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Cybermatics: Cyber–physical–social–thinking hyperspace based science and technology

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HIGHLIGHTS

- We establish a cyber–physical–social–thinking (CPST) hyperspace architecture to explain the Cybermatics.
- Interconnected Cybermatics refers to dynamics and variability of Internet of anything.
- Intelligent Cybermatics considers computing algorithms for system infrastructure.
- Green Cybermatics addresses energy issues to ensure efficient communications and networking.

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ABSTRACT

The Internet of Things (IoT) is becoming an attractive system paradigm, in which physical perceptions, cyber interactions, social correlations, and even cognitive thinking can be intertwined in the ubiquitous things' interconnections. It realizes a perfect integration of a new cyber–physical–social–thinking (CPST) hyperspace, which has profound implications for the future IoT. In this article, a novel concept Cybermatics is put forward as a broader vision of the IoT (called hyper IoT) to address science and technology issues in the heterogeneous CPST hyperspace. This article covers a broaden research field and presents a preliminary study focusing on its three main features (i.e., interconnection, intelligence, and greenness). Concretely, interconnected Cybermatics refers to the variants of Internet of anything, such as physical objects, cyber services, social people, and human thinking; intelligent Cybermatics considers the cyber–physical–social–thinking computing to provide algorithmic support for system infrastructures; green Cybermatics addresses energy issues to ensure efficient communications and networking. Finally, open challenging science and technology issues are discussed in the field of Cybermatics.

1. Introduction

The Internet of Things (IoT) becomes an attractive system paradigm to realize universal interactions among the ubiquitous things through heterogeneous spaces. The future IoT is expected to be characterized by the comprehensive perception, reliable transmission, and intelligent processing to achieve pervasive interconnections, intelligence, and efficiency [1,2]. It enables things to establish dynamical and seamless interconnections across heterogeneous spaces. During the things' interactions, it brings out a series of explosions of connection, information, service, and intelligence. Smart connectivity and effective interactions for addressing a certain task with an ultimate performance are highly demanding trends. It will bring an inevitable reconfigurable combination of emerging science and technology issues to launch a new research area.

To trace the derivation of the IoT, it is originated from the networks of computers, which realizes the connections among multiple devices in the computer networks. Afterwards, the Internet of Computers (IoC) emerges to address the cyber entities' data exchanging in the cyber space. Along with the wireless sensing and mobile communications being involved into the Internet, physical objects (e.g., passive tags) establish interconnections with backend databases via the standard communication protocols.

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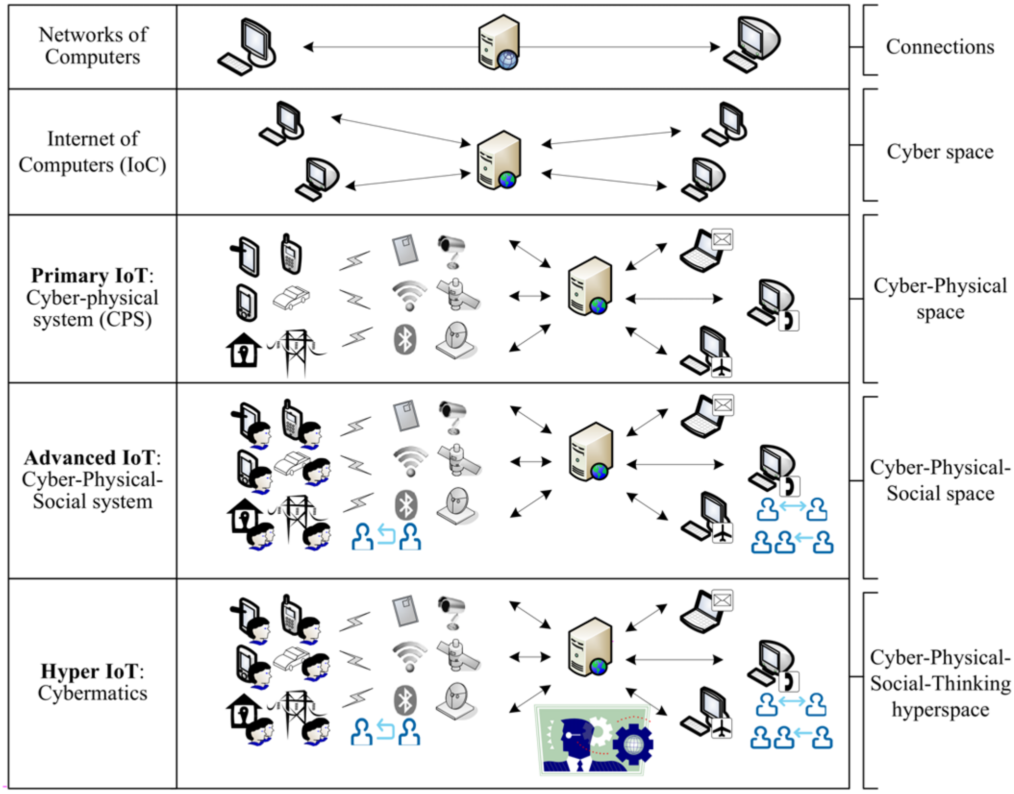

Fig. 1. The main phases in the evolution of the IoT.

Accordingly, the cyber–physical system (CPS) appears to be an embryonic form of the IoT, which is an integration of computation, networking, and physical processes, and realizes that the physical objects are mapped into the cyber space as the cyber entities for more convenient interactions. Thereafter, the social attributes (e.g., ownerships, and affiliation relationships) are considered to address the complicated interconnections, and to achieve the interfusion of the cyber–physical space and social space. It brings an advanced version of the IoT, called cyber–physical–social system.

Beyond the informationization and intelligentization requirements, the IoT confronts another challenging issue, which requires the IoT should evolve towards a wise and soulful ecosystem with more abstract human thinking participation (e.g., wisdom, attention, emotion, self-awareness, and subconsciousness). The future IoT not only considers human cognition capacities (e.g. brain's visual signal processing, neuron reflex, and attention distribution), but also learns much from the society principles. Thus, it is necessary to introduce human intelligence and social organization for designing a harmonious system architecture [3–5], and the cyber–physical–social–thinking (CPST) hyperspace is accordingly established by merging a new dimension of thinking space with the cyber–physical–social space. Note that wisdom along with the intelligent interactions of data, information and knowledge are through the CPST hyperspace. Fig. 1 illustrates the main phases during the evolution of the IoT.

The CPST hyperspace derives from an attractive item "hyperworld" [6], which has a basic characteristic of direct mapping between virtual and real worlds via active devices (e.g., sensors, actuators, and middlewares). Along with the development of smart computing, the hyperworld is assigned with more characteristics (e.g., ubiquitous services and connections) [7]. Currently, the hyperworld is developing into CPST hyperspace by coupling data, information, knowledge, and cognition related cyber interactions, physical perceptions, social correlations, and human thinking. The CPST hyperspace has three basic implications: *integration*, *interconnection*, and *interaction*.

1. The CPST hyperspace is integration of multiple spaces involving the cyber–physical–social–thinking elements. There may be different space combinations, such as cyber–physical space, cyber–social space, cyber–thinking space, and cyber–physical–thinking space;
2. The CPST hyperspace is interconnection of multiple spaces, which are interlinked with each other referring to the same type of space (e.g., several physical spaces being connected), or different types of spaces (e.g., physical space and thinking space being connected);
3. The CPST hyperspace is interaction of multiple spaces via the cyber space, and establishes communications for exchanging information to achieve ubiquitous intelligence.

Based on the CPST hyperspace, we propose a novel concept Cybermatics, which is regarded as a broader vision of the IoT (i.e., hyper IoT) to address the science and technology issues in the heterogeneous spaces. This article covers a broaden research field and presents a preliminary study focusing on its three main features: interconnection, intelligence, and greenness.

- Interconnected Cybermatics referring to the dynamics and variability of the IoT (i.e., Internet of Anything), indicates that the things establish seamless connectivity according to the physical perception, cyber interactions, social correlations, and thinking communications. It mainly refers to the variants of Internet of Objects (IoO), Internet of Services (IoS), Internet of People (IoP), and Internet of Thinking (IoTk).
- Intelligent Cybermatics regarding super-mechanisms for harmoniously addressing the CPST hyperspace, mainly focuses on the cyber–physical–social–thinking computing to provide algorithmic support for system infrastructures. The algorithms convert the raw sensing data into abstractions to provide reasonable, accessible, and understandable for human beings, along with the human's cognition being extracted for wisdom.

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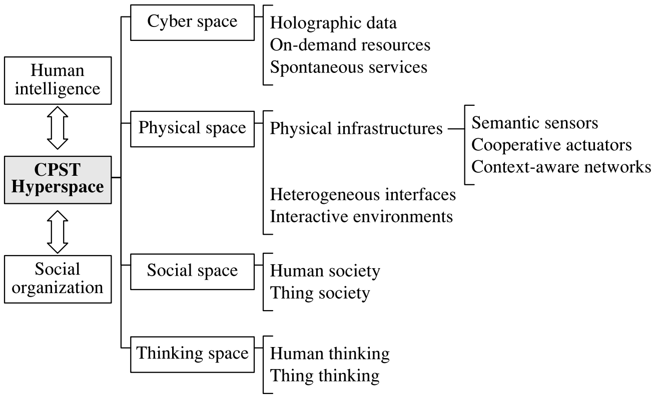

Fig. 2. The CPST hyperspace and its main components.

- Green Cybermatics aims to address energy issues to ensure efficient communication and networking in the hyperspace, and to provide power-saving mechanisms for minimizing energy consumption in sustainable networks.

The remainder of the paper is organized as follows. Section 2 presents the established CPST hyperspace. Section 3, Section 4 and Section 5 respectively introduce the related works on the interconnected Cybermatics, intelligent Cybermatics, and green Cybermatics. Section 6 discusses the open challenges, and Section 7 draws a conclusion.

2. The cyber–physical–social–thinking (CPST) hyperspace architecture

The CPST hyperspace covers the cyber space, physical space, social space, and thinking space. Fig. 2 shows the CPST hyperspace and its main components involving the cyber, physical, social, and thinking dimensions, which involves human intelligence and social organization to ensure the organic interactions among ubiquitous things.

2.1. Cyber space

Cyber space is derived from the terms of "cybernetics" and "space" in control networks. Along with the prosperity of the Internet, the cyber space is assigned with more representations. In the Cybermatics, it refers to the generalized information resources, including virtual and digital abstractions to achieve interconnections among cyber entities. Note that a cyber entity may have multi-identity status (including a core identity and other temporary or assistant identities), and is independent of space–time constraints. The cyber infrastructures are required to support uniform standards and protocols, and to transform the cyber space into a self-developing intelligent information computing ecosystem [8]. During the cyber interactions, a cognitive information framework is a central component to provide the intelligent data, resource, and service management. It indicates that holographic data management, on-demand resource management, and spontaneous service management should be considered to achieve intelligence during cyber interactions.

- *Holographic data management* aims to provide holistic data services for massive data storage. The emerging cloud storage and cloud computing realize the data remotely stored in an online cloud server without considering the local infrastructure limitations. In the Cybermatics, data management is mainly based on loosely federated distributed database through public interfaces to provide approaches for storage, retrieval, and maintenance. The data management technologies (e.g., data mining, and data fusion) should be developed to reduce data redundancy, and to enhance the flexibility of data discovery [9,10]. Besides, several platforms such as IBM InfoSphere and EMC Greenplum, have emerged for big data management with high performance, polymorphic storage, and unlimited linear scalability.
- *On-demand resource management* is to address cyber resources in virtual computing environments, in which resource management mainly refers to the resource naming (e.g., resource description framework (RDF), and web ontology language (OWL)), resource addressing (e.g., domain name system (DNS)), resource discovery (e.g., distributed hash table (DHT)), and resource allocation. Several computing technologies (e.g., autonomic computing, utility computing, and grid computing) are available for on-demand resource provisioning. Meanwhile, virtual machine (VM) technology is available for the fine-grained cloud resources without compromising the quality of service (QoS). On-demand resource strategies, which scale energy consumption with the dynamic demands, can also enhance the green communications and networking [11].
- *Spontaneous service management* manages online spontaneous services during distributed interactions. In order to achieve heterogeneous services, simple object access protocol (SOAP) based web resources and RESTful web resources can be applied to support dynamic service provision. Thereinto, resource-oriented architecture (ROA) is a RESTful architecture, which provides a commonsense set of rules and procedures for designing RESTful web services according to the principles of addressability, uniform interface, and statelessness [12]. Additionally, multicast mechanisms (e.g., web service discovery) can be applied for providing service discovery, and context-aware service adaptation should be addressed considering the mobility, convergence and integration of emerging wearable devices.

In the Cybermatics, virtual networks (e.g., virtual local area network (VLAN), and virtual private network (VPN)) and virtualization (full, partial, and paravitualization) bring positive perspective for the resource-constrained network components in the cyber space.

2.2. Physical space

Physical space refers to the real world conceived in linear dimensions, in which physical objects are respectively perceived and controlled by sensors and actuators to establish interactions via the communication channels, remote collaboration, real-time localization, and autonomy maintenance. A physical object may be mapped into the cyber space as single or multiple cyber entities for interconnections, during which energy consumption, electromagnetic spectrum compatibility, and space–time consistency should be considered to achieve the seamless mapping of the cyber–physical space. The physical space mainly addresses the issues of physical infrastructures, heterogeneous interfaces, and interactive environments. For the physical infrastructures, the main components (e.g., sensors, actuators, and networks) are assigned with advanced requirements.

- *Semantic sensors*: Sensors act as detectors and converters to capture the physical data for pervasive perception, and are mainly low-cost devices with the limited storage, power, computation, and communication capabilities. In the Cybermatics, semantic sensors can be designed to manage the massive data, for which hybrid sensing modes are available to achieve an ambient intelligence (referring to an object is sensitive and responsive to the presence of other objects). The smart sensors provide semantic-integration context awareness to support adaptability and scalability of meta-services. Note that participatory sensing is

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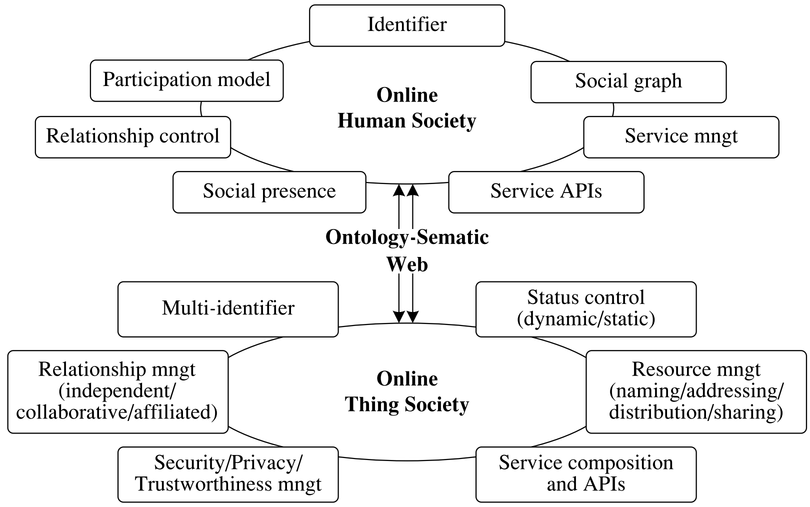

Fig. 3. The online human society and thing society.

proposed as an automated sensing system [13], whereby individuals and communities use mobile devices to capture the surrounding data (e.g., time-location trace), and it offers unprecedented observational capacity at the scale of individuals. Additionally, satellite-routed sensor systems [14] appear to realize global-scaled data collection, in which "divide and conquer" approach is utilized to enhance effective data perception.

- *Cooperative actuators*: Actuators have the functions of automation and control, and convert the collected physical data into action commands to realize enhanced efficiency in self-adaptive mode [15]. In the Cybermatics, collaborative actuators should be organized in network-connected ecosystems to achieve aggregated functionality.
- *Context-aware networks*: Context-aware networks are the synthesis of the dumb networks and intelligent computer networks. Thereinto, the dumb networks apply the intelligent peripheral devices and a core network without controlling or monitoring application creation or operation, and the intelligent networks prefer to supply, monitor and control application creation and operation. The ambient networks infrastructures realize the main functionality including context information gathering, processing and distributing [16]. In the Cybermatics, there are wired and wireless networks in the contexts, in which the wireless networks appear to be more flexible with the enhanced mobility and scalability. However, the wireless network technologies bring several open issues [17], referring to the hybrid network structure (e.g., heterogeneous mode, and hierarchical mode), dynamic network deployment (e.g., one-time, incremental, and random), communication modality (e.g., single-hop, and multi-hop), network topology (e.g., single hop, star, multi-hop, mesh, and multi-tier), coverage (e.g., sparse, dense, and redundant). Thereinto, the context-aware mobile and wireless networking (CAMoWiN) is emerging to deliver a large amount of heterogeneous context via wireless channels.

Meanwhile, heterogeneous interfaces and interactive environments become noteworthy during the convergence of mobile communications, next-generation Internet, and cable television networks in the physical space.

2.3. Social space

Social space is a logical architecture, which is an integration of the social attributes and social intra-/inter-relationships owned by the human beings and other physical objects or cyber entities.

In the Cybermatics, the social space can be formally described in the semantic representations to address the issues such as ownership control management, affiliation relationship modeling, trustworthiness evaluation, and human behavior formalization. The human learning principles (e.g., cognitive psychology, and decision neuroscience) and social rules can be introduced in the human-thing coexistence, and the social space considers both human society and thing society, which include the offline and online modes. Note that the "thing" in the "thing society" refers to a narrow sense including a device, an equipment, and a physical object. The offline mode is the society in the real world, and the online mode is based on the social network platforms. Fig. 3 shows the ontology-semantic web based online human society and thing society.

- *Human society* provides supervision, organization, coordination, restraint, and other effects on the human activities and social events, and addresses the issues referring to educational training, behavioral conventions, legal regulations, social administration, public services, and economic supervision for the social participants. The Cybermatics promotes the recombination on social organizations, social morphology, and social relations. In the Cybermatics, social networking services accelerate the popularity of the online human society. In a typical online human society model [18], the human's profiling mainly includes identifier, participation model, social graph, relationship control, social presence, service management, and service APIs.
- *Thing society* refers to that a physical object establishes inherent and acquired relationships with other physical objects or cyber entities in both real and digital worlds. Things' social attributes reflect direct or indirect correlation with the affiliated human beings. Recently, a social network of intelligent objects, called social IoT (SIoT) is proposed based on the social relationships among physical objects [4]. There are several manlike socialized relationships in the SIoT, including parental, collaboration, ownership, communal sharing, equality matching, authority ranking, and market pricing relationships. Towards the online thing society, the things' profiling's main components include multi-identifier, status control, relationship management, resource management, and service composition/APIs. In the thing society, the social relationships are organized in an autonomous mode for improving the network scalability during service discovery. Additionally, the things could look for the desired services based on their friendships in distributed manners [19]. It is important to define

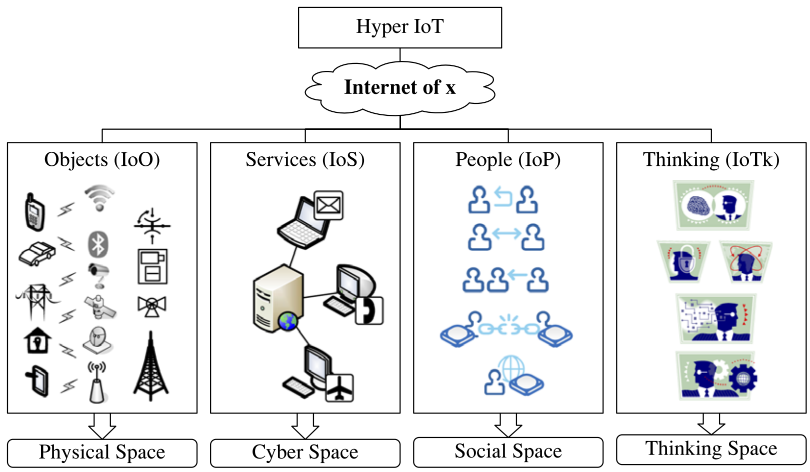

Fig. 4. The hyper IoT conceptual model.

appropriate rules for the things to select the right friends, which will impact the service performance in the thing society.

In the Cybermatics, the social space mainly focuses on the social factors, including organizational structure, standardization, social value system, and goal/task/context driven behaviors. Thereinto, service socialization becomes more noteworthy along with the development of social networking. Traditional services in the real world can be associated with those in the digital world to achieve enhanced effects. For instance, question-and-answer (Q&A) service's socialization becomes social Q&A (e.g., Yahoo Answer, and Quora), and location service's socialization brings the location-based social networking services (e.g., Foursquare). Based on the social relationships, the socialized services can provide more interested and valuable information for the circles of society. Moreover, socially aware networking (SAN) arises with social awareness (e.g., social relationships and interactions) considerations. This emerging SAN paradigm is applicable to several networks [20,21], including opportunistic networks, mobile social networks, delay-tolerant networks, and ad hoc networks.

2.4. Thinking space

Thinking space addresses thoughts and ideas related issues of the human beings and other things, which are reflections of human brain's activities and things' observations on the objective existence of the CPST hyperspace. There are both human thinking and thing thinking in the Cybermatics. Thereinto, the human thinking is regarded as the control of associating, which is described as "*a revolutionary step of the highest order directed against slavish obedience by the organism to environmental dictatorship*" [22]. The thing thinking shall be formed by learning from biological organisms' behaviors and activities. Note that the "thing" in the "thing thinking" has the same meaning with that in the "thing society", and refers to a narrow sense including a device, an equipment, and a physical object. Both human thinking and thing thinking include the process of analysis, synthesis, judgment, and reasoning based on the representations and abstract conceptions.

- *Human thinking* refers to the innate or acquired thinking activities to establish the direct mapping between the thinking space and cyber space. Human physiological and mental characteristics (e.g., conditioned reflex, attention allocation, and emotional control), can be introduced for designing more spiritual interactive mechanisms. The human thinking aims to perceive, interpret, represent and model the surrounding environments and contexts for decision making and forecasting. In the Cybermatics, there are typical human thinking methods (e.g., six thinking hats method, mind mapping, brainstorming, lateral thinking, funnel thinking, and scamper), and the merits of natural and social phenomena can also be absorbed by human beings for interpenetrative wisdom.
- *Thing thinking* is derived from Turing's open issue "*Can machines think?*", and developed to the question "*When things start to think?*" [23,24]. In the Cybermatics, the artificial intelligence (AI), intelligent real/virtual objects, and ubiquitous intelligence have become pervasive forms of the thing thinking. The thing thinking is originally based on the logic computing such as machine learning, expert systems, and natural language processing (NLP). Thereafter, a set of nature and manlike inspired intelligences emerge to support the thing thinking. Thereinto, the nature inspired intelligence is an anthropomorphic representation on natural criteria and natural phenomenas, including instinctive animal behaviors (e.g., spiders spinning webs, birds building nests, woodpecker anti-shock, and ants delivering food), and plant behaviors (e.g., positive heliotropism, and hydrotropism). The bionic algorithms such as ant colony optimization (ACO), genetic algorithm (GA), particle swarm optimization (PSO), and shuffled frog leaping algorithm (SFLA), are designed by imitating the behavior rules in the biological evolution and natural behaviors. Manlike intelligence algorithms (e.g., artificial neural networks (ANN), artificial immunity, emotion recognition, and fuzzy logic) are also popular to support the thing thinking. Meanwhile, social intelligence is applied to support the thing thinking in the terms of autonomy, multi-agent negotiation, and web semantics. Currently, the thing thinking prefers to invoke pervasive context-aware computing to achieve enhanced intelligence.

3. Interconnected Cybermatics: the Internet of anything

Interconnected Cybermatics refers to the dynamics and variability of the Internet of anything, which realizes the ubiquitous interactions through the CPST hyperspace. In this work, the variants of Internet of anything are explained according to the typical aspects of the Internet of Objects (IoO), Internet of Services (IoS), Internet of People (IoP), and Internet of Thinking (IoTk), as shown in Fig. 4.

3.1. Internet of objects

The IoO focuses on the connected physical objects to address data perception and network accessing issues, for which low-cost information gathering and dissemination devices are adopted to facilitate ubiquitous interactions. Thereinto, the physical objects are assigned with some kind of attachment, embedment, blending (AEB) of computers, sensors, actuators, networks, and other devices [25]. The generalized sensors are applied to capture potentially enormous amounts of data to realize target identification and object cyberlization. The main sensing and networking technologies include radio frequency identification (RFID), Bluetooth, ZigBee, Wi-Fi, infrared induction, ultra wideband (UWB), global positioning system (GPS), radar sensor network (RSN), and other mobile communications. Note that actuators (e.g., valve, and switch) can be connected with the sensors into the wireless sensor and actor networks (WSAN) to execute the appointed instructions and to perform networking related functionalities. Machine-to-machine (M2M) communications emerge as a promising communication paradigm, in which millions to trillions of machines connect to the mobile communications network infrastructures (e.g., the third generation partnership project's evolved packet system (3GPP's EPS)).

In the Cybermatics, identifiers (i.e., ID) and non-identifiers (i.e., nID) can be jointly applied for object identification. The concept of nID is originally proposed to describe the nID-objects (i.e., birds) in an airport aviation risk management [26]. Here, the nID-object indicates that the object has no available ID but need to be identified, recorded, connected and operated for utilization. The nID is necessary supplement to provide attribute related information for unique or non-unique identification and configuration. The typical nID involves the aspects of space–time, biometric, and physicochemical characteristics.

- *Space–time characteristics* can be used for object recognition based on temporal and spatial uniqueness. Thereinto, time information as a unique parameter is dynamically varied, and space information is also changed according to different positions.
- *Biometric characteristics* including physiological characteristics (e.g., fingerprint, DNA, hand geometry, palm vein, face, and retina/iris) and behavioral characteristics (e.g., typing rhythm, gait, and voice), can be applied for identification. The biometric characteristics should provide high identification accuracy in human interface applications.
- *Physicochemical characteristics* mainly refer to the non-unique attributes such as frequency spectrum, electromagnetic scattering, radar cross section (RCS), and photosensibility. The sensing technologies (e.g., radar, and infrared locator) are available for detecting such parameters.

3.2. Internet of services

The IoS is an ecosystem to adopt the Internet as a medium for service discovery, invocation and execution, and is envisioned as a global platform for the retrieval, combination and utilization of interoperable resources [27]. The complex applications based on the composition and collaboration among diverse services appear in cross-layer business domains, and the IoS facilitates real-time observation and adaptation of intra and cross interactions. Applying the IT technologies (e.g., electronic data interchange (EDI), remote procedure call (RPC), service-oriented architecture (SOA), and representational state transfer (REST)), web services are emerging as a collection of networked services accessible via standardized protocols, whose functionality can be automatically discovered and integrated to form more complex services in online applications. The web services are expected to act as enablers of seamless application-to-application integration. In the Cybermatics, SOA is a mainstream strategy for multiple application consolidation based on structured collections of discrete services. A set of formal approaches such as web service description language (WSDL), universal description, discovery, and integration (UDDI), and business process execution language (BPEL), are used for defining the web services. In the SOA frameworks, the configurable services interoperate with other services to support business processes spanning across organizational boundaries.

In the Cybermatics, cloud computing plays a major role for the IoS, enabling the on-demand provisioning of applications, platforms, and computing infrastructures [28]. Current cloud service frameworks (e.g., cloud storage, and cloud computing) realize individual data remotely stored in an online cloud server, and provide great conveniences for users to enjoy the on-demand cloud services. Towards the cloud services, everything as services (XaaS) virtualizes the distributed resources (e.g., servers, networks, and storage) in a common pool. Besides the infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS), there are additional service forms (e.g., data/information/knowledge/network/communications as a service) to achieve universal service provisioning, and wisdom as a service (WaaS) is an attractive conception for the future XaaS [29]. In the Cybermatics, a suite of management tools, including service instance life-cycle management, metering, billing, and dynamic configuration, are applied in large-scale cloud applications.

Recent projects have been launched to support the IoS. For instance, the ICT collaborative project—collaborative open market to place objects at your service (COMPOSE) [30] is developed for seamless service integration. It provides an open and scalable infrastructure, in which associated services can be combined, managed, and integrated during interactions. The cross-European technology platforms (X-ETP) group's future internet research agenda analyzes the research issues for the IoS. Dissimilar service requirements are presented for both single and multiple infrastructure providers [31].

- *Single infrastructure providers* should support the dynamic service provisioning, QoS, service level agreement negotiation, service scalability, service payment, and context-aware services.
- *Aggregating infrastructure providers* should address the service deployment across different providers, and enable the interoperability and portability of the distributed services.

3.3. Internet of people

The IoP addresses the human beings oriented applications, in which a person is a full peer with other networked persons for unrestricted interaction and resource sharing. The IoP confronts serious challenges, for which the social and economic contracts for individuals and organizations are undergoing a fundamental change in the future digital societies [32]. In the real-time data driven interconnections, the networked people are assigned with the capabilities of accessing transparency, dynamic participation, and accountability.

In the Cybermatics, a social network may be an embryo of the IoP, referring to an online social architecture composed by social actors (e.g., individuals, and organizations) and the corresponding dyadic ties [33]. The web based social networks realize to connect people who share the interests and activities without political, economic, and geographic boundaries. From the perspective of social networking services, the whole structure of social entities can be analyzed to identify the local/global social patterns, determine the influential entities, and monitor social relationship topology dynamics. The social networks can be regarded as the reflection of human society and thing society, and the interdisciplinary approaches including psychology, sociology, statistics, and graph theory can be introduced to analyze social network services. Thereinto, ontology based semantic descriptions can be applied to describe the social structures, nodes and edges, the social network data should be anonymized for analysis with user privacy considerations, and adaptive algorithms may be applied for detecting the dynamic social network structures.

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3.4. Internet of thinking

The conception of the IoTk is first proposed on an open forum "*Top 10 Questions in Intelligent Informatics/Computing*" in the World Intelligence Congress for the Turing Year [34]. To trace the origin of the computer networks, which have evolved into the networks of computers (i.e., Intranet and Internet). The network of computers can be extended to the network of machines by universalization and interconnection, and turns out to be the Internet of Computers (IoC), in which the generalized machines accordingly establish interconnections along with realizing pervasive perception and intelligent data processing.

Along with the report "*Mapping the Brain and Its Function: Integrating Enabling Technologies into Neuroscience Research*" being issued in 1991, neuroscience and informatics are merged into an emerging research area. Human cognition can be introduced to support the IoTk, which is expected to be a potential ultimate stage of the IoT. In the IoTk, human, nature, and society are collaborative beyond the space–time constraints, and human subjective initiative breaks the cyber–physical–social limitations. Note that the IoTk does not exaggerate the effects of abstract mind, soul, mind, spirit, and subconsciousness to lead to subjective idealism, and is based on the physical objects, cyber entities, and social correlations to achieve a wise state of interconnections. The wise state of interconnections means that ubiquitous things establish smart interrelations in pervasive modes.

In the Cybermatics, the IoTk is assigned with "*4C*" labels, including collection, connection, coordination, and creation.

- *Collection*: The IoTk refers to omnipresent human thinking related data perception, in which sensors and surrounding environments jointly comprise the ubiquitous contexts. In the IoTk, diverse sensing technologies are applied to realize the human body electrical signal identification, human brain information acquisition, human consciousness extraction, and human behavior tendency prediction. It turns out that the comprehensive collection realizes to "*copy*" and "*refine*" the human thinking data to support the further information interactions. Meanwhile, the thinking data collection is accordingly achieved for inter-mapping between physical space and cyber space, in which the human body sensors are currently popular for detecting the brain wave, infrared body heat, emotion, and other parameters. More challenging technologies should be developed to realize the advanced requirements. For instance, an individual accidentally lose memory, the formerly collected thinking data is expected to be "*reloaded*" into one's brain for supportive therapy.
- *Connection*: The IoTk involves heterogeneous network communications to achieve the interconnection among multiple individuals. The typical local networks include body sensor networks (BSNs) and body area networks (BANs), and the next generation communications such as long-term evolution (LTE)-Advanced, WirelessMAN-Advanced (IEEE 802.16 m), and IPv6 over low power wireless personal area networks (6LoWPAN), can also be applied during peer-to-peer (P2P) communications. Additionally, robust data transmission mechanisms should be designed for reliable network connectivity. It is expected that the thinking among different persons can be connected to establish an interactive perspective.
- *Coordination*: The IoTk provides cooperative services to achieve synergetic thinking, and joint coordination activities are launched to facilitate an optimum interaction in the distributed environments. Seamlessly information exchanging measurement for the geographically dispersed individuals is anticipated to enhance human thoughts to realize an aggregated functionality. Meanwhile, quadruple space coordination is important for the self-organization of human thinking, and there may be one or more *opinion leaders* to play more pivotal roles during the cooperation and coordination. It is also possible to realize an attractive prospect of "*human thinking accessing, transfer, discovery, and sharing*" like other resources.
- *Creation*: The IoTk promotes creative behaviors, activities, and events for the human society. In order to realize the creativity of human thinking, intelligent computing may be introduced by absorbing the advantages of heuristic algorithms and bionic computing. Hybrid thinking mode should be considered to achieve intelligent decision support, and the combination of multiple thinking can be aggregated to provide smarter services.

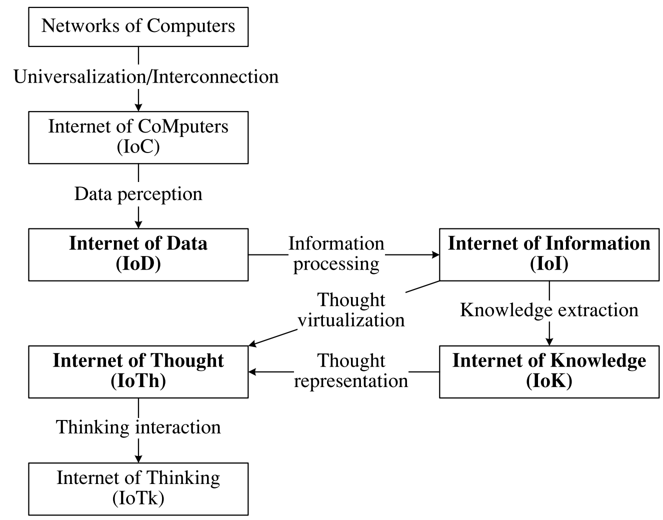

Fig. 5. The interrelations of the IoTk related concepts.

Fig. 5 illustrates the interrelations of the IoTk related concepts, including the Internet of Data (IoD), Internet of Information (IoI), Internet of Knowledge (IoK), and Internet of Thought (IoTh).

- *The IoD* accentuates the pervasive data perception for the ubiquitous things. Data is becoming a crucial element for function implementation along with physical data being collected by sensors, cyber data being exchanged during communications and sessions, and social data being used for management strategies. The massive data should be managed in an interoperable mode to achieve comprehensive data networking, and the virtualization and federation mechanisms can be applied for heterogeneous data acquisition and single-sign-on (SSO) data accessing.
- *The IoI* is an enhanced form of the IoD, and emphasizes the information processing for service support. Information as the reflection of things' objective attributes, forms the exchangeable knowledge, and aims to provide bidirectional services for applications. Meanwhile, a huge quantity of information is expected to be generated from the raw data, and it should be protected against unauthorized access. The event-driven information management and information-centric networking can be applied to support the context-aware information discovery and sharing.
- *The IoK* is an updated form of the IoI, and highlights the formal knowledge extraction. The knowledge extraction may be performed based on the structured (e.g., relational databases), unstructured (e.g., language, emotion, texts, and images), and semi-structured sources. Thereinto, several approaches, including ontology, text mining, semantic modeling, and sparse oracle-based adaptive rule (SOAR), can be applied for automatic knowledge extraction. The knowledge extraction

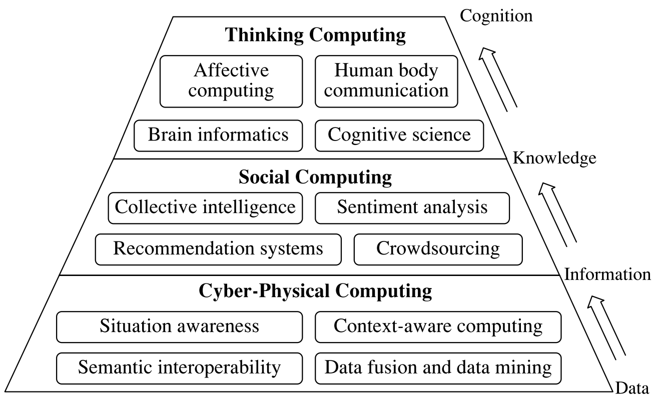

Fig. 6. The data–information–knowledge–cognition based cyber–physical–social–thinking computing technology framework.

serves different applications, including web content/usage mining in the semantic web, dependability analysis in wireless networks, and hierarchical modeling in fuzzy neural networks.

- *The IoTh* is an advanced form of the combination of the IoI and the IoK, in which thought refers to ideas or an arrangement of ideas that result from thinking. The thought virtualization and thought representation are particularly introduced to achieve the CPST hyperspace harmonization. The IoTh evolves towards the IoTk by involving the space–time unrestrained thinking interactions, which refer to an individual's real thoughts in the physical space, and the corresponding cyber entities' virtual thoughts in the cyber space.

4. Intelligent Cybermatics: cyber–physical–social–thinking computing

Computing technologies play an elemental role in facilitating the intelligent circumstance monitoring, semantic analysis, social behavior modeling, and insight generation. The cyber–physical–social computing has been emerged to support human-centric paradigms, and addresses data, information, and knowledge to integrate, correlate, interpret, and provide contextually relevant abstractions for human beings [35]. Beyond such computing mode, the cyber–physical–social–thinking computing should provide a holistic treatment of human thought and thinking to achieve supportive wisdom. Fig. 6 presents the data–information–knowledge–cognition based computing technology framework.

4.1. Cyber–physical computing

4.1.1. Situation awareness

Situation awareness (SA) refers to a cognitive process of perceiving physical objects within the space–time domain for comprehension and anticipation. It aims to provide decision support for complex areas including the air traffic control, marine navigation, power supervisory, military response, and emergency services. The SA involves identifying, processing, and comprehending the critical elements of information on what is happening in the vicinity, and predicts how behaviors, tendency, and events will impact the goals and objectives. A general SA model is in a sense–process–actuate control loop [36], includes three levels: perception, comprehension, and projection.

- *Perception*: Perception is to capture status, attributes and dynamics of objects in the physical space, and realizes an awareness of the situational elements (e.g., object, behavior, tendency, and event) and the corresponding states (e.g., location, condition, and mode). For the perception, event correlation, cue detection, and recognition are applied for heterogeneous data acquisition.
- *Comprehension*: Comprehension is to address the cluttered data into actionable knowledge by the pattern recognition, interpretation, and evaluation. Here, situation assessment and threat assessment are two elemental aspects for intelligent event reasoning and decision making.
- *Projection*: Projection is to extrapolate the objects' future actions, and is achieved through status knowledge, environmental dynamics, and situational comprehension. It launches integrated strategies and responses to address the undesirable situations. Moreover, coordination and prioritization of multiple events should be considered for resource allocation and contingency planning.

Table 1
The required elements for a sufficient SA.

	Required element factors
Perception	Generation data, transmission planned outage, load forecast, transaction schedule, planned and actual reserve, switch status, breaker status, neighboring system information, identification of limit violation.
Comprehension	Deviation the actual and planned states, status of equipment, system capability, system vulnerability, available action.
Projection	Future system state, action implementation time.

Table 1 shows requirements for a sufficient SA. Note that an insufficient SA may bring a delayed, incorrect or deficient response to endanger system stability and availability for electrical disturbances. It is usually caused by several factors, including the software application, real-time measurements, environmental factors, automation, and individual factors.

In the Cybermatics, urban SA become particularly popular to support localization services, and to establish an online common operational picture (COP), which realizes to display all gathered and combined data from multiple sensing sources into a single presentation. Particularly, large-scale SA applications (e.g., video-based surveillance) stress the available computation and communication infrastructures [37], which are inherently distributed, interactive, dynamic, stream based, computationally demanding, and needing real-time or near real-time guarantees. Considering the ubiquitous computing, a situation awareness architecture (EXEHDA-SA) is established to support acquisition, processing, and dissemination of contextual information in highly distributed environments [38].

4.1.2. Context-aware computing

Context awareness is a core feature for the heterogeneous things in the pervasive computing systems, and it is necessary to design suitable context models and reasoning approaches to enable collaboration and distributed reasoning. The context-aware computing covering a broad range of functionalities, techniques, methods, models, applications, and middleware systems, can be available in the Cybermatics. A typical context management system refers to four phases in a context life cycle [39], including context acquisition, context modeling, context reasoning, and context distribution.

- *Context acquisition*: The contexts need to be acquired as raw data by heterogeneous sensors, and the context acquisition approaches are varied according to the following factors: responsibility (e.g., pull, and push), frequency (e.g., instant event, and interval event), context source (e.g., sensor hardware, middleware infrastructure, and context service), sensor type (e.g., physical sensors, virtual sensors, and logical sensors), and acquisition process (e.g., sense, derive, and manually provided).

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- *Context modeling*: The collected data (called low-level context) need to be modeled for context representations. There are static context and dynamic context models, for which traditional modeling methods, including key-value, markup schemes (e.g., extensible markup language), graphical (e.g., unified modeling language, and object role modeling), object-/logic-/ontology-based modeling (e.g., RDF, RDF Schema, and OWL), are also available in the Cybermatics.
- *Context reasoning*: The modeled data need to be processed to extract high-level context information. The main reasoning schemes include supervised learning (e.g., artificial neural network, Bayesian networks, decision tree learning, and support vector machines), unsupervised learning (e.g., clustering, and k-nearest neighbors), fuzzy logic, reasoning rules (e.g., If-Then-Else, MiRE, and PRIAMOS), ontological reasoning (e.g., first-order predicate logic), and probabilistic reasoning (e.g., Dempster–Shafer, hidden Markov models, and Naïve Bayes).
- *Context distribution*: The high-level and low-level context information need to be distributed to the users in the context, in which query and subscription are two popular methods for context distribution.

In the Cybermatics, context-aware pervasive computing environments become prevailing [40], covering the applications from a context logger of mobile devices, to a system with contextualized learning capacities, and to an algorithm for reducing the complexity of contextual information retrieval. Meanwhile, the quality of experience (QoE) as an aggregate of QoS and human user related metrics becomes noteworthy for mobile computing systems, and context-aware QoE models are accordingly proposed to determine relationships between user contexts and QoE parameters [41]. Moreover, visual behaviors and brain activities are expected as promising sensing modalities for assessing the cognitive context to prompt the cognition-aware computing systems [42].

4.1.3. Semantic interoperability

The European Interoperability Framework (EIF) defines semantic interoperability as an ability of systems to process information received from external sources in a meaningful manner [43]. It enables universal computability, logic inferencing, knowledge discovery, and data federation among complex information systems, and becomes popular for addressing web services. In cloud environments, the semantic interoperability framework is essential to support inter-cloud cooperation, seamless information exchange, and data portability. It is easier for the distributed agents to perform information exchanges among heterogeneous information sources via a common cloud.

Web semantic interoperability can be realized by a semantic triangle model [44], which introduces *reference*, *symbol* and *referent* for message presentation. Thereinto, reference and symbol are linked by a symbolization relationship; reference and referent are linked by a reference relationship; and symbol and referent have no direct relationship. Accordingly, point-to-point semantic integration and semantic web are two typical modes for achieving semantic interoperability in distributed networks.

- *Point-to-Point semantic integration*: In the point-to-point mode, messages are represented by complete semantic descriptions, and each message minimum semantic unit includes both symbols and descriptions of referents [45]. The point-to-point semantic integration suffers from information redundancy and incoherency problems due to subjective communications.
- *Semantic web*: The semantic web refers to the web of linked documents enabling users to create data, build vocabularies, and write rules for information processing [46]. In the semantic web, ontology is used to describe the heterogeneous data in semantic contexts to achieve data integration with unambiguous conceptualizations. It realizes to establish correlation between a symbol and referents in an objective communication. Meanwhile, ontology related issues (e.g., ontology acceptance, ontology maintenance, and ontology expressiveness) should also be addressed in the semantic web.

In the Cybermatics, the semantic interoperability is compatible with human interoperability to provide knowledge based services. The human interoperability is elemental for supporting semantic interoperability in a manner that enhances the collaboration through cooperative and coordinated human cognition activities. Meanwhile, business oriented interoperability also confronts challenges since the businesses usually operate in different industrial, geopolitical, and regulatory contexts for information exchanging. Universal business language (UBL) and semantics translation mechanisms are initiatives to develop common business document scheme to achieve interoperability. Accordingly, the semantic interoperability should address the distributed, heterogeneous, autonomous and dynamic data to provide on-demand services by discovering and aggregating available resources.

4.1.4. Data fusion and data mining

In the Cybermatics, data fusion and data mining are pivotal data processing technologies for handling massive distributed data to extract knowledge and information.

Data fusion refers to an integration of raw data and knowledge into consistent, accurate, and useful representations, and is widely used in the areas of object recognition, environment mapping, and localization. Multisensory data fusion combines heterogeneous observations to provide probabilistic descriptions on environments or contexts [47]. Different resolutions based sensors (e.g., optic, thermal, and radar), and different geographic information system (GIS) data types (e.g., elevation, and vector map) should be integrated for data fusion. The main probabilistic modeling and fusion mechanisms include the Bayesian, probabilistic grids, Kalman filter, sequential Monte Carlo filter, log linear opinion pool, neural networks, and fuzzy logic. According to the aspects of centralized/decentralized, local/global, modular/monolithic, and heterarchical/hierarchical, data fusion is organized in different interactive modes. The data fusion can further reduce data redundancy and curtail network loads for wireless communications, in which the in-network data is fused for transmission.

Data mining is an essential process of knowledge discovery for analyzing data (usually big data) in different perspectives, and summarizing data into useful information [48]. It aims to determine systematic correlations or consistent patterns among data fields in large-scale relational databases, and involves the anomaly detection (e.g., outlier, change, and deviation detection) and association rule learning (e.g., dependency modeling). Generally, data mining can be classified into four categories: clustering (classify patterns-unlabeled), classification (classify patterns-labeled), association rules (find events-nonsequential), and sequential patterns (find events-sequential) [49].

In the Cybermatics, predictive data mining is a popular approach, which consists of three phases (i.e., exploration, model building/validation, and deployment). The exploratory data analysis (EDA) is common statistical method to identify systematic relations between variables when there are no (or incomplete) priori expectations [50]. Besides, the classification tree is an emerging analytic approach to predict or explain responses on categorical dependent variables.

4.2. Social computing

In the Cybermatics, the social computing highlights social intelligence by capturing social dynamics, appointing virtual social

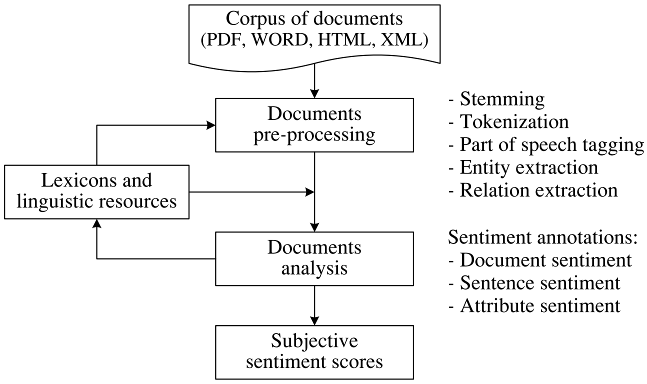

Fig. 7. A typical sentiment analysis system.

agents, and managing social knowledge. It is regarded as an intersection of recommendations, trust/reputation systems, and social networks [51], and goes beyond the general personal computing, facilitating collaboration and social interactions.

4.2.1. Collective intelligence

The nature and society mainly demonstrate emergent and self-organizing behaviors resulting from limited local interactions among the constituent parts. Such behaviors belong to a phenomenon of collective intelligence, which refers to group-aware sensing and computing with a large number of individuals' dynamic participation. The collective intelligence refers to a community engagement to address a formidable task, and is superior to individual judgment within an appropriate collective range. The gathering of the collective intelligence is characterized by massive and contextual background knowledge and advanced reasoning to establish mutual mapping between humans and machines. The main enabling technologies include crowding computing, participatory sensing, social sensing, and crowdsourcing [52]. Being similar to a bee colony's social behaviors, the participants of collective intelligence may complete a challenging task far beyond an individual's ability, through a reasonable planning, scheduling, and collaboration.

The collective intelligence emphasizes the informatics areas, including group awareness oriented heterogeneous data management and social integration, social networking based group data communication and interactions; unconscious group collaboration based social event correlation, and selective attention based cross-awareness information cognitive computing. Along with the flourishing of Web 2.0, the collective intelligence should be developed to support user driven services and cooperation dynamics [53]. There are two types of collective intelligence for the user driven services: experiences of service composition, and activity knowledge extracted from the web, which jointly accelerate creating service compositions by enforcing user experiences and activity-aware functional semantics for the converged applications [54]. Note that the collective intelligence has dual effects (i.e., positive and negative) during the group cooperation, and an inappropriate utilization may cause an overwhelming result.

4.2.2. Sentiment analysis

Sentiment analysis (i.e., opinion mining) refers to identifying and extracting subjective information by the NLP, text analysis, computational linguistics, and other machine learning methods. Multimodal sentiment analysis, which is featured with discourse structure, concepts-based, and fine-grained analysis [55], becomes prevailing for automatic identification of opinions, emotions, evaluations, judgments, and polarity. During the sentiment analysis, opinions from thought leaders and ordinary people jointly affect the decision making process. Generally, the sentences are classified into objective sentences (e.g., facts) and subjective sentences (e.g., explicit opinions, beliefs, and views). Fig. 7 shows a typical sentiment analysis system [56], referring to document, sentence, and attribute sentiment analysis.

- *Document sentiment analysis* is the simplest form of sentiment analysis to conjecture the expressed opinion in a document. Supervised learning and unsupervised learning are two main approaches for the document sentiment analysis. Thereinto, the supervised approaches define a finite set of classes (e.g., positive, negative, and neutral), for which the classification algorithms such as DT, KNN, SVM, logistic regression (LogR), NB classifier, and linear classifier (LC), can be applied to establish a classification model. The unsupervised approaches are to determine the phrases/words' semantic orientation.
- *Sentence sentiment analysis* is a higher level sentiment analysis for identifying a fine-grained view of multiple opinions expressed in a document about the same entity. The subjective/objective sentences should be determined to analyze the corresponding polarity, and mainly refer to condition, question, and sarcasm.
- *Attribute sentiment analysis* addresses the sentiment expressions recognition within a given document and the relevant attributes (i.e., aspects, and features). The attributes in a corpus can be determined by extracting all noun phrases (NPs), and only the high-frequency NPs (i.e., the frequency is beyond an experimental threshold) are kept for analysis.

4.2.3. Recommendation systems

Recommendation systems (i.e., recommender systems) support users to address information overloads by identifying rating or preferences to recommend certain items.

In the Cybermatics, recommender systems provide information filtering for personalization applications such as websites, news, movies, products, and other online services. A utility matrix model is available to represent the pairwise "user-item", and a value is assigned to evaluate the known preference of a user for an item. A long-tail phenomenon exists in the cyber–physical space, in which the physical institutions provide only the most popular items, while the corresponding cyber institutions provide the entire range of items (including both tail and popular items). The adaptive clustering method can be applied to address the long-tail problem. Recently, context-aware recommender systems (CARS) [57] become attractive for technology enhanced learning, in which the contexts mainly include physical context (e.g., temperature, and traffic flow), computing context (e.g., bandwidth, and spectrum), and user context (e.g., profile, location, and social situation). The popular recommendation approaches include collaborative filtering, content-based filtering, demographic approaches, and knowledge based approaches.

- *Collaborative filtering* is a pattern filtering process involving collaboration among multiple agents, viewpoints, and data sources. It realizes recommendation based on similarity measures between users and items. Thereinto, the user location and interaction time should be considered to recommend scattered and pervasive context embedded networked objects.
- *Content based filtering* generates recommendations from the items' associated features and other users' ratings. It regards recommendation as a user-specific classification issue, and learns a classifier for users' preferences based on an item's features.
- *Demographic recommender* provides recommendations according to a user's demographic profile, and the recommended items can be produced for different demographic niches by combining the ratings of users.
- *Knowledge based recommender* suggests items based on inferences about a user's needs and preferences, for which the

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knowledge will contain an item's explicit functional features for satisfying the user's requirements.

4.2.4. Crowdsourcing

Crowdsourcing is an online and distributed problem-solving and production model [58], and aims to obtain required services, ideas, and functions by soliciting contributions from a large number of online community members. The crowdsourcing leverages the loosely coupled crowd's wisdom to perform complex tasks (e.g., human intelligence tasks (HITs)) in a distributed, participatory, and task-oriented computing systems. It aims to achieve knowledge discovery, to comprehend human behaviors, and to evaluate the crowd's opinions. Note that the crowdsourcing does not always provide accurate results due to the unknown quality of the participative crowd. Meanwhile, the crowdsourcing is available to obtain relevance judgment and assessment in information retrieval systems. Anticheating mechanisms are required to improve quality-of-information (QoI) [59], including administering qualification tests, evaluating workers' enthusiasm, analyzing the work efficiency, removing low-quality workers, and detecting random/uniform spammers. Particularly, quality control is noteworthy in crowdsourcing systems, which covers several task components including task definition, user interface, granularity, and incentives policy [60]. Different approaches such as expert review, independent input/output agreement, ground truth, majority consensus, contributor evaluation, and real-time shepherding, can be applied for the quality control of the crowdsourcing. In the Cybermatics, crowdsourcing is expected to evolve towards "*crowdservicing*", which leverages cloud computing, semantic web, and service-oriented computing for web-scale problem-solving.

4.3. Thinking computing

4.3.1. Affective computing

Emotion as an aspect of human intelligence plays a significant role during human decision-making process, and emotional intelligence related computing becomes attractive in the Cybermatics. Affective computing (i.e., emotional computing) is first defined as "*computing that relates to, arises from, or deliberately influences emotions*" [61], and further develops to recognize, interpret, process, and simulate human's cognitive states and empathy, and enhances self-understanding and interpersonal communication. In order to support the affective computing, human machine interfaces (HMI) are required to address more challenging issues (e.g., affective evaluations, and ethical quandaries) in a self-governing mode [62]. Accordingly, physiological sensors based intra-body communications (IBC) realizes to capture the human neurophysiological information (e.g., facial expressions, body gestures, and other physiological signals) for enhancing the emotional cognition capacities. Existing analysis approaches, including the Bayesian networks, SVM, KNN, linear discriminant analysis, and neural networks, can be applied to achieve automatic emotion recognition.

4.3.2. Human body communication

Human body communication (HBC) adopts the human body as a transmission medium or channel for body-proximal wireless communications [63], in which a sensing body data from a biomedical sensor is transmitted to another sensor through the human body. It can be applied in BSNs/BANs with several merits, including low power consumption, high security, and high efficiency. The IEEE 802.15.6 is a standard developed to support the HBC in wireless body area networks. According to the operating principles, the HBC is classified into galvanic coupling and capacitive coupling, thereinto the galvanic coupling is impractical for BSN/BAN applications.

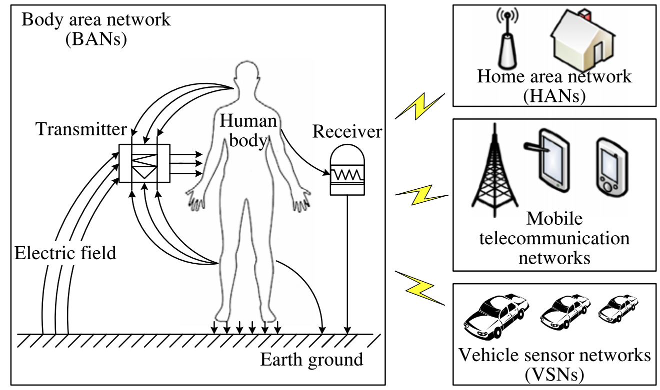

Fig. 8. A human body near field communication model.

In the Cybermatics, the HBC is not limited to the human intra-body data transmission, and also considers the human thinking related data intra-body and inter-body communications. The body signals (e.g., autocrine signals, paracrine signals, and endocrine signals) should be correlated with the human thinking. There are electric-field and electric-current based approaches to support the HBC, and Fig. 8 shows a human body near field communication model. The BANs can be connected with other networks such as home area networks (HANs), mobile telecommunication networks, and vehicle sensor networks (VSNs). During communications, a transmitter and a receiver use the potential difference signal so that an internal electric-field is dominant over an external radiation field when the transmitting electrode and receiving electrode are disposed around the human body. Note that the receiver's signal electrodes are susceptible to electromagnetic interference, and its ground electrodes are also susceptible due to the floating capacitance with the earth ground.

4.3.3. Brain informatics

Brain informatics (BI) is a systematic methodology to address brain sciences in the human information processing system (HIPS). The BI focuses on the human brain's functions, referring to the aspects such as human perception, attention, emotion, memory, reasoning, decision making, and problem solving [64]. It applies the experimental, computational, and cognitive neuroscience measures to develop the brain's features and principles.

In the Cybermatics, the BI uses the web-intelligence-centric information technologies (e.g., intelligent web, and knowledge grids) to enable high-speed, large-scale analysis, simulation, and computation, and to enhance human brain data, information, and knowledge sharing. The informatics enabling the brain technologies (e.g., electroencephalography (EEG), and magnetoencephalography (MEG)) bring new insights for the BI, and refer to the research areas such as cognitive experimental design, brain data management, analysis and simulation. The existing techniques, including blind signal separation, independent component analysis, principal component analysis, auditory scene analysis, edge detection, and formant detection in the auditory/visual signal processing, can be applied in the BI to promote the emergence of a global brain.

Cyber-individual (i.e., Cyber-I, and CI) is an attractive BI based concept [65], which is proposed to describe the mapping relationships between a Real-individual (i.e., Real-I) in the physical space and the corresponding Cyber-Is in the cyber space. Fig. 9 shows the Cyber-I conceptual model, involving the CI-mind, CI-pivot, CI-spine, and CI-applications. Towards a Cyber-I, there are three levels: state level (i.e., classified data, and associated memory), behavior level (i.e., abstracted behaviors, and specified recurrence), and mind level (i.e., intention prediction, and situation deduction).

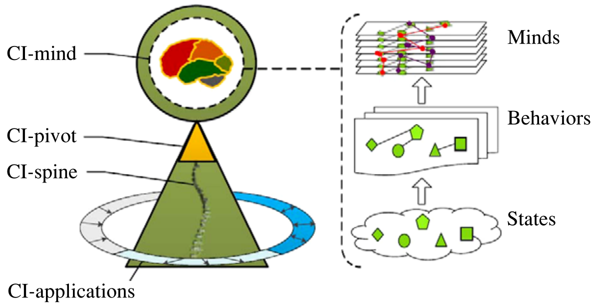

Fig. 9. The Cyber-I conceptual model [65].

- CI-mind imitates the human brain's functionalities or operating mechanisms, and its outcomes approach or approximate a Real-I's thinking or decision making.
- CI-pivot realizes to dispatch and distribute information among a Cyber-I's different layers with security protection and privacy preservation.
- CI-spine provides heterogeneous interfaces, including the standard drivers, middlewares and protocols between the internals and externals, such as smart devices, software agents, and online services.
- CI-applications (e.g., CI-vehicles, and CI-phones) support both Real-Is and Cyber-Is, and support an open, flexible, and friendly platform for the third party to develop and plug in applications.

Several projects are launched as a collaborative research initiative to support the BI. For instance, the US's brain activity map project (i.e., BRAIN Initiative) is to map the brain's cells and neural connections in entirety. Mechanisms for brain sensing and recording electrical activity need to be developed to track brain processing patterns at the thought speed. Related areas such as neuroinformatics and nanobiotechnology promote to address massive sets of brain data. Meanwhile, European Union (EU)'s human brain project (HBP) is organized around the following complementary areas: future neuroscience, future medicine and future computing.

4.3.4. Cognitive science

Cognitive science mainly covers the engineering, information, environmental, life, social and noetic sciences. It includes the research areas such as AI, psychology, philosophy, neuroscience, linguistics, and anthropology. According to "*thinking can best be understood in terms of representational structures in the mind and computational procedures that operate on those structures*" [66], cognitive science aims to achieve an advanced intelligence (referring to language, memory, and emotion), especially focusing on information representation, reasoning, and transformation.

The human-in-the-loop cyber–physical-systems (HiLCPS) [67] realizes to simplify the networked systems, which augment human interactions with the physical space. The HiLCPS measures cognitive activity by the body and brain sensors, infer the intent through embedded system based analysis, and translate the intent into robot control signals to influence the physical environment by actuators. It mainly refers to embedded system design, brain–computer interface algorithm design, assistive robotics, and innovative networking in the cyber–physical systems.

The ambient intelligence becomes noteworthy to provide the necessary infrastructures to transparently access sensors, processors, and actuators using standardized protocols regardless of hardware and operating systems. Considering the human activity and context recognition, an ambient intelligence calls are achieved for an opportunistic activity recognition paradigm [68], in which the recognition methods dynamically adapt to available sensor data. The things can understand the ubiquitous contexts, including location, activities (e.g., gestures, body posture, and locomotion modes), cognitive states, affective states, social interactions, and environmental states.

Human learning principles can be applied in user-centered systems, which benefit from a process model based on principles derived from the human psychology and neuroscience to emulate how human acquires task knowledge in the dynamic contexts [69]. A bidirectional processing mechanism between internal knowledge representation (i.e., human knowledge) and external knowledge representation (i.e., networks of objects), and an uncertainty-driven arbitration mechanism are foundational for designing the user-centered systems. Related computational principles, enhanced by an enriched understanding of the psychology and neuroscience of human learning, will significantly improve the user's experiences in different scenarios.

5. Green Cybermatics: green communications and networking

Green communications and networking have the potential to significantly reduce energy consumption and enhance energy efficiency, and further accelerate the evolution of the Internet of Energy (IoE). The green communications, networking and information technologies are applied to reduce global greenhouse gas (GHG) emissions to achieve low-carbon society [70,71]. Fig. 10 shows the IoE model and enabling technologies. In the IoE, both energy flow and information flow are through the power cycle including generation, transmission, distribution, and utilization. Here, distributed energy sources (DER) are connected into the IoE for flexible power supply. Towards the related technologies enabling green Cybermatics, there are two main aspects: devices/systems, and algorithms/models.

5.1. Devices and systems

5.1.1. Advanced metering infrastructure

Advanced metering infrastructure (AMI) is an intelligent architecture to automatically measure, collect, store, and analyze power information for intelligent management. In the emerging smart grid, the AMI is an important system component to enable two-way communication between power utilities and users [72]. The integration of multiple technologies, including smart metering, programmable communicating thermostats (PCTs), building automation systems (BASs), vehicle-to-grid (V2G), meter data management system (MDMS), and open standardized interfaces, protocols, and APIs are introduced to support the AMI. Thereinto, a smart meter periodically records consumption of electric energy, and establishes connections for real-time power monitoring and billing purposes. The dynamic electric pricing information enables load control devices (e.g., smart thermostats) to modulate electric demand according to the pre-defined user preferences. Fig. 11 illustrates an AMI system model, including the smart meters, communications infrastructures (e.g., edge routers/collectors/aggregaters, operational gateways, and utility head-end), networks (e.g., home, field, neighborhood, and wide area networks), and MDMS. Note that ZigBee, RFID, Wi-Fi, WiMAX, fiber or cellular networks can be applied for communications in the utility wide area networks (WANs), and the DER is suitable for small-scale power generation in the HANs.

Demand side management (DSM) mainly refers to demand response programs (i.e., load shifting) and energy efficiency and conservation programs, and realizes the flexible interactions for an individual to shift the power demand during peak periods. The AMI realizes that an individual can obtain the information on the current energy usage and real-time electricity prices.

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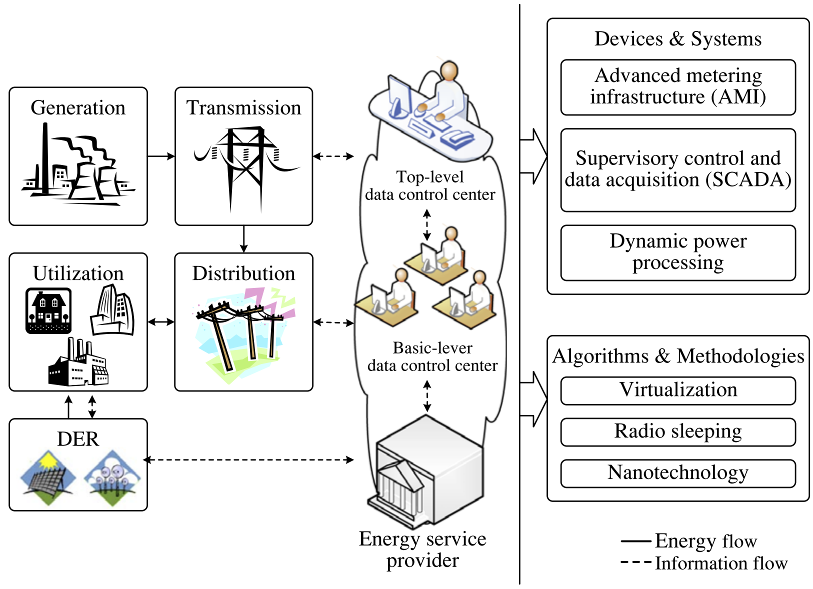

Fig. 10. The IoE model and enabling technologies.

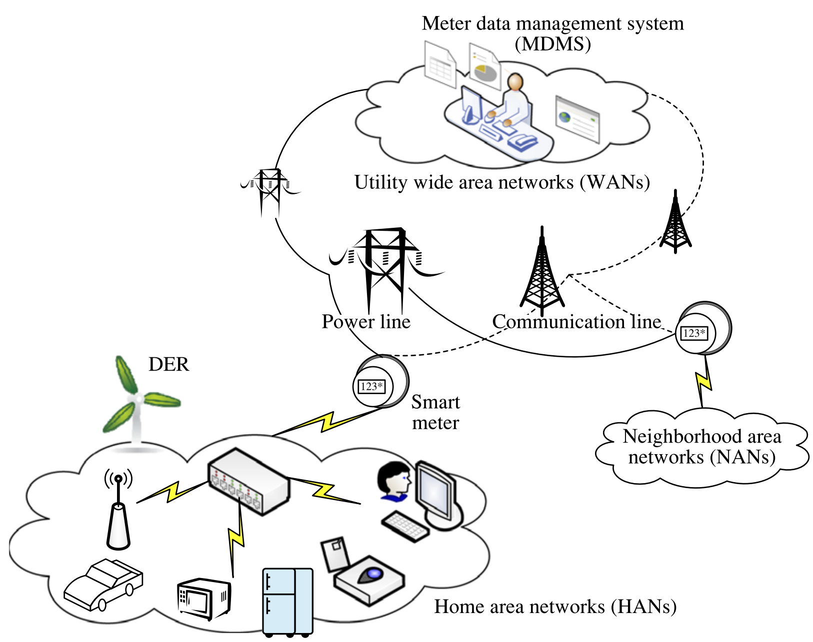

Fig. 11. An AMI system model.

In the Cybermatics, the AMI contributes to the achievement of future power grid vision. Table 2 shows the AMI related architectures [73], including advanced distribution operations (ADO), advanced transmission operations (ATO), and advanced asset management (AAM).

5.1.2. Supervisory control and data acquisition

Supervisory control and data acquisition (SCADA) provides power monitoring and controlling in utility communication networks, and has been widely applied in large-scale power systems such as photovoltaic (PV) power plant for controlling the geographically dispersed nodes. The typical SCADA system mainly comprises a HMI, remote terminal units (RTUs), programmable logic controllers (PLCs), and communication infrastructures. In the Cybermatics, the SCADA evolves towards the dynamic monitoring and decision system (DYMONDS), which realizes adaptive load management (ALM) and variable resource integration for future electric energy systems. Meanwhile, the SCADA and phaser measurement unit (PMU) measurements can be jointly applied for adaptive distributed state estimation, and distributed intelligent Micro-electro-mechanical systems (MEMS) is the direction for supporting the power optimization [74].

5.1.3. Dynamic power processing

The lower-power circuits based dynamic power processing is promising to reduce energy consumption, in which dynamic voltage and frequency scaling (DVFS) and dynamic power management (DPM) are typical approaches.

- *DVFS* is an approach for real-time power management, in which a processor/microprocessor's clock frequency is decreased to allow a corresponding reduction during the voltage supply. The DVFS allows a hardware design to reduce average power consumption while enabling high performance, and the DVFS

Table 2
The AMI related architectures.

	Descriptions
AMI	Establish communications with the user to provide time stamped system information.
ADO	Use AMI communications to collect distribution information, and use AMI information to improve operations.
ATO	Use ADO information to improve operations and manage transmission congestion and voltage, and use AMI to realize users access to markets.
AAM	Use AMI, ADO, and ATO information and controls to improve operating efficiency and asset utilization.

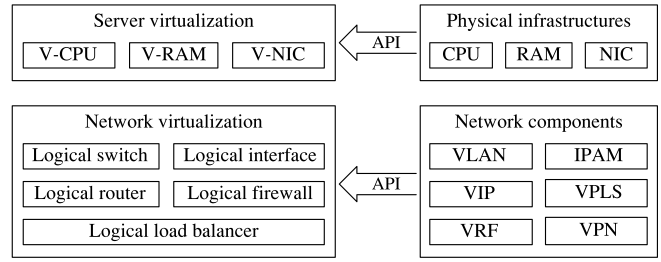

Fig. 12. The server virtualization and network virtualization.

based embedded and mobile devices usually work in a low-power mode [75]. Existing DVFS transition overhead schemes suffer from significant inaccuracies (e.g., an inaccuracy on the DC–DC converters and frequency synthesizers). Incorrect and inaccurate DVFS transition overheads create obstacle for determining the precise break-even time, and cause unnecessary energy losses. Additionally, the dynamic voltage scaling (DVS) is also an efficient method to dynamically adjust system supply voltage for energy reduction. A DC–DC converter is a key electronic device for voltage regulation in the very large scale integration (VLSI), and should be designed to minimize the dissipated energy and peaks.

- *DPM* dynamically reconfigures an electronic system to provide requested services with the minimum load of system components. It aims to achieve energy saving by selectively shutting down or reducing the performance of the idle components. Emerging mechanisms can be applied to support the DPM in the Cybermatics. For instance, model-free reinforcement learning (RL) becomes prevailing to design an adaptive DPM framework for addressing the variations and uncertainties. The hierarchical DPM can be designed to enhance energy efficiency of system components (e.g., microprocessor, and I/O interfaces) in an embedded system. The field programmable gate array (FPGA) can be used in the multi-processor system on chips (MPSoCs) to reduce the energy consumption based on the idleness of processors.

During the heterogeneous network (HetNet) deployment in the Cybermatics, energy efficiency optimization can be addressed by power allocation policies considering a heterogeneous realtime and non-real-time traffic [76]. Particularly, green energy and adopting heterogeneous networks have been recently promoted as a strategic shift for reducing greenhouse gas emission in cellular mobile communications [77].

5.2. Algorithms and methodologies

5.2.1. Virtualization

Virtualization including full/partial virtualization and paravirtualization, refers to create a virtual entity for physical resources (e.g., server, network, and storage) for resource reorganization and optimization. It is an uncoupled operation to realize independence between services and physical infrastructures. There are hardware virtualization and software virtualization in the Cybermatics. Hardware virtualization (e.g., extended page table (EPT), and single root I/O virtualization (SR-IOV)) refers to the creation of a VM for operating an operating system (OS), and can provide higher implementation performance. Software virtualization (e.g., virtualized memory management unit (MMU), and paravirtualized I/O) has flexible manageability to be executed on the VMs without the underlying hardware resource limitations. Accordingly, a hybrid virtualization architecture (HYVI) introduces paravirtualization to achieve enhanced manageability such as VM migration and flexible network packet filtering, and uses hardware virtualization for high scalability [78]. Particularly, the VMs encapsulate virtualized services according to practical management policies, and play roles on GHG emission reduction involving the trade-offs of performance, energy savings, and QoS.

In the Cybermatics, the virtualization brings several benefits such as system isolation and protection (e.g., virtual private networks), coexistence of multiple systems, efficient testing and debugging, transparent migration, and separation of code license agreements. Thereinto, server virtualization realizes a physical server's attributes are decoupled and reproduced in virtualization hypervisor (e.g., V-CPU, v-RAM, and V-NIC), and are assembled in an arbitrary combination to establish a unique virtual server. Fig. 12 shows the server virtualization and network virtualization [79], which achieve the progressive process of "decoupling–reproduction–automation". Virtualized hardware equipments realize to aggregate multiple servers on the same platform for reducing the hardware costs, and service migration can be used for load balancing and energy saving by load transfers.

Moreover, network virtualization is an attractive approach to combine available resources into a network by dividing an available bandwidth into independent channels [80], which can be reassigned to a server in real-time mode. Network virtualization reproduces logical units (e.g., logical switches, logical interfaces, logical routers, logical firewalls, and logical load balancers) to be assembled in a virtual network topology. It aims to provide services for virtual network components (e.g., VLAN, IP address management (IPAM), virtual IP address (VIP), virtual private LAN service (VPLS), virtual routing forwarding (VRF), and VPN).

5.2.2. Radio sleeping

Energy efficiency is a challenging issue in wireless sensor networks (WSNs), in which the radio communication is a major contributor for energy consumption. Radio sleeping is an effective mechanism to reduce energy consumption for sensing nodes, and mainly refers to topology control and sleep–awake protocol.

- *Topology control* exploits the node redundancy to provide more spatial reuse and power conservation while maintaining the network connectivity and coverage. Sleeping based topology control algorithms (e.g. cluster based energy conservation (CEC)) ensure energy conservation by sleeping the redundant nodes in both static and dynamic networks. Distributed dynamic network topology control can be designed to reduce energy consumption for power-limited multi-agent networks.
- *Sleep–awake*protocol reduces energy demand of communication through dynamically switching radio between the sleeping mode and active mode. Considering a radio component as main source of energy depletion, the energy-preserving medium access control protocols become popular approaches [81], which adopt a low-power radio mode for putting the radio to sleep. During communications, a deep sleep mode has low current draw and high energy cost to switch the radio into an active mode, and a light sleep mode has quick switching to an active mode with a higher current draw. A trade-off of deeper

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sleep and lighter sleep should be adaptively launched according to practical traffic conditions. Towards the wakeup strategies, existing mechanisms include on-demand, periodic, and asynchronous wakeup. Concretely, the on-demand wakeup mode uses an out-band signaling to awake sleeping nodes in an on-demand manner; the periodic wakeup mode periodically wake up the low-power sleeping nodes in a synchronized manner to communicate with another node, which is used in IEEE 802.11 power save mode; the asynchronous wakeup mode makes that each node follows a wakeup schedule without requiring global synchronization. Besides, discontinuous reception and transmission (DRX/DTX) mechanisms can also be applied to allow communication devices to turn off radio interfaces into sleeping mode, the DRX/DTX optimization should be designed for energy-efficient sleep scheduling with QoS considerations (e.g., traffic bit-rate, packet delay, and packet loss rate).

Meanwhile, software-defined radio access networks become popular for designing a traffic load balancing framework, which will significantly reduce the communication overheads between users and base stations [82].

5.2.3. Nanotechnology

Nanotechnology launches a nano-scale field in the Cybermatics, and promises efficient and energy-saving solutions by creating high performance devices, equipments, and platforms to achieve the Internet of nanothings [83,84]. The nanotechnology promotes green Cybermatics in the following aspects:

- *Ubiquitous sensing*: Nano-technology is attractive in designing new sensors and actuators with improved performance (e.g., higher sensitivity/electivity, shorter response time, and longer lifetime). Thereinto, nano-materials (e.g., carbon nanotubes (CNT), graphene, gold nano-particles, and nano-wire) are widely used in practical applications.
- *Communication networks*: Nano-technology is promising to improve the performance in wired and wireless communications, and achieves high bandwidth demands and low energy efficiency in radio frequency communications. The possible communication channels for the nano-scale sensor networks (being similar to WSNs) include molecule communication, nano-electromagnetic communication, and quantum communication.
- *High performance computing*: Nano-materials are applied to design high performance computing systems, including molecular electronic devices, carbon based nano-materials, and memristors. The nano-technology may replace the silicon semiconductor based technologies with lower power consumption and higher energy efficiency.

6. Open science and technology issues

6.1. Open science issues

In the Cybermatics, there are several challenging science issues due to the ubiquitous explosions of connection, information, service, and intelligence.

6.1.1. Connection explosion based efficient data fusion

The connection explosion is caused by the universal sensing, networking, and communications involved into the CPST hyperspace. Interconnections are established in the local and global domains, in which a huge amount of real-time data is collected and transformed for further exploitation and utilization. In the Cybermatics, object identification technologies such as RFID, Bluetooth, infrared sensors, and radar realize the preliminary interconnections via edging terminals, middlewares, interfaces, and standard protocols. The wired and wireless communication and transmission networks, including the Internet, WSNs, wireless ad hoc networks, wireless mesh networks, mobile communication networks, telecommunications networks, and power line communications, can also be applied to support the hyper IoT applications. Considering the pervasive network coexistence and convergence, such connection explosion brings challenges for the data exchanging. The captured distributed raw data may refer to incompatible data format, incomparable packet size, and inconsistent communication pattern, thus it is necessary to achieve efficient data fusion for the multi-source heterogeneous systems.

6.1.2. Information explosion based limited perception

The information explosion appears along with the interactions among the ubiquitous things enabling the global information sharing and exchanging. The increasing information flooding bring contradictions compared with the limited perception capacities in the CPST hyperspace. Particularly, in the cyber–social space, more and more people establish an era of "We-Media", which means everyone may create grassroots journalism for disseminating and making them popular through social networking services (e.g., microblog, podcasting, and groupmessage). Unlike the macro-content based traditional media, the We-Media focuses on micro-content to achieve hugely enlarged influences of public voices. While, an individual's subjective perception is limited, and it is extremely difficult to address the mass information with diverse credibility. The limited perception brings challenges on the intelligent decision support and opinion recommendation systems in the social computing.

6.1.3. Service explosion based accurate servicing

The service explosion is an outcome of the cloud computing, in which the SOA and XaaS aim to cover any forms of available resources. In the Cybermatics, the service management suffers from serious resource centered issues including semantic resource description, on-demand resource allocation, spontaneous resource discovery, and cooperative resource sharing. Moreover, the online resources based cloud services also bring challenges to provide more accurate services for an individual or a group. Personalized service modes should fully consider the special demands instead of pushing "large and all-inclusive" services.

6.1.4. Intelligence explosion based heuristic intelligence

The intelligence explosion of human beings and other things enhances the Cybermatics, and the heuristic intelligence accordingly appears to promote the ubiquitous intelligent interactions during the cyber-to-thinking mapping. In the Cybermatics, the heuristic intelligence tends to be strong AI, which is expected to match or exceed the human intelligence. Bionic algorithms become popular to support the heuristic intelligence. For instance, human attention (e.g., sustained, selective, and divided attention) distribution [85] can be learned to perform resource allocation in heterogeneous sensor networks. Human hormone based endocrine regulating mechanism [86] can be applied during information transmission to achieve distributed self-organization management in autonomous infrastructures.

Meanwhile, an unsupervised learning of language and ontology (e.g., syntax, semantics, morphology, phonology, and prosody) may be an essential aspect of heuristic intelligence. To apply the supervised algorithms in an unsupervised mode by learning to predict naturally occurring information remains an available approach. Ensemble learning (e.g., random forests, and boosting) appears to adopt multiple models, such as classifiers or experts

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to improve multi-modal learning or contextual fusion. During developing the heuristic intelligence algorithms, the hybrid computational loads (e.g., motor load, sensory load, conscious load, and motivational load) [87], should be considered to avoid performance degradation.

6.1.5. Philosophy, ethical and social issues

The Cybermatics launches inevitable rethinking towards the philosophy, ethical and social issues. The world outlooks of materialism and idealism become more controversial due to the thinking space merging into the cyber–physical–social space. Several questions should be addressed, such as could the thing or human thinking control the physical space? could the thing thinking have absolute superiority over the human thinking? and how to maintain the thinking space in an orderly pattern? Furthermore, ethics is also suffering from severe challenges due to the human thinking related operations, including thinking transplantation, unauthorized thinking interception, and malicious thinking disturbance.

Towards the social issues, education and standardization become noteworthy in the Cybermatics.

- *Education*: It is necessary for reconsidering how to revise the traditional science and technology system to adapt for the Cybermatics, how to educate the coming generation of engineers and researchers, and how to enhance the education course program with the reasonable subject support. To propel the science and technology evolution with hybrid cyber–physical–social–thinking hyperspace considerations becomes significant. Particularly, the higher education programs confront increasing pressures to transfer itself into an advanced mode [88], and need to ensure that the next generation of engineers understand how to design and build technological systems that reflect the altered expectations of openness and participation.
- *Standardization*: Standardization activities are developing by communities, among which the most relevant standards are launched by the international standards organizations (ISO, IEC, and ITU), national and regional standards institutes (e.g., NIST, ETSI, and CEN), and other standards counterparts (IETF, IEEE, and EPCglobal). The main contributions involve networking, communications, and applications to support the Cybermatics. For instance, the IETF addresses the IP connectivity to develop 6LoWPAN and routing over low power and lossy networks, and develops constrained RESTful environments (CoRE) and constrained application protocol (CoAP) for the web service architectures and protocols. Towards the IoT issues, the ITU Telecommunication Standardization Sector establishes the *Global Standards Initiative on Internet of Things (IoT-GSI)*, which aims to promote a unified recommendation for the IoT enabling worldwide service providers to offer the wide range of services. For the smart grid application, the NIST published a special publication "*NIST Framework and Roadmap for Smart Grid Interoperability Standards*" [89], and is collaborating with other global standards organizations to facilitate standards coordination and to enhance the development of the smart grid. The IEEE standards association also propels the smart grid interoperability and interconnection standardization.

6.2. Open technology issues

6.2.1. Space–time consistency

In the Cybermatics, space and time information is essential during the cross-space mapping, and space–time interactive patterns influence the scattered, pervasive context-embedded things in distributed networks [90]. The space–time consistency mainly refers to time synchronization and space–time registration. It is relatively easier to address local space–time issues, while turns to be a thorny problem in the large-scale heterogeneous networks due to the communication delays and dynamic accumulation errors.

Time synchronization to an external time reference (e.g., coordinated universal time (UTC)) along with preserving synchronization among neighboring sensors, is crucial for wireless communications. To address this issue, existing approaches mainly include three modes: receiver–receiver mode (e.g., reference broadcast synchronization (RBS)), sender–receiver mode (e.g., timing-sync protocol for sensor networks (TPSN)), and pairwise mode (e.g., flooding time synchronization protocol). Due to the multi-sensor collaboration, the time synchronization becomes more critical for the sensors deployed in hostile environments. Note that the traditional time synchronization schemes are mainly designed for homogeneous sensor networks, and may cause accumulated synchronization errors due to multi-hop relays in the heterogeneous sensor networks. Meanwhile, a satellite time service system (e.g., GPS) is usually used as a common time reference in mobile telecommunications, which require high-accuracy time synchronization between neighboring base stations. While, the time synchronization would be lost in the case that the satellite systems become unavailable [91], and it is essential to design distributed time synchronization solutions without the satellite time reference limitation.

Space–time alignments are the prerequisites for multi-sensor data fusion systems, in which the heterogeneous sensors (e.g., optical theodolite, electronic support measure (ESM), and radar) may have different sampling frequencies and measurement systems. The space–time registration becomes necessary for transferring the acquired data into the same space–time level. The main registration algorithms include the least squares, maximum likelihood estimation, 3-point parabola interpolation, and Kalman filter.

6.2.2. Big data and small data (iData)

Big data has been applied in various applications (e.g., e-business, and bioresearch), and confronts several challenges during data acquisition, storage, search, sharing, transfer, analysis, and visualization. It should particularly address the issues such as ensuring data reliability, reducing data redundancy, and enhancing data sharing. Recently, small data (iData) becomes more attractive, and refers to an integrated system for an individual. The real-time individual data (e.g., behaviors, preferences, social interaction, and entertainment) is collected and analyzed to establish a personal data ecosystem. Among a huge amount of data volumes, the distributed small pieces loosely joined iData provides personalized services, and realizes to extract the real valuable information for further supporting the efficient, intelligent and fast decision making. The big data and iData respectively breadth and depth oriented data analysis in the Cybermatics: the big Data focuses on a relatively wide range of data processing, while the iData only addresses a small world of an individual to provide the "intimate and thoughtful" services.

6.2.3. Security, privacy and trust

Existing researches on the issues of security, privacy and trust (SPT) mainly refer to the security recommended measures, trust strategies, communications based cryptographic algorithms, and applications oriented security solutions [92]. In the Cybermatics, SPT mechanisms mainly referring to key distribution, authentication, access control, secure routing, encryption, signature, intrusion detection/tolerance, and threshold cryptograph, should be designed according to the heterogeneous sensing and mobile networking based communications and application requirements. Among the diverse approaches, authentication is the most popular method to ensure the identity validity of the interactive things.

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The authentication operators are adopted according to the physical infrastructures. Thereinto, bitwise logical operators, permutation, and pseudorandom number generator (PRNG) can be applied by ultra-lightweight devices (e.g., passive RFID tag); hash function, cyclic redundancy check (CRC), and message authentication code can be applied for safeguard in lightweight applications; and the full-fledged encryption and signature algorithms can be used in the resource-unlimited scenarios. Meanwhile, datagram transport layer security (DTLS) is an underlying security protocol to guarantee authenticated and confidential data transmission.

Besides, safety management is another challenging issue, and operational controls should be enhanced for safeguards. It is necessary to specify the infrastructure usage policies, safety precautions, regulations, and emergency plans to avoid human errors and system malfunctions.

6.2.4. Energy management

Energy management becomes important for Cybermatics due to the limited physical infrastructures and cyber capabilities. The traditional energy management aims to realize persistent lifetime by the energy harvesting and dynamic power management. In the Cybermatics, energy management mainly considers reducing energy consumption by power-saving technologies (e.g., energy feedback, and virtualization).

Miniaturization is the trend to manufacture smaller infrastructures (including mechanical, optical and electronic devices) to reduce cost and improve performance. However, conventional chips driven computing technology is fast approaching the limits of miniaturization, thus it becomes extremely urgent to develop new materials (e.g., carbon nano-tubes, and quantum particles). Additionally, microgrids, virtual power plant (VPP), and demand side response (DSR) also become attractive to address the energy supply–demand balance. Furthermore, the emerging IoE confronts both space dimensions (e.g., balance energy supply–demand in different areas) and time dimensions (e.g., preserve sufficient energy for future utilization) during the energy management. It requires the traditional power grid to improve energy usage efficiency, enable intelligent information interaction, and increase renewable energy access to the smart grid.

7. Conclusion

In this work, we have established a novel CPST hyperspace by merging the thinking space into the cyber–physical–social space, and highlighted the importance of the human intelligence and social organization. Based on the CPST hyperspace, the Cybermatics is introduced according to its interconnected, intelligent, and green features. For the interconnected Cybermatics, the variants of the Internet of anything are discussed involving the physical objects, cyber services, social people, and human thinking. The IoTk and other related concepts including IoD, IoI, IoK, and IoTh are particularly introduced. For the intelligent Cybermatics, the enabling technologies are presented to support cyber–physical–social–thinking computing from the perspective of data–information–knowledge–cognition, in which cyber contexts, physical infrastructures, social behaviors, and human cognition are involved to achieve ubiquitous intelligence. For the green Cybermatics, existing power-saving schemes are analyzed to achieve efficient communications and networking. Furthermore, the open science issues are discussed considering the ubiquitous explosions of connection, information, service, and intelligence, and other philosophy, ethical and social issues. Meanwhile, the space–time consistency, big data/iData, SPT, and energy management are accordingly discussed as the open technology issues. In the future, the Cybermatics is expected to be an indispensable research area for influencing the future academia and industry.

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