Metaverse: Architecture, Technologies, and Industrial Applications

Chen Yang[1], Yingchao Wang[1], Yinfei Jiang[2], Shulin Lan[2*], Lihui Wang[3]

***Abstract*—Metaverse has attracted widespread attention all over the world since its inception, promising significant potential in shaping a better vision for human society. It is regarded as "the ultimate form of the Internet". However, the metaverse is still in its infancy, and the research on the relevant system architecture, enabling technologies, and practical applications are far from mature. To foster the advancement of the metaverse, this paper proposes a general metaverse architecture from the aspects of the constituent elements, operating system, roles, interaction modes, security and regulation, and also discusses the key technologies in the metaverse. Finally, the potential industrial research perspectives and application scenarios of the metaverse are presented.**

I. Introduction

The concept of metaverse was initially introduced in the science fiction *Snow Crash* [1] in 1992, and it has been enriched by some early attempts, such as second life [2], 3D virtual worlds [3], and lifelogging [4]. Recently, social, education and manufacturing metaverses have also been proposed. They can be categorized as entertainment metaverse or industrial metaverse. The entertainment metaverse centered around the games, social activities and media sector. It aims to provide users with interactive and engaging virtual experiences, social interactions, and recreational activities. While the industrial metaverse focuses on industrial sectors such as manufacturing, logistics and engineering, and its main objective is to enhance productivity, efficiency, automation and human-machine collaboration. Some studies have attempted to define the concept and architecture of the metaverse. Wang et al. [5] defined the metaverse as a fully immersive, hyper-spatiotemporal, and self-sustaining virtual shared space that combines the ternary physical, human, and digital worlds. Duan et al. [6] proposed a three-tier metaverse architecture, including infrastructure, interaction, and ecosystem. Lee et al. [7] designed the metaverse architecture from the perspectives of technology and ecosystem. Lim et al. [8] systematically analyzed the underlying hardware of the metaverse from four aspects, including infrastructure, driving engine, virtual world, and physical world. Although these metaverse concepts and architectures emphasize the creation of immersive experiences and the fusion of real and virtual interactions, current studies fail to provide a comprehensive and systematic view and ignore some key metaverse elements and issues, such as identity, multiple roles, and relationships. Although our previous study [9] proposed a novel metaverse architecture in terms of metaverse elements, operating systems, roles, and interaction modes, it still needs to be enriched by introducing the security and regulation aspect and some key elements such as openness, rule, and culture. Besides, key technologies of the metaverse and the potential metaverse application are not analyzed in [9].

Therefore, combining our previous work [9] with emerging technologies, this paper proposes the 5-dimensional general architecture of the metaverse from the aspects of key elements, operating system, roles, interaction modes, security and regulation in Section II. To the best of our knowledge, we are the first to propose a comprehensive metaverse concept from the dimension of system architecture, roles, interaction modes, security and characteristics. Then we outline key technologies that empower the metaverse and emphasize their roles in supporting the metaverse in Section III. In Section IV, we present potential industrial research perspectives and highlight application scenarios in the full product lifecycle. Section V concludes the paper with remarks.

The contributions of this paper are as follows:

- We propose a 5-dimensional general architecture of the metaverse, which paves the way to realize the practical metaverse.
- We list the state-of-the-art key technologies as the foundation of the metaverse and analyze the challenges and gaps between the latest technologies and the requirements of reaching the metaverse.
- We present the latest practice and potential application scenarios in the industrial metaverse, which guide the realization of the metaverse.

II. Metaverse Architecture

A. Overview of the Metaverse Architecture

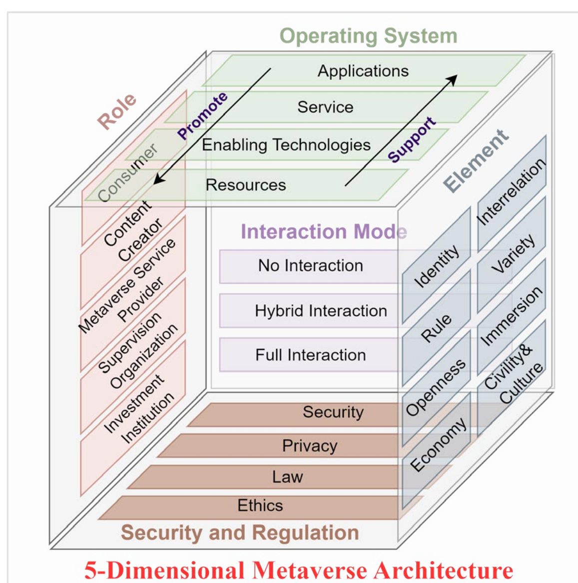

Figure 1. 5-Dimensional Metaverse architecture.

In this paper, we synthesize the characteristics of the industrial and entertainment metaverses and consider the metaverse as an open, immersive, and diverse complex surreal system in which the physical and virtual worlds merge and interact. Going beyond reality, it is empowered by new information and computing technologies. The user can live as a digital avatar and experience an alternative life in virtuality, which will blur the lines between the physical and virtual worlds. To make the metaverse concept clear, we proposed a novel and general metaverse architecture (as shown in Figure 1) with multiple views and tried to analyze the metaverse from different perspectives in the following parts.

B. Key Elements of the Metaverse

Roblox Corporation proposed eight elements for the metaverse: identity, variety, friends, anywhere, immersive, economy, low friction, and civility [10]. We extend these eight elements with other important features and classify them into the following elements.

1) Identity: It is the identification and representation of an object, which is the basic element of all kinds of activities in the metaverse. There are roughly two types of "players" in the metaverse. One is an avatar (digital object) with all or part of individual information and private data, representing the identity of the physical objects such as people and things. The other is digital/meta-human which is the creation of virtual objects (based on modeling, simulation, and AI technologies to enrich and maintain the virtual metaverse environment). They usually have no relationship with the physical world and are similar to the non-player characters in games today.

2) Interrelation: It is the state of people or things interacting and influencing each other, including social relationships such as friendship, kinship, hostility, etc., and non-social relations such as correlation and causation between variables.

3) Rule: It refers to the laws of nature, including known rules such as the second law of thermo-dynamics and unknown rules. In metaverse, it also refers to the rules defined by virtual worlds, such as a virtual world without gravity.

4) Immersion: Immersion is the technical requirement to support the immersive experience and activities of users in the metaverse, including realistic perception and interaction, as well as low friction.

5) Openness: It means that anyone and everything can enter the persistent virtual universe of the metaverse at anytime and anywhere. In the future, with the expansion of the scope and scale of metaverse applications, more and more physical entities and resources will be connected and integrated into the virtual world.

6) Variety: There are a lot of content creators such as professional/user/AI-generated content in the metaverse, which brings about variety. Considering users' expectations for the development of the metaverse, they design and create small worlds or sub-metaverse with different values, social forms, economic systems, rules and systems, thereby boosting the metaverse toward diversification.

7) Economy: The economy of the metaverse is not only the cornerstone of asset circulation and management in the virtual world, which promotes building an ecosystem of the metaverse but also can connect with the economic system of the physical world. For example, the virtual currency created with blockchain technology is highly popular worldwide.

8) Civility and Culture: These originated from the avatars of physical people in the metaverse and are the products of the metaverse at a certain stage of development. These avatars quickly form social groups on a certain scale in the metaverse through various social activities. Then, a series of rules and institutions are formulated to restrict the activities of social groups in the metaverse. Finally, metaverse civility and culture are formed after a series of continuous improvements and reforms.

C. Operating System

The operating system of the metaverse is mainly divided into four layers: resources, enabling technologies, services, and applications.

1) Resources Layer: It is the infrastructure of the metaverse, including storage, computing, communication and networks, data acquisition and other auxiliary devices, such as mobile phones, tablets, virtual reality (VR) helmets, cloud servers, communication base stations.

2) Enabling Technologies Layer: Enabling technologies of the metaverse determines how far the metaverse can go in the future. This layer mainly includes multi-modal perception and fusion technologies, DT, interaction technologies, end-edge-cloud computing, communication and networking technologies, identifier resolution technology, AI, and security and privacy technologies. These will be described in detail in Section III.

3) Service Layer: It is the basis of content and ecosystem creation in the metaverse. The main function of the services is to provide basic or integrated interfaces and technical support for various virtual environments and content creation in the metaverse. The service layer mainly includes the content creation platform which provides a series of design and creation tools for content creators to quickly develop metaverse content, the virtual environment generation platform, and the virtual economic system which is mainly used to support economic activities in the metaverse, including digital trading, assets transaction rules.

4) Applications Layer: The metaverse is mainly applied in the fields of entertainment, education, medical treatment, and industrial production. According to the needs of daily production and life, customized metaverse applications are built to bring an immersive experience to enrich and change the entertainment lifestyle of human beings. To an extent, work and life can be empowered, industrial production efficiency can be improved, and human lifestyle can be changed through the deep integration of the virtual and physical worlds in the metaverse.

D. Virtual-real Interaction Modes

There are different interaction modes of the metaverse: no interaction, hybrid interaction, and full interaction.

1) No Interaction: It means that there is no mapping relationship between the virtual world and the physical world. Designers' ideas or imagination are just transformed into such a metaverse that is a relatively independent virtual space. It may not be called a metaverse in the strict sense, because it could not evolve with the physical world.

2) Hybrid Interaction: It should be the mainstream application mode of the metaverse for a long time since it not only ensures a certain degree of interaction between the physical and virtual worlds but also leaves spaces for digital creation. These features can ensure the practical application significance of the metaverse as well as improve the scalability of the metaverse in the space-time dimension.

3) Full Interaction: The idea of full interaction is to replicate a digital space in the metaverse that is the same as the physical world, including humans, objects, and environments. It can realize real-time and two-way interaction of the virtual and physical worlds through relevant sensing, computing, communication, and interaction technologies. However, too much interaction is not conducive to fully realizing the potential of the metaverse, since too much non-essential interaction will lead to the waste of resources and increase the possibility of network attacks.

E. Roles of the Metaverse Ecosystem

The development of the metaverse will accelerate the division of labor so that different roles can collaboratively build the metaverse ecosystem in a more efficient and professional way. At present, the roles in the metaverse can be roughly divided into consumers, content creators, metaverse service providers, supervision organizations, and investment organizations.

F. Security and Regulation

This dimension aims to ensure the healthy, safe, and sustainable operation and development of the metaverse.

1) Security and Privacy: The metaverse reuses some traditional Internet technologies and infrastructure, so it also faces the security and privacy issues of traditional cyberspace, including network attacks, vulnerability, privacy exposure, and unsafe AI algorithms, etc. In addition, due to the openness, identity, immersion, and civilization features of the metaverse, security and privacy issues show new characteristics, such as the attack surface being more extensive, the attack method being more diversified and the harm being more serious. These prime concerns hinder metaverse development. Therefore, there is an urgent need to develop systematic security and privacy protection methods and systems in terms of device security, network security, data security, service security, and application security.

2) Law and Ethics: The open and free environment of the metaverse will become a hotbed of various social and ethical issues. First, the highly virtualized nature of the metaverse may allow participants to accomplish many things that are illegal in the real world, such as violence, pornography, and psychotropic drugs. Second, economic crimes such as initial coin offerings and illegal trading of virtual currencies are likely to occur. Third, AI-based algorithms and models have continually led to ethical issues, and with the metaverse breaking down restrictions of race, color, age, gender, etc., ethical issues in the real world will be magnified in the virtual universe. Therefore, the metaverse is in urgent need of effective legal regulation and ethical constraints.

III. Key Technologies

We list some key enabling technologies for the metaverse.

A. Multi-modal Perception and Fusion

Since humans interact with the environment through a variety of senses such as visual, auditory, tactile, olfactory, gustatory, vestibular, and proprioception in the physical world, multi-modal perception and fusion are technical requirements to support the metaverse immersive experience. On the other hand, not only the multi-modal physical senses but also emotions are needed. It is necessary to extract and fuse sentiment information from multimodal data such as speech, intonation, posture, and physiological signals to realize emotional perception and interaction. According to the stage at which multi-modal information fusion occurs during information processing, it can be divided into data-level, feature-level, and decision-level fusion. The data-level fusion directly processes and combines raw data, such as alignment and stacking of signals, which can be used to support multi-modal physical senses. Feature-level fusion refers to the information fusion at the level of feature representation and extraction of the raw data, commonly used in multi-modal machine learning such as emotion recognition. Decision-level fusion refers to the fusion of the outputs of decision-making models based on multi-modal data, which has better anti-interference performance and relatively low requirements for sensor performance and type. However, it ignores the mutual influence of multi-modal information, and requires effective weight allocation for the results.

B. Digital Twin

The digital twin (DT) is the digital replication of objects or systems in the physical world. By virtualizing physical objects, these replicas, known as twin models (avatars), are seamlessly integrated into both the physical and cyber spaces. Twin models serve as abstractions of the functions performed by their physical counterparts. Real-time data about physical *things* can be utilized to validate and adjust twin models, or to drive their execution. In the metaverse, DT leverages real-time data for understanding, analyzing, learning, reasoning, and optimizing physical entities through computation and simulation. Through real-time dual interactions, DTs bridge the gap between the physical and digital worlds, forming a close control loop. With data gathering and processing, the twin models are updated and evolve throughout the lifetime of the physical entity [11] in the metaverse. In short, DT enables the mapping of the physical world to the virtual world which in turn can react to the physical world [12]. Therefore, DT is one of the core technologies to realize the metaverse.

C. Virtual-Real Interaction Technologies

1) Extended Reality (XR): XR encompasses all immersive technologies that expand human perception of reality by either blending the virtual and "real" worlds or creating fully immersive experiences. VR, augmented reality (AR) and mixed reality (MR) also exist on the spectrum of XR technologies to provide entrance to the metaverse. VR can provide a person with a simulated, immersive, and interactive virtual environment. AR, on the other hand, overlays or integrates digital imagery into the real world, as perceived through a camera or display, enhancing the real-world experience. MR is often seen as an intermediary between AR and VR, allowing users to interact with virtual entities within physical environments. However, the current XR is not enough to support the landing of the metaverse, for example, due to delay, weight and other reasons, wearing the XR device for a long time may cause discomfort, such as dizziness in wearing the XR helmet. Future XR devices tend to be much small, portable, and low-cost to allow users to access the metaverse anytime, anywhere.

2) Brain-computer Interface (BCI): BCI establishes a connection between the neural activity of the human brain and the external physical world by deciphering individual brain signals into recognizable commands for computer devices or robots [13]. BCI serves as a direct communication pathway, linking the electrical activity of the brain with an external device. Through BCI and multi-modal interaction technologies, the metaverse can provide a high degree of immersive experience by feeding multi-modal signals such as visual, olfactory, and haptic stimuli to the user, which can greatly help people with disabilities. However, the current BCI technologies are not mature enough to support the metaverse, due to problems such as unknown sensory stimulation mechanisms and non-uniform BCI standards. Meanwhile, since invasive BCI interfaces will cause certain damage to human bodies, future metaverse research will focus on the study of the non-invasive BCI interfaces, such as using electroencephalogram and artificial intelligence.

D. End-Edge-Cloud Computing

Efficient real-time computation is essential to provide an immersive experience based on a huge amount of multi-modal data, such as for data acquisition, rendering, data processing, etc. Cloud computing is a competitive and pragmatic paradigm for the metaverse since it has sufficient storage and computing resources. The state-of-the-art metaverse architectures and applications use a centralized cloud approach for avatar physics emulation, 3D animation, and graphical rendering. However, such a centralized approach is unfavorable as it suffers from service delays and privacy issues. In contrast, the heterogeneous end and edge computing infrastructure can reduce the communication delay due to its proximity to the end users and may alleviate privacy concerns as some private data can be processed locally [12], but the computation, storage, and energy resources of these distribute devices is insufficient to support the whole metaverse. Therefore, end-edge-cloud computing is a novel and inevitable computing paradigm that combines the advantages of these three computing models. It can flexibly allocate computing resources on demand to meet the anytime and anywhere computing requirements of the metaverse, thereby enhancing the user experience and quality of service. End-edge-cloud computing can be divided into vertical collaboration, horizontal collaboration, and integrated collaboration modes according to the computing hierarchy. However, as silicon-based chips are reaching their limits, Moore's Law seems to be dead. The end-edge-cloud computing will hit a bottleneck that comes from the von Neumann architecture. The emergence of non-von Neumann computing theories and paradigms represented by quantum computing, photonic computing, and brain-like computing has brought light to the change in the advanced computing area.

E. Communication and Networking

Communication and networking technologies empower ubiquitous network access and real-time data transmission between the real and virtual worlds, as well as among various sub-metaverses, while openness and immersive experience of the metaverse places higher demands on them, such as ultra-low latency, large bandwidth, and high reliability. The fifth generation (5G) mobile communication technology is being deployed in all over the world. Metaverse use cases, such as remote cloud-based XR, 3D animation and graphical rendering, can somewhat be supported by 5G networks. However, the existing 5G networks can not realize the 5G specifications, such as the ideal ultra-low latency of 1ms cannot be achieved by the current not-stand-alone 5G mode while the latency exceeds 50 milliseconds in some cases, which is not enough to support the immersive experience of the metaverse. The sixth generation (6G) is the evolution of 5G, and pursues greater coverage, more computing power, and faster sensing efficiency, rather than just communication performance improvement. In 6G, integrated communication, sensing, and computing can provide real-time and ultra-reliable communications for the metaverse, and the integrated space-air-ground network can achieve seamless and ubiquitous network access to metaverse services.

F. Identifier Resolution Technology

With the development of the metaverse, more and more physical entities and resources will realize interaction with the virtual world. How to realize the efficient management of such a large number of physical objects and virtual resources will restrict the development potential of the metaverse. Identifier resolution technology in the industrial Internet assigns unique identity codes to entities and virtual objects through identity codes. This identity code can record and trace the life cycle information of virtual or physical objects, to better realize the life cycle management. In other words, identifier resolution technology can be used to build the identities and data services of physical entities and virtual resources in the metaverse. The metaverse requires identifier resolution technology to have the following characteristics:

- Robust identifier resolution architecture. Since the metaverse has a huge amount of physical and virtual resources with wide-area distribution and complex mapping relationships, the identifier resolution system must be highly fault-tolerant and robust to ensure the stability of data and interactive services of the metaverse.

- Secure identity authentication. It can ensure the establishment of a secure connection between two parties employing protocol constraint or encryption, which is the basis of metaverse's secure operation.
- Fast traceability. Massive interactions between the virtual and physical worlds and data services for the metaverse will inevitably lead to network congestions and other problems. Fast traceability helps to find and solve these problems in time.

G. Artificial Intelligence

AI technology acts as the "brain" of the metaverse, which will accelerate the construction of virtual environments and ecosystems in the metaverse. On the one hand, AI has been applied in the image recognition, natural language processing, multi-modal sentiment analysis, recommendation, and user movement prediction fields in recent years, and the R&D results in these fields can be transplanted into the ecosystem construction of the metaverse. For example, social relation analysis and personal preference analysis are inseparable from the support of AI. On the other hand, by merging AI with other technologies, such as XR, multi-modal fusion, DT, BCI, the metaverse can provide secure, scalable, and realistic virtual worlds on a reliable and always-on platform. For example, massive and customized virtual scenarios can be automatically generated and presented through AI to users in an organized manner. AI generated content, represented by AI generated art, is becoming an important trend for content generation in metaverse.

H. Security and Privacy

The metaverse is an open, shared, and persistent digital environment where an increasing number of human activities occur within virtual spaces. As user information, sensitive data, and immersive experiences become more prevalent, the need for robust encryption and protection against attacks becomes paramount. Consequently, security and privacy concerns will grow in significance. Blockchain technology is widely acknowledged as the foundational framework for security and privacy in the metaverse due to its decentralized, immutable, and transparent nature. With its point-to-point transmission mechanisms, smart contracts, and consensus mechanisms, etc., blockchain is a promising solution to provide users complete control of their data thereby securing the privacy of digital content and data of the metaverse. On the other hand, blockchain's digital encryption technology, distributed storage, hash function, etc. ensure the security of data in the metaverse. In addition, since blockchain facilitates the process of recording transactions and tracking assets in the metaverse, digital assets in the metaverse are also possible to be traded. Non-fungible tokens and virtual currencies created through blockchain technology are very popular worldwide. The non-fungible token represents irreplaceable and indivisible tokens that mark the uniqueness and ownership of assets in the metaverse. As an important part of the economic system in the metaverse, it tends to become the cornerstone of the metaverse economy.

IV. Industrial Metaverse Applications

Metaverse can transform a physical factory and create a virtual factory based on their digital twin models, which can significantly increase the level of digitization, intelligence, and personalization of modern manufacturing. In this section, we briefly discuss several industrial applications of the metaverse from a product lifecycle perspective to support the growing personalized and customization production.

A. Demand Alignment and Design Cooperation

With the growing demand for product customization and personalization, mass-personalized production will become a mainstream manufacturing model, which requires customer engagement in product design and manufacturing processes, or even in the entire life cycle of the product [14], [15]. With the help of the metaverse, this is expected to be possible. The metaverse is an open and interactive public space where customers, designers, and manufacturers around the world can collaborate on product design [14] just like in-person meetings. In the metaverse, customers can co-design and configure their products with virtual modular components and AI generated content or interact directly with designers remotely for more personalized customization. Designers and manufacturing engineers can build digital models of products in the metaverse's virtual environment for vivid and immersive display to customers and simulate product operation and performance to determine if the product design makes sense and is optimal. This can greatly reduce the number of time-consuming and expensive field tests and save a lot of R&D time. Meanwhile, modifications can be made based on feedback from customers and manufacturers, or even directly from connected running products. In addition, the metaverse gives designers a digital footprint of the complete lifecycle of a product, which allows designers to use this historical information to make informed design decisions or iterative product optimization, resulting in shorter design cycles and fewer manufacturing costs. In short, metaverse can meet customers' individualized and customized demands, forming lean production with user participation, multi-person collaboration and closed-loop optimization based on historical information and real-time simulation feedback.

B. Processing and Assembly

The identity, openness, and immersion feature of the metaverse enable lifelike monitoring, diagnosis, maintenance, prediction, and optimization of the entire manufacturing process, thus promoting remote lean manufacturing with different stakeholders in the loop. The metaverse brings multi-modal data from different on-site sources to vividly present a production process in a real-time visualization way, so that engineers can use the collected data and visual information to monitor performance, diagnose exceptions and faults, test product quality and repair equipment remotely. For example, engineers anywhere can use XR devices to identify equipment problems promptly and instruct field technicians or robots to perform the appropriate equipment maintenance. Meanwhile, the metaverse constantly collects, analyses, and accumulates multi-modal data from physical factories to provide a solid basis for decision-making in smart factories such as energy saving, process optimization, and quality management. It also allows metaverse users to predict the performance of manufacturing systems, build industrial models, explore optimization plans and validate the feasibility of process designs. For example, the metaverse allows manufacturers to test potential process flows, shop floor layouts, etc. to support flexible reconfigurable manufacturing for future customized and personalized production. Moreover, human-centered collaborative human-machine production is another important application area for the industrial metaverse, which effectively integrates human intelligence to enhance production efficiency.

C. Product Testing, Maintenance, and Recycling

The dynamic working environment of a complex product can be modeled and simulated by the metaverse to perform large-scale complex product testing in the shared virtual space without the need of the physical prototyping and reveal potential issues before the product is released to the market. Metaverse may also allow potential customers to participate in virtual product testing for marketing purposes. For example, in automotive industry, through test driving of real cars and traffic conditions in the metaverse, users can obtain immersive experience anywhere, anytime. Meanwhile, the metaverse makes product maintenance more convenient and intelligent. Based on the product's historical data, metaverse can be used to track the product performance and health conditions in real time, perform predictive maintenance and show the status, faults, and repair solutions of the product visually through the virtual world twin. Moreover, the open, diverse nature of the metaverse community promises to enable the development of product recycling and reuse as a creative industry where products are redefined and redesigned thanks to the creativity of the metaverse community.

D. Management and Skill Training

The metaverse can make management and skill training such as marketing, customer relationship and supply chain management, more transparent, vivid, interesting and inspiring. A large number of participants anywhere can join the training or education metaverse to enjoy the teamwork training, teaching or discussions. For example, the metaverse digital twin tracks products from raw materials to finished products and delivery, improving the visibility and traceability of supply chain processes, so that managers can optimize the processes. Skills training is another promising application scenario for the metaverse. The fusion of the real and virtual worlds can help employees to create a vivid and realistic learning environment, and hands-on courses involving working with workmates, machines or tools can be delivered through the metaverse's interactive technology.

V. Conclusions

In this paper, we have discussed the architecture, enabling technologies, and industrial applications of the metaverse. Specifically, we have presented a novel multi-dimensional metaverse architecture that integrates key elements, operating system, roles, interaction modes, security and regulation. Afterward, some key enabling technologies are discussed to support the metaverse. Further, we have discussed existing/ potential applications for industrial metaverse from a product lifecycle perspective. Our future work includes the utilization of AI and end-edge-cloud computing to enable time-sensitive interaction and smooth user experience. We will also validate the proposed architecture with specific industrial cases. We expect that this paper can shed light on the basic elements, composition, and application prospects of the metaverse, and elicit more pioneering research in this emerging field.

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