Smart Manufacturing Based on Cyber-Physical Systems and Beyond

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Abstract: Cyber-physical systems (CPS) have gained an increasing attention recently for their immense potential towards the next generation smart systems that integrate cyber technology into the physical processes. However, CPS did not initiate either smart factories or smart manufacturing, and vice versa. Historically, the smart factory was initially studied with the introduction of the Internet of Things (IoT) in manufacturing, and later became a key part of Industry 4.0. Also emerging are other related models such as cloud manufacturing, social manufacturing and proactive manufacturing with the introduction of cloud computing (broadly, the Internet of Services, IoS), social networking (broadly, the Internet of People, IoP) and big data (broadly, the Internet of Content and Knowledge, IoCK), respectively. At present, there is a lack of a systemic and comprehensive study on the linkages and relations between these terms. Therefore, this study first presents a comprehensive survey and analysis of the CPS treated as a combination of the IoT and the IoS. Then, the paper addresses CPS-based smart manufacturing as an eight tuple of *CPS*, *IoT*, *IoS* and *IoCK* as elements. Further, the paper extends the eight-tuple CPS-based manufacturing to social-CPS (SCPS) based manufacturing, termed wisdom manufacturing, which forms a nine tuple with the addition of one more element, the *IoP*, and which is based on the *SCPS* instead of *CPS*. Both architectures and characteristics for smart and wisdom manufacturing are addressed**.** As such, these terms' linkages are established and relations are clarified with a special discussion. This study thus contributes as a theoretical basis and as a comprehensive framework for emerging manufacturing integration**.**

Keywords: Cyber-physical system; Smart manufacturing; Wisdom manufacturing; Socio-cyber-physical system; Industry 4.0; CIMS

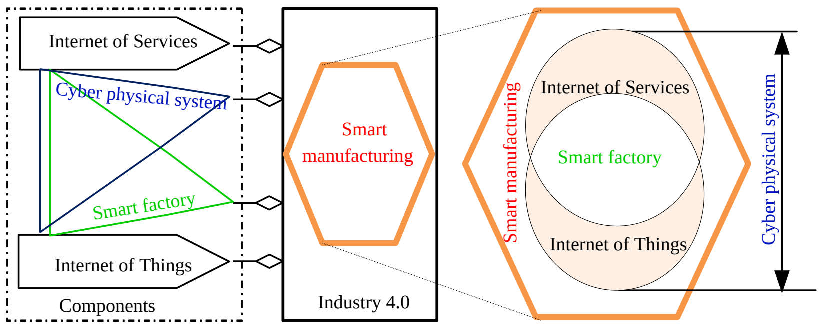
1. Introduction

Manufacturing is the backbone of our modern society. With advances in information and communication technology (ICT), the introduction of the Internet of Things (IoT) and the Internet of Services (IoS) in manufacturing has initiated Industry 4.0 in Germany, i.e. the fourth industrial revolution (Kagermann et al. 2013), which is transforming today's factories into smart ones (Zuehlke 2010; Hermann et al. 2015).

Similarly, in the United States, the Smart Manufacturing Leadership Coalition (SMLC 2011) has worked on a new manufacturing paradigm, called smart manufacturing, which encompasses the sophisticated practice of generating and applying data-driven manufacturing intelligence throughout the manufacturing life cycle of a product with the wide adoption of advanced sensing, control, modeling, and platform technology (Davis et al. 2015); In China, the Internet of Manufacturing Things has been investigated by the use of IoT in manufacturing (X. Yao et al. 2014b), and smart (intelligent) manufacturing is recognized as a key topic in the ten-year national plan "Made in China 2025" (Xinhua 2015).

As time goes by, more two components are added to Industry 4.0 besides the IoT and IoS. Of the four key components of Industry 4.0, i.e. IoT, IoS, the smart factory, and cyber-physical systems (CPS) (Hermann et al. 2015), the last one is identified as the most prominent. Therefore, those terms mentioned above are linked together as shown in Fig. 1, where smart manufacturing (SM) is part of Industry 4.0, and in turn, the smart factory is part of SM. And CPS can be viewed as the combination of the IoT and IoS for brevity. As such, Industry 4.0 is said to be based on CPS, and so is the SM.

A CPS is a system of collaborating computational elements controlling physical entities (Wikipedia 2017), as the integration of computation with physical processes. Such integration in manufacturing, however, is not new. The term "computer integrated manufacturing systems (CIMS)" has been used to describe the integrated manufacturing system that combines physical processes with computing. However, most such CIMS adopted centralized control schemes with limits inside a factory, and lack of context-awareness, flexibility, and self-configuration. Now, the IoT and CPS technologies such as RFID (radio-frequency identification) and sensor networks offer advanced monitoring and control of real-world processes at an unprecedented scale, which make a big difference to CIMS. This study will address such integrated manufacturing systems based on CPS and beyond.



(a) Four key components of Industry 4.0 (b) Smart manufacturing in Industry 4.0

Fig. 1. Smart manufacturing linked with the four components of Industry 4.0

2. Cyber-Physical Systems

2.1. An Overview of CPS

The terminology of CPS was first coined at the National Science Foundation (NSF) in the United States around 2006 (Wolf 2007), describing a physically-aware engineered system that tightly collaborating "cyber" components - those that can compute, communicate, and control - with the physical world, providing a wide range of services available on the Internet.

A CPS is a complex system composed of many heterogeneous elements, and specific system structures are usually required for different application scenarios. Dong et al. (2012) proposed a four-layer architecture with a bottom-up view of physical layer, network layer, co-processing layer and application layer. X.-L. Wang et al. (2010) proposed a service-oriented CPS architecture that consists of sensor and actuator node modules, network modules, and resource and service modules. Bogdan and Marculescu (2011) proposed a more sophisticated architecture that consists of 6 layers. Other CPS architectures were also proposed in similar ways (Derler et al. 2012; Dillon et al. 2011). From the view of abstract model, CPS consist of the physical world, communication networks, and the cyber space, as shown in Fig. 2. The physical world refers to the physical objects, processes or environment to be monitored or controlled. The cyber space refers to the next generation information infrastructure, including services, applications, and decision-making units. The communication networks refer to intermediate components which are responsible for bridging the cyber space with the physical world. In the view of technical composition, CPS includes but not limited to the IoT, and IoS. The existing Internet provides CPS with a lot of mature network technologies, such as IP/TCP, XML, access control, network link, publish/subscribe model, etc. However, the real realization of CPS still requires a lot of new technologies, such as mobile node localization, semantic analysis of heterogeneous data, sensor network coverage, and the issue of mass data transmission.

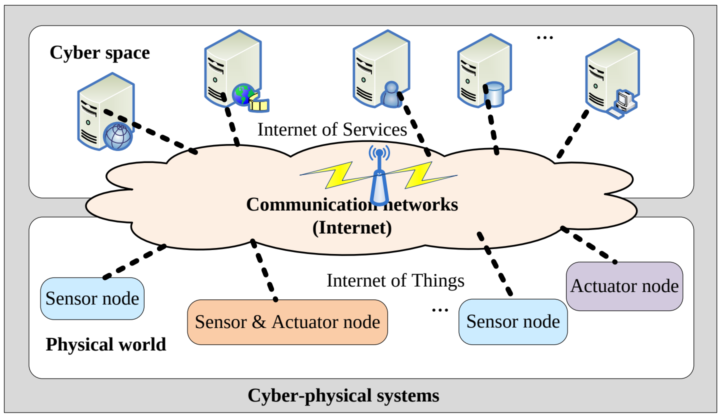


Fig. 2. Holistic view of cyber-physical systems

2.2 Terms Associated with CPS

CPS strongly connect to existing techniques or currently popular terms such as embedded systems, wireless sensor networks (WSN), IoT, Cyber-Physical Internet (CPI), Web of things (WoT), and even wisdom web of things (W2T). In other words, these terms can be viewed as instances of the more general class of CPS.

Compared with CPS, the embedded system control is mostly based on continuous dynamic feedback, in which the details of the implementation process are often ignored, such as mode conversion, error detection, time constraints and other issues (E. A. Lee 2008). It is therefore unable to realize the effective monitoring of the stability, transient recovery and parameter changes with time occasions. While CPS are capable to solve the consistency and efficiency issue of large scale complex giant systems in multi-dimensional heterogeneous environment.

WSN consist of a large number of micro sensor nodes deployed in the specific area to monitor physical or environmental conditions (Araujo et al. 2014), which belong to an open loop monitoring mode with largely static configuration. In addition, most of WSN are faced with the problem of limited node number (De Amorim et al. 2008). While CPS contain not only the sensors but also actuators, and characterized by the closed-loop control. Development of WSN will contribute to the implementation of CPS. The significance role of WSN to industrial communication and control processes has been discussed in (Araujo et al. 2014).

The term IoT was first coined in 1999 (Atzori et al. 2010). Now, IoT greatly overlaps with CPS. The most important difference is that IoT originally targeted the identification of objects whereas CPS focus on the exchange and feedback of information in order to control things (Ma 2011). Today IoT also involves the control of physical objects. Besides, Anis used the term Cyber-Physical Internet (CPI) to address the interoperability of existing heterogeneous CPS under a universal umbrella network (Koubâa and Andersson 2009). Enlightened by IoT, WoT was proposed to integrate physical things into the World Wide Web in a unified framework by standard web service technologies (Dillon et al. 2011). As the extension of WoT, the notion of W2T (Zhong et al. 2013) was proposed as a holistic intelligent methodology for realizing the harmonious symbiosis of humans, computers, and things in the hyper world.

CPS represent a core opportunity area and source of competitive advantage for innovation economy in the 21st century, and have attracted wide attention from the industry, academia as well as government. NSF provided enormous funds to promote transformative research and foster innovation on CPS since it showed huge potential impacts on national interests (PCAST 2007). European Commission also recommended CPS research in Horizon 2020 program (Owen et al. 2012). The President's Council of Advisors on Science and Technology (PCAST 2008) reports recommended CPS as one of the six transformative civil technologies propelling American economic growth, and considered it as a core opportunity area and source of competitive advantage for the US. Some research initiatives were recommended in specific application domains (Sha et al. 2008; Shi et al. 2011). Specially, manufacturing empowered by CPS, namely smart manufacturing, will be addressed in the following section.

3. Smart Manufacturing Based on CPS

A manufacturing system involves numerous types of decision-making at all of its levels and has a wide range of operations needed to be optimized. However, traditional hierarchical control architecture and its rigid nature do not afford the level of agility, flexibility, and scalability that companies require to remain competitive in today's environment. The evolution towards CPS has led to new possibilities that enable improved integration of distributed heterogeneous devices and systems, ranging from the physical device or tool control level up to the higher levels of the business process management system. Large hierarchically monolithic systems are therefore replaced by configuring loosely coupled, autonomous, proactive and reusable units in a flat manner.

3.1. Limitations of Existing CIM

Although CIM has been proposed towards improving productivity and competitiveness for companies, such a promise has not fulfilled as people expected. The deficiencies of existing integrated manufacturing systems are mainly manifested in the following aspects:

1) *Lack of real time data*: Because lack of CPS support, traditional manufacturing systems were open loop, and poor in real-time data acquisition and processing, and some requisite manufacturing information was either unavailable or behindhand. Manufacturing enterprises lack the capability to accommodate the uncertainties and changes (Zhang et al. 2015).

2) *Information islands*: Modern versatile and complex products make them involve numerous manufacturing activities, which need integrating devices in shop-floors up to enterprise resources planning

vertically and covering related resources beyond the boundary of a single enterprise horizontally at the same time (Z. M. Bi and Kang 2010). Currently, the existing solutions are mainly based on the use of some standards and middleware in order to overcome integration problems. These solutions generally fail as they do not scale to large number of applications, and also fail as they do not provide more flexibility and agility (Z. Bi et al. 2014).

3) *Insufficiency of intelligence and proactivity*: Present control systems execute a fixed program and they can only process fixed-configured data in a determined cycle time. The assignment or control of the functions is most of the time happening outside of the module by means of a fixed program, and they have inflexible interfaces that cannot communicate new unknown information (Verl et al. 2012).

3.2. Smart Manufacturing

The ICT application in enterprises has led to the emergence of smart manufacturing (SM) or cyber-physical production systems. SM has attracted extensive attention from the industrial and academic communities (Davis et al. 2015), and is expected to affect significantly the manufacturing. The Office of Science and Technology Policy (OSTP) and Office of Management and Budget (OMB) have urged supporting of R&D in advanced manufacturing to 'strengthen U.S. leadership in the areas of robotics, cyber-physical systems, and flexible manufacturing" as a promotion of sustainable economic growth and job creation' (Peter and John 2010). The SMLC defines 'Smart manufacturing is the intensified application of advanced intelligence systems to enable rapid manufacturing of new products, dynamic response to product demand, and real-time optimization of manufacturing production and supply chain networks' (SMLC 2011). As shown in Fig. 1, the smart factory has become a key component of Industry 4.0 (Lasi et al. 2014). Manufacturing enterprises can benefit greatly from the adoption of CPS infrastructure in their information systems:

1) *Real time data access*: Traditional planning and scheduling of manufacturing is mainly at the macro level with rare detailed information. CPS can overcome such problems with the following characteristics: a) pervasive sensing of objects; b) seamless integration of virtual computing models and physical objects; and c) a large number of nodes. Real-time data acquisition and access of manufacturing relevant information anytime and anywhere allows decision makers to make better-informed decisions (Huang et al. 2008; Huang et al. 2009), while CPS give an immediate access to information in production sites based on distributed intelligence for smart objects. Therefore, acquiring states of the manufacturing relevant or system feedback information is available to support closed-loop decision making, and high-level system scheduling and controlling can promptly accommodate uncertainties such as diagnostics, performance indicators and traceability. The agility and robustness of manufacturing systems are greatly enhanced.

2) *Reconfigurable and interoperable capabilities*: Traditional solutions of integrating heterogeneous systems such as custom-developed device drivers or third-party integration are costly and demanding, but also point-to-point communications are inflexible (Maione and Naso 2001). While cloud computing and Web services technologies adopted for smart CPS are dynamic and reconfigured (Gunes et al. 2014). Entities of such systems are scalable and modular (plug and play) and applicable across distributed sectors with a high

level of autonomy, going far beyond what current SCADA and DCS can deliver today. With the support of the service-oriented approaches, modular design as well as open system architectures, each device can offer its functionality as services in scenario-specific ways and combine other services in a cross-layer form on-demand, which can be leveraged to build smart CPS with a high level of autonomy. As such, a CPS-based manufacturing system can be decomposed into sub-systems, where components are exposed as services and dynamically added or removed, and functionalities can be performed as reconfiguration and composition of those services to complete complex tasks when there is a need. As for reconfigurable manufacturing systems based on CPS, they are easily upgradable and readily integrated into new modules or functions. Reconfigurable capability and its key role in future manufacturing were discussed by Mehrabi et al. (2000). The system integration and interoperability in manufacturing is not only at the lower level of physical devices, but also at the higher level of business process management. Application level communication across the enterprise based on service-oriented high-level protocols greatly increased the interoperability and adaptability of manufacturing enterprises (Schuh et al. 2015). An adjustment can be done by shifting the manufacturing entities to a central resource pool like a cloud by standard web service interfaces, and all existing physical components in production are delivered over a network as a service without any hardware changes (Verl et al. 2012).

3) *Decentralized decision-making*: The industrial environments are becoming increasingly distributed and networked, which are different from conventional hierarchical or centralized monolithic structures throughout, and a change toward a decentralized flat automation and a new service-oriented generation is needed, that is, interaction across devices and systems is completely independent of the physical location. SM allows interoperable service-oriented collaboration between distributed business applications, and enables equipment in process operations to autonomously recognize and respond to situations, thus making it different from traditionally implemented enterprise hierarchy (Feld et al. 2012; J. Lee et al. 2015). Sensing, modeling and analysis are used to predict events, and operations are controlled to mitigate the impact of risk or uncertainty. CPS-based manufacturing enables better control of production processes by using the IoT to improve model-based state estimation and bias detection, and to accomplish manufacturing tasks with high quality and flexibility.

4) *Intelligence and proactivity*: Current implemented ICSs have some hindrances such as a lot of incompatibilities among devices and systems, 'hard coded' data, business applications fixedly configured and used, and reactive automation instead of proactivity. SM is capable of:

a) Proactivity: a large number of distributed entities are fused as a conglomerate of autonomous, proactive, fault-tolerant and reusable units based on intelligent control algorithms, and scalable and modular architectures, which have the ability of working in a proactive manner, initiating collaboration and interacting mutually to achieve the common objectives (Shrouf et al. 2014), like the vision where machines predict failure and trigger maintenance processes autonomously discussed in J. Lee et al. (2011).

b) Intelligence: machines are able to autonomously control their maintenance and repair strategies depending on the degree of workload, and ensure backup capacities to maintain production in the case of maintenance-related interruptions. Smart machines are capable to perform "predict and prevent" practice, instead of "fail and fix" operation, by using instruments such as sensors, actuators, controllers and other distributed computational devices. Furthermore, smart algorithms are expected to provide machines the capability of managing themselves and adjusting to sophisticated and dynamic circumstances with minimal human intervention (Ruiz-Arenas et al. 2014).

3.3. CPS-based Smart Manufacturing Architecture

A manufacturing system is used to produce value-added goods via various manufacturing resources such as machines, tools, labor and so on. So is CPS-based smart manufacturing or Cyber-Physical Production System (CPPS)(L. Wang et al. 2015), which, however, has distinctive characteristics with the introduction of the next generation ICT infrastructure such as IoS, IoT and CPS. A CPPS can be described as an eight-tuple:

$$(\textbf{\textit{Input, Relation, CPS, IoS, IoT, IoCK, Factory, Output}}) \qquad (1)$$

where ***Input*** represents the entity set of input elements, including the customer requirements, materials, energy, capital and labor; ***IoS*** represents the operations of services such as connection, communication, interaction and interoperation, and collaboration among services based on virtualization, cloud computing and web service technologies; ***IoT*** can be treated as a superset of sensing and actuating components that comprise smart ‘things’; ***CPS*** bridges the physical and cyber worlds in manufacturing, and provides the technical standards in terms of the specifications of data exchange, processing, and communications within the network; ***IoCK*** represents Internet of Content and Knowledge, more specifically, data, information and Knowledge; ***Relation*** represents the interactions among system components, the joint action and collaboration of IoT, IoS IoCK and CPS; ***Factory*** stands for the place where raw materials are transformed into finished goods to satisfy customer needs with the supports of the ***IoT***, ***IoS, IoCK*** and ***CPS*** according to the ***Relation*** in manufacturing processes; and ***Output*** represents the content set of output elements such as products and/or services as well as solutions. Such a tuple model includes the four key components as shown in Fig. 1.

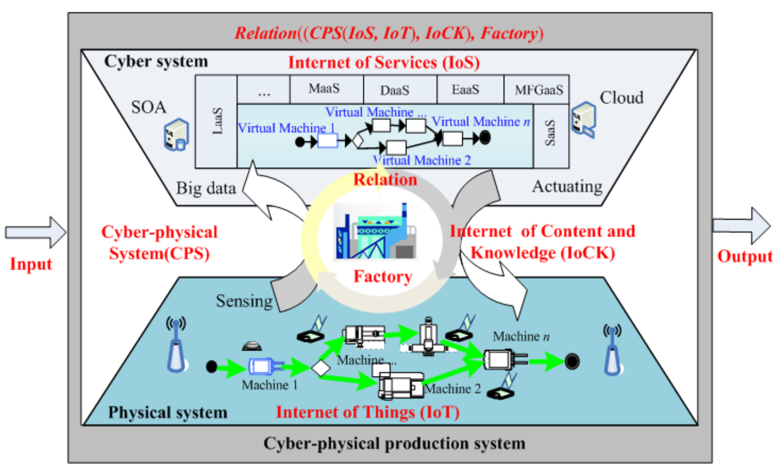


Fig. 3 An architecture for CPS-based manufacturing

Fig. 3 gives a reference architecture for the CPS-based manufacturing, which illustrates the constitutional components and their interactions. Its major blocks are described as below:

(1) *Physical manufacturing resources (Physical system)*: including instruments such as sensors, actuators, controllers and other distributed computational devices for sensing and controlling physical manufacturing resources.

(2) *Communication networks:* bridging the cyber and physical worlds to make cyber manufacturing services tightly coupled with their physical counterparts so that context data can be captured via smart sensors, and then can be used in real-time visualization of business processes, and vice versa, business information can be downwards to device level.

(3) *Cyber manufacturing services (Cyber system):* creating and managing services required by users or applications; virtualizing and encapsulating all manufacturing resources and capabilities involved in the whole life-cycle of manufacturing into cloud services, including "Design as a Service (DaaS)", "Manufacturing as a Service (MFGaaS) ", "Simulation as a Service (SaaS) ", "Experimentation as a service (EaaS)", "Management as a Service (MaaS)", "Maintenance as a Service (MAaaS)", "Logistics as a Service (LaaS)", etc.

The physical system consists of things integrated by the IoT, the cyber system consists of services integrated by the IoS, and the CPS bridges the physical and cyber by communication networks. As the whole system consists of a set of modular components and their interactions, data acquisition, communication and decision-making are essential functions for each module. Decision making in the manufacturing system is based on the acquired data. As such, big data can be employed in manufacturing vertically and horizontally to enhance the intelligence and efficiency of design, production, service process and so forth. Therefore, CPS-based manufacturing not only covers resources in the whole life-cycle of manufacturing horizontally but also conducts the physical components functioning to associated virtual entities with relevant services vertically.

3.4. Other Models Associated with CPS-based Manufacturing

Similar to SM, other models like wireless manufacturing (WiM) (Huang et al. 2009), ubiquitous manufacturing (UbiM) (J. Y. Lee et al. 2011; Suh et al. 2008), and Service-oriented manufacturing (SOM) such as industrial product-service systems (IPSS) (Meier et al. 2010) and cloud manufacturing (Ren et al. 2015) have also been proposed and researched. They were introduced to solve different problems in industry practices and have particular emphasis on specific areas. Meanwhile, they have some different aspects that complement each other and can be incorporated in the broader context of CPS-based SM. Specifically, WiM and UbiM pay more attention to physical devices or systems with increased communication capabilities and data processing power, while SOM put more emphasis on the higher level of the cyber space, e.g. business-level applications, ways of work organizing and business models.

For control of physical devices at the low level, WiM and UbiM can be leveraged to build advanced functionality or infrastructure into CPS-based SM. WiM uses wirelessly networked sensors to collect and process real-time field data to improve the quality and productivity in the manufacturing processes, which focuses on closing the loop of production planning and control for adaptive decision making (Huang et al.

2009). UbiM is the utilization of the product information obtained via ubiquitous computing technology for the product manufacturing (Suh et al. 2008), whose key features include ubiquitous access to information involved in entire product life cycle and transparent information exchange between stakeholders throughout the supply chain (J. Y. Lee et al. 2011; Suh et al. 2008). WiM and UbiM overlap at some points, both aiming at effectively collecting and processing real time field data from manufacturing, thus speeding up decision processes in production planning and control.

For managing the business processes and service composition at the high level, SOM is helpful to enrich the cyber dimension of CPS-based smart manufacturing. As a SOM model, an IPSS (Meier et al. 2010) is viewed as the integration of products and services by selling functionality instead of selling products, consisting of integrated product and service shares, while cloud manufacturing (Ren et al. 2015) can be treated as a flexible and collaborative manufacturing service model, whose manufacturing resources and capabilities are encapsulated into cloud services to form a shared pool where resources can be used on demand. These models have mostly focused on their own application areas and are successful in their respective fields. For instance, cloud manufacturing provides flexible and on-demand manufacturing services for users with enhanced experience; IPSS help manufacturing enterprises achieve servitization by combination of products and services in a system in order to increase the profit margin and level of competitive advantage.

In fact, the aforementioned models are able to be extended based on their advantages and incorporated together, therefore contributing to CPS-based SM that is aimed to achieve as ‘the whole is greater than the sum of its parts’. To this end, innovation must be put onto such transformation, i.e., starting with connectability, followed by interoperability, devices and systems need to be implemented with cloud-based architecture supporting the cyber-physical dynamic infrastructure.

In Industry 4.0, SM connects all components as a cyber-physical production system along the value chain, forming a flexible and smart automation system expected to be effective, safe, and efficient for reorganization at run time (Mordinyi and Biffl 2015). Sensor-embedded "smart products" can percept the surrounding environment and cooperate with each other. Via cloud computing, massive data can be systematically processed according to specific contexts (Hashem et al. 2015). Based on CPS, products control their own manufacturing processes in a decentralized and modular way, and smart embedded things can work collaboratively over the Internet "cloud" (Huang et al. 2008). All that will revolutionize manufacturing industry, shifting current rigid, central hierarchical control to decentralized one with new potential for improved efficiency, adaptability and flexibility of manufacturing, and integrating customers, supplier and other partners into business processes to provide customers with enhance experiences (Jay Lee et al. 2014).

So far, CPS enabling technologies such as RFID and WSN have been applied in production, transportation and supply chain management. However, to achieve intelligence or even wisdom in manufacturing, humankind innovations are required. In particular, the integration of the affective, conative, and cognitive aspects of human abilities in manufacturing is in demand.

4. Wisdom Manufacturing: Beyond CPS-Based Smart Manufacturing

Although SM tries to eliminate tightly coupling integration with the use of the IoT and IoS, as well as gets many other benefits, human (social) aspects still do not get enough attention. As manufacturing enterprises are socio-technical systems, there is a need to address social aspects in manufacturing as well. The introduction of the four pillars of Future Internet – (1) Internet by and for People, or Internet of People (IoP) for brevity; (2) Internet of Contents and Knowledge (IoCK); (3) Internet of Things (IoT); and (4) Internet of Services (IoS) - in manufacturing contexts results in the so-called wisdom manufacturing (WM) in the form of socio-cyber-physical systems (SCPS) (X. Yao et al. 2014a). Compared with the SM being described by the eight-tuple in the form of CPS, WM can be described as a nine-tuple by adding one more element (***IoP***) with an extended element ***SCPS*** to replace the ***CPS***:

$$(\boldsymbol{Input, Relation, SCPS, IoP, IoS, IoT, IoCK, Factory, Output}) \qquad (2)$$

As such, WM can be respectively diagramed as Fig. 4, where each tuple element is shown up respectively.

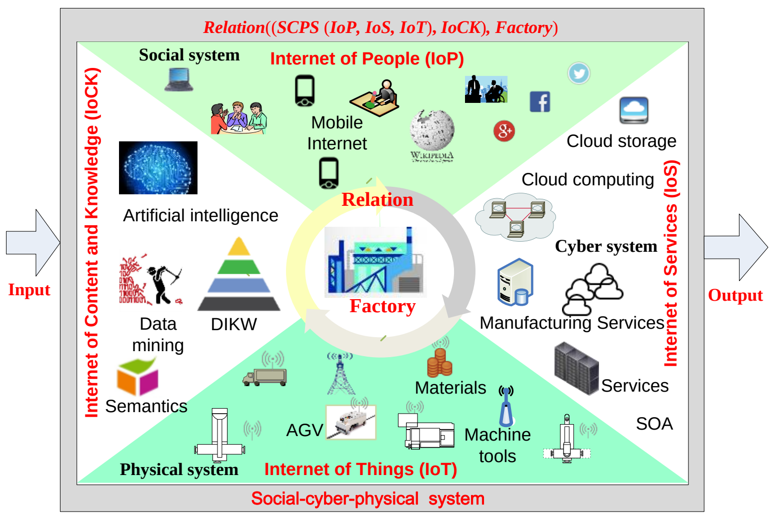


Fig. 4 An architecture for the social-cyber-physical production system

From the organizational semiotics perspective, WM integrates the social, cyber, and physical systems as a whole and covers all the six semiotic levels – the physical, empirical, syntactical, semantic, pragmatic, and social levels as well as corresponding levels of interoperability (X. Yao and Lin 2016; X. Yao et al. 2017). From Fig. 5, it can be clearly seen that the SCPS are the extension of CPS by adding the social system (or the pragmatic and social semiotic levels). And the same goes for WM and SM. The physical system focuses on the physical (manufacturing) resources, ubiquitous computing/ubiquitous intelligence (UI) and signal communications, consisting in the IoT. The social system focuses on intentions, beliefs, human interactions, human knowledge, and collective intelligence (CI), consisting in the IoP, which interconnects stakeholders, and provides online communities for design, creation, and sales of products.

As a consequence, there are three control loops in the WM system. In the physical system, smart things (or objects) are able to act adaptively and automatically with ubiquitous intelligence (UI), and local device control is implemented. In the cyber system, for example, the Service Web 3.0 (viewed as the result of the convergence of the Semantic Web and the IoS), provides on-demand services over the Internet (devices or business processes can be invoked as “everything as a service”). In the social system, stakeholders can make decision on manufacturing and context information/knowledge from lower levels with tacit knowledge and collective intelligence (CI) for control of the enterprise value creation processes, and the SECI (Socialization-Externalization-Combination-Internalization) model (Nonaka and Takeuchi 1995) can be realized via social networking tools.

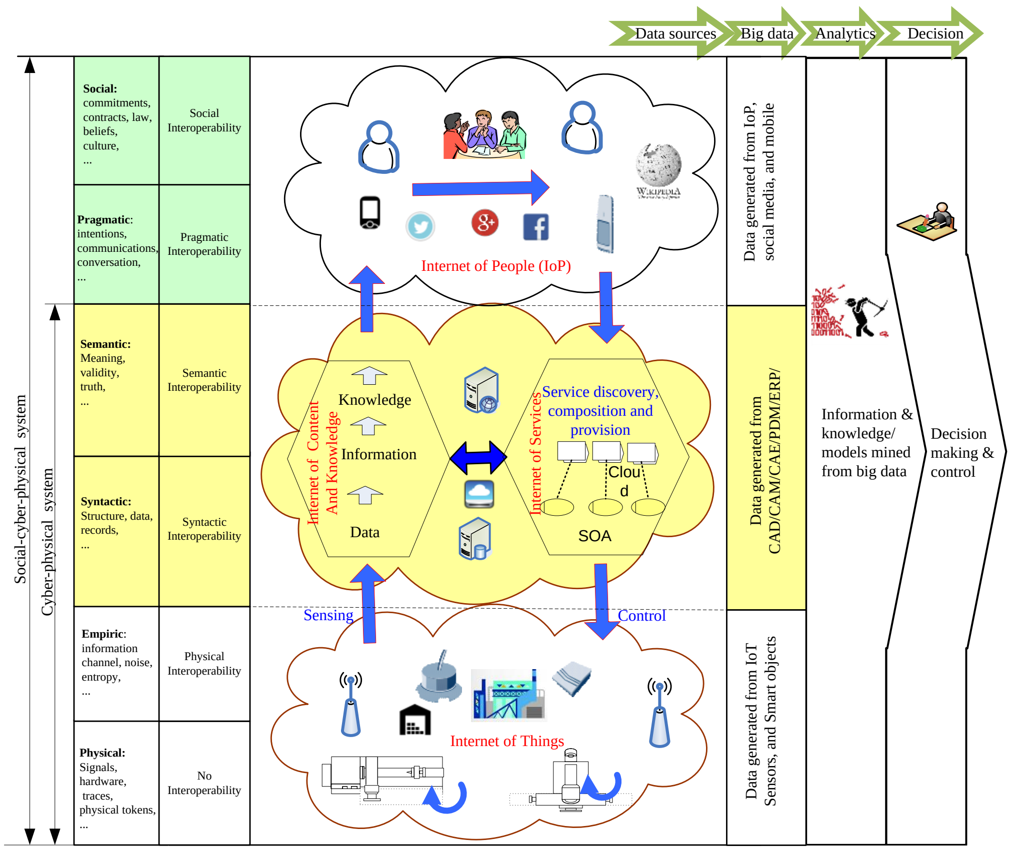


Fig. 5 Control loops and big data in wisdom manufacturing

5. Discussion

Traditional CIM is featured by tightly-coupled integration (hard-wiring) with inefficiency and poor interoperability. Early CIM or digital manufacturing focused on physical- and data-interoperability. Before the advent of SM, the use of artificial intelligence (AI) or (explicit) knowledge in manufacturing had resulted in intelligent manufacturing. In the 2010s, instead of intelligent technologies in manufacturing, we are seeing a similar convergence of “smart” technologies in manufacturing with the potential to radically improve the management of manufacturing enterprises in the entire product value chain in order to deliver more options and new service modes to customers. Such “smart” technologies cover a wide spectrum of domains, which are initially referred to as IoT technologies, and then include many other related technologies such as IoS, CPS, and big data.

We can clearly see the difference between intelligent manufacturing and wisdom manufacturing after the introduction of the IoT, IoS and IoP in intelligent manufacturing, as shown in Fig. 6, where the IoT bridges the cyber and physical systems with real-time responses, and makes manufacturing smart; the IoP interconnects stakeholders (users), and makes manufacturing socialized; and the IoS makes manufacturing service-oriented with loosely-coupled integration and provides pay-per-use services.

The future of manufacturing lies in innovation and sustainability, where manufacturers proactively create new markets for customized/personalized products in the ability of the environment to sustain economic growth, human activities and well-being. In different ages, there are different metrics for evaluating manufacturing systems such as cost, quality, speed, customization and innovation (Krishnamurthy 2007), of which the last two are most important in the age of Industry 4.0. As an emerging concept targeting to provide collaborative manufacturing by integrating things, computers and humans, ubiquitous, artificial and collective intelligence, as well as explicit and tacit knowledge as a whole (Xifan Yao et al. 2015), especially in that human participation and collaboration in networked communities give birth to innovation in product design and manufacturing, wisdom manufacturing can meet such a need.

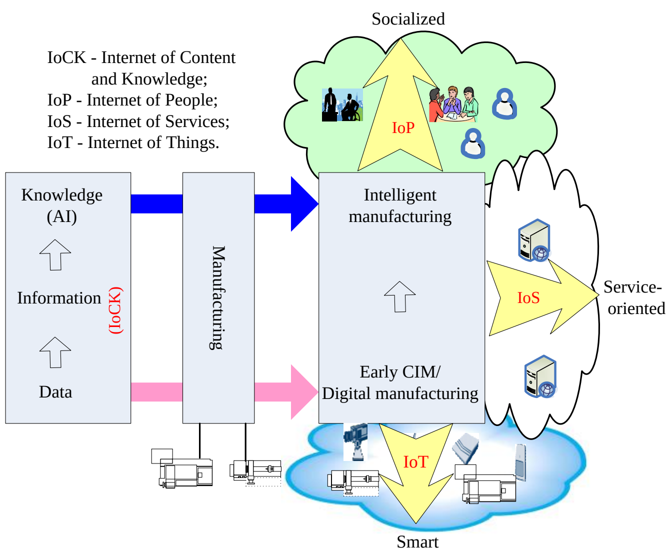


Fig. 6 The impacts of the IoT, IoS and IoP on integrated manufacturing

The IoT can be used to optimize energy efficiency (Shrouf and Miragliotta 2015) in addition to cost and time savings in manufacturing. Further, big data in conjunction with IoT enables production cleaner (Zhang et al. 2017) and even sustainable (Dubey et al. 2015). In addition, data can be converted into interoperability service for integration (Pang et al. 2015). As the process of obtaining on-demand services, ideas, or contents by soliciting contributions from a crowd, especially from an online community, crowdsourcing (Poetz and Schreier 2012) becomes more attractive for an alternative source of generating ideas for new products. The introduction of the IoP promotes innovation, customization, knowledge sharing and sustainability in wisdom manufacturing in a global context (X. Yao et al. 2014a), and further leads to the emergence of social manufacturing (X. Yao and Lin 2016). As such, wisdom manufacturing can be considered as a kind of sustainable manufacturing as it balances economic, environmental, and social needs (X. Yao et al. 2017).

As such a result of the use of the IoT, IoS and IoP in manufacturing, big data generated from the SCPS becomes more and more critical to implement new manufacturing paradigms. Thus, such kind of big-data driven manufacturing, termed ‘proactive manufacturing’ has been proposed (Xifan Yao et al. 2017), which is viewed as the further development of predictive manufacturing (Jay Lee et al. 2013). Although not expressed in eq. (1) or (2) explicitly, big data as well as its resultant information/knowledge in a sense stands for IoCK, and links the main tuple elements as stated above. In other words, it is big data that bridge the IoT, IoS, IoCK and IoP (X. Yao et al. 2017).

The proposed CPS-based architecture (Fig. 3), especially the SCPS-based architecture (Fig. 4) can provide a theoretical basis for emerging smart/wisdom manufacturing integration, and helps us with a comprehensive understanding of all emerging smart models and their relations, as shown in Fig. 7. In parallel to the four pillars of IoP, IoCK, IoT, and IoS (which are analogous to four legs of the elephant, while the entire elephant serviced as an analogy that manufacturing should be seen from a comprehensive way), there are social manufacturing, big-data driven manufacturing (proactive manufacturing/predictive manufacturing), the smart factory (the Internet of Manufacturing Things), and cloud manufacturing. Under the umbrella of CPS-based production, there is smart manufacturing that covers the smart factory, cloud manufacturing, and even big-data driven manufacturing. While under the umbrella of SCPS-based production, it is wisdom manufacturing that covers smart manufacturing and social manufacturing.

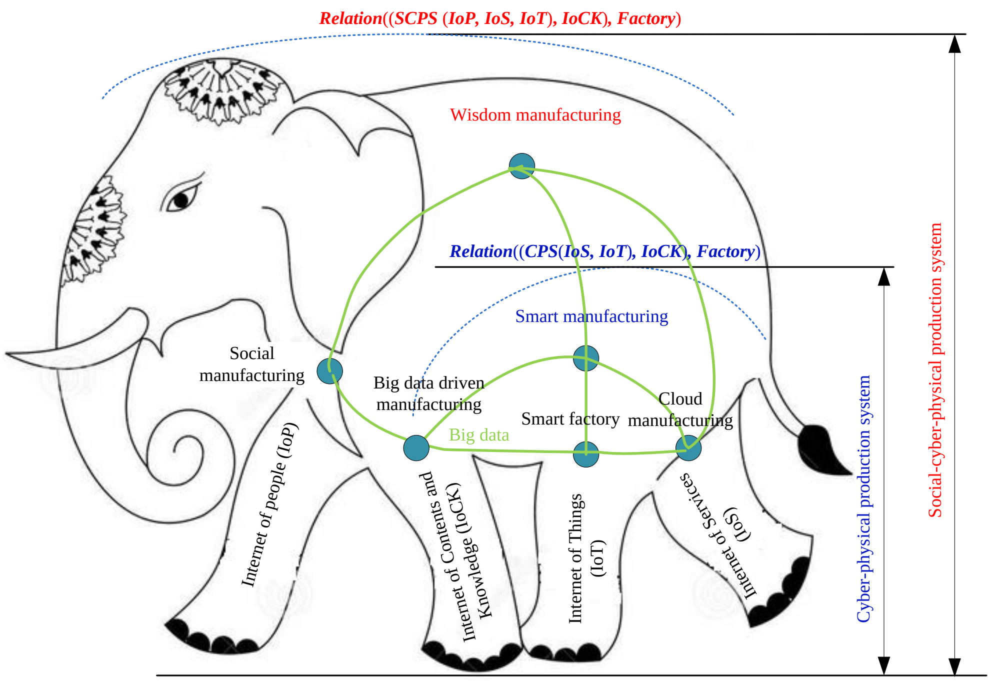


Fig. 7 Emerging smart models and their relations in parallel to IoP, IoCK, IoT, and IoS

6. Conclusion

This paper has first discussed the architecture and attributes of CPS compared with other related systems and technologies, and given a brief summary of CPS. Then CPS-based manufacturing has been addressed as an eight tuple with the characteristics of real-time data access, reconfiguration, interoperation, decentralized decision making, intelligence, and proactivity to overcome the limitations of existing integrated manufacturing systems. Finally, the eight-tuple CPS-based manufacturing is extended to a nine-tuple vision of manufacturing in the form of SCPS, called wisdom manufacturing (wise manufacturing). This has more prominent characteristics such as social computing, community, crowdsourcing, customization/ personalization, and furthermore promoting innovation and sustainability in manufacturing.

In short, smart manufacturing can be seen as a production paradigm based on CPS that is linked by the IoT, IoS and IoCK, and wisdom manufacturing can be viewed as a SCPS-based production paradigm that goes beyond such CPS-based smart manufacturing with the IoP to further link the social system. Wisdom manufacturing takes account of both technological and human factors in production; so it can better meet the future manufacturing needs - innovation and sustainability that requires that economic, environmental, and social aspects are taken into account.

This study fills the gaps between IoT/IoS and CPS, between CPS and smart manufacturing, and between smart manufacturing and wisdom manufacturing. However, such a study just focuses on a comprehensive overall framework and theoretical basis for emerging smart manufacturing integration; so more research effort is needed in the future on the main components of the proposed SCPS architecture.

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