IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received September 17, 2016, accepted October 5, 2016, date of publication October 19, 2016, date of current version November 18, 2016.
Digital Object Identifier 10.1109/ACCESS.2016.2619360

A Review of Technology Standards and Patent Portfolios for Enabling Cyber-Physical Systems in Advanced Manufacturing

AMY J. C. TRAPPEY[1], (Senior Member, IEEE), CHARLES V. TRAPPEY[2], USHARANI HAREESH GOVINDARAJAN[1], JOHN J. SUN[1], AND ALLEN C. CHUANG[1]
[1]Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Hsinchu 300, Taiwan
[2]Department of Management Science, National Chiao Tung University, Hsinchu 300, Taiwan

Corresponding author: A. J. C. Trappey (trappey@ie.nthu.edu.tw)

ABSTRACT Cyber-physical systems (CPS) are a collection of transformative technologies for managing interconnected physical and computational capabilities. Recent developments in technology are increasing the availability and affordability of sensors, data acquisition systems, and computer networks. The competitive nature of industry requires manufacturers to implement new methodologies. CPS is a broad area of engineering which supports applications across industries, such as manufacturing, healthcare, electric power grids, agriculture, and transportation. In particular, CPS is the core technology enabling the transition from Industry 3.0 to Industry 4.0 (I 4.0) and is transforming global advanced manufacturing. This paper provides a consolidated review of the latest CPS literature, a complete review of international standards, and a complete analysis of patent portfolios related to the 5C's CPS architecture model by Lee *et al.* The critical evaluation of international standards and the intellectual property contained in CPS patents is unaddressed by the previous research and will benefit both academic scholars and industry practitioners. The analysis provides a basis for predicting research and development future trends and helps policy makers manage technology changes that will result from CPS in I 4.0. This paper covers the emerging I 4.0 standards from the International Organization for Standardization, the International Electrotechnical Commission, and China's Guobiao standards followed by a patent analysis covering global patents issued in the U.S., Europe, China, and the World Intellectual Property Organization.

INDEX TERMS Cyber physical systems (CPS), Industry 4.0, patent analysis.

NOMENCLATURES

AML	Automation Markup Language
AIDC	Automatic Identification and Data Capture
BOG	Board of Governors
CIM	Computer Integrated Manufacturing
CPS	Cyber Physical Systems
CRM	Customer Relation Management
DIN	Deutsches Institut für Normung
DNC	Distributed Numerical Control
DWPI	Derwent World Patents Index
EDDL	Electronic device description language
EPO	European Patent Office
ERP	Enterprise Resource Planning
ETSI	European Telecommunications Standards Institute
FDI	Field Device Integration
FMS	Flexible Manufacturing Systems
GB	Guobiao Standards (Standardization Administration of China)
GB/T	Guobiao Standards Recommended
GB/Z	Guobiao Standards Guide
GS1	Global Standards Organization
HART	Highway Addressable Remote Transducer Protocol
ICT	Information and Communication Technologies
IEC	International Electrotechnical Commission
IEC/TC	International Electrotechnical Commission Technical Committee
IEEE	Institute of Electrical and Electronic Engineers

IEEE-SA	Institute of Electrical and Electronic Engineers Standards Association
IERC	European Research Cluster for the Internet of Things
IETF	Internet Engineering Task Force
IMS	Integrated Manufacturing Systems
IoP	Internet of People
IoS	Internet of Services
IoT	Internet of Things
IP	Intellectual Property
IPC	International Patent Classification
IPdM	Intelligent Predictive Maintenance
ISO	International Organization for Standardization
ISO/TC	International Organization for Standardization Technical Committee
IT	Information Technology
ITU-T	ITU Telecommunication Standardization Sector
I 4.0	Industry 4.0
NC	Numerical Control
NCAP	Network Capable Application Processor
NoSQL	Not-only-SQL
NTF	Normalized Term Frequency
OASIS	Organization for the Advancement of Structured Information Standards
OEM	Original Equipment Manufacturer
OGC	Open Geospatial Consortium
PLC	Programmable Logic Controller
QoS	Quality of Service
R&D	Research and Development
RFID	Radio Frequency Identification
RMS	Reconfigurable Manufacturing Systems
SAC	Standardization Administration of the People's Republic of China
SCM	Supply Chain Management
SG8	Strategic Group 8
SMB	Standardization Management Board
SME	Small and Medium Enterprises
SQL	Structured Query Language
TEDS	Transducer Electronic Data Sheet
T-F matrix	Technology-Function matrix
TI	Thomson Innovation
UKIPO	United Kingdom Intellectual Property Office
US	United States
USPTO	United States Patent and Trademark Office
WIA-PA	Wireless Networks for Industrial Automation Process Automation
WIPO	World Intellectual Property Organization
W3C	World Wide Web Consortium

I. INTRODUCTION

CPS is the merger of cyber (electric/electronic) systems with physical things [10], [11]. CPS helps mechanical systems to perceive the physical world, process these perceptions as data on computers, make calculations, and inform systems to take actions to change process outcomes. He [12] presented the concepts of Computation, Communication, and Control with information in the center to model dynamic results, such as real-time sensing, dynamic control and information service for large systems. A major challenge for original equipment manufacturers (OEMs) is the need to control cost for components manufactured [3]. CPS is a tool to overcome this challenge with characteristics such as timeliness, distribution, reliability, fault tolerance, security, scalability and autonomous operation to enhance the transition from I 3.0 to I 4.0 [3]–[16]. CPS gives industrial objects micro intelligence to achieve mass customization for today's short lifecycle products. Smart manufacturing systems that are intelligent and autonomous require synchronization to produce products of high quality, with variety, at low costs, and with reduced time to satisfy diverse consumer demands. FIGURE 1 shows the industrial evolution transition from I 1.0 to the current generation I 4.0. The key enablers that lead to the increment jumps in each generation are associated with the critical concepts underlying the changes over time. CPS, Internet of Services (IoT), and Smart Factories are the four key components of I 4.0 [17] and CPS is the central focus of this research paper.

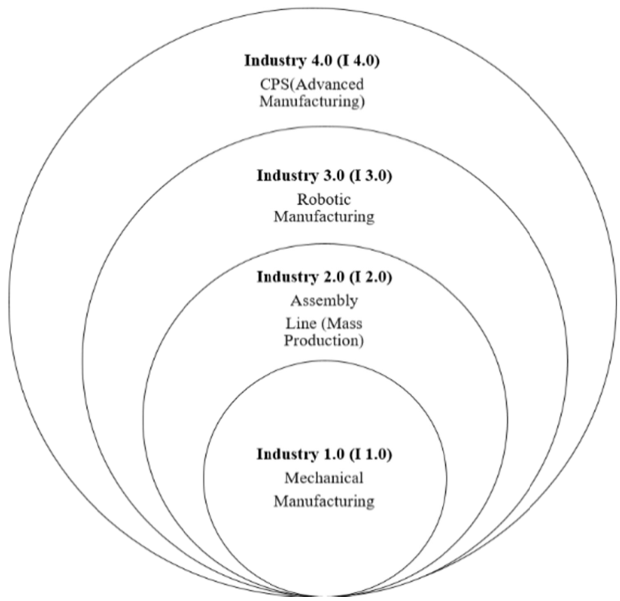


FIGURE 1. Industry evolution graph [14].

This research refers to the latest developments in the field of I 4.0 and provides the background and introduction of CPS followed by an overview of CPS layerings. The use of an accepted CPS architecture [1] avoids redundancy in analysis and description. The analysis of the standards landscape for CPS in the Industry 4.0 context consolidates information from governing bodies such as the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC) and the Guobiao Standards (Standardization Administration of China GB). The research provides an I 4.0 patent landscape for CPS using information from the World Intellectual Property Organization (WIPO) and the United States Patent and Trademark Office (USPTO). Finally, a research and development outlook provides a basis to discuss future development trends and the implications for CPS in I 4.0.

Our paper follows a dual approach that covers standards followed by patents. Patents are exclusive rights granted to the inventor for a limited period in exchange for public disclosure of the invention. The invention is a unique creation of a product or a process. On the other hand, standards are published documents that serve as a fundamental building block for product or process development and include methods for insuring usability, predictability, safety all parties involved in the manufacture of goods or delivery of services. A standard ensures intra and inter-operability of products and services produced and its compliance is mandatory for product commercialization [18]. Standard essential patents (SEPs) create the intersection between patents and standards. SEPs provide limited monopolies to manufacture products or business opportunities that comply with technical standards. The analytics presented is both qualitative and quantitative with a focus on SEPs to understand the dynamics between standards and patents and to forecast future trends from management and technology perspectives.

A. MOTIVATION

The motivation for this paper satisfies the need to understand the applications of CPS for tracking, monitoring, and improving products and processes. Processes undergo continuous improvement throughout the life cycle and require optimized performance and improved quality. There are challenges to implementing CPS including interoperability, affordability and network integration of existing and new engineering systems. Costs of manufacturing increase when there is a poor understanding of standards, which decreases interoperability and discourages small and medium-sized companies from investing in CPS [19]. This paper defines the technical standards, their equivalence in different countries and the use of patent portfolios to increase interoperability and the licensing of intellectual property for the implementation of CPS across a broad range of industries. The German Standardization Roadmap – Industry 4.0 (Version 2) [18] also supports the view for studying standardization during the development phase when SEPs are often created and analyzed.

B. COMPUTER-SUPPORTED SEARCH AND REVIEW METHOD OVERVIEW

The methodology for this research begins with a literature search and collection and archival of research from a variety of forums and databases where documents relevant and related to industrial engineering and related applications are stored. Literature with relevant CPS information and the terminologies must fit the five categories of the 5C model. This model, the CPS architecture model by Lee et al. [1] is the fundamental reference model for our research. Extracted CPS terms and those terms relevant to manufacturing and industrial engineering partition the literature into a manageable set for analysis. Using the initial set of terms, the construction of a CPS ontology uses the terms most relevant and appropriate for the analytic scope of this paper. Simultaneously, a standards search based on reports from the leading standardization bodies yields standards terms that relevant to the 5C model and are included in the CPS ontology. Finally, a patent query search string based on the terms of the CPS ontology is constructed. The search string enables the search of international patent databases for standard essential patents. In order to access the largest pool of global patents, the search uses the Thomson Innovation intellectual property (IP) search platform. The search results in a huge volume of raw IP data that is text and data mined using standard algorithms. The R software provides the text and data mining algorithms used to extract various statics and consolidate the results into the meaningful analytic knowledge to formulate the conclusions of this publication.

II. LITERATURE REVIEW FOR CPS WITH FOCUS ON MANUFACTURING

This section is a consolidation of the literature review [1]–[11], [17], [20]–[98] centered on CPS which targets engineering with applications in cross-disciplinary areas of science and manufacturing. In order to maintain the focus of our core research on standards and patents relevant to the categories of CPS architecture, the 5C's (Connection, Conversion, Computation, Cognition, Configuration), the architecture, the ontology, the applications, challenges and future roadmap are reviewed. FIGURE 2 depicts the distribution of articles reviewed.

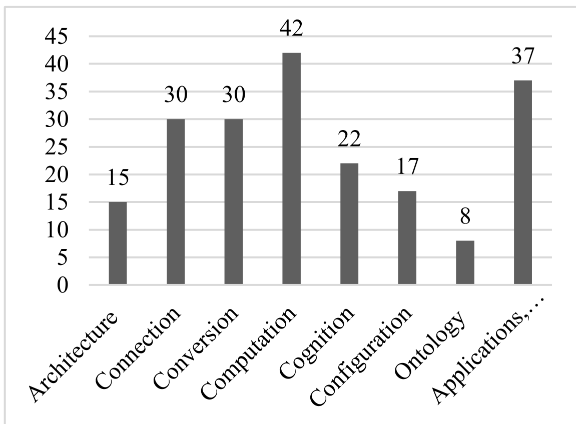


FIGURE 2. Literature review statistics [1]–[11], [17], [20]–[98].

A. CPS ARCHITECTURE

An architecture is an element of modularity and is an organized structure for implementing a technology. Using an architecture helps integrate a technology with minimal effort into an existing or newer ecosystem and there are many proposed architectures for CPS. The literature review [1]–[11], [17], [20]–[98] shows that the papers [1], [7], [10], [29]–[31], [33], [41], [45], [46], [50], [61], [68] have CPS architecture centric summarizations. Most have proposed theoretical and derived architectures.

The architecture proposed by Lee et al. [1] provides a detailed review of the publications. Our research requires a comprehensive and descriptive architecture because of the close association that must be formed between the I 4.0 research context and the associated publications [21], [33]. The proposed architecture is the Five-layer configuration (the 5C cyber-physical architecture) shown in FIGURE 3.

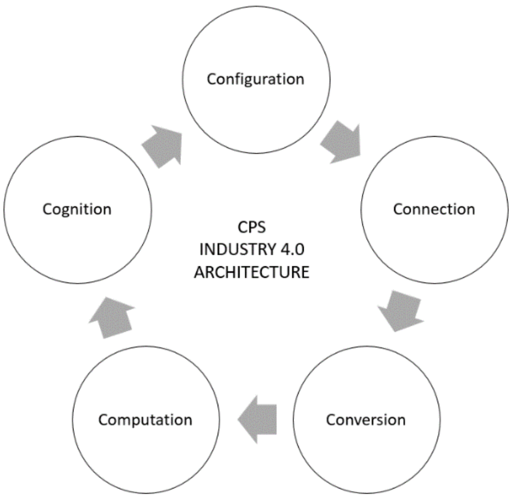


FIGURE 3. 5C CPS architecture for I 4.0 [1].

"Connection" is represented as the bottom most layer and is consists of the first step towards achieving integration using elements like sensors, actuators, and protocols. The connections become significant when integrated to create complex systems like Enterprise Resource Planning (ERP), Customer Relation Management (CRM), and Supply Chain Management (SCM) systems. "Conversion" is the step where many types of interferences are made from information derived from sources like big data analytics and cloud computing. From an industrial engineering viewpoint, new analytic models help solve problems such as calculating the remaining life of a component in complex multi-item or multi-machine systems. "Computation" is the step that uses algorithms, software, and computer-based infrastructures to analyze current practices and predict future behavior of logical software constructs like architectures, algorithms, and security. "Cognition" presents the knowledge gathered in the above steps for making decisions. Finally, "configuration" is the transformation of the intelligence into action (movement from cyberspace to physical space). This helps machines translate decisions into real world actions.

The literature demonstrates many models that apply to a similar research analysis but upon closer review do not fit the focus of the research plan. For example, one researcher presents a three-layer CPS model consisting of a physical layer base, an intermediary data layer, and a service layer as top most layer [21]. Another researcher used a mesh based 5-component Internet centered architecture connecting elements such as physical devices, control systems, and service frameworks [7]. A prototype-centered architecture for CPS with various interchangeable components link the changing physical world at the bottom to the abstraction of information in the middle, and finally leading to a real time context awareness at the top [10]. Other authors represented human machine interaction via CPS using a 6-layer model consisting of the physical/mechanical system at the bottom, followed by embedded systems, sensors and actuators, electronic hardware, software and human machine interfaces at the top [29]. A Real-Time Service-Oriented Framework called RT-Llama that considers various protocols [45] and a two box hybrid simulator architecture with a network layer encapsulating simulation core and the management layer encapsulating various analytics [46] are a few of the other architectures that were reviewed in detail. We choose the architecture proposed by Lee et al. [1] as base architecture for our research because of its simplicity, which let us assign standards and SEP's with high clarity in its architectural levels.

B. CPS KEY POINTS

CPS is a broad subject and the applications are numerous. This section deals with publications that are relevant to CPS [1]–[11], [17], [20]–[98]. Key points that are important for industrial and manufacturing engineering determine the classification and selection of papers relevant to the 5C model. Manufacturing is vital to economic growth and must be sustainable. From the literature, manufacturing must become more intelligent and capable of rapidly adapting to physical infrastructures to perform change management. This makes manufacturing more responsive to changing global markets and better able to satisfy customers' needs [32]. I 4.0 is a German concept proposed as a white paper to include information technology (IT) in the manufacturing sector [20]. This term is the summation of all technologies, standards, and frameworks that point towards the fourth industrial revolution. I 4.0 refers to the interrelation of technologies that facilitate the emergence of the smart factory by improving tools, processes, and outcomes [97]. Increasing global competitiveness requires better product quality, lower labor costs, shorter product life cycles, and more flexible outsourcing. Manufacturers recognize that end users do not want to pay for incremental quality improvements. Manufacturers are adjusting their processes and production by focusing on factors related to customizing products and reducing time to market. Leveraging the advantages of novel production strategies, such as CPS, agile manufacturing, and mass customization, helps manufacturers merge integrated networks that link core competencies [29]. Hermann et al. [98] proposes six design principles for CPS in I 4.0 that include interoperability, virtualization, decentralization, real-time capability, service orientation and modularity. Development of a single complete I 4.0 standard is time-consuming because of varying worldwide communication standards and the high volume of industrial data requiring collection, processing and transformation into actionable intelligence.

1) *Key review points for the 5C-connection layer*

Connection is the bottom most layer and is the first step towards integrating elements like sensors, actuators, and protocols. Papers referenced [2]–[4], [20]–[24], [26], [29], [30], [32], [37], [39], [44], [46], [50], [52]–[54], [58], [65], [66]–[71], [73], [78], [83], [86], [91] contains CPS research relevant to the connection layer. The commonality among this literature pool relates to sensors, actuators, controllers, protocols and networking. Also included is the interoperability between different networks and networking elements using vertical and horizontal integration approaches. Key attributes relevant to CPS and the connection layer follow in the discussion below.

A sensor is a device that sends an output when detecting changes in quantities, qualities, or events. Sensors and actuators are objects that collect information about the environment utilized by the upper 5C layers. Sensors most commonly detect temperature, weight, motion, vibration, acceleration, humidity, and location. In recent years, the prices of sensors have dropped significantly. As a result, it is now possible to collect an abundance of data directly from the manufacturing shop floor. These data are accessible for higher-level process and processing using the Internet [29]. The connection layer also deals with protocols and networks when considering factors such as power, range and storage capacity. The Internet protocol (IP) is the backbone of all modern networking and CPS has many networking enablers to achieve IP connectivity such as third generation (3G) and fourth generation (4G) networks combined with architectures such as local area networks (LAN), metropolitan area networks (MAN) and wide area networks (MAN). Using these various networking topologies, data transmission uses a wired or a wireless setup. A technology review by Deloitte further emphasizes the importance of connection layer for smart, connected manufacturing and as a base for I 4.0. The layer proposed is a combination of several commonly known elements such as the industrial Internet, connected enterprises, smart manufacturing, manufacturing 4.0, the Internet of everything, and the Internet of things for manufacturing [30]. FIGURE 4 depicts the product impact and potential applications map. IBM emphasizes how information technology and the availability of low-cost sensors create new service value propositions [31].

2) *Key review points for 5C - conversion layer*

Conversion is the step where many types of inferences are made from information derived from data sources such as big data analytics and cloud computing. Papers referenced as [4], [5], [20], [21], [23]–[25], [27], [29], [37], [39], [44], [46], [52]–[54], [57]–[59], [66], [69]–[71], [73], [83]–[87], [91], and [92] contain the CPS points relevant to the conversion layer. The conversion layer focuses on converting data to information using data processing and big data analysis and data applications where intelligent products carry all necessary information of their production processes. Data is knowledge only when it became information which needs information management step to filter and correlate data that is both old and new [57].The foundation of I 4.0 is to acquire relevant information in real time through integration of various entities involved in the value-added processes [21]. There is communication with production resources in the value chain with independent decision making by machines to forecast their breakdown periods and schedule their own maintenance [27]. The volume of data in storage, transfer and processing from I 4.0 requires a next-level Digital Infrastructure [23].While the concept to achieve greater storage for historic data to predict future trends is plausible, new data technologies are required. Apache Hadoop is one of new big data software solutions and is similar to other emerging big data technology platforms like Redis, SimpleDB, CouchDB, MongoDB, Terrastore, HBase, and Cassandra technologies that provide both data storage and communication between components [25]. The commonality across these technologies is the usage of a technique called NoSQL which is a column-oriented, key-value and document-based model. This is unlike the conventional structured query language (SQL), which is a row and a column data representation methodology used in relational database management systems.

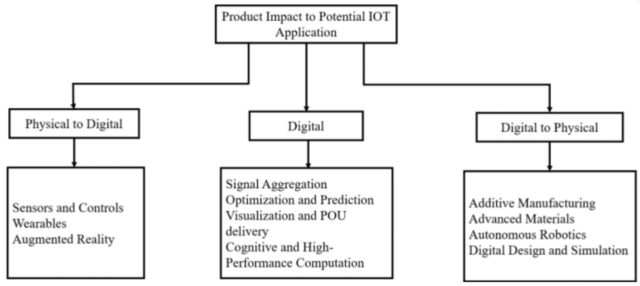


FIGURE 4. Product impact mapped to potential applications [23].

3) *Key review points for 5C - computation layer*

Computation is the step that uses algorithms, software, and computer-based infrastructures to analyze current and predict future behavior all logical software constructs like the architecture, algorithms, and security. Papers referenced in relation to the computation layer include [4], [20], [21], [23], [24], [27], [29], [40], [41], [44], [45], [47]–[52], [54]–[59], [64]–[71], [73], [76], [78], and [83]–[91]. The computation layer is a service oriented architecture (SOA) where software provides services and generates advantages such as high reusability and faster time to develop and deploy software, an integrated development environment (IDE) which helps programmer write software using rapid application development (RAD), object oriented and programing (OOP) which helps to visualize software modules as objects and their interactions and behaviors with other objects, and unified markup language (UML) which is a way to visualize design of systems. Other applications include inter and intra business data transfer technologies for extensible markup language (XML) which is a flexible text based data transfer format, and JavaScript Object Notation (JSON) which is an object based data notation for the design and transfer of algorithms for real-time remote control, scheduling, maintenance, social and big data analysis to predict current and evolving trends. Operating systems, programming languages, user interfaces, and networking technologies have become more elaborate with software managing information flow control, error control, redundancy, reliability and latency in heterogeneous global networks for application in I 4.0 [4], [58].

4) *Key review points for 5C - cognition layer*
Cognition presents the knowledge gathered in the higher layers for decision support. Papers referenced relevant to the cognition layer include [4], [20], [21], [23], [32], [35], [40], [42], [47], [49], [50], [52], [59], [61]–[63], [66], [72], and [87]–[89]. Cognition helps solves problems like finding a tool location inside a factory and implementing Intelligent Predictive Maintenance (IPdM). IPdM detects changes in the physical conditions of equipment for signs that indicate an increasing reliability of failure. Alerts signal workers to schedule or immediately provide maintenance to maximize the service life of equipment without increasing the risk of further failure such a complete system shutdown. The six proposed steps to achieving IPdM include sensor and data acquisition, signal pre-processing and feature extraction, maintenance decision-making, key performance indicators, maintenance scheduling optimization, and feedback control and compensation [32]. The cognitive layer provides sufficient functionality to detect and convey current and future system information to customers, providing order status and warnings about potential delays. Failures that require actions signal operators on a real time basis over the Internet or via mobile applications to coordinate faster error resolution [47]. Virtualization and remote operation abilities for factories saves time and money by transmitting control information, providing dedicated functionality for equipment controlled via remote service centers to eliminate faults and prevent failures. Possibilities of outsourcing these functions to service providers provide cost benefits and better quality services [42].

5) *Key review points for 5C - configuration layer*
Configuration is the transformation of the intelligence into action (movement from cyberspace to physical space). Papers referenced for this layer include [2], [3], [20], [21], [23], [30]–[32], [35], [42], [48], [57], [59], [64], [72], [74], and [89]. CPS configuration is for learning, optimization, customization, adaptation, enhancement, self-organization and auto-assembly [2]. To achieve this goal within I 4.0, artificial intelligence applications provide goal management, planning and behavior control. The idea is that the system will automatically modify goals to meet changing operating conditions and then autonomously adjust behavior to accommodate the changed goals [20]. Configurational awareness provides short-term flexibility, medium-term response to external influences and improved production resilience [21]. Social data analytics define social trends and dynamically reconfigure systems. For example, a connected gas turbine interacting with social and machine networks will decide autonomously to adjust to demand and supply conditions [23]. Augmented reality makes it possible to monitor machine data during maintenance and repair work, and to control maintenance tasks via cloud computing [37]. Posada et al. [24] provide research on key technologies needed for I 4.0 that include mass customization, automatic adaptation, and value chain improvement. Using these concepts industries can produce small quantities, fit individual needs and achieve intra and inter-machine awareness. Further connecting the cyber and physical world using ICT helps improve, track, optimize and interconnect asset infrastructures distributed around the world. Concepts like social machines and Internet networks, augmented operations, and virtual production apply these technologies. FIGURE 5 depicts the collaborative interaction between the cyber and physical world.

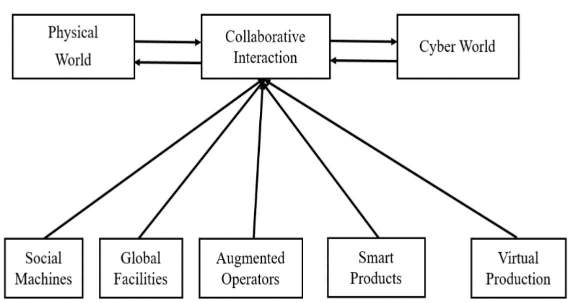


FIGURE 5. **Collaborative interaction between cyber and physical worlds [23].**

Brettel et al. [29] describe a CPS manufacturing landscape where individualized production using mass customization, and horizontal integration and end-to-end integration using the Internet of services. Mass customization focuses on manufacturing personalized products in high quantity under accepted quality constraints. This solves the problem of economies of scale versus economies of scope (striking a balance between customer satisfaction and production cost). Mass customization requires flexible processes, modularized product design, and integration between supply chain members along the value chain. The horizontal integration concept is to help small and medium enterprises (SME) that have limited resource and investment but want to be involved. Through integration, SME's produce or assemble complex products in a collaborative manufacturing environment and work together as a virtual enterprise to avoid investment risk by combining scarce resources.

6) *Applications, future roadmap, and challenges*
CPS concepts relevant to applications, the future roadmap and challenges refer to research by [2]–[4], [6], [8], [9], [11], [20], [22], [23], [25]–[27], [28]–[35], [38], [41], [43], [52], [56], [60], [61], [63], [65], [75]–[77], [79]–[82], and [90]. CPS applications link both consumer and business domains. For the consumer domain, deployment targets home automation, lifestyle flexibility, health care and transport systems. Some of the emerging functions include automation for lighting, safety, fitness, diagnosis, elderly care, navigation, emergency services and geographic tagging. For the business domain, applications target manufacturing, retailing, public services, and energy production. The technology functions include product testing, advanced manufacturing signaling and diagnostics, e-logistics, product and machine tagging, e learning, government and health asset management, smart grids, and enhanced environmental protection.
The future roadmap proposed in the literature shows increased research in improving manufacturing with static production lines that are hard to reconfigure, a need to make new product variants, and a better response to customer requests. There is a need for dynamic production lines; smart products that move autonomously from one CPS enabled processing module to another and the dynamic reconfiguration of production lines [31]. Power grids efficiency improves since increased measurements and additional information from various locations enables processing, monitoring, protection of services, and control [46].
The major challenges are closed boxed embedded systems where the nature of the system prevents communication, collaboration and inter-connectivity networking. The programming languages used to create these embedded systems are usually low level assembly languages or languages like C which is different from the software that Internet or mobile applications. Engineering design and practices that depend on embedded software design and closed system solutions become a limitation [4]. In the area of standardization which is essential for technology diffusion and adaptation by the industrial engineering environment, specialists predict that the creation of a complete Industry 4.0 standard will take at least 10 years [39] while many standards already exist in fragments across Europe, America, and China. The first step to creation of a complete standard requires understanding the current standards landscape [18]. This topic serves as the core motivation for the next section that identifies and visualizes the standards used in the 5C layered architecture.

III. STANDARDS FOR CPS

A standard is a published document that serves as the fundamental building block for product or process development and defines usability, predictability, and safety. A standard ensuring intra and inter-operability of goods and services produced and manufacturing compliance is mandatory for the future of CPS. Many international organizations are developing relevant standards. If enterprises are creating specific standards to follow, then I 4.0 technologies and solutions are evaluated and utilized.

A. STANDARDIZATION BODIES

The standardization organizations such as IEEE, ETSI, IERC, IETF, ITU-T, OASIS, OGC, W3C, and GS1 are critical to the technology development of CPS [99]. The international organization IEC and ISO have established many relevant standards for CPS. This study focuses on CPS standards, which considers industry technical specifications officially issued by the international standards holders such as IEC and ISO.

1) *International Electrotechnical Commission (IEC) [100]*
The IEC, established in 1906, is the oldest international organization for Electrotechnical Standardization. The IEC is responsible for standardization in the field of electrical engineering and electronic engineering. IEC's Standardization Management Board (SMB) is the agency managing the IEC technical specifications and standardization. SMB is responsible for strategic planning, adjustment, execution and supervision of the activities of the Technical Committee. IEC/SMB/SG8 is the strategic working group for smart manufacturing technologies and is responsible for developing I 4.0 technical standards. The results of IEC/TC65 (technical committee 65) are critical to I 4.0 since the results focus on industrial processes, measurement, control, and automation.

2) *International Organization for Standardization (ISO) [101]*
The ISO, established in 1947, is an independent and non-government organization with 162 global members. The organization brings experts together to share knowledge and develop international standards. The ISO works closely with the IEC on the development of I 4.0 standards. For instance, ISO/TC 184 is important to the international standardization of I 4.0 and focuses on automation systems and integration.

3) *Deutsches Institut für Normung (DIN) [102]*
DIN is a German national standardization organization founded in 1975, and is located in Berlin. DIN is a

very important national standardization organization. Many of DIN's standards become ISO standards that are internationally recognized.

4) *Standardization Administration of the People's Republic of China (SAC) [103]*
SAC is a subordinate group of the China State Administration of quality supervision and administration of public institutions with authority to create and promote the standards.

5) *IEEE Standards Association (IEEE-SA) [104]*
IEEE-SA is an international organization for industry standards governed by the Board of Governors (BOG) elected by IEEE-SA members. The IEEE-SA standards development process is open to IEEE-SA members and non-members from more than 160 countries. IEEE's mission is advancing technology for the benefit of humanity by providing a globally open, inclusive and transparent environment for market relevant, voluntary consensus standardization.

6) *The World Wide Web Consortium (W3C) [105], [106]*
W3C is a non-profit international organization for the development of web standards such as CSS, SVG, WOFF, the Semantic Web stack, XML, HTML, and a variety of APIs. W3C is working with many other IoT industry alliances and standards development organizations to solve the lack of interoperability across platforms in the emerging IoT field.

B. FRAMEWORK OF CPS STANDARDS

This section maps the CPS ISO/IEC standards landscape to the five-layered architecture explained in Section II. FIGURE 6 depicts the ISO/IEC standards and corresponding Chinese standards (GB) [107]–[164]. Appendix A provides the detailed descriptions of these standards.

1) *Smart connection level*
The smart connection level studies how to obtain data from the physical objects. The most common technique is the use of Automatic Identification and Data Capture (AIDC). The following descriptions are the relevant standards for AIDC. The ISO/IEC 19762:2016 [107] provides terms and definitions for AIDC. The ISO/IEC 15459 series [108] specifies the unique identification for registration procedures, common rules, individual transport units, individual products and product packages, individual returnable transport items, and groupings.
Important to CPS is the use of sensors for the automatic collection of data from manufacturing systems. The ISO/IEC/IEEE 21450:2010 [109] defines the basic functions required to control and manage smart sensors. The ISO/IEC/IEEE 21451 [110] series defines the Network Capable Application Processor (NCAP) information model, communication protocols, and Transducer Electronic Data Sheet (TEDS) formats for smart sensors. The standard methods to control these sensors are very important. The IEC 61131 series [111] identify the principal functional characteristics of programmable controller systems. The IEC 61499 [112] defines a generic model for distributed control systems based on the IEC 61131 standard. The IEC 61131 and IEC 61499 help establish a reliable, interchangeable control system.

2) *Data-to-information conversion level*
Data-to-information conversion defines processing data from the smart connection level and analyzing the information. The IEC 61804-3, IEC 61804-4, IEC 61804-5, and IEC 61804-6 (Electronic device description language, EDDL) [113] are used to describe the characteristics of devices. The IEC 61360 series [114]

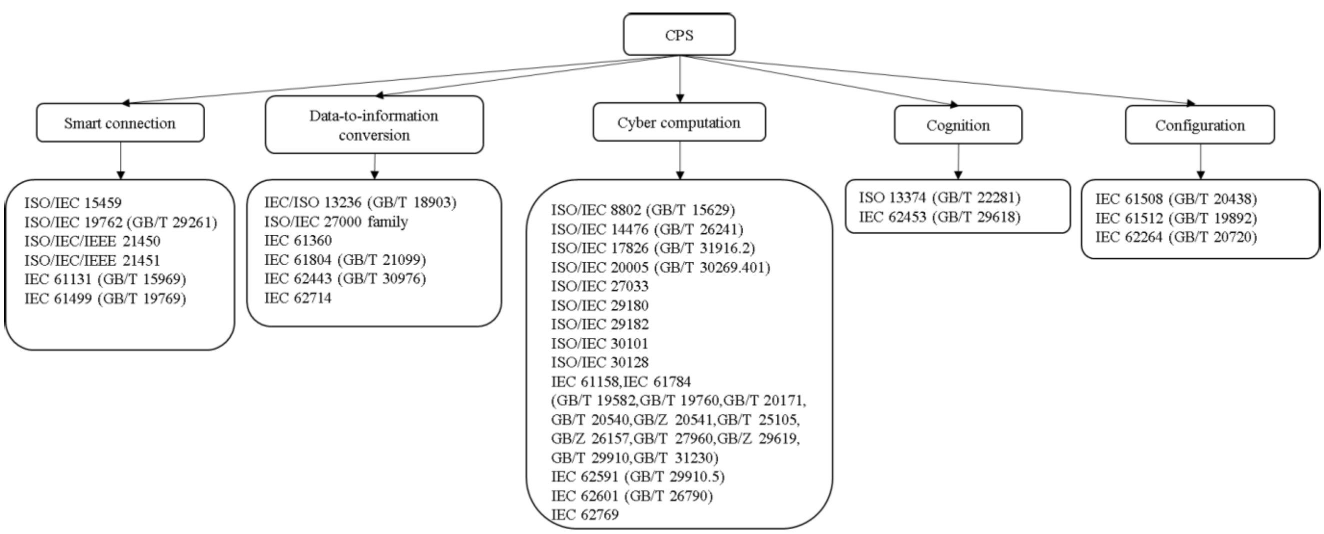


FIGURE 6. **CPS standard structure [1], [19], [99], [107]–[164].**

provides a basis for the clear and unambiguous definition of characteristic properties (data element types) of all elements of electrotechnical systems from basic components to sub-assemblies and full systems. Further, the IEC 62714 series [115] provides a data exchange format called the Automation Markup Language (AML).

The above standards ensure that there is a unified data format. The IEC/ISO 13236:1998 [116] establishes a high-quality system for the Information Technology (IT) environment. Since the security of data is an important issue, the ISO 27000 standard [117] provides the best practice recommendations for information and security risks management and control. The IEC 62443 series (ISA99) [118] is used to ensure the security of industrial automation and control systems and provides comprehensive security protection.

3) *Cyber computation level*

Communication is the most important element considered at the cyber and computation control level. The CPS data and information exchange require several relevant standards. The standards include wired and wireless communication. The ISO/IEC 8802 [119] provides the set of international standards which describe local area networks. There are several standards for wired communications. The IEC 61158 series [120] and IEC 61784 series [121] are standards for fieldbus types and profiles including foundation field buses, common industrial protocols, PROFIBUS and PROFINET, P-Net, WorldFIP, INTERBUS, SwiftNet, CC-Link, HART, VNET/IP, TCnet, EtherCAT, Ethernet POWERLINK, Ethernet for Plant Automation (EPA), Modbus, SERCOS, Rapi Net, SafetyNet p and MECHATROLINK. These protocols enable real-time distributed control in CPS and wireless communications. The IEC 62591:2016 (Wireless HART^{TM}) [122] and IEC 62601:2015 (WIA-PA) [123] are suitable for industrial wireless communication of industrial measurement, monitoring, and control. The ISO/IEC 14476 series [124] enhances the communications transport protocol to ensure that there is a good quality of service (QoS).

A good industrial network requires the above communication standards to link the sensor network and machine network. ISO/IEC 20005:2013 [125], ISO / IEC 29180 [126], ISO/IEC 29182 [127], ISO/IEC 30101:2014 [128], and ISO/IEC 30128:2014 [129] are used to build intelligent, reliability and secure sensor networks. There are several standards related to the cyber level. The ISO/IEC 17826:2012 [130] specifies the interface to access cloud storage and to manage the data stored within. The ISO/IEC 27033 series [131] ensures network security. The IEC 62769 series [132] (FDI) is used to integrate the devices with the use of communications technology.

4) *Cognition level*

The cognition level focuses on monitoring and making decisions. The ISO 13374 series [133] provides the basic requirements for open software specifications, which allow machines to monitor data and information processing and communication. The IEC 62453 [134] helps integrate all devices regardless of the suppliers.

5) *Configuration level*

The configuration level contains the standards of overall control for CPS. The IEC 61512 [135] defines the models for batch control used in the process, the terms, and the data models. The IEC 62264 [136] used for enterprise control system integration increases uniformity and consistency of interface construction. The standard reduces the risk, cost, and errors associated with implementing these interfaces. The IEC 61508 [137] increases security and ensures life cycle safety for industrial process control.

IV. A SYSTEMATIC APPROACH IN CPS PATENT ANALYSIS

This research constructs the ontology of CPS based on the 5C architecture layers and the keywords found in the CPS literature. After the construction of ontology, this research selecting the keywords for the patent search. The ontology helps to understand the scope of CPS and improve the efficiency of the patent search. This study analyzes the patent after the patent search. A systematic approach, shown in FIGURE 7, is the scientific and consistent process of analyzing global CPS patents based on the underlined CPS domain ontology.

The research must collaborate with expert to verification in the process of constructing ontology, selecting keyword to search patents and establishing the technology-function matrix.

A. KEYWORDS EXTRACTION

Test mining enables the collection of words or phrases from large amounts of unstructured text found in patent documents. The results help the R&D personnel in companies predict trends in the development of technology [165]. Keywords extraction, widely used in the text mining, consists of two parts.

The first part is sorting out the keywords used in the process of building the ontology based on the CPS-related literatures. Ontology architectures divide a domain knowledge or concept into other sub-classes, thus helping the readers quickly understand the complete structure of a domain knowledge. This study constructs the ontology of CPS using the 5C architecture layers and the keywords found in the CPS literature [1], [15], [16], [45]–[96]. The larger number of times a keyword appears in a key literature, the more important the keyword is. Therefore, the research identifies CPS related keywords from the literature, thus classifying them into 5C architecture layers based on their definitions.

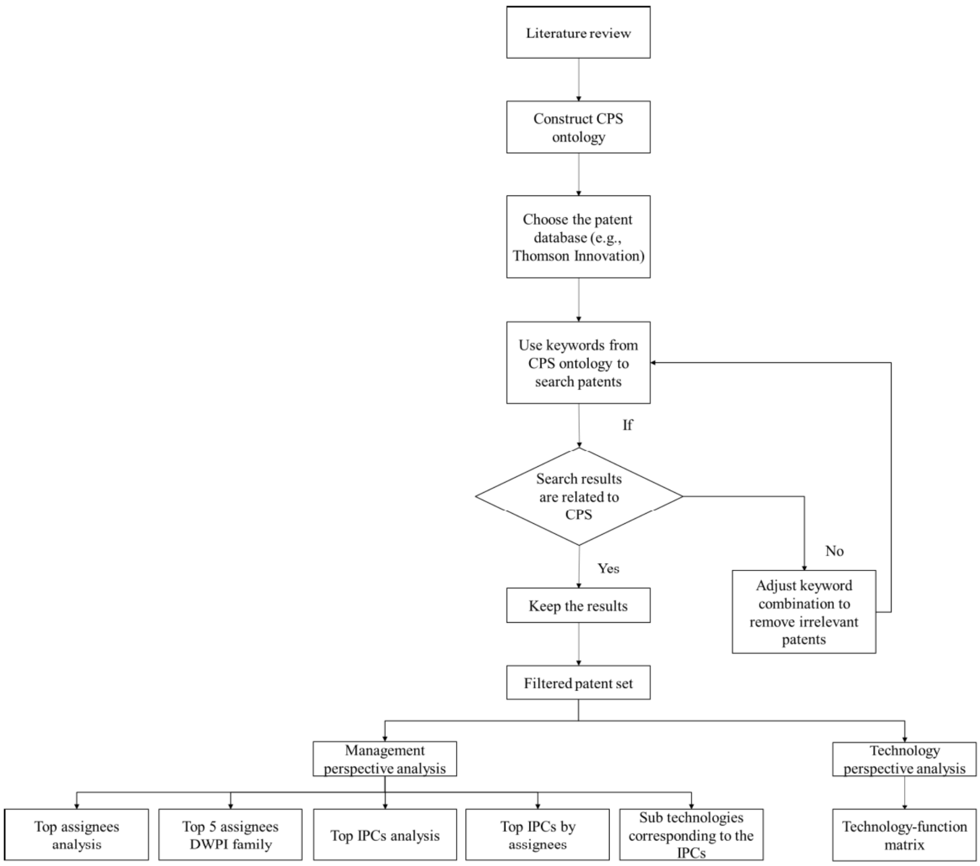


FIGURE 7. **Patent collection and analysis.**

The second part is about extracting the top 100 keywords from both the patent documents and each term library for the function and technology based on its Normalized Term Frequency (NTF) by using R software to conduct term comparison of each function and technology to each patent, which afterwards establishes the technology-function matrix (T-F matrix) [166]. The technology-function matrix, depicted in part D, provides information about the development trends of patent technologies useful for R&D personnel in companies to determine their research strategies to license or develop technology.

Our researchers must collaborate with subject matter experts in Industrial Technology Research Institute (ITRI, for advanced manufacturing related keywords) and experts in Institute of Information Industry (III for ICT, IoT, and cloud computing related keywords) for further verification and refinement.

B. ONTOLOGY CREATION

FIGURE 8 shows the derived CPS ontology. The first layer is for smart connection that obtains external information and data through sensors. The sub-technical fields consist of embedded systems, 3D printing, robotic sensors, power, energy, cameras, actuators, controllers, circuits, plug and play, enterprise manufacturing systems, and condition-based monitoring [1], [15], [16], [46], [50], [52]–[54], [58], [65], [67]–[71], [73], [78], [83], [86], [91]–[96].

The second layer manages data-to-information conversion. This layer enables the analysis and conversion of data collected by the connection layer into actionable information. The sub-technical fields of the second layer consist of data processing and smart analysis. Data processing includes image and video processing systems, data security, database management systems, multidimensional data correlation, and data harmonization. Smart analysis includes self-awareness, prediction, statistical evaluation, power management techniques, diagnostics and health management [1], [15], [16], [46], [52]–[54], [57]–[59], [66], [69]–[71], [73], [83]–[87], [90]–[96].

The third cyber computation layer is referred to by the short name, cyber. The goal of the cyber layer is to collect information for a broad range and create a comprehensive communication platform for components and systems. The sub-technical field consists of communication, middleware, software, a central information hub, computation, and networked control [1], [15], [16], [45], [47]–[52], [54]–[59], [64]–[71], [73], [76], [78], [83]–[86].

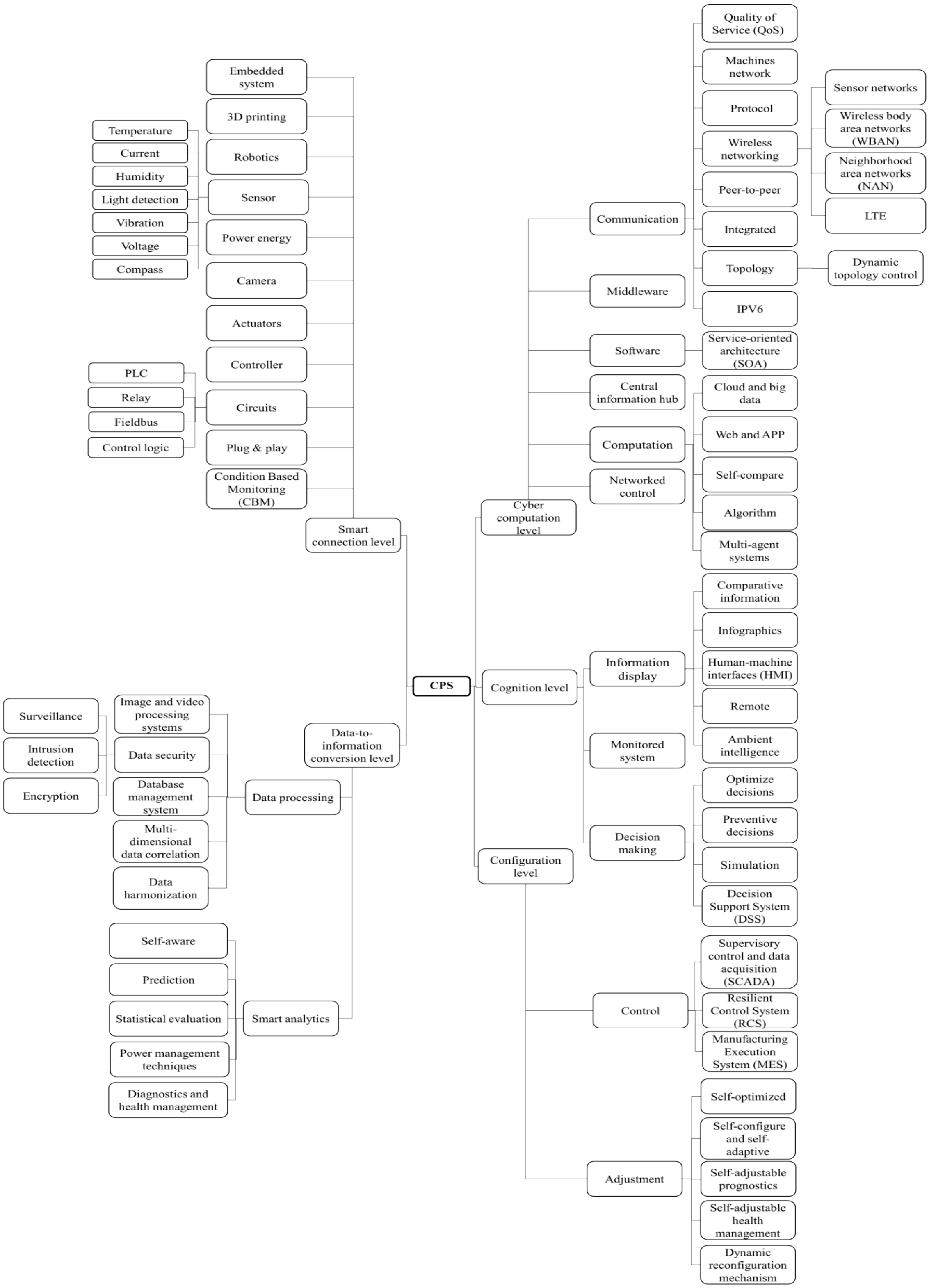


FIGURE 8. **Ontology for CPS using references [1], [15], [16], [45]–[96].**

The fourth level is the cognition layer. The data from the cyber level is cognitive based and used for decision-making. The sub-technical fields consist of information display, monitoring systems, and decision-making [1], [15], [16], [47], [49], [50], [52], [59], [61]–[63], [66], [72], [74], [87]–[89], [92]–[96]. The last level is the configuration layer.

The goal of configuration is to achieve self-adjustment in response to external parameters, demand, and environmental changes. The sub-technical fields consist of controls and adjustment [1], [15], [16], [48], [57], [59], [64], [72], [74], [89], [92]–[96].

C. PATENT SEARCH AND META-ANALYSIS

After the CPS ontology is constructed, a patent database is selected and the keywords from the ontology are used to create a search strings and search strategies to retrieve related patents from global databases. Thomson Innovation (TI) [167] is an integrated global patent database system that enables researchers to reliably search and retrieve global patent data. CPS focuses on the control of devices, so the study uses the equipment-related keywords in the first-level search. Then, the machine, equipment, production, manufacturing, factory, plant, device, and other manufacturing-related keywords help limit the CPS patents to a smaller set related to the manufacturing industry. Third, by combining technically related keywords such as remote and cloud, the search better targets CPS patents that often span layers. If the search results do not meet expectations, the study adjusts the keywords until the results are consistent across the CPS structure. The patent analysis consists of five parts for the managerial perspective. The top 10 assignees, top 10 IPC classes, and top 5 assignees DWPI family are the statistical results from the TI system.

1) *Top assignees analysis*
   Analysis of the top assignees identifies the technology leaders in the field of CPS. This study analyzes the number of patents held by the top 10 assignees.
2) *Top 5 assignees DWPI family*
   This study uses the DWPI family function of the TI to analyze the patents with applications ongoing in different countries or regions. DWPI is the abbreviation of Derwent World Patents Index, a special database used by Thomson Innovation to provide simple English text, searchable descriptions, and interpretations of the patents. The index refers to the titles, abstracts, drawings, DWPI classes, and DWPI codes instead of complex terminologies. This approach helps readers understand the technology bounds of the patents and the search. The patent abstracts are rewritten in DWPI to emphasize novelty, use, advantage, technical and drawing description of the patents [168], [169]. Through this analytic approach, patents of high quality and commercial value enables the researchers to estimate the potential market distribution and technology control of specific companies.
3) *Top ten IPCs analysis*
   IPC is a hierarchical classification for patents' technologies, divided into section, subsection, class, subclass, group and subgroups. The IPC classifies patents based on their technologies. This study discusses the top ten IPC classes to understand the technical focus in CPS. The top 10 IPCs are G05B 19/418, G05B 19/042, G05B 19/00, G05B 19/18, G06F 19/00, G05B 19/05, G05B 23/02, G05B 11/01, H04L 29/06, and G05B 19/02. The IPCs are mainly distributed in G05B class (technology focus: Control or regulating systems in general; functional elements of such systems; monitoring or testing arrangements for such systems or elements) and H04L class (technology focus: Transmission of digital information, e.g. telegraphic communication).
   CPS has many applications in monitoring the operation and production status of equipment by using the production or failure information from sensor network and cloud technology, which means that CPS focuses on the development in equipment monitoring and the networking technology, and the findings correspond to the IPC G05B and H04L classes. Theses IPCs include G06F 19/00 (technology focus: Digital computing or data processing equipment or methods, specially adapted for specific applications), G05B 23/02 (technology focus: Electric testing or monitoring), G05B 19/042 (technology focus: Using digital processors), and H04L 29/06 (technology focus: Characterized by a protocol). These classes are highly related to the CPS technologies, such as sensor networking, data processing, smart analytics, wireless networking, computation, cloud technology, and equipment monitoring. Test mining the CPS-related sub-technologies found under these four IPC classes yield terms control, remote, compute, cloud, protocol, wireless, command, processor, and monitor, which match with the CPS key technologies and the relevant application functions.
4) *Top IPCs by assignees*
   This part focuses on the patent portfolio of the first ten assignees in the top ten IPC classes and defines the assignees' key technology development areas.
5) *Sub technologies corresponding to the IPCs*
   This section places the top 20 technology classes (as defined by the IPC) that correspond to the CPS ontology. The analysis uses the R statistical software to extract the keywords from patents in each IPC class. The keywords define the key technology development trends of patents within classes.

D. TECHNOLOGY-FUNCTION MATRIX

A computer-assisted patent technology-function matrix (T-F matrix) is the research approach used to map the technical aspects of the patents to functional uses [166]. There are a number of steps to construct the technology function matrix. First, this study uses the ontology to decide the keywords of technologies and functions. After collection, the related literature of each technology and function uses R statistical software to extract the top 100 keywords and then rank these keywords based on its Normalized Term Frequency (NTF). Finally, the keywords of each technology and function are automatically compared with the keywords of each patent by using the R statistical software. Afterwards, the location of each patent in technology-function matrix is determined [166].

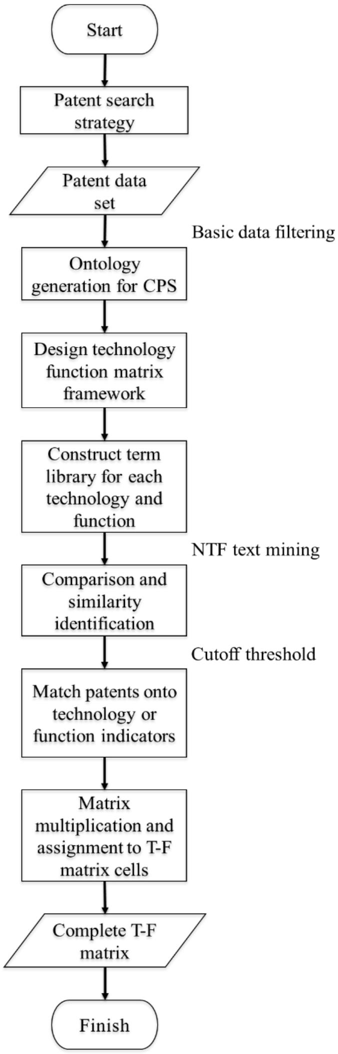


FIGURE 9. **Technology-function matrix generation methodology.**

FIGURE 9 shows the flowchart of the T-F matrix construction system, which is a generalizable platform and can be used to analyze patent pools from any given domains. The T-F matrix is a visualization of a given domain's patent count distribution with respect to their technology and function characteristics. The indicators of the technology-function matrix for both technology and function dimension are based on the ontology of CPS defined in FIGURE 8. The connection level, conversion level, and the cyber level are primarily about CPS techniques, which are used as the indicators of technologies. The other two levels focus on the application and feedback controls [16], which form the indicators of functions. Moreover, some keywords related to technique application in the first three levels are also used for defining the indicators of functions. The indicators of technologies include sensors, actuators, controller, circuits, sensor network, data processing, smart analytics, protocol, wireless networking, computation, cloud, and networked control. The indicators of functions include integrate, information display, monitor, remote, secure, real time, predict, and diagnostic. The indicators of technologies are composed of technology and hardware. The indicators of functions are containing within the layers of CPS. For example, CPS uses wireless networking technology to achieve remote control and uses computation technology to enhance security.

The major steps for automatically building the T-F matrix are as follows [166].

Step 1: Construct Technology and Function ontology relevant to CPS.

Step 2: Combine ontology generated in step 1 to generate a Technology Function Framework, i.e., indicators in both dimensions.

Step 3: Generate the ontology term library for all technology and function indicators.

Step 4: Text-mine frequencies of terms in patents using Normalized Term Frequency (NTF) to rank terms for each patent.

Step 5: Compare patent terms and term libraries generated in Step 3.

Step 6: Use the third quartile value threshold to decide patent counts for all technology and function indicators.

Step 7: Multiply the patent counts, in two dimensions, from step 6 and place into T-F matrix.

V. CPS PATENT LANDSCAPE ANALYSIS FROM A MANAGEMENT PERSPECTIVE

Patents are exclusive rights granted to the inventor for a limited time in exchange for public disclosure of the invention which is a solution to a specific problem which may be a product or a process. When many such exclusive rights are held by a single entity it becomes a patent portfolio which gives the holding entity market monopoly over the product, process or technology and creates revenue generating opportunities from licensing and cross licensing, offers first-mover advantages, and encourages investment.

Standard essential patents (SEP) are patents with claims to technology that must be used to comply with a technical standard. Understanding the dynamics of these claims is important to forecast future trends and the evolution of businesses in the marketplace. This section of IP landscape and analytics focuses on the importance of SEP's for CPS which relates to the standards analysis of the previous section. We obtain patent portfolios using the Thomson Innovation (TI) patent search database. The patent search is set to find patents dated between January 1^{st} 2006 and December 31^{st} 2015. This study searches the granted CPS patents from the United States, Germany, Europe, and includes WIPO application patents. The granted patents have higher values than patent applications (patents which have been applied for, are under review, but have not been officially registered as granted patents). Moreover, patents applications in WIPO have higher values than other application patents because patent applicants can file international patent applications under the patent cooperation treaty (PCT), which helps patent applicants who look for international patent protections of an invention to simplify the process of applying for separate patents in different countries simultaneously [170]. The patent search conducted used the keywords that match each layer of CPS and resulted in 1,401 patents.

This section provides the presentation of the patent landscape analysis used for the smart connection, data-to-information conversion, cyber computation, cognition, and configuration levels. The description includes top assignees, CPS key players; CPS patents' top IPCs, and the technology-function matrix. FIGURE 10 shows the patent publishing trends from 2006 to 2015. The number of patents has gradually increased.

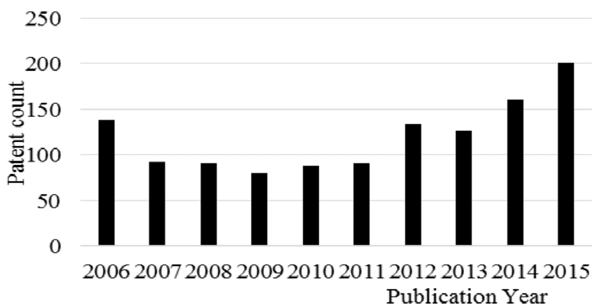


FIGURE 10. Patent publishing trends.

A. TOP ASSIGNEES – CPS KEY PLAYERS

Referring to TABLE 1, the top 10 assignees are Siemens, Rockwell, ABB, Fisher Rosemount, Honeywell, Mitsubishi, Schneider, General Electric, Invensys, and Fisher controls. The leader is Siemens from Germany with 107 patents followed by Rockwell from the USA with 59 patents. In third place is ABB from Switzerland with 52 patents. Fisher Rosemount and Honeywell from the USA follow ABB. The former has 38 patents, and the latter has 24 patents. Siemens is a pioneer in the field of electronics. Siemens's I 4.0 patent numbers are approximately equal to the sum of the patents for enterprises ranked 6 to 10. Siemens holds a leading position in this field. The top ten patent assignees account for 1/4 of the total number of CPS patents found in the database. Bosch, Trumpf, SAP, and Festo are four additional German companies holding CPS patents.

TABLE 1. Top assignees rankings.

Rank	Top assignees	Country	Patent count
1	Siemens	Germany	107
2	Rockwell Automation Tech	USA	59
3	ABB	Switzerland	52
4	Fisher Rosemount Systems	USA	38
5	Honeywell International	USA	24
6	Mitsubishi Electric	Japan	23
7	Schneider	France	19
8	General Electric	USA	17
9	Invensys Systems	UK	14
10	Fisher Controls	USA	11

TABLE 2. The leading 20 IPC classes and their CPS patent counts.

Rank	Current IPC	Content	Count
1	G05B 19/418	Total factory control, i.e. centrally controlling a plurality of machines, e.g. direct or distributed numerical control (DNC), flexible manufacturing systems (FMS), integrated manufacturing systems (IMS), computer integrated manufacturing (CIM)	428
2	G05B 19/042	Using digital processors (G05B 19/05 takes precedence)	325
3	G05B 19/00	Program control systems	225
4	G05B 19/18	Numerical control (NC)	150
5	G06F 19/00	Digital computing or data processing equipment or methods, specially adapted for specific applications	130
6	G05B 19/05	Programmable logic controllers	121
7	G05B 23/02	Electric testing or monitoring	104
8	G05B 11/01	Automatic controllers (Electric)	76
9	H04L 29/06	Characterized by a protocol	64
10	G05B 19/02	Program control systems (Electric)	64
11	G05B 19/04	Program control other than numerical control, i.e. in sequence controllers or logic controllers	62
12	H04L 29/08	Transmission control procedure	60
13	G05B 15/02	Systems controlled by a computer (Electric)	57
14	G05B 15/00	Systems controlled by a computer	53
15	G06F 15/16	Combinations of two or more digital computers each having at least an arithmetic unit, a program unit and a register, e.g. for a simultaneous processing of several programs	48
16	G06Q 10/00	Administration; Management	44
17	H04Q 09/00	Arrangements for executing specific programs	42
18	G06F 07/00	Methods or arrangements for processing data by operating upon the order or content of the data handled	41
19	B25J 09/16	Program controls (total factory control, i.e. centrally controlling a plurality of machines, G05B 19/418)	40
20	G08C 17/02	Using a radio link	38

B. OBSERVING TOP ASSIGNEES WITH KEY PATENT FAMILIES

In this part, the research reviews the top five assignees' patent families. The research selects the patents that have more family members indicating patents filed in multiple countries with greater importance. For instance, Siemens patent US7703093B2, referring to a process control for operating a technical plant or installation, which helps operators perform remote diagnosis, has 21 family members. These patents are under the WIPO, EPO, Australia, Japan, China, Germany and the United States. Rockwell Automation Tech patent US8126574B2, which provides for diagnostics, and prognostics performed on control systems, computing devices, processes, and machines, especially the methods for optimizing utilization of machines used in the industrial automation environment, has 15 family members. These patents are filed in the EPO and the United States. ABB's patent US8994543B2, concerning a diagnosis and maintenance device for a switch gear assembly, like a low-voltage switch gear assembly, which facilitates the remote retrieval or remote access to the secured or stored information, has 11 family members in WIPO, EPO, Australia, Germany and the United States. Fisher Rosemount Systems' patent US8509926B2, which relates to process control systems within plants, enables remote monitoring or communication with the plants from distant positions and has 19 family members. They are patents filed in WIPO, EPO, China, Japan and the United States. Honeywell International patent WO2010120442A2 is about the cloud computing in equipment health monitoring applications, which promotes remote monitoring and control of equipment health. It has 11 family member patents filed and protected in WIPO, EPO, Australia, Japan, China, Canada and the United States.

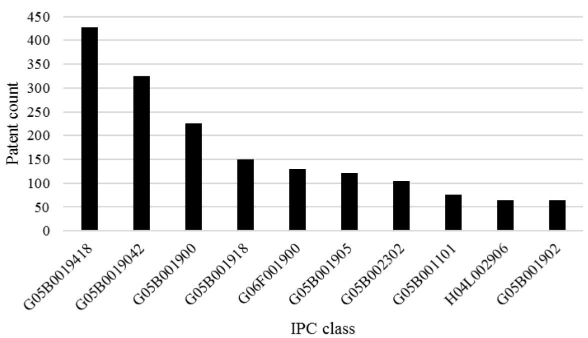


FIGURE 11. Top 10 IPC classes for CPS patents.

C. CPS PATENTS' TOP IPC CATEGORIES

The top 10 IPC classes for global CPS utility patents found are depicted in FIGURE 11, while TABLE 2 list the definition of the top 20 technical IPC categories (to be thorough in the IPC category explanation) and the CPS patent counts belonging to these IPC classes. For the leading International Patent Classification (IPC) analysis, the G05B (Control or regulating systems in general; functional elements of such systems; monitoring or testing arrangements for such systems or elements) class dominates the field of CPS. About 1/3 of the patents belong to G05B19/418 (Total factory control, including control of a plurality of machines, direct or distributed numerical control, flexible manufacturing systems, integrated manufacturing systems, and computer integrated manufacturing) with 428 patents. The core concept of CPS is to integrate all devices. The G05B19/042 (Using digital processors), G05B19/00 (Program control systems), and G05B19/18 (Numerical control) belong to the G05B class and are ranked second, third, and fourth with 325, 225, and 150 patents. G06F19/00 (Digital computing or data processing equipment or methods, specially adapted for specific applications) is a classification of data processing and computing and ranked fifth with 130 patents. Similarly, G06F15/16 and G06F07/00 relate to data processing with 48 and 41 patents. H04L29/06 and H04L29/08 relate to data transmission with 64 and 60 patents. Therefore, control, data processing, and data transmission are the three main technologies of this field. CPS requires control technology to achieve optimization and prediction. Likewise, data transmission and processing between different devices are also important to achieve the purpose of CPS.

D. TOP IPCs VERSUS ASSIGNEES ANALYSIS

TABLE 3 shows the number of patents owned by the top 10 assignees in the top 10 IPC classes include Siemens, Rockwell, ABB, Fisher Rosemount, Honeywell, Mitsubishi, Schneider, General Electric, Invensys, and Fisher Controls. All of the top assignees have patents with an IPC code of G05B 19/418 and G05B19/042. Siemens has the largest number of patents in these two categories. The number of patents owned by Rockwell in G05B19/18 (Numerical control) is

TABLE 3. Top IPC classes by assignee.

IPC \ Assignee	SIEI	ROCW	ALLM	ROEC	HONE	MITQ	SCHN	GENE	IVSY	FICO
G05B 19/418	**45**	21	**29**	15	10	4	8	2	9	6
G05B 19/042	**38**	18	17	**25**	5	2	7	**4**	3	7
G05B 19/00	**10**	1	2	0	2	1	1	4	1	0
G05B 19/18	**7**	**11**	1	0	3	1	1	2	3	1
G06F 19/00	**11**	**7**	1	1	1	0	1	1	0	0
G05B 19/05	**17**	**19**	0	3	1	**13**	5	3	0	3
G05B 23/02	**12**	4	**7**	**7**	2	1	1	5	1	1
G05B 11/01	**8**	**7**	1	4	5	0	0	2	1	1
H04L 29/06	3	3	4	**5**	0	0	**5**	0	**6**	4
G05B 19/02	0	0	0	0	**2**	0	0	0	0	0

greater than the other assignees. Mitsubishi has few patents in these IPC classes except the G05B19/05 (Programmable logic controllers) class. Mitsubishi has 13 patents in the G05B19/05 class. These assignees focus on the technological development for controls since the G05B class has more patents than other classes. Schneider and Invensys have the largest number of patents in H04L 29/06 (characterized by a protocol) and the two companies merged in 2014.

E. SUB-TECHNOLOGIES' PATENT ANALYTICS WITH RESPECT TO THEIR IPCs

Feldman et al. [165] propose text mining to study large amounts of unstructured text from patent documents to extract a collection of words or phrases. These keywords help R&D personnel predict trends in the development of technology. TABLE 4 illustrates the top 20 IPCs corresponding to the five layers of CPS. The research uses the R statistical software to extract the keywords from patents in each IPC class, to group the main sub-technologies of patents in each layer. In the connection layer, most patents fall in the IPC class G05B19/00, and the main sub-technologies contain signal, robot, control, remote, wireless, monitor and sensor. G05B19/18 ranks second and the sub-technologies contain robot, signal, remote, control, command, measure, sensor, and communication. Other sub-technologies that appear in this layer are PLC, logic, module, actuator, control device, electronic device, transmission, program, intelligent, monitor, process, and server. The conversion layer has the largest number of patents for G05B19/042, whose sub-technologies related to field device, module, signal, process, communication, monitor, and wireless. Ranking second is G06F19/00, with the sub-technologies robot, data, control, remote, compute and process. G06F07/00 is in the third place, with the sub-technologies transaction, signal, remote, message, wireless, and compute. The network layer has the largest number of patents in H04L29/06 class, with the sub-technologies processor, access, message, protocol, signal, communication device, wireless and compute. Ranking second is H04L29/08, with the sub-technologies processor, message, process control, cloud, software, control, protocol and wireless. The rest of sub-technologies are code, module, command, processor, mobile, interface, server, reconfigure, signal, program, network, monitor, and identification. The largest number of patents in the cognition layer are in the G05B23/02 class, its sub-technologies include a monitor, process, remote, signal, process control, mobile, display, and server. G05B15/02 is in the second place, whose sub-technologies include process, signal, display, remote control, server, interface, and software. Ranking third is G06Q10/00, and the sub-technologies are electronic, signal, remote, algorithm, display, and monitor. The configuration layer only contains the G05B19/418 class, with the sub-technologies module, control, manage communication, remote, compute and monitor.

TABLE 4. Top 20 IPCs that correspond to the five layers.

Level	IPC class	Sub technologies corresponding to the IPC	Patent count
Smart connection	G05B 19/00	Signal, robot, control, remote, wireless, monitor, sensor	225
	G05B 19/18	Robot, signal, remote, control, command, measure, sensor, communication	150
	G05B 19/05	Module, program, remote, PLC, signal, communication, logic, safety, apparatus	121
	G05B 11/01	Module, process control, appliance, signal, remote, automation, actuator	76
	G05B 19/02	Signal, control device, electronic device, remote, transmission, command	64
	G05B 19/04	Robot, module, remote, program, automation, sensor, intelligent, monitor	62
	G05B 15/00	Robot, sensor, display, monitor, remote, process, command, signal, communication	53
	H04Q 09/00	Data, remote control, apparatus, signal, monitor, wireless, network	42
	B25J 09/16	Module, server, remote, monitor, control, signal, sensor, control program	40
Data-to-information conversion	G05B 19/042	a field device, module, signal, process, communication, monitor, wireless	325
	G06F 19/00	Robot, data, control, remote, compute, process	130
	G06F 07/00	Transaction, signal, remote, message, wireless, compute	41
Cyber computation	H04L 29/06	Processor, access, message, protocol, signal, communication device, wireless, compute	64
	H04L 29/08	Processor, message, process control, cloud, software, control, protocol, wireless	60
	G06F 15/16	Code, module, message, command, processor, protocol, interface, server	48
	G08C 17/02	Communication, reconfigure, signal, wireless, mobile , identification, monitor, network	38
Cognition	G05B 23/02	Monitor, process, remote, signal, process control, mobile, display, server	104
	G05B 15/02	Process, signal, display, remote control, server, interface, software	57
	G06Q 10/00	Electronic, signal, remote, algorithm, display, monitor	44
Configuration	G05B 19/418	Module, control, manage, communication, remote, compute, monitor	428

Based on the above findings, the remote control technology has the greatest emphasis in this field and appears in 14 out of the 20 IPC categories. In addition, monitor, robot, module, sensor, control, wireless, signal, process also appear several times, which means that these sub-technologies are the key elements in the patents.

TABLE 5. Technology-function matrix.

Technology \ Function		F1	F2	F3	F4	F5	F6	F7	F8	Sum
Connection	Sensors (T1)	43	78	**120**	62	44	48	71	**91**	557
	Actuators (T2)	36	51	**87**	42	24	28	**70**	57	395
	Controller (T3)	25	76	**85**	40	30	34	71	**94**	455
	Circuits (T4)	127	155	**254**	155	84	125	**173**	149	1222
	Sensor network (T5)	159	207	**344**	**264**	144	151	212	**215**	**1696**
Conversion	Data processing (T6)	98	189	**267**	**200**	98	122	172	150	1296
	Smart analytics (T7)	148	212	**324**	**235**	120	133	208	178	**1558**
Cyber	Protocol (T8)	113	114	**218**	**164**	109	130	145	96	1089
	Wireless networking (T9)	62	59	**127**	**105**	74	55	69	67	618
	Computation (T10)	118	134	**274**	**215**	129	138	177	109	1294
	Cloud (T11)	126	183	**334**	**277**	168	136	183	148	**1555**
	Networked control (T12)	68	77	**134**	**109**	59	62	84	75	668
	Sum	1123	1535	**2568**	**1868**	1083	1162	**1635**	1429	12403

NOTE: INTEGRATE (F1), INFORMATION DISPLAY (F2), MONITOR (F3), REMOTE (F4), SECURE (F5), REAL TIME (F6), PREDICT (F7), DIAGNOSTIC (F8)

VI. ANALYTICAL PERSPECTIVES OF THE PATENT TECHNOLOGY-FUNCTION MATRIX

TABLE 5 shows the T-F matrix of this study constructed using computer-assisted data and text mining algorithms. The detailed method of T-F matrix creation follows in Section IV. TABLE 5 shows the maximal value of the matrix is the use of sensor networks (T5) in monitors (F3) with 344 patents. This shows that patents focused on the use of various types of sensors such as temperature, current, humidity, detection, light, vibration, voltage, and compass sensors on a variety of devices are leading the technology function trend. Monitoring the operation and production status of equipment by using the production or failure information from sensor network is a very important development. This trend follows the use of cloud technology (T11) in the monitors (F3) and the use of cloud technology (T11) in remote control (F4) with 334 and 277 patents. These two categories relate to the aforementioned categories. The data collected by the sensors through the cloud technology including cloud storage and cloud computing to process data to achieve remote monitoring and subsequently control production. In addition, there are a large number of patents in sensor networks (T5) for diagnostics (F8). The data collected through the sensor monitor the condition of the equipment and also provide further diagnostic analyses of equipment and production. Besides, cloud technology (T11) has the largest number of patents in the secure (F5) function area.

Reddy [171] considers that the four deployment models for cloud computing, such as public clouds, private clouds, community clouds and hybrid clouds, require dynamic and thoroughly integrated mechanisms to maintain the security of information. The findings are the same as his, and information security is important for cloud technology. The connection level has more patents in the monitor (F3), prediction (F7) and diagnostics (F8) function areas. This means that the patents focus on the collection of information to monitor the equipment and production conditions as well as for prediction and diagnostics. The conversion level and cyber level have more patents in the monitor (F3) and remote control (F4) fields. This means that the patents are concentrated on the use of connections and computing technology to connect with the collection of data for the monitoring and remote control of production lines. Based on the number of patents, most patents claim advanced sensor networks, smart analytics, and cloud processing to achieve effective monitoring, remote control, and prediction. Observing the numbers of patents in technologies and functions found that the basic functions such as monitoring and remote control have more patents than the higher level functions such as prediction and diagnosis. Moreover, the numbers of patents in technologies about processing, analytics, and computation, which are data processing (T6), smart analytics (T7), computation (T10), and cloud (T11), are higher than patents about networking, which includes protocol (T8), wireless networking (T9), and networked control (T12). There are fewer patents in the fundamental technologies, including sensors (T1), actuators (T2), and controller (T3). CPS uses the computer, sensors, and by combining network technologies to connect machines, equipment, and cyber systems. Through mutual communication and interaction, CPS integrates the virtual and physical world with increased applications for sensor networks. Information and communication technologies are for the interconnection and communication between multiple machines, equipment, and cyber systems that are the essential features of CPS.

Compared to the sensor network (T5) technology, the patents of stand-alone sensors (T1) technology is few. The advanced technologies of CPS focus mostly on sensor communication for the network instead of the sensor itself. Furthermore, the interconnection and intercommunication of sensors helps integrate the virtual and physical technologies. The result of the technology-function matrix analysis and the analysis of top 20 IPCs' sub-technologies show that the remote control and monitoring is a competitive sector. These areas of technologies are of high importance. Because CPS has the functions of remote monitoring and built-in prognostic functions, systems assist in the testing of production line process, and the monitoring of production equipment or material consumption. CPS applies to real-time fault diagnosis or intelligent prognosis. For example, many companies in the iron and steel industry apply the sensor and information and communications technologies to monitor the temperature, width, thickness, and quality indices of semi-finished parts during the production process.

VII. CONCLUSIONS

Cyber-physical systems are expected to play a major role in the design and development of future engineering systems providing new capabilities that far exceed today's levels of autonomy, functionality, usability, reliability, and cyber security. Advances in CPS research, and development considers the key enabler of Industry 4.0 in various industrial sectors. Other key technologies adopted, e.g., IoT, sensors, and cloud computing are integral to CPS. CPS development accelerates through close collaboration between academic disciplines in computation, communication, control, and other engineering and automation disciplines [10]. This research paper provides a consolidate literature review as the basic background and defines the state of the art for CPS. The analysis and grouping of technical standards for CPS, set by international standardization organizations, based on the CPS architecture of smart connection levels, data-to-information conversion levels, cyber levels, cognition levels and configuration levels. CPS standard essential patents analyzed from both managerial and technical perspectives based on CPS ontology schema. The CPS patent counts and assignees analysis, IPCs analysis, analysis of sub-technologies corresponding to the IPCs, and technology function matrix analyzed in the paper. The results support claims made by the previous literature [44] regarding advances of IoT technologies for CPS development and implementation in the context of Industry 4.0. The findings help scholars and industry practitioners understand the latest trends in I 4.0 technical standards and patents. The research also benefits small and medium companies to integrate I 4.0 solutions and adopt themselves to the changing global industrial environment. These research results also help guide research and development to achieve globally inter-operable CPS for enhancing the manufacturing ecosystem for Industry 4.0.

APPENDIX

See Tables 6–10.

TABLE 6. Smart connection level standards.

Title	Scope of deliverable (*Italics indicates exact wording of standard*)	Corresponding standard of China
ISO/IEC 15459 series, Information technology - Automatic identification and data capture techniques - Unique identification [108]	Unique identification is used in many places such as item, transport unit, returnable transport item, and grouping. The ISO/IEC 15459 consists of 6 parts: Part 1: Individual transport units; Part 2: Registration procedures; Part 3: Common rules; Part 4: Individual products and product packages; Part 5: Individual returnable transport items (RTIs); Part 6: Groupings. *The ISO/IEC 15459 series, which can include additional rules for which level of identification should be used, are often made available from the Issuing Agency.*	
ISO/IEC 19762:2016, Information technology - Automatic identification and data capture (AIDC) techniques - Harmonized vocabulary[107]	The ISO/IEC19762:2016 *provides terms and definitions for automatic identification techniques and data entry fields are based on which other specialized sections in various technical fields, and the essential terms that must be employed by non-technical users to communicate with specialists in automatic identification and data capture techniques.*	GB/T 29261 series, Information technology - Automatic identification and data capture(AIDC) techniques - Vocabulary [157]
ISO/IEC/IEEE 21450:2010, Information technology - Smart transducer interface for sensors and actuators - Common functions, communication protocols, and Transducer Electronic Data Sheet (TEDS) formats [109]	The ISO/IEC/IEEE 21450:2010 *defines the functions that are to be performed by a transducer interface module (TIM) and the common characteristics for all devices that implement the TIM. It specifies the formats for Transducer Electronic Data Sheets (TEDS) and also defines a set of commands to facilitate the setup and control of the TIM as well as reading and writing the data used by the system. Application programming interfaces (APIs) are defined to facilitate communications with the TIM and with applications.*	
ISO/IEC/IEEE 21451 series, Information technology - Smart transducer interface for sensors and actuators [110]	Part 1: Network Capable Application Processor (NCAP) information model that *defines an object model with a network-neutral interface for connecting processors to communication networks, sensors, and actuators.*	
	Part 2: Transducer to microprocessor communication protocols and Transducer Electronic Data Sheet (TEDS) formats that *defines a digital interface for connecting transducers to microprocessors. It describes a Transducer Electronic Data Sheet (TEDS) and its data formats. It defines an electrical interface, read and write logic functions to access the TEDS, and a wide variety of transducers.*	

TABLE 6. ***(Continued.)*** **Smart connection level standards.**

	Part 4: Mixed-mode communication protocols and Transducer Electronic Data Sheet (TEDS) formats that *define the protocol and interface that allows analog transducers to communicate digital information with an ISO/IEC/IEEE 21451 object. It also defines the format of the Transducer Electronic Data Sheet (TEDS), which is based on the ISO/IEC/IEEE 21451-2 TEDS.*	
	Part 7: Transducer to radio frequency identification (RFID) systems communication protocols and Transducer Electronic Data Sheet (TEDS) format. *Part 7 defines data formats to facilitate communications between radio frequency identification (RFID) systems and smart RFID tags with integral transducers (sensors and actuators). It defines new Transducer Electronic Data Sheet (TEDS) formats based on the ISO/IEC/IEEE 21451 series of standards. It also defines a command structure and specifies the communication methods with which the command structure is designed to be compatible.*	
IEC 61131 series, Programmable controllers [111]	IEC 61131 series is an IEC standard for programmable controller. IEC 61131 series consists of 9 parts. Part 1: General information. *It identifies the principal functional characteristics of programmable controller systems.* Part 2: Equipment requirements and tests. Part 3: Programming languages. Part 4: User guidelines. Part 5: Communications. Part 6: Functional safety. Part 7: Fuzzy control programming. Part 8: Guidelines for the application and implementation of programming languages. Part 9: Single-drop digital communication interface for small sensors and actuators (SDCI).	GB/T 15969 series, Programmable controllers [139]
IEC 61499 series, Function blocks [112]	IEC 61499 series *defines a generic architecture and presents guidelines for the use of function blocks in distributed industrial-process measurement and control systems (IPMCSs). It also defines requirements for software tools and rules for the development of compliance profiles.* IEC 61499 series consists of 3 parts. Part 1: Architecture. Part 2: Software tool requirements. Part 4: Rules for compliance profiles	GB/T 19769 series, Function Blocks for industrial - process measurement and control system [143]

TABLE 7. **Data to - information conversion level standards.**

Title	Scope of deliverable (*Italics indicates exact wording of standard*)	Corresponding standard of China
IEC/ ISO 13236:1998, Information technology - Quality of service: Framework [116]	IEC/ ISO 13236:1998 is to *provide a common basis for the coordinated development and enhancement of the wide range of standards that specify or reference Quality of Service (QOS) requirements or mechanisms in an Information Technology (IT) environment. It offers a means of developing or enhancing standards relating to QOS and provides concepts and terminology that will assist in maintaining the consistency of related standards.*	GB/T 18903-2002, Information technology-Quality of service: Framework [140]
ISO/IEC 27000 family, information technology - security techniques [117]	ISO/IEC 27000 family provides the best practice recommendations on information security management, risks and controls within the context of an overall information security management system (ISMS).	
IEC 61360 series, Standard data elements types with associated classification scheme for electric items [114]	IEC 61360 series *provides a firm basis for the clear and unambiguous definition of characteristic properties (data element types) of all elements of electrotechnical systems from basic components to sub-assemblies and full systems. It also provides It provides a means for the computer-sensible representation and exchange of such data, allowing for the implementation of dictionary systems dealing with data delivered according to either of the standards.* IEC 61360 consists of 3 parts. Part 1: Definitions - Principles and methods. Part 2: EXPRESS dictionary schema. Part 4: IEC reference collection of standard data element types and component classes.	
IEC 61804-3, IEC 61804-4, IEC 61804-5, IEC 61804-6 Function blocks (FB) for process control - Electronic device description language (EDDL) [113]	These four parts of IEC 61804 series define the EDDL. EDDL is a language that can be used to describe the characteristics of devices. Device suppliers can use EDDL to create Electronic Device Description (EDD) files instead of using XML.	GB/T 21099-3-2010, Function block (FB) for process control-Part 3: Electronic device description language (EDDL)

TABLE 7. ***(Continued.)*** **Data to - information conversion level standards.**

		GB/T 21099-4-2010, Function block (FB) for process control - Part 4:EDD interoperability guideline [150]
IEC 62443 series (ISA99), Security for Industrial Automation and Control Systems [136]	IEC62443 series is divided into 4 parts including general, information security program, system technology and component technologies. IEC62443 series of standards used these 4 parts to achieve comprehensive security protection. *The primary goal of the IEC 62443 series is to provide a flexible framework that facilitates addressing current and future vulnerabilities in Automation and Control Systems and applying necessary mitigations in a systematic, defensible manner. IEC 62443 series is to build extensions to enterprise security that adapt the requirements for business IT systems and combines them with the unique requirements for strong availability needed by Automation and Control Systems.*	GB/T 30976.1-2014, Industrial control system security-Part 1:Assessment specification GB/T 30976.2-2014, Industrial control system security-Part 2:Acceptance specification [161]
IEC 62714 series, Engineering data exchange format for use in industrial automation systems engineering - Automation markup language [115]	IEC 62714 series is *a solution for data exchange focusing on the domain of automation engineering. The data exchange format defined in the IEC 62714 series (Automation Markup Language, AML) is an XML schema based data format and has been developed in order to support the data exchange in a heterogeneous engineering tools landscape. The goal of AML is to interconnect engineering tools in their different disciplines, e.g. mechanical plant engineering, electrical design, process engineering, process control engineering, HMI development, PLC programming, robot programming, etc.* IEC 62714 series consists of 2 parts. Part 1: Architecture and general requirements. Part 2: Role class libraries	

TABLE 8. **Cyber level standards.**

Title	Scope of deliverable (*Italics indicates exact wording of standard*)	Corresponding standard of China
ISO/IEC 8802 series, Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks [119]	The ISO/IEC 8802 includes many parts, such as ISO/IEC TR 8802-1:2001, ISO/IEC 8802-2:1998, ISO/IEC/IEEE 8802-3:2014, ISO/IEC/IEEE 8802-3-1:2015, ISO/IEC 8802-5:1998, ISO/IEC/IEEE 8802-11:2012, ISO/IEC/IEEE 8802-22:2015, and ISO/IEC/IEEE 8802-15-4:2010. *It provides an introduction to the set of International Standards which describe local area networks.*	GB/T 15629 series, Information technology-Local and metropolitan area networks [107]
ISO/IEC 14476 series, Information technology - Enhanced communications transport protocol [124]	The ISO/IEC 14476 series is used to enhance communications transport protocol. It consists of 6 parts. Part 1: simplex multicast transport, Part 2: QoS management for simplex multicast transport, Part 3: duplex multicast transport, Part 4: QoS management for duplex multicast transport, Part 5: N-plex multicast transport, and Part 6: QoS management for n-plex multicast transport.	GB/T 26241 series, Information technology - Enhanced communication transport protocol [154]
ISO/IEC 17826:2012, Information technology - Cloud Data Management Interface (CDMI) [130]	ISO/IEC 17826:2012 *specifies the interface to access cloud storage and to manage the data stored therein. It is applicable to developers who are implementing or using cloud storage.*	GB/T 31916.2-2015, Information technology-Cloud data storage and management-Part 2:Object-based cloud storage application interface [163]

TABLE 8. **(*Continued.*) Cyber level standards.**

ISO/IEC 20005:2013, Information technology- Sensor networks- Services and interfaces supporting collaborative information processing in intelligent sensor networks [125]	The ISO/IEC 20005:2013 *specifies services and interfaces supporting collaborative information processing (CIP) in intelligent sensor networks which includes: CIP functionalities and CIP functional model, common services supporting CIP, common service interfaces to CIP.*	GB/T 30269.401-2015, Information technology - Sensor networks - Part 401: Collaborative information processing: Services and interfaces supporting collaborative information processing [164]
ISO/IEC 27033 series, Information technology - Security techniques - Network security [131]	The ISO/IEC 27033 series is to *provide detailed guidance on the security aspects of the management, operation and use of information system networks, and their interconnections. Those individuals within an organization that are responsible for information security in general, and network security in particular, should be able to adapt the material in ISO/IEC 27033 series to meet their specific requirements.* ISO/IEC 27033 series consists of 6 parts. Part 1: Overview and concepts. Part 2: Guidelines for the design and implementation of network security. Part 3: Reference networking scenarios - Threats, design techniques and control issues. Part 4: Securing communications between networks using security gateways Part 5: Securing communications across networks using Virtual Private Networks (VPNs) Part 6: Securing wireless IP network access.	
ISO/IEC 29180：2012, Information technology - Telecommunications and information exchange between systems - Security framework for ubiquitous sensor networks [126]	The ISO/IEC 29180:2012 *describes the security threats to and security requirements of the ubiquitous sensor network (USN). In addition, it categorizes the security technologies according to the security functions that satisfy the said security requirements and where the security technologies are applied in the security model of the USN.*	
ISO/IEC 29182 series, Sensor networks: Sensor Network Reference Architecture (SNRA) [127]	The ISO/IEC 29182 series contains seven sections and *provides the guidance for designing and developing the sensor networks. The purpose is to increase interoperability of sensor networks, and make sensor network components run smoothly. The ISO/IEC 29182 series focuses on a generic architecture for sensor networks. It can be used by sensor network designers, software developers, system integrators, and service providers.*	
ISO/IEC 30101:2014, Information technology - Sensor networks: Sensor network and its interfaces for smart grid system [128]	The ISO/IEC 30101:2014 *is for sensor networks in order to support smart grid technologies for power generation, distribution, networks, energy storage, load efficiency, control and communications, and associated environmental challenges. It describes the interfaces between the sensor networks and other networks; Sensor network architecture to support smart grid systems; Interface between sensor networks with smart grid systems; Sensor network based emerging applications and services to support smart grid systems.*	
ISO/IEC 30128:2014, Information technology - Sensor networks - Generic Sensor Network Application Interface [129]	The ISO/IEC 30128:2014 *specifies the interfaces between the application layers of service providers and sensor network gateways. It Describes Generic sensor network applications' operational requirements; Sensor network capabilities; Mandatory and optional interfaces between the application layers of service providers and sensor network gateways.*	

TABLE 8. ***(Continued.)*** **Cyber level standards.**

IEC 61158 series, Industrial communication networks - Fieldbus specifications [120]	The IEC 61158 series is the fieldbus standard. IEC 61158 series consists of 6 parts. Part 1: Overview and guidance for the IEC 61158 and IEC 61784 series, Part 2: Physical Layer specification and service definition, Part 3: Data Link Service definition, Part 4: Data Link Protocol specification, Part 5: Application Layer Service definition, Part 6: Application Layer Protocol specification. These standards are formulated for real-time distributed control and composed of many industrial computer network protocols.	GB/T 19582, GB/T 19760, GB/T 20171, GB/T 20540, GB/Z 20541, GB/T 25105, GB/Z 26157, GB/T 27960, GB/Z 29619, GB/T 29910, GB/T 31230 [141][142][145][147][148][152][153][156][159][160][162]
IEC 61784 series, Industrial communication networks - Profiles [121]	The IEC 61784 series is the profiles standard of fieldbus. IEC 61784 consists of 5 parts. Part 1: Fieldbus profiles, Part 2: Additional fieldbus profiles for real-time networks based on ISO/IEC 8802-3, Part 3: Functional safety fieldbuses, Part 4: Security, and Part 5: Installation of fieldbuses. IEC 61784 series *defines a set of protocol specific communication profiles based primarily on the IEC 61158 series. It can be used in the design of devices involved in communications in factory manufacturing and process control.*	
IEC 62591:2016, Industrial networks – Wireless communication network and communication profiles - Wireless HART™ [122]	IEC 62591:2016 *defines a wireless communication network, including physical layer service definition and protocol specification, data-link layer service and protocol, application layer service and protocol, network management, security, communication profile, wireless procedures and gateway*.	GB/T 29910.5-2013, Industrial communication networks - Fieldbus specifications - Type 20 HART specification - Part 5:WirelessHART wireless communication network and communication profile [160]
IEC 62601:2015, Industrial networks - Wireless communication network and communication profiles - WIA-PA [123]	IEC 62601 *defines the system architecture and the communication protocol of Wireless networks for Industrial Automation - Process Automation (WIA-PA). WIA-PA system architecture and communication protocol are discussed in this standard, and suitable for industrial measurement and monitoring of wireless network system.*	GB/T 26790 series, Industrial wireless networks WIA specification [155]
IEC 62769 series, Field Device Integration (FDI) [1]	IEC 62769 provides the specifications of Field Device Integration (FDI). IEC 62769 series consists of 12 parts. Part 1: Overview. Part 2: FDI Client. Part 3: FDI Server. Part 4: FDI Packages. Part 5: FDI Information Model. Part 6: FDI Technology Mapping. Part 7: FDI Communication Devices. Part 101-1: Profiles – Foundation Fieldbus H1. Part 101-2: Profiles – Foundation Fieldbus HSE . Part 103-1: Profiles – PROFIBUS. Part 103-4: Profiles – PROFINET. Part 109-1: Profiles – HART and WirelessHART	

TABLE 9. **Cognition level standards.**

Title	Scope of deliverable (*Italics indicates exact wording of standard*)	Corresponding standard of China
ISO 13374 series, Condition monitoring and diagnostics of machines - Data processing, communication and presentation [133]	ISO 13374 series is to *provide the basic requirements for open software specifications which will allow machine condition monitoring data and information to be processed, communicated and displayed by various software packages without platform-specific or hardware-specific protocols.* IEC 13374 series consists of 4 parts. Part 1: General guidelines. Part 2: Data processing. Part 3: Communication. Part 4: Presentation.	GB/T 22281 series, Data processing, communication and presentation [151]
IEC 62453 - Field device tool (FDT) interface specification [134]	IEC 62453 introduces the concept of FDT as well as the definition of the relevant terms about FDT. *FDT is used for standardization of communication and configuration interfaces between all field equipment and host systems. This standard is applicable to all kinds of industrial applications, such as engineering system, monitoring and diagnostic applications.*	GB/T 29618 series, Field device tool(FDT)interface specification [158]

TABLE 10. Configuration level standards.

Title	Scope of deliverable (*Italics indicates exact wording of standard*)	Corresponding standard of China
IEC 61508 series, Functional safety of electrical/ electronic/ programmable electronic safety-related systems [137]	IEC 61508 series *covers those aspects to be considered when electrical/ electronic/ programmable electronic (E/E/PE) systems are used to carry out safety functions. A major objective of this standard is to facilitate the development of product and application sector international standards by the technical committees responsible for the product or application sector.* The IEC 61508 series has seven parts. Part 1: General requirements. Part 2: Requirements for electrical/ electronic/ programmable electronic safety-related systems. Part 3: Software requirement. Part 4: Definitions and abbreviation. Part 5: Examples of methods for the determination of safety integrity levels. Part 6: Guidelines on the application of IEC 61508-2 and IEC 61508-3. Part 7: Overview of techniques and measures	GB/T 20438 series, Functional safety of electrical/ electronic/ programmable electronic safety-related systems [146]
IEC 61512 series, Batch control [135]	The IEC 61512 series defined *the models for batch control as used in the process industries and terms that help explain the relationships between these models and terms. The IEC 61512 also defined the data models that describe batch control as applied in the process industries, data structures for facilitating communications within and between batch control implementations and language guidelines for representing recipes.* The IEC 61512 series consist of 4 parts. Part 1: Models and terminology. Part 2: Data structures and guidelines for languages. Part 3: General and site recipe models and representation. Part 4: Batch production records.	GB/T 19892 series, Batch control [144]
IEC 62264 series, Enterprise - control system integration [136]	IEC 62264 is an international standard for enterprise-control system integration. *Its goals are to increase uniformity and consistency of interface terminology and reduce the risk, cost, and errors associated with implementing these interfaces.* The IEC 62264 series consists of 5 parts. Part 1: Models and terminology. Part 2: Object and attributes for enterprise-control system integration. Part 3: Activity models of manufacturing operations management. Part 4: Objects models attributes for manufacturing operations management integration. Part 5: Business to manufacturing transactions	GB/T 20720 series, Enterprise-control system integration [149]

REFERENCES

[1] J. Lee, B. Bagheri, and H.-A. Kao, "A cyber-physical systems architecture for industry 4.0-based manufacturing systems," *Manuf. Lett.*, vol. 3, pp. 18–23, Jan. 2015.

[2] T. Sanislav and L. Miclea, "Cyber-physical systems—Concept, challenges and research areas," *J. Control Eng. Appl. Informat.*, vol. 14, no. 2, pp. 28–33, 2012.

[3] T. Samad and A.-M. Annaswamy, "The impact of control technology," *IEEE Control Syst. Soc.*, vol. 31, no. 5, pp. 26–27, Oct. 2011.

[4] E.-A. Lee, "Cyber-physical systems—Are computing foundations adequate?" in *Proc. Position Paper NSF Workshop Cyber-Phys. Syst., Res. Motivat., Techn. Roadmap*, vol. 2. Oct. 2006, pp. 1–9.

[5] A. Bhave, B.-H. Krogh, D. Garlan, and B. Schmerl, "View consistency in architectures for cyber-physical systems," in *Proc. IEEE/ACM Int. Conf. Cyber-Phys. Syst. (ICCPS)*, Apr. 2011, pp. 151–160.

[6] J. Shi, J. Wan, H. Yan, and H. Suo, "A survey of cyber-physical systems," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Nov. 2011, pp. 1–6.

[7] L. Hu, N. Xie, Z. Kuang, and K. Zhao, "Review of cyber-physical system architecture," in *Proc. 15th IEEE Int. Symp. Object/Compon./Service-Oriented Real-Time Distrib. Comput. Workshops (ISORCW)*, Apr. 2012, pp. 25–30.

[8] L. Sha, S. Gopalakrishnan, X. Liu, and Q. Wang, "Cyber-physical systems: A new frontier," in *Machine Learning in Cyber Trust*. New York, NY, USA: Springer, 2009, pp. 3–13.

[9] W. MacDougall, *Industrie 4.0—Smart Manufacturing for the Future*. Berlin, Germany: Germany Trade & Invest, 2014.

[10] Y. Tan, S. Goddard, and L.-C. Pérez, "A prototype architecture for cyber-physical systems," *ACM SIGBED Rev.*, vol. 5, no. 1, p. 26, Jan. 2008.

[11] R. R. Rajkumar, I. Lee, L. Sha, and J. Stankovic, "Cyber-physical systems: The next computing revolution," in *Proc. 47th Design Autom. Conf. (DAC)*, Jun. 2010, pp. 731–736.

[12] J. He, "Cyber-Physical Systems," (in Chinese), *Commun. China Comput. Federation*, vol. 6, no. 1, pp. 25–29, 2010.

[13] J. C. Maxwell, *A Treatise on Electricity and Magnetism*, vol. 1. Oxford, U.K.: Clarendon, 1892.

[14] Industrie 4.0 Working Group. (2013). *Securing the Future of German Manufacturing Industry–Recommendations for Implementing the Strategic Initiative*, accessed on Apr. 20, 2016. [Online]. Available: http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Material_fuer_Sonderseiten/Industrie_4.0/Final_report__Industrie_4.0_accessible.pdf

[15] K.-D. Kim and P.-R. Kumar, "Cyber–physical systems: A perspective at the centennial," *Proc. IEEE*, vol. 100, Special Centennial Issue, pp. 1287–1308, May 2012.

[16] A. Guo, D. Yu, Y. Hu, S. Wang, T. An, and T. Zhang, "Design and implementation of data collection system based on CPS model," in *Proc. Int. Conf. Comput. Sci. Mech. Autom. (CSMA)*, Oct. 2015, pp. 139–143.

[17] M. Hermann, T. Pentek, and B. Otto, "Design principles for industrie 4.0 scenarios," in *Proc. 49th Hawaii Int. Conf. Syst. Sci. (HICSS)*, Jan. 2016, pp. 3928–3937.

[18] DIN e. V., Berlin, Germany. (Jan. 2016). *German Standardization Roadmap—Industry 4.0 (Version 2)*, accessed on Sep. 10, 2016. [Online]. Available: http://www.din.de/blob/65354/f5252239daa596d8c4d1f24b40e4486d/roadmap-i4-0-e-data.pdf

[19] Ministry of Industry and Information Technology of the People's Republic of China and Standardization Administration of the People's Republic of China. (2015). *National Intelligent Manufacturing Standard System Construction Guidelines*, accessed on Sep. 10, 2016. [Online]. Available: https://www.dke.de/resource/blob/929020/7080b1667308545c088901b39a111756/manufacturing-guidelines-data.pdf

[20] It's OWL Clustermanagement GmbH. (2014). *On the Road to Industry 4.0: Solutions From the Leading-Edge Cluster It's OWL, Intelligent Technical Systems OstWestfalenLippe*, accessed on Apr. 20, 2016. [Online]. Available: http://www.its-owl.com/fileadmin/PDF/Informationsmaterialien/2015-On_the_road_to_Industry_4.0_-_Solutions_from_the_Leading-Edge_Cluster_it_s_OWL.pdf

[21] S. Allenhof, "Implementation of an example application facilitating industrie 4.0," M.S. thesis, Dept. Signal. Syst., Chalmers Univ. Technol., Gothenburg, Sweden, 2015, accessed on Apr. 20, 2016. [Online]. Available: http://publications.lib.chalmers.se/records/fulltext/222879/222879.pdf

[22] A.-W. Scheer, "Industry 4.0 the industrial big change, a German perspective on a global challenge," *Boao Rev.*, vol. 13, pp. 18–20, Jul. 2015.

[23] J. Bechtold, A. Kern, C. Lauenstein, and L. Bernhofer, *Industry 4.0—The Capgemini Consulting View*. London, U.K.: Capgemini Consulting, 2014.

[24] J. Posada *et al.*, "Visual computing as a key enabling technology for industrie 4.0 and industrial Internet," *IEEE Comput. Graph. Appl.*, vol. 35, no. 2, pp. 26–40, Mar./Apr. 2015.

[25] X. Yuan, C. J. Anumba, and K. M. Parfitt, "Review of the potential for a cyber-physical system approach to temporary structures monitoring," *Int. J. Archit. Res.*, vol. 9, no. 3, pp. 26–44, 2015.

[26] E. Rosenberg, M.-H. Haeusler, R. Araullo, and N. Gardner, "Smart architecture-bots and industry 4.0 principles for architecture," in *Proc. 33rd eCAADe Conf.*, vol. 2. Sep. 2015, pp. 251–259.

[27] P. Gölzer, P. Cato, and M. Amberg, "Data processing requirements of industry 4.0—Use cases for big data applications," in *Proc. Eur. Conf. Inf. Syst. (ECIS)*, May 2015, pp. 1–13.

[28] Y. Feng, "Future development possibilities of talent management under the influence of 'industry 4.0,"' M.S. thesis, Dept. Manage., Univ. Vaasa, Vaasa, Finland, 2016, accessed on Apr. 20, 2016. [Online]. Available: https://www.tritonia.fi/download/gradu/6900

[29] M. Brettel, N. Friederichsen, M. Keller, and M. Rosenberg, "How virtualization, decentralization and network building change the manufacturing landscape: An industry 4.0 perspective," *Int. J. Mech., Ind. Sci. Eng.*, vol. 8, no. 1, pp. 37–44, 2014.

[30] B. Sniderman, M. Mahto, and M.-J. Cotteleer. (2016). *Industry 4.0 and Manufacturing Ecosystems—Exploring the World of Connected Enterprises*, accessed on Apr. 20, 2016. [Online]. Available: https://dupress.deloitte.com/dup-us-en/focus/industry-4-0/manufacturing-ecosystems-exploring-world-connected-enterprises.html

[31] InterConnect. (2016). *Industry (Industrie) 4.0 and IoT, IBM's Point-of-View and Potential Technical Approaches*, accessed on Apr. 20, 2016. [Online]. Available: https://www-304.ibm.com/events/tools/interconnect/2016ems/REST/presentations/PDF/InterConnect2016_1648.pdf

[32] K. Wang, "Intelligent predictive maintenance (IPdM) system—Industry 4.0 scenario," *WIT Trans. Eng. Sci.*, vol. 113, no. 10, pp. 259–268, 2016.

[33] J. Lee. (2014). *Recent Advances and Transformation Direction of PHM*, accessed on Apr. 20, 2016. [Online]. Available: https://www.nist.gov/sites/default/files/documents/el/isd/Keynote_Lee_IMS-University_of_Cincinnati_updated.pdf

[34] H.-M. Ing. (2014). *The Human Role in Cyber-Physical Systems*, accessed on Apr. 20, 2016. [Online]. Available: http://www.europe-aim.eu/wp-content/uploads/2012/07/Meier-The-Human-Role-In-Cyber-Physical-Systems.pdf

[35] MPDV. (2015). *News of the Future Concept MES 4.0-Industry 4.0: MES Supports Decentralization*, MPDV Mikrolab GmbH, Berlin, Germany, accessed on Apr. 20, 2016. [Online]. Available: https://www.mpdv.com/uploads/tx_news/NEWS_International_2015_web_02.pdf

[36] IT2Industry. (2014). *IT2Industry 2014-Review*, accessed on Apr. 20, 2016. [Online]. Available: http://it2industry.de/media/website/files/pdf/rueckblick-it2industry-electronica.pdf

[37] APROS-Consulting & Service. (2014). *Globally Networked-Controlled as if by Magic-Industry 4.0*, accessed on Apr. 20, 2016. [Online]. Available: http://news.blog.apros-consulting.de/globally-networked-controlled-as-if-by-magic-industry-4-0/

[38] M. Blanchet, T. Rinn, G.-V. Thaden, and G.-D. Thieulloy. (2014). *Industry 4.0: The New Industrial Revolution-How Europe Will Succeed*, Roland Berger Strategy Consultants, accessed on Apr. 20, 2016. [Online]. Available: http://www.rolandberger.com/media/pdf/Roland_Berger_TAB_Industry_4_0_20140403.pdf

[39] Sercos International e.V. (2013). *Industry 4.0 With Sercos on the Threshold of the Next Industrial Revolution*, accessed on Apr. 20, 2016. [Online]. Available: http://www.sercos.com/literature/pdf/sercos_news_0213_en.pdf

[40] J. Lee, H.-A. Kao, and S. Yang, "Service innovation and smart analytics for industry 4.0 and big data environment," *Procedia CIRP*, vol. 16, pp. 3–8, 2014.

[41] N. B. Pronios. (2015). *CPS and Other 'smart' Systems: A Review*, accessed on Apr. 20, 2016. [Online]. Available: https://connect.innovateuk.org/documents/407758/30061168/Systems+overview_London_05_11_15_f.pdf/5cc9d758-0785-4725-915c-4319a24179af

[42] M. M. Herterich, F. Uebernickel, and W. Brenner, "The impact of cyber-physical systems on industrial services in manufacturing," *Procedia CIRP*, vol. 30, pp. 323–328, 2015.

[43] L. Gehrke *et al.* (2015). *Industry 4.0, A Discussion of Qualifications and Skills in the Factory of the Future: A German and American Perspective*, accessed on Apr. 20, 2016. [Online]. Available: https://www.researchgate.net/publication/279201790_A_Discussion_of_Quali_cations_and_Skills_in_the_Factory_of_the_Future_A_German_and_American_Perspective

[44] LexInnova. (2016). *Internet of Things: 2016 Patents and Perspectives*, accessed on Apr. 10, 2016. [Online]. Available: http://www.lex-innova.com/lexinnova-resources/white-papers/

[45] K.-J. Lin and M. Panahi, "A real-time service-oriented framework to support sustainable cyber-physical systems," in *Proc. 8th IEEE Int. Conf. Ind. Informat.*, Jul. 2010, pp. 15–21.

[46] H. Georg, S.-C. Müller, C. Rehtanz, and C. Wietfeld, "Analyzing cyber-physical energy systems: The INSPIRE cosimulation of power and ICT systems using HLA," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2364–2373, Nov. 2014.

[47] S.-S. Setty *et al.*, "A unified framework for the design of distributed cyber-physical systems—Industrial automation example," in *Proc. IEEE 10th Conf. Ind. Electron. Appl. (ICIEA)*, Jun. 2015, pp. 996–1002.

[48] G. Lanza, N. Stricker, and R. Moser, "Concept of an intelligent production control for global manufacturing in dynamic environments based on rescheduling," in *Prco. IEEE Int. Conf. Ind. Eng. Eng. Manage.*, Dec. 2013, pp. 315–319.

[49] I. Etxeberria-Agiriano, I. Calvo, A. Noguero, and E. Zulueta, "Configurable cooperative middleware for the next generation of CPS," in *Proc. 9th Int. Conf. Remote Eng. Virtual Instrum. (REV)*, Jul. 2012, pp. 1–5.

[50] S.-H. Choi, I.-B. Jeong, J.-H. Kim, and J. J. Lee, "Context generator and behavior translator in a multilayer architecture for a modular development process of cyber-physical robot systems," *IEEE Trans. Ind. Electron.*, vol. 61, no. 2, pp. 882–892, Feb. 2014.

[51] B. Vogel-Heuser, C. Diedrich, D. Pantförder, and P. Göhner, "Coupling heterogeneous production systems by a multi-agent based cyber-physical production system," in *Proc. 12th IEEE Int. Conf. Ind. Informat. (INDIN)*, Jul. 2014, pp. 713–719.

[52] N. Jazdi, "Cyber physical systems in the context of industry 4.0," in *Proc. IEEE Int. Conf. Autom., Quality Testing, Robot.*, May 2014, pp. 1–4.

[53] T. Vollmer and M. Manic, "Cyber-physical system security with deceptive virtual hosts for industrial control networks," *IEEE Trans. Ind. Informat.*, vol. 10, no. 2, pp. 1337–1347, May 2014.

[54] S. Iarovyi, W. M. Mohammed, A. Lobov, B. R. Ferrer, and J. L. M. Lastra, "Cyber–physical systems for open-knowledge-driven manufacturing execution systems," *Proc. IEEE*, vol. 104, no. 5, pp. 1142–1154, May 2016.

[55] D. Stokic, S. Scholze, C. Decker, and K. Stöbener, "Engineering methods and tools for collaborative development of industrial cyber-physical based products and services," in *Proc. 12th IEEE Int. Conf. Ind. Informat. (INDIN)*, Jul. 2014, pp. 594–599.

[56] R. Harrison, D. Vera, and B. Ahmad, "Engineering methods and tools for cyber–physical automation systems," *Proc. IEEE*, vol. 104, no. 5, pp. 973–985, May 2016.

[57] I. Dumitrache, S.-I. Caramihai, and A. Stanescu, "From mass production to intelligent cyber-enterprise," in *Proc. 19th Int. Conf. Control Syst. Comput. Sci.*, May 2013, pp. 399–404.

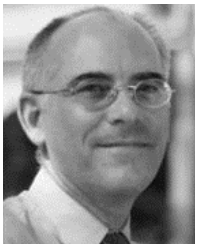
[58] T. Watteyne *et al.*, "Industrial wireless IP-based cyber–physical systems," *Proc. IEEE*, vol. 104, no. 5, pp. 1025–1038, May 2016.

[59] J. Haupert, S. Bergweiler, P. Poller, and C. Hauck, "IRAR: Smart intention recognition and action recommendation for cyber-physical industry environments," in *Proc. Int. Conf. Intell. Environ. (IE)*, Jun./Jul. 2014, pp. 124–131.

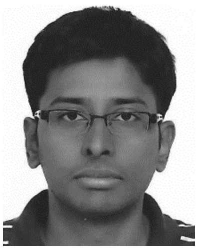
[60] C. W. Axelrod, "Managing the risks of cyber-physical systems," in *Proc. IEEE Long Island Syst., Appl. Technol. Conf. (LISAT)*, May 2013, pp. 1–6.
[61] M. Heiss, A. Oertl, M. Sturm, P. Palensky, S. Vielguth, and F. Nadler, "Platforms for industrial cyber-physical systems integration: Contradicting requirements as drivers for innovation," in *Proc. Workshop Modeling Simulation Cyber-Phys. Energy Syst. (MSCPES)*, Apr. 2015, pp. 1–8.
[62] T. Facchinetti and M.-L. Della Vedova, "Real-time modeling for direct load control in cyber-physical power systems," *IEEE Trans. Ind. Informat.*, vol. 7, no. 4, pp. 689–698, Nov. 2011.
[63] Q. Zhu and T. Başar, "Robust and resilient control design for cyber-physical systems with an application to power systems," in *Proc. 50th IEEE Conf. Decision Control Eur. Control Conf.*, Dec. 2011, pp. 4066–4071.
[64] N.-G. Nayak, F. Dürr, and K. Rothermel, "Software-defined environment for reconfigurable manufacturing systems," in *Proc. 5th Int. Conf. Internet Things (IOT)*, Oct. 2015, pp. 122–129.
[65] P. Leitão, J. Barbosa, M. E. C. Papadopoulou, and I. S. Venieris, "Standardization in cyber-physical systems: The ARUM case," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2015, pp. 2988–2993.
[66] V. Skormin, A. Dolgikh, and Z. Birnbaum, "The behavioral approach to diagnostics of cyber-physical systems," in *Proc. IEEE AUTOTEST*, Sep. 2014, pp. 26–30.
[67] D. Lukač, "The fourth ICT-based industrial revolution 'Industry 4.0'—HMI and the case of CAE/CAD innovation with EPLAN P8," in *Proc. 23rd Telecommun. Forum Telfor (TELFOR)*, Nov. 2015, pp. 835–838.
[68] P. Basanta-Val, M. García-Valls, and I. Estévez-Ayres, "Towards a cyber-physical architecture for industrial systems via real-time Java technology," in *Proc. IEEE 10th Int. Conf. Comput. Inf. Technol. (CIT)*, Jun./Jul. 2010, pp. 2341–2346.
[69] D. B. Rawat, C. Bajracharya, and G. Yan, "Towards intelligent transportation Cyber-Physical Systems: Real-time computing and communications perspectives," in *Proc. SoutheastCon*, Apr. 2015, pp. 1–6.
[70] G. Salles-Loustau and S. Zonouz, "Towards resilient cyber-physical control systems," in *Proc. IEEE Global Conf. Signal Inf. Process. (GlobalSIP)*, Dec. 2015, pp. 662–666.
[71] M. Elattar and J. Jasperneite, "Using LTE as an access network for internet-based cyber-physical systems," in *Proc. IEEE World Conf. Factory Commun. Syst. (WFCS)*, May 2015, pp. 1–7.
[72] J. Ruan, W. Yu, Y. Yang, and J. Hu, "Design and realize of tire production process monitoring system based on cyber-physical systems," in *Proc. Int. Conf. Comput. Sci. Mech. Autom. (CSMA)*, Oct. 2015, pp. 175–179.
[73] C. Klötzer and A. Pflaum, "Cyber-physical systems as the technical foundation for problem solutions in manufacturing, logistics and supply chain management," in *Proc. 5th Int. Conf. Internet Things (IOT)*, Oct. 2015, pp. 12–19.
[74] R. Drath and A. Horch, "Industrie 4.0: Hit or hype? [Industry forum]" *IEEE Ind. Electron. Mag.*, vol. 8, no. 2, pp. 56–58, Jun. 2014.
[75] N. Mao and J. Tan, "Probabilistic event processing with negation operators in cyber physical systems," in *Proc. Int. Conf. Cyber-Enabled Distrib. Comput. Knowl. Discovery (CyberC)*, Sep. 2015, pp. 120–126.
[76] C. Scheuermann, S. Verclas, and B. Bruegge, "Agile factory—An example of an industry 4.0 manufacturing process," in *Proc. IEEE 3rd Int. Conf. Cyber-Phys. Syst., Netw., Appl. (CPSNA)*, Aug. 2015, pp. 43–47.
[77] M. Saggiomo, M. Kemper, Y.-S. Gloy, and T. Gries, "Weaving machine as cyber-physical production system: Multi-objective self-optimization of the weaving process," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2016, pp. 2084–2089.
[78] K. Ahmed, J. O. Blech, M. A. Gregory, and H. Schmidt, "Software defined networking for communication and control of cyber-physical systems," in *Proc. IEEE 21st Int. Conf. Parallel Distrib. Syst. (ICPADS)*, Dec. 2015, pp. 803–808.
[79] J. Pfeffer *et al.*, "Towards collaborative plant control using a distributed information and interaction space," in *Proc. IEEE 20th Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2015, pp. 1–4.
[80] M. Lom, O. Pribyl, and M. Svitek, "Industry 4.0 as a part of smart cities," in *Proc. Smart Cities Symp. Prague (SCSP)*, May 2016, pp. 1–6.
[81] U. Dombrowski, T. Wagner, and C. Riechel, "Concpt for a cyber physical assembly system," in *Proc. IEEE Int. Symp. Assembly Manuf. (ISAM)*, Jul./Aug. 2013, pp. 293–296.
[82] S. Sridhar, A. Hahn, and M. Govindarasu, "Cyber–physical system security for the electric power grid," *Proc. IEEE*, vol. 100, no. 1, pp. 210–224, Jan. 2012.
[83] F.-J. Wu, Y.-F. Kao, and Y.-C. Tseng, "From wireless sensor networks towards cyber physical systems," *Pervasive Mobile Comput.*, vol. 7, no. 4, pp. 397–413, 2011.
[84] F. Pasqualetti, F. Dorfler, and F. Bullo, "Attack detection and identification in cyber-physical systems," *IEEE Trans. Autom. Control*, vol. 58, no. 11, pp. 2715–2729, Nov. 2013.
[85] Y. Mo *et al.*, "Cyber–physical security of a smart grid infrastructure," *Proc. IEEE*, vol. 100, no. 1, pp. 195–209, Jan. 2012.
[86] J. Wan, M. Chen, F. Xia, D. Li, and K. Zhou, "From machine-to-machine communications towards cyber-physical systems," *Comput. Sci. Inf. Syst.*, vol. 10, no. 3, pp. 1105–1128, 2013.
[87] J. Wan, H. Yan, H. Suo, and F. Li, "Advances in cyber-physical systems research," *Trans. Internet Inf. Syst.*, vol. 5, pp. 1891–1908, 2011.
[88] H. J. La and S. D. Kim, "A service-based approach to designing cyber physical systems," in *Proc. IEEE/ACIS 9th Int. Conf. Comput. Inf. Sci. (ICIS)*, Aug. 2010, pp. 895–900.
[89] J. Wan, D. Zhang, S. Zhao, L. T. Yang, and J. Lloret, "Context-aware vehicular cyber-physical systems with cloud support: Architecture, challenges, and solutions," *IEEE Commun. Mag.*, vol. 52, no. 8, pp. 106–113, Aug. 2014.
[90] A. Hahn, A. Ashok, S. Sridhar, and M. Govindarasu, "Cyber-physical security testbeds: Architecture, application, and evaluation for smart grid," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 847–855, Jun. 2013.
[91] J. Wan, D. Zhang, Y. Sun, K. Lin, C. Zou, and H. Cai, "VCMIA: A novel architecture for integrating vehicular cyber-physical systems and mobile cloud computing," *Mobile Netw. Appl.*, vol. 19, no. 2, pp. 153–160, 2014.
[92] Energetics Incorporated. (2012). *Cyber-Physical Systems: Situation Analysis of Current Trends, Technologies, and Challenges*, accessed on Aug. 16, 2016. [Online]. Available: http://events.energetics.com/NIST-CPSWorkshop/pdfs/CPS_Situation_Analysis.pdf
[93] E. A. Lee, "Cyber physical systems: Design challenges," in *Proc. 11th IEEE Int. Symp. Object Compon.-Oriented Real-Time Distrib. Comput. (ISORC)*, May 2008, pp. 363–369.
[94] Y. Wang, M.-C. Vuran, and S. Goddard, "Cyber-physical systems in industrial process control," *ACM SIGBED Rev.*, vol. 5, no. 1, Jan. 2008, Art. no. 12.
[95] M. Garetti, L. Fumagalli, and E. Negri, "Role of ontologies for CPS implementation in manufacturing," *Manage. Prod. Eng. Rev.*, vol. 6, no. 4, pp. 26–32, 2015.
[96] W. Wolf. (2009). *Cyber-Physical Systems*, accessed on Aug. 16, 2016. [Online]. Available: http://people.cs.ksu.edu/~danielwang/Investigation/CPS_Concept/Cyber_physical_Systems.pdf
[97] H. Kagermann, "Change through digitization—Value creation in the age of industry 4.0," in *Management of Permanent Change*. Wiesbaden, Germany: Springer, 2015, pp. 23–45.
[98] M. Hermann, T. Pentek, and B. Otto, "Design principles for industry 4.0 scenarios," Working Paper, Tech. Univ. Dortmund, Dortmund, Germany, Feb. 2015.
[99] IERC. (2015). *Internet of Things Position Paper on Standardization for IoT Technologies European Research Cluster on the Internet of Things*, accessed on Apr. 20, 2016. [Online]. Available: http://www.internet-of-things-research.eu/pdf/IERC_Position_Paper_IoT_Standardization_Final.pdf
[100] ISO. (2016). *About ISO*, accessed on Apr. 10, 2016. [Online]. Available: http://www.iso.org/iso/home/contact_iso.htm/
[101] (2016), accessed on Apr. 10, 2016. [Online]. Available: http://www.iso.org/iso/home/contact_iso.htm/
[102] (2016). *DIN Standards*, accessed on Jun. 18, 2016. [Online]. Available: http://www.din.de/en/about-standards/din-standards
[103] SAC. (2016). *About SAC*, accessed on Jun. 18, 2016. [Online]. Available: http://www.sac.gov.cn/
[104] IEEE-SA. (2016). *About IEEE-SA*, accessed on Jun. 18, 2016. [Online]. Available: http://standards.ieee.org/about/index.html
[105] W3C. (2016). *Web of Things at W3C*, accessed on Aug. 25, 2016. [Online]. Available: https://www.w3.org/WoT/
[106] W3C. (2016). *W3C Mission*, accessed on Aug. 25, 2016. [Online]. Available: https://www.w3.org/Consortium/mission
[107] *Information Technology—Automatic Identification and Data Capture (AIDC) Techniques—Harmonized Vocabulary*, document ISO/IEC 19762, 2016.

[108] *Information Technology—Automatic Identification and Data Capture Techniques—Unique Identification*, document ISO/IEC 15459, 2014–2015.
[109] *Information Technology—Smart Transducer Interface for Sensors and Actuators—Common Functions, Communication Protocols, and Transducer Electronic Data Sheet (TEDS) Formats*, document ISO/IEC/IEEE 21450, 2010.
[110] *Information Technology—Smart Transducer Interface for Sensors and Actuators*, document ISO/IEC/IEEE 21451, 2010–2011.
[111] *Programmable Controllers*, document IEC 61131, 2000–2013.
[112] *Function Blocks*, document IEC 61499, 2012–2013.
[113] *Function Blocks (FB) for Process Control—Electronic Device Description Language (EDDL)*, document IEC 61804-3, IEC 61804-4, IEC 61804-5, and IEC 61804-6, 2003–2015.
[114] *Standard Data Elements Types With Associated Classification Scheme for Electric Items*, document IEC 61360, 2005–2016.
[115] *Engineering Data Exchange Format for Use in Industrial Automation Systems Engineering—Automation Markup Language*, document IEC 62714, 2014–2015.
[116] *Information Technology—Quality of Service: Framework*, document IEC/ ISO 13236, 1998.
[117] *Information Technology—Security Techniques*, document ISO/IEC 27000, 2016.
[118] *Security for Industrial Automation and Control System*, document IEC 62443 (ISA99), 2008–2015.
[119] *Information Technology—Telecommunications and Information Exchange Between Systems—Local and Metropolitan Area Networks—Specific Requirements*, document ISO/IEC 8802, 1998–2016.
[120] *Industrial Communication Networks—Fieldbus Specifications*, document IEC 61158, 2007–2014.
[121] *Industrial Communication Networks—Profiles*, document IEC 61784, 2010–2016.
[122] *Industrial Networks—Wireless Communication Network and Communication Profiles—WirelessHART*, document IEC 62591, 2016.
[123] *Industrial Networks—Wireless Communication Network and Communication Profiles—WIA-PA*, document IEC 62601, 2015.
[124] *Information Technology—Enhanced Communications Transport Protocol*, document ISO/IEC 14476, 2002–2010.
[125] *Information Technology—Sensor Networks-Services and Interfaces Supporting Collaborative Information Processing in Intelligent Sensor Networks*, document ISO/IEC 20005, 2013.
[126] *Information Technology—Telecommunications and Information Exchange Between Systems—Security Framework for Ubiquitous Sensor Networks*, document ISO/IEC 29180, 2012.
[127] *Information Technology—Sensor Networks: Sensor Network Reference Architecture (SNRA)*, document ISO/IEC 29182, 2013–2015.
[128] *Information Technology—Sensor Networks: Sensor Network and Its Interfaces for Smart Grid System*, document ISO/IEC 30101, 2014.
[129] *Information Technology—Sensor Networks—Generic Sensor Network Application Interface*, document ISO/IEC 30128, 2014.
[130] *Information Technology—Cloud Data Management Interface (CDMI)*, document ISO/IEC 17826, 2012.
[131] *Information Technology—Security Techniques-Network Security*, document ISO/IEC 27033, 2010–2016.
[132] *Field Device Integration (FDI)*, document IEC 62769, 2015.
[133] *Condition Monitoring and Diagnostics of Machines—Data Processing, Communication and Presentation*, document ISO 13374, 2003–2015.
[134] *Field Device Tool (FDT) Interface Specification*, document IEC 62453, 2009–2016.
[135] *Batch Control*, document IEC 61512, 1997–2009.
[136] *Enterprise—Control System Integration*, document IEC 62264, 2007–2016.
[137] *Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems*, document IEC 61508, 2010.
[138] *Information Technology—Local and Metropolitan Area Networks*, document GB/T 15629, 1996–2014.
[139] *Programmable Controllers*, document GB/T 15969, 2002–2015.
[140] *Information Technology—Quality of Service: Framework*, document GB/T 18903, 2002.
[141] *Modbus Industrial Automation Network Specification*, document GB/T 19582, 2008.
[142] *CC-Link (Control & Communication Link) Specification*, document GB/T 19760, 2008.
[143] *Function Blocks for Industrial-Process Measurement and Control System*, document GB/T 19769, 2012–2015.
[144] *Batch Control*, document GB/T 19892, 2005–2007.
[145] *EPA System Architecture and Communication Specification for Use in Industrial Control and Measurement Systems*, document GB/T 20171, 2006.
[146] *Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems*, document GB/T 20438, 2006.
[147] *Digital Data Communication for Measurement and Control-Fieldbus for Use in Industrial Control Systems*, document GB/T 20540, 2006.
[148] *Digital Data Communication for Measurement and Control-Fieldbus for Use in Industrial Control Systems—Type 10: PROFINET Specification*, document GB/Z 20541, 2006.
[149] *Enterprise-Control System Integration*, document GB/T 20720, 2006–2015.
[150] *Function Block (FB) for Process Control*, document GB/T 21099, 2007–2015.
[151] *Data Processing, Communication and Presentation*, document GB/T 22281, 2008–2011.
[152] *Industrial Communication Networks—Fieldbus Specifications-Type 10: Profinet IO Specifications*, document GB/T 25105, 2014.
[153] *Digital Data Communication for Measurement and Control-Field-Bus for Use in Industrial Control Systems—Type 2: Controlnet and Ethernet/IP Specification*, document GB/Z 26157, 2010.
[154] *Information Technology—Enhenced Communication Transport Protocol*, document GB/T 26241, 2010.
[155] *Industrial Wireless Networks WIA Specification*, document GB/T 26790, 2011–2015.
[156] *Ethernet POWLINK Communication Profile Specification*, document GB/T 27960, 2011.
[157] *Information Technology-Automatic Identification and Data Capture (AIDC) Techniques—Vocabulary*, document GB/T 29261, 2012–2014.
[158] *Field Device Tool (FDT) Interface Specification*, document GB/T 29618, 2013–2015.
[159] *Digital Data Communication for Measurement and Control-Fieldbus for Use in Industrial Control Systems—Type 8: INTERBUS Specification*, document GB/Z 29619, 2013.
[160] *Industrial Communication Networks—Fieldbus Specifications—Type 20 HART Specification*, document GB/T 29910, 2013.
[161] *Industrial Control System Security*, document GB/T 30976, 2014.
[162] *Industrial Ethernet Fieldbus EtherCAT*, document GB/T 31230, 2014.
[163] *Information Technology—Cloud Data Storage and Management—Part 2: Object Based Cloud Storage Application Interface*, document GB/T 31916.2, 2015.
[164] *Information Technology—Sensor Networks—Part 401: Collaborative Information Processing: Services and Interfaces Supporting Collaborative Information Processing*, document GB/T 30269.401, 2015.
[165] R. Feldman *et al.*, "Knowledge management: A text mining approach," in *Proc. PAKM*, vol. 98. Oct. 1998, p. 9.
[166] M.-Y. Tang, "Auto-generated technology-function matrixes for patent analysis of additive manufacturing in the dental industry," M.S. thesis, Dept. Ind. Eng. Eng. Manage., Nat. Tsing Hua Univ., Hsinchu, Taiwan, 2016.
[167] Thomson Innovation. (2016). *About Patent Research*, accessed Apr. 10, 2016. [Online]. Available: http://info.thomsoninnovation.com/
[168] Thomson Innovation. (2002). *Read Patents, Not Just Papers*, accessed on Sep. 10, 2016. [Online]. Available: http://pt.tmu.edu.tw/%A4H%A4~%B0%F6%B0V%C1%BF%B8q/%B1M%A7Q%C0%CB%AF%C1%BBP%B1M%A7Q%A4%C0%AAR.pdf
[169] J.-C. Syu, "Technology trends analysis via patent and scientific publication—A case study of etching," M.S. thesis, Graduate Inst. Technol., Innov. Intell. Property Manage., Nat. Chengchi Univ., Taipei, Taiwan, 2007.
[170] WIPO. (2015). *PCT—The International Patent System*, accessed on Sep. 10, 2016. [Online]. Available: http://www.wipo.int/pct/en/faqs/faqs.html
[171] Y.-B. Reddy, "Cloud-based cyber physical systems: Design challenges and security needs," in *Proc. 10th Int. Conf. Mobile Ad-Hoc Sensor Netw. (MSN)*, Dec. 2014, pp. 315–322.

AMY J. C. TRAPPEY (M'08–SM'16) received the Ph.D. degree in industrial engineering from Purdue University. Her research interests are in knowledge engineering and intelligent systems, particularly for IP and patent analytics, e-business, and e-manufacturing. Prof. Amy Trappey is currently serving as the Associate Editor of the *Advanced Engineering Informatics* and the IEEE TRANSACTIONS on SMC: SYSTEMS. She is an ASME and ISEAM Fellow.



CHARLES V. TRAPPEY received the Ph.D. degree in consumer science from Purdue University, USA, the M.S. degree in quantitative business analysis from Louisiana State University, USA, and the LL.M. degree in IP Law from the Queensland University of Technology, Australia. His research interests are in innovation and technology forecasting, patent informatics, and technology marketing. Prof. Charles Trappey is an Australia Trademark Attorney and a member of the Australian Computer Society.



USHARANI HAREESH GOVINDARAJAN received the M.Tech. degree in computer science from AUUP, India, the M.Sc. degree in informatics from Delhi University, India. He is currently pursuing the Ph.D. degree with the Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Taiwan.

JOHN J. SUN is currently pursuing the M.S. degree with the Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Taiwan.

ALLEN C. CHUANG is currently pursuing the M.S. degree with the Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Taiwan.