Toward human-centric smart manufacturing: A human-cyber-physical systems (HCPS) perspective

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CONTENTS

1. Introduction

- In smart manufacturing, disruptive technologies, such as metaverse, big data analytics (BDA), industrial Internet-of-Things (IIoT), digital twin (DT), and artificial intelligence (AI), are advancing rapidly, shaping the industry and society, and redefining the role and position of humans[1–6].
- Traditional boundaries between humans and technologies have been blurred, especially reflected in recent concepts including Industry 5.0, Society 5.0, Operator 5.0, etc. [7–9].
- Along with technological innovation, system integration with human-in-the-loop considerations is one of the most important features to develop human-centric smart systems. [10].

1. Introduction

In literature, there are two viewpoints on the evolution of HCPS:

1. Integrating cyber context in the human-physical system (HPS)

- From the viewpoint of Zhou et al. [10], a traditional manufacturing operation system is an HPS consisting of two major components, namely humans and physical systems.
- The advanced digital and intelligent manufacturing systems are characterized by the emergence of cyber systems into HPS, transforming the traditional binary HPS into the ternary HCPS.

1. Introduction

In literature, there are two viewpoints on the evolution of HCPS:

2. *Integrating human/society context in cyber-physical system (CPS)*

- CPS enabling improved efficiency, accountability, sustainability, and scalability of processes is an embedded system.
- One important element often overlooked in current CPS research is the knowledge of human users of their tasks and the culture of the organization.
- The creativity, flexibility, and problem-solving competence of human stakeholders and the organizational culture instilled by leaders to relentlessly pursue improvements in operations are strongly needed to advance the CPS.

1. Introduction

- No matter from which perspective, and whether human-in-the-loop or human-out-of-the-loop, advanced manufacturing technologies are created by humans, serve humans, and work together with humans.
- Thus, integrating both human and cyber contexts in the smart manufacturing systems, instead of placing humans outside the systems, is important.
- This study presents a holistic view of HCPS by comprehensively covering all related issues.

2. Fundamentals of HCPS

2.1. Definitions of HCPS

- HCPS-related definitions have been presented using various terms, including HCPS [10], cyber-physical-human system (CPHS) [38], human-in-the-loop cyber-physical systems (HiLCPS) [21], and social cyber-physical system (SCPS) or cyber-physical social system (CPSS) [39].
- Table 1 summarizes typical HCPS-related concepts and definitions.
- Despite various acronyms coined, all these definitions share common understandings, in terms of system components, sub-systems, and taxonomy.
- In a system of interest, let H, C, P be the set of human, cyber, and physical components, respectively and R be the set of existing relations.
- Then, three kinds of relations can be well defined:

2. Fundamentals of HCPS

Table 1
Related terminology and concepts on HCPS.

Concept and acronym	*Content or definitions*
HCPS	• A composite intelligent system comprising humans, cyber systems, and physical systems with the aim of achieving specific manufacturing goals at an optimized level. This intelligent system is called human–cyber–physical systems (HCPS) [10]. • HCPS are defined as systems engineered to: (a) improve human abilities to dynamically interact with machines in the cyber- and physical-worlds by means of 'intelligent' human-machine interfaces, using human-computer interaction techniques designed to fit the operators' cognitive and physical needs, and (b) improve human physical-, sensing-, and cognitive-capabilities, by means of various enhanced technologies [14]. • A human-cyber-physical system is a physical system with a "cyber brain" that engages humans in myriad aspects from system operation to service delivery [40].
CPHS	• Cyber-Physical-Human Systems (CPHS) are complex engineered sociotechnical systems in which computers, sensing, and communication devices and humans cooperate to jointly perform missions (and tasks) over time and across space [41]. • CPHS are also defined as "a class of safety-critical socio-technical systems in which the interactions between the physical system and cyber elements that control its operation are influenced by human agent(s). CPHS objectives are achieved through interactions among: physical system (or process) to be controlled, cyber elements (i.e., communication links and software), and human agents who monitor and influence the operation of cyber-physical elements" [38].
HiLCPS	A typical HiLCPS consists of a loop involving a human, an embedded system (the cyber component), and a physical environment. Basically, the embedded system augments a human's interaction with the physical world [21].
CPSS	The CPSS integrates the social components into the CPS. CPSS constitutes: (a) a physical system, (b) its social system including human beings, and (c) the cyber system that connects physical and social systems [39].

2. Fundamentals of HCPS

2.1. Definitions of HCPS

- $R^X: X \times X \rightarrow R$, where, X is "H", "C", or "P"
- $R^{XY}: X \times Y \rightarrow R$, where, X and Y are "H", "C", or "P" and $X \neq Y$
- $R^{HCP}: H \times C \times P \rightarrow R$

- Totally, there are seven types of relations: RH, RC, RP, RHP, RHC, RCP, RHCP.
- All of these are subclasses of the systemic Relation class, the relation leads to the emergence of HCPS (or called CPHS or other acronyms).
- The emergence of HCPS is defined by the following rules:

2. Fundamentals of HCPS

2.1. Definitions of HCPS

$$\exists H, \exists C, \exists P, \exists R^{CP}, \exists R^{HP} \Leftarrow \exists R^{HCP}$$

$$\exists R^{HCP} \Rightarrow \exists HCPS$$

- In other words, an HCPS emerges if there is at least one Cyber, one Physical, and one Human component, with at least two relations between them, RCP and RHP, which lead to an RHCP that is responsible for the emergence of an HCPS

2. Fundamentals of HCPS

2.2. Core elements of HCPS

- Three basic elements of HCPS are humans, cyber systems, and physical systems, which are analyzed in the following three sections.

2.2.1. The context of humans

- In HCPS, humans include “operators” and “agents” who influence or operate the system, and “users” who receive services.
- Along with technological and industrial revolutions, humans’ roles have also evolved, as shown in Fig. 1, namely Human 1.0, Human 2.0, Human 3.0, and Human 4.0.

2. Fundamentals of HCPS

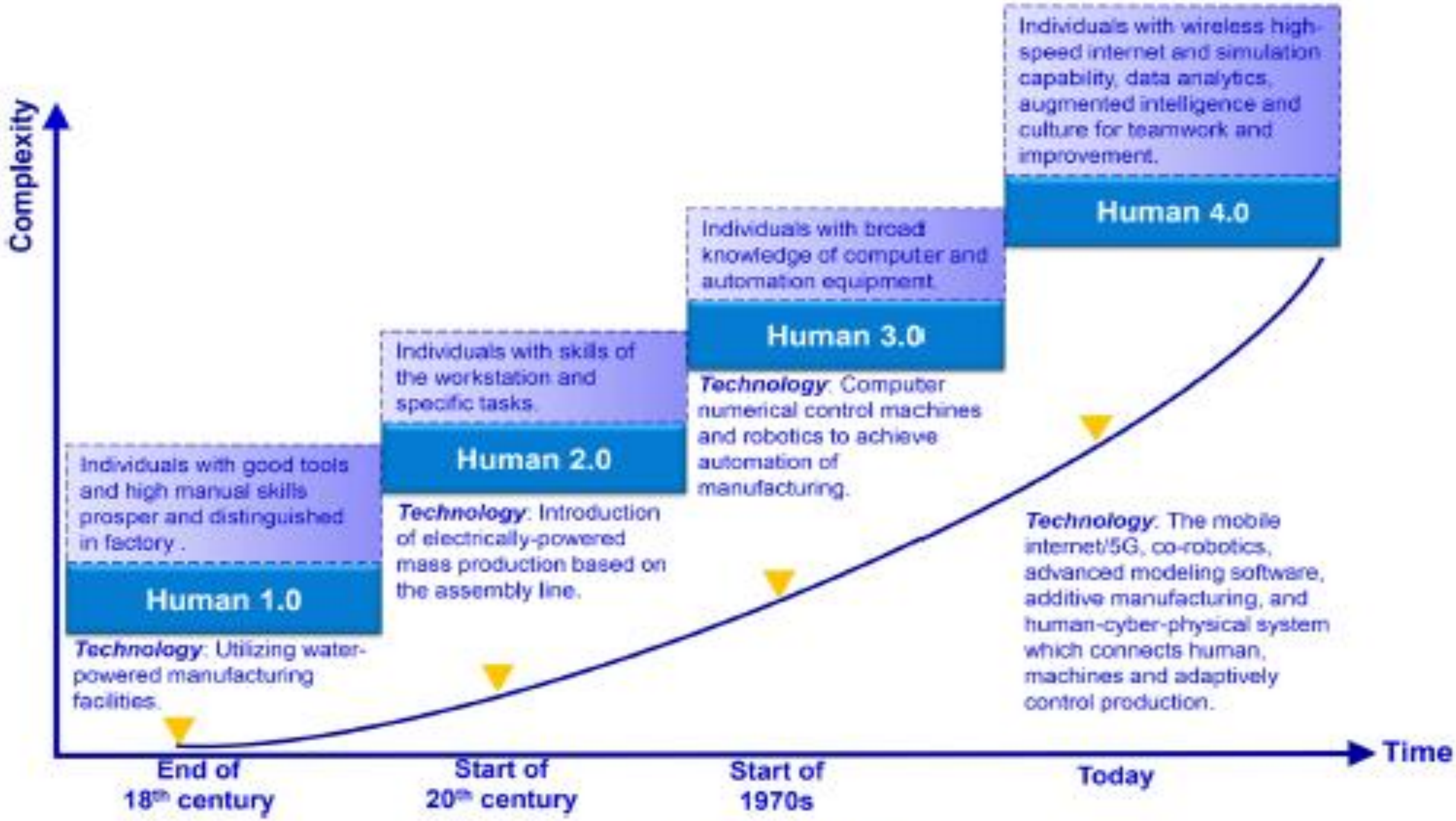


Fig. 1. Paradigms of humans in industry.

2. Fundamentals of HCPS

2.2.2. The context of a physical system

- A physical system may be narrowly defined as physical machines based on related physical laws.
- In a broad sense, a physical system is the materials, energy and resources, sensors and actuators, infrastructure, and environment.
- Innovations on the physical system have been accomplished during past decades, including additive manufacturing (AM) and smart materials.

2.2.3. The context of a cyber system

- Cybernetics is the foundation of the creation of modern intelligent systems.
- In recent decades, the focus has been shifted to cyberspace and cyber system.
- Cyberspace is a collection of interconnected computerized networks [46].
- In a broad sense, a cyber system may include sensing, communication, networking, storage, database, information technology (IT) infrastructure, computer-aided simulation, control, and artificial intelligence (AI) / machine learning (ML), etc., in which communication, computing, and control are significant.

2. Fundamentals of HCPS

2.3. Taxonomy/typology of HCPS

- From the control perspective (or the CPS-human relationship perspective), it is natural to classify HCPS into human-in-the-loop and human-out-the-loop, as shown in Fig. 2. Meanwhile, from the human-centric perspective, HCPS can be further categorized into three types:
- ***Human decision and action*.**
  - Human inputs are integrated into the cyber world and human is the operator or involved in the actuation process of the system. The human-robot collaboration is the most common type of HCPS in the manufacturing industry .
- ***Machine decision and action*.**
  - Human inputs are integrated into cyberspace, but the actuation is triggered and implemented automatically by machines rather than humans.
- **H*uman action when necessary*.**
  - Human is the operator and only involved in the actuation process of the system to implement changes or controls in the physical world.

2. Fundamentals of HCPS

2.3. Taxonomy/typology of HCPS

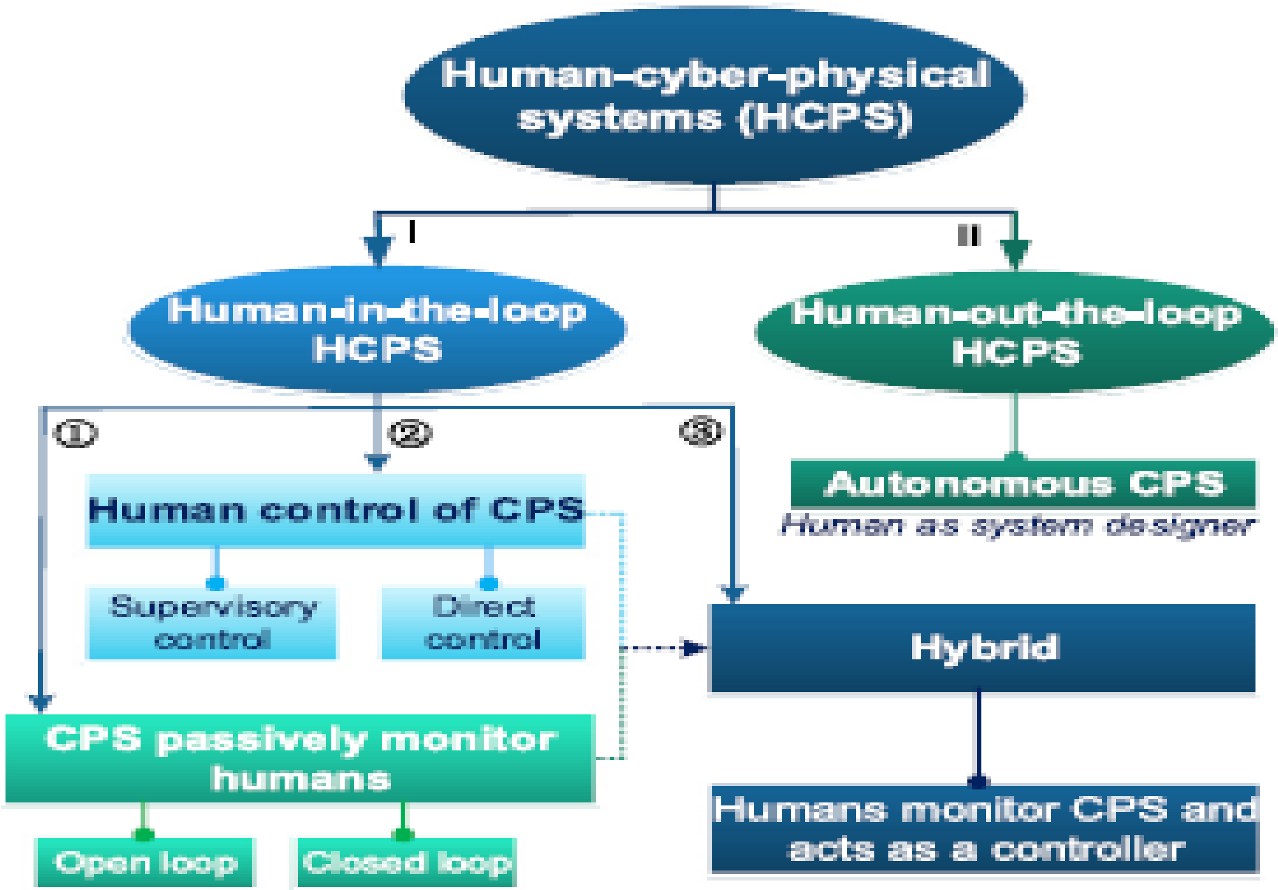


Fig. 2. Taxonomy of HCPS [20,38].

3. Framework of HCPS

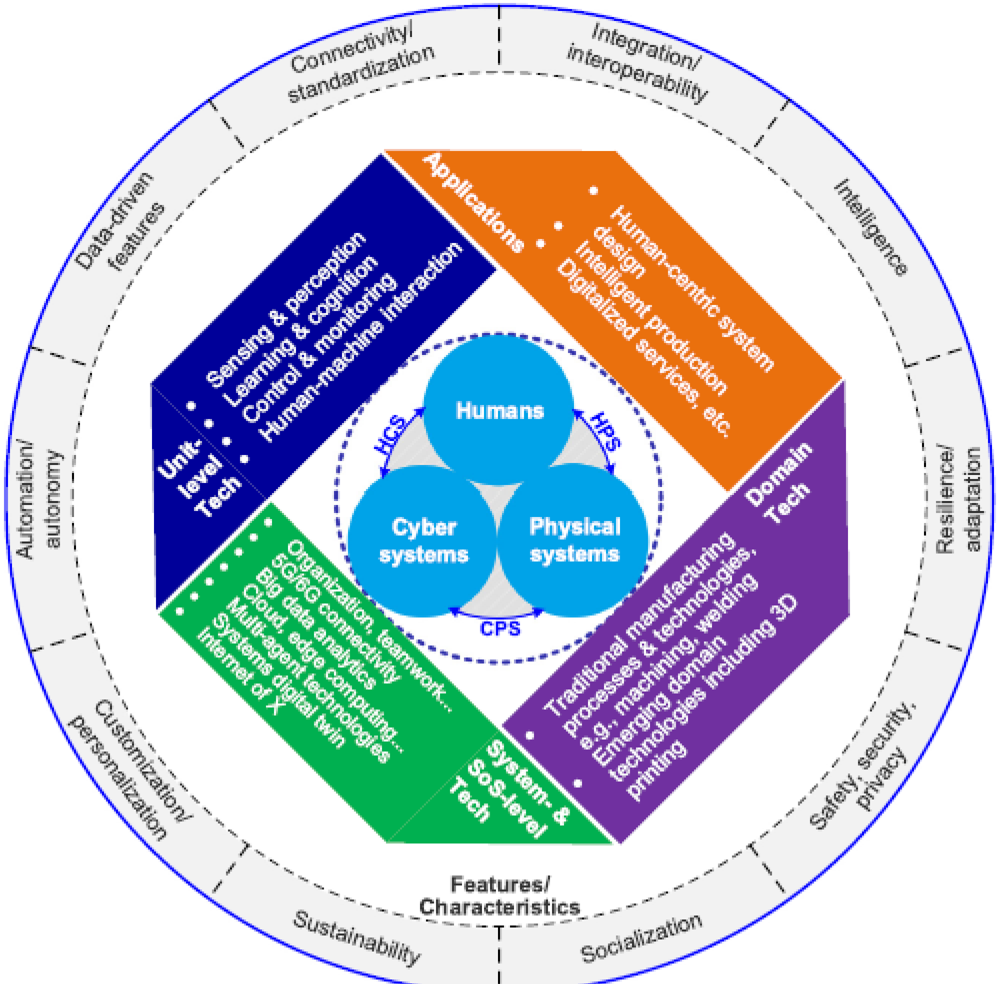


Fig. 3. The overall framework of HCPS.

3. Framework of HCPS

3.1. Human-physical systems (HPS)

- In traditional manufacturing systems, humans either complete tasks by themselves or via machines in the context of HPS [10]. With computerization and digitalization, many repetitive manual tasks in HPS have been automated.
- Some complex tasks that require flexibility and ad hoc problem-solving skills still need humans (e.g., innovation, design, operating complex machines). HPS, e.g., human factor/ergonomics [52] and human-machine relationship [53], are still critically important [43].

3. Framework of HCPS

3.2. Human-cyber systems (HCS)

- Humans continue to play a key role as the most viable flexible solution to meet the needs of future manufacturers, which promotes the emergence of HCS under Industry 4.0.

- Krogh and Mears clarified HCS in manufacturing including smart connection level, data-to-information level, cyber level, cognition level, and configuration level.

- The main forms of HCS include software, database, knowledge engineering, and Internet-of-People.

3. Framework of HCPS

3.3. Cyber-physical systems (CPS)

- In CPS, related information is monitored and synchronized between the physical systems and the cyber computational systems. Intelligent machines can perform more efficiently and resiliently by utilizing advanced information analytics in CPS.
- CPS-related techniques include monitoring and control, embedded system, digital twin, industrial internet, and cloud computing.

4. Enabling technologies of HCPS

4. Enabling technologies of HCPS

- The enabling technologies of HCPS are surveyed from the perspectives of the domain, unit-level and system- and SoS-level technologies, as shown in Table 2, and the underlined relationship among those technologies for HSM implementation is further depicted in Fig. 4.

4. Enabling technologies of HCPS

4. Enabling technologies of HCPS

Table 2
Enabling technologies of HCPS.

Domain technologies		• Traditional manufacturing processes and technologies, e.g., machining, welding, forging, casting. • Emerging domain technologies including additive manufacturing and sustainable technologies
Unit-level technologies	*Sensing and perception*	• Sensors for humans • Humans as sensors
	Learning and cognition	• Human-machine learning • Cognitive computing
	Control and monitoring	• Human remote monitoring and control • Human digital twin [55,56]
	Human-machine interaction	• Human factor engineering/ergonomics • Extended reality [57] • Human-robot collaboration and safety assurance • Bioelectric signals interface
System- and SoS-level technologies		• Organization, teamwork, and culture • 5G/6G/satellite connectivity • Big data analytics • Cloud, edge computing, and Blockchain • Multi-agent technologies • Systems digital twin • Internet-of-X

4. Enabling technologies of HCPS

4. Enabling technologies of HCPS

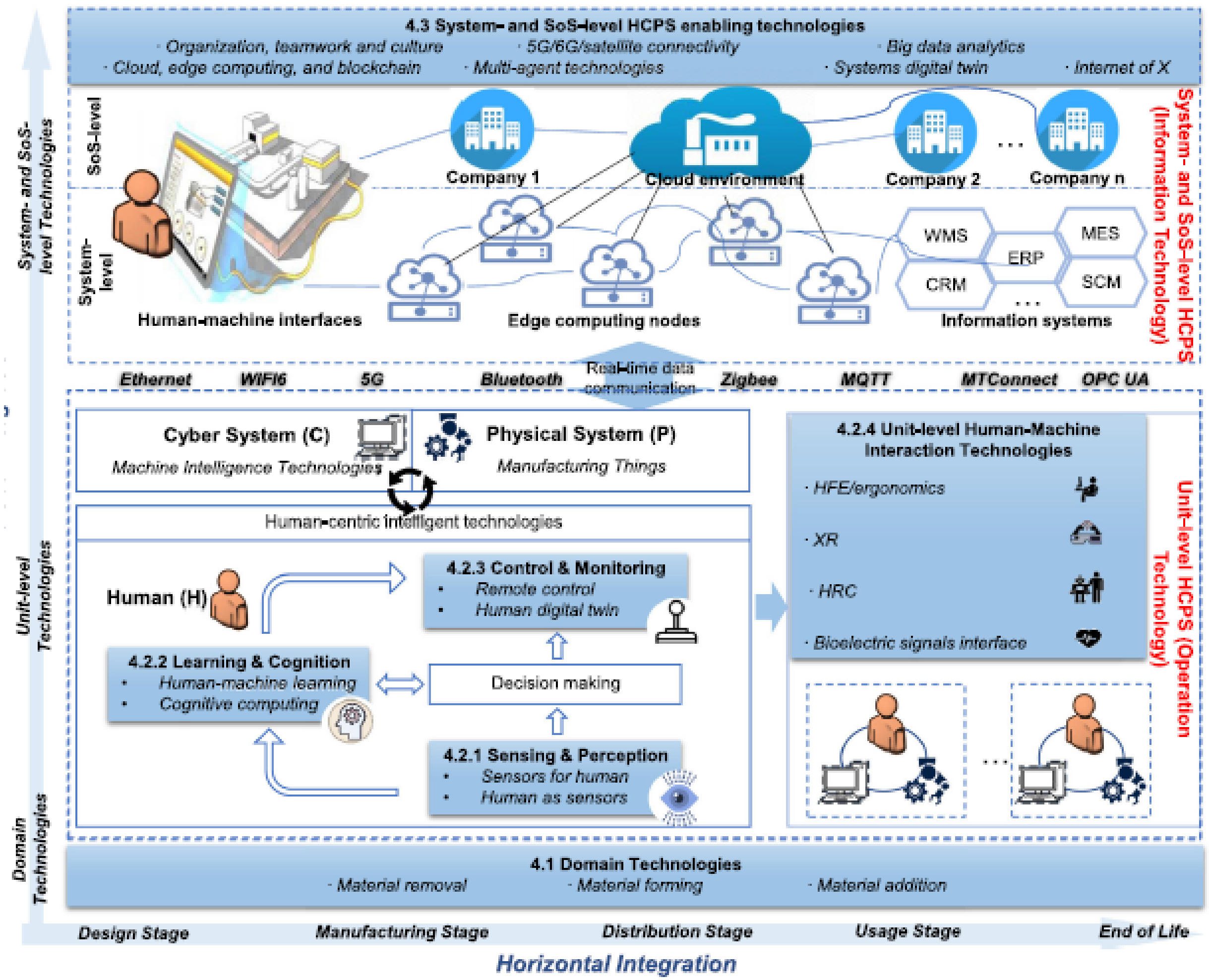


Fig. 4. The relationship among enabling HCPS technologies for HSM.

4. Enabling technologies of HCPS

4.1. Domain technologies

- Domain technologies include special technologies adopted in the specific principles/fields, such as manufacturing, energy, transportation, agriculture, etc.
- In the manufacturing sector, the domain manufacturing technologies can be divided into material removal material forming, material joining and material addition technology, which serve as the fundamental basis for developing HSM functionalities from a HCPS perspective.
- In particular, emerging manufacturing technologies such as AM have the potential to change the current production paradigm and people’s life in the context of HCPS.

4. Enabling technologies of HCPS

4.2. Unit-level technologies

- Unit-level technologies cover the individual agents and their interactions in the HSM, including both humans (e.g., operators, engineers) and manufacturing “things” (e.g., robots, machine tools).
- They are the building blocks to achieve the HSM system, of which collaborative intelligence (co-intelligence or CI) plays a significant role in unit-level technologies of HCPS, where humans can learn from machines and machines can learn from humans.
- Both humans and machines can also join forces to learn from their experience and the environment to achieve a team objective.

4. Enabling technologies of HCPS

4.2. Unit-level technologies

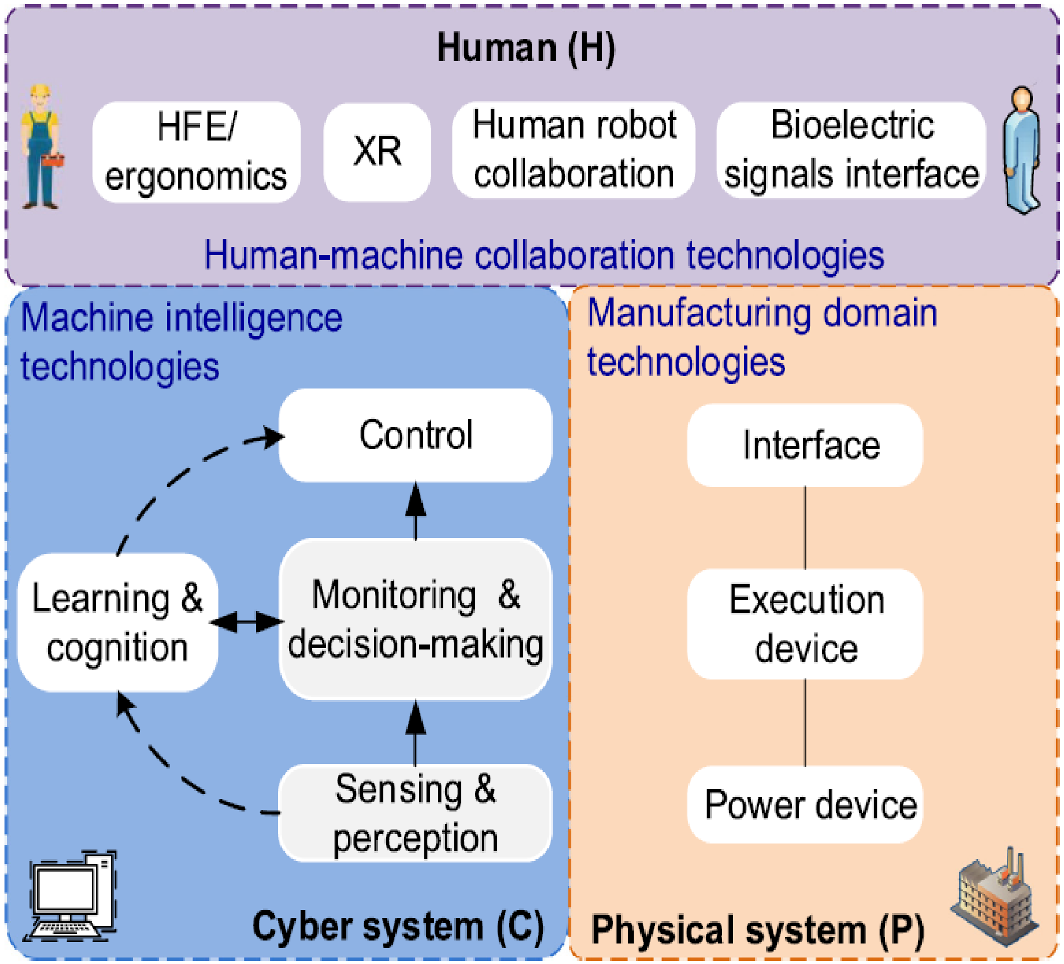


Fig. 5. Unit-level technologies in HCPS [10].

4. Enabling technologies of HCPS

4.2.1. Sensing and perception

- In general, sensing and perception of humans and machines are the process of data collection and structuring as well as the prerequisite for subsequent analysis, decision-making, and execution.
- In HCPS, other than the smart hardware sensors for human-machine interactions, humans can act as social sensors.

4. Enabling technologies of HCPS

4.2.1.1.

- ***Sensors for humans.***

– As humans are more involved in HCPS, new sensing and perception technologies are used to collect human data.

- ***Human motion detection and tracking sensors*.**

– Wearable inertial sensors can monitor a human's motion and provide the data for constructing a human digital twin.

- ***Wearable devices or cameras for mental and physical health monitoring***

– When the operator cannot concentrate on tasks, smart sensors (e. g., smart watch) can recognize it and provide information to the system, changing the production pace, and avoiding possible accidents [12].

- ***Biometric sensors***

– Human body electrical signals, e.g., electroencephalogram, electromyography, and others have been demonstrated to be capable to control physical machines [64].

4. Enabling technologies of HCPS

4.2.1.2. Humans as sensors.

- One of the humans’ roles is sensing as illustrated in Human 4.0 in Fig. 1 [66].
- Humans can be sensors in factories, especially for collecting information that other sensors cannot easily recognize.

4. Enabling technologies of HCPS

4.2.2. Learning and cognition

- HCPS has multi-modal perception abilities and, more importantly, learning and cognition capabilities, which support the manufacturing system to handle complex and uncertain problems. Learning in HCPS has four purposes:

  (1) learn about the operational environment

  (2) learn about the humans

  (3) learn about the CPS

  (4) learn how to mutually adapt.

4. Enabling technologies of HCPS

4.2.2. Learning and cognition

- Learning in HCPS can exploit multiple sensor sources, take a variety of forms, and satisfy different needs.
- In practice, complicated factors are noisy sensor data, partial observability, and disruptive events.
- Both offline and online learning play important roles in adaptive HCPS.
- Typical learning and cognition are presented in two parts: human-machine learning and cognitive computing.

4. Enabling technologies of HCPS

4.2.2.1. Human-machine learning.

- Humans are good at teamwork, understanding complex situations, and making high-level decisions, while machines are good at computing or implementing high-precision tasks.
- Therefore, during close interaction and collaboration, humans and machines can learn from each other, from the sensed operational environment, and from actions taken in an operational environment.
- Ansari et al. [70] studied the concept of “mutual human-machine learning” to describe the process in that humans and machines mutually benefit from each other and create new value bi-directionally.

4. Enabling technologies of HCPS

4.2.2.1. Human-machine learning.

- The enhanced ability comes from humans and machines mutually assisting each other in the context of human-robot collaboration is referred to as "collaborative intelligence"
- Machines can learn from humans from many perspectives.
- For instance, by imitating humans' gestures or motions, a robot can learn how to perform a task as humans. Humans can directly teach a robot by moving their end-effector without pre-programming [70].
- In turn, equipped with smart sensors and analytic abilities, cognitive machines or cyber systems can observe and evaluate human activities for a better solution, such as a better process planning sequence.
- Humans can reject the solution offered by machines, thereby teaching them the working logic of human intelligence.

4. Enabling technologies of HCPS

4.2.2.2. Cognitive computing.

- Cognitive intelligence is embodied in the ability of manufacturing systems to analyze, understand, and interpret data to undertake complex tasks such as reasoning, decision-making, and creation [73].
- Cognitive computing supports cognitive intelligence, allowing machines to simulate the cognitive process of humans, thereby reaching the level of human intelligence.
- The human cognitive process can be divided into two phases:

  (1) the perception of the surrounding environment and

  (2) the analysis and decision-making of information [74].
- Decisions induce corresponding executions that change or affect the environment again, forming a closed-loop [74].

4. Enabling technologies of HCPS

4.2.2.2. Cognitive computing.

- Several multi-modal sensor technologies, reinforcement learning, deep learning, and cloud computing are enabling technologies supporting cognitive computing.
- With the gradual acceptance of the human-centricity concept, cognitive intelligence algorithms such as emotional computing focusing on human emotions and psychology have emerged [75].
- Affective computing in manufacturing mainly uses various sensors to obtain the human pulse, expression, voice, and body motions, assisted by psychological science and cognitive science, to recognize human emotions.

4. Enabling technologies of HCPS

4.2.3. Control and monitoring

4.2.3.1. Remote monitoring and control.

- Due to reasons like extreme weather and COVID-19 pandemic, humans are not able to be present to the manufacturing onsite.
- Thus, remote monitoring and control technologies are necessary. Beyond the traditional teleoperation method (such as using a joystick), new technologies have emerged.
- The joystick teleoperation and remote vision system based on camera on the robot (providing robot’s perspective) have been combined to achieve faster and more convenient remote control [77].

4. Enabling technologies of HCPS

4.2.3. Control and monitoring

4.2.3.1. Remote monitoring and control.

- Tactile sensor-based remote-control technology can provide feedback to humans and significantly improve user immersion [77].
- The inertial sensor-based remote control can synchronously manipulate the corresponding machine based on the measured human motion [78].
- Such remote control is combined with virtual reality (VR) and augmented reality (AR) to realize a more user-friendly and safer human-machine interaction [79,80].

4. Enabling technologies of HCPS

4.2.3.2. Human digital twin.

- DT is a promising technology to realize HCPS in smart manufacturing by integrating humans, physical entities, and the cyber world [81].
- DT is not only a geometrical representation but also a physical multi-scale model, dynamically updated with the change of its physical counterpart [82].
- As a model-based monitor and control method, DT aims to realize a continuous, closed-loop improvement in the production life cycle [83].
- In smart manufacturing, human workers embrace irreplaceable problem-solving capabilities, flexibility, and versatility.
- Thus, except for physical entities, operators should also be represented by another digital twin, referred to as human digital twin (HDT) [56].
- Sparrow et al. [55] considered HDT as a necessary technology to promote the integration of HCPS. The realization of HDTs needs to solve two issues: (1) the communication between humans and machines and (2) human mental state and physical behavior modeling, including psychological and physical behaviors [55].

4. Enabling technologies of HCPS

4.2.3.2. Human digital twin.

- For human mental state modeling, smart sensors and machine learning algorithms can be applied to monitor the critical parameters of human mood and mental health [82].
- For the modeling of human physical behaviors, as shown in Fig. 6, the physical posture and position of humans can be obtained through sensors and mapped with DTs, which can be used for human-machine state monitoring and prediction [84].
- A method to monitor the health of the human lumbar spine in real-time based on HDT [85] has been developed.
- A VR-based human-robot collaboration (HRC) simulation system and integrated HDT to predict whether a safety accident will occur more accurately has been studied [86].
- In view of HCPS, HDT is conducive to monitoring humans' work status in real-time and providing bidirectional feedback between humans and machines [55].

4. Enabling technologies of HCPS

4.2.4. Human-machine interaction

- In the HCPS system, various human-machine interaction media have advanced to realize the data exchange and human-machine collaboration between humans and CPS

4. Enabling technologies of HCPS

4.2.4.1. Human factor engineering (HFE)/ergonomics.

- In the unit-level, HFE mainly improves human-machine interactions from two aspects, namely physical and cognitive ergonomics.
- In physical ergonomics, HFE focuses on the safety of human-machine interaction, and uses wearable smart devices to collect humans' health-related data to get a feedback and improvement on their working conditions.
- In cognition, HFE utilizes a virtual model to improve perception and understanding and proposes innovative methods (such as VR/AR) in human-machine interaction to reduce mental strain and support the decision-making process [43].

4. Enabling technologies of HCPS

4.2.4.2. Extended reality in manufacturing.

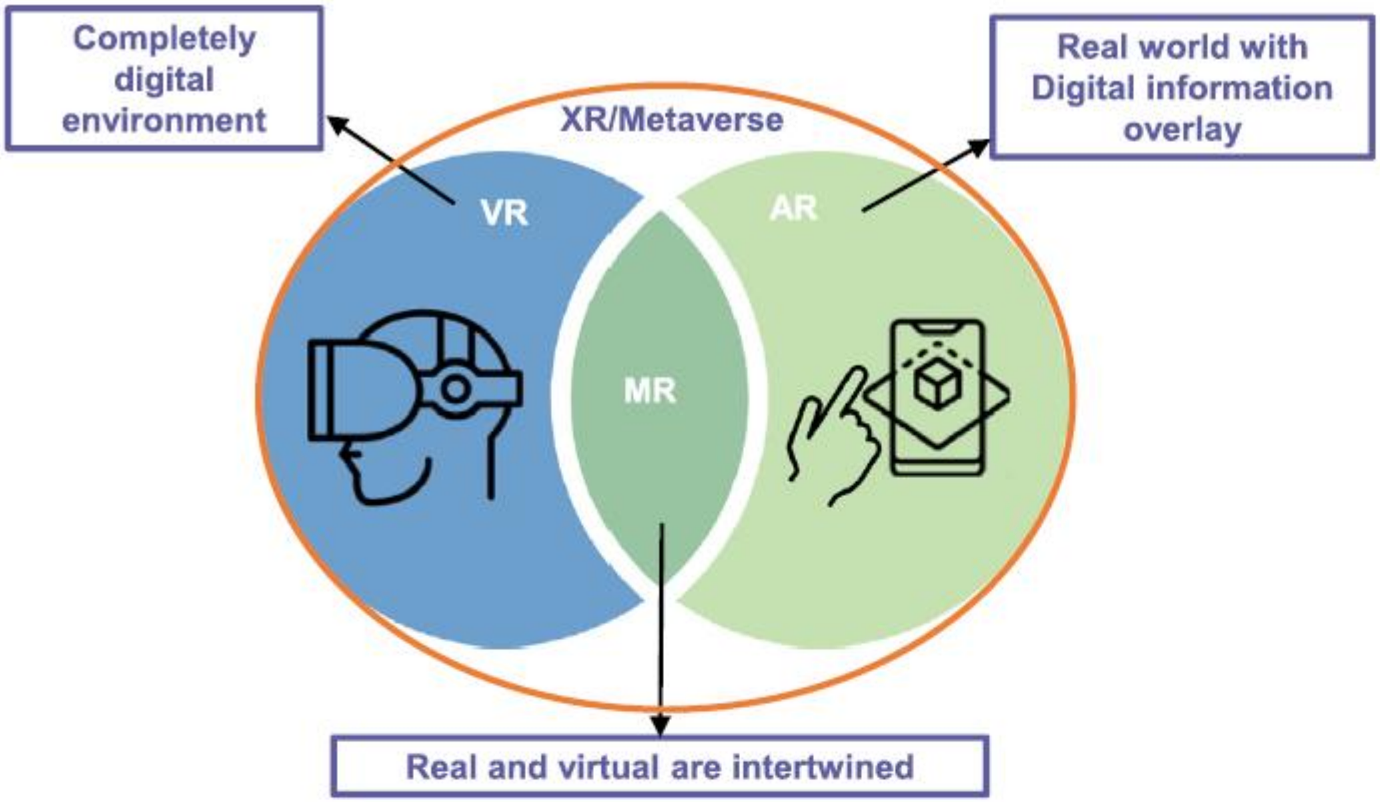


Fig. 7. XR (Extended Reality) [57].

4. Enabling technologies of HCPS

4.2.4.2. Extended reality in manufacturing.

- AR is an effective interface for real-time communication in HCPS, e. g., in HRC [92,93]. The main contribution of AR in human-machine interaction is to impose multi-modal information onto the physical world in real-time to enhance human perception.

- By combining it with intelligent algorithms, databases, 5 G, cloud computing, and others, AR can obtain and analyze data from the environment in real-time to help human operators recognize, position, and track in manufacturing operations, thereby reducing human workload and improving human cognitive ability [92].

- Based on the IoT, AR can also integrate human data into CPS, to realize real-time and two-way communication between humans and machines, mutually improving cognitive capability [94]. Enhancing perceptive and cognitive abilities by AR, human operators have better safety and security assurance while interacting with machines [95].

4. Enabling technologies of HCPS

4.2.4.2. Extended reality in manufacturing.

- Viewing and interacting with virtual but real-scale objects is one of VR’s most substantial functional support [88]. The visualization support of VR in manufacturing is mainly embodied in two aspects [96].
- One is that VR can visualize unapproachable or dangerous industrial scenes to support remote control or training operators in a virtual environment without risking in dangerous work areas, thereby ensuring the safety of workers.
- The second is that VR can visualize the required data, especially in the early stage of product design. By providing model visualization and simulation, designers can obtain more visual details and find design problems earlier and quicker.
- For example, VR allows people to experience the design in the virtual space, which can optimize ergonomics or human-machine interaction experience.

4. Enabling technologies of HCPS

4.2.4.3. Human-robot collaboration.

- HRC has evolved from human-robot coexistence, interaction, and cooperation to today's symbiotic collaboration [13], a paradigm to realize adaptively mutual support between humans and robots with capabilities of perception, cognition, execution, and self-learning through real-time communication [68].

4. Enabling technologies of HCPS

4.2.4.3. Human-robot collaboration.

- With the advancement of communication, data storage, and computing abilities, symbiotic HRC places multiple human operators and robots into a collaborative environment with following characteristics:

– Humans and robots would take charge of different roles during collaboration. When assigning tasks, humans are intuitive, robots are adaptive. That is, tasks and roles are not specified in advance but dynamically assigned.

– Robots embrace context awareness, perception, cognition, and decision-making capabilities.

– The information exchange is real-time, two-way, and multi-modal.

– The resources and information are shared by DTs.

– Robots have self-learning capabilities.

– Human safety is guaranteed. Compared with fully automated or manual operations, symbiosis HRC combines the advantages of humans and machines and can improve work efficiency and flexibility.

4. Enabling technologies of HCPS

4.2.4.4. Bioelectric signals interface.

- In addition to traditional interaction methods, such as vision and tactile, the bioelectric signals interface that uses human bioelectric signals to directly control machines has also been extensively studied in the past few decades [64,97].
- The brain-computer interface (BCI) is a bioelectric signals interface that supports the direct interaction between the human brain and the external environment without relying on body movement [99]. It is an innovative multi-modal human-machine interaction that can be effective in symbiotic HRC [100,101].

4. Enabling technologies of HCPS

4.2.4.4. Bioelectric signals interface.

- Brain robotics is an important application of BCI. The combination of BCI and deep learning enables brain robotics to understand human intentions by analyzing the electroencephalogram (EEG), allowing the human brain to directly control the robot [100].
- The electromyography (EMG) signal interface is another promising human-machine interaction method. A hand gesture recognition algorithm based on deep learning, which collects the arm EMG signal through a smart wearable armband, infers the hand motion intentions, then drives the dexterous robot hand to mimic corresponding actions [102].
- Meanwhile, exoskeleton robots are generally used to enhance the operators' muscles or assist the wearers as an extra limb. The transmission of human motion intentions to an exoskeleton by EMG signals has been investigated to realize harmonious collaboration between human operators and exoskeleton robots [64].

4. Enabling technologies of HCPS

4.3. System- and SoS-level technologies

- In HCPS, system- and SoS-level technologies support the vertical and horizontal integration of HSM, respectively.
- They are mainly responsible for processing massive amounts of user generated and product-sensed data and making decisions to support human-centric product design, manufacturing, and service optimization, in a real-time interaction and integration manner [90].

4. Enabling technologies of HCPS

4.3.1. Organization, teamwork, and culture

- Industry 5.0 is a value-driven ideological revolution in manufacturing [103]. One of its core perspectives is putting the well-being and interests of humans in a critical position. The industry should promote employment and ensure people's livelihood [104].

- In addition to pursuing high quality, high efficiency, and low cost, human aspects are in the new focus in HCPS. In the human-centric concept, factories should create a safe and comfortable working environment as well as preserve the fundamental rights of workers [8].

- By optimizing organization, teamwork, culture, and more intelligent assistance systems, a more innovative and comfortable working environment can be created and ensure that the operators can pursue better personal development [8]. Advanced technologies (e.g., MR, collaborative robots) allow operators to undertake more creative and value-adding work, which in turn helps people realize their self-value.

4. Enabling technologies of HCPS

4.3.2. 5 G/6 G connectivity

- The 5th generation mobile network (5G) can advance the capabilities of complex manufacturing systems by significantly improving the communication capacity, data transmission rate, coverage nodes, and real-time performance.
- International Telecommunication Union Radiocommunication Sector (ITU-R) has identified three scenarios for the future development of 5G, including mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable and low latency communication (URLLC) [90].
- 5G is essential for HCPS, where a large number of heterogeneous nodes communicate and generate massive data and information transmission between layers [105].
- The interaction between humans and CPS also depends on 5G, such as monitoring humans' physical and mental state, using VR/AR to perform tasks in real-time, and remote controlling and HRC.

4. Enabling technologies of HCPS

4.3.3. Big data analytics

- With the advancement of cyber technologies, various data were generated along with human activities (e.g. production, consumption, and daily life), thus we entered the Era of Big Data [107].
- Big data analytics is an approach that uses artificial intelligence, data mining, and statistical methods to analyze, systematically extract information from, or otherwise deal with data sets that are too large or complex to be dealt with by traditional data-processing application software [108].
- The most common big data analytics applications in the manufacturing industry are monitoring and predicting [109]. For instance, a data-driven sustainable manufacturing framework for maintenance and prediction has been proposed [110].

4. Enabling technologies of HCPS

4.3.3. Big data analytics

- The big data analytic model would update, learn, and evaluate during the interaction within the dynamic manufacturing environment [108]. Human factors, such as the manual correction of unreasonable results, the influence of expert knowledge, and the big data analytics with human interpretation, can promote the cognitive level of manufacturing systems.
- For example, a data-driven approach for opportunistic maintenance has the best performance in noise reduction if the algorithm results are supervised by an expert who will constantly update the hyper parameters [111].

4. Enabling technologies of HCPS

4.3.4. Cloud, edge computing, and blockchain

- There are two deployment approaches for cloud computing:
- smart manufacturing with cloud computing
- cloud manufacturing [112].

- Smart manufacturing with cloud computing means that cloud service providers can offer plug-and-play computing services for enterprises and individual users in a decentralized environment.
- Cloud manufacturing (1) integrates manufacturing processes, such as production, distribution, and sales, (2) connects organizations such as customers, service providers, and enterprises, and (3) provides on-demand services to optimize the utilization of manufacturing resources.
- Combining edge computing and other new data storage and processing technologies with cloud computing can extend manufacturers' data computing, storage, and network capabilities from the cloud to the edge, significantly reducing latency [109,113].
- Blockchain has innovative benefits such as decentralization and immutability, which adds credibility and transparency to cloud

4. Enabling technologies of HCPS

4.3.5. Multi-agent technologies

- In HCPS, it is necessary to regard human existence and behavior as a key element [12]. To enhance the flexibility and scalability of human-in-the-loop manufacturing systems, manufacturing control architecture has evolved from hierarchy-based centralized control to heterarchical decentralized control [115].
- Under this distributed control network, multi-agent systems (MAS) refer to a group of organized agents that represent the behaviors of objects of a system, capable of interacting and negotiating among them through peer-to-peer communication to achieve individual goals and adaptively respond to the fast-changing requirements of products [12].
- For example, a distributed intelligent algorithm based on MAS and reinforcement learning that can solve scheduling problems by the autonomous decision-making of machines with intelligent agents has been proposed [116].

4. Enabling technologies of HCPS

4.3.6. Systems digital twin (SDT)

- In HCPS, SDT means the integration of DT of physical machines and HDT, and their interaction.
- SDT is a virtual counterpart in HCPS, monitoring, controlling, and predicting the various process in the digital world and promoting continuous improvement of humans, manufacturing processes, and their balance [83].
- SDT can make the original data-driven manufacturing systems more responsive, adaptable, and predictable [109].

4. Enabling technologies of HCPS

4.3.6. Systems digital twin (SDT)

- Connecting assets, humans and services, SDT helps to visualize a virtual environment representing every key aspect.
- Combined with AI and ML, data throughout the entire production process can be tracked and analyzed by SDT, which is beneficial to find the source of failures in maintenance, improve abilities to predict future demand, and analyze production efficiency bottlenecks.
- At the SoS-level, establishing a distributed SDT-based production network between companies can provide unprecedented operability and visibility in real-time [82].
- In terms of implementing SDT, a four-layer technology stack that includes communication, representation, computation, and micro services has been created [83]. An architecture that uses DT integrating cyber-physical data to improve product design, manufacturing, and service has been proposed [117].

4. Enabling technologies of HCPS

4.3.7. Internet-of-X

- In HCPS, the IoT is an integrated and innovative application of the new-generation information and communication technology.
- The integration of AI and IoT leads to the Internet of Intelligent Things (IoIT), equipping manufacturing systems with reasoning, analyzing, and decision-making abilities in addition to perception and execution.
- IoIT establishes a broad network that extensively connects various nodes such as humans, machines, and services. Researchers proposed the Internet of Everything [119], Internet of All [19], and other similar concepts, unified as the Internet of X, including IoT, Internet of People (IoP), and Internet of Service (IoS).

4. Enabling technologies of HCPS

4.3.7. Internet-of-X

- Through wearable smart devices, exoskeleton, or human-brain interfaces as media, IoP considers humans as nodes of the manufacturing network [120]. Human operators are increasingly participating in the tasks and are playing different roles in different situations.

- Nunes et al. [19] considered that human operators are mainly in charge of data acquisition, state inference, and actuation in the production process. Works are shared with task performers, monitors, controllers, performance analyzers, and behavior influencers [67].

- IoS represents a transformation from a product-oriented paradigm to a service-oriented model, that is, servitization. With the development of IoT, assisted by cloud computing, digital twin, and big data analytics, a smart product-service system (PSS) based on connected smart devices is proposed [121].
- It takes digitization and servitization as its goals and satisfies customers' individual needs by providing personalized products and services. In particular, the human-in-the-loop hybrid innovation method represents a process of human-

4. Enabling technologies of HCPS

4.3.7. Internet-of-X

- To conclude, humans are integrated into the Internet-of-X with the development of information and connection technologies, while cloud computing and edge computing provide data storage and computing capabilities.
- Blockchain guarantees data and information security, and the combination of big data analytics and AI bring perception, cognition, and prediction capabilities for the entire HCPS.

5. Features and characteristics of HCPS

5. Features and characteristics of HCPS

- Other than the core features of CPS-enabled manufacturing systems such as integration, intelligence, collaboration, and reconfigurability, the HCPS leverages these capabilities based on a human-centric perspective by emphasizing several typical features, as highlighted in Table 3.

5. Features and characteristics of HCPS

5. Features and characteristics of HCPS

Table 3
Features and characteristics of HCPS.

Features	Definitions or content
Connectivity/ Standardization	Ensure real-time data exchange between cyber-physical assets.
Integration/ Interoperability	Realize the association with virtualization, real-time, and computational capabilities.
Data-driven features	Conduct data management and analytics using existing techniques and methods in diverse domains.
Intelligence	Enable to work independently or collaboratively, and provide decision support capabilities in line with organizational goals.
Automation/ Autonomy	Use modularized, flexible, and reconfigurable systems to realize autonomous manufacturing activities in the production process.
Resilience/ Adaptation	Leverage the cognitive functions from human operators and CPS techniques to recover from the disturbance and exception, and to maintain the stability and robustness of manufacturing systems.
Customization/ Personalization	Enable the low volume and high variety of products and related services to meet individual customer demands with human-in-the-loop.
Safety/ Security/Privacy	Ensure human-machine cooperation safety with cyber security and personal data privacy concerns in smart manufacturing systems.
Sustainability	Maintain the sustainable competitiveness of manufacturing processes and human capital management from a long-term perspective.
Socialization	Achieve the globalization and decentralization process with extended resource sharing, improved value creation, and enhanced user participation.

5. Features and characteristics of HCPS

5.1. Connectivity and standardization

- The connectivity and standardization aspects in HCPS do not solely rely on human contributions but rather, augment human-centric capabilities through capabilities such as visual sensing, communication and inference, big data analytics, and state influencing interactions.
- With smart factories being progressively viewed as a network of cooperative agents to perform both physical and cognitive tasks, the fundamentals of these systems include goal-orientation, control, and co-agency to facilitate human-machine teamwork [123,124].

5. Features and characteristics of HCPS

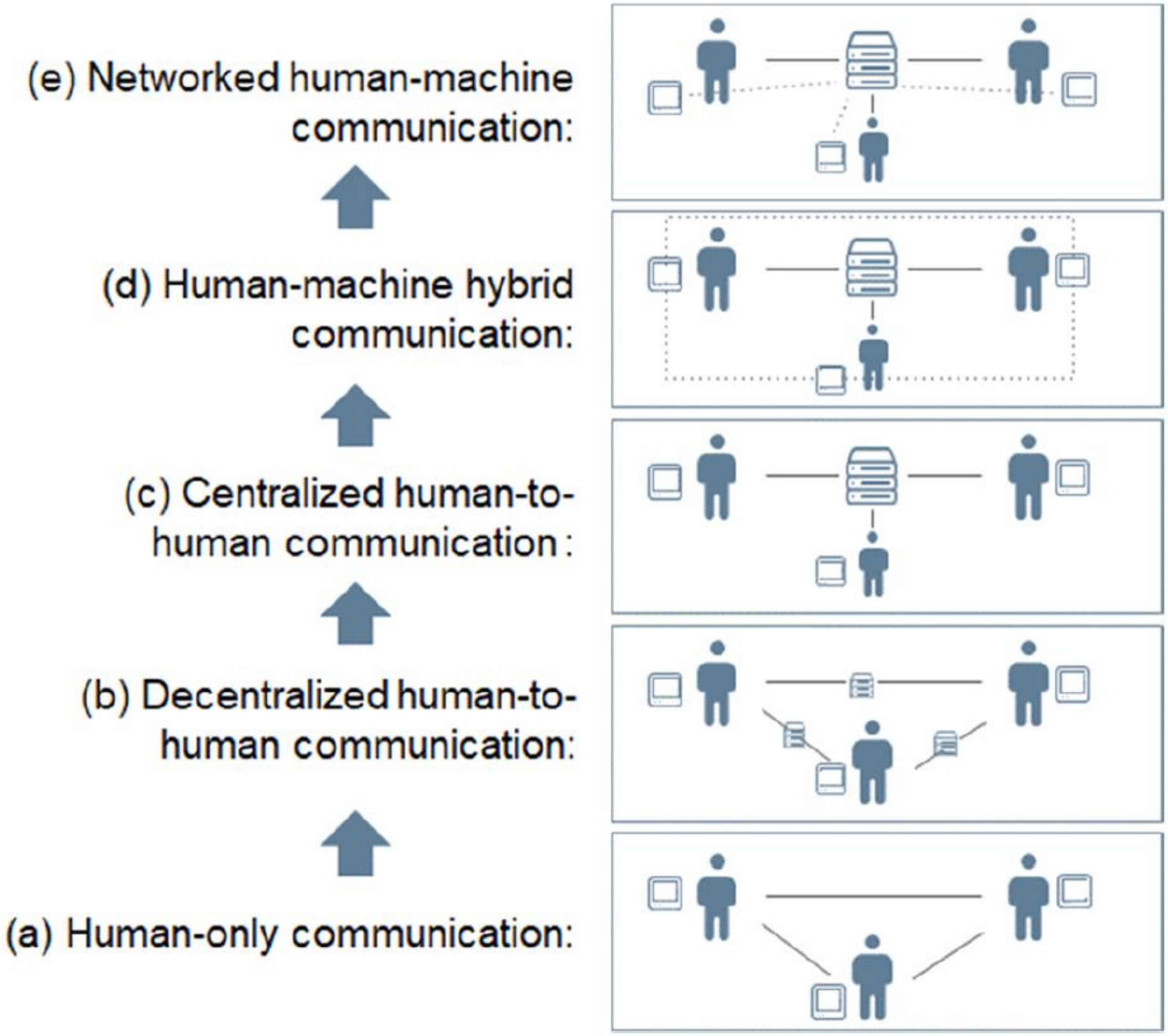


Fig. 8. Types of HCPS communications (derived from [12]).

5. Features and characteristics of HCPS

5.2. Integration and interoperability

- Integration and interoperability of HCPS have been highlighted through the 5C methodology [125]. From the aspects of connection, communication, collaboration, etc., the role of integration serves to link sub-systems to function as a single entity.
- Interoperability within HCPS would enable multiple human-machine entities to understand each other, thus utilizing the other system's functionality.
- As such, establishing integrated and interoperable frameworks based on smart factory scenarios would allow collaborative work and cooperative goals attained.

5. Features and characteristics of HCPS

5.2. Integration and interoperability

- Using the 5C methodology, horizontal, vertical, and end-to-end integrations provide alternative structures for inter- and intra-enterprise collaborations as well as a cyber-physical data network system.
- Besides these points, integration of Industry 4.0 technologies within existing factory setups must consider negotiation and convergence mechanisms to ensure smooth coordination of tasks, human safety, system security, personal privacy, heterogeneous data management, complex process planning, and decision support approaches [129–131].

5. Features and characteristics of HCPS

5.3. Data-driven features

- For HCPS in smart manufacturing, massive human-generated data and product-sensed data containing valuable information and knowledge should be examined in a data-driven manner, including data collection, information retrieval, and knowledge generation as the core aspects from every aspect of the product lifecycle engineering process [132].
- Following that, storage and retrieval linking to the use of data lakes, graph databases, and cloud platforms are discussed to facilitate ease of data access, while data filtering and cleaning techniques serve to ensure that only appropriate information is passed on.

5. Features and characteristics of HCPS

5.3. Data-driven features

- The data-information-knowledge-wisdom (DIKW) hierarchy, as a typical knowledge management structure, can be utilized within smart manufacturing domains to support the data-driven and knowledge-intensive decision making [133].
- Moreover, to overcome challenges such as data duplication, iterations, applications involving big data analytics and production processes, and business model integration, data structures can be referenced from digital twin systems, to form a viable approach for managing these complex HCPS structures to improve their efficiency [55].

5. Features and characteristics of HCPS

5.4. Intelligence

Intelligence is another key feature of the integrated HCPS system, which can be further regarded as human intelligence, machine intelligence, and collaborative intelligence.

5.4.1. Human intelligence

- The meaning of human intelligence is the ability of human beings to learn and understand the knowledge as well as to have the techniques and skills, to manage and manipulate related domain process/system and process parameters/activities innovatively and creatively to realize the goals of an enterprise or systems and to make them successful.
- In the book “Human-Intelligence-Based Manufacturing”, Yoshimi [135] proposed the concept of anthropocentric intelligence-based and thought model-based manufacturing. Martensson et al. [136] investigated the human-centric

5. Features and characteristics of HCPS

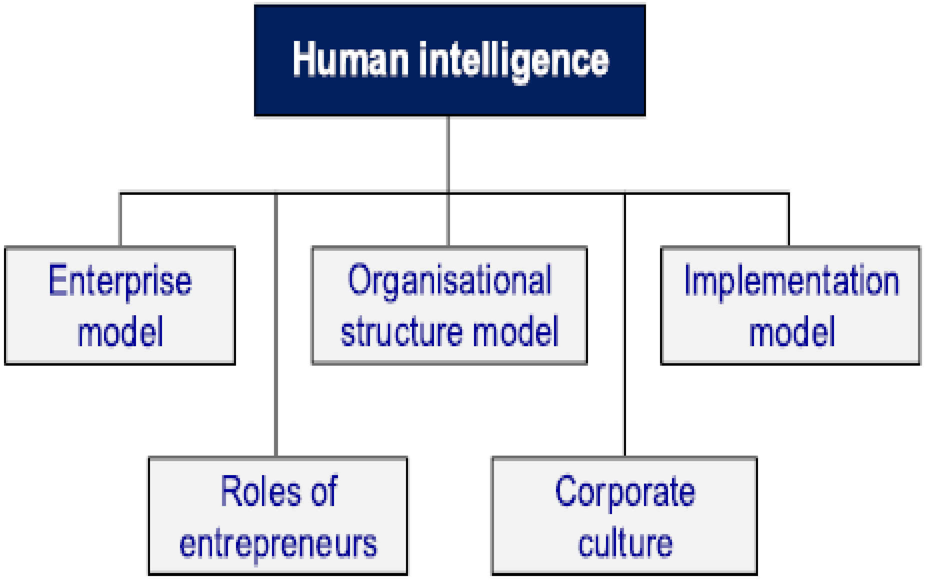


Fig. 9. Research framework on human intelligence [134].

5. Features and characteristics of HCPS

5.4.2. Machine intelligence

- AI innovation has flourished in advanced manufacturing in many scenarios [137].
- Deep learning allows for: machines to learn, facial recognition for biometric mapping [138], process automation for productivity and safety [139], big data analytics for knowledge generation [140], chatbots for zero human intervention services [141], and cloud and quantum computing to aid ease and efficiency of data access and other computational processes [142].

5. Features and characteristics of HCPS

5.4.2. Machine intelligence

- Meanwhile, empowered by cutting-edge cognitive computing, many efforts have been done to bridge the gap between human intelligence and machine intelligence in the HCPS with cognitive intelligence capabilities [74].

- Techniques, such as visual reasoning [14] and knowledge graph and graph embedding [72], allow machines to emulate the human brain's reasoning process, so as to timely and correctly understand, interpret, and respond to humans' behaviors and instructions in a natural manner [73].

5. Features and characteristics of HCPS

5.4.3. Collaborative intelligence (CI)

- According to a survey of Harvard Business Review, “Humans and AI are joining forces” [143], CI is based on Humans-Assisting-Machines (train, explain, sustain) and Machines-Assisting-Humans (amplify, interact, embody) primitives.
- In the former case, humans need to apply competencies not just related to teaching machines what to do in certain situations (train, e.g., setting thresholds), but also to explain how such decisions are taken (explain, e.g., risk analysis, fault trees) and to be able to defend such decisions against objections (sustain, e.g., by simulations and forecasts).
- In the latter case, amplify-interact-embody must be modelled and implemented in such a configurable and self-adaptable way, so that humans are empowered to interact with work objects using a machine or a robot as the third arm.
- In turn, machines can constantly consider train-explain-sustain in an ever-ending loop towards human-machine collaboration.

5. Features and characteristics of HCPS

5.4.3. Collaborative intelligence (CI)

- The role of CI within HCPS includes the use of human-system integration, whereby the gaps linking human interactions and shop floor assets are examined to ensure a safe working environment with high output consistency and efficiency [144].
- Human factors are core attributes in which control overrides, risk of human error, responsibility and supervision, and level of required automation will determine the right role for automatic machining processes within smart factories. .
- Reasoning frameworks, causal modelling, and knowledge generation play a key role to support human-in-the-loop approaches through machine training or learning, inference, and cross-domain processes.
- Ultimately, hybrid intelligence has the potential to reconfigure both assets and processes and facilitate different stakeholders for the value co-creation process through digital servitization paradigms [146,147].

5. Features and characteristics of HCPS

5.5. Automation and autonomy

- Human-centric automation [148] is a design practice of HCPS that aims to ensure that the automation designers allocate to humans the tasks best suited to humans as well as facilitate the human-system cooperation in complex systems.
- There are different forms of automation and autonomy depending on how humans and machines work together, such as human-oriented collaboration, machine-oriented collaboration, and human-machine collaboration [43].

5. Features and characteristics of HCPS

5.6. Resilience/adaptation

- The feature of resilience and adaptation means the HCPS can leverage the cognitive function of humans and utilize the cyber-physical elements to recover from the disturbance and exception and maintain a stable and robust state.
- As shown in Table 4, human operators can actively change their roles in the HCPS from outside the control loop to within it, to have more interaction and take charge of the control capacity within the system [149].
- In this case, human reliability should be assured to make the resilience and adaptation towards the positive side rather than the negative side. A dissonance control was discussed for human reliability regarding dissonance-oriented stability analysis, identification, and control [32].

5. Features and characteristics of HCPS

Table 4
Adaptation in HCPS [149].

Adaptation type	Triggering criteria	Desired outcome	Refs.
Task re-allocation from human to machine	Human cognitive load exceeds the threshold; accumulated fatigue; human error rate increases	Human cognitive load is managed in a normal range	[151]
Task re-allocation from machine to human	Unknown situation by CPS; CPS request; CPS malfunction	Superior settlement of unexpected disturbances	[151]
Machine adopts to human	Variances of human preference and information query mechanism	Improved information delivery of S/N ratio to human particularly with increased time stress over time	[152]
Human adapts to machine	Request of machine control change; context variation causes control transfer	Enhanced capacity to tackle with operational activities and statuses	[153]

5. Features and characteristics of HCPS

5.6. Resilience/adaptation

- The sensing and perception technologies can improve the context-awareness of the whole system, the AI-based data analytics can provide the system with valuable information and reference based on the sensed context data, which can further trigger some control and adjustment with some pre-defined rules or knowledge [150].

5. Features and characteristics of HCPS

5.7. Customization/personalization

- With the ubiquitous utilization of cyber technologies and the consideration of the human-centric aspect, manufacturing is shifting from mass production towards personalization [154,155], which is one of the core characteristics of HCPS.
- Based on the human-in-the-loop interaction with products, the product-related data, as well as the user-generated data can be collected for generating and updating the product design tailored to the customers’ demands and preferences.
- It is promising to involve humans as users in the design procedure with the open architecture [156], as well as the interactive and immersive development mode enabled by the digital twin [157], virtual reality [158], augmented reality [159], etc., which benefits to maximize the participation of humans who desire to perform imagination and innovative design and allow designers truly to be aware of consumers’ expectations.

5. Features and characteristics of HCPS

5.7. Customization/personalization

- In addition to the design phase, personalization also appears in other lifecycle phases in the context of HCPS, such as manufacturing, usage, maintenance, recycling, etc.
- The production line can be reconfigured to adapt to the production order [160], while product-service during the operation can be adjusted and customized according to users' uniqueness and preference [161].
- Moreover, different strategies for maintenance and recycling can be derived from the historical experience and evolved with the accumulated data and knowledge [162].

5. Features and characteristics of HCPS

5.8. Safety, security, and privacy

- Safety, security, and privacy are also important features of HCPS, varying from human operation safety to cyber security and data privacy, etc.
- On human safety, human operators are still needed in some scenarios to perform tasks. Thus how to secure their safety and avoid any accident remains a considerable problem. For example, in the human-robot collaboration, human operators often need to collaborate with the robots to execute the assembly tasks [163].
- In this case, human operators may be in touch with the robots, causing a collision, physical injury, even disability. There have been some approaches to mitigating this concern, such as lowering the speed of robots based on linear or nonlinear estimation [164] and computer vision-based approach [165] to detecting a collision.

5. Features and characteristics of HCPS

5.8. Safety, security, and privacy

- On cyber security, there are many potential attacks existing in the HCPS, since HCPS embraces various cyber technologies that produce, transmit, and process a large amount of security- and privacy-sensitive data in manufacturing systems [166].
- The physical components are driven by electronics that are controlled by software via networking. During this process, the electronics are the appealing targets for invasive hardware attacks, side-channel attacks, etc. [167].
- Software suffers from runtime attacks, malicious programs, viruses, etc. [168]. Communication protocols are susceptible to protocol manipulation [169].
- Even human operators involved in the manufacturing systems can be exposed to phishing and social attacks [170].

5. Features and characteristics of HCPS

5.8. Safety, security, and privacy

- With the increasing connections and interactions among devices, humans, industrial systems, etc., data privacy has become a critical issue for protecting enterprise interests, particularly in the current prevailing big data and cloud-based environment [171,172].
- To make sure the privacy-preserving data is safe, various methods have been developed. For example, hybrid execution mode utilizes the public cloud to process the non-sensitive data while the data with confidentiality and privacy is computed with the private cloud [173].
- Similarly, federated learning conducts data analytics with decentralized raw data stored and preserved in the local servers to minimize the risk of data leakage [174].
- Specific description formats for manufacturing services requests and delivery can be designed to well safeguard intellectual property [175].
- Besides, data encryption and identification methods can be developed to secure individual privacy and ethics, such as de-identification policies [176], blockchain [177], homomorphic encryption [178], etc.

5. Features and characteristics of HCPS

5.9. Sustainability

- Sustainability is an essential feature of HCPS, which is not just about what is produced aiming at the market and customers but how the procedure is performed to gain sustainable competitiveness [179].
- One objective of sustainability is focused on the elements contributed to manufacturing. For example, due to the continuously increasing energy price, the expenditure on energy consumption and raw materials takes a great part of the production cost [180].
- The overall production cost would be reduced, and enterprises could obtain more profits when the sustainability criteria and strategies are introduced and followed in the manufacturing environment.
- Human capital sustainability is also needed to be considered since humans own massive knowledge and how stakeholders will leverage such knowledge will highly transform smart manufacturing [181].

5. Features and characteristics of HCPS

5.10. Socialization

- Socialization is another essential feature of HCPS, which emerges with extended resource sharing, improved value creation, and enhanced user participation assisted by the utilization of cyber technologies [181]. In terms of extended resource sharing, manufacturing, as a service-related industry, intends to make full use of available resources to balance the distributed manufacturing resources and prevent the insufficient resource usage ratio.
- The extended resource sharing happens within an enterprise, between diverse enterprises, and even among industries and across areas, achieved by adopting reconfigurable functionality [183], supply chain management [184], and product-service system [121], respectively.

5. Features and characteristics of HCPS

5.10. Socialization

- For the improved value creation, the value carrier changed from product-based to service-oriented and will contribute to social value creation. Besides, the measurement of value has been enriched with multi-criteria evaluation to make it more comprehensive for social activities and users [185,186].
- For the enhanced user participation, the role of users or consumers has been given more meanings and transformed to multiple identities from only to be users or consumers [155]. For example, with the appeared mass customization and personalization, users are not just buyers, but have opportunities to select expected products and interactions in the product design process.

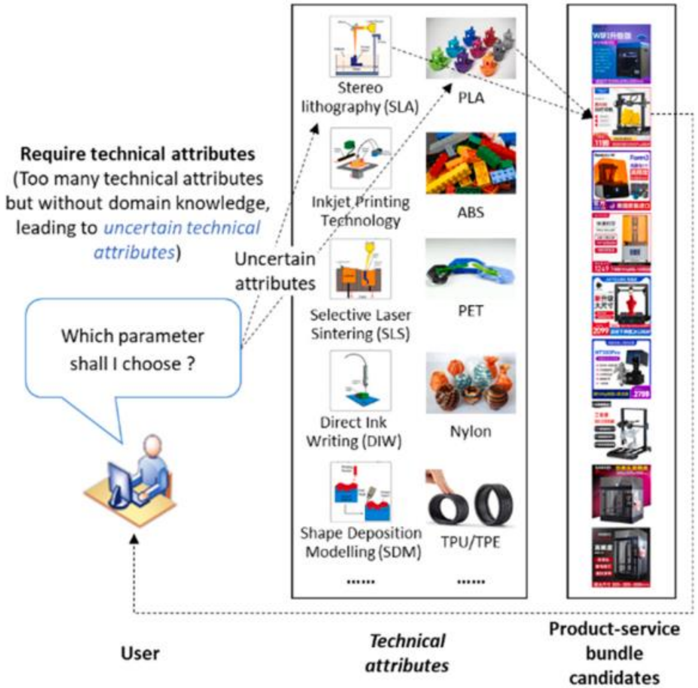
6. Representative examples

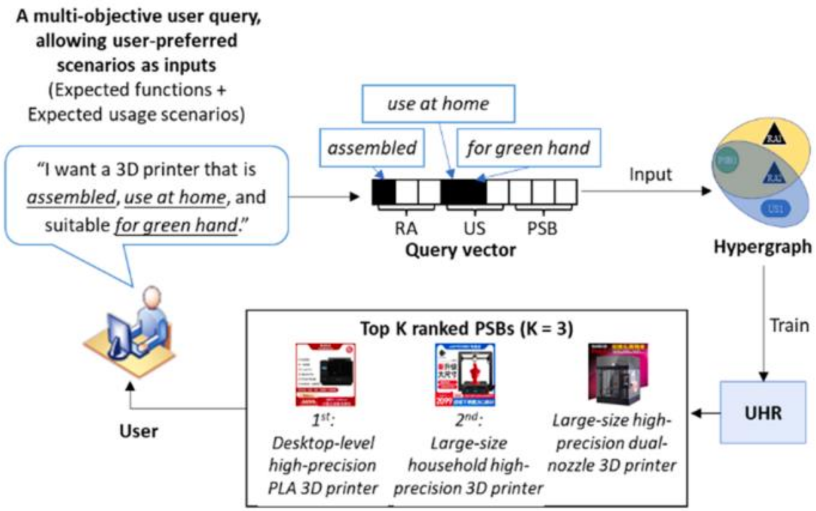
6.1. Human-centric smart product-service system design

- Smart product-service systems have attracted increasing attention recently in both academia and industry [121,161].
- By leveraging new IT and digital technologies, smart connected products, together with digitalized services have been shaping human-centric smart solution design towards mass personalization.

6. Representative examples

6.1. Human-centric smart product-service system design





6. Representative examples

6.1. Human-centric smart product-service system design

- Different from the conventional product-service system (PSS) configurators, the smart configurator allows user-preferred configurations expressed by natural language.
- Meanwhile, the platform system collects user's preferred requirement attributes (RA), their expected usage scenarios (US), and the other automatically collected USs information in the context, as raw inputs, to return a list of top product-service bundles regarding the ranking score to fulfill the user query.
- Moreover, the backend solution hypergraph can self-complement new solutions dynamically, to enable the close-loop design iterations.

6. Representative examples

6.1. Human-centric smart product-service system design

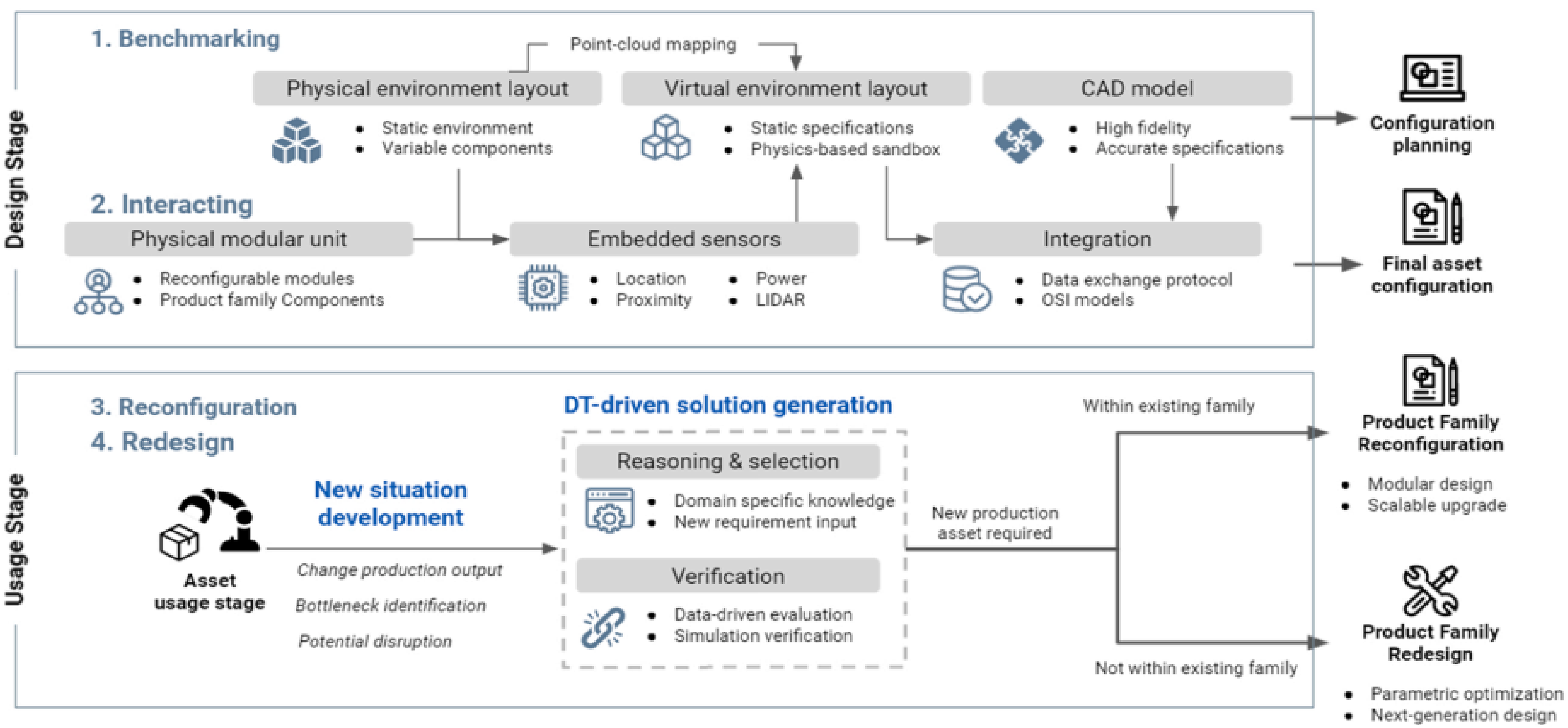


Fig. 11. Digital twin-enabled product family reconfiguration and redesign [157].

6. Representative examples

6.2. Intelligent human-robot collaboration

- In HCPS factories, complex manufacturing tasks require human and robotic agents' bidirectional engagement. The symbiotic HRC aims to achieve the best combination of human and robots' complementing competencies for flexible automation [188].
- A symbiotic HRC system possesses the skills and ability of perception, processing, reasoning, decision-making, adaptive execution, mutual support, and self-learning through real-time multimodal communication for context-awareness [13].

6. Representative examples

6.2. Intelligent human-robot collaboration

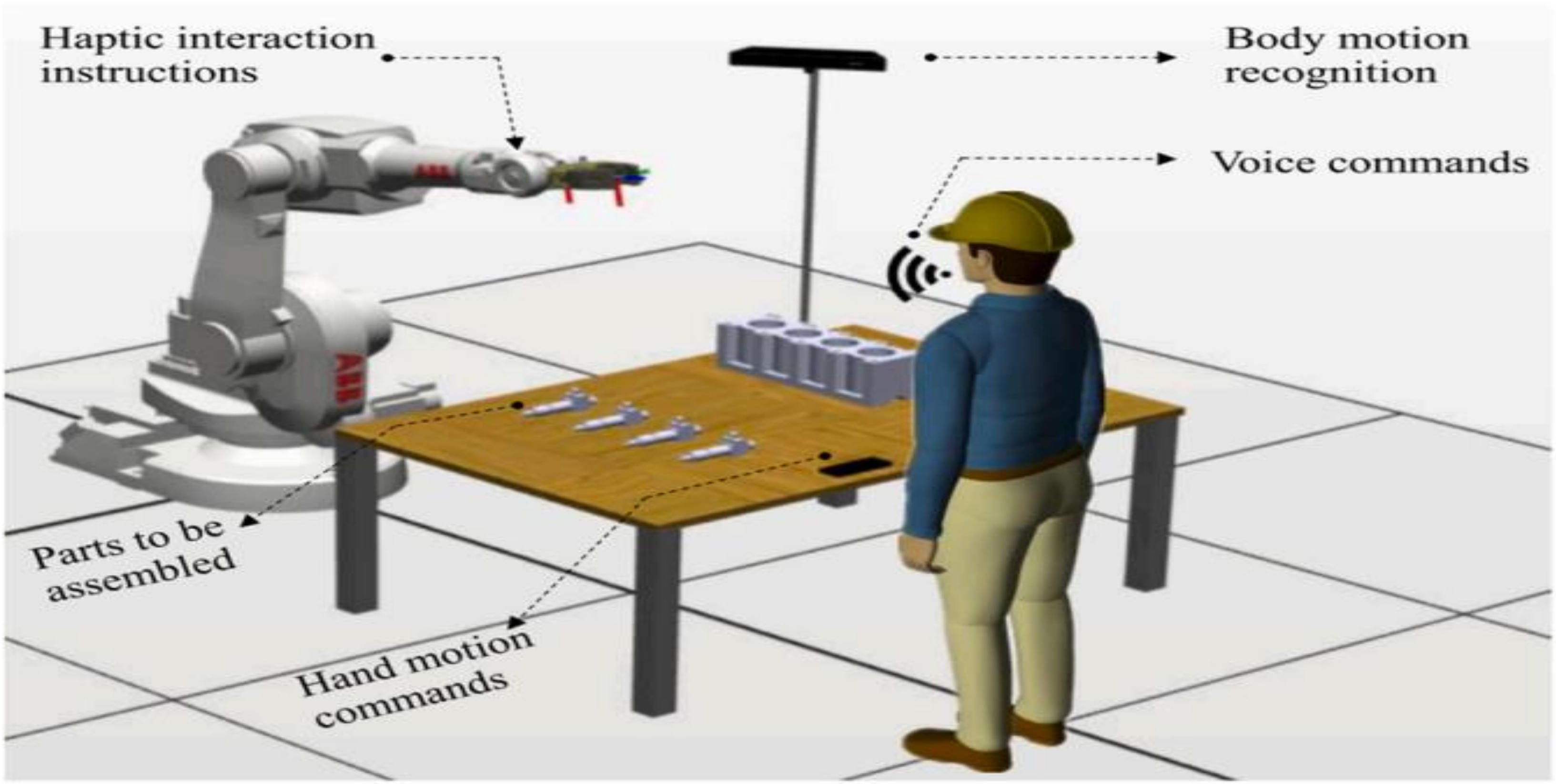


Fig. 12. Multimodal symbiotic human-robot collaboration [189].

6. Representative examples

6.2. Intelligent human-robot collaboration

- The symbiotic HRC opens the way to active collision avoidance, planning and control cockpit, adaptive robot control, and mobile operator assistance.
- Based on this definition, human and robotic agents form a society that is to solve complex manufacturing tasks which require the combination of their complementing competencies.
- To further improve the cognitive capabilities in HRC systems, a foreseeable cognitive manufacturing paradigm - Proactive HRC is rising, which aims to achieve “a self-organizing, bi-directional collaboration between human operators and robots in manufacturing activities, where they can proactively work for a common goal in every execution loop over time” [68].

6. Representative examples

6.2. Intelligent human-robot collaboration

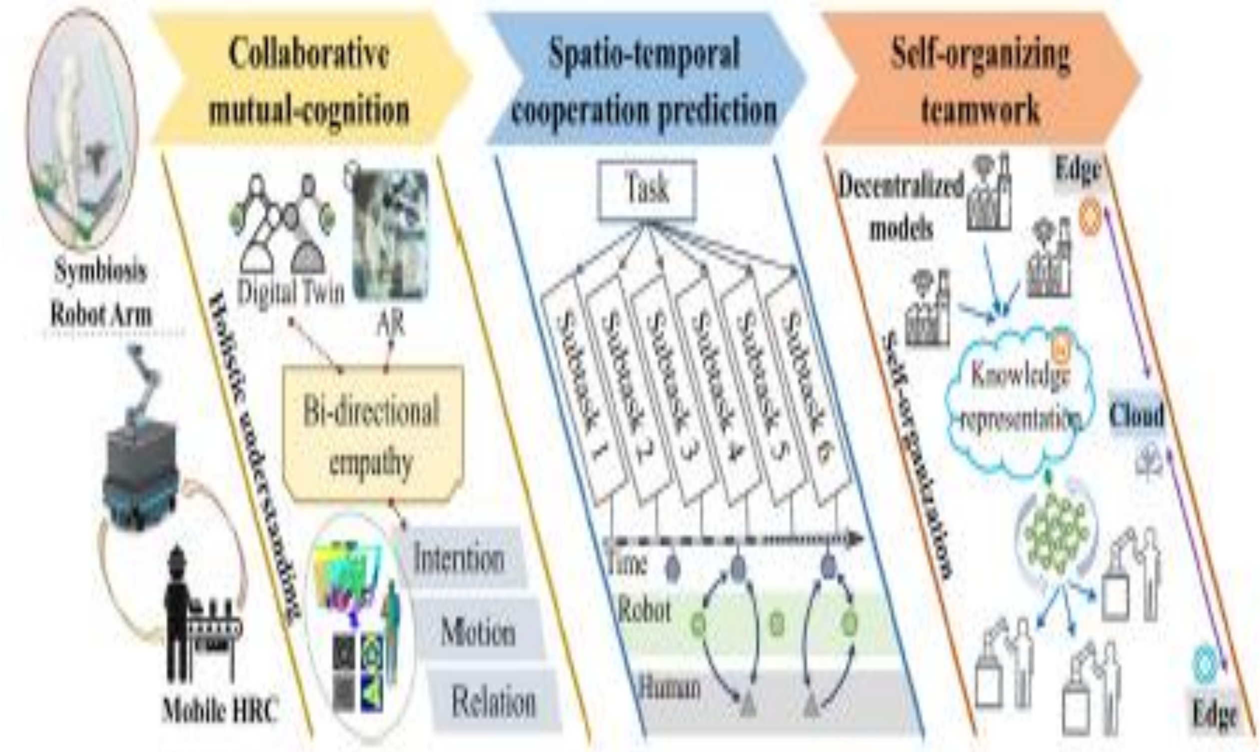


Fig. 13. Proactive human-robot collaboration [68].

6. Representative examples

6.3. Digitalized services for human well-bing

- In the mass personalization era, users' personal requirements can be directly transmitted to the production process via cloud computing and AM techniques. In this context, a cloud-based design and AM of custom orthoses, as shown in Fig. 14, has been studied [193].

6. Representative examples

6.3. Digitalized services for human well-bing

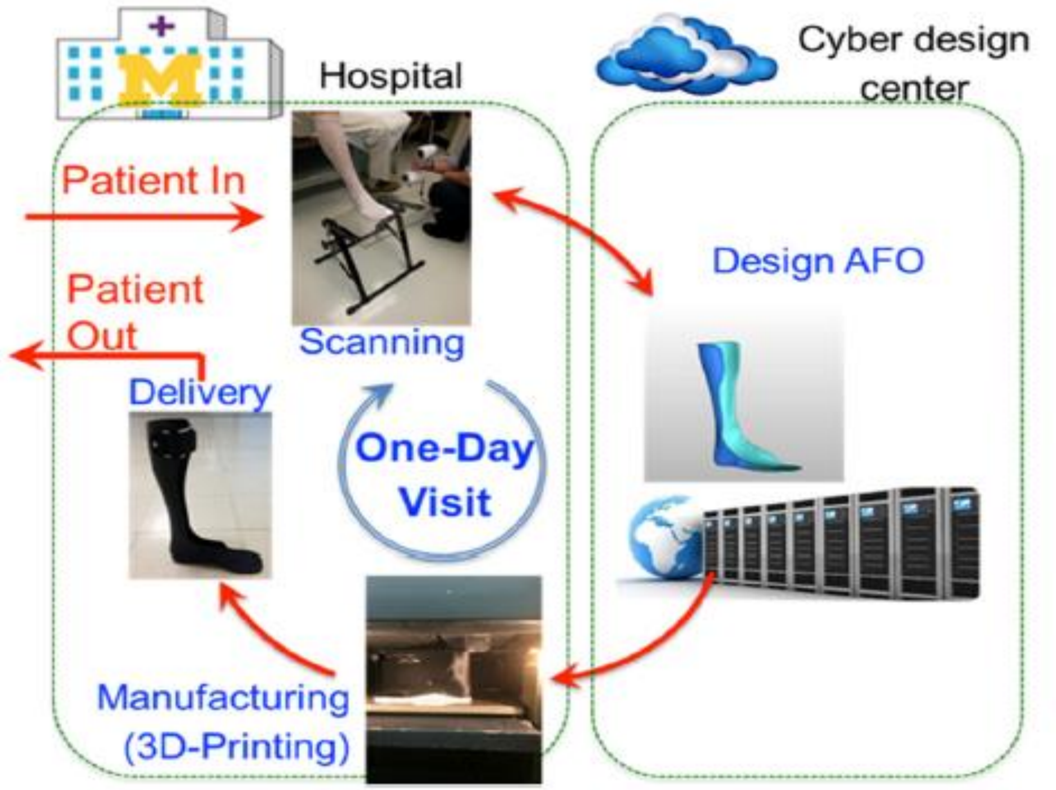


Fig. 14. Cloud-based personal servitization for custom ankle-foot orthoses [193].

6. Representative examples

6.3. Digitalized services for human well-bing

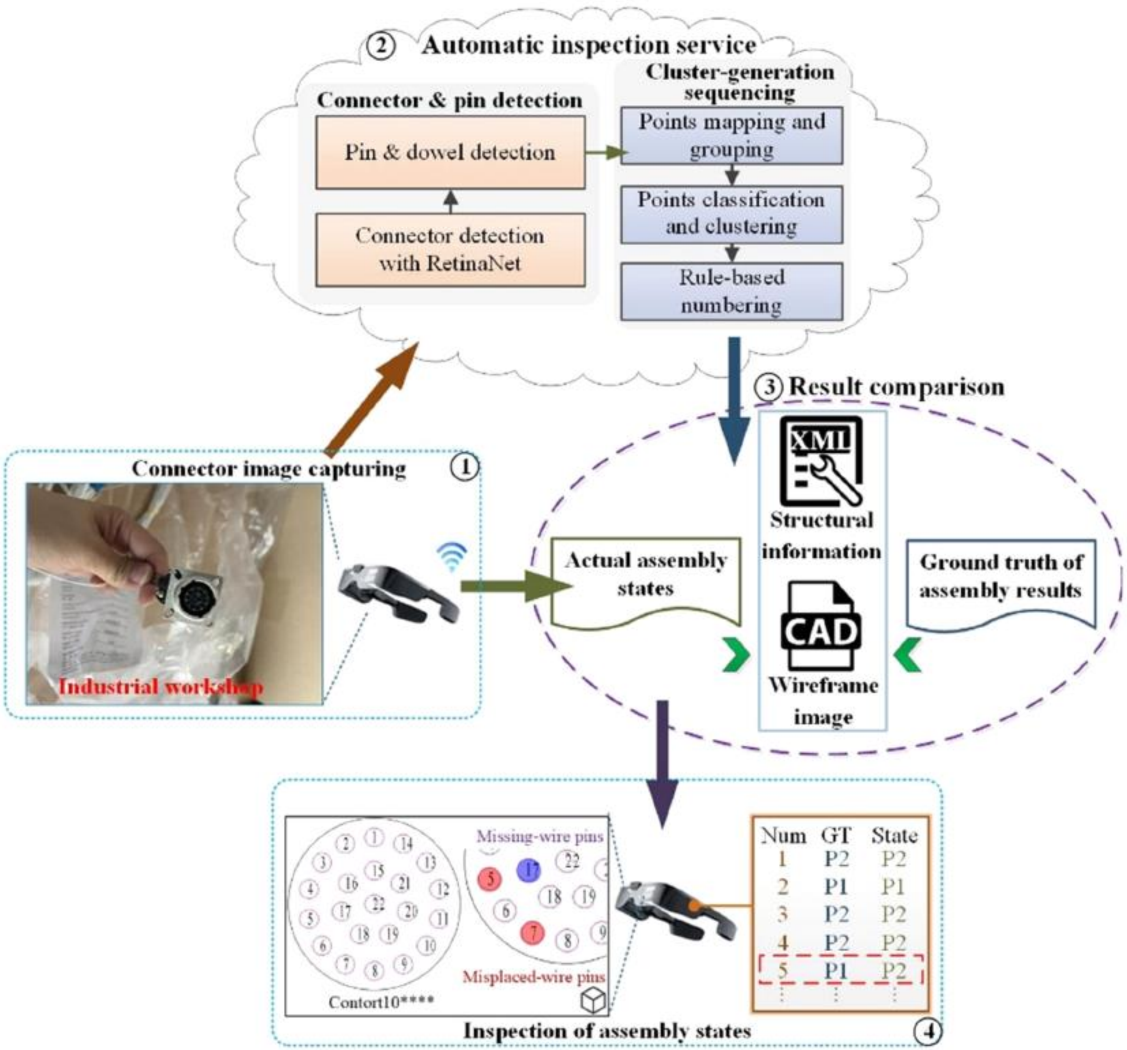


Fig. 15. AR-based manufacturing servitization for human-centric assembly [192].

7. Summary and Perspective

- In this work, the basic concepts, components, taxonomy, framework, and subsystems of HCPS were discussed comprehensively, to provide theoretical foundations and to promote the design, evaluation, and implementation for HSM.
- Meanwhile, the enabling technologies, including emerging domain technologies (e.g., additive printing, sustainable technologies), unit-level technologies (e.g., sensing, learning, control, human-machine interaction), and system-level technologies (e. g., cloud computing, system digital twin, Internet-of-X), were analyzed in detail.
- Ten core features and characteristics of HCPS were further introduced for realizing HSM, including connectivity, integration, adaptation, socialization, etc.
- Finally, typical applications of HCPS in human-centric design, production, and service are presented with linkage to its enabling technologies and core features/characteristics. Several promising future perspectives of HCPS-based HSM are highlighted as follows.
- Several promising future perspectives of HCPS-based HSM are highlighted as follows.

7. Summary and Perspective

- ***Humachine.***
  - To the best of our knowledge, the word “Humachine” was proposed firstly on the cover of a 1999 MIT Technology Review [194].
  - Recently, its connotation has been extended to enterprise level exploring combining human and machine virtues at the enterprise level an organization, company, or corporation [195].
  - In the context of HCPS, better process and mechanism designs of system elements (humans and CPS) are critical for the success of future Humachine, from the human-centric perspective rather than the techno-centric perspective.
- ***Human digital twin (HDT).***
  - HDT is one of the key issues for the successful implementation of HCPS and HSM.
  - Research and applications of HDT may be less than that on DT of machines and equipment
  - HDT could draw much more attention if one wants to design and implement manufacturing systems from the HCPS perspective.
  - Meanwhile, human physical twins (HPT) are a promising topic.

7. Summary and Perspective

- ***Mutual cognition for intuitive collaboration.***
  - Either existing HCPS systems or human-machine interactions are mostly conducted by following pre-defined instructions, thus far from an efficient cognitive integration of machine/robotic automation and human cognitions, especially when facing similar but new manufacturing tasks.
  - Empowered by cutting-edge cognitive science, XR, and cognitive computing techniques, mutual cognitive systems between humans and manufacturing things should be established to achieve intuitive collaboration with higher manufacturing efficiency
- ***Self-X capabilities for cognitive mass personalization.***
  - Today’s smart manufacturing systems lack sufficient flexible automation capabilities to achieve cognitive mass personalization [72,73].
  - To mind this gap, a Self-X cognitive manufacturing network should be established with human-in-the-loop consideration to achieve a higher level of automation, including *self configuration, self-optimization*, and *self-adjusting/adaptive/healing* capabilities.

7. Summary and Perspective

- ***Brain robotics***.
  - Brain robotics would be a central element in future HCPS-based manufacturing.
  - For example, in human-centric assembly, brainwaves are used to control robots that are effective in noisy factory environments and when operators are occupied with other tasks.
  - Signal processing, brainwave patterns classification, deep learning are necessary technologies for brain robotics.

7. Summary and Perspective

- ***Metaverse-based manufacturing (Meta-Mfg.)***.
  - In a metaverse framework, one can
  - 1) easily drag-and-drop your assets in a physics-based simulation safer and more efficient, without needing to perform significant physical testing
  - 2) ease the access for user-generated design on low-cost, easy-to-build products with more specific measurements and advanced CAD-like software
  - 3) undertake collaborative design and manufacture in an immersive manner with knowledge sharing
  - 4) reduce risk to quality control by more detailed, physics-based designs with lower return rates
  - 5) increase transparency for customers with improved visibility into the supply chain process with 3D representations, including how products are built, distributed, and sold.

7. Summary and Perspective

- ***X 5.0 (Industry 5.0 and Society 5.0)***.
  - In recent years, Industry 5.0, Society 5.0, Operator 5.0 are proposed, though Industry 4.0 and Operator 4.0 were just proposed years ago.
  - If CPS is recognized as the “operating system” or core technology for *X 4.0* (e.g., Industry 4.0, Engineering 4.0, Education 4.0), HCPS would be the theoretical foundation and HSM as the “operating system” for the upcoming *X 5.0* (e.g., Industry 5.0, Operator 5.0, Engineering 5.0, Education 5.0, and Society 5.0).

8. Opinion

- I found out that there are various roles and fields that humans have in the smart manufacturing process.
- It is important to devise a system with the ability to reduce errors, increase productivity and efficiency, and cope with provocation situations, including humans inside the system, such as hpcs, rather than just achieving full automation except humans.

Thank you

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Ubiquitous Computing & Security Laboratory