a relational database. The acquisition of attributional information has been reliant upon indirect approaches such as long-term statistics, field surveys, and image recognition, etc. The attributional information such as this is discontinuous on the time scale and it is typically compiled to a specific spatial unit, so it often lacks geographical and temporal accuracy. The proliferation of mobile devices is transforming this situation. It is becoming possible to continuously track when, where, and how people and objects appear and move. In this context, significant advances have been made with the use of location sensors and other devices enabled to be part of IoT, the Internet of Things. IoT connects people and things to networks. With location and time associated, it then becomes possible to continuously accumulate information in the cloud regarding the presence, movement, and status of people and things. From there it becomes possible to learn behaviors and extrapolate trends, to consider what was there previously, and to predict what might happen next (Bosch, 2018).

Location sensors themselves are nothing new for the “geo-family.” There has been a tremendous amount of activity with global navigation satellite systems (GNSS). GPS (United States) and GLONASS (Russia) have been around for half a century, and recent newcomers include BeiDou (China), Galileo (European Union), and QZSS (Japan). Even in indoor spaces that GNSS cannot reach, radio-frequency identification (RFID), Wi-Fi positioning and pseudo-GPS systems have been developed to enable positioning in

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underground spaces, and applications have been found in fields such as orientation, logistics and disaster prevention (Bekkali, Sanson, & Matsumoto, 2007; Gu, Lo, Member, & Niemegeers, 2009; Huang, Lee, Ho, Wu, & Lai, 2015; Liu, Member, Darabi, Banerjee, & Liu, 2007).

Location-aware IoT is referred to as Geo IoT (Kim, 2017), and it is attracting attention as a core technology of what is being called the Fourth Industrial Revolution, enabling cyber-physical systems (CPS), which integrate physical world systems with cyber world systems. Such CPS seamlessly transacts back and forth in cyber and physical spaces, and has the capacity to monitor the environment, control machines, and support human decision making in sophisticated ways (Okumura, 2017). Industry has moved quickly responding to the trend. The Geo IoT World Conference has been organized since 2016 in Brussels, and was held in North America in 2019 for the first time at the Geo IoT America Conference in San Francisco (www.geoiotworld.com). Some industrial Geo IoT solutions are available on the Internet. GISinc provides a Geo IoT platform to integrate smart devices and equipment that are able to communicate using a Wi-Fi, Bluetooth, or Li-Fi network integrated into indoor or outdoor LED lighting infrastructure (<https://www.gisinc.com/>). Ubisense runs a SmartSpace platform to integrate Geo IoT products for manufacturers and transit management strategies (<https://www.ubisense.net/>). However, these commercial platforms are developed for specific services, while the ability of context-aware technologies is still limited. Rubio et al. (2018) proposed a common-sense reasoning system with indoorGML for modeling buildings using semantic relationships and context management.

What we call “context” here is a condition or circumstance that is relevant to an event, a fact, or an object, etc., in the geospatial world. To be context-aware a system must be sensitive to ambient conditions and able to respond to change sensitively. This calls for a seamless integration of sensing, processing and actuation (SPA) in cyber and physical worlds (Spillman, 1996). Considering the complexity of the conditions in spatial and temporal dimensions, SPA will not be a simple extension of existing systems. Instead, it requires a transformation of conventional industries, including geospatial technologies. Kim (2017) has identified core research areas relating to spatial, location, and sensor data for Geo IoT in the context of smart cities: acquisition, storage, analysis, disclosure, and service. Meanwhile, CPS has been widely discussed in manufacturing, driverless driving, and engineering, etc. However, because of differences in their roots, the terms themselves as well as their connections in the cyber and geophysical worlds have not yet been discussed extensively.

This paper reviews the state of the art of IoT and CPS and clarifies the characteristics of the technology from the perspective of geo space. We examine system architecture, possible applications and future challenges for CPS in the geographic dimension.

2. Thinking spatially about IoT and CPS

2.1. Definition of IoT

The roots of IoT can be traced back to RFID and ubiquitous computing in the early 2000s. Srivastava (2006) defined IoT as a concept of connecting: “anytime, anywhere and any media (3A), resulting into sustained ratio between radio and man around 1:1.” Networked Enterprise & RFID & Micro & Nanosystems (2008) defined IoT as “Things having identities and virtual personalities operating in smart spaces using intelligent interfaces to connect and communicate within social, environmental, and user contexts.” The semantic meaning of IoT is considered to be a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols. Such a developed IoT will be “a global infrastructure for the information society enabling advanced services by interconnecting (physical and virtual) things based on, existing and evolving, interoperable information and communication technologies” (Cosmas, 2015). Kranenburg (2008) described IoT this way: “A dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual ‘Things’ have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network.” In general, the services of IoT will involve three types of interaction: (1) people to people, (2) people to machines/things, and (3) things/machines to things/machines, interacting through the Internet (Patel & Patel, 2016).

From these descriptions we can see that definitions of IoT range from the mention of devices to networks, communication, and more broadly, a global network infrastructure supporting communication in virtual and physical worlds. The power of IoT relies on the ability of objects to sense, connect, and communicate. Eventually, IoT could evolve into the “Internet of Services (IoS) to control the global networks for business purposes” (Jamaludin, 2018). Therefore, IoT is considered to be a key technology in a new industrial revolution, as we can see in Industry 4.0 (Germany) and Society 5.0 (Japan).

Geo IoT includes a spatial component and refers to location-aware IoT (MindCommerce, 2016). It supports the acquisition, management, analysis and visualization of data generated in geophysical environments. Just as location determination has become an essential element of communications, presence detection and context-aware technologies will become keys to the long-term success of IoT. However, discussions so far have tended to focus on sensing devices and networks, and have paid less attention to mechanisms for incorporating context dimensions into processing, as well as dynamic spatial models that provide appropriate services to users acting in the environment. That part of the functions is largely the role of CPS as discussed below.

2.2. Definition of CPS

The term “cyber-physical systems” can be traced back to a position paper by Branicky, Cenk, and Liberatore (2001), who proposed research to merge the cyber and physical worlds at a fundamental level in highly interconnected cyber-physical systems in which components interact asynchronously at event times. However, further development of the concept had to wait until 2006 when it was highlighted by Helen Gill of the National Science Foundation in the United States (Lee, 2006). The US President's Council of Advisors

on Science and Technology (PCAST) placed CPS at the top of the priority list for federal research investment in 2007 (Sha, Gopalakrishnan, Liu, & Wang, 2008), and this initiative was followed by the European Union's ARTEMIS (Advanced Research and Technology for Embedded Intelligence Systems), Japan's Society 5.0, China 2025, South Korea's Industry 4.0, and Germany's Industry 4.0 etc.

Generally speaking, CPS is a fusion of the cyber world and physical world and can be characterized various ways: "Physical and engineered systems whose operations are monitored, controlled, coordinated, and integrated by a computing and communicating core" (Monostori et al., 2016). "CPS perceive the physical world, process the data by computers, and affect and change the physical world" (Hu, Xie, Kuang, & Zhao, 2012). Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa. "Cyber-physical systems (CPS) are complex systems with organic integration and in-depth collaboration of computation, communications and control (3C) technology" (Lee & Seshia, 2015; Liu et al., 2017). CPS is expected to be a transformative technology for managing interconnected systems between physical assets and computational capabilities (Baheti & Gill, 2011).

The interaction between the physical and cyber worlds is of key importance: CPS is about the intersection, not the union, of the physical and the cyber (Rajkumar, Lee, Sha, & Stankovic, 2011). It is not sufficient to separately understand the physical components and the computational components. We must understand their interaction. "By the integration of physical processes with computation and communication in cyber space CPS has the ability to add more intelligence to social life. Wireless sensor networks (WSN) can be a vital part of CPS as strong sensing capability is one of the major driving factors for CPS applications" (Haque, Aziz, & Rahman, 2014). These definitions describe the functions of CPS, sensing, computation, communication, collaboration, and controlling, etc. The commonality of the above definitions is the transaction between the cyber world and physical world. "CPS requires the close interaction between the two distinct worlds. The interactions involve the discrete dynamics in the cyber space and the continuous dynamics in the physical space" (Shen, 2015).

The functionality of CPS relies on sensitivity to context. High performance is the result of advances enabling seamless interaction between the cyber and physical worlds. This involves challenges for CPS in SPA, and CPS overlaps with IoT in dealing with SPA. So far, research into CPS has been partitioned into isolated subdisciplines such as sensors, communications and networking, control theory, mathematics, software engineering, and computer science. "CPS research is still in its infancy," as Baheti and Gill (2011) stated. Professional and institutional barriers have resulted in narrowly-defined, discipline-specific research and education venues in academia for the science and engineering disciplines. All these considerations are especially important when applying the technology to the geospatial world.

2.3. The spatiality of CPS

CPS is spatial. Rooted in factory automation, CPS has been studied in manufacturing that demands highly accurate operation. On the other hand, driven by the progress of GNSS and indoor positioning, for IoT more attention has been paid to sensing and tracking objects in an open environment. The prevalence of mobile devices bridges the two streams together, adding the spatial dimension to CPS, ranging from indoor systems to outdoor conditions. We have seen achievements in engineering projects where CPS works in closed conditions. Typical examples can be found in smart electric power grids, Intelligent Transportation Systems, urban utilities (gas, waterworks, sewage), manufacturing systems, aerospace systems, and defense systems, etc. These examples are considered to be traditional CPS (Guo, Hu, & Hu, 2018), where inputs and outputs of the systems are uniquely programmed, and communications are operated linearly so that the system is bounded and secured. Position and attribute in such a system are usually programmed separately as independent variables and treated as *position with attributes* in conventional geodatabases and GIS.

The evolution of mobile devices and IoT is changing the industrial map of information technology, from closed to open systems. One of the hottest and most advanced technologies today may be the driverless vehicles driving in open environments. Emerging CPS can be observed in efforts to connect vehicles and smart cities in large geographical areas. Open systems work in broader spaces, which means very different conditions from closed systems, in the sense of security, energy consumption, mobile dynamic environment, and system stability. Guo et al. (2018) discussed three areas for applications of mobile CPS: vehicular networking systems, healthcare systems, and mobile education. A key feature of CPS in geo space is the free flow back and forth of SPA between IoT sensors, communication networks and cloud servers, where position and attribute are no longer only independent variables. Instead, either position or attributes could be an input to predict the other dynamically. The objective of using position and attributes is to control the behavior of the CPS in real time rather than accumulating them into a relational database. In this sense, in this paper we express the relationship between position and attribute as "position \times attribute," (multiplicative) instead of the conventional *position + attribute* (relational), where " \times " expresses more sophisticated processing and interactions among factors.

When CPS is spatialized in the geographic world we refer to it as "Geo CPS." Revolutions are also occurring in fundamental layers of this technology. CPS is leaving the laboratory, going out into society, and raising critical issues in the geographic space. For instance, smart electric power grids are transforming into open systems that can accept distributed renewable energy sources; waterworks may be integrated to include independent well or rooftop tank systems; driverless vehicles must simultaneously respond to traffic conditions; healthcare robots must communicate with patients according to their conditions. The synergy effects of position and attributes present both opportunities and challenges in CPS.

Geo CPS is also special. The physical world outside the laboratory is much more complex than inside and comes with a high degree of uncertainty. These open conditions call for advanced specifications in system design, power supply, and protocols for real-time communication. These systems are increasingly distributed and interconnected. They are often safety-critical, so existing techniques focus on reducing latency to provide real-time performance. While low latency is useful, a shared and precise notion of

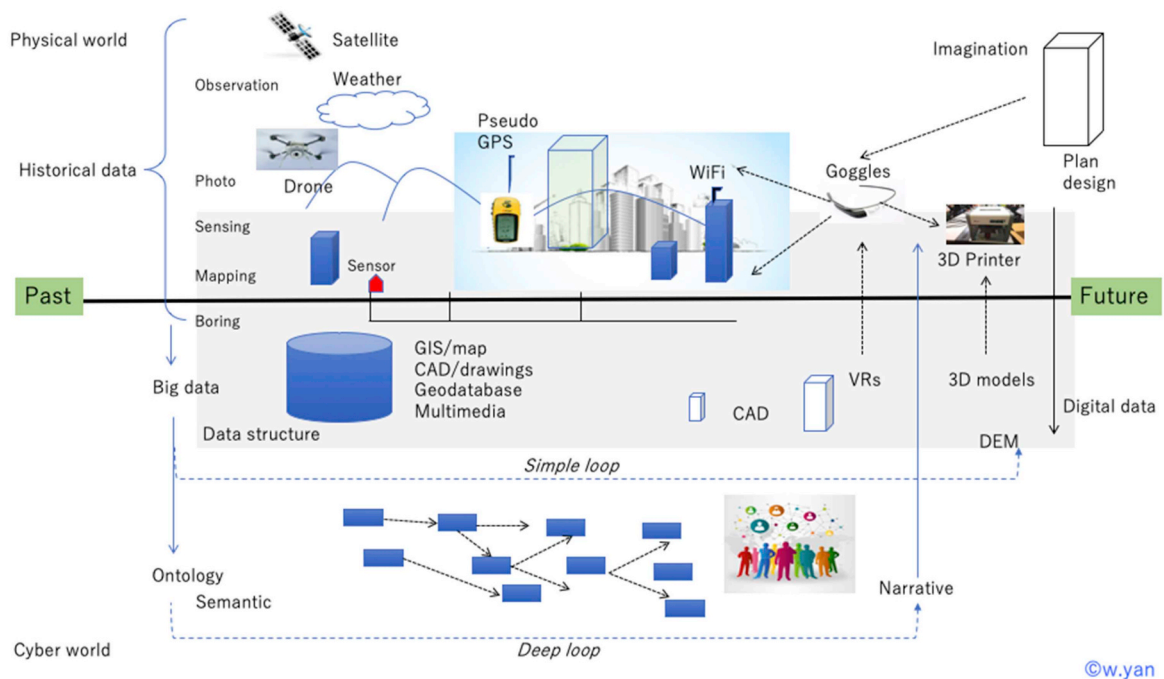


Fig. 1. Concept of the integrated IoT and CPS (prepared by author).

time is key to enabling coordinated action in distributed CPS. From this perspective, [Sandeep and Rajkumar \(2017\)](#) argued for a global Quality of Time (QoT)-based architecture, centered around a shared virtualized notion of time, based on the timeline abstraction. [Dai, Wang, Jin, and Ma \(2018\)](#) designed a Quality aware Truthful Incentive mechanism for cyber-physical enabled geographic crowd-sensing called Geo-QTI. Different from existing mechanisms, Geo-QTI appropriately accommodates the utilities of various stakeholders: requesters, participants and the crowdsourcing platform, and explicitly takes into account the requesters' quality requirements and participants' quality provision. Therefore, Geo CPS is not a simple extension of CPS from manufacturing factories. It brings new capabilities that not only support 3D geometric modeling of environments and buildings, but can also describe how the environment evolves based on interactions among the entities in the environment, and can enable more sophisticated reasoning processes ([Rubio et al., 2018](#)).

3. Integration of IoT and CPS in geo space

The concept of the integrated IoT and CPS is illustrated in [Fig. 1](#). A physical world is an objective space surrounding us, while a cyber world is a subjective one built by computational recognition and models. This figure illustrates the flow of information between cyber and physical worlds in geographic dimensions, rather than devices as typically described in conventional literature.

In the physical world, satellite images and ground observation data are accumulated in a cyber database. That data is managed, analyzed by geographic information systems (GIS), modeled with computer-assisted design (CAD), rendered by virtual reality (VR) and digital elevation modeling (DEM), and then reproduced as a model or actual object by 3D printing, etc. Alternatively, the output could be projected to the physical space with tools such as goggles, digital glasses, or drones, and used for decision-making or taking action. This is the simple loop as indicated in [Fig. 1](#) that has been realized by integration of various devices.

The emergence of IoT has rapidly accelerated the cycle of observation, accumulation, processing and reproduction, and precision has been largely improved. Rather than sensors only, IoT is all about connections ([Ray, 2018](#)). We would like to say that CPS is about services. Having people connected to the Internet is like having a vast brain in the cyber world, external to the brains of living things. CPS provides a means for us to look back at the past and look forward into the future, supported by various devices and deep learning machines in addition to location sensors and communication sensors. With such features, a cyber-physical system can be created not only for the integration of IoT devices but also for multimedia content.

CPS is seen as a means of coming to grips with the static and dynamic spatial relations between and among the two worlds. The functionality of CPS will be built on the ability of sensing, cognition and mapping of the physical space deployed in a specific context. Sensing is the technology to recognize the static and dynamic situation of the physical world, cognition is applied to understand the ways in which the "world" works, and mapping is for rebuilding the physical "world" in cyber space. The context where IoT and CPS work is a multi-dimensional world in which space-time could range from microscopic to astronomical scales. The domain of concern and therefore the nature of space are defined by a particular problem. The solution to the problem will rely on our understanding of the nature, structure, and function of phenomena in the physical world. The performance of CPS will be largely determined by the

ability of systems to process, analyze, and represent the vast amount of data that is gathered and stored through IoT. With the advent of computers and scientific instrumentation, we have gone from a problem-rich, data-poor world to one that is both data-rich and problem-rich, but currently lacks adequate capacity to bring data to bear upon problem-solving. We are harvesting the achievements of this progress through real-time interactions of cyber and physical spaces, in areas such as navigation, on-demand delivery, and facial recognition, etc. However, we have not yet reached the point where that kind of data can be used at the much deeper level of cyber-physical spaces. The full development of such technology requires a deep loop in Fig. 1, learning and design in data and knowledge, dynamic transactions in real time between the two spaces at semantic levels, and sophisticated function of narratives.

On the other hand, as illustrated in Fig. 1, the physical world in the past is observed, converted and stored in the cyber world as images, texts, photos and maps etc. CPS is often considered a system to regenerate digital content in the cyber world for visualization of the physical world so that we can use the visualization to learn from the past and look into the future. Therefore, time is also a critical dimension. The functionality of CPS depends on the accumulation of data sensing in the cloud, the capability of learning and processing within the system, and the design of the system architectures. Currently, there are two architectures in Geo CPS to realize information integration: layer-stack based pseudo-CPS, and content integration-based true-CPS. Next, we will look at information integration and system architectures for each of these.

4. The architecture of Geo CPS

4.1. Pseudo cyber-physical systems (PCPS)

Pseudo CPS achieves information integration visually by using the position of IoT as a key to overlay real time observations onto the cyber space provided from providers. Car navigation is one example of this. The GNSS system obtains the location, which is displayed on a digital map provided by DVD or internal HDD, and the user sees the current location. Road traffic information is sent with a delay of a few minutes via vehicle information and communication system (for instance, VICS in Japan), and that is displayed on the monitor. That information is in a separate layer, not incorporated into the map data. A similar technique can be seen with augmented reality (AR) (Khalid, Fathi, & Mohamed, 2015). It is integrated to look as though a simulation or an image in cyber space is superimposed on the physical space.

With PCPS, information providers digitize and create dimensional layers of the physical world to create a defined cyber world. System integration is done by superimposing the layers. Each of the layers could come from different providers, and if they all conform to data exchange specifications, pseudo integration can be achieved. Users are outside the system, and the information flow is one-way from the provider to the user's device. In PCPS, there is a time offset between the actual status in the physical world and each layer of the cyber world. Changes in the physical world are not immediately reflected. Only rarely is there direct communication between layers of the cyber world. The system performance, in particular the interpretation of information, depends on the user's proficiency.

This kind of pseudo CPS has been widely realized and applied. Doctors can provide telemedicine while they observe a monitor. Space centers can control a space station while watching monitors. Disaster response headquarters can make emergency response decisions while observing a large screen that combines information from multiple locations and departmental functions. Traffic management centers can monitor road conditions in real time.

PCPS combines and links together the components of the information system. People play a key role as operators and contribute much to efficiency improvements. Meanwhile, there are issues. For example, operator training takes time, systems may not be well suited to strategic decision making, and systems might be partially optimized but not necessarily result in improved overall productivity.

4.2. True cyber-physical systems (TCPS)

To get a sense of true-CPS, it is worth considering various initiatives being undertaken to bring on the next industrial revolution. Among the national initiatives we can find visions of true-CPS (TCPS), aiming at true integration of cyber and physical systems. TCPS uses IoT online to obtain and monitor vehicle position, traffic conditions, and the peripheral environment in the physical world, process everything in real time in the cyber world, conduct integrated analysis for any layer, and actuate people and moving objects. That could be called a true cyber-physical system. Driverless autonomous driving is a good example. TCPS could be presented in various ways, but Gubbi, Buyya, Marusic, and Palaniswami (2013) illustrated a basic architecture as shown in Fig. 2. On the left side, various IoT devices obtain information from the physical space and provide it to the cloud via network gateways. On the right side, the database, scheduling and resource optimization functions are all handled in the cyber space. These functions are connected with the physical space in real time. This could be seen as a typical architecture for the deep loop in the conceptual framework of Fig. 1.

It is crucial to have a common operating platform in order to be able to connect IoT devices to the network. For that, one solution is the Urban Operating System (UOS) (Living PlanIT: <http://www.living-planit.com>). This operating platform is organized with four layers: sensor/actuator, supervisory, control and application. The sensor/actuator layer contains various devices in the physical world. Their information is aggregated locally and delivered to the Internet in real time. The supervisory layer organizes data sources, conducts analysis and simulations, and provides that to the application layer. IoT devices are monitored and controlled at the control layer. UOS is considered a business solution rather than a commercial package. As an application, Hitachi Ltd. has applied the system in large-scale development projects.

The concept of UOS is city as a computer, and in that scenario an IoT input/output device is like a driver connected to the operating system and controlled in real time. Meanwhile, while it is ensuring security and privacy the central processing unit also handles monitoring and management, data gathering, analysis, and simulation, and again realizes each type of user service. In order

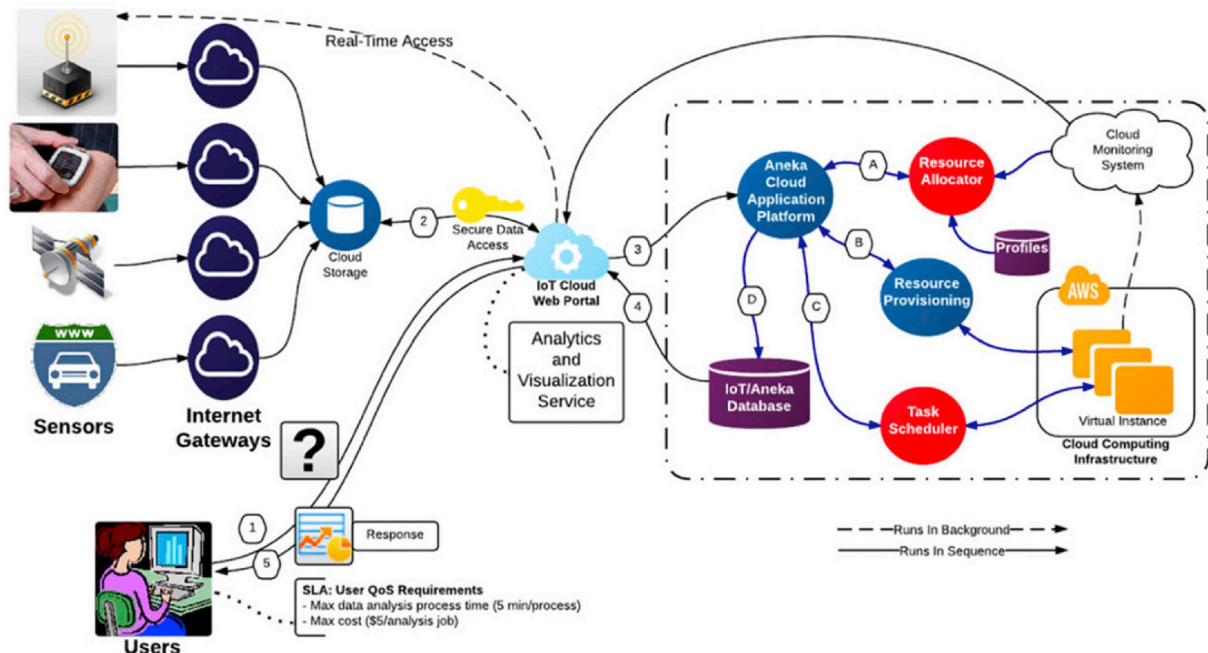


Fig. 2. Front end and back end information flow in CPS (Gubbi et al., 2013).

to accomplish all of this, the system must have shared frameworks such as an aggregator that controls a diversity of IoT sensors and actuators, a protocol to communicate all of that with the cloud, a data sharing structure, and privacy/security assurance, etc. It is the UOS that fulfills all of those functions.

In that scenario we have one computer with a diversity of devices coexisting in an operating system environment, and it enables data acquisition and storage, learning, analysis, and output, etc. The aim of UOS is to realize a similar thing at the city level, working across departments and responsibilities, and conceptually this means truly becoming a smart city. Under the condition of UOS, we could imagine the value being created from connectivity based on a platform by integrated utilization of sensor data from different industries and sectors, as well as public data, and citizen data.

5. Potential applications for Geo CPS

Geo CPS systems are attracting attention as core technologies to create the society of the future. At the building or household level, they are essential for indoor movement, health, entertainment, security, and appliance control. In blocks and neighborhoods, they have functions in smart meters, factories, real estate, environment, research, and marketing, etc. In traffic, mobility, and infrastructure management, there are applications in highways, emergency transport, parking, traffic volume control, and logistics, etc. At the national and city level, there are various applications, including remote sensing, safety and security, smart city, smart grids, utilities, and environmental conservation, etc. Here we will look at some major examples of IoT and CPS in geospatial realm.

5.1. Construction industry and construction equipment

The construction industry involves much outdoor work. In the Japanese market, the emphasis of construction work is shifting to maintaining existing infrastructure. Besides facing the retirement of baby-boomer generation workers, it is also plagued by a shortage of skilled workers. The Ministry of Land, Infrastructure, Transport and Tourism has been focusing on the use of information technology (IT) in the construction industry. i-Construction and CPS are being promoted as keys to improve labor productivity. Construction equipment manufacturers are driving this shift (COCN 2017). Some researchers have proposed a concept of CPS to give a better understanding of the systems and how they can be implemented in the construction industry by integrating them with AR technology to make decisions in real-time. Mobile AR handheld location-aware technology is one potential application utilizing the concept of CPS integrated with the AR approach (Akanmu, Anumba, & Messner, 2013; Mohd, Khalid, Fathi, & Mohamed, 2014).

Komatsu Ltd. has made significant progress with IoT and the automation of power excavators, having developed a product that represents true CPS. Drones are used to conduct basic surveys for civil engineering work and high precision terrain models can be generated in real time. The terrain models are provided as input to the excavator equipment and compared with design data, and the amount of earth to be excavated or filled is calculated. This is then sent directly to the excavator's operating system, and the excavation work starts automatically. If instructions are received while work is in progress, changes can be made in real time. The work record is stored, making it easier to track the history of the work. After completion the drone is sent up again, and completed

drawings are created when this is combined with the work record. This system works automatically and seamlessly, with image sensing by drones, real-time 3D terrain modeling, real-time progress measurement with sensors embedded in the excavators, and work management performed while referring to design drawings. Work that previously could only be done by an operator who had years of experience can now be done after three days of training, resulting in a significant saving of labor and boost to efficiency.

5.2. Water resources and infrastructure management

Water resources include extensive geographical areas from regions upstream to downstream of a river, and administrative functions range from watershed conservation, water rights management, water quality monitoring, and the operations of purification plants and water supply facilities, all the way to water delivery, utility fee collection, and the management of sewer systems, rainwater treatment, sewage treatment, and flood prevention, etc. Because large areas are involved, these tasks often span multiple jurisdictions, each with different departments responsible. These days the water sector in Japan is dealing with increasing risks of disasters due to climate change, decreasing demand due to the shrinking population, and a shortage of engineers due to the aging population, and the burdens of maintaining aging infrastructure are on the rise. Meanwhile, the water supply sector is really a watershed-based system from water source to consumer, and big data is being accumulated in enormous quantities through resource management, infrastructure maintenance and operation, and consumer services. Currently, however, this is all fractured vertically into administrative systems that deal with forests, rivers, water supply, and so on, and their operations information systems are not linked. To address this, IoT is seen with high expectations by the Ministry of Land, Infrastructure, Transport and Tourism, municipalities and water-related utilities and businesses (Wang, 2012). For river management, the traditional system of issuing contracts department by department is being reviewed, and more integrated approaches are being considered. In watershed management, for example, IoT is being tested in an integrated inspection system for Lake Biwa, an important freshwater lake on the island of Honshu. Using tablet computers and head-mounted displays, inspectors and investigators will be able to work with both hands free while referring to work manuals even as they check flood gate conditions during emergencies such as typhoons.

5.3. Environmental conservation and resource management

Environmental conservation and resource management are other areas where CPS has much to offer. GPS is a core technology of CPS. It was originally developed for military purposes, but quickly found other applications such as measurement and environmental surveying (Fang et al., 2014). With GIS an enormous quantity of paper maps was digitized and for the first time we had a computer-based cyber world. Today, Google Earth and other applications are accumulating a vast amount of data in the cyber world from maps, satellite imaging, geolocation, and environmental surveys, etc. We can access digital maps anytime and anywhere via the Web or smartphone. However, whether the map is on paper or digital, these are not the real world but rather, the product of human perceptions of the world. The information therein depicted has a time lag and some abstraction from the map maker is involved, so some limitations arise when it comes to using them in policies and systems, etc. Furthermore, while this huge amount of geographical information and knowledge exists in the cyber world, it can usually only be projected onto two-dimensional screens, so there are constraints in how we can visualize this information. CPS is opening up ways to address these issues.

One example is the Augmented Reality Sandbox system developed by the University of California, Davis. It works exactly as the name suggests, like a sandbox, and has enormous theoretical and practical significance. The system captures an image of a pile of sand and creates a three-dimensional topographic model in real time. Contour lines are instantly created and projected back onto the sand, and the terrain is rendered with colors indicating the elevations. If the shape of the sand is modified, the change is instantly reflected in the 3D model. Changes in a water catchment due to topographical changes are simulated in real time. This tool is easy to use, but it perfectly integrates the physical world and the cyber world, going back and forth easily between the two.

We can find cases where data and knowledge are accumulated in the cyber world and then reproduced in the physical world. Examples of both being done in an integrated manner can be found in museums, information centers, exhibits, and in education, but they are also appearing in environmental businesses. One company in Hohhot City (Inner Mongolia Autonomous Region in China), refers to itself as an ecological environment group (M-Grass, <http://www.mengcao.com>). In just over 20 years it has grown from small local flower shops to become a massive corporation with a chain of businesses in bio-grass growing, urban landscaping, park greening, and post-mining restoration with an emphasis on water, soil, air, people, grass, livestock, and microbes. This company has developed big data from 3000 collected samples of 1800 grassland plant species, 20,000 samples from 2800 plant specimens, and 300,000 samples of soil types from the vast northern arid and semiarid regions of Inner Mongolia. Using this data it created large testing and display facilities outside of Hohhot where it displays plant and soil specimens, products, and successful ecological restoration projects. The company has created a large model to represent Inner Mongolia's soil distribution, and it is connected in real time to GIS data, grassland resource data, and sensor networks at each test site in Inner Mongolia. Customers can specify a location and are then directed to information about climate conditions, endemic grass species, grass best suited for ecosystem restoration, and work methods.

5.4. Accessibility and mobility

In the physical world, it has long been understood that people will appear at specific times and spaces to receive services. However, information technology is changing the flow of people and things, and Geo CPS is changing lifestyles. By being connected with the cyber world through Geo IoT, the location of one spot in the physical world gives rise to a huge array of significance. The key here is the location, combined with the “presence” of a person or object (MindCommerce, 2016). From this presence, it is possible to

have a variety of interpretations—for example, that the person passed through a certain location, that the person appeared here, or that the person utilized the facilities, etc. Also, conventionally, this presence may be seen as nothing more than an instantaneous event, but with CPS it is possible to attach much more profound significance by looking at the time of day, length of time at that location, and frequency of being present there. It is also possible to consider and analyze where, when, and how a person or thing or moving object appeared, and use that information to redesign the accessibility to that mobility, facility, or service.

Take the example of the taxi. The opportunity to provide service arises if a match can be found between a taxi and a (prospective) passenger being in the same space at the same time. Typically, both parties would not know where the matching will occur and had to wait for it to happen. Matching would occur where taxis and users both gather, in locations where the incoming and outgoing human flow is high, such as at train stations, hotels, and bus stops. That would leave some people who wanted a taxi unable to get one. Meanwhile, taxis would drive around without a passenger, wasting time and fuel. Services like Uber eliminate this problem in one stroke based on Geo CPS. When a request is received from a prospective passenger, a car in the vicinity is automatically assigned and immediately sent to the location. During this time the user and the taxi are connected in the cyber world, so the frustration of waiting is reduced and reliable matching can occur. In cyber space there is a dramatic boost in the visibility of the driver and the user, who are both in the physical world.

Another example is package delivery services in Japan. A delivery service is a matching of the time and place of the delivery agent and the recipient. In this industry, the ratio of repeat deliveries on an annual basis is dozens of percent and results in the waste of resources. If one party is not present at the appointed time, the delivery item ends up being sent back for re-delivery at a later time. This is a mismatch between service rhythm and lifestyle rhythm. To address this, companies handling electronic transactions collaborated with convenience stores, which rank high as intersection points in time and space, and they were able to increase the matching ratio. With a receipt issued from an electronic transaction, the user can pick up the package at any time. Alternatively, if the package is placed in shared mailbox in an apartment building, the recipient can pick up the package simply by opening the lock with a smartphone app.

5.5. City Brain in China

Alibaba, the largest e-commerce company of China, has developed the ET City Brain (ETCB) system in cooperation with the city of Hangzhou (population of about eight million) in Zhejiang Province, integrating public administrative data, Internet cloud data, IoT sensing data, and image sensing data for the purpose of urban management (see Fig. 3). The functions of City Brain are designed with the concept of one keyboard, one standard, one cloud and one network, displayed with a common interface, standardized specifications, shared database, AI support, and ubiquitous access. By joining ETCB, governmental departments such as natural conservation, police, urban utilities, healthcare, hospitals, and road transportation can allocate their resources dynamically in response to events in the physical world. The system was first tested in Xiaoshan Ward and then applied to the entire downtown area of Hangzhou. Thanks to the system, it has been reported that vehicle speeds have increased by 15% in Shaoshan Ward and traffic accidents can now be detected automatically with an accuracy of 92% in the city.



Fig. 3. The sensing, processing and actuation (SPA) system of City Brain, Alibaba.
Source: <https://et.aliyun.com/brain/city>

The concept of City Brain was also introduced in the Xiong'an New Area, a state-level new development project located 100 km southwest of Beijing, 50 km east of downtown Baoding and 100 km west of Tianjin. As a leading-edge development project initiated directly by President Xi Jinping, the planning, design and construction of the area are being conducted in innovative ways. Every detail of the new area is first designed in the cyber world using building information modeling (BIM) and city information modeling (CIM). Physical components are constructed based on the design, and then monitored and managed digitally in the cyber world. This is called a twin-city development, which means that the components built up in the physical world will be mirrored simultaneously in the cyber world. This technology has been applied in the construction of the Public Service Center district and trial demonstrations were deemed a great success (see Fig. 4). The start-up zone and infrastructure projects are under ongoing construction.



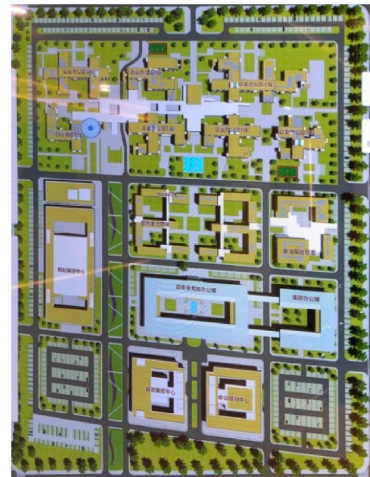
(a) Driverless bus



(b) Poles equipped with multiple sensors



(c) Cashier-free supermarket



(d) Layout of Public Service Center district

Fig. 4. Scenes in the Public Service Center district of Xiong'an New Area (photos by author).

6. Future challenges for Geo CPS

In our physical world, work is typically divided by sector, industry, field, and project. Many information systems function in a closed environment that is defined by the particular specifications. Each system is created for that part of the work only. Horizontal collaboration and data sharing are difficult. This may have worked well during the early days of information technology. However, vertically fragmented systems like these create a “multiplication” barrier which limits innovations.

The power of IoT enables people and devices to sense information and receive instructions from distant places, regardless of the sector, field, or department. Conversely, CPS can instruct or control moving objects in the physical world. It will be crucial to have significantly higher precision in specifications for efficiency, reliability, and stability. Thus, IoT must not only gather information on location and attribute, but also serve as smart sensors, smart devices, and smart systems that can actively respond, make decisions, and act in response to usage conditions, environmental conditions, and vicinity conditions. This requires CPS to go out from the

laboratory into the geo world, and requires GIS to evolve from the additive storage of “position + attribute” to multiplicative functions, to be actuated by both position and attribute. This will mean a deeper dimension of information and knowledge processing in the cyber world, as illustrated in Fig. 1. Based on all of that, business models will have to be reexamined. Thus, it will be essential to consider the following challenges.

System boundaries: IoT involves networks of sensors to digitally measure, monitor, and control the physical world, while the aim of CPS is to unify the management of a massive amount of stocks or assets dispersed in the physical space. Until now, most of the assets have been managed in closed environments in the physical world. In such a closed environment, systems and business models are built upon well-defined conditions within a limited system boundary. For instance, a robot could stand behind the reception desk to receive visitors; an operator could touch on the screen to communicate with the machine. Going forward, this will have to be done in open environments. Here *open* means sharing, co-existing, and co-habiting with different systems, and collaborating and co-operating with diverse stakeholders, including governments, corporations, private sector, and citizens, etc. The boundaries of the openness determine the complexity of the CPS. It could be a front desk between a robot and a customer, a closed field at a construction site, a floor in a hospital, or a vast motorway network. Working in such a diversity of open operating environments in geo space, Geo CPS requires a high level of sophistication in terms of data policies, security, technical specifications, and so on.

Data policies: For CPS, big data is the key to success. The data platforms for geolocation were created in the IT era. But now that is not sufficient for real time IoT services. Going forward, it will be important to consider things from the perspective of technology and systems, including the linkages with open data policy. What kinds of data platforms are needed, how should data policies be structured, and how can this be mainstreamed? In Japan the government has launched the Dynamic Mapping Project for Autonomous Driving with manufacturers playing a key role, and data specifications are being tested. This kind of action is also needed in other sectors and areas.

Security: This word can have various interpretations. For example, in the cyber world it can mean the robustness of a network, or safety, or the protection of personal information. In the physical world it can mean measures against terrorism, or accident prevention, or disaster prevention, or risk reduction, etc. However, with increasing integration of the cyber world and physical world, it will be crucial to see both as the same thing, in a unified way. The use of spatial information is becoming increasingly intelligent in terms of data, information, and knowledge. This cannot be done without big data and AI, and it will be important to consider how to proceed.

Compatibility of component technologies: We are witnessing increasing diversity in terms of IoT platforms and content, the controlled objects and purposes, with drones, high-precision GPS, Quasi-Zenith Satellite Systems, indoor location, communications, and complex sensors, etc. While there is increasing specialization and expert sophistication, it is also important to have bridging functions for business, society, and the diffusion of Geo CPS. To those ends, there is a need for the further development of expertise, tools, platforms, products and services.

This article has provided an overview of Geo IoT and CPS, which integrates the cyber world and the physical world from the perspective of geo-space. Although some business sectors have taken the lead, generally speaking there are still few successful examples in sectors that are intimately connected with the geo-physical space, such as manufacturing, construction, infrastructure maintenance and management. The future will surely bring more technological advances and practical applications.

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