Journal of Manufacturing Systems 76 (2024) 314–319

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Technical note

Industrial Metaverse: A proactive human-robot collaboration perspective

Shufei Li [a,d], Hai-Long Xie [b], Pai Zheng [a,*], Lihui Wang [c,*]

[a] Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region of China
[b] School of Design, South China University of Technology, China
[c] Department of Production Engineering, KTH Royal Institute of Technology, Sweden
[d] Centre for Advanced Robotics Technology Innovation, Nanyang Technological University, Singapore

ARTICLE INFO

Keywords:
Industrial Metaverse
Human–robot collaboration
Smart manufacturing
Human-centric manufacturing

ABSTRACT

Human-centricity, sustainability, and resilience are becoming core values in modern manufacturing, with human–robot collaboration (HRC) in high demand for flexible automation. However, human–robotic swarms are typically designed to target one specific procedure and cannot fully share their autonomy. The Metaverse, characterized by socialized avatars in a virtual-physical fused world, holds the promise of Proactive HRC. In line with this evolutionary roadmap, this paper presents a futuristic perspective on the industrial Metaverse for Proactive HRC and identifies its six embodiments. A representative universe that supports online and offline human users/operators in the design, machining, and maintenance of aeroengine turbine blades is introduced to spark and accelerate future implementation of the industrial Metaverse for Proactive HRC. The current challenges and future opportunities of this paradigm are also highlighted. It is hoped that this work can attract further investigation and discussions, providing useful insights to both academic and industrial practitioners in smart manufacturing.

1. Introduction

Today's manufacturing industry is undergoing a transformation towards human-centricity, sustainability, and resilience, driven by pressing challenges such as an aging workforce, labor shortages, complex production processes, and the demands of mass personalization [1]. Flexible automation, marked by digitalization, collaboration, and networking, is essential for the modern factory and is key to driving industry growth. The integration of human, machine, and robotic skills and intelligence offers a promising solution for creating such a human-centric smart manufacturing environment [2].

Numerous studies have been conducted in this area. To establish connections, Digital Twin (DT) technology is integrated into production lines and equipment to represent, simulate, and optimize the physical environment through real-time mapping [3]. Artificial Intelligence (AI) methods, including robot learning and the latest advancements in embodied AI, are enhancing manufacturing systems with proactive decision-making and human-like intelligent abilities [4]. For collaborative tasks, humans and high-payload industrial robots are placed in a shared workspace to perform manipulations while ensuring collision avoidance and human safety [5]. Lastly, interactive Mixed Reality (MR) systems are being developed to provide visualized feedback, including 360-degree video calls for remote presence of shop-floor environments [6]. This ongoing evolution is significantly impacting various manufacturing activities such as dis/assembly, welding, grinding, and drilling.

Nevertheless, how to extend the best complementing competencies and empathic collaboration skills [7] between human and robotic agents is what one should consider carefully and seriously. It is crucial to focus on placing humans at the center of production, providing opportunities for learning new skills, enhancing the perception of digital information, and taking on more challenging tasks that require problem-solving abilities. At the same time, improving the well-being and job satisfaction of human workers by creating more ergonomic, comfortable, safer, and attractive working conditions throughout the product lifecycle is essential. Additionally, robots should be promoted to competently perform dexterous, contact-rich operations with robustness and in a low-code manner.

The concept of the Metaverse [8] can contribute to these goals. The Metaverse prospect expedites a series of foundational technologies, like XR (Virtual Reality (VR), Augmented Reality (AR) and MR), AI, Computer Graphics (CG), Blockchain, robotics, 3D printing, edge computing, 5G even 6G network, etc, creating an expansive and immersive digital world where users can socialize, work, play, and engage in various activities through avatars [9]. Furthermore, the industrial Metaverse [10], as a specialized branch of the broader Metaverse concept, is emerging to create interactive digital environments that mirror

* Corresponding author.
E-mail addresses: pai.zheng@polyu.edu.hk (P. Zheng), lihuiw@kth.se (L. Wang).

https://doi.org/10.1016/j.jmsy.2024.08.003
Received 30 June 2024; Received in revised form 21 July 2024; Accepted 5 August 2024
Available online 14 August 2024

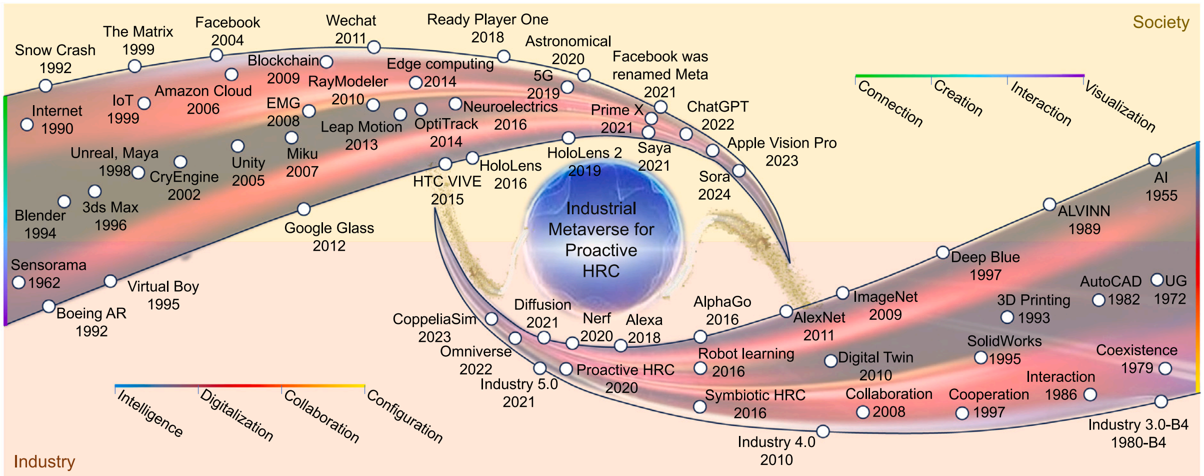

Fig. 1. Evolution towards industrial Metaverse for Proactive HRC.

physical industrial operations, allowing for proactive collaboration, simulation, and optimization of production processes. It may reshape the way products are designed, produced, delivered to customers, used and maintained, allowing people to intuitively experience the entire product lifecycle. Humans can fulfill dual roles: as societal users focusing on personal needs, and as industrial operators handling production tasks.

On this basis, it is essential to figure out (1) the evolution pathway of the industrial Metaverse in collaborative industrial processes, (2) its embodiment in future evolvement, and (3) representative examples in manufacturing environments. This paper shares the authors' view from the perspective of a proactive human–robot collaborative relationship, to advance its real-world implementation.

2. Evolution towards industrial metaverse for proactive HRC

The industrial Metaverse derives from revolutions in both societal and industrial sectors and evolves into a pursuit of Proactive Human-Robot Collaboration (Proactive HRC), as shown in Fig. 1. In society, the evolution of Metaverse is represented in levels of visualization, interaction, creation and connection. In industry, the transformation is reflected in aspects of intelligence, digitalization, collaboration, and configuration.

Dating back to the 1990s, numerous new terms and technologies began attracting attention, such as AR, 3D CG, Internet, and Metaverse, which was popularized by the science fiction novel "Snow Crash" [8]. AR was notably proposed by Boeing Corporation for industrial use during this period [11], later expanding into daily societal activities. Since then, various hardware innovations have transformed visualization and interaction modes between humans and the physical world, including Google Glass [12], OptiTrack,[1] HTC VIVE,[2] Neuroelectrics,[3] HoloLens,[4] and Apple Vision Pro.[5] Similarly, a plethora of software like 3ds Max,[6] Unity,[7] the recent ChatGPT[8] and Sora[9] have provided feasible solutions for the intuitive creation of virtual environments overlaid on the physical world. Additionally, evolving technologies such as the Internet-of-Things (IoT) [13] and Blockchain [14], along with enterprises like WeChat[10] and Facebook[11] (renamed Meta), are striving to build connections between humans and both the physical and virtual worlds.

In industry, since the introduction of diverse machines and robots, factories have been seeking new technologies to tackle production stress for new, variable products within a shorter time to market. AI algorithms have been adapted from societal applications to industrial uses for production planning, optimization, quality control, and maintenance. For example, recent developments in NeRF [15] and Diffusion models [16] are being utilized for dexterous robotic learning and control, enhancing industrial intelligence. Besides, digitalization has long been a goal in manufacturing, supported by numerous techniques like UG NX,[12] AutoCAD,[13] SolidWorks,[14] DT, Omniverse,[15] and CoppeliaSim,[16] all of which aid in developing virtual industrial simulation environments that map real-time data from physical factory settings. Accordingly, the evolution from human–robot coexistence, interaction, and cooperation to collaboration [17], alongside the progression from Industry 1.0 to Industry 4.0 and the emerging Industry 5.0 [18], is dedicated to creating a collaborative, configurable production system among multiple human–robotic agents in a physically and virtually fused world.

New technologies are emerging rapidly and seem to be converging towards the same goal. Both society and industry sectors are working towards creating *an intelligent world, where humans and robots can easily create, interact, collaborate, and configure within digitalized, visualized, and connected physical-virtual settings*—this is the essence of the Industrial Metaverse for Proactive Human-Robot Collaboration. This foreseeable paradigm radiates abundant benefits for both society and industry in turn.

3. A futuristic perspective on industrial metaverse for proactive HRC

Industrial Metaverse for Proactive HRC is essential to tackle several issues existing in conventional production approaches for complex,

1 https://optitrack.com.
2 https://www.vive.com/sea.
3 https://www.neuroelectrics.com.
4 https://www.microsoft.com/en/hololens.
5 https://www.apple.com/apple-vision-pro.
6 https://www.autodesk.com/products/3ds-max.
7 https://unity.com.
8 https://chatgpt.com.
9 https://openai.com/index/sora.
10 https://www.wechat.com.
11 https://www.facebook.com.
12 https://plm.sw.siemens.com/en-US/nx/manufacturing/cam-software.
13 https://www.autodesk.com/products/autocad.
14 https://www.solidworks.com.
15 https://developer.nvidia.com/omniverse.
16 https://www.coppeliarobotics.com.

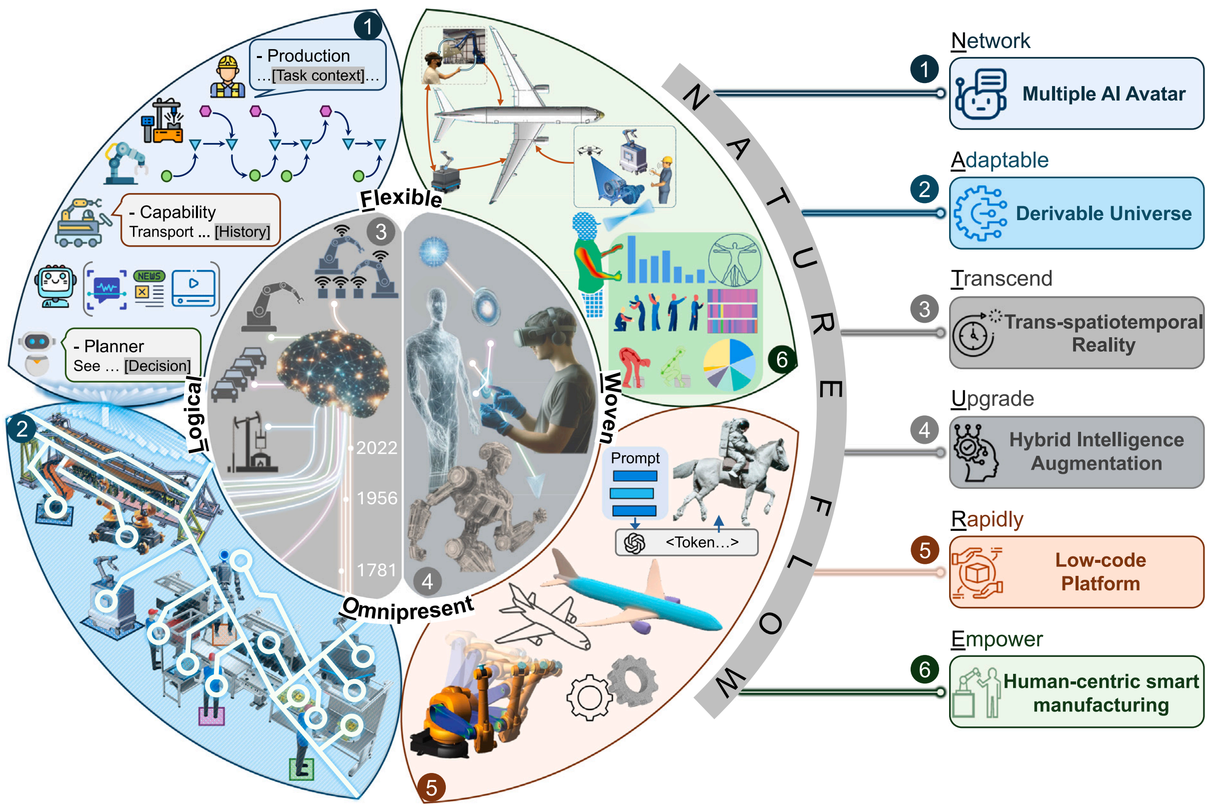

Fig. 2. Industrial Metaverse for Proactive human–robot collaboration.

personalized products, such as slow design iteration, inflexible manufacturing processes, limited distribution tracking, inadequate usage assistance, and inefficient maintenance throughout the product lifecycle. In this context, a futuristic perspective of this paradigm is illustrated in Fig. 2, containing six embodiments: multiple AI avatar, derivable universe, trans-spatiotemporal reality, hybrid intelligence augmentation, low-code creation platform, and human-centric smart manufacturing. These elements elaborate on NATURE features of the industrial Metaverse for Proactive HRC—network, adaptable, transcend, upgrade, rapidly, and empower—enabling core values of FLOW (flexible, logical, omnipresent, and woven relationships) among these components. Similarly to the "Nature Flow" in ecosystems, all elements including data, resources, and operations within the industrial metaverse move smoothly, interact efficiently, and integrate seamlessly for optimized productivity.

❶*Multiple AI Avatar*: Instead of humans being involved only when the virtual-physical world is connected and real-time feedback is possible, multiple AI avatars can act as high-fidelity digital humans, possessing the same level of knowledge and expertise as humans. Humans may be offline, but the Metaverse remains connected to the physical world. The avatars can represent humans to continue the work while the humans are taking breaks or sleeping. Especially with the latest Large Language Models (LLMs), online and offline AI avatars can perform diverse operational skills with various types of robots in cooperative manipulations, interactive tasks, and collaborative production activities, with an accurate understanding of vision, language, and multimodal communication information.

❷*Derivable Universe*: Existing digitized systems often lack the ability to quickly deploy to new scenarios. The derivable universe highlights the potential to spontaneously create multiple, unique, and specialized virtual worlds for diverse new physical environments. These worlds stem from a common underlying framework containing a shared, fundamental set of rules and principles, fostering customized experiences. A four-layer framework is proposed to implement this vision. Spatial intelligence at a high semantic level enhances the understanding of manipulation representations and geometrical relationships between virtual models and physical environments. Function blocks at a low control level provide modular automation for efficient process control and rapid deployment of new functionalities. Object-oriented programming promotes modularity, reusability, and maintainability of the codebase. Blockchain ensures secure, immutable data management and traceability.

❸*Trans-SpatioTemporal Reality*: Human is limited by individual domain knowledge in production. Trans-spatiotemporal reality allows users to access the wisdom of experts and great minds across different time periods and spatial locations as if they were experiencing it in real-time, so that the time scalability and space expandability become a reality in the Metaverse. To unlock this capability, shared industrial knowledge, resources, and production capabilities immersed in the Metaverse can be encoded and decoded by LLMs with vast 7B to 65B parameters. Meanwhile, Retrieval-Augmented Generation (RAG) and KG methods can structurally integrate and refine specific task knowledge for recommendation, enabling connected users to design, create, and interact with products with expert-level insights and skills.

❹*Hybrid Intelligence Augmentation*: Beyond integration, augmenting hybrid intelligence between human intelligence and AI is necessary for collaborative decisions in human–robotic swarms in production. This AI 2.0 paradigm aligns human–robotic behaviors across semantics (intention), knowledge (memory), action (consecutive movement), and mutual cognition (explanation). Integrating predicted production situations, humans can modify, correct, and constrain task goals while the robot verifies and fine-tunes manipulation with shared control autonomy to enhance bidirectional assistance — humans assisting robots and robots assisting humans — in collaborative tasks for optimized operation processes.

❺*Low-Code Platform*: Instead of writing detailed code requiring deep domain knowledge, humans in the industrial Metaverse can utilize graphical interfaces and end-to-end modules to deploy adaptive solutions for changing production needs, promoting rapid prototyping

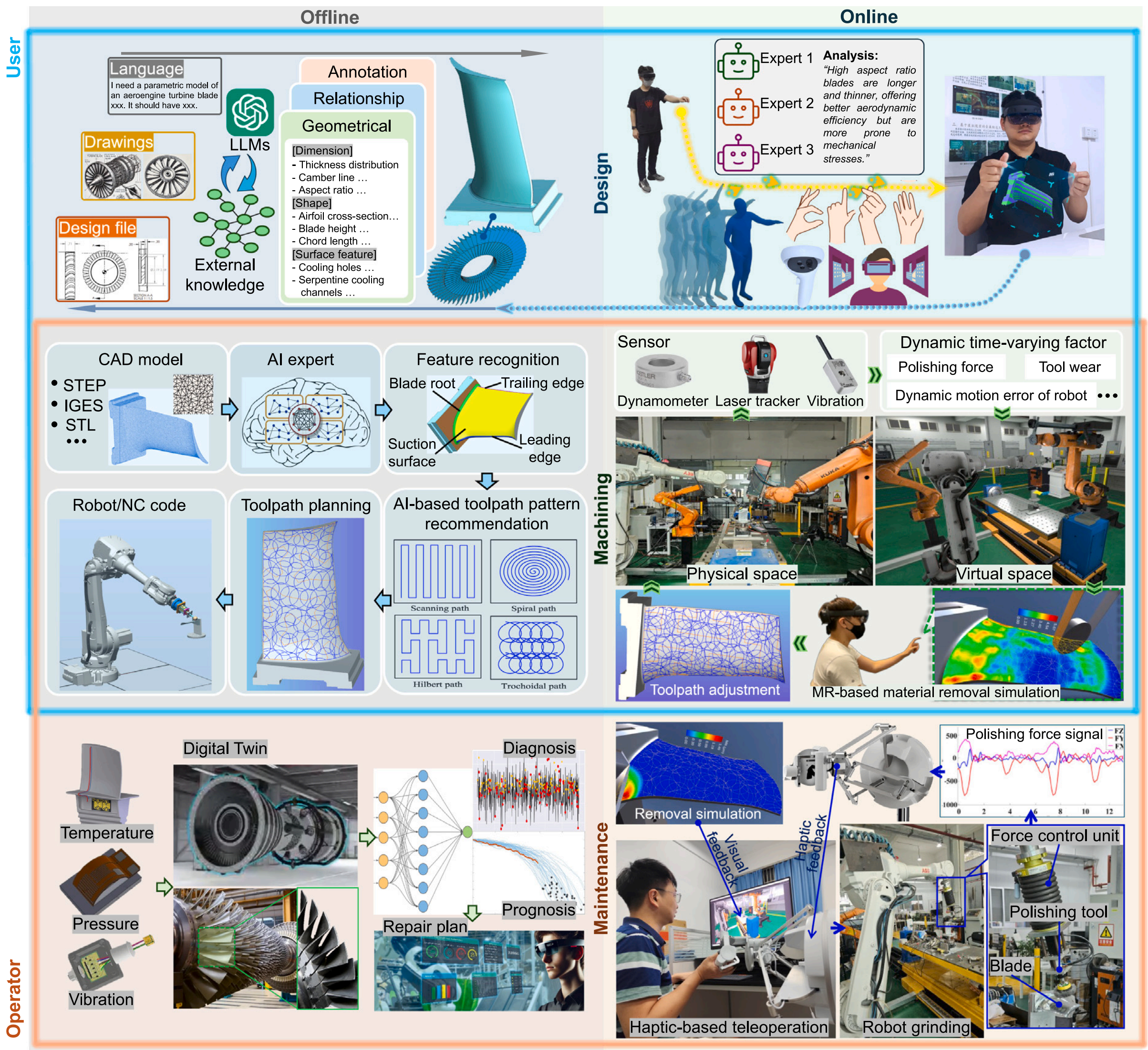

Fig. 3. Industrial Metaverse for manufacturing processes of aeroengine turbine blade.

of diverse mechanical products. As users, humans design parametric models of industrial parts with irregular shapes using AI-Generated Content (AIGC) technologies, such as Sora and GPT-4o, from prompts and CAD drawings. As operators, humans can transfer precise, dexterous manipulation skills to industrial robots through demonstration, teleoperation, language prompts, brainwaves, and physical interaction, facilitated by AI simulators like MuJoCo and Habitat, for seamless robot task scaling by simulating real-world conditions.

❻*Human-Centric Smart Manufacturing*: Modern factories are increasingly prioritizing human-centric principles in manufacturing activities, including dependence on human abilities (such as operation and cognition) for complex tasks and ensuring human well-being (considering ergonomic and cognitive factors) during long-term work. To achieve such a human-in-the-loop system, humans should intuitively access manufacturing resources, tasks, planning, operations, and onsite operation processes in a virtual-physical fused Metaverse, enabling them to interact and make real-time changes to real-world situations. Robots should proactively execute parallel tasks, sequential operations, and co-manipulation aligned with human intentions, functioning like extensions of the human body.

4. A representative example of human-robot symbiotic metaverse

The aeroengine turbine blade is a central mechanical component in the manufacturing industry, with strict requirements for design, machining, and maintenance processes. The industrial Metaverse for Proactive HRC can effectively manage the blade lifecycle, addressing urgent challenges of design variants, increased machining complexity, and high surface quality maintenance, as shown in Fig. 3. Humans serve as users during the design and machining phases and work as operators during the machining and maintenance phases. They can participate in these manufacturing activities both offline (through AI avatar interaction) and online (by proactively influencing the physical world).

Design: The design stage involves the creation, modification, and identification of parametric CAD models to meet diverse scenario needs. *Offline*, the description of a CAD model (language, drawings, or drafts) from a human avatar is parsed by LLMs integrated with external knowledge to identify key geometrical parameters, relationships, and designer insights. These parametric constraints are then delivered to parametric CAD software for 3D model generation. The avatar-guided generative design process represents trans-spatiotemporal reality. *Online*, human users make adjustments to the model via hand controllers, gestures, and interfaces, and see real-time updates in an immersive MR environment with recommendations from AI experts. Model refinement is synchronized back to the CAD software, regenerating the parametric constraints and reorganizing the human avatar description. Hybrid intelligence augmentation is integral to the interactive design process, after which the model is delivered to the factory for the forming process.

Machining: The machining stage focuses on the compliant polishing process, extensively used as the finishing process in blade shaping. This includes generating end-to-end robotic machining trajectories, adaptively adjusting machining parameters, and real-time simulation of material removal. *Offline*, the AI expert can customize the optimal toolpath (scanning, spiral, Hilbert, or trochoidal paths) for different machining features (blade root, leading edge, trailing edge, suction surface, etc.) identified from the CAD model. The toolpath is then translated into robot G-code in a low-programming manner to achieve high-precision and efficient polishing of the entire blade. *Online*, Metaverse simulations are shared among multiple experts in an immersive MR environment to evaluate the actual polishing effects (material removal distribution, residual height, surface roughness, etc.) by incorporating dynamic and time-varying factors from various sensors in the physical space during machining processes. Collaborative modification and optimization of the toolpath are then sent to the robot for closed-loop feedback control of the entire polishing process, representing hybrid intelligence augmentation.

Maintenance: The maintenance stage aims to repair surface wear through diagnosis, prognosis, and grinding processes. *Offline*, embedded sensors (e.g., temperature, pressure, vibration) on blades continuously collect data during usage to build the DT of the physical system following the derivable universe principle. Anomalies and current health status in diagnosis, remaining useful life, and potential failure timings (e.g., wear and tear) in prognosis are verified by an AI avatar to proactively aid in repair planning and training for maintenance technicians. *Online*, a haptic-based robot teleoperation system for blade repair grinding is developed to ensure profile accuracy after filling the worn and damaged areas with materials. Far from the hazardous machining environment, the operator can dynamically perceive the polishing force through a haptic device, observe the polishing effect while wearing an immersive MR helmet, and adaptively adjust key polishing parameters via shared human–robotic intelligence and skills, enhancing human-centric concerns.

5. Challenges and opportunities

The industrial Metaverse advances Proactive HRC [2] by integrating dual human roles as both societal users and industry operators within human–robotic swarms. Further exploration is needed in the area of smart manufacturing, as illustrated in Fig. 4. Humans can physically and virtually interact with equipment, production lines, factories, and the industry chain throughout the product lifecycle, including design, production, distribution, usage, and end-of-life stages. Challenges exist in modeling these scenarios, composite elements, collaboration mechanisms, and data aspects. Firstly, developing a dynamic evolution model that integrates humans, the physical world, and the virtual environment lacks feasible solutions, particularly when considering real-time updates of the entire scenario, predictions in product lifecycle management, and the symbiotic interplay between the industry system and end consumers. Then, the AI avatars of humans and robots in the Metaverse lack high-fidelity model representation and multimodal communication abilities across the hybrid physical-virtual world based on natural vision, language, tactile, and brainwave signals. Furthermore, the collaboration mechanism for human–robotic swarms requires more exploration to achieve mutual-cognitive, empathic, self-organizing teamwork and coevolution. Lastly, the vast data in the Metaverse faces difficulties in management, distribution, transmission, privacy, and visualization.

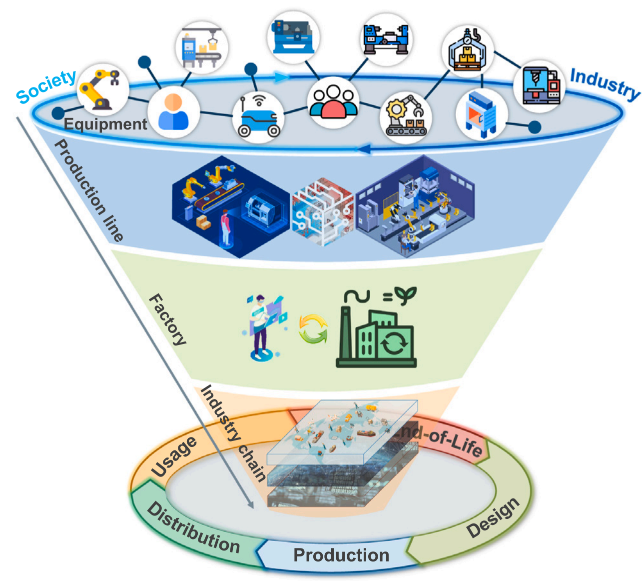

Fig. 4. Industrial Metaverse of Proactive HRC in smart manufacturing.

The futuristic perspective presented in this article envisions a "Nature Flow"—the six embodiments described in Section 3—highlighting a long-term pursuit to address these challenges. In addition to the features mentioned above, further exploration of technical, practical, and ethical theories is needed for real-world implementation. This includes developing evaluation indices for human well-being in the loop, balancing lightweight models and high-rendering visualization, mitigating the hallucination impact in LLMs, low-code programming from CAD to robot native control code, loud-based PLC (Programmable Logic Controller) for industrial control networks, and Blockchain-based communication and privacy protection. The industrial Metaverse can be widely applied, showing advantages in various tasks, such as human–robotic swarms for large aircraft assembly and companionship between astronauts and space robots. We hope our perspectives on the industrial Metaverse for Proactive HRC will inspire more insightful discussions, validations, and counterarguments on this topic.

CRediT authorship contribution statement

Shufei Li: Writing – original draft, Visualization, Resources, Methodology, Conceptualization. **Hai-Long Xie:** Writing – original draft, Visualization, Validation, Resources. **Pai Zheng:** Writing – review & editing, Validation, Supervision. **Lihui Wang:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work is partially supported by the General Research Fund (GRF) from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 15210222 and PolyU15206723), COMAC International Collaborative Research Project (COMAC-SFGS-2023-3148) and the PolyU-Rhein Koester Joint Laboratory on Smart Manufacturing (H-ZG6L).

References

[1] Wang L. A futuristic perspective on human-centric assembly. J Manuf Syst 2022;62:199–201.

[2] Li S, Zheng P, Liu S, Wang Z, Wang XV, Zheng L, Wang L. Proactive human–robot collaboration: Mutual-cognitive, predictable, and self-organising perspectives. Robot Comput-Integr Manuf 2023;81:102510.

[3] Tao F, Sun X, Cheng J, Zhu Y, Liu W, Wang Y, Xu H, Hu T, Liu X, Liu T, et al. makeTwin: A reference architecture for digital twin software platform. Chin J Aeronaut 2024;37(1):1–18.

[4] Li S, Zheng P, Pang S, Wang XV, Wang L. Self-organising multiple human–robot collaboration: A temporal subgraph reasoning-based method. J Manuf Syst 2023;68:304–12.

[5] Katsampiris-Salgado K, Haninger K, Gkrizis C, Dimitropoulos N, Krüger J, Michalos G, Makris S. Collision detection for collaborative assembly operations on high-payload robots. Robot Comput-Integr Manuf 2024;87:102708.

[6] Netland T, Stegmaier M, Primultini C, Maghazei O. Interactive mixed reality live streaming technology in manufacturing. Manuf Lett 2023;38:6–10.

[7] Li S, You Y, Zheng P, Wang XV, Wang L. Mutual-cognition for proactive human-robot collaboration: A mixed reality-enabled visual reasoning-based method. IISE Trans 2024;(just-accepted):1–17.

[8] Stephenson N. Snow crash. Penguin UK; 1994.

[9] Mourtzis D, Panopoulos N, Angelopoulos J, Wang B, Wang L. Human centric platforms for personalized value creation in metaverse. J Manuf Syst 2022;65:653–9.

[10] Lee J, Kundu P. Integrated cyber-physical systems and industrial metaverse for remote manufacturing. Manuf Lett 2022;34:12–5.

[11] Thomas PC, David W. Augmented reality: An application of heads-up display technology to manual manufacturing processes. In: Hawaii international conference on system sciences. Vol. 2, ACM SIGCHI Bulletin; 1992, p. 659–69.

[12] Huang S-H, Yang Y-I, Chu C-H. Human-centric design personalization of 3D glasses frame in markerless augmented reality. Adv Eng Inform 2012;26(1):35–45.

[13] Lee I, Lee K. The internet of things (IoT): Applications, investments, and challenges for enterprises. Bus Horiz 2015;58(4):431–40.

[14] Iansiti M, Lakhani KR, et al. The truth about blockchain. Harv Bus Rev 2017;95(1):118–27.

[15] Wen B, Tremblay J, Blukis V, Tyree S, Müller T, Evans A, Fox D, Kautz J, Birchfield S. Bundlesdf: Neural 6-dof tracking and 3d reconstruction of unknown objects. In: Proceedings of the IEEE/CVF conference on computer vision and pattern recognition. 2023, p. 606–17.

[16] Ze Y, Zhang G, Zhang K, Hu C, Wang M, Xu H. 3D diffusion policy. 2024, arXiv preprint arXiv:2403.03954.

[17] Liu S, Wang L, Gao RX. Cognitive neuroscience and robotics: Advancements and future research directions. Robot Comput-Integr Manuf 2024;85:102610.

[18] Xu X, Lu Y, Vogel-Heuser B, Wang L. Industry 4.0 and industry 5.0—Inception, conception and perception. J Manuf Syst 2021;61:530–5.