

## Review Article

# Anthropocentric Approach for Smart Assembly: Integration and Collaboration

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Recently, anthropocentric or human-centric approaches renewed its importance in smart manufacturing especially for assembly applications where human dexterity and informal knowledge are dispensable at present and in the near future. This paper analyzes the integration, design, and collaboration issues regarding anthropocentric researches in the past few years mainly in assembly domain. First of all, towards closed-loop system integration, the researches on integrating human in the cyber-physical system are elaborated and summarized. Then, human-centric designs (HCD) especially in shop-floor assembly field are analyzed. To emphasize human-robot hybrid assembly, several related issues including collaboration paradigm, task planning and assignment, interaction interfaces, and safety are discussed. At last, a survey on human cognitive and social limitation management is elaborated. Related research challenges and directions are discussed.

## 1. Introduction

In recent years, as innovations led to high usage of automation and information technologies in industries, from Industry 4.0, Smart Plant to “Dark Factory”, lots of people believed that there would be less humans involved in the manufacturing sectors in the future. Consequently, industrial researches mainly focused on the development of manufacturing system with enabling novel technologies, including Internet of Things, Big Data, Cyber-Physical Systems, Machine Learning, Additive Manufacturing, and Robotics [1]. To some extent, humans once as key elements in production system such as assembly lines are somehow neglected.

Apparently, industrial robots have made great progress in replacing repetitive, monotonous tasks including handling, sorting, and welding. However, with the applications and implementations of new manufacturing paradigms, many have realized that humans as key roles cannot be easily replaced by advanced technologies at least in the foreseeable future. Particularly in the field of assembly, a great amount of tasks are not simple routine work but subtle operations where

humans’ dexterity, informal expertise, and tacit knowledge are indispensable [2]. Furthermore, introducing novel technologies makes manufacturing system much more complicated. Therefore, highly skilled, well-trained people are more important to make systems sustainable and resilient [2].

Human roles in complex manufacturing system have not been a new issue since the introduction of automation [3]. The anthropocentric approach changes the question from how to replace humans to how to better complement and assist humans. In the European Factories of the Future Research Association (EFFRA) Roadmap 2020, human-centricity is prerequisite to cope with social challenges. Anthropocentric or human-centric (human-centered) approaches are getting more and more attention in the past few years [4–6]. Based on the academic publications, this paper focuses on the recent researches towards anthropocentric manufacturing approaches for smart assembly system including human-CPS integration, human-centric design, human-robot collaboration, and human limitations management.

The rest of the paper organized as follows: Section 2 discusses the integration of human in cyber-physical system.

The framework of human-in-the-loop CPS (HCPS) is presented. Section 3 reviews the human-centric design in the shop-floor level. In Section 4, human-robot collaboration in hybrid assembly is elaborated, and collaboration paradigms, task plan and assignment, immersed vision based interaction interfaces, and human safety issues are reviewed. Section 5 analyzes the human limitations towards manufacturing requirements in future generation. Section 6 discusses challenges and concludes the research.

## 2. Integrating Human in Cyber-Physical System

Cyber-physical system (CPS) is one of the most important enabling technologies in Industry 4.0 era. CPS is a closed-looped system which integrates dynamic physical processes with communication, controlling, computing, and other novel information technologies [7]. Despite different angles of definitions and interpretations, the core characteristics of CPS are the same, including the connection between cyber and physical world, real-time data exchange, and bidirectional information flows with closed loops [8]. In manufacturing domain, CPS are sometimes referred to CPPS (Cyber-Physical Production System) [9].

Generally, there are two major development routes of CPS [10], namely, “technocentric” and “anthropocentric” approaches. In “technocentric” route, manufacturing process is determined by enabling technologies of CPS, such as advanced robots and machine tools, Artificial Intelligence (AI), and Digital Twins (DW). Under this circumstance, the autonomy of skilled workers is limited. While in “anthropocentric” scenario, on the one hand, the skilled workers guide the implementation of CPS, on the other hand, CPS supports the decision-making process of skilled workers.

Introducing “anthropocentric” CPS in smart factories will result in mutual transitions from human-machine cooperation to active collaboration, which is characterized by cyber-physical-social interactions, knowledge exchange, and reciprocal learning [11]. Recent researches have renewed the focus on human either as an operator or supervisor in CPS related manufacturing. Human as a composite factor in the CPS defines a new type of CPS-based systems, either called Cyber-Physical-Human System (CPHS) [12], Anthropocentric Cyber-Physical System (ACPS) [13], or Human-Cyber-Physical-System (HCPS) [14]. In this article, the abbreviation of HCPS is preferred to symbol human as the center aspect in the CPS loop.

The HCPS can be characterized by the features as interoperability, sociability, flexibility, adaptability, autonomy, etc. [13]. In HCPS [14], intelligent machines are supposed to replace a great portion of human physical and mental tasks which makes humans more concentrated on creative work. From HPS (Human-Physical system), CPS to HCPS, humans transfer parts of cognitive and learning work to cyber system, which enable the cyber system with the ability to “cognize and learn”. With human-in-the-loop hybrid enhance intelligence, the capability of the manufacturing system to cope complex, uncertain problems will be essentially improved [14]. The framework of HCPS is presented in Figure 1.

From the perspective of anthropocentric approach, CPS may impact or improve the health, learning, and operative performance of human workers [15]. Integrating human in CPS framework will make manual operations more secure and efficient which will also enhance process control and improve quality especially in product assembly domain [16]. A framework called “CyFL-Matrix” which can help both industrial stakeholders and researchers to navigate the operational and social sustainability performance impacts of improvement projects towards HCPS is proposed in [15]. An adaptive human-centric reference architecture for automation system is proposed in [17], in which machines and automation systems adapt to the cognitive and physical demands of humans in a momentary and dynamic manner.

Anthropocentric CPS represents the trend of CPS both objectively and methodologically. However, compared to traditional manufacturing environments, the degree of complexity dramatically increases among all domains of HCPS [18]. For one thing, human behaviors are hard to be regulated and anticipated, causing disturbances and exceptions in the control loop, which further influence the stability and harmony of HCPS. To enhance the resilience of HCPS, these dissonance caused by human behaviors must be interpreted, modelled, and managed [19]. For another, human role in HCPS alters as application domain changes from design, operation, maintenance, and service. Therefore, from decisional level to operational level, or both, the corresponding reference framework should be established to model such variations.

## 3. Human-Centered Design for Shop-Floor Assembly

As briefed in the last section, the design of smart manufacturing system favored a technocentric approach which gave priority to the definition and allocation of tasks with automated system and computing resources, only taking human operators into consideration at the end of the design process [20]. This kind of design approach assumes human as “magic” who must behave perfectly when unexpected situations happened [21]. However, as the technological accidents are caused primarily by human errors (63%) [20], putting human in the control loop of smart manufacturing system implies human-centered design (HCD) framework and method to cope with more and more complex problems.

HCD approach is not only required in human-machine interactive interfaces but also in shop-floor level system design. Shop-floor assembly system design is usually required when a new manufacturing system is to be build or an existing one needs to be renewed. By placing the human in the center of the Industry 4.0 design [22], three perspectives (abstraction, decision-making, and innovativeness) as well as two components (human and CPS) constructed the analysis and design framework. Therefore, a set of key performance indicators (KPI) can be introduced to analyze and assess design scheme [22].

Taking workplace design for example, current shop-floor level industrial robots (machinery) applications separate the workplace of human and robots (machinery) cells due

to safety considerations. In human-centered mode, human operators and robots coexist in the same space to execute assembly tasks either individually or cooperatively [23]. Towards a fulfilled HCD of workplaces, not only the physical aspects but also the cognitive ergonomic aspects need to be considered during the design processes. Concerning the cognitive workload related to manufacturing operations at different decisional levels, in [24], a human-in-the-loop framework concerning the design of workplaces was proposed to classify the fabrication tasks of production processes according to their cognitive complexity. In the ergonomic analyses phase, unlike traditional methods, which only observe operators in the actual running workplace, the impact of design plans including human actions and reactions can be simulated and verified by immersed vision based approaches. To apply a HCD approach, the improvement of human posture, stress, and satisfaction is possible by assessing different setups in Mixed Reality (MR) environment [6]. Likewise, in the design phase, the concept virtual ergonomics [25] applied Digital Manufacturing (DM) tools with the ability to insert digital human models and other virtual resource models in the production plant. The above approach is able to simulate assembly tasks in workplaces, making human-centered design possible.

Note that HCD simply considers not only the human factor aspects such as workload, posture, and stress but also higher anthropocentric aspects such as human satisfaction [17] and emotion. Both human knowledge and cognitive limitations need to be represented, analyzed, and integrated in the design phase. Furthermore, HCD method should be considered through the life cycle of the system. As the Industry 4.0 solutions proposed by Bosch, the people including designers, workers, and users are the key roles in the connected plant supporting decisions based on contextual digital information, assistance functions, and ability amplifier for human operators as well as adaptive workplace ergonomics.

#### 4. Human-Robot Collaboration for Hybrid Assembly

Human-robot collaboration (HRC) concerning the interaction, communication, and collaboration between humans and robots received a lot of attention recently. The EU project ROBO-PARTNER has promoted a hybrid solution concerning the safe cooperation of human operators with autonomous and self-learning/adapting robotic systems [26]. HRC has a wide range of research topics such as safety, learning-by-demonstrations, imitation learning, and cognitive systems. This section focuses on the human-centered approach mainly for shop-floor level assembly, covering domains as human-robot collaboration paradigm, task planning and assignment, multimodal interaction interfaces, and interaction safety.

*4.1. The Evolution of Human-Robot Collaboration Paradigm.* Recently, researches have come to realize that the fusion of the robot's precision, repeatability, strength, and duration with human's dexterity, perception, intelligence, and flexibility

will promote the overall performances of assembly systems, especially in Small and Medium-sized Enterprises (SMEs), where the balance of productivity, flexibility, and adaptability are of high significance [27]. In this case, the hybrid assembly paradigm has risen as a feasible and effective paradigm for human-robot collaborations.

Generally, in hybrid assembly paradigm, manufacturing resources as humans, robots, sensors, and other devices share the same workspace. Based on the space and time perspectives [28]: the classification of human-robot collaboration can be categorized as in Figure 2.

*4.1.1. Humans Share Stationary Workplace with Robots but Their Activity Time Does Not Overlap.* For example, in [29], an interactive cooperation between human supervisor and the welding robot is presented. The human operator is responsible for teaching the robot by demonstration; the robot executes the welding process. Because the human operator and the robot share the same workplace in different time periods, the risk of human operator is minimized.

*4.1.2. Close Collaboration Where Humans and Robots Contacted Directly Both in a Shared Workspace and Time.* Traditional industrial robots (mostly multijoint robots) are not considered autonomous enough to allow close interaction with humans [23]. Recently, a new type of robots—cobots (from collaborative robots) is designed for collaboration with human operators which allow safely physical human-robot contact. Based on cobots, collaborative human-robot manufacturing framework for homokinetic joint assembly was presented in [30]. In the proposed approach, direct physical contact is successfully managed with sensor based control; the cobots can firstly lighten the burden of the operator and secondly comply his needs in the latter. A Portable Assembly Demonstration (PAD) system for robots to learn complex assembly skills from human was presented in [31]. The assembly script generated by PAD is implemented on a Baxter robot. Using a RGB-D camera, motions, tools, and parts in the assembly process can be recognized. Moreover, assembly states are estimated based on the 3D part models created by a 3D scanner.

*4.1.3. Humans and Robots (Mainly AGVs) Collaborate in a Dynamic Space and Time.* In this paradigm, humans are responsible for critical assembly tasks, while AGVs support the human operators with correct components and materials in the correct time. The human operators may move from one assembly station to another followed by AGVs with necessary resources. In some applications, AGV and multijoint cobot are integrated together not only for transportation but also for assisting human with picking or sorting abilities, which is very practical in large scale product assembly or system maintenance.

Although the introduction of cobots is anticipated as a promising approach to facilitate close human-robot collaboration, the cobot itself still has limitations. First of all, the workload of cobots is relatively low compared to typical industrial robots. Secondly, cobots' speed is controlled for

safety considerations which will decrease the efficiency of the operation. Last but not least, the working range and accuracy of cobots are insufficient for some application scenarios. For this reason, while the development of cobots highlights new compound materials, mechanical structures and heterogeneous sensors to improve accuracy, speed, workload, and intelligence, traditional robots and HRC paradigms are still required in various industrial application demands.

*4.2. Task Planning and Assignment.* In HRC, both human and robot can perform assembly tasks within their respective abilities. Consequently, task planning and assignment rises as an important issue for HRC process control. Proper task assignment plans will increase productivity, maximize system performance, and even minimize human operators' physical as well as cognitive workload at the same time.

A task can be decomposed into several subtasks in a hybrid assembly, then the subtasks will be assigned to humans or robots based on criteria concerning their different advantages. Based on dual Generalized Stochastic Petri Net (GSPN), the assembly task allocation process for human-robot coordinated cell manufacturing was modelled in [32], and Monte Carlo method and Cost-effectiveness analysis for Multiple-Objective Optimization are proposed for strategy generation and optimization. In [33], an intelligent decision-making algorithm was proposed which allows human-robot task allocation in the same workplace, where schedules are automatically generated and evaluated using multiple criteria.

The result assigned task needs to be automatically transformed into robots and human respectively. Towards seamless human-robot collaboration, a two-level hierarchical representation of the task is proposed in [34] which could be directly translated into robotic commands. The assignment results are correspondingly generated after assessment and evaluation in different application scenarios. Based on Robot Operating System (ROS) [35], the assembly sequence data exported from the Off-Line Programming (OLP) tools to a neutral XML format, graphical interfaces for human-robot tasks coordination is developed with the ability to review the previous and upcoming tasks.

Human factors (ergonomics) are closely relative issues which must be considered in task assignments. A multicriteria approach and algorithm are proposed in [27] to plan the human-robot hybrid cell layout and task in the same time. In a skill-based task assignment approach proposed in [28], with the assembly task description model, the skills of human and robots are compared according to the requirements. An integrated (feed-forward & feedback) optimum subtask allocation scheme is proposed in [36] for the assembly triggered by two-way trust (human's trust in robot and robot's trust in human). A set of ergonomics, quality, and productivity criteria is designed to choose the most suitable plans.

*4.3. Immersed Multimodal Interaction Interfaces.* Multimodal interaction interfaces including visual guidance [37], voice commands [38], and haptic and force control are popular research topics in HRC. Due to the unpredictability of human

behaviors, unified modal control framework is always needed to adapt signal alteration from heterogeneous sensor sources, such as vision, position, and force [39]. However, in actual assembly scenarios, environmental noises are always too big to distinguish the verbal commands by humans. While haptic and force control are more feasible, the reliability of actual usage is always worried by industrial users. In addition, haptic and force sensors and controllers are generally integrated in the product design of cobots in recent years. Therefore, in this sector, the immersed visual based interfaces including VR (Virtual Reality), AR (Augmented Reality), and wearable devices are highlighted.

VR and AR interactive technologies enable reproduction of the main characteristics of HRC, highlighting or even emphasizing particular aspects of the collaboration [30]. Especially, AR can provide digital information for increased situational awareness, emphasizing different objects, recommending optimized motions, and improving the trust and context-awareness of HRC [40, 41]. Also, AR can be used as an assistant to generate assembly sequence and visual instructions for each assembly steps; therefore, the burden of operators is alleviated [42].

In addition, wearable devices such as smart-watches can be developed as assistive means with AR applications in order to help operators provide feedback and interact with the AR system [43]. Also, with sensors and Apps in smart-phones, smart-watches, and other wearable devices, the position of humans' arms and legs is monitored in real-time. Therefore, the ergonomics effects are able to be evaluated and improved [44]. A human-robot interaction architecture for intuitive control of dual armed robot is proposed in [45]. The human body gesture can be recognized using Kinect Xbox and mapped to robot control command based on ROS. An AR tool is presented in [46] to support human operators in a shared assembly workplace. With immersion capabilities of AR technology, not only the assembly processes, status, and instructions are visualized, but also the operator's safety is enhanced. In [47], interactive assembly virtual environment based on physical models is developed, the results of assembly operations can be displayed in the form of 3D visualization, and human can correct the obvious errors by HRC mechanism to ensure the final assembly plan is feasible. An immersed VR environment for large parts assembly process assessment was built in [48] by recording and analyzing human's main movement with the help of Oculus and Kinect.

*4.4. Interaction Safety.* Safety is the most crucial issue when introducing robots to the shop-floor. In the traditional robot application scenarios, human and industrial robots are strictly separated with fences. However, accidents still happened due to misconduct or malfunction. While in HRC, the safety issues become more complicated, as the degree of complexity dramatically increases in the operation and maintenance domains [18].

To make HRC safety available, multiple sensors need to be integrated to avoid or prevent collisions either externally or internally. In external sensors based safety model, visual sensors and motion detectors are integrated into robots' control

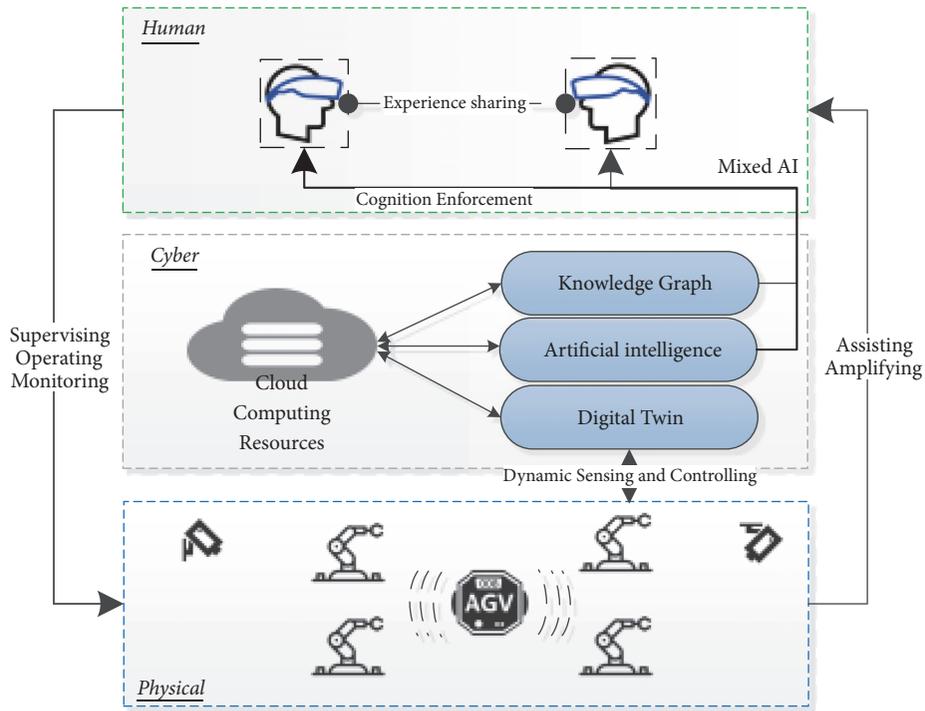


FIGURE 1: The framework of integrating human in the CPS loop.

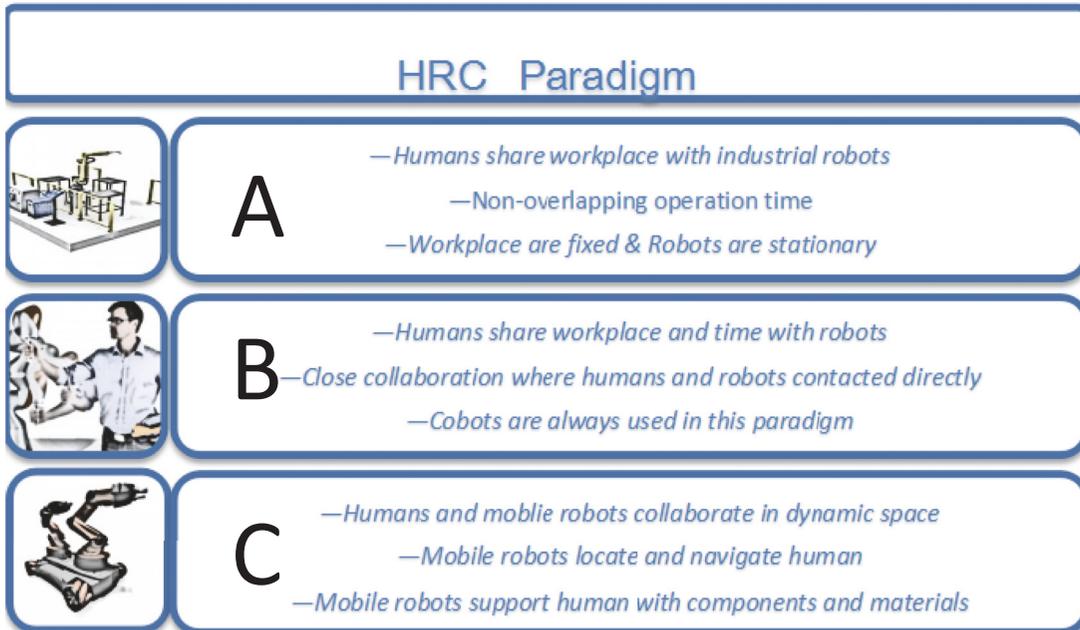


FIGURE 2: HRC paradigms.

system to avoid collision with human. Virtual 3D models of robots and real camera images of operators for real-time are used for collision avoidance in [37]. With the collision detection result, the robot can be adaptively controlled in human-robot assembly scenarios to keep human operator safe. A 3D ToF (Time of Flight) vision sensor to detect

potential risks of collisions is introduced in [49]. The safe detour trajectory will be automatically generated within one second during assembly process.

Although the external sensors based model has been proved effectively in many researches by demonstrations and experiments, the actual industrial implementations are

quite low. One of the reasons is this kind of safety cannot be completely trusted by human in the complex industrial application areas where even small chance of failures in sensors and control system may still cause serious damage to humans. Besides the external safety model, the internal safety will improve the safety level during HRC. The internal safety is implemented when the cobots are developed, as new kinematics, materials, and internal sensors are integrated in the cobots to avoid injury to humans. Safety cobots are already used in automobile assembly lines in several leading manufacturers [50]. Because the safety is the primary goal in cobots' design objectives, such safety is inherent and intrinsic, despite the sacrifices in workload, working radius, and speed.

In recent years, several standards regarding robot safety use are published by ISO, including ISO 10218, ISO/TS 15066. While ISO 10218 focuses on the standards for safety of industrial robots, ISO/TS 15066 provides guidelines for the design and implementation of a collaborative workspace. Note that the safety factors varies among different robot types, workloads, powers, geometric shapes, assembly processes, multiple aspects of safety which still need to be considered and analyzed.

## 5. Human Limitation Management

The anthropocentric approaches which put humans in the center also have its challenges. One of the reasons is that human has limitation comparing to robots and automation systems. Only by managing both technology and human limitations can the smart manufacturing system be reliable, flexible, and effective.

Human limitations are the main causes of human related errors and failures. Categorized from memory, perception to motion aspect of human, about 16 types of errors are proposed in [51]. In smart manufacturing environment, although many operations are executed automatically, human errors are still of great importance, especially omissions and the incorrect selection of variants. Human failure modes include misuse, false indication, and mode confusion [52]. Based on these modes, a CPS safety analysis and simulation platform called CP-SAP is developed and a cyber-physical human dynamic fault tree is designed in [52]. In order to access human errors, human errors probability (HEP) and human reliability probability (HRP) are proposed as indicators for the relative occurrence of errors and respectively faultless actions [51]. The definition of the above two concepts is as follows:

$$\begin{aligned} \text{HEP} &= \frac{\text{number of observed errors}}{\text{number of the possibilities for an error}} \\ &= \frac{n}{N}, \end{aligned} \quad (1)$$

$$\text{HRP} = 1 - \text{HEP}$$

From the ergonomic points of view, the limitations of human in the manufacturing system exist both physically and cognitively. For the past few years, as automatic machines and robots replaced lots of heavy work, the physical burdens of

human have dropped rapidly. However, the cognitive burdens are increasing because of the growing complexity of systems, ever-changing manufacturing requirements, and the frequent human-machine interactions. Stress is one major cognitive limitation. In HRC assembly paradigm, the moving industrial robots may induce stress on human operators. A framework to integrate human cognitive factors (fatigue, stress, skill level, emotional state, etc.) is proposed in [53]; the cognitive layer is presented enabling intelligent response to the changes from the data perceived from the environment. When coming near the robots, the stress of human operator rises, which can be measured by skin potential values [54]. Hence, the proper parameters and principles can be established for HRC.

Aging is another important issue regarding sustainable manufacturing. One of trends in Industry 4.0 or smart manufacturing is that fewer operators have to be employed in manufacturing shop-floors. However, skilled and experienced workers are always required in highly automation factories to manage and maintain the growing complexity of intelligent system. By the year 2025, it has been estimated that the proportion of working individuals over the age of 50 years will be 32% in Europe, 30% in North America, 21% in Asia, and 17% in Latin America. In 2050, around half of workers will be aged over 50 in developed countries [55]. Because of the decreasing physical and cognitive capacities of aging workers, including decrease of visual ability, acoustic ability, musculoskeletal force, and motion capabilities, the resilience to the job workload will reduce correspondingly. Therefore, the manufacturing framework must be adaptive to cope with the aging issue [55]. The adaptive manufacturing can compensate the aging limitations to guarantee job performances. Furthermore, the senior experts' knowledge and experience are needed to improve the learning curve of new operators [17].

Besides the general limitation management of human workers, here we argue that the human limitation should be modelled individually in the future research because each person has limitations in different aspects and degrees. The unique profile of each worker needs to be established by data mining or big data analysis. Such profile can be extracted as input to the anthropocentric manufacturing system, in which the configuration varies respectively for each person in each context. For example, when a left-handed operator is logging in, the information display and operation interfaces will correspondingly change for this new parameter to achieve better anthropocentric performances.

## 6. Discussion and Conclusion

The relation of human and technology in the manufacturing domain has been a concerning issue along with the pervasive applications of advanced automation and information technologies including robots, IoT, and AI. By analyzing the publications and latest research findings, we find that besides the advancement of technology, the "anthropocentric" approaches are attracting more and more attention in the past few years. Many have realized that human having a key role should not be replaced or weakened in

smart manufacturing or other new manufacturing paradigm, especially in assembly domain. However, that is not to say that the progress of technology implementations should be decelerated. On the contrary, the importance of novel technologies is more highlighted to better help and assist human.

In this paper, the origin of anthropocentric assembly method is discussed. Towards a closed-loop system, the human-centric CPS (HCPS) related researches are summarized. Human-centric designs (HCD) especially in shop-floor assembly field are analyzed. Aiming at human-robot hybrid assembly, several related issues including collaboration paradigm, task planning and assignment, interaction interfaces, and safety are highlighted. Finally, several aspects of human cognitive and social limitations are discussed.

In the future, regarding anthropocentric assembly, challenges still remained. First, current CPS frameworks are not adaptive enough to integrate human in the loop. New applicable HCPS architectures need to be researched based on the digitalization of human both physically and cognitively. Second, although human-robot hybrid assembly is an ongoing trend in industries, the intelligence and efficiency of cobots are not sufficient enough to support every application. Heterogeneous sensors and intelligent controllers, safe materials and structures, multimodel interfaces should be further researched to meet the requirements. Last but not least, considering physiological, emotional, cognitive, and social limitations, individualized human models and profiles are required to be interpreted and investigated to better adjust to different assembly applications.

## Conflicts of Interest

The authors declare no conflicts of interest.

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