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A review of the smart world

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HIGHLIGHTS

- Smart world evolutions and representative projects are respectively surveyed.
- Smart world elements and the smart world driven applications are explained.
- Enabling technologies and trends are presented for identifying perspectives.

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ABSTRACT

Smart world is an attractive prospect with comprehensive development of ubiquitous computing involving penetrative intelligence into ubiquitous things, including physical objects (e.g., wearable devices), cyber entities (e.g., cloud services), social people (e.g., social networking) and human thinking (e.g., brain cognition). This work systematically overviews related works in the field of the smart world, and explains prospects in emerging areas. The smart world evolutions are discussed through four progressive phases, and the representative projects are accordingly introduced. Meanwhile, smart world elements and the smart world driven applications are respectively analyzed in the contexts of cyber–physical–social-thinking hyperspace. Moreover, enabling technologies including ubiquitous intelligence, web intelligence, brain informatics, social computing, big data, and security and privacy are respectively discussed. Finally, perspectives referring to ubiquitous sensing, ubiquitous object modeling, smart services, and philosophical, ethical and legal issues, are presented for identifying trends and challenges in the smart world.

1. Introduction

Smart world is an attractive prospect involving penetrative intelligence into ubiquitous things, including physical objects, cyber entities, social people, and human thinking. It begins with several smart applications such as smart city, smart home, and smart agriculture, are changing traditional lifestyles, and will eventually encompass all aspects of the cyber, physical, social, and thinking spaces [1]. In the smart world, ubiquitous things are basic elements to construct such smart applications, in which ubiquitous computing is an essential prerequisite for service support and ambient intelligence.

In a certain degree, an ultimate goal of the smart world is an integrated cyber–physical–social-thinking hyperspace involving comprehensive interconnections and intelligence of physical perception, cyber interaction, social correlation, and cognitive thinking through the whole aspects of everyday life [2]. Increasingly, the heterogeneous hyperspace will cover countless smart devices, applications, and networks. From a philosophical perspective, the smart world fundamentally changes the existent environments, and it indicates that the surrounding world becomes almost entirely integrated with human beings with more fuzzy boundaries. For instance, the number of internet-connected devices are exceeded that of people on the Earth. By 2020, there will be 50 billion, and be on average approximately seven internet-connected devices per person. Meanwhile, available computing capability keeps rising, and inexpensive sensors, actuators, and processors become more prevalent in applications. Meanwhile, physical objects have

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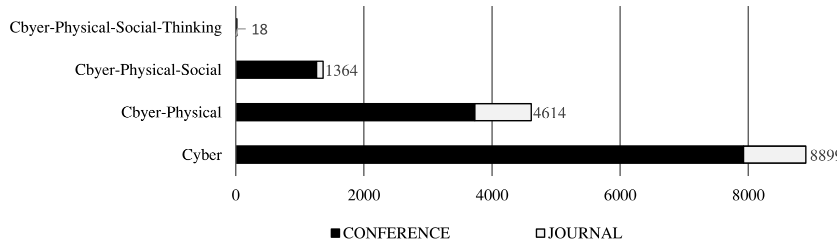

Fig. 1. The related paper in the cyber, physical, social, and thinking spaces.

more flexible interactive modes to connect with the human and the corresponding homes, buildings, vehicles, and critical infrastructures [3].

How to make ordinary things become smart with ubiquitous intelligence is a central issue [4,5]. For one aspect, ubiquitous computing is the most important issue for the smart world, with the motivation of making our lives convenient, comfortable and informed. Therefore, current research projects have been focused on frameworks, technologies and infrastructures to support the smart world. For example, both qualitative and quantitative approaches are available to evaluate human, social, and environmental risks of pervasive computing, and the heterogeneity of diverse spaces may lead to incompatibility [6–8]. For the other aspect, ambient intelligence raises an interaction mode between people and environment, which directly accelerates paradigms of the smart world. Ambient intelligence builds upon advances in sensor and actuator networks, pervasive computing and artificial intelligence [9,10], and is characterized by invisible or embedded computational capabilities. Along with the development of mobile computing, agents and context-aware technologies are implemented to build smart applications, and ambient intelligence is anticipated to present opportunities and challenges for people with diverse needs and requirements, and mobile computing [11–14].

During the development of the smart world, cyber–physical–social-thinking hyperspace as a typical system architecture, is established by involving an novel concept of the "Internet of Thinking" (IoTk) [2]. Meanwhile, several fundamental issues have also been proposed in the aspects of Internet of Things [15–17]. For instance, how will "people" exist in the physical, social, cyber and thinking quaternionic spaces? Will ubiquitous things really be self-cognition and secure enough to safeguard humans and environments? Could the Internet become a runaway super monster or a super living organism? Also, Smart computing is emerging as an important computing paradigm, which effectively applies computer hardware, software, social media and communication networks together with ubiquitous smart devices, computational intelligence and intelligent systems to achieve various innovative applications.

This work aims to present a survey on the smart world, and the remainder of the paper is organized as follows. Section 2 presents the evolution of the smart world and representative projects. Section 3 discusses the smart world elements and the smart world driven applications. Section 4 introduces the typical enabling technologies, and Section 5 analyzes the perspectives of the smart world. Finally, Section 6 draws a conclusion.

2. Smart world evolutions and representative projects

2.1. Development phases of the smart world

According to the information technology and the related researches areas, the smart world evolutions accompany the integration of cyber–physical–social-thinking hyperspaces. There are four progressive phases as follows.

- *Embryonic phase* emerges along with the networks of computers and/or the Internet of computers for addressing the data exchanging in the cyberspace.
- *Emerging phase* realizes that physical objects are mapped into the cyberspace as cyber entities for interactions, and launches the cyber–physical spaces.
- *Developing phase* establishes the cyber–physical–social spaces involving social attributes and social computing to address the complicated interrelationships.
- *Rapid progress phase* involves human interactions to achieve ubiquitous interactions between the external real world and the internal thinking world, and further improve the cyber–physical–social-thinking hyperspace.

Fig. 1 shows the related papers with the topic of cyber, physical, social, and thinking spaces, and the researches on the cyber–physical–social-thinking hyperspaces still in its infancy.

2.1.1. Embryonic phase

In 1991, Weiser [18] proposed a remarkable vision that a variety of computers would become essential parts of everyday objects, and ubiquitous computing was defined to support associated applications. In 1999, pervasive computing was proposed by IBM, and ambient intelligence is also proposed by the European Union's Information Society Technologies Program Advisory Group (ISTAG). It describes a new vision where people are surrounded by intelligent and intuitive interfaces, and the surroundings would be recognized to respond to the presence of individuals in an invisible way. Afterwards, microminiaturization of electronic chips and electro-mechanical devices further impel the development of mobile/ wireless communications and IPv6-based next generation Internet. Ambient environments, including smart objects with embedded or attached small or tiny networked computers/processors, assist people in performing tasks more automatically, precisely, and reliably. Meanwhile, the resulting integration can be adopted in dynamic cyber contexts [4].

Subsequently, hyperworld was proposed referring to real-virtual bi-directional mapping relationships between the real and the virtual worlds, and was an embryonic version [1]. It draws a mapped, combined, interactive paradigm that laid foundation for cyber–physical systems, and presents an early vision of the smart world involving direct-mapping modeling, directly controlled computing, and active sensing and actuating.

2.1.2. Emerging phase

In 2004, Bohn et al. [19] identified smart things as able to explore environments, communicate with other smart things, and interact with human beings, thereby helping users address tasks in intuitive ways, and attempted to classify the social, economic, and ethical implications of pervasive computing and ambient intelligence. Afterwards, Ma proposed the concept of the smart world in 2005 [1], describing the smart world as a highly digital physical space created in hyperspace. Ubiquitous things mainly include physical objects, spaces/environments, and systems pervaded by ubiquitous intelligence, referring to the aspects of connection, sensing, computing, communication, and action. Relatively independent individual machines/devices are not regarded as ubiquitous intelligence. As the essential elements of the smart world, ubiquitous things can sense, compute, communicate and perform adaptive actions according to different goals and situated contexts. Ubiquitous sensors, devices, networks, and information propel the smart world, in which computational intelligence is distributed throughout physical environments providing reliable and relevant services. Ubiquitous intelligence will change the computing landscape by enabling new applications and systems to be developed and computing possibilities to be significantly extended. By enhancing objects with intelligence, many tasks and processes could be simplified, and interactive physical spaces (e.g., workplaces and homes) could become more efficient, safer, and more enjoyable. Heterogeneous ubiquitous things establish smart environments, services, and applications by applying ubiquitous computing.

Ubiquitous intelligence is assigned to ubiquitous things, and there are various kinds and levels of intelligence for different objects, environments, systems, and even humans. However, there is no sufficient description of how to represent varying levels of intelligence. In 2006, ubisafe computing was proposed to evaluate computing environments through a unified methodology, by which a variety of conventional and new safety problems are systematically solved [4]. Several architectures and frameworks have been proposed [20–22]. The emerging phase forms an embryonic IoT, which aims at a ubiquitous intelligence of real physical things [23,24] and realizes interconnections among multiple smart devices in computer networks.

2.1.3. Developing phase

Social computing [25] highlights social intelligence, including collective intelligence, sentiment analysis, recommendation systems and crowd sourcing. Over the past nearly twenty years, computational intelligence has evolved from logic-based artificial intelligence, nature-inspired soft computing, and social-oriented agent intelligence to cyber–physical–social integrated ubiquitous intelligence. In specific, socially aware networking (SAN) emerges as a new field [26]. SAN applies to various types of networks (e.g., opportunistic networks, mobile social networks, delay-tolerant networks, ad hoc networks, etc.) characterized by social awareness. The state-of-the-art researches on SAN mainly include three aspects: routing and forwarding, incentive mechanisms, and data dissemination [26]. Then, according to SAN concepts, quite some independent research activities that investigated the potentialities of integrating SAN into IoT. As a result, Social Internet of Things (SIoT) paradigm has developed. SIoT is populated by intelligent objects permeating everyday life with the emergence of cyber–physical–social computing with the potential to support novel applications and networking services for the IoT in more efficient ways. In particular, social systems are evolving with cyber systems and physical systems, along with the popularity of online social networking. Social networks become cyber–physical interactions, which have associated social attributes and social relationships of the human beings and other physical objects or cyber entities, such as using social networks to search Internet resources, to route traffic, or to select effective policies for content distribution. Recent research shows that most of the SIoT features are similar to those observed in social networks of humans through the simulations, which model the mobility of objects and their relationships [27]. To conclude, at this stage, the capability in human beings and devices to discover, select, and use objects with their services in the IoT is augmented. Besides, a level of trustworthiness is enabled to steer the interaction among the billions of objects which will crowd the smart world. Also, the convergence of physical, cyber, and social spaces will exhibit a variety of complicated characteristics, present challenging open issues in the field of smart world.

2.1.4. Rapid progress phase

Thinking computing includes affective computing, human body communication, brain informatics, and cognitive science [28]. For the thinking space, the space–time consistency becomes crucial during an individual's cyber mapping, and it brings considerations towards how to achieve the space–time unification between an individual's thinking and the corresponding cyber thinking, how to perform the space–time identification between an individual's thinking and other associated entities' thinking, and how to address the space–time redundancy among multiple cyber thinking [2]. For example, there are multiple hyper-connected worlds for each person, and there are one-to-many interactions during the accompanying or associated human interactions (e.g., psychological activities and thinking). Thus, brain informatics emphasizes systematic approaches for investigating information processing mechanisms, including collecting, measuring, modeling, transforming, and mining human cognitive data obtained from various experiments. Zhong et al. worked on a unified and holistic framework of machine intelligence, human intelligence, and social intelligence by incorporating Web intelligence and brain informatics [29,30]. In particular, brain informatics is developing in terms of computer hardware, software, social media and communication networks together with smart services and computational intelligence to support innovative applications. A wide range of systems such as cognitive computers and cognitive robots are developed with the improved understanding on brain science [31,32]. Therefore, the smart world is gaining implications and gradually becoming a cyberspace-driven combination of physical, social and thinking spaces to integrate heterogeneous hyperspaces.

In summary, the convergence of cyber, physical, social, thinking spaces impels a version of the smart world that focuses on the ubiquitous intelligences of physical objects, cyber services, social people, and cognitive thinking. According to the published papers in the IEEE Xplore Digital Library, Here, the whole world can be regarded as a gigantic system consisting of myriad systems [33]. For each of the four stages of smart world development, diverse distinguished features can be identified, although the boundaries are fuzzy. Concretely, in the embryonic phase, real-virtual direct mapping and an embryo of the cyber–physical system are the main characteristics of the smart world. The smart world is characterized cyber–physical integration in its emerging phase, and the development phase features the cyber–physical–social system, social computing, and SIoT. The rapid phase focuses on human interactions to achieve ubiquitous interaction between the external real world and internal thinking space by introducing thinking computing, which involves affective computing, human body communication, brain informatics, and cognitive science.

2.2. Representative projects

There are representative projects covering broad areas that promote the progress of the smart world. Table 1 classifies the main related projects into two categories: (1) *Architecture*: smart space, smart structure, smart machine, and organizations; (2) *Industrialization*: smart city, smart grid, smart community, smart home, smart building, smart factory, smart machine, smart hospital, smart agriculture, and others.

2.2.1. Architecture

Smart Space: The project on IBM's Smarter Planet is proposed to address new issues on a Smart Planet in 2008. IBM aims to build a Smart Planet with other companies, cities, and communities around the world, and the Smart Planet refers to the areas of big data, cities, cloud, commerce, energy, mobile enterprise, security, and social business [34]. In particular, it highlights to make the best of the potential of smarter systems (e.g., smart grids, water management systems) achieve economic growth and societal progress.

Table 1
Comparison among different electrical energy storage approaches.

Category	Name	Related research projects
Architecture	Smart space	IBM's smarter planet, NIST smart space and meeting room projects
	Smart structure	SPIE smart structures/NDE 2016
	Smart machine	Predictions 2015: Smart machines
	Organization	Smart future initiative
Industrialization	Smart city	Smart city expo, IEEE smart cities, smart city (Google), smart cities USA
	Smart grid	Smart grid solutions (Siemens), smart grids SRA 2035
	Smart community	The Kitakyushu smart community project, smart + connected communities (Cisco)
	Smart home	The internet of things: Smart houses, smart traffic, smart health, smart appliances
	Smart building	Smart buildings & homes
	Smart factory	The dawn of the smart factory
	Smart hospital	Best of 2014 how to design a smart hospital
	Smart agriculture	Smart agriculture, smart agri-food, smart forest
	Others	Smart textiles & nanotechnology, smart artifacts

In 2011, IBM announced the smarter computing framework to support the Smart Planet and an initiative of "IBM Smarter Cities" was launched to provide advanced hardware, middleware, software and service solutions for city governments and agencies. Meanwhile, STIMULANT [35] focuses on transforming static physical spaces into dynamic interactive environments, and crafts human-scale, site-specific digital experiences to create unique and lasting interactions. EIT Digital [36] mentions that smart retail, smart buildings and smart urban experiences become more popular, and resource optimization based smart spaces should be presented for both Internet service providers and customers. NIST smart space and meeting room projects [37] focus on context-aware smart meeting rooms for detecting ongoing human activities for real-time respondence. It aims to develop tools consisting of data formats, distributed processing, metadata and measurement algorithms for smart meeting rooms.

Smart Structure: A smart structure is a system containing multi-functional elements for performing sensing, control, and actuation. Smart materials are applies to re-construct different smart structures with particular functions such as sensing and actuation. Moreover, smart systems are further established by smart structure with distributed sensors and actuators along with accommodating time-varying exogenous conditions [38]. SPIE Smart Structures/NDE 2016 (SPIE) [39] is the international society advancing an interdisciplinary approach to the science and applications of light for optics and photonics. The conference of Smart Structures/NDE 2016 is its latest planned event, which will focus on energy harvesting, civil infrastructure monitoring involving smart sensing networks, and non-destructive evaluation tools.

Organizations: Smart future initiative [40] was founded in January 2009 with the goal of establishing a forum for triggering, developing and communicating innovative ideas and providing expertise on the technological developments and trends determining current and future life in a fast changing society. Smart environments, ambient intelligence, and ubiquitous and pervasive computing multi-areas receive focus, considering prominent themes such as humans in the loop, smart cities, smart airports, smart privacy, ambient computing and communication environments, and disappearing computers. Many events and talks have been held, and highly influential publications have been produced. The public buildings sector "SMARTSPACES" [41] will be an attractive untapped potential for energy savings. Specifically, SMARTSPACES service will enable Europe government significantly to improve building energy management. The implementation of operational services covers 11 pilot sites, 550+ buildings around 8 countries.

2.2.2. Industrialization

Smart City: The world's population is predicted to achieve 9.3 billion in 2050 [42], and the percentage of the urban population will rise to 70% along with a serious problem of urbanization. Against this backdrop, it is feared that the world will see an explosive increase in energy consumption. Thus, each country regards the development of the domestic smart city industry as a higher priority in its national strategies. A typical smart city project referring to real estate development, basic infrastructure, smart infrastructure, life services, and lifestyles, culture and art, is performed with the purpose of smart city development [42]. IBM Smarter Cities project [43] aims to serve thousands of cities worldwide for smart management, including public safety, health services, education, infrastructure, energy, water, and environmental facets. Smart city expo attempts to explore the relevance and innovative solutions to present prototypes in the smart city plaza. Meanwhile, IEEE Smart Cities Initiative [44] has been bustling with activity, and Trento, Italy and Wuxi, China have been selected to join Guadalajara, Mexico in piloting a global, multidisciplinary effort to help municipalities apply information technology to improve the quality of their citizens' lives.

Smart Grid: Smart grid establishes interactions between power link and communication link for transforming the traditional power grid into the Internet of energy, and enables customers and utilities to jointly perform power usage management [45]. Siemens focuses on smart grid to offer an ecological spectrum of products, services and solutions for the protection, automation, planning, monitoring and diagnosis of the power grid infrastructure. It provides scalable and flexible solutions satisfied interoperability and security requirements of industrial standards for utilities and cities [46]. Smart Grids SRA 2035 project focuses on establishing smart electricity distribution systems, smart electricity transmission systems, smart customer technologies and integrated smart grid systems by 2035.

Smart Community: In Esri project [47], the features of Smart Communities are safe, livable, prosperous, healthy and well-fun. Kitakyushu Smart Community Project [48] creates social structures by innovative lifestyles, business patterns, and urban planning styles through the establishment and operation of a smart energy management center, which is designed to establish mechanisms to address energy distribution issues, and energy usage visualization may promote lifestyles and business styles modification. Cisco Smart+ Connected Communities [49] apply intelligent networking capabilities to improve next-generation vehicles and public transport. Australian Smart Communities Association (ASCA) project [50] facilitates, promotes and advises on how communities can build livable, sustainable, workable smart cities in Australia.

Smart Home: Smart home includes main features including device control, home view, and intelligent customer services. For example, lights and air conditioning can be operated by mobile devices and smart televisions in smart home systems. Moreover, in addition to the screen operation interface, voice commands

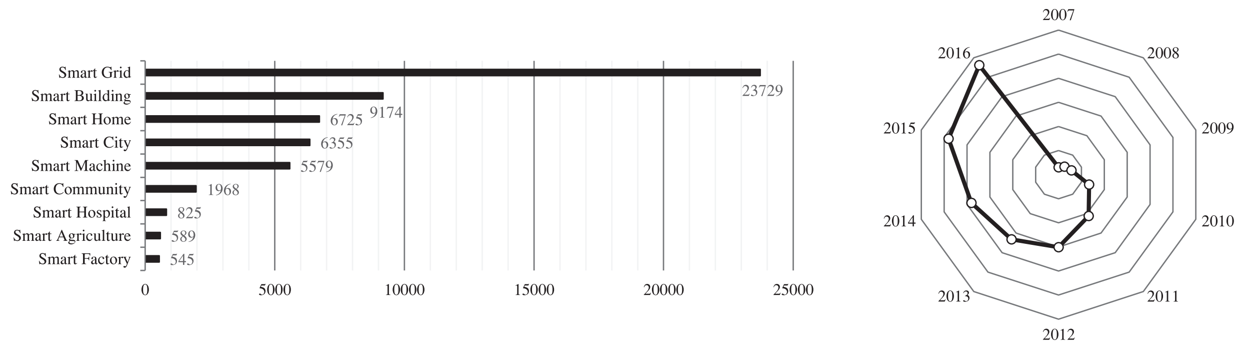

Fig. 2. The related papers in the typical smart applications in the past ten years.

and a custom configuration file are supported. The home view function refers to remote visualization, allowing the user to control the conditions at home in real time, through opening the camera and synchronously uploading a scenario that does not constitute private content through the network to the user's smart phone or smart wristwatch. Smart customer service is the function that assists the devices' running condition and warns the intelligent system if the device is broken. Project smart home [51] aims to home automation using one or more electronic devices to control basic home functions automatically. It is a system integrator that helps users with identification of home automation requirements, selection of hardware, and the implementation of devices and applications.

Smart Building: Smart buildings & homes project [52] aims to explore smart building solutions to energy management, security management, and environmental control, and is characterized by smarter, greener, more efficient, and more livable, including the smart factory, smart hospital, smart agriculture, smart forest, and others. A smart building project [53] provides services for owners and developers to conveniently manage, operate and satisfy environmental and financial objectives. This integrated system encompasses a wide range of functions, from education, health care to residential, office, and manufacturing.

Smart Factory: Towards digital manufacturing, the boundary between the real and virtual manufacturing environments are demolished for creating an emerging industry [54,55]. The real manufacturing environments are converging with the virtual manufacturing elements to enable the entire lifecycle organizations of products and facilities. Thereinto, Smart Textiles & Nanotechnology [56] focuses on several emerging fields such as nanotechnology, smart fabrics and interactive textiles. SmartFactory [57] develops innovative production mechanisms which are suitable for a variety of applications in different industrial branches, and aims to further the use and spread of those technologies and to set the grounds for their utilization.

Smart Machine: Predictions 2015 Smart Machines Project indicates robots, self-driving cars and other cognitive computing systems can make decisions for problems solution without human intervention [58]. A smart machine may apply machine-to-machine (M2M) technology to act as a digital descriptor with both positive and negative social effects. In business, the competitive advantages of smart machines may bring higher profit margins and lead to more efficient manufacturing processes. Furthermore, National Center for Manufacturing Science's Smart Machine Pilot Project (SMPP) [59] is to improve the performance of factory equipment. For example, associated companies install equipment to monitor the operation status of the manufacturing processes, and it will equip machines at various sites with the capability to automatically and consistently respond their performance. Autonomous software provides monitor data to identify anomalies and address pending problems for reliable management.

Smart Hospital: Smart hospital focuses on the information flows of medicine, patients, and doctors to achieve intelligent recommendation and management, which can improve the quality of services (e.g., scheduling policy) for more reasonable healthcare resource utilization. The healthcare providers should consider the patient experiences focusing on connectivity, communication, and information sharing [60]. Data mining modules should be designed for across-hospitals sharing, which could conspicuously reducing the time cost to implement a similar data-mining program [61]. Recently, the LIFE SMART Hospital project [62] is demonstrated at the Hospital Universitario Rio Hortega in Spain, and will increase the hospitals resilience to climate the accompanied issues.

Smart Agriculture: Smart agriculture was launched to highlight essential information on how to improve crop plantation, animal husbandry, forestry and fishery. The Smart Agri Food project [63] has selected 50 of the top European ICT small and medium enterprises and web entrepreneurs to develop smart applications and services for agriculture using FIWARE technologies following a Europe-wide call that resulted in over 150 applications. Concentrating on the areas of arable farming, livestock farming and horticulture, the selected SMEs has embarked on the first stage of prototype development. KITZ Corporation has started KITZ water solutions since 2012 [64], and Climate-Smart Agriculture Project [65] is the first World Bank project in Africa for increased productivity, enhanced resilience and reduced greenhouse gas emissions. Meanwhile, the United States Department of Agriculture (USDA) Forest Service [66] deploys sensors and telecommunications devices to create an integrated monitoring for air, water, and forest resources protection according to rural and densely populated areas requirements. Currently, northern research station's experimental forests are established as fundamental infrastructure to construct smart forest networks, and smart forest-fire early detection sensory systems become an important aspect.

According to the works in the IEEE Xplore Digital Library, Fig. 2 shows the related papers distribution in the typical smart applications during the past ten years. The researches on the topic of smart grid are far beyond other smart applications, and increases rapidly in the recent five years.

3. Smart world driven applications in the smart world

3.1. Smart world elements

Smart world is a converged cyber–physical–social-thinking hyperspace characterized by ubiquitous interconnection, intelligence, and computing. It incorporates varied ubiquitous things, including physical objects, cyber services, social people, and cognitive thinking [28]. The infiltration of all aspects of the physical space, cyberspace, social space and thinking space, will promote the smart world.

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Physical space is the basis of the smart world [28], comprising its essential elements. In physical space, there are many ordinary real objects (e.g., furniture, cars, and appliances), which are perceived and controlled by sensors and actuators and interconnected using wireless communications to establish the interactions in the cyber–physical–social-thinking hyperspace. Such physical things are characterized by sensing, computing, communicating and taking certain adaptive actions according to their functions, which are indispensable to the smart world and are becoming increasingly pervasive. With 50 to 100 billion physical things expected to be connected to the Internet by 2020, the physical space will be full of interconnected and smart things. Physical space mainly addresses fundamental issues of the smart world, such as sensing technology, physical object models, and network infrastructure construction. Currently, many physical-based technologies such as radio frequency identification (RFID), short-range wireless communications, localization, and context-awareness are playing essential roles in the smart world.

Cyberspace, as the core driving power of the smart world [33], is significant to the overall human society, closely conjugated with physical, social and thinking space. Various ordinary things and entities in conventional physical, social and thinking spaces mapped into the cyberspace as one or more cyber entities, and their behaviors, relationships, and events should be considered in the corresponding cyber entities by dynamic representations. With the ubiquity of digital and smart things, the existing novel digital space called cyberspace, in which cyber entities achieve interconnection and interaction via virtual, digital, and ubiquitous abstraction, is promoting the cyber-enabled smart world. Internet Distributed Computing, web computing, mobile computing, cloud computing, context-aware computing and other cyber technologies are exhibiting an increasingly outsized impact on every aspect of the world. The smart world is actually the cyber-connected quaternionic convergent world. Cyberspace makes it possible to interconnect and interact among the three conventional worlds and generates abundant data, i.e., big data.

Social space features the social-inspired interactivity of smart world as the social attributes, relationships, and activities of ubiquitous things should be considered and studied as they grow increasingly smarter [67]. The social space is not only the independent traditional human society, but the one that overlaps both the physical space and the cyberspace for unrestricted interaction and resource sharing by social effects (e.g., interpersonal communication, psychological health, personal relationships, group membership, social identity, and community involvement) [68]. For example, social networks are distributed and composed of a set of social actors (e.g., individuals, groups, and organizations) and their interaction relationships to support various activities for human entities or e-business platforms. Social media such as Facebook, LinkedIn, and WeChat have been facilitating human interactions instead of face-to-face communications [69,70].

Thinking space mainly focuses on human beings' and artificial things' cognition issues, which are reflections of human brains' activities in smart world [28,33,67,71], and future ubiquitous things will have the abilities of independent thinking and decision-making. Human cognition capacities and human social principles are considered to enhance ubiquitous human–human, human–thing and thing–thing interactions in thinking space. The concept of the Internet of Thinking (IoTk) is proposed to focus on brain informatics for analyzing human brain data to better understand human thought, memory, learning, decision-making, emotion, consciousness and social behaviors beyond space–time constraints [72]. It assists in building human brain inspired computing paradigms, and facilitates the achievement of ubiquitous intelligence to allow the human subjective initiative to break cyber–physical–social limitations.

Table 2
Category of smart applications.

Element	Application	Details
CP space	CPS	Industry control system
		Environmental monitoring
	E-business	Online shopping
		E-bank
		E-payment
		E-government systems
	Smart grid	Smart meters
		Smart transmission
	Smart agriculture	Smart equipment
		Smart irrigation
		Pest control
	Smart city	Smart infrastructure
		Smart utilities
		Smart roads
CPS space	Smart media	Facebook
		LinkedIn
		WeChat
	Social IoT	Service discovery
		Resource management
	Social computing	Crowdsourcing
		Recommendation system
CPT space	Wearable application	MindWave
		MindFlex
		Brainlink
		Emotiv Epoc
	Affective computing	Physiological sensors
		Human machine interfaces
		Artificial intelligence

3.2. Smart world driven applications

Based on the four dimensional space elements, the smart world has developed a series of related applications to solve specific problems using its underlying technologies. These applications began to emerge in recent years and will gradually be improved as required. With computing intelligence integrated into various devices, connectivity, cooperativity and intelligence have been major features of current smart applications of concern to people. For clarity, the existing applications constituting the smart world are depicted from the perspective of the driving elements, which can be roughly classified into cyber–physical space, cyber–physical–social space, and cyber–physical-thinking space. Smart applications are widely used in many respects and play an increasingly important part in this changing world to satisfy personal demand, improve family life quality, and facilitate the harmony of the whole society. Table 2 describes the taxonomy of popular and important smart applications that have attracted much attention in recent years, leading to the evolution of the smart world.

3.2.1. Cyber–physical space driven applications

Cyber–physical space driven applications are instantiations combining the capabilities of computing, communications and data storage to monitor or control objects in the physical space [73]. With information as the centers, cyber–physical space focuses the characteristics of computing, communication and control by embedded systems, sensors, and wireless network on achieving real-time sensing, dynamic control and information service in large-scale systems and determine the state of the environment. A typical cyber–physical driven instantiation is e-business, which has been a widely applied paradigm since it was first proposed. E-business involves online shopping (e.g., Amazon, Alibaba), e-banking, e-payment, e-government systems (e.g., electronic tax), and more. To keep up with increasing power demand, smarter energy management is needed to supply electricity more efficiently and reliably. The smart grid is such a paradigm, using the smartest technology to generate and distribute power throughout the country in a simple but effective system [74,75] consisting of millions of individual pieces and parts-power lines, sensors, controls, computer systems to improve energy delivery, informed consumption and reduced environmental impact in the physical space. Compared with the modern power grid, the smart grid offers a self-monitoring and self-healing power delivery architecture with two-way communication [76]. In the smart grid, data on energy usage will be collected and disseminated by the advanced metering infrastructure (AMI), which is an important component of information flow and makes power usage much more efficient. The USA had installed approximately 36 million smart meters by May 2012, according to the statistics released by the institution for electric efficiency, and nearly 80 million smart meters are expected to be installed in China [77].

Agriculture plays an indispensable role in human subsistence and development, and it is required to consider developing smart agriculture in rural areas to improve resource utilization, reduce costs and minimize the effect on the environment. In addition to the challenges of rural areas, cities also face many problems, such as the management of infrastructure, environmental monitoring, and traffic. With the popularization of IPv6, cities will increase the density of sensors and actuators on local streets, parks, and buildings to gather comprehensive data on public usage, air quality, noise levels, and then use the collected data to provide better and more efficient services [78]. Physical objects mapping into cyberspace, are conjugated with cyber entities to improve the conventional physical space, and provide better service via the interconnection, interaction, and intelligence of cyber–physical entities.

3.2.2. Cyber–physical–social space driven applications

The rapid development of cyber technologies has promoted convenient and personalized forms of socialization and has dramatically shortened the cyber–social distance for the same physical distance among social entities. At the same time, many smart applications have appeared that integrate the social context and social attributes of human beings and other physical entities and cyber entities to address complicated interconnections through the cyber–physical–social space. These applications focus on both human society and thing society to establish their respective social networks. Social media, which is oriented to human society, such as Facebook, LinkedIn, and WeChat, has been facilitating human interactions instead of face-to-face communications, accelerating the popularity of the online human society. On the other hand, things, as another important part of the world, have their inherent and acquired relationships with other physical things or cyber entities in both the real and digital worlds.

The social IoT considers the social attributes, relationships and networking of ubiquitous objects for improving service discovery, and is established based on the social relationships among physical objects [79]. The enormous human social networks and thing social networks provide a perfect context for social computing, regarded as an intersection of recommendations, trust/reputation systems, and recommended systems [80].

Social computing reflects social intelligence and facilitates social collaboration and interactions. In the smart world, the amounts of data coming into being in each space are too massive to obtain accurate and useful information. Recommendation systems involving social computing provide information filtering for personalized demands and enable users to target their concerns better. Crowdsourcing was first proposed by Howe and Robinson in Wired Magazine in 2006 [81] and was defined as an online, distributed problem-solving and collaborative model enabled by people-centric web technologies to solve various problems for academic or commercial purposes [82]. Social computing is applied to crowdsourcing platforms to capture crowd wisdom while reducing the costs and time of addressing various fundamental challenges.

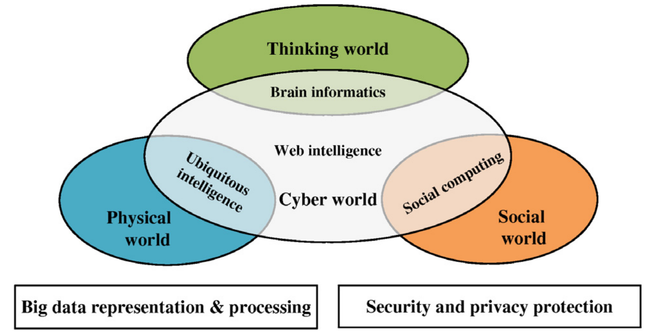

Fig. 3. Enabling technologies of smart world.

3.2.3. Cyber–physical-thinking space driven applications

With the development of driving elements, smart applications are becoming increasingly diverse. Considering inherent human physiological characteristics (e.g., consciousness capture, emotional control, attention allocation), smart applications are required to evolve towards a wiser ecosystem with the participation of thinking. Wearable device applications focusing on brain waves have raised widespread concern among businesses and consumers because of their novelty and utility. Many companies are working on smart wearable devices (e.g., MindFlex, MindWave, Brainlink, Emotiv Epoc) with biosensor chips designed to detect brain signals (e.g., electroencephalography (EEG)) and make manipulations.

Apart from direct applications of physiological signals, there are deeper studies in progress in the cyber–physical-thinking space. The term emotion, as a potential source of intelligence, refers to relationships among external incentives, thoughts, and changes in internal feelings [83] and affects human decision-making and work effectiveness by subtle degrees, making affective or emotion-related computing more significant. Affective or emotional computing defined as "computing that relates to, arises from, and deliberately influences emotion", has changed enormously in the past decade and is further developing to enhance self-understanding, improve communication among people, and reduce stress [84]. With the further research and development of thinking space (such as human machine interfaces and artificial intelligence algorithms), many machines are able or will be able to recognize human emotion, ideally at the same level that people can.

With these applications developing towards standardization, universality, and popularization, the smart world becomes a cyberspace driven hyperspace to achieve physical perception, cyber interaction, social correlation, and cognitive thinking. Gradually, smart applications will permeate into the synergistic quaternionic domain with elements driven by cyber–physical–social-thinking space. Eventually, the smart world will result in qualitatively different lifestyles from today.

4. Enabling technologies

The smart world involves multi-disciplinary technologies, including ubiquitous intelligence, web intelligence, brain informatics, social computing, big data, and security and privacy. The smart world integrates the physical, cyber, social and thinking spaces, as shown in Fig. 3. Concretely, the fusion of cyber–physical spaces relies on ubiquitous intelligence, the fusion of cyber–social spaces is driven by social computing, the fusion of cyber-thinking spaces requires brain informatics, and web intelligence is the kernel of the cyberspace. Additionally, big data representation & processing, and security and privacy protection are the common requirements for the hyperspace.

4.1. Ubiquitous intelligence

Ubiquitous intelligence [85] integrates the cyberspace and physical space and leverages the pervasively interconnected ubiquitous things [1], essentially refers to technologies in devices, networks and context awareness.

- *Device awareness* involves device intelligence that allows proactive awareness of the environment via ubiquitous things. Manifold ubiquitous things have been designed to augment the experience of life. U-things usually involve multiple elements, such as communicators, multimedia entertainment and business processing devices. Based on the characteristics of the applicability of embedded objects, ubiquitous things can be divided into five classes: accompanying, portable, hand-held, wearable, implanted or embedded. All these devices differ in terms of their computing resources; they are designed to be tailored to diverse application scenarios. An accompanying device can be conveniently taken along with the clothes. Portable devices are usually designed for two-handed operation and have the much stronger computing capability. Handheld devices are usually operated by hand and have relatively low computing resources. Wearable devices are usually operated hands-free and run autonomously. Implanted or embedded devices are cyber objects embedded into physical substance and used to intelligently sense and act on the physical space.
- *Network awareness* is embodied by network intelligence with the ability to autonomously interconnect ubiquitous things. However, the diverse districts and variety of ubiquitous things face rigorous network challenges. The network is essentially heterogeneous, featuring a mixture of various network forms with different protocols, interfaces, rates and stabilities. Examples include existing wired and wireless networks, LAN and Internet, IP based and nonIP (e.g., Zigbee). It is definitely a tricky task to support seamless migration in a heterogeneous network. Several architectures are presented to address the heterogeneity of diverse networks [86]. iCAR system applies dual interfaces to integrate cellular and ad-hoc networks and mainly focuses on improving channel capacity under cell congestion. In [87], a unified architecture was proposed for integrating cellular and ad-hoc networks. The authors used mobile clients as relays to enhance the data throughput under a single cell without additional cost. To account for seamless migration in a heterogeneous network, Bell Labs proposed Mobile IP [88] technology, which provides a type of solution for seamless migration in complex and heterogeneous networks. PIE (personal information environment) [89], started by IBM, integrates the same user's personal information on multiple devices into heterogeneous networks and provides a solution to enable the seamless migration of a user's property. Another critical technology in network intelligence is deep packet inspection, which provides a promising approach for improving the business intelligence of data networks, to help understand users' activities and marketing requirements.
- *Ubiquitous intelligence* can offer proactive and adaptive computing services through context-aware technologies. Context awareness is an intelligence that can be seen as the process of using context (situation, entity can be person, place or object) to provide information or services to users. In Smart Space, the goal of the context awareness system is mainly to perform tasks that explicitly acquire context from underlying sensing devices, such as RFID, a location tracker, or a temperature sensor. To accomplish this goal, suitable context representation models and reasoning approaches should be researched to enable high-level semantic acquisition of the raw sensing data. The typical approaches can be mainly divided into knowledge based [90] and probability based [91,92]. All the disperse ubiquitous things are connected via a network and can be coordinated in a distributed way to exhibit smart capabilities by leveraging context-aware technologies.

4.2. Web intelligence

Web intelligence is the combination of artificial intelligence and data processing technologies in the field of the Web or Internet [93]. Artificial intelligence can involve knowledge representation, knowledge discovery, data mining, intelligent agent, and other areas. Data processing technologies involve communication, cloud computing, ubiquitous devices, and more. All these technologies propel the research and development of new-generation web science. Web Intelligence Consortium (http://wi-consortium.org/) has been established, and IEEE/WIC/ACM International Conferences on Web Intelligence have been initialized to conduct the related researches.

Web intelligence has shaped and constructed the smart world from multiple application requirements. In business applications, web mining and multi-agent technologies are applied to create smart business. Web mining is used to discover and extract information by leveraging data mining technologies [94], which mainly address, business analysis of customer data (e.g., browsing and purchase record) to support business decisions. Moreover, multi-agent technologies such as risk management, and management simulation, in which each agent acts as a self-organized and autonomous software element to automatically make decisions according to common sense and knowledge, greatly benefit e-commerce. The coordination of multiple agents allows complex tasks to be partitioned and accomplished by a single intelligent agent. There are web intelligence applications such as medical services [95] and education [72].

Web of things (WoT), as an emerging web intelligence, further incorporates ubiquitous things into the Web and expands the scope of web intelligence towards cyber, physical and social spaces. Specifically, WoT can model the function of ubiquitous things as linked resources [23] and provide a uniform access interface for users' required computing services (e.g., global weather data and geographic data). These data can be integrated into the WoT and become conveniently available to the public. Improving the WoT is based on allowing each thing in the WoT to be aware of each other and offer the right service for the right object in the right context, leading to the coinage of the term wisdom WoT (W2T) [96]. The data of ubiquitous things in the wisdom WoT can be parsed and abstracted as knowledge to support higher applications. Likewise, the applications exhibited on the Web can act on underlying smart devices or ubiquitous things to form a data cycle for the wisdom WoT.

4.3. Brain informatics

Brain informatics focuses on human brain information processing in macro and micro levels by experimental, computational, and cognitive neuroscience [29]. It examines the human brain from an information perspective and also uses informatics to support brain science. Here, web intelligence is promising and applicable to brain informatics, providing a powerful platform. Agent-based grid mining technology is adopted to build brain portals [97] and is available to represent information and obtain knowledge from source data produced by brain measurement instruments (e.g., fMRI). Moreover, a brain information based cloud platform is established to realize human-level collective intelligence and mind sharing for providing wisdom services [32].

From the perspective of brain–computer interaction, the cyber individual (Cyber-I) becomes an attractive concept [30]. Each individual in the physical space corresponds to a virtual human in the cyberspace. The virtual human is a digital description for a real human, including thinking, emotion, personality, and behavior. Cyber-I provides an evaluation platform for cognitive model and personal attributes. For brain–computer communication [98], brain signals can be detected by electroencephalogram (EEG), brain–computer interface (BCI) and other equipment for translation into device control signals. Using this method, BCI helps users convey their wishes (e.g., operate a robot arm or type a word). BCI as a bridge will narrow the gap between cyberspace and thinking space. Some BCI systems have been developed for diverse applications, e.g., eye-gaze EEG-based BCI [99] and wearable sensor arrays [100].

The brain data modeling represents functional relationships among different brain data resources, and brain information processing systems are presented for systematic investigation and understanding of human intelligence [101]. A systematic methodology to investigate human information processing mechanisms includes four core issues: systematic investigation of cognitive experiments, systematic human brain data management, and systematic human brain data analysis and simulations. According to such a brain informatics methodology, data cycle is proposed referring to measuring, collecting, modeling, transforming, managing, mining, interpreting, and explaining. A brain data model can be constructed to explicitly indicate the relationships among various human brain data sources [102]. Generally, conceptual modeling of data is an effective mechanism to integrate data, information, and knowledge for various data utilizations coming from information systems. However, the conceptual model of brain data should be a new-style conceptual model of data, which is oriented to various data requests coming from information systems. The existing studies on conceptual modeling of brain data include the following three types: conceptual schema design of brain database (e.g., electroencephalo graph database, and neuroimage database), conceptual schema design of metadata, and domain ontology modeling. Graphical modeling language such as View-Fact-Dimension-Model [103], Entity-Relationship (ER) model [104], and OWL (web ontology language) [105], are also available for practical applications.

4.4. Social computing

Social computing and sensing focus on the fusion technologies in cyber, physical and social spaces. Social computing investigates social activities and behavior from the macro view, whereas social sensing focuses on examining the social interaction from the technical view. Specifically, based on sensing data from human mobile devices, social interaction can be analyzed and augmented via data mining and computing aid technologies. There are several issues as follows:

- *Real-time data sensing:* A substantial number of sensor devices can be used to sense social individual activity data. The social sensors should support the real data transmission under a complex environment and have much better mobility for tailoring to changes in individual activities.
- *Human interaction behavior analysis:* Research can be conducted on individual behavior recognition and analysis. Based on the study of individual behavior, mobility and interaction, aspects of group social interaction, such as group formation, organized structure, and interaction patterns, can be investigated by social network analysis, machine learning and data mining.
- *Efficient social interaction support:* As the basis of understanding the individual social interaction, it is necessary to examine strategies and mechanisms for supporting efficient and smart social interactions.
- *Social sensing software framework design and methodology:* Research on systematic design methods for developing the software infrastructure of social computing and sensing.
- *Social computing or sensing applications:* Research on applications to multiple domains, for instance, health care, public security, smart intelligent transport, and urban management.

Social computing involves human–computer interaction, social network analysis, and sociological, psychological, economic, and anthropological theories [25]. For instance, Lazer et al. [106] mentioned that the data from our daily life such as phone calls, emails and e-commerce portals can be used to help understand the individual, organization and society. Social sensing is applied to sense social interactions, and to collect information from a large number of people for drawing an overall picture for analyzing dynamic social interactions. Crowd density can also be estimated by estimating the density of Bluetooth devices in public health services.

4.5. Big data

The data in the smart world originate from the whole of the cyber, physical, social and thinking spaces; therefore, it demonstrates the features of big data. Specifically, big data exhibits volume, variety, veracity and velocity. However, it is challenging to represent and process the data from the smart world because such data are typically heterogeneous and voluminous. Furthermore, unstructured, semi-structured and structured data are mixed in the smart world, imposing heavy burdens on the current computing infrastructure. The essential technologies of big data mainly involve two features: big data representation and processing techniques.

- *Big data representation*: Big data representation and processing will be the fundamental technology to enable the smart world. To effectively represent the various types of data in the smart world, an appropriate representation model is required. Existing approaches use logic and ontology to describe the model. However, most of them cope poorly with unstructured data. Hence, a unified data representation model is needed to counter this problem. A tensor model is employed to integrate and represent the unstructured, semi-structured, and structured data in uniform [107]. The tensor model is scalable and makes it possible to dynamically append new orders using a tensor extension operator.
- *Big data processing*: To efficiently process large-scale data, existing approaches mainly address this issue by dimension-reduction techniques, which can significantly reduce the number of variables in big data and avoid the effect curse of dimensionality. In particular, PCA [108], SVD [109,110] and ICA [111,112] based methods are usually used to enable dimension reduction. The core concept of all these approaches is to reduce the data volume by removing redundant or useless variables from the data. For nonlinear dimension reduction techniques, multidimensional scaling (MDS) [113] can map the high-dimensional data representation while maintaining the pairwise distances between data points as much as possible. Similarly, Isomap [114] retains the geodesic distance between data points. Moreover, a neural network also can be used to perform dimensionality reduction. The basic

idea is that high-dimensional data can be converted to low-dimensional code via a multi-layer neural network [115], and machine learning techniques can be used to obtain a suitable initial weight for the neural network.

Although multiple approaches can address dimension reduction, these approaches are oriented only to relatively low dimensions and are unable to adapt to exceedingly high dimension (i.e., more than 10 dimensions) reduction under the smart world application scenario. Tensors provide a very promising solution for enabling very high dimension reduction. Kuang et al. [107] proposed using the recursive incremental high order singular value decomposition (HSVD) method to address the issue. The computing can be performed on streaming data to efficiently gain the core data set. In addition, dimension reduction is computationally intensive, and it is difficult to speedily obtain the core data set. Lanczos-based high order singular value decomposition [116] proposes that the decomposition can be distributed in a cloud computing platform to efficiently process big data. In short, tensor decomposition will provide the opportunity to effectively and efficiently process big data in the smart world.

4.6. Security and privacy

Security and privacy are critical factors that will significantly influence the development of the smart world. Existing technologies are insufficient for addressing the issues of security and privacy and the structure and security level because, the smart world involves the data fusion of four dimensional spaces. Worse, existing technologies cannot counter the threats for BCI when the thinking space is highly fused with the other three dimensional space because this situation provides multiple sources at which hackers can attack the systems. Hence, the aspects of security and privacy are expected to be concerned.

First, most existing security solutions are aimed at cyberspace, physical space and social space, such as research on examining the security of smart grids [117], security and privacy for smart vehicles [118], and privacy for smart healthcare [119]. All these domains are facing grand challenges from the cyber, physical and social space, where various types of attacks are found. Typical security attacks involve data gathering, imitation and blocking [120]. To conquer the issues of security and privacy for this triple space, a cyber–physical–social-based security architecture is proposed for the future IoT [121], and security management, physical security and information security are considered to address the different security requirements of IoT layers. With reference to security, data anonymity, confidentiality and integrity need to be guaranteed, as well as authentication and authorization mechanisms in order to prevent unauthorized users (i.e., humans and devices) to access the system.

In the thinking space, which is closely related to the security and privacy of BCI. With the rapid development of brain–computer interaction technologies, a host of emerging BCI applications has been developed. The accompanying security and privacy problems of BCI can badly affect the widespread application of BCI and result in emotional and physical harm to individuals. The first malicious BCI application is called brain spyware, which can extract private information such as credit card passwords from users' EEG signals. A feasible approach to prevent and mitigate BCI attacks is enabled by the BCI anonymizer [95]. Its basic concept is to pre-process neural signals before they are stored and transmitted, allowing all illegal information to be removed except the required command for the BCI. The future advancement of the security and privacy of BCI will rely on the coordination of neural scientists, engineers, ethicists, and governments. For the smart world, invading the brain may not be a vision restricted to science fiction movies as the cyber–physical–social-thinking hyperspaces are highly interconnected and can be interoperated.

5. Perspectives

The smart world is becoming more attractive, with qualitatively different lifestyles and trends to achieve fusion of physical perception, cyber interaction, social correlation, and cognitive thinking through a perfect convergence of the cyber–physical–social-thinking hyperspace.

The ultimate goal of the smart world is to achieve the harmonious symbiosis of humans, computers, and society. However, there are various impediments to establishing the future smart world, which refers to an interdisciplinary domain with branches such as computer science, mathematics, physics, sociology, psychology, and philosophy. The smart world will benefit from the improvement and diffusion of these areas. According to the results of the open forum "Top 10 Challenges for Smart Worlds" in Smart World Congress [72], the increasing interest and crucial research challenges mainly involve ubiquitous sensing, ubiquitous object modeling, smart services, and philosophical, ethical and legal challenges impeding the deeper integration of cyber–physical–social-thinking spaces and the development of the smart world.

5.1. Ubiquitous sensing

Not only does ubiquitous sensing promise to enhance awareness of the cyber, physical, and social contexts, but it also captures thinking or mental activities such as cognitive load, fatigue or emotion, thus providing support for services and applications. Ubiquitous sensing directly acts on heterogeneous environments, which is electronic-enhanced real spatial environments covering both internal and external environments of the ubiquitous things. Here, the internal environments refer to the objects' self-condition and status, and the external environments include not only the relatively powerful components (e.g., gateways), but also the concrete geographic positions.

Ubiquitous sensing is tightly coupled with activity recognition by a rapidly growing number of sensors and continues crossing new barriers, giving us new ways to interact with the environment. For instance, several smart and aware environments, include classrooms, living rooms, meeting rooms, and offices are developed and implemented incorporating into ubiquitous sensing and recognition. There are three main requirements for the environments: *Existence*: The u-environments are physical environments equipped with electronic or mechanical devices and embedded systems, which are in different shapes, sizes, forms, and functions; *Irritability*: The u-environments own different levels of perception, cognition, analysis, reasoning and anticipation abilities for the internal and external surroundings, on which proper actions are performed as responses; *Serviceability*: The u-environments aim to provide suitable services to users without hardware limitations.

There are several features for ubiquitous sensing as follows:

- *Self-calibration*: As the converged spaces can dynamically change, the sensors in an aware environment need to be able to calibrate automatically and adapt to the environment as needed through communicating their state and their coverage area to each other and develop a model of the environment [122].
- *Networking*: Combinations of processors and sensors needed to build aware environments require an elaborate networking infrastructure to support both high-bandwidth and low-bandwidth data transmission as determined by context and sensor/processor abilities.
- *Distributed computing*: The computing infrastructure serves as the brain for the environment where all the information regarding space is processed.

- *Various sensors*: include optical and audio sensors, mobile and wearable sensors [123], embedded sensors, and etc. For example, modern smart phones are equipped with a variety of sensors that can be used to continuously monitor the activities and locations of the users.

There are massive amounts of information on physical, social, and thinking spaces. However, the sensing resources exploited to accomplish the mapping of physical space, social space, and thinking space to cyberspace are limited. The contradiction of the information explosion and limited sensing resources is the pressing problem in ubiquitous sensing. Thus, it is critical to explore solutions from selective sensing and resource management optimization. Meanwhile, there are some hot topics for ubiquitous sensing research.

- Human-centric sensing focuses inward and attempts to capture mental activities (e.g., cognitive load, fatigue, and emotion), and interpretation of eye-gaze sensing and body gestures/postures.
- Smart phone-centric ubiquitous sensing applications, which use a smart phone in conjunction with external sensors for data acquisition, processing, display, communication, and storage.
- Application and experimental evaluation of quantitative verification of sensor-enabled systems.

5.2. Ubiquitous object modeling

The ubiquitous objects are defined referring to the physical objects which are attached, embedded or blended (AEB) with computers, networks, and other terminals. They can own full capabilities of sensing, actuating, computing and communicating due to device miniaturization and wireless communications. ubiquitous objects are such ones which can sense, actuate, compute, communicate, and perform adaptive actions, reactions and pro-actions according to the dynamic situations.

With the rapid development of the smart world and its applications, the quantity and variety of objects in the physical, social and thinking spaces that connect to the Internet and their interactions are growing rapidly. Ubiquitous object modeling refers to mapping relations between physical–social-thinking spaces and cyberspace such that objects map into cyberspace as virtual entities. On the one hand, objects in physical and social spaces feature unique characteristics that continue under the constraints of time and space. However, the virtual entity counterparts of physical and social objects in cyberspace, in most cases, can lead to mapping inconsistency, which is an essential and core challenge. On the other hand, a single object has various attributes in heterogeneous and diverse spaces: even in thinking space, it is difficult to capture the attributes of a human, which is the bottleneck for further study.

5.3. Smart services

The smart world is envisioned as an era in which ubiquitous things can automatically and intelligently serve people in a collaborative manner. There are a large number of applications that can be included as smart services. According to technical features, smart services can be divided into four types: identity-related services, information aggregation services, collaborative-aware services, and ubiquitous services.

Ubiquitous services aim to apply service oriented architecture (SOA) to maintenance service of IoT systems, which still carry a huge potential for further gains in cost and energy savings. In SOA based IoT systems [124], each device is a service consumer and if desirable can be a service provider offering services or share resources and interacts with service consumers via compatible service APIs. SOA technologies (such as REST, CoRE) enable publishing, discovery, selection, and composition of services offered by IoT devices. The important application scenarios proposed for SOA-based IoT systems include e-health (continuing care) [125] smart product management, smart events for emergency management, etc. More specifically, service management suffers from serious resource-centered issues, including semantic resource description, on-demand resource allocation, automatic resource discovery, and cooperative resource sharing. Moreover, online resource-based cloud services also introduce challenges in providing more accurate services for an individual or a group. Especially, although lots of IoT (Internet of Things) applications have been developed, the systematic method to construct IoT services is still obscure. To address these issues, an event-driven service-oriented architecture for IoT services is proposed, which separately use resource information to create IoT services, use independent and shared events to run the IoT services, and use the event session to coordinate the IoT services. The other architecture called a wisdom as a service (WaaS) architecture of IT applications is presented.

According to the challenge that online resource-based cloud services need to provide more accurate services for an individual or a group, there are a large number of solutions focused on service discovery, selection, and composition [27].

5.4. Philosophical, ethical and legal issues

The smart world launches inevitable rethinking of philosophical, ethical and legal issues. The future world becomes more controversial because of merging of the thinking space into the cyber–physical–social spaces. Research on human beings, such as brain informatics, are suspected of illegal use. The importance of a broad social acceptance of the smart world and some related ethical and privacy questions must be addressed simultaneously, assessing the human, social, and environmental risks [7].

In the future, people will live in a smarter environment overlaid with sensing, actuating and computing technologies, where humans will be responsible only for providing the creativity. A green IoT targeting in a sustainable smart world is imperative, by reducing the energy consumption of IoT [17]. Even the environment as a whole tends to become a more subservient artifact. In this sense, the world immediately surrounding us becomes almost entirely integrated with us and will almost disappear someday.

6. Conclusion

The smart world represents a high-potential research area whose significance is growing rapidly due to increasing academic and industrial demands. In this work, on the one hand, development history, related research projects, driven elements, smart applications, and enabling technologies are reviewed in the field of the smart world. The smart world, as a quaternionic convergent world, is characterized by four fundamental features: physical based, cyber-enabled, socially inspired, and brain abstracted. The smart world is increasingly progressing along with a further fusion of cyber–physical–social-thinking hyperspace characterized by ubiquitous interconnection, intelligence, and computing. U-things such as physical objects, cyber services, social people, and cognitive thinking are defined as minimum elements with ubiquitous intelligence to construct the smart world. On the other hand, future research trends and challenges emphasize fine-grained ubiquitous intelligence, which is characterized by the features of seamless connection, flexibility, controllability, and humanization. Smart applications highlight the tradeoffs of specific functionality requirements, user-friendliness and privacy. More studies will be necessary regarding user lifestyles, satisfaction, requirements,

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security, and adaptation to smart systems. We optimistically look forward to a ubiquitous IoT-assisted world that is both connected and smarter due to ubiquitous sensing and ubiquitous modeling to provide a variety of smart services. The smart world is expected to be an indispensable research area influencing future academia and industry.

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