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SURVEY

Toward Trustworthy Metaverse: Advancements and Challenges

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ABSTRACT The Metaverse, a transformative digital realm, holds immense promise for reshaping industries and human interactions while potentially addressing global challenges and democratizing opportunities. However, it also introduces a spectrum of complexities that demand careful navigation. To establish trustworthiness within the Metaverse ecosystem, gaining a deep understanding of its applications, challenges, and existing solutions is imperative. In this comprehensive survey, we first delve into Metaverse applications, drawing insights from existing literature. Subsequently, we explore the diverse challenges the Metaverse presents, analyzing them through the lens of existing research. We then scrutinize the overall trustworthiness of the Metaverse environment and investigate existing solutions to previously identified challenges through a thorough review and analysis of pertinent literature. Lastly, we discussed future research directions aimed at fostering a trustworthy Metaverse environment. This comprehensive review can provide an overview of the Metaverse, its application domains, challenges, existing solutions and research directions for many multidisciplinary studies.

INDEX TERMS Metaverse, Blockchain, data privacy, edge computing, adaptive artificial intelligence.

I. INTRODUCTION

The world we live in is now extended to a world that combines the coexistence of our natural world and virtual places. Education, communication, and daily activities are now shifting toward a world where everything interacts digitally, which is also known as the Metaverse. Metaverse combines ‘‘Meta’’ and ‘‘Verse,’’ where Meta means beyond, and Verse tells the universe. In other words, it is a 3D virtual world of an integrated network where everyone can exist in both the natural world and virtual places through avatars at the same time [1]. Metaverse is now considered the next marvellous thing and the next version of the internet. Although the concept of Metaverse was first described by Neil Stevenson in 1992 in his novel Snow Crash, recently, it is attracting much interest among researchers and investors [2]. The increasing number of publications in recent years in various bibliographic databases with the keywords ''Metaverse'', ‘‘Mixed Reality’’, and ‘‘eXtended Reality’’ used in their metadata, as shown in Figure 1, is evidence of that.

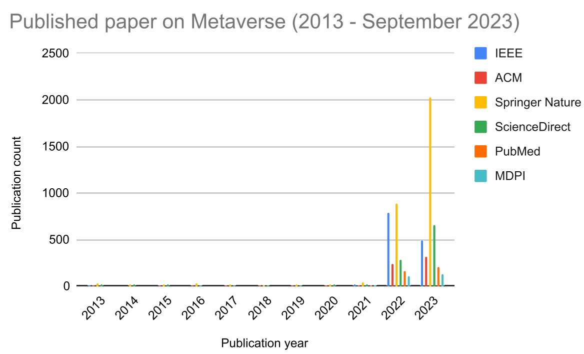

FIGURE 1. Paper published on Metaverse in different databases from January 2013 to September 2023.

The associate editor coordinating the review of this manuscript and approving it for publication was Paulo Mendes.

Additionally, Metaverse Group, a Metaverse investment-based real estate company, recently bought virtual land for a hilarious price of 2.43 million on a decentralized virtual reality platform familiar as Decentraland. Metaverse's overall revenue opportunity is expected to rise from USD 500 billion to USD 800 billion from 2020 to 2024 [3]. On the other hand, in gaming, different examples of Metaverse, like Roblox, Fortnight, and Sandbox are increasing at a tremendous rate [4]. At the same time, an enormous number of audiences started to explore Metaverse in detail after the press briefing of Marc Zuckerberg, where he announced the name change of Facebook to Meta [5].

The most crucial factor about Metaverse is that it is not for any specific age group or region but for the entire world. Therefore, it can change the looks of the current world and bring a new dimension to our culture and life. With this rapid growth and interest in Metaverse, it is also essential to build and maintain the trustworthiness of Metaverse and its application to ensure the user's acceptance and trust [6]. Nowadays, with good user experience and efficiency, users also want a system they can easily trust and use without facing any challenges. For this, the trustworthiness of a system is significant to gain user interest. When it comes to the trustworthiness of Metaverse, it not only points to the security and ethical perspective but also a wide range of challenges that should be overcome.

No specific article surveyed the challenges of the overall Metaverse ecosystem and then reviewed their solutions based on existing papers as shown in Table 1. Here, no paper surveyed the overall Metaverse's applications, challenges and existing solutions. Therefore, to assist investors and researchers in developing the Metaverse ecosystem and making it trustworthy, a comprehensive and informative study is required with detailed advancements, application domains, challenges and their solutions by exploring the existing research papers. It will help researchers and stakeholders understand the Metaverse ecosystem's current situation and what is necessary for future development. Considering this research gap and necessity, this survey paper has been conducted where it offers in-depth insights and evaluation of the advancement and challenges of Metaverse, along with the solutions to these challenges proposed by researchers and future research directions. Table 2 discusses the main questions of this survey and where they are answered. Furthermore, Figure 2 illustrates the PRISMA flow diagram for this survey paper's selection process.

Briefly, the main contributions of this paper are summarized as follows.

- An introduction to Metaverse, it's history, architecture and recent advancements.
- Exploration of diverse application domain of Metaverse and advancement done by researchers.
- Discussion of different challenges of Metaverse with a taxonomy.
- Review and analysis of existing work done by researchers to overcome the challenges of Metaverse.

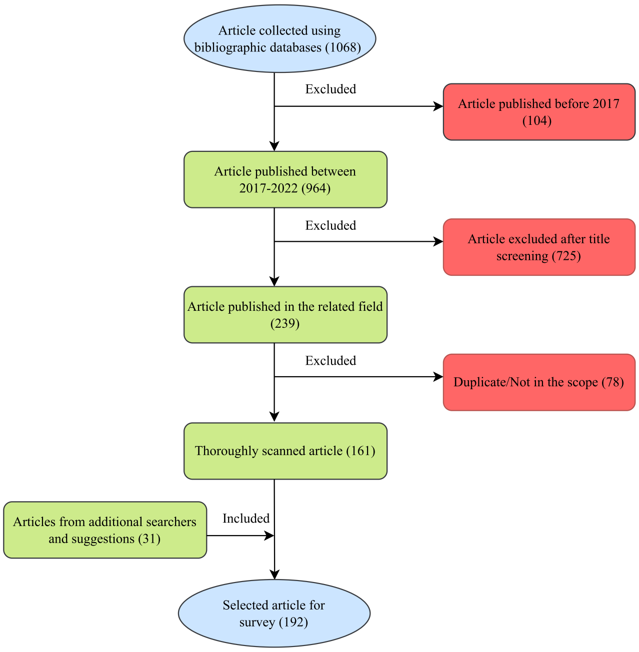

FIGURE 2. PRISMA flow diagram of paper selection process for this survey.

- Future research direction for making the Metaverse ecosystem trustworthy.

The rest of the paper is structured as follows: section II highlights the history, architecture and advances of the Metaverse. Section III describes the applications of Metaverse and section IV addresses the challenges of Metaverse from a different perspective. After that, section V reviews the existing literature and their proposed solutions to overcome the challenges of Metaverse. Finally, section VI discusses the future research opportunities and section VII concludes the paper.

II. METAVERSE

The Metaverse, derived from the composite words "transcendence meta" and "universe," refers to a networked virtual 3D environment where real and virtual worlds interact, allowing for fully immersive experiences and collaborative activities [11]. The Metaverse has evolved from its early focus on the structure of virtual worlds to become a platform for content-focused social interactions.

Since 1838, when Verhoeff first described binocular vision, the idea of a Metaverse has been taking shape [12] and then Neil Stevenson first used the word "Metaverse" (the duplicate of the real world)in 1992. After that, the popular science fiction movie Matrix introduced the public to the idea of the Metaverse in 1999 [13]. The next major event was the idea of a digital twin, which was first suggested in 2002 [14]. A digital twin is a virtual representation of an object or system that spans its lifecycle and is updated from real-time data. Because the Metaverse is entirely virtual, virtual currency was required. ThereBucks, an online virtual currency, was

TABLE 1. Comparative analysis of existing survey papers with our paper.

Reference	Taxonomy	Applications	Challenges	Existing Solutions	Result Analysis	Future Direction	Contributions
Sun *et al.* [7]	✓	✓	✓ (Only Privacy & Security)	✗	✗	✓	This paper introduced and analyzed the concept, framework, supporting technologies, and only the security & privacy issues of the Metaverse, as well as discuss its potential impact and research directions.
Wang *et al.* [2]	✓	✗	✓ (Only Privacy & Security)	✓	✗	✓	This paper provided a comprehensive survey of the fundamentals, security, and privacy challenges of the Metaverse, along with a discussion of potential countermeasures and open research directions for the development of future Metaverse systems.
Ning et al. [8]	✓	✓	✓	✗	✗	✗	This paper provided an overview of the development status, technical framework, and characteristics of the Metaverse, as well as its potential application areas and associated challenges.
Huang et al. [9]	✓	✓	✓ (Focused on Privacy & Security)	✓ (Only Privacy & Security)	✗	✗	This paper identified the four key characteristics of the Metaverse, survey its current progress and applications across economic sectors, and analyze the associated security and privacy challenges.
Sami et al. [10]	✓	✓	✓	✗	✗	✓	This paper surveyed Metaverse's development pipeline, covering infrastructure, digitization, user interactions, and their impact on enabling technologies and domains, offering insights for understanding and contributing to the Metaverse ecosystem.
This paper	✓	✓	✓	✓	✓	✓	This paper offers a comprehensive survey of the Metaverse, including its applications, challenges, existing solutions, and future research directions, providing valuable insights for multidisciplinary studies and fostering trustworthiness within the Metaverse ecosystem.

TABLE 2. Major research questions of this survey.

Research Question	Discussion
What are the main applications of Metaverse	Discussed in Section III
What are the main challenges of Metaverse	Discussed in Section IV
Is Metaverse trustworthy?	Discussed in Section V-A
How to overcome the challenges to make Metaverse trustworthy?	Discussed in Section V-B

initially offered in 2003 [15]. The next year, Roblox created the online gaming platform, which was also a step towards Metaverse [16]. After that, when Google unveiled the Cardboard device and Google AR Glass in 2014, the Metaverse notion took on a new dimension [17]. In 2015, the Ethereum Blockchain and Decentraland created a groundbreaking virtual environment called the Metaverse [18]. In order to improve the Metaverse user experience, 2016 saw the introduction of devices like Oculus, Pokémon Go, Microsoft HoloLense, etc. In 2021, Facebook officially changed its name to Meta with the goal of launching a significant Metaverse initiative [5]. After the Benetton group's Stepping Into the Metaverse With Retail Project, the Metaverse received a new dimension in 2022 [19]. Apple announced the release date for "Apple Vision Pro" in 2023 [20], to completely transform the Metaverse experience, it will build a new route. Additionally, investors and tech giants from all over the world are gradually investing more in the Metaverse in order to sustain itself in the future of the virtual world.

A. ARCHITECTURE

The Metaverse is a concept that describes a virtual world or universe, a collective virtual shared space. It's a place where individuals can interact with each other and digital objects in a seamless and interconnected manner. To achieve such a complex and interconnected virtual environment, various technologies and dependencies play a crucial role. Figure 3 illustrates the architecture of the Metaverse. (To draw the Figures of this paper, used icons were taken from https://www.flaticon.com/).

Metaverse is shaped by several key technologies. Artificial Intelligence (AI) plays a crucial role in enhancing user experiences, personalizing content, creating lifelike avatars, providing real-time translations, optimizing content delivery, and generating dynamic environments based on user preferences and behaviour [21], [22]. Blockchain technology ensures transparency, immutability, and security within the Metaverse, enabling the creation of virtual economies, managing digital assets, and establishing ownership rights over

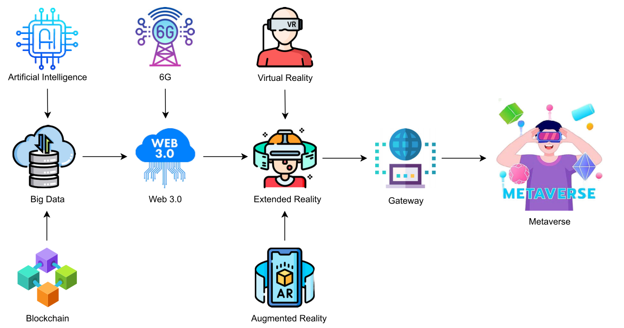

FIGURE 3. Architecture of the Metaverse.

virtual goods through Non-Fungible Tokens (NFT) [23]. Big Data technologies are essential for processing and analyzing the vast amount of data generated by user interactions, virtual environments, and economic activities, leading to improved user experiences and system performance [24]. The upcoming 6G wireless communication technology is pivotal for the Metaverse, enabling seamless real-time communication, reduced latency, and enhanced interactions between users and devices within the virtual environment [25]. Web 3.0, the next generation of the internet, is a fundamental dependency for the Metaverse, facilitating decentralized Applications (dApp) and smart contracts that enable trustless interactions and secure transactions of digital assets within the virtual world [26]. Finally, eXtended Reality (XR) technologies encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) allow users to immerse themselves in the virtual environment, interact with digital objects, and experience a blend of the real and digital world within the Metaverse [27]. Together, these technologies create a multifaceted architecture that forms the foundation of the Metaverse and its diverse functionalities.

Metaverse is a convergence of various cutting-edge technologies. Each of these dependencies contributes to creating a seamless, immersive, and interconnected virtual world where users can interact, transact, and explore in new and exciting ways. As technology continues to advance, the potential of the Metaverse is likely to expand, leading to novel experiences and opportunities across numerous industries and aspects of our lives.

B. ADVANCEMENTS

The Metaverse is a transformative concept gaining momentum with exciting opportunities for investors and businesses. It offers a shared virtual reality space for user interaction and creation, holding immense potential across industries. Leading companies are heavily investing in Metaverse-related projects, fueling the race to capitalize on this emerging frontier. From virtual real estate to gaming, education, and more, the Metaverse presents a promising landscape for innovative ventures.

Major corporations are actively embracing the potential of the Metaverse, recognizing it as the ''next chapter'' for the Internet and a significant opportunity for various industries. For instance, the world's leading social media network, Facebook, made a significant move in October 2021, announcing its rebranding as Meta, signalling its commitment to the Metaverse [5]. The company revealed plans to invest a substantial 10 billion into the development of the Metaverse [28]. Gartner, a leading research and advisory firm, has identified the Metaverse as one of the top five emerging trends and technologies for 2022 [29]. This recognition has resulted in substantial investment, with global spending on VR/AR, foundational technologies for the Metaverse, projected to rise from 12 billion USD in 2020 to 72.8 billion USD in 2024. Consequently, industries like gaming, retail, arts, healthcare, and Blockchain are positioning themselves to play pivotal roles within this emerging ecosystem. As user engagement increases in virtual spaces, 3D AR advertising is anticipated to proliferate on social media platforms [30].

Businesses across various sectors are making substantial investments in Metaverses, recognizing their potential for entertainment and professional applications. Gaming platforms are incorporating Metaverse-like features, allowing virtual concerts and other interactive experiences. The growing popularity of the Metaverse is evident with people even buying virtual real estate, reinforcing the notion that this technology is indeed here to stay. However, Decentraland, a renowned virtual-reality platform, faced a setback in October 2022 when it confirmed a relatively low number of monthly active users compared to previous months [31]. This decline has led some to believe that the market of Metaverse is not adequately stabilized.

III. APPLICATIONS

The Metaverse spans numerous application domains, from immersive gaming to virtual education, virtual commerce and social interaction. It reshapes how we connect, learn, work, and entertain in a dynamic, interconnected virtual world. Figure 4 visualizes different application domains of Metaverse.

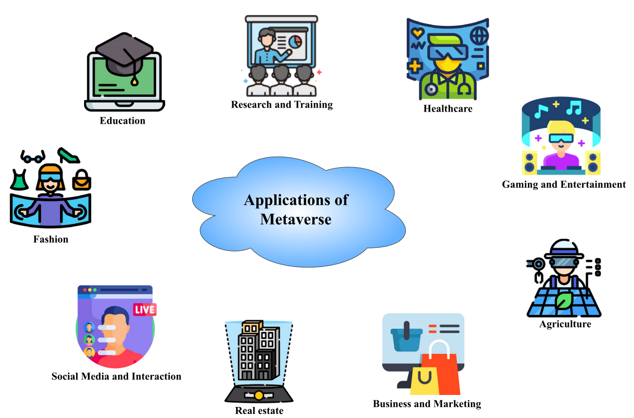

FIGURE 4. Applications of the Metaverse.

A. EDUCATION

In the realm of education, Metaverse encompasses the utilization of virtual reality, augmented reality, and mixed reality

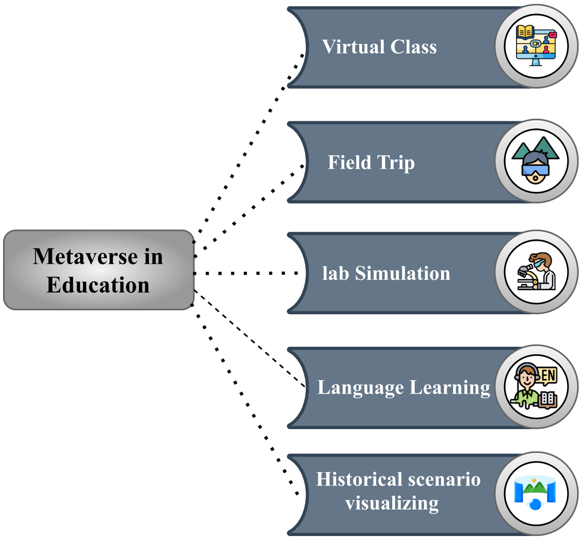

FIGURE 5. Metaverse in education.

technologies to craft immersive learning encounters, enriching students' comprehension across diverse subjects [32]. The potential for learning within the Metaverse is truly captivating; students can roam alongside dinosaurs, refine intricate surgical skills, and reconstruct history from scattered fragments. Moreover, the Metaverse holds the promise of bridging geographical disparities in education by enabling colleges in underserved regions to collaborate seamlessly with distant counterparts, thereby expanding opportunities for support and collaboration. Though teaching effectively in a virtual setting has consistently remained a focal point of research [1], [33], the COVID-19 pandemic's onset has significantly expedited the expansion of online education [34]. Figure 5 illustrates diverse applications of Metaverse in education.

Currently, Metaverse is used for all areas of educational purposes. Metaverse is used in the educational domain of biology by Rodríguez et al. where they focused on building virtual molecular models for display in augmented and virtual reality on the web [35]. Christopoulos et al. proposed the use of virtual reality escape rooms [36] to support interdisciplinary learning and promote conceptual understanding in biology education. Zhou et al. presented a technology-aided biological microscope learning system based on virtual reality (VR) and augmented reality (AR) [37]. Morimoto et al. proposed a visionary model called BioVR that allows students to experience evolution in virtual worlds [38]. Arslan et al. reviewed the overall development of AR Application for Biology Education [39].

Ismail et al. created an augmented reality-based learning media for physics education, specifically on electric concepts, to be used in classroom learning and daily life applications [40]. Rizki et al. developed the "Adventuring Physics" game app with AR integration on Android to enhance physics learning, foster concept visualization, and simplify understanding of abstract materials for students [41]. Metaverse was also used for making the learning of physics fun by Suprapto et al. where they developed an AR application for learning the atomic model [42]. Sung et al. developed a real-time simulation system for physics education based on parallel processing, which includes a video see-through AR system and a real-time soft body simulator using GPU [43]. Additionally, Lai et al. reviewed practical AR implementation for education, specifically in the field of physics education [44].

Metaverse was used by Fanguy et al. for teaching Acid-Base interaction prediction through Hard and Soft Acids and Bases (HSAB) theory to students [45], Abdinejad et al. used a combination of different 3D animation and AR to enhance students' learning and grasp of chemistry through enhanced visualizations of complicated molecular structures and organic chemistry reactions [46], Mazzuco et al. conducted a systematic literature review to address the use of AR in chemistry education [47]. Metaverse is also used for language learning where Wu et al. proposed an innovative educational framework for language education in the Metaverse [48]. Aydın presented a theoretical contextualization of the Metaverse as a foreign language learning environment [49]. A systematic review of previous studies on AR and VR in language learning, analyzing 88 articles from five perspectives, was presented by Huang et al. [50].

The use of Metaverse can be found in diverse education sectors like geography where Jong et al. proposed a pedagogical framework called Learner-Immersed Virtual Interactive Expedition (LIVIE) that integrates immersive and interactive virtual inquiry-based fieldwork into the learning and teaching of physical geography [51]. In agricultural learning, Khansulivong et al. proposed a novel agricultural online learning technology leveraging the Metaverse [52]. The effectiveness of Metaverse is also observed in nursing education [53], physical education [54] and medical education [55].

The Metaverse provides students with a fully immersive educational experience, particularly in practical and laboratory classes. It allows students to journey back in time, offering them the opportunity to directly observe the intricate elements of historical architecture when studying ancient architectures [56]. Lee et al. developed an aircraft maintenance simulation based on VR and Metaverse and conducted an experiment comparing it to a video training method. The experiment showed that the group using their proposed system scored higher than the video training group on both knowledge tests, indicating the educational effectiveness of Metaverse and virtual practical classes [57]. According to Gruson et al. the revolution around the Metaverse offers different opportunities for Laboratory medicine, particularly with the rise of Meta-clinical laboratories (MetaLab) [58]. A VR educational program using a multiuser virtual anatomy laboratory experience was developed by Gonzalez-Romo et al., where digital specimens created using

FIGURE 6. Metaverse in research and training.

photogrammetry techniques were imported into a virtual simulated neuroanatomy dissection laboratory [59]. Furthermore, The Virtual Laboratory Learning Environment: VLLE on Metaverse provides a platform for students to engage in hands-on learning experiences in a virtual setting [60].

B. RESEARCH AND TRAINING

Metaverse is set to transform conventional research and training by providing immersive environments for simulations, data analysis and collaborative learning. It enables researchers and learners to explore new frontiers and develop their skills in virtual worlds. Figure 6 illustrates diverse applications of Metaverse in research and training.

The fusion of Metaverse and VR is transforming research. It enables researchers to explore virtual realms, gain insights and revolutionise disciplines. This innovative synergy enhances data visualization, enables experiments in virtual environments and pushes the boundaries of knowledge. Valmaggia and Lucia discussed the application of VR in the research and therapy of psychosis [61]. Bohil et al. discussed the use of VR in neuroscience research and therapy, emphasizing the importance of contextually rich simulations with multiple sensory cues for greater ecological validity in virtual environments [62]. Coelho et al. discussed the use of VR technology as a superior methodology in achieving improvements in both the research and treatment of the causes of acrophobia [63].

Virtual reality is also used in product design and manufacturing within industries [64].

The Metaverse has emerged as a pioneering platform for training, transforming the way individuals learn new skills and knowledge. This immersive virtual space offers unique opportunities for interactive and immersive training experiences. From simulations that reproduce real-life scenarios to collaborative learning environments, Metaverse has redefined the training environment. The use of Metaverse can be seen in Diverse training domains like space flight and flight simulators, driving, medical surgery training, social development training, education, military and maritime and shipping.

Valentino et al. discussed the implementation of virtual reality in flight simulator training [65]. A conceptual design of a work mode for space flight control from the perspective of the Metaverse was proposed by Zhang et al. [66]. Bruguera et al. developed a new space flight simulator that combines VR and realistic computational models to investigate the application of this technology in astronaut training [67]. A Metaverse embedded learning and training framework for drivers in rolling stock for productivity, quality, and safety enhancements was developed by Danylec et al. The potential use of Virtual Reality (VR) software as a new direction in developing training tools in medical education was discussed by Fertleman et al. [68]. [69]. Koo and Huilyung introduced the concept of training in lung cancer surgery through the Metaverse, including extended reality, in the smart operating room of Seoul National University Bundang Hospital, Korea [70].

A Metaverse-based social skills training program for children with Autism Spectrum Disorder (ASD) to improve social interaction was proposed by Lee et al. [71]. Rutkowski et al. provided a systematic review and meta-analysis of the effectiveness of virtual reality-based interventions in various rehabilitation training fields like neurological, orthopaedic, geriatric, and pediatric patients [72]. A Metaverse-based training system that utilizes Deep Reinforcement Learning (DRL) technology to improve evacuation efficiency was proposed by Gu et al. [73]. Jensen et al. conducted an overall review of the utilization of head-mounted virtual reality displays in the realms of education and training [74]. A framework for training scenarios in the Maritime and Shipping industry using Virtual Reality and the Metaverse was introduced by Markopoulos et al. [75]. Upadhyay et al. reviewed and explored the adoption of Metaverse as a training ecosystem [76].

To improve training and development by scenario, Hajjami et al. explored the potential contribution of the Metaverse [77]. Additionally, Hawkins et al. showcased how virtual reality-based training tools integrate sensory immersion, sentiment data, voice biometrics, and cognitive computing systems across 3D digital worlds [78].

C. HEALTHCARE

Integrating the Metaverse into healthcare transforms the approach to medical treatment and health services. This innovative digital realm offers unique opportunities for experiential patient care, medical education and research. The Metaverse is transforming healthcare from telemedicine consultations in a virtual environment, emergency patient response, drug discovery and data management to medical simulations and therapeutic interventions. Figure 7 illustrates diverse applications of Metaverse in healthcare.

The use cases of the Metaverse environment in digital anti-ageing healthcare were discussed by Mozumder et al. [79]. Román-Belmonte et al. discussed the applications of Metaverse in the field of musculoskeletal disease management [80]. The use cases of Metaverse and virtual health care in Ophthalmology were discussed by Tan et al. [81]. Sharma et al. discussed the challenge of providing adequate healthcare on board ships and described the expansion of the maritime healthcare sector due to digitalization and automation through Metaverse [82]. The applications of the

FIGURE 7. Metaverse in healthcare.

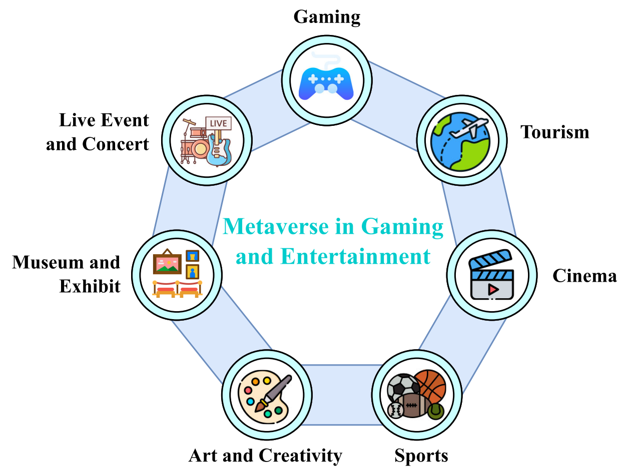

FIGURE 8. Metaverse in gaming and entertainment.

Metaverse in cardiovascular medicine, such as enhancing medical visits through avatar-based patient-doctor consultations and integrating telemedicine services, were explored by Skalidis et al. [83].

One of the most common use cases of Metaverse in healthcare is operating different surgical tasks. Methods were presented to simulate drilling and cutting of the bone using a burr and a motorized oscillating saw by Arikatla et al. allowing for low computational cost bone drilling or cutting while providing high fidelity haptic feedback suitable for real-time virtual surgery simulation [84]. Kim et al. discussed the state-of-the-art of Metaverse technology relevant to plastic surgery [85]. In other work, Aïm et al. discussed the use case of VR training in Orthopaedic surgery [86] and Ayoub et al. provided an overview of the literature on the application of virtual and augmented reality in oral and maxillofacial surgery [87]. The current applications of VR and AR in spine surgery were presented by Yoo et al. where VR is generally applied to teaching and preparation, and AR is utilized in surgical settings [88].

Noben et al. utilized the Metaverse to educate expectant mothers about cesarean surgery and to help alleviate their pre-procedure anxiety [89]. Setiawan et al. developed a VR application that incorporates training for a range of exercise activities to support pregnant women in improving their physical fitness. The application of Metaverse services in the healthcare industry was explored by Lee and Chang Won from a strategic perspective [90]. Mohamed et al. Zaman et al. and Thomason et al. separately discussed how the Metaverse may be used in the future to change, enhance, and possibly transform health care [91], [92], [93]. Furthermore, Zeng et al. highlighted the potential of the Metaverse as a new paradigm and the next frontier specifically in cancer care [94].

D. GAMING AND ENTERTAINMENT

Metaverse is revolutionizing gaming and entertainment, offering immersive experiences, social interactions and unlimited creative possibilities. Gamers and content creators are now exploring vast virtual worlds, forging new narratives and redefining the future of interactive entertainment. Figure 8 illustrates diverse applications of Metaverse in gaming and entertainment.

The Metaverse is rapidly transforming online gaming platforms, offering players an unprecedented level of immersion and connection. Whether exploring virtual worlds, competing in multiplayer adventures or taking part in creative challenges, there is a game for everyone in the Metaverse [4]. Fortnite https://www.fortnite.com/ is a multiplayer online video game that can be played in the virtual world. Minecraft is a sandbox video game that has also evolved into the Metaverse world https://www.minecraft.net/en-us/vr. Roblox https://www.roblox.com/ is another voxel-graphic online multiplayer Metaverse game targeted at a younger audience. Roblox's valuation reached $45 billion when it went public in 2021. In the First Quarter of 2023, it had 66.1 million daily active users and Net cash provided by operating activities were $173.8 million https://ir.roblox.com/news/news-details/2023/Roblox-Reports-First-Quarter-2023-Financial-Results/default.aspx. Gaming in Metaverse can also be considered as a source of income. Dope Wars https://dopewars.gg/ is a decentralized, play-to-earn gaming Metaverse platform with customize avatars and inspired by the hip-hop culture. Similarly, Revomon https://revomon.io/ is a Metaverse gaming platform that combines VR in an NFT play-to-earn game.

Numerous research studies have also been conducted with a specific focus on gaming within the Metaverse. Bhattacharya et al. proposed a scheme called Game-o-Meta that integrates federated learning in the Gaming Metaverse (GM) environment [95]. Tayal et al. highlighted the potential of the use of gamification in the Metaverse, which can have practical implications for various industries such as education, marketing, and finance [96]. Additionally, Jian et al. discussed how Metaverse has evolved the concept of gaming from traditional video games to online games and now to the concept of virtual reality gaming [97]. Another study by Jungherr et al. discussed the role of game engine companies in the commercial success of the games industry and how game engine companies like Epic Games aim to build Metaverse-like experiences through games like Fortnite [98].

Virtual Reality concerts and live performances in the Metaverse have become increasingly popular due to the COVID-19 epidemic and the rise of immersive technology [99], [100]. Kusuma et al. conducted a descriptive-qualitative analysis of two virtual concerts held by La Prima Course and Bandung Philharmonic during the COVID-19 pandemic, providing insights into the positive impact of these concerts on children's activities at home [101]. These events are held in virtual environments, allowing people to attend concerts and festivals from the comfort of their own homes. Some popular platforms for virtual reality concerts include Fortnite https://www.fortnite.com/, Roblox and https://www.roblox.com/ Wave https://wavexr.com/. Artists such as Travis Scott https://youtu.be/wYeFAlVC8qU, Ariana Grande https://youtu.be/RiM0moNk74o and Justin Bieber https://youtu.be/UAhGvhvcoyY have held successful virtual concerts in the Metaverse. Virtual reality concerts can be fully digital experiences or can feature live-action projections through the use of 360-degree video. To take the virtual concert experience to the next level, Oh et al. proposed a network framework for virtual concerts that aims to provide an immersive experience of exchanging interactions between performers and audiences [102]

The Metaverse is rapidly emerging as a transformative force in the tourism industry, promising travellers immersive and personalized experiences. With a mix of virtual reality, augmented reality and interactive platforms, Metaverse offers travellers the opportunity to explore destinations, plan holidays and engage in virtual tourism activities from the comfort of their homes or through on-site developments. It can also enhance the booking process and provide helpful information to tourists [103]. Pestek et al. discussed how recent trends in VR have changed the way the tourism and hospitality industry communicates their offerings and meets the tourists' needs [104]. A comprehensive conceptual framework called the PEI framework, which encompasses the determinants and consequences of presence in virtual reality for tourism marketing, was proposed by Yung et al in order to develop the tourism sector in Metaverse [105]. Furthermore, Buhalis et al. discussed how Metaverse can revolutionize tourism experiences and transform tourism management and marketing in the future [106].

The Metaverse also serves as a dynamic hub for film [107], media [108], sport [109], art [110], creativity [111], museums and exhibitions [112]. This digital realm is transforming the way we consume, engage and create content across these diverse fields, promising endless possibilities for immersive and interactive experiences. Whether it's entering a virtual cinema, attending a virtual sporting event, exploring digital art galleries or touring museums virtually, the Metaverse is revolutionizing entertainment as we know it.

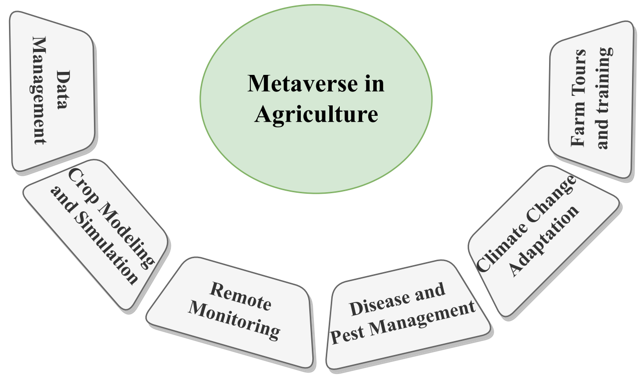

FIGURE 9. Metaverse in agriculture.

E. AGRICULTURE

The Metaverse has the potential to revolutionize agriculture and farming practices. One of the main advantages of Metaverse in agriculture is its ability to collect and analyze real-time data from farms. Metaverse can also encourage farmers to encourage more farmers to adopt innovative farming practices, which can lead to further benefits and improvements on the farm. Through the Metaverse, agriculture can connect with its urban cousins and better explain where food comes from. In the digital space, it is possible to visit a farm and share your observations with other avatars, and agriculture can use the Metaverse to tackle food shortages we face around the world. Farmers have the opportunity to create a digital twin of their farm to plan the most efficient harvest [113]. Figure 9 illustrates diverse applications of Metaverse in agriculture.

AgriVerse is a Metaverse-based agricultural platform that aims to optimize the production chain in agriculture by saving costs, increasing efficiencies, and breaking information silos, leading to sustainable agriculture [114]. Metaverse is also effective in creating immersive virtual farm simulation that provides realistic on-farm experiences to the public. Users can visit the virtual farm, walk through various sites where dairy cows are raised, and learn how dairy products are produced through the virtual experience [115]. Ulagammai et al. proposed an augmented reality-based intelligent precision agriculture system that utilizes smart sensors and deep learning algorithms for efficient irrigation and water management [116]. Virtual farm tours using VR glasses and tablets can be effective tools to increase transparency in agricultural activities and provide insights into pig husbandry conditions [117]. Kumari et al. discussed the future perspective of VR technology adoption in an emerging economy, specifically in the agriculture sector [118]

According to Xi et al. AR can potentially support more efficient farm management activities in aquaculture ponds: water quality management, remote collaboration, and boardroom discussion is [119]. A novel AR system was designed by Huuskonen et al. to help farmers supervise the operation of two autonomous agricultural machines, focusing on fleet management and ensuring safe operation [120]. AR is also used in precision farming, such as information communication, remote monitoring, and increased interaction [121]. Huuskonen et al. presented an AR-based novel approach to automatically determine the locations for soil samples based on a soil map created from drone imaging after ploughing [122]. Diverse agricultural activities like livestock farming, and aquaculture are also diving into Metaverse for a better outcome [123]. Metaverse has also been used in plant disease detection where Ponnusamy et al. developed a low-cost augmented reality system for on-field analysis of plant disease detection [124].

F. BUSINESS AND MARKETING

Metaverse is revolutionizing business, commerce, retail and digital marketing, providing a dynamic platform for innovative customer engagement [125]. In this virtual space, online shopping becomes an immersive experience, replicating the in-store experience and allowing users to digitally browse, buy and personalise products. Metaversus e-commerce, or meta-commerce, facilitates brand immersion and enables companies to simulate manufacturing plants, supply chains and retail spaces, streamlining operations and improving customer experiences [126]. Generative artificial intelligence will enhance these virtual spaces, offering new data sources. Businesses are also taking advantage of the Metaverse to meet consumers where they are and anticipate future trends, consolidating their presence in this evolving digital landscape.

Rathore and Bharati identified the radical impact of the Metaverse on modern marketing strategies [127]. An innovative business model of an e-commerce platform that combines live commerce with Metaverse using digital twin technology, overcoming the limitations of existing online shopping, was proposed by Jeong et al. [128]. The virtual world of Metaverse has the potential to diminish obstacles to traditional and adopting it improves customer experience and economic growth. Chakraborty et al. explored the rise of Metaverse-based technologies in the e-commerce industry as a viable and practical alternative to traditional technologies [129]. Furthermore, Cheah et al. investigated the impact of the Metaverse on marketing and proposed a new paradigm to address the challenges and opportunities it presents for consumer interaction with brands [130].

G. SOCIAL MEDIA AND INTERACTION

The Metaverse is ushering in a new era of social media and interaction, transcending the boundaries of traditional platforms. This digital frontier is transforming how we connect, communicate and collaborate online. In Metaverse, social experiences become immersive, allowing users to interact with friends, family and strangers in virtual spaces that blur the boundaries between the physical and digital worlds. From virtual gatherings and events to shared digital adventures, Metaverse redefines the notion of social networking and re-imagines how we interact with others in a rich, 3D and connected environment. Figure 10 illustrates diverse applications of Metaverse in social media and interaction.

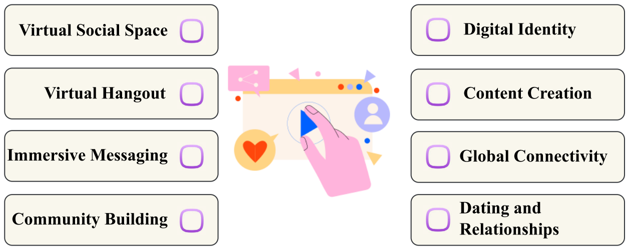

FIGURE 10. Metaverse in social media and interaction.

Hennig-Thurau et al. provided evidence that real-time multi-sensory social interactions in the Metaverse, accessed through virtual-reality headsets, can generate more value for interactants regarding interaction outcomes compared to those on the 2-Dimensional (2D) internet [131]. Metaverse is having significant advancements in haptic, tactile internet, and multimedia applications in the context of the emergent communication paradigms, such as semantic, holographic, and goal-oriented communication, which are expected to enable an energy and spectrally efficient Metaverse with ultra-low latency [132]. Jiaxin et al. described Metaverse as the future form of interaction that has appeared in science fiction works and is gradually being revealed with the development of internet technology [133]. Additionally, Metaverse-based social VR games are having a significant impact on users well-being, particularly for socially isolated individuals with low self-esteem [134]. By identifying the significant importance of the Metaverse platform and competing in the future of the communication world, global companies like Samsung and Facebook have already made notable financial investments in developing Metaverse platforms and related marketing [135]. Metaverse is also creating new opportunities for dating and relationship platforms with its potential like immersive messaging, global connectivity and community building.

H. FASHION

In the fashion industry, Metaverse serves as a dynamic hub beyond mere clothing, where fashion, technology and individuality meet. Here, users can create custom avatars, curate digital wardrobes and explore limitless fashion possibilities. Fashion events and runway shows within Metaverse redefine industry conventions and offer immersive global experiences [136]. Designers and brands are using this digital landscape to showcase exclusive virtual wardrobe experiences, accessories and even virtual fitting rooms where customers can digitally try on clothes before they buy. Figure 11 illustrates a virtual shop where virtual avatars are exploring fashion collections.

FIGURE 11. Virtual avatar exploring fashion collections.

Emerging technologies such as Blockchain, Non-Fungible Token (NFT), Artificial Intelligence (AI), Machine Learning (ML), and VR are impacting the fashion industry and luxury brands by reshaping luxury brands, reinventing consumer experience, and altering consumer behaviour [137]. virtual fashion shows, virtual try-on experiences, and virtual shopping in the Metaverse are acting as innovative marketing tools for fashion brands by creating immersive brand experiences and engaging with consumers in new ways [138]. Top fashion brands like Gucci, Louis Vuitton, Tommy Hilfiger and Dior have already invested in Metaverse to utilize this new market. Dai et al. discussed how Metaverse is evolving the sustainability and brand marketing model of smart kids-wear [139]. Metaverse is creating new brand-consumer immersive experiences, building communities, exploring new revenue streams, engaging in new forms of influencer marketing, and ensuring product traceability. Identifying these new opportunities, leading sportswear brands like Nike and Adidas have already announced their entry into the Metaverse with the launch of their NFT products [140]. Metaverse is also evolving in fashion streetwear by using the avatar as it becomes an extension and model of the individual by communicating through their appearance, similar to how people communicate their ideas and values through their looks and apparel in the real world. This close link between the Metaverse and fashion opens up new spaces of expression and application methods for fashion [141].

Trujillo et al. highlighted the growing interest of the fashion industry in Blockchain-based virtual worlds, with luxury brands experimenting with NFT collectibles and creating Decentraland wearables [142]. A concept called the VR fitting room was discussed by Cobben and Suzanne, which allows consumers to have an immersive and hyper-personalized online shopping experience. The consumer puts on VR glasses and enters a virtual space with a digital twin that can try on clothes. The surrounding environment can be adapted to the clothes being worn, providing a richer context for the consumer to evaluate the clothing [143]. Wang et al. proposed a clothing design system that utilizes virtual reality technology to improve the efficiency of clothing design and reduce waste in the process. By leveraging virtual reality technology, the proposed system can provide designers with a more immersive and realistic experience, allowing them to visualize and manipulate clothing designs in a virtual environment [144]. Sayem et al. discussed how using digital media platforms improves product innovation and opportunities for further improvement in the fashion industry [145]. Metaverse is also used in the fashion industry to enhance sustainability by reducing waste and the carbon footprint [146].

FIGURE 12. Virtual real estate in the Metaverse.

I. REAL ESTATE

Virtual real estate in the Metaverse consists of digital land and property within virtual worlds. Users can buy, sell, and customize these properties, which hold value for their location, aesthetics, and potential for social interaction and commerce. This virtual asset offers creative opportunities, social engagement, and potential financial gains as the Metaverse grows in prominence. Figure 12 illustrates a virtual real estate.

Lee and Yu Xin analyzed the applications of Metaverse in the real estate industry [147]. A novel approach was proposed by James et al. to examine the convergence of finance, technology, and law in the Metaverse real estate market to avoid potential pitfalls [148]. Ante et al. analyzed the investigation of retail investor motivations for owning digital real estate in the crypto-metaverse. The study identified four distinct motivational groups among Metaverse landowners: Aesthetics and Identity, Social and Community, Speculation and Investment, and Innovation and Technology [149]. Fioretto et al. delved into the distinctive realms of physical and virtual real estate markets, including the application of Nigel Gilbert's model [150]. Voraprapa et al. analyzed the cryptocurrency unit of account in virtual real estate transactions, shedding light on the economic dynamics of this emerging market within Blockchain-based Metaverses [151]. Athira et al.

TABLE 3. References of selected articles published on different Metaverse Application Domain.

Application Domain	Study Count	References
Education	26	[35] - [60]
Research and Training	18	[61] - [78]
Healthcare	16	[79] - [94]
Gaming and Entertainment	18	[95] - [112]
Agriculture	12	[113] - [124]
Business and Marketing	6	[125] - [130]
Social Media and Interaction	5	[131] - [135]
Fashion	11	[136] - [146]
Real Estate	6	[147] - [152]

explored how the residential real estate sector can leverage the emerging Metaverse concept, a digital interconnected world through virtual reality, to enhance consumer experiences. The study's experiment with potential home buyers demonstrates that the atmosphere in the virtual environment significantly influences satisfaction, perceived enjoyment, and purchase intention compared to the physical environment [152].

Here, Table 3 further visualizes the distribution of selected articles across different Metaverse applications domain.

IV. CHALLENGES OF THE METAVERSE

The Metaverse presents exciting possibilities but faces significant challenges, including privacy concerns, digital identity issues, and the need for seamless interoperability among diverse virtual worlds. Figure 13 visualize some of the major challenges of Metaverse and their diverse concerns.

A. SECURITY AND CONFIDENTIALITY SAFEGUARDS AND MORAL UNCERTAINTIES

The emergence of the Metaverse marks a profound shift in the digital landscape, yet it introduces a multifaceted array of challenges like security, confidentiality safeguards, and ethical uncertainties. Inhabitants of this interconnected virtual realm face pressing issues concerning the safeguarding of personal data, the risk of privacy breaches, and the ever-present threat of cyberattacks. Balancing the imperative for innovation with the need for rigorous security measures remains a continuous technical struggle within the Metaverse's dynamic environment.

The privacy challenges in the Metaverse revolve around the need for users to disclose personal data to engage virtually, which increases privacy concerns. The Metaverse's decentralized governance framework presents challenges in establishing clear responsibilities and accountabilities for user privacy. In addition, the immersive nature of Metaverse creates difficulties in avoiding the collection of personal data at multiple access points, often coupled with service consent requirements, further exacerbating privacy dilemmas. According to Far et al. users' need for an untraceable environment raises concerns about privacy and security while establishing trust in a decentralized environment without trusted third parties is difficult. Additionally, Proving the security and ownership of valuable assets such as Digital Twin (DT) is paramount as they are attractive to hackers. They also raised concerns about personal data protection, unauthorized access, data breaches and cyber-attacks, which underpin the need for strong data protection measures in the Metaverse [153]. According to Letafati et al., Metaverse confronts significant technical security challenges, including the lack of a comprehensive overview of risks, insufficient attention to specific use-cases like healthcare, and vulnerabilities across network layers, ML and AI models, and distributed ML models [154]. In another work Adil et al. classify Metaverse's technical security challenges as maintaining client authentication parameters, preventing unauthorized access, addressing the security requirements of integrated technologies such as IoT, Wireless Sensor Network (WSN), Unmanned Aerial Vehicle (UAV), Internet of Vehicles (IoV), and Internet of Everything (IoE) applications, ensuring interoperability to overcome open security issues, and addressing integration security challenges in 5G and 6G-based Metaverse applications [155]. According to Chen et al., technical security challenges include privacy concerns arising from the merging of physical and digital realities, identity theft risks from identity manipulation, cybersecurity threats such as hacking and data breaches, theft of virtual property, and the need for effective content management mechanisms to ensure security [156].

Concern was raised regarding potential intrusive privacy attacks by collecting personal, mental, physical, and environmental data from Metaverse accessories attached to the human body by Qamar et al.. They also highlighted the potential of huge attack surface in the Metaverse due to interlinked technologies, providing attackers with various opportunities to exploit and the Lack of repositories for reporting security vulnerabilities and limited policy guidelines for XR consumers, application developers, device manufacturers, and stakeholders [157]. In another work, Chen et al. also raised concern about wearable devices such as VR glasses and headsets, which are used to access the Metaverse for collecting user data, including biometric features, which, if leaked, can pose a serious threat to user privacy. Additionally, Metaverse requires strong authentication and access control to protect user avatars and digital assets. Flaws in smart contracts and phishing attacks can lead to identity theft and loss of assets [158]. The possible security concerns about future attacks guided by AI were mentioned by Kürtünlüoğlu et al. as the interaction of AI-guided software with users in various activities will make it challenging to make a difference between software bots and humans [159]. Sfar et al. identified three key security challenges in the context of the Internet of Things (IoT): data confidentiality, privacy, and trust and criticized the lack of attention given to authentication, integrity, and access control, which were considered as parts of the key issues defined by the authors [160]. Furthermore, the rise of the darkverse, a private space within the Metaverse for illegal activities and communication among criminals, presents a significant security concern. It operates similarly to the dark web but is unindexed, making it challenging to locate [161].

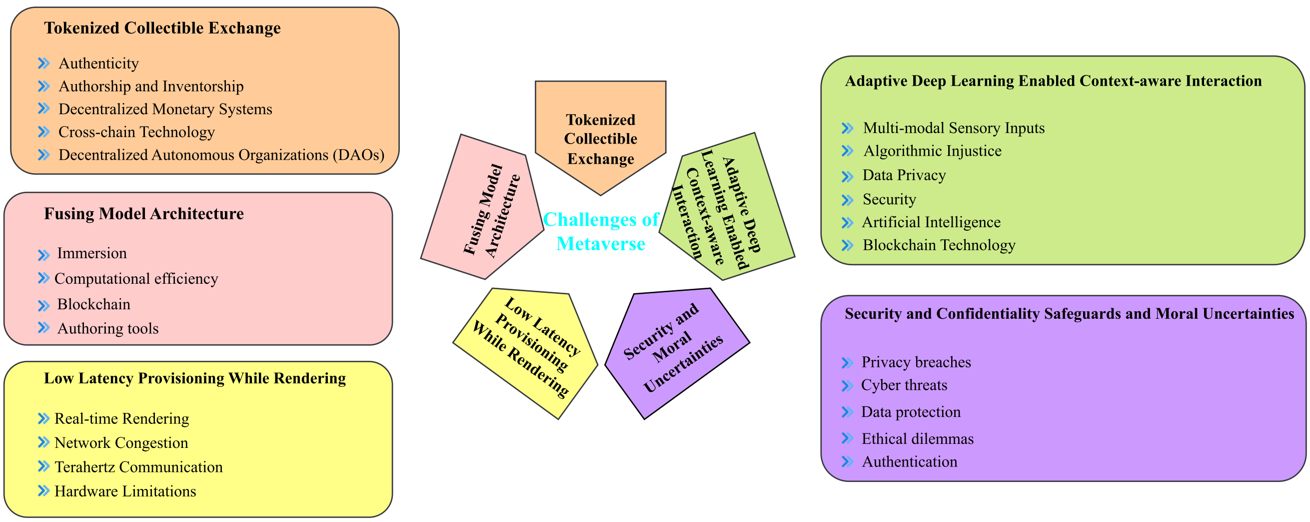

FIGURE 13. Challenges of Metaverse.

The emergence of the Metaverse also raises significant ethical challenges, including privacy, security, social consequences, and the ethical dimensions of design-driven and people-driven decisions in the digital space. These challenges delve into the ambiguity of ethics, exploring the subjectivity versus objectivity debate, while also addressing conflicts between self-interest and the common good. According to Smith et al. the unintended consequences of the hyper-connected, algorithmic, and virtualized economic context of the Metaverse may not always be socially and humanly acceptable, particularly for vulnerable groups in society [162]. The tokenization of assets in the Metaverse, such as Non-Fungible Tokens (NFTs), raises ethical questions regarding ownership, value, and exploitation [163]. The use of artificial intelligence and algorithms in the Metaverse can also lead to ethical dilemmas related to privacy, bias, and discrimination. Additionally, the importance of perspective and the question of "what is ethical truth?" are also major ethical challenges in the Metaverse.

B. TOKENIZED COLLECTIBLE EXCHANGE

The exchange of tokenized collections within the Metaverse creates a fascinating but technically complex and challenging area. As digital realms have evolved, significant barriers to interoperability between different virtual environments have emerged. Ensuring the provenance and authenticity of collections in this digital space is a pressing issue. In addition, the creation of secure and efficient trading platforms for these tokenized assets presents significant technical challenges in order to facilitate seamless transactions within Metaverse.

Huang et al. highlighted a range of challenges of Metaverse, including the complexities of determining authorship and inventorship of AI-generated content and the need to tackle risks associated with avatars, such as fraud and security issues. The discussion revolved around the importance of decentralized financial systems within Metaverse, emphasizing the role of cross-chain technology in wallet applications as there is a strong advocacy for fostering cross-Metaverse interoperability to bridge different platforms [164]. Regarding tokenized collectible exchange challenges, Wang et al. spanned the domains of usability, security, governance, and extensibility. Usability issues include addressing slow transaction confirmations and high gas prices on Blockchain platforms like Ethereum. Security and privacy concerns involve issues such as NFT data inaccessibility and the need for enhanced anonymity and privacy measures [165].

Furthermore, Rehman et al. discussed issues such as intellectual property rights, cybersecurity threats, security and privacy concerns, smart contract vulnerabilities, and the environmental impact of Blockchain technologies [166]. The complexity of tokenized collectible exchanges is further complicated by regulatory ambiguities and the requirement for uniform protocols. This underscores the importance of innovative solutions and cooperative endeavours to harness the potential of this emerging virtual economy fully.

C. FUSING MODEL ARCHITECTURE

The emergence of the Metaverse has ushered in a new era of digital interaction and immersion, presenting exciting opportunities for enhancing user experiences. However, one of the foremost challenges in this dynamic landscape lies in the fusion of diverse model architectures. Integrating various virtual worlds, AI-driven agents, and sensory inputs into a seamless and cohesive Metaverse requires overcoming substantial hurdles related to interoperability, scalability, and computational efficiency.

Huang et al. argued that the existing scenario of the Metaverse is biased towards re-creating virtual land, buildings, and cities, rather than recording the development, changes, and iterations of real-world cities and buildings based on existing information data. This opens a challenge in creating a Metaverse that incorporates real-world information using BIM, CIM, Blockchain technology, etc. [167]. Yang et al. discussed that the fusion of AI and Blockchain in the Metaverse poses several emerging research challenges, such as handling high transaction volumes and ensuring the security and efficiency of digital products and markets. Additionally, they raised concerns about the development of authoring tools to enable users to easily produce original content and gain rewards efficiently in the digital economy of the Metaverse as well as the need to address the identity and value of digital objects in the virtual world, as they determine value instead of undifferentiated labor in the conventional economy [168].

In addition, integrating model architectures in the Metaverse can add additional complexity, such as achieving a seamless integration of different technologies and data sources, including Building Information Modeling (BIM), City Information Modeling (CIM) and Blockchain, to accurately incorporate real-world information. This requires standardized protocols and interoperability between these systems. The fusion of AI and Blockchain within the Metaverse raises concerns about the secure and efficient management of large transaction volumes, especially in digital product markets, and there is an urgent need to develop user-friendly authoring tools for the creation of original content, enabling fair rewards in the digital economy [169].

D. LOW LATENCY PROVISIONING

Low latency provisioning within Metaverse is a multifaceted challenge, highlighting the paramount importance of providing users with a seamless and real-time rendering experience. In the ever-evolving world of virtual worlds and augmented realities, user expectations are leaning towards instant responsiveness and deep immersion. However, achieving low latency in this context is a complex task. There are several obstacles to overcome, including network congestion, hardware limitations and the demanding computational tasks involved in rendering complex virtual environments. These technical complications underscore the importance of addressing latency issues to provide users with the immersive and responsive experience they require in the Metaverse.

Akyildiz et al. emphasized the need for advanced wireless communication technologies, including terahertz communication, semantic communication, and space-air-ground-sea integrated networking, to provide high-speed, low-latency connectivity for multimedia devices [170]. Yu et al. highlighted three critical areas of concern: the integration of heterogeneous 6G technologies and the importance of managing diverse communication resources efficiently, emphasizing the role of AI models in predicting network congestion and optimizing resource allocation, and the significance of delivering a comprehensive five-sense user experience within the Metaverse. Additionally, they highlighted the importance of research into modelling user perception, developing adaptive systems, and ensuring fairness in resource allocation, AI-Generated Content (AIGC) and its potential for enhancing the Metaverse where they acknowledged the challenges of real-time content generation, data privacy and security, computational power, privacy-preserving AI, and secure data sharing to support the demands of multiple users and AIGC within the Metaverse [171]. Awan et al. discussed that the rapid development and proliferation of connected devices in the Metaverse-based Internet of Things (IoT) has led to increased network traffic, which has led to latency problems. Existing methods to reduce latency, such as service placement algorithms, the development of wireless communication technologies and edge computing, do not fully take into account the unique characteristics of the Metaverse, in particular, the significant trust dependency due to the lack of a central authority [172].

Additionally, Zhang et al. discussed that the client device typically has weaker computing capability compared to the server, which can lead to increased latency in the authentication and key exchange process [173]. Some critical challenges related to low-latency provisioning in the Metaverse were addressed by Chang et al. Challenges like limited resources, computing power and sensing tools hinder achieving full immersion, materialization and interoperability. There are also privacy concerns as Metaverse has the potential to monitor users' physiological reactions and body movements, which could risk exposing sensitive personal data. Network latency adds to the challenges as it affects real-time interactions and the responsiveness of the virtual world. It also raises resource allocation issues that require efficient allocation and use of resources to ensure a seamless user experience [174]. According to Aslam et al. the main challenge to achieve the low latency required for Metaverse deployment is to achieve latency below 1 microsecond in 6G wireless systems. This is key to delivering real-time and immersive Metaverse experiences [175]. The wireless communications, networking, and computing for Digital Twin (DT) are still in their infancy, making it difficult to achieve the necessary low latency for a fully immersive and pervasive Metaverse experience [176]. Therefore, maintaining a consistent, high-quality user experience requires not only cutting-edge technology but also the ability to adapt to rapidly changing conditions within the Metaverse, making this a pivotal challenge for developers and engineers striving to unlock the full potential of immersive digital environments.

E. ADAPTIVE DEEP LEARNING ENABLED CONTEXT-AWARE INTERACTION

Integrating adaptive deep learning and context-aware interaction within Metaverse is a cutting-edge frontier, accompanied by a series of formidable technical challenges. To successfully navigate this dynamic landscape, addressing privacy and security concerns in virtual environments is paramount. In addition, seamlessly integrating the real-world context into the Metaverse presents complex technical hurdles. Managing the complexity arising from multimodal sensory inputs is also critical. Developing adaptive algorithms that can evolve in the ever-changing Metaverse ecosystem remains a significant technical challenge.

The main challenge in context-aware adaptive deep learning-enabled interaction lies in developing deep learning models that can adapt to contextual factors such as user preferences, environmental conditions, and task requirements. Handling of artificial intelligence models and data in immersive multimedia applications can be a significant concern due to the standard features of these applications, such as high fidelity, immersive interaction, and open data exchange between people and the environment [177]. Concern related to the risk of algorithmic injustice in learning systems that rely on historical data, leading to biases and exclusions, was raised by Rospigliosi et al.. They also raised concern that the deep learning process can be determined by data extracted from internet usage patterns without proper monitoring and supervision, which can reinforce biases and exclusions [178]. Additionally, a unique problem of Non-Independent and Identically Distributed (Non-IID) data in the industrial practice of the Metaverse was discussed by Zeng et al., where the data generated by industrial equipment is continuously streaming and heterogeneous. Traditional deep learning methods struggle to handle this type of data, leading to reduced performance and efficiency [179]. Optimizing computing resources for training meta-models, handling statistical uncertainties, and ensuring privacy in federated learning was some of the major concern raised by Khan et al. where overcoming limitations, such as scalability, slow convergence and enabling efficient distributed training, remained a key focus for enhancing the Metaverse systems [180].

The challenges of adaptive deep learning-enabled context-aware interaction in the Metaverse are mainly developing intelligent contextual interaction-enabled deep learning techniques for understanding and responding to user context, ensuring seamless integration of context-aware interactions, overcoming barriers to real-time context processing, designing efficient algorithms for large-scale environments, and meeting the need for personalized interactions that adapt to the preferences and needs of individual users.

Here, Table 4 further discusses some of the main challenges that were mentioned by researchers, for a better understanding of them.

V. TOWARDS TRUSTWORTHY METAVERSE

A. IS METAVERSE TRUSTWORTHY?

The question of trustworthiness in the emerging realm of the Metaverse is a critical concern that warrants thorough examination. While the concept of a Metaverse holds great promise, it also raises numerous potential challenges and risks across various applications that may undermine its trustworthiness.

One primary concern revolves in the realm of social interactions is, whether the Metaverse poses significant risks to user privacy. As individuals immerse themselves in virtual environments and engage in social activities, the collection of vast amounts of personal data becomes inevitable, opening the door to potential misuse or unauthorized access. Moreover, the Metaverse's reliance on advanced technology, such as virtual reality and augmented reality, introduces vulnerabilities in terms of cybersecurity, making users susceptible to hacking, identity theft, and malicious attacks, undermining the overall trustworthiness of the platform. Another crucial aspect is the Metaverse's economic applications, such as virtual economies and digital currencies, raise concerns about financial security and fraud. In these virtual economies, where real-world assets and transactions are increasing. intertwined with virtual assets and currencies, users may face risks associated with scams, fraudulent schemes, and economic instability. Trust in these systems becomes crucial, but their decentralized and often unregulated nature can create a fertile ground for financial misconduct and exploitation. Additionally, the Metaverse's impact on mental and emotional well-being is also a big concern, as users spend more time in virtual environments. As a result, concerns emerge about addiction, social isolation, and the blurring of boundaries between the virtual and physical worlds. Trust in the Metaverse's impact on mental health is essential, as it can either enhance or deteriorate the well-being of its users, depending on how it is designed and regulated. Furthermore, ethical concerns surrounding content moderation and the potential for the Metaverse to host harmful or illegal content also contribute to doubts about its trustworthiness. As diverse challenges continue to rise, the Metaverse ecosystem is still not considered fully trusted by many. Striking a balance between free expression and protecting users from harm is a complex challenge, and the Metaverse's governance structures will play a pivotal role in determining whether it can be considered a trustworthy space for diverse communities.

B. OVERCOMING THE CHALLENGES OF METAVERSE

1) SECURITY AND CONFIDENTIALITY SAFEGUARDS AND MORAL UNCERTAINTIES

A multi-faceted approach is essential to effectively address the security challenges of the Metaverse. This starts with a comprehensive understanding of potential security issues across hardware, software, systems and platforms. Infrastructure deployment, including computing, cloud, network and digital assets, must prioritize system security to mitigate the inherent risks. Operational considerations should extend to functional and network security, potentially requiring robust security guarantees at the operating system level. Adopting a Zero Trust Architecture (ZTA) [181] model offers a promising solution to address privacy, security and control concerns in the Metaverse. Furthermore, security and efficiency can be enhanced through user authentication and data integrity verification within Metaverse applications using Non-Fungible Token (NFT) and Proof-of-Stake (PoS) consensus algorithms.

By addressing an intrusion-based network attack within the Metaverse environment through the use of digital twins

TABLE 4. Major concerns of Metaverse raised by researchers.

Reference	Challenge	Description
Far *et al.* [153]	Privacy and Security	Users demand untraceable environments raises privacy and security concerns, challenging the establishment of trust in decentralized settings without relying on trusted third parties.
Letafati *et al.* [154]	Privacy and Security	Technical security challenges, such as the absence of a comprehensive risk overview, inadequate focus on specific domains like healthcare, and vulnerabilities across network layers, ML/AI models, and distributed ML models.
Qamar *et al.* [157]	Privacy Attack	Intrusive privacy breaches can happen when personal, mental, physical, and environmental data is collected through Metaverse accessories worn on the human body.
Kürtünlüoğlu *et al.* [159]	Identity Verification	The interaction of AI-guided software with users in various activities will pose a challenge in distinguishing between software bots and humans.
Calvo *et al.* [163]	Ethical Concern	Use of AI and algorithms in the Metaverse can lead to ethical dilemmas related to privacy, bias, and discrimination.
Huang *et al.* [164]	Authorship	Complexities arise when determining authorship and inventorship of AI-generated content.
Wang *et al.* [165]	Usability Issues	low transaction confirmations and high gas prices create challenges on Blockchain platforms like Ethereum.
Yang *et al.* [168]	Multi-Model Integration	Integrating AI and Blockchain in the Metaverse creates challenges like managing high transaction volumes and ensuring digital product and market security and efficiency.
Fu *et al.* [169]	Multi-Model Integration	Complexities arise in seamlessly integrating various technologies and data sources, including BIM, CIM, and Blockchain, for precise real-world information incorporation.
Awan *et al.* [172]	Latency Problem	The rapid growth of connected devices in the Metaverse-based IoT has resulted in heightened network traffic, which is causing latency issues.
Zhang *et al.* [173]	Latency Problem	Client devices usually have lower computing power than servers, potentially causing increased latency during authentication and key exchange.
Duong *et al.* [176]	Latency Problem	Wireless communications, networking, and computing for Digital Twins (DT) are in the early stages, posing challenges in attaining the required low latency for a fully immersive Metaverse experience.
Zeng *et al.* [179]	Adaptive Interaction	Non-IID data from industrial equipment is constantly streaming and heterogeneous, posing challenges for traditional deep learning methods to handle such data effectively.

and Software-Defined Networking (SDN), Krishnan et al. proposed a method that involved constructing a behaviour monitoring and profiling system. In this method, security protocols were initially assessed on digital twins and subsequently deployed in real networks operating in the Metaverse environment [182]. Ruth et al. addressed the security concern of unsecured AR content sharing in the Metaverse by introducing a content-sharing control mechanism implemented as a prototype on HoloLens. This mechanism allows remote users to share AR content with both inbound and outbound control [183]. A cloud-based privacy leakage forensics scheme as an alternative approach to addressing privacy violations and governance-related threats was introduced by Zoo et al. Their scheme was designed to collect digital evidence without accessing users' private data in a simulated virtual environment. It employed techniques such as taint investigation and RAM mirroring. In the context of the Metaverse era, this approach aims to combat identity theft, data breaches, and network-related attacks, which are significant concerns [184]. According to Imamguluyev et al., implementing a fuzzy logic approach to decision-making

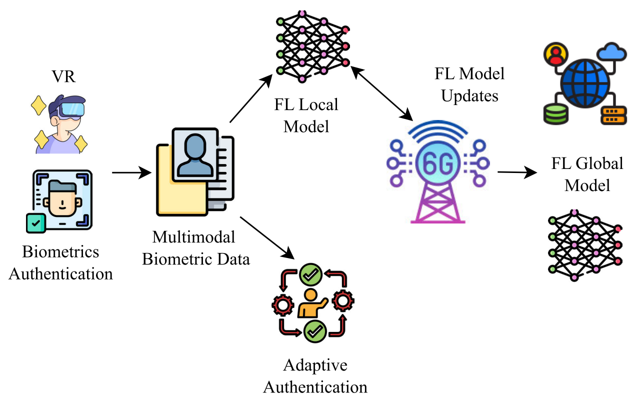

FIGURE 14. MetaGuard architecture.

can help address ethical concerns in the Metaverse, allowing for more nuanced and adaptable responses to uncertain and complex situations. Companies and regulators can integrate fuzzy logic into their decision-making processes to navigate ethical challenges in the Metaverse effectively [185].

A comprehensive research agenda for zero-trust user authentication in the context of social Virtual Reality (VR), an early prototype of the Metaverse, was presented by Cheng et al.. They proposed MetaGuard, an innovative privacy-preserving authentication framework that leverages federated learning and multimodal biometrics to provide continuous and adaptive user authentication in this emerging virtual environment. Figure 14 represents the proposed MetaGuard approach, which encompasses four key steps: exploring biometrics-based authentication for continuous user verification in VR, employing federated learning for safeguarding user privacy in biometric data, enhancing authentication accuracy through multimodal data integration, and improving the usability of zero-trust security via adaptive authentication [186].

Din et al. proposed a Context-Aware Cognitive Memory Trust Management (CACMTM) system specifically designed for achieving trustworthy communications in intelligent transportation systems. It uses a multi-dimensional trust evaluation model and integrates Blockchain for security and transparency. Figure 15 illustrates the system model, which consists of four core modules that work synergistically to create a robust trust management solution. These modules include the trust evaluation module, which evaluates the behaviour and feedback of IoT devices; the trust decision module, which uses game theory to determine access permissions; the trust updater module, which maintains up-to-date trust scores based on real-time conditions and device behaviour; and the Knowledge module, which manages a comprehensive database of device histories and applies advanced machine learning to identify potential threats and enrich decision-making within the cognitive networked cyber-physical transportation systems environment [187]. Together, these modules form a comprehensive framework for trust management, ensuring secure and informed access control decisions.

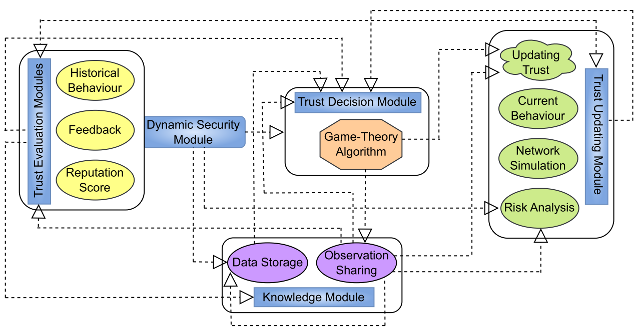

FIGURE 15. **CACMTM architecture.**

Kwon et al. explored the integration of quantum techniques with the Metaverse, focusing on security, randomness, computation, and communication. They proposed a method using Quantum Random Number Generation (QRNG) and Quantum Key Distribution (QKD) to bolster Metaverse security against present and future cyber-attacks, while also considering the potential application of quantum algorithms for complex optimization problems within the Metaverse [188]. Additionally, Zhu et al. presented a heuristic greedy technique for dynamic node blocking, aimed at mitigating physical, social, and information-spreading threats in Metaverse applications. Their proposed approach focuses on minimizing the dissemination of misinformation in online social networks within the Metaverse [189]. Furthermore, to address the ethical challenges of Metaverse, businesses need to develop transparent policies, engage in ethical decision-making processes and prioritize responsible data use. This includes considering the best ethical course of action that benefits all stakeholders, rather than solely profit-driven decisions. Fostering constructive discussions involving different stakeholders can raise awareness and promote responsible behaviour in the Metaverse ecosystem.

2) TOKENIZED COLLECTIBLE EXCHANGE

Overcoming the complex challenges surrounding the exchange of tokenized collectibles within the Metaverse requires a comprehensive approach. To overcome the interoperability barriers between different virtual environments, it is essential to develop standardized protocols and interfaces to ensure seamless asset transfer between digital realms. Ensuring the provenance and authenticity of collections can be achieved by integrating Blockchain technology, which offers transparent and immutable records to verify the history and ownership of assets. In addition, creating secure and efficient trading platforms requires robust security measures and optimized infrastructure, including high-performance Blockchain networks, to reduce transaction costs and latency. Collaborative efforts and continuous technological improvements within the Metaverse community are key to making this fascinating digital realm more accessible and secure for users.

García et al. proposed CopyrightLY, a decentralized application for authorship and copyright management in the emerging decentralized creator economy. It utilizes public Blockchains and NFTs to establish real ownership, enhances metadata with semantic technologies, and introduces a unique token system for handling authorship claims. Additionally, it enables licensing NFTs with semantic metadata, fostering creative economies in Metaverse environments, and serves as a Proof of Concept in the European Next Generation Internet ONTOCHAIN project [190]. Hari et al. expanded the utility of decentralized finance (DeFi) by proposing the integration of Non-Fungible Tokens (NFTs) into the realm of real estate property assets. It explored using Blockchain technology and NFTs to create a secure and traceable system for tokenizing and trading real estate assets. It offers a potential solution to enhance liquidity and accessibility in the real estate market while addressing property management and exchange challenges [191]. A decentralized cross-domain authentication scheme utilizing Blockchain technology was developed by Shen et al. This method employed anonymous authentication protocols and incorporated trust and identity-based encryption through a consortium Blockchain. It was demonstrated to be secure against various types of attacks, including identity theft, privacy breaches, and man-in-the-middle attacks [192].

A game-theoretical approach to form Nash-stable social clusters was proposed by Wang et al., where they ensured fair revenue distribution among avatars based on their learning contributions and introduced a lightweight Blockchain-based system for decentralized AI model aggregation, optimizing efficiency through on-chain and off-chain collaboration while electing validating nodes for consensus. They also outlined a watermark-based method for shared FedAI ownership verification, where joint watermarks are generated and embedded in models to trace potential infringements, and external verification was facilitated through a scoring mechanism and consensus among model owners [193]. Li et al. utilized Blockchain to address privacy and network security issues in the Metaverse, implementing a decentralized forensics method through smart contracts to enhance convenience and reduce costs for multiple entities and platforms [194]. Furthermore, Guan et al. tackled transaction and economy-based attacks in the Metaverse by leveraging Blockchain technology. They proposed a privacy-preserving Blockchain scheme based on zero-knowledge proofs to protect sender-recipient linkage, account balances, and transaction amounts [195].

3) FUSING MODEL ARCHITECTURE

Overcoming the challenges of integrating model architectures within Metaverse involves adopting standardization and interoperability to ensure seamless compatibility between different systems. The use of a modular design approach, complemented by well-defined application programming interfaces (APIs) and frameworks, further simplifies the process, allowing developers to easily integrate independent and reusable components into different Metaverse environments.

To achieve the fusion of diverse model architectures in the Metaverse while overcoming hurdles related to interoperability, scalability, and computational efficiency Qu et al. have suggested the use of multi-modal machine learning techniques, which have shown success in complex real-world problems [196]. Falchuk et al. introduced an innovative approach that leverages avatar confusion and private copies to enhance privacy preservation for digital footprints within Metaverse applications. This method offers comprehensive protection against digital footprint attacks and various privacy threats [197]. Han et al. introduced a hierarchical game approach to dynamically synchronize digital twins in the Metaverse environment, adapting synchronization intensities based on the status information collected from physical entities by end devices and virtual service providers [198]. Furthermore, for multi-modality image fusion, deep learning models with effective architectures have been proposed by Liu et al. to handle demanding fusion tasks and preserve target and textural details [199].

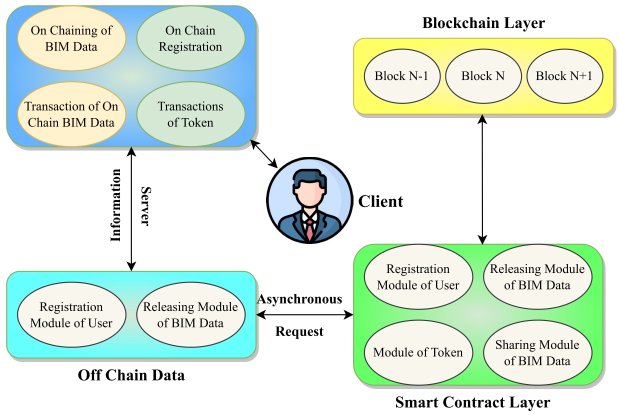

FIGURE 16. Blockchain integrated BIM framework.

A Blockchain-enabled Metaverse system was implemented by Xu et al. that integrated hardware and software components efficiently and allocates resources effectively. It incorporates an On-Demand Trusted Computing Environment (OTCE) technique based on local trust evaluation, utilizes a hypergraph representation of the Metaverse, and maps trust values to security plans, enabling flexible application environments with strong security guarantees and dynamic resource allocation based on changing trust values [200]. Liu et al. proposed Slicing4Meta architecture that seamlessly integrates Metaverse-as-a-Service (MaaS) models and multi-dimensional resources, comprising three key functions: Metaverse Service Management Function (MSMF) for user requirements translation, Virtual Orchestration and Management Function (VMOF) for Metaverse Service Instances (MSIs) orchestration, and MaaS Management Function (MMF) for MaaS model management. This holistic integration enables customizable and scalable Metaverse services for immersive user experiences, effectively merging the physical and virtual realms [201]. Tang and Hou developed a preliminary framework for Metaverse, facilitating the fusion of holographic and physical architectural elements to meet users' needs seamlessly. Architects and designers can leverage this framework to create immersive experiences, integrating virtual and physical realms, thus ensuring architectural requirements are met while reducing carbon footprint in Metaverse architecture through innovative design approaches [202].

The convergence of emerging wireless communication networks, Blockchain, Web 3.0, artificial intelligence, and NFT can further enhance the capabilities of the Metaverse. For instance, The integration of BIM and Blockchain enables secure and transparent sharing of project data, streamlines communication and coordination between stakeholders, and facilitates the tracking and monitoring of project changes and transactions. Figure 16 illustrates the integration of BIM and Blockchain. This Blockchain-based BIM data transaction system consists of four layers: an information server, an off-chain data layer, a smart contract layer and

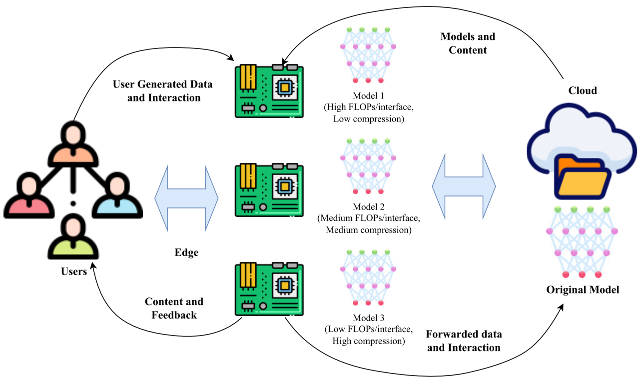

FIGURE 17. Visual representation of edge intelligence in immersive multimedia applications.

a Blockchain layer. The Blockchain ensures secure storage of BIM data sources by leveraging the encryption, tamper-resistance and decentralized storage capabilities of the Blockchain. The smart contracts automate BIM data transactions, covering the storage of user information, release of BIM data within the chain and data transactions. These steps include ID registration, log-in, encrypted ID storage, BIM data publishing and storage, and token-based BIM data transactions that allow users to access and purchase preferred BIM data [167].

4) LOW LATENCY PROVISIONING

Ensuring optimal latency during Metaverse rendering requires a comprehensive strategy that starts with the use of state-of-the-art rendering technologies and algorithms that prioritize low-latency rendering through optimized pipelines, hardware acceleration, and real-time ray-tracing exploration. In parallel, the selection of high-speed, low-latency networks, such as 5G or 6G, and strategically placed content delivery networks (CDNs) is key to minimizing data transmission delays. In addition, the implementation of edge computing, adaptive rendering techniques and continuous performance monitoring will ensure a responsive and immersive Metaverse experience, while promoting scalability and adaptability.

Wang et al. developed a framework that seamlessly combines accuracy and latency-aware edge intelligence for immersive media, leveraging adaptive deep learning model deployment and data streaming. Their implementation harnesses the power of edge computing to enhance the immersive media experience, supporting high fidelity, interactive features, and efficient data exchange while demonstrating the advantages of edge intelligence for conventional mechanisms like content placement and rate adaptation, as well as emerging technologies like 360-degree and virtual reality streaming [203]. Figure 17 visualizes the representation of edge intelligence in immersive multimedia applications. The infrastructure designed for the immersive Metaverse aims to be accessible at the edge, offering a range of functionalities encompassing communication, networking, computation, and Blockchain support. In this emerging infrastructure paradigm, edge computing serves as a vital intermediary layer positioned closer to users, bridging the gap between the cloud and user devices [204]. Within the edge environment, interactions and data generated by users in immersive multimedia applications can be efficiently processed through a "device-to-edge" offloading approach, while the cloud can also delegate certain tasks to the edge, such as executing compressed deep learning models for local inference services. This shift towards edge computing in the Metaverse promises reduced costs, lower latency, enhanced scalability, and improved privacy protection.

To achieve low latency in a joint UpLink and DownLink (UL-DL) scenario, Yu et al. introduced a novel multi-agent reinforcement learning algorithm called Asynchronous Actors Hybrid Critic (AAHC). This algorithm optimizes decisions pertaining to computation offloading, channel assignment, and DL transmission power, ensuring both reliability and reduced latency in the system [205]. Awan et al. have developed a trust-based resource allocation framework for the Metaverse that not only enhances the secure sharing of computational resources but also reduces latency and improves overall performance. Their innovative approach incorporated a reputation system, decentralized trust management and a trust-verifying consensus mechanism, which together enhance security, trust and cooperation among Metaverse entities, resulting in significant latency reduction, improved scalability and enhanced detection of malicious nodes, as demonstrated by simulation results that outperform existing methods [172]. To achieve low latency in Metaverse applications, Duong et al. proposed the integration of multi-tier computing, which combines edge and cloud computing resources. This approach allows for faster data processing. Additionally, they leverage ultra-reliable and low-latency communications (URLLC) capabilities offered by 6G networks to meet the Metaverse's stringent quality-of-service (QoS) requirements, ensuring minimal latency and facilitating a more immersive and pervasive Metaverse experience [176]. In another work, multi-tier computing empowered wireless Ultra-Reliable and Low-Latency Communication (URLLC) in 6G networks has also been considered by Huynh et al. as a key technique to achieve low latency in Metaverse applications [206].

Aslam et al. put forth a layered reference model for the Metaverse, seamlessly integrating with 6G wireless networks to enable real-time user interactions bridging the physical and virtual realms. To attain low latency, they underscored the necessity of incorporating ultra-low latency support architectures, prioritizing spectral and energy efficiency considerations in the evolution of 6G networks, thus ensuring the Metaverse's responsiveness and immersive user experience [175]. A solution to optimize the control latency in Software-Defined Wide Area Network (SD-WAN) by considering the dynamic state of each switch and the programmability of critical flows was approached by Qi et al. [207]. Zhang et al. discussed that using an authentication protocol that transfers computational tasks from the client to the server can reduce the overall latency in the Energy Internet of Thing (EIoT) systems in the Metaverse era. This approach allows the client to have fewer computing tasks, leveraging the stronger computing capability of the server, resulting in reduced latency [173]. Furthermore, According to Cao et al., although achieving low latency in the Metaverse can be challenging, optimizing the structure of short-packet communication can potentially improve key performance indicators such as latency and reliability. Implementing Quality of Service (QoS) mechanisms to prioritize time-sensitive traffic can also help ensure low latency for critical applications [208].

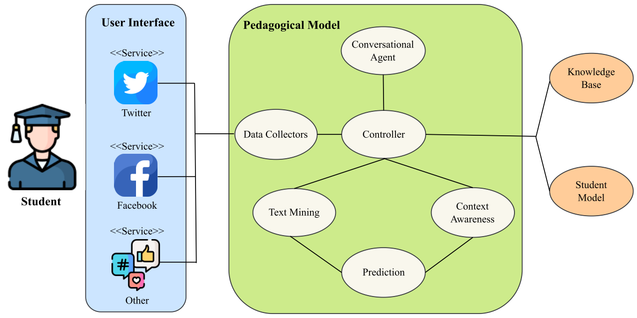

FIGURE 18. iCollab architecture.

5) ADAPTIVE DEEP LEARNING ENABLED CONTEXT-AWARE INTERACTION

Achieving adaptive Deep Learning enabled context-aware interaction involves integrating deep learning models with context-aware mechanisms to create intelligent systems capable of responsive adaptation. It begins with the development of robust deep learning architectures for data analysis, followed by the incorporation of real-time contextual analysis using techniques like RNNs, CNNs, FL and NLP. Further enhancements involve reinforcement learning and adaptive control mechanisms for context-informed decision-making. Collaboration between experts and considerations for data governance and privacy are essential. This holistic approach results in systems that can intelligently adapt to evolving situations and user needs, ensuring responsible and effective context-aware interactions.

According to Khan et al., achieving context-aware adaptive deep learning interaction includes potential techniques like distributed split federated learning (DSFL), digital avatars, and privacy-preserving approaches like federated learning (FL) [180]. Guo et al. presented a distributed learning approach that encompasses an offline training phase driven by Deep Reinforcement Learning (DRL) and an online phase employing game theory, effectively addressing the complex challenge of scalability and adaptation in wireless VR systems. Additionally, the paper tackled the often-overlooked issues of real-time rendering and data correlation in wireless VR, proposing a framework that leverages MEC servers to offload real-time rendering tasks and optimize caching, ultimately enhancing the quality of wireless VR experiences [209]. A novel deep learning-based solution for point cloud geometry coding that can efficiently adapt to the content's characteristics was proposed by Guarda et al.. It divided the point cloud into 3D blocks and selected the most suitable deep learning coding model for each block, maximizing compression performance [210]. Jamshidi et al. integrated a system that involves creating a networked and self-regulating digital ecosystem that can adapt to the context and provide personalized experiences for users by leveraging the capabilities of the digital twin and advanced intelligent technologies [211]. An adaptive projection augmented reality (AR) system that uses deep learning-based object recognition to project virtual data onto real objects, providing rich visual feedback, information and user interfaces to users, was also presented by Park et al.. This innovative approach not only enhances the user experience but also addresses the problem of high installation costs typically associated with traditional projection AR systems and offers a more cost-effective alternative [212].

Oliveira et al. proposed a novel system called iCollab that achieves adaptive deep learning-enabled Context-aware interaction by employing an intelligent agent that spans various web-based platforms, effectively integrating both formal and informal learning opportunities. It leverages contextual information, including learner profiles, temporal data, artefact properties, and time availability, to dynamically adapt learning resources and activities to individual students, offering personalized challenges, references, or peer interaction invitations while utilizing natural dialogue to provide answers and additional resources for an ongoing, context-aware interactive learning experience [213]. Though this system is not proposed for the Metaverse environment, the proposed idea can be used for the Metaverse ecosystem as well. Figure 18 illustrates the proposed model architecture.

Furthermore, The key recommendations given by Rosenberg regarding the security concern on context-aware interaction et al. include restricting the storage of user data by platform providers, regulating emotional analysis for advertising purposes, disclosing virtual product placements to users, and requiring transparency when users interact with simulated personas controlled by AI agents, particularly those with promotional agendas [214]. Additionally, Zhang et al emphasized the need for a theoretical understanding of neural networks for improved model design and resistance to adversarial attacks, discussing intrinsic and post-hoc interoperability techniques. Also, the paper underscored the importance of protecting security and preserving privacy in virtual-real interactions, suggesting strategies like avatar creation and data encryption to mitigate privacy risks in the Metaverse ecosystem [215].

Here, Table 5 further analyzes some of the proposed methods to overcome the challenges of Metaverse across different application domains. To overcome the challenges, techniques like Federated Learning, Blockchain, and Zero-trust authentication are integrated with the Metaverse ecosystem.

TABLE 5. Analysis of existing methods to overcome challenges of the Metaverse.

Reference	Goal	Domain	Model	Results
Zeng *et al.* [179]	Overcoming challenges of non-i.i.d. data, learning forgetting, and scarce communication bandwidth	Industrial Metaverse	HFEDMS	Improves the classification accuracy by at least 6.4% and saves both the overall run-time and transfer bytes by up to 98%
Cheng *et al.* [186]	Zero-trust user authentication in social virtual reality (VR)	VR authentication	MetaGuard	Accuracy: Less than 10%
Din *et al.* [187]	Privacy-preserving trust management system for trustworthy communications	Intelligent Transportation Systems	CACMTM	Accuracy: 96.3%, Computational overhead: 120 ms, Execution time: 7.24 ms (faster than the existing approaches)
Guan *et al.* [195]	Efficient privacy-preserving account-model Blockchain based on zk-SNARKs	Privacy	BlockMaze	Transaction verification time: 14.2 ms, Transaction generation time: 6.1-18.6 s, and Throughput is around 20 TPS
Yu *et al.* [205]	Latency and reliability optimization in the Metaverse over wireless communications	Wireless Communications	AAHC	Number of iterations: 3.5, Total delay: 3.7 ms, Retransmission rate: 52%, Max uplink rate: 17.08 Gbps, Energy cost: 0.07 J
Qi *et al.* [207]	Optimizing the control latency in SD-WANs by solving a critical programmability-aware problem	Software-Defined Wide Area Networks (SD-WANs)	CPSCM	Reduce the control latency by up to 27.5% compared with the baseline algorithms.
Guo *et al.* [209]	Development of adaptive wireless virtual reality framework for wireless networks	Wireless virtual reality	Adaptive VR framework	Achieved up to 15.4% and 49.7% gains in terms of quality of experience (QoE) utility value compared to Q-learning and greedy algorithms respectively and up to 134% gains in average latency compared to greedy algorithms (Experimental Scenario:22 Base Stations and 100 users)
Guarda *et al.* [210]	Development of adaptive deep learning-based point cloud geometry coding	Point Cloud	ADL-PCC	Proposed ADL-PCC solution is able to efficiently code both sparse and dense point clouds (PCs), outperforming MPEG G-PCC Trisoup with average quality gains up to 4.9 dB and 5.7 dB for PSNR D1 and PSNR D2.
Jamshidi *et al.* [211]	Making of bacteria digital twins based on image processing for assisting experts in speeding up the process and reducing diagnostic errors	Digital twinning (microorganism)	EfficientNet V2-S	Validation accuracy: 99.58%, Test accuracy: 99.33%
Awan *et al.* [172]	Enhancing performance and security in the Metaverse through latency reduction using trust and reputation management	Performance, Security and Latency of Metaverse	Trust-Based Resource Allocation Framework	Resource availability: 96%, Resource waiting time: 1.7 s, Latency reduction: 45% (Outperforms SPLR and MHECF methods in all categories)

Though advancement is going on, most of them are still in their initial phase as their accuracy, performance and efficiency need to be more accurate to provide users with a trustworthy virtual environment. Additionally, more advanced techniques like Quantum Computing, Neuromorphic Computing, and Homomorphic Encryption should be integrated with Metaverse ecosystem, as well as focusing on making this virtual world environment-friendly.

VI. FUTURE RESEARCH OPPORTUNITIES

To overcome the existing challenges and make the Metaverse ecosystem trustworthy the importance of further

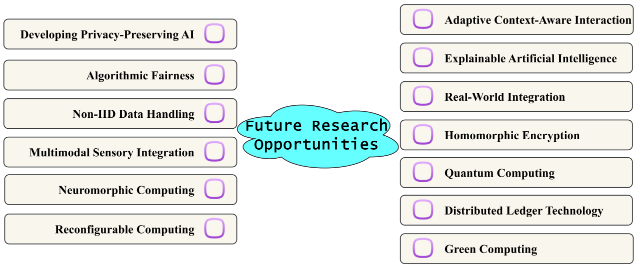

FIGURE 19. Future research opportunities for making the Metaverse trustworthy.

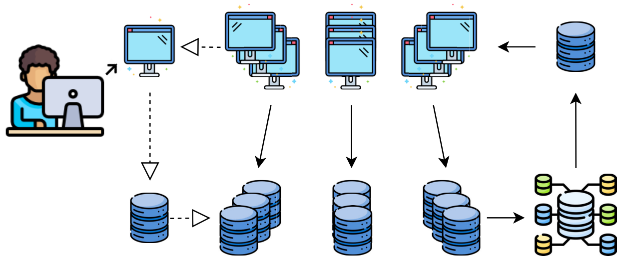

FIGURE 20. Workflow of federated learning.

development and research is significant. This section discusses the future directions that will play a vital role in determining the future of Metaverse and Figure 19 visualizes some of the key future research opportunities.

1) DEVELOPING PRIVACY-PRESERVING AI

Privacy-preserving AI is key to protecting users' personal data and maintaining trust in the Metaverse. It ensures that individuals can participate in immersive virtual experiences without compromising their privacy, fostering a safe and ethical digital environment while encouraging wider adoption and participation in the Metaverse. Therefore, it is applied in diverse Metaverse domains such as virtual commerce, healthcare simulations, social interactions, and immersive learning environments. For achieving privacy-preserving AI in the Metaverse, techniques such as federated learning should be implemented, which allows training AI models on decentralized user data without sharing raw information. Figure 20 illustrates the working procedure of Federated Learning, where instead of directly sending the users' personal data, only the local model of that user is sent to the central server for model training. However, though researchers have already proposed fl-enabled Metaverse architecture [179], [216], it's still in the initial phase. One of the major challenges of FL integration in Metaverse is related to communication efficiency, as model updates need to be synchronized across distributed devices, and ensure privacy and security, as sensitive user data must be protected during the training process. Therefore, research should be done to overcome challenges related to scalability, slow convergence and privacy in distributed training, increasing the efficiency of Metaverse systems. In addition, research should be done focusing on the use of differentiated privacy methods to add noise to the data, along with robust authentication and user-friendly privacy controls, to ensure user privacy is protected while enabling AI-driven experiences in Metaverse.

2) ADAPTIVE CONTEXT-AWARE INTERACTION

Adaptive context-aware interaction is crucial in the Metaverse. It personalizes experiences based on user preferences and real-time context, enhancing engagement and satisfaction across diverse applications like gaming, education, and commerce. This is essential in smart homes, virtual assistants, healthcare, gaming, and autonomous vehicles for personalized and responsive user experiences. However, achieving adaptive context-aware interaction in the Metaverse includes several challenges, such as developing efficient context-sensing technologies, ensuring real-time data processing and analysis, and creating scalable and interoperable systems across diverse Metaverse platforms. To overcome these issues, research should be done in refining adaptive AI algorithms for accuracy and responsiveness, exploring edge computing solutions for reduced latency, and investigating distributed systems to handle massive volumes of contextual data. Additionally, developing robust AI mechanisms and standardizing context data formats can lead to more seamless and secure context-aware interactions in the evolving Metaverse.

3) ALGORITHMIC FAIRNESS

Algorithmic fairness in the Metaverse is crucial for creating equitable and unbiased virtual experiences, promoting inclusivity, and preventing discrimination in AI-driven interactions and content recommendations. Developing fair AI models that account for diverse user data and contextual nuances, addressing algorithmic bias and ensuring transparency in AI decision-making are some of the main challenges to achieving algorithmic fairness. Therefore, research should be done on refining fairness-aware machine learning techniques, creating standardized fairness evaluation metrics for virtual environments, and exploring AI explainability methods for better understanding and mitigating biases. Furthermore, work should be done on developing scalable algorithms and privacy-preserving techniques for enhancing fairness while safeguarding user data in the evolving Metaverse.

4) EXPLAINABLE ARTIFICIAL INTELLIGENCE (XAI)

The importance of XAI is significant in the Metaverse to increase user trust and transparency. It provides users with insight into AI-driven decisions, fosters a sense of control and understanding, and enables responsible and ethical AI interactions in virtual environments. Implementing XAI is significantly necessary in the Metaverse for virtual health consultations, AI-driven virtual assistants, content recommendations, and immersive educational experiences to enhance user trust and understanding. This is key to ensuring that AI systems in the Metaverse are aligned with user expectations and values, ultimately contributing to a more inclusive

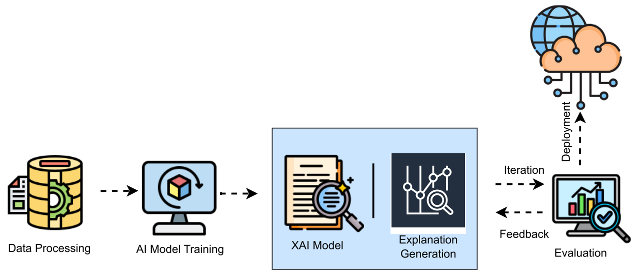

FIGURE 21. Workflow of XAI.

and trustworthy digital realm. XAI techniques encompass a variety of approaches, including rule-based systems, feature importance analysis, and model interpretability methods such as Local Interpretable Model-Agnostic Explanations (LIME) and Shapley values. Figure 21 illustrates the working procedure of explainable artificial intelligence. However, adapting these techniques is highly challenging to the dynamic and immersive nature of virtual environments, addressing the inherent trade-off between model interpretability and performance, and ensuring that explanations are presented in user-friendly ways suitable for the Metaverse's unique interaction paradigms. To overcome these challenges and integrate the XAI techniques in the Metaverse ecosystem, research should be done focusing on the development of XAI methods specifically tailored to Metaverse-specific data and applications, creating real-time and interactive explanations that seamlessly integrate with virtual experiences, and exploring decentralized and privacy-preserving XAI solutions to uphold user trust and comprehension as the Metaverse continues to evolve.

5) NON-IID DATA HANDLING

Non-IID (Non-Independently and Identically Distributed) data handling is essential in the Metaverse due to its dynamic user-generated content, enabling personalized experiences and improved content recommendations. Effective management of non-IID data ensures AI models adapt to individual user behaviours, enhancing engagement and satisfaction in the virtual environment. Techniques like federated learning [217], transfer learning [218], and meta-learning [219] are some of the most suitable solutions to overcome this issue. For instance, federated learning allows AI models to be trained across decentralized data sources while preserving user privacy [220]. In the Metaverse, this can mean aggregating user data from diverse virtual environments to improve AI recommendations without compromising individual privacy.

However, developing algorithms suitable for dynamic, context-aware virtual spaces, addressing data heterogeneity arising from different Metaverse platforms and applications, and ensuring privacy-preserving solutions that safeguard sensitive user information is a significant challenge that needs to be overcome. Therefore, research opportunities for this scenario are abundant and include refining federated learning methods optimized for Metaverse-specific data sources and interactions. Additionally, exploring novel transfer learning strategies for adapting models to non-IID data scenarios within the virtual realm is essential. Researchers can also investigate decentralized and privacy-enhancing approaches to handle diverse data sources, promoting personalized and context-aware virtual experiences while maintaining robust user privacy protections.

6) REAL-WORLD INTEGRATION

From the Metaverse perspective, real-world integration is one of the main pillars for creating seamless interactions between the virtual and physical worlds, unlocking innovative applications and maximizing the Metaverse's utility and impact. Integrating the Metaverse with the real world involves developing interfaces and protocols for data exchange between virtual and physical systems, incorporating IoT devices and sensors, and creating APIs for cross-realm interactions. For proper integration of these two worlds, existing challenges include ensuring data accuracy, security, and privacy, as well as addressing the heterogeneity of real-world data sources. Therefore, work needs to be done on advancing interoperable standards and secure data sharing mechanisms, exploring edge computing solutions for real-time integration, and enhancing AI-driven decision-making in mixed-reality environments, ultimately enabling richer, context-aware, and more immersive Metaverse experiences that seamlessly blend the virtual and physical worlds.

7) MULTIMODAL SENSORY INTEGRATION

Multimodal sensory integration in the Metaverse is key to creating immersive and realistic virtual experiences by combining visual, auditory, haptic and other sensory inputs. Metaverse for gaming, virtual conferences, telemedicine, virtual tourism, marketing and immersive training are some of the applications areas where it can play a vital role in enhancing realism and user engagement [221]. This requires the development of synchronized data acquisition systems and advanced machine learning techniques to fuse sensory data. However, real-time synchronization of sensory inputs, handling hardware constraints and ensuring privacy and security are among the main challenges. To overcome these problems, research should focus on refining synchronization methods, improving sensory feedback mechanisms and exploring new sensory modalities, ultimately enabling more authentic and engaging Metaverse interactions that could revolutionize fields ranging from gaming to healthcare.

8) HOMOMORPHIC ENCRYPTION

Homomorphic encryption is a cryptographic technique that allows computations to be performed on encrypted data without revealing the underlying information. It can play a significant role in the Metaverse ecosystem, as it has features such as preserving user privacy and data security while enabling AI-driven interactions and analysis. More specifically, it is essential in the Metaverse for secure virtual

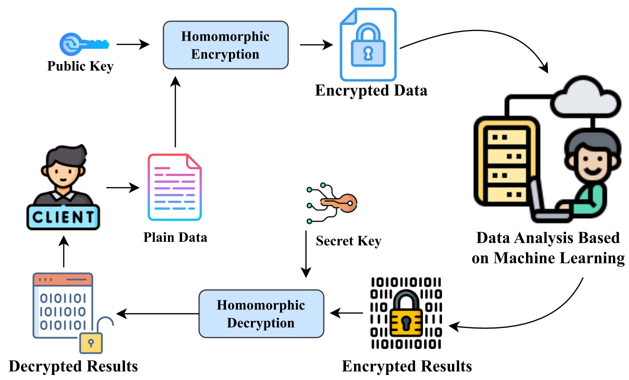

FIGURE 22. **Working procedure of Homomorphic Encryption.**

commerce, confidential data sharing, private user identity verification, and encrypted content processing. Implementing Homomorphic Encryption in the Metaverse means integrating encryption and decryption functions into virtual environments, allowing AI models to operate on encrypted user data [222]. Figure 22 illustrates the working procedure of Homomorphic Encryption. However, this poses challenges due to the computational overhead, as encryption operations can be resource intensive, and to ensure that encrypted data remains secure during processing. Hence, further importance should be given to homomorphic encryption and optimization of encryption schemes for real-time interactions, the development of efficient algorithms for handling large-scale data, and the exploration of privacy-preserving techniques to address challenges such as user profiling and recommendation schemes within virtual environments. Standardizing encryption protocols and increasing interoperability will also be key to achieving seamless integration of different Metaverse platforms and applications.

9) NEUROMORPHIC COMPUTING

In computer architecture, neuromorphic computing is an approach inspired by the structure and function of the human brain. It involves the design of hardware and algorithms that mimic neural networks, enabling efficient and brain-like information processing [223]. In the Metaverse, neuromorphic computing will be essential in achieving human-like cognitive capabilities in virtual environments, including natural language understanding, real-time decision-making and immersive sensory interactions. The implementation will involve the development of specific neuromorphic hardware and neural network models capable of simulating human-like cognition and perception in the virtual world. Designing energy-efficient hardware, scaling neural networks to complex virtual environments, and ensuring compatibility with existing virtual and augmented reality technologies will be challenging. This will open up significant research opportunities for researchers, including the development of hardware technologies for faster and more energy-efficient neuromorphic chips, the development of sophisticated neural network architectures capable of handling diverse Metaverse data, and the exploration of ethical and privacy considerations for cognitive artificial intelligence systems in virtual environments. In addition, achieving real-time adaptability and seamless integration of neuromorphic computing in the evolving Metaverse is an important issue to overcome.

10) QUANTUM COMPUTING

Quantum computing exploits quantum mechanics and qubits to process information exponentially faster than classical computers, which is crucial for the data-intensive tasks of the Metaverse. In the Metaverse, quantum computing is vital in handling massive data sets, cryptography and simulating complex virtual environments at unprecedented speeds. Implementing quantum computing in the Metaverse involves the integration of quantum processors and algorithms to enhance data processing, security and realism of virtual simulations [224]. This is challenging due to the need for quantum-resistant cryptography to protect sensitive data, the development of quantum algorithms adapted to virtual environments, and the significant technical complexity of building and maintaining quantum hardware. Therefore, the focus should be on optimizing quantum algorithms for Metaverse-specific tasks such as real-time simulations and data analysis, testing quantum networks in distributed Metaverse environments, and addressing the practical limitations of scaling quantum hardware. Ethical considerations and cybersecurity measures in quantum computing are also increasingly important areas for the safe and responsible development of the Metaverse.

11) RECONFIGURABLE COMPUTING

Reconfigurable computing is critical in the Metaverse, as it can adapt hardware resources on the fly to meet the dynamic and intensive computing needs of immersive virtual environments. It enables real-time optimization, improving performance, responsiveness and user experience and is essential in the Metaverse for dynamic resource allocation, real-time virtual environment adaptations and personalized content rendering. To implement Metaverse in the ecosystem, it can integrate hardware such as Field-Programmable Gate Arrays (FPGAs) for versatile processing tasks. This ensures that Metaverse can efficiently handle complex simulations, interactive experiences and high-quality visualizations, providing users with a seamless and immersive digital realm. Additionally, further research should be done on the development of reconfigurable hardware for real-time Metaverse interactions, the design of adaptable software ecosystems that seamlessly integrate into virtual environments, the investigation of ethical dimensions related to dynamic hardware changes within the virtual realm, and the emphasis on standardization and interoperability to promote the widespread adoption of reconfigurable computing in the Metaverse.

12) DISTRIBUTED LEDGER TECHNOLOGY

Distributed ledger technology (DLT) is a decentralized and distributed digital system that records transactions across multiple nodes or computers, ensuring data transparency, security and immutability. Key DLT technologies include Blockchain, Hashgraph and Directed Acyclic Graphs (DAG) [225]. DLT is vital to establish trust in the Metaverse, enable secure peer-to-peer transactions, and ensure the ownership and provenance of digital assets such as virtual real estate or game objects. The implementation of DLT in the Metaverse involves the integration of DLT platforms and smart contracts for the management of virtual assets, identity verification and secure transactions and this also faces significant challenges such as scalability issues, power consumption and the need for interoperability between different DLT systems. Ensuring privacy while maintaining transparency is also a major challenge. Therefore, future research should focus on improving scalability solutions, developing energy-efficient consensus mechanisms, improving privacy techniques within DLT, and establishing standards to ensure DLT interoperability across platforms within Metaverses.

13) GREEN COMPUTING

Green computing refers to environmentally conscious computing practices that aim to reduce the environmental impact of technology through energy-efficient hardware, sustainable software design and responsible resource management. In the Metaverse, green computing is critical to minimizing the energy requirements of resource-intensive virtual environments, data centers, and hardware infrastructures [226]. The implementation of green computing in the Metaverse includes designing energy-efficient servers, optimizing software and rendering algorithms, and using renewable energy sources in data centers. However, implementing it in the Metaverse has significant challenges, such as balancing performance and energy efficiency, reducing data center energy consumption, and managing resource-intensive AI and rendering tasks. Therefore, Priority should be given to developing sustainable hardware architectures tailored to virtual environments, optimizing distributed computing for energy savings, and exploring advanced rendering techniques that minimize energy consumption without compromising the user experience. Research should also focus on developing green data centers and implementing guidelines and standards for sustainable computing practices in the Metaverse.

VII. CONCLUSION

The Metaverse promises an immersive environment without limits and has broad development and application prospects. Metaverse is still taking shape, and brands from all industries are coming in front to play a role in designing it. This paper attempted to provide an in-depth idea about the applications and challenges of Metaverse. Then, it also discussed existing solutions proposed by researchers and future research directions to make the Metaverse ecosystem trustworthy. With the growing interest and usage of Metaverse in the current world that significantly impacts our lives, it is crucial to understand whether it is trustworthy and what improvements it needs. All the Key factors in the virtual reality space need to work together to achieve common standards and protocols for building virtual worlds for the Metaverse to become fully trusted and developed. Regulatory bodies should also establish scrutiny and monitor how to make this Metaverse concept fully trusted and a reality.

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REFERENCES

[1] J. E. M. Díaz, C. A. D. Saldaña, and C. A. R. Ávila, ''Virtual world as a resource for hybrid education,'' *Int. J. Emerg. Technol. Learn.*, vol. 15, no. 15, pp. 94–109, Aug. 2020.
[2] Y. Wang, Z. Su, N. Zhang, R. Xing, D. Liu, T. H. Luan, and X. Shen, ''A survey on metaverse: Fundamentals, security, and privacy,'' *IEEE Commun. Surveys Tuts.*, vol. 25, no. 1, pp. 319–352, 1st Quart., 2023.
[3] S.-M. Park and Y.-G. Kim, ''A metaverse: Taxonomy, components, applications, and open challenges,'' *IEEE Access*, vol. 10, pp. 4209–4251, 2022.
[4] N. G. Narin, ''A content analysis of the metaverse articles,'' *J. Metaverse*, vol. 1, no. 1, pp. 17–24, 2021.
[5] S. Kraus, D. K. Kanbach, P. M. Krysta, M. M. Steinhoff, and N. Tomini, ''Facebook and the creation of the metaverse: Radical business model innovation or incremental transformation?'' *Int. J. Entrepreneurial Behav. Res.*, vol. 28, no. 9, pp. 52–77, Dec. 2022.
[6] E. Toreini, M. Aitken, K. Coopamootoo, K. Elliott, C. G. Zelaya, and A. van Moorsel, ''The relationship between trust in AI and trustworthy machine learning technologies,'' in *Proc. Conf. Fairness, Accountability, Transparency*, Jan. 2020, pp. 272–283.
[7] J. Sun, W. Gan, H.-C. Chao, and P. S. Yu, ''Metaverse: Survey, applications, security, and opportunities,'' 2022, *arXiv:2210.07990*.
[8] H. Ning, H. Wang, Y. Lin, W. Wang, S. Dhelim, F. Farha, J. Ding, and M. Daneshmand, ''A survey on the metaverse: The state-of-the-art, technologies, applications, and challenges,'' *IEEE Internet Things J.*, vol. 10, no. 16, pp. 14671–14688, Jul. 2023.
[9] Y. Huang, Y. J. Li, and Z. Cai, ''Security and privacy in metaverse: A comprehensive survey,'' *Big Data Mining Anal.*, vol. 6, no. 2, pp. 234–247, Jun. 2023.
[10] H. Sami, A. Hammoud, M. Arafeh, M. Wazzeh, S. Arisdakessian, M. Chahoud, O. Wehbi, M. Ajaj, A. Mourad, H. Otrok, O. A. Wahab, R. Mizouni, J. Bentahar, C. Talhi, Z. Dziong, E. Damiani, and M. Guizani, ''The metaverse: Survey, trends, novel pipeline ecosystem & future directions,'' 2023, *arXiv:2304.09240*.
[11] Y. Guo, T. Yu, J. Wu, Y. Wang, S. Wan, J. Zheng, L. Fang, and Q. Dai, ''Artificial intelligence for metaverse: A framework,'' *CAAI Artif. Intell. Res.*, vol. 1, no. 1, pp. 54–67, Sep. 2022.
[12] R. K. Jones and D. N. Lee, ''Why two eyes are better than one: The two views of binocular vision,'' *J. Experim. Psychol., Hum. Perception Perform.*, vol. 7, no. 1, pp. 30–40, 1981.
[13] S. Tunca, B. Sezen, and V. Wilk, ''An exploratory content and sentiment analysis of the guardian metaverse articles using Leximancer and natural language processing,'' *J. Big Data*, vol. 10, no. 1, p. 82, May 2023.
[14] J. Zhang, C. Chen, Y. Zhang, Y. Cui, P. Han, N. Meng, and Y. Xu, ''The framework and practices of digital twin city,'' in *Proc. IEEE 12th Int. Conf. Electron. Inf. Emergency Commun. (ICEIEC)*, Jul. 2022, pp. 111–116.
[15] P. Hemp, ''Avatar-based marketing,'' *Harvard Bus. Rev.*, vol. 84, no. 6, pp. 48–57, 2006.
[16] Y. Kou and X. Gui, ''Harmful design in the metaverse and how to mitigate it: A case study of user-generated virtual worlds on roblox,'' Assoc. Comput. Mach., New York, NY, USA, Tech. Rep., 2023.
[17] B. G. P. Lindeque, B. A. Ponce, M. E. Menendez, L. O. Oladeji, C. T. Fryberger, and P. K. Dantuluri, ''Emerging technology in surgical education: Combining real-time augmented reality and wearable computing devices,'' *Orthopedics*, vol. 37, no. 11, pp. 751–757, Nov. 2014.
[18] Y. El Faqir, J. Arroyo, and S. Hassan, ''An overview of decentralized autonomous organizations on the blockchain,'' in *Proc. 16th Int. Symp. Open Collaboration*, Aug. 2020, pp. 1–8.

[19] S. Chrétien-Ichikawa, ''Shanghai fashion and post-1990s youth through the phygital lens,'' in *Creative Industries and Digital Transformation in China*. Cham, Switzerland: Springer, 2022, pp. 117–146.

[20] Y. Maeng, C. C. Lee, and H. Yun, ''Understanding antecedents that affect customer evaluations of head-mounted display VR devices through text mining and deep neural network,'' *J. Theor. Appl. Electron. Commerce Res.*, vol. 18, no. 3, pp. 1238–1256, Jul. 2023.

[21] T. Huynh-The, Q.-V. Pham, X.-Q. Pham, T. T. Nguyen, Z. Han, and D.-S. Kim, ''Artificial intelligence for the metaverse: A survey,'' *Eng. Appl. Artif. Intell.*, vol. 117, Jan. 2023, Art. no. 105581.

[22] B. C. Cheong, ''Avatars in the metaverse: Potential legal issues and remedies,'' *Int. Cybersecurity Law Rev.*, vol. 3, no. 2, pp. 467–494, Dec. 2022.

[23] F. Regner, N. Urbach, and A. Schweizer, ''NFTs in practice–non-fungible tokens as core component of a blockchain-based event ticketing application,'' Assoc. Inf. Syst., Atlanta, GA, USA, Tech. Rep., 2019.

[24] H. Zhang, S. Lee, Y. Lu, X. Yu, and H. Lu, ''A survey on big data technologies and their applications to the metaverse: Past, current and future,'' *Mathematics*, vol. 11, no. 1, p. 96, Dec. 2022.

[25] F. Tang, X. Chen, M. Zhao, and N. Kato, ''The roadmap of communication and networking in 6G for the metaverse,'' *IEEE Wireless Commun.*, vol. 30, no. 4, pp. 72–81, Aug. 2022.

[26] L. V. Kiong, *Web3 Made Easy: A Comprehensive Guide to Web3: Everything You Need to Know About Web3, Blockchain, DeFi, Metaverse, NFT and GameFi*. Independently Published, 2022.

[27] D. Adams, ''Virtual retail in the metaverse: Customer behavior analytics, extended reality technologies, and immersive visualization systems,'' *Linguistic Phil. Invest.*, vol. 10, no. 21, pp. 73–88, 2022.

[28] N. Kshetri, ''Web 3.0 and the metaverse shaping organizations' brand and product strategies,'' *IT Prof.*, vol. 24, no. 2, pp. 11–15, Mar. 2022.

[29] R. Wagner and D. Cozmiuc, ''Extended reality in marketing—A multiple case study on Internet of Things platforms,'' *Information*, vol. 13, no. 6, p. 278, May 2022.

[30] G. McLean and A. Wilson, ''Shopping in the digital world: Examining customer engagement through augmented reality mobile applications,'' *Comput. Hum. Behav.*, vol. 101, pp. 210–224, Dec. 2019.

[31] A. Drapkin. (2023). *Metaverse Companies: Who's Involved and Who's Investing in 2023—Tech.co*. Accessed: Jul. 26, 2023. [Online]. Available: https://tech.co/news/metaverse-companies

[32] G.-J. Hwang and S.-Y. Chien, ''Definition, roles, and potential research issues of the metaverse in education: An artificial intelligence perspective,'' *Comput. Educ., Artif. Intell.*, vol. 3, Jan. 2022, Art. no. 100082.

[33] C. Collins, ''Looking to the future: Higher education in the metaverse,'' *Educause Rev.*, vol. 43, no. 5, pp. 50–52, 2008.

[34] P. Tarkar, ''Impact of COVID-19 pandemic on education system,'' *Int. J. Adv. Sci. Technol.*, vol. 29, no. 9, pp. 3812–3814, 2020.

[35] F. Cortés Rodríguez, M. Dal Peraro, and L. A. Abriata, ''Online tools to easily build virtual molecular models for display in augmented and virtual reality on the web,'' *J. Mol. Graph. Model.*, vol. 114, Jul. 2022, Art. no. 108164.

[36] A. Christopoulos, S. Mystakidis, E. Cachafeiro, and M.-J. Laakso, ''Escaping the cell: Virtual reality escape rooms in biology education,'' *Behav. Inf. Technol.*, vol. 42, no. 9, pp. 1434–1451, Jul. 2023.

[37] X. Zhou, L. Tang, D. Lin, and W. Han, ''Virtual & augmented reality for biological microscope in experiment education,'' *Virtual Reality Intell. Hardw.*, vol. 2, no. 4, pp. 316–329, Aug. 2020.

[38] J. Morimoto and F. Ponton, ''Virtual reality in biology: Could we become virtual naturalists?'' *Evol., Educ. Outreach*, vol. 14, no. 1, p. 7, Dec. 2021.

[39] R. Arslan, M. Kofoğlu, and C. Dargut, ''Development of augmented reality application for biology education,'' *Turkish J. Sci. Educ.*, vol. 17, no. 1, pp. 62–72, Mar. 2020.

[40] A. Ismail, G. Rahayu, M. A. K. Putera, N. N. Aghniya, and S. Gumilar, ''Development of augmented reality as physics learning media on electric concepts,'' *IOP Conf. Ser., Mater. Sci. Eng.*, vol. 1098, no. 4, Mar. 2021, Art. no. 042006.

[41] I. A. Rizki, H. V. Saphira, Y. Alfarizy, A. D. Saputri, R. Ramadani, and N. Suprapto, ''Adventuring physics: Integration of adventure game and augmented reality based on Android in physics learning,'' *Int. J. Interact. Mobile Technol.*, vol. 17, no. 1, pp. 4–21, Jan. 2023.

[42] N. Suprapto, W. Nandyansah, and H. Mubarok, ''An evaluation of the 'PicSAR' research project: An augmented reality in physics learning,'' *Int. J. Emerg. Technol. Learn.*, vol. 15, no. 10, pp. 113–125, 2020.

[43] N. J. Sung, J. Ma, Y. J. Choi, and M. Hong, ''Real-time augmented reality physics simulator for education,'' *Appl. Sci.*, vol. 9, no. 19, p. 4019, Sep. 2019.

[44] J. W. Lai and K. H. Cheong, ''Educational opportunities and challenges in augmented reality: Featuring implementations in physics education,'' *IEEE Access*, vol. 10, pp. 43143–43158, 2022.

[45] M. Fanguy and R. Kharbash, ''Using a metaverse to teach students to predict the interaction of acids and bases using hard and soft acids and bases (HSAB) theory,'' *J. Chem. Educ.*, vol. 100, no. 9, pp. 3709–3716, Sep. 2023.

[46] M. Abdinejad, B. Talaie, H. S. Qorbani, and S. Dalili, ''Student perceptions using augmented reality and 3D visualization technologies in chemistry education,'' *J. Sci. Educ. Technol.*, vol. 30, no. 1, pp. 87–96, Feb. 2021.

[47] A. Mazzuco, A. L. Krassmann, E. Reategui, and R. S. Gomes, ''A systematic review of augmented reality in chemistry education,'' *Rev. Educ.*, vol. 10, no. 1, p. e3325, Apr. 2022.

[48] J. G. Wu, D. Zhang, and S. M. Lee, ''Into the brave new metaverse: Envisaging future language teaching and learning,'' *IEEE Trans. Learn. Technol.*, early access, Mar. 23, 2023, doi: 10.1109/TLT.2023.3259470.

[49] S. Aydın, ''The metaverse in foreign language learning: A theoretical framework,'' *Innovational Res. ELT*, vol. 3, no. 2, pp. 12–19, Dec. 2022.

[50] X. Huang, D. Zou, G. Cheng, and H. Xie, ''A systematic review of AR and VR enhanced language learning,'' *Sustainability*, vol. 13, no. 9, p. 4639, Apr. 2021.

[51] M. S. Jong, C. Tsai, H. Xie, and F. K.-K. Wong, ''Integrating interactive learner-immersed video-based virtual reality into learning and teaching of physical geography,'' *Brit. J. Educ. Technol.*, vol. 51, no. 6, pp. 2064–2079, Nov. 2020.

[52] C. Khansulivong, S. Wicha, and P. Temdee, ''Adaptive of new technology for agriculture online learning by metaverse: A case study in faculty of agriculture, National University of Laos,'' in *Proc. Joint Int. Conf. Digit. Arts, Media Technol. ECTI Northern Sect. Conf. Electr., Electron., Comput. Telecommun. Eng.*, Jan. 2022, pp. 428–432.

[53] J. C. De Gagne, P. S. Randall, S. Rushton, H. K. Park, E. Cho, S. S. Yamane, and D. Jung, ''The use of metaverse in nursing education: An umbrella review,'' *Nurse Educator*, vol. 48, no. 3, pp. E73–E78, 2023.

[54] J.-E. Yu, ''Exploration of educational possibilities by four metaverse types in physical education,'' *Technologies*, vol. 10, no. 5, p. 104, Sep. 2022.

[55] S. Sandrone, ''Medical education in the metaverse,'' *Nature Med.*, vol. 28, no. 12, pp. 2456–2457, Dec. 2022.

[56] A. A. Gaafar, ''Metaverse in architectural heritage documentation & education,'' *Adv. Ecol. Environ. Res.*, vol. 6, no. 10, pp. 66–86, 2021.

[57] H. Lee, D. Woo, and S. Yu, ''Virtual reality metaverse system supplementing remote education methods: Based on aircraft maintenance simulation,'' *Appl. Sci.*, vol. 12, no. 5, p. 2667, Mar. 2022.

[58] D. Gruson, R. Greaves, P. Dabla, S. Bernardini, B. Gouget, and T. K. Öz, ''A new door to a different world: Opportunities from the metaverse and the raise of meta-medical laboratories,'' *Clin. Chem. Lab. Med.*, vol. 61, no. 9, pp. 1567–1571, Aug. 2023.

[59] N. I. Gonzalez-Romo, G. Mignucci-Jiménez, S. Hanalioglu, M. E. Gurses, S. Bahadir, Y. Xu, G. Koskay, M. T. Lawton, and M. C. Preul, ''Virtual neurosurgery anatomy laboratory: A collaborative and remote education experience in the metaverse,'' *Surgical Neurol. Int.*, vol. 14, p. 90, Mar. 2023.

[60] P. Chatwattana, P. Saisong, K. Rojanapasnichwong, and W. Khiankhokkruad, ''Virtual laboratory learning environment: VLLE on metaverse for university in Thailand,'' *Int. J. Eng. Pedagogy*, vol. 13, no. 5, pp. 30–41, Jul. 2023.

[61] L. Valmaggia, ''The use of virtual reality in psychosis research and treatment,'' *World Psychiatry*, vol. 16, no. 3, pp. 246–247, Oct. 2017.

[62] C. J. Bohil, B. Alicea, and F. A. Biocca, ''Virtual reality in neuroscience research and therapy,'' *Nature Rev. Neurosci.*, vol. 12, no. 12, pp. 752–762, Dec. 2011.

[63] C. M. Coelho, A. M. Waters, T. J. Hine, and G. Wallis, ''The use of virtual reality in acrophobia research and treatment,'' *J. Anxiety Disorders*, vol. 23, no. 5, pp. 563–574, Jun. 2009.

[64] L. P. Berg and J. M. Vance, ''Industry use of virtual reality in product design and manufacturing: A survey,'' *Virtual Reality*, vol. 21, no. 1, pp. 1–17, Mar. 2017.

[65] K. Valentino, K. Christian, and E. Joelianto, ''Virtual reality flight simulator,'' *Internetworking Indonesia J.*, vol. 9, no. 1, pp. 21–25, 2017.

[66] K. Zhang, Z. Qiao, F. Zhao, and H. Lu, "A study on the work mode of spacecraft flight control from the perspective of the metaverse," in *Proc. IEEE 13th Int. Conf. Electron. Inf. Emergency Commun. (ICEIEC)*, Jul. 2023, pp. 228–234.

[67] M. B. Bruguera, V. Ilk, S. Ruber, and R. Ewald, "Use of virtual reality for astronaut training in future space missions-spacecraft piloting for the lunar orbital platform-gateway (LOP-G)," in *Proc. 70th Int. Astron. Congr.*, 2019, pp. 1–10.

[68] C. Fertleman, P. Aubugeau-Williams, C. Sher, A.-N. Lim, S. Lumley, S. Delacroix, and X. Pan, "A discussion of virtual reality as a new tool for training healthcare professionals," *Frontiers Public Health*, vol. 6, p. 44, Feb. 2018.

[69] A. Danylec, K. Shahabadkar, H. Dia, and A. Kulkarni, "Cognitive implementation of metaverse embedded learning and training framework for drivers in rolling stock," *Machines*, vol. 10, no. 10, p. 926, Oct. 2022.

[70] H. Koo, "Training in lung cancer surgery through the metaverse, including extended reality, in the smart operating room of Seoul National University Bundang Hospital, Korea," *J. Educ. Eval. Health Professions*, vol. 18, p. 33, Dec. 2021.

[71] J. Lee, T. S. Lee, S. Lee, J. Jang, S. Yoo, Y. Choi, and Y. R. Park, "Development and application of a metaverse-based social skills training program for children with autism spectrum disorder to improve social interaction: Protocol for a randomized controlled trial," *JMIR Res. Protocols*, vol. 11, no. 6, Jun. 2022, Art. no. e35960.

[72] S. Rutkowski, P. Kiper, L. Cacciante, J. Mazurek, and A. Turolla, "Use of virtual reality-based training in different fields of rehabilitation: A systematic review and meta-analysis," *J. Rehabil. Med.*, vol. 52, no. 11, pp. 1–16, 2020.

[73] J. Gu, J. Wang, X. Guo, G. Liu, S. Qin, and Z. Bi, "A metaverse-based teaching building evacuation training system with deep reinforcement learning," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 53, no. 4, pp. 2209–2219, Apr. 2023.

[74] L. Jensen and F. Konradsen, "A review of the use of virtual reality head-mounted displays in education and training," *Educ. Inf. Technol.*, vol. 23, no. 4, pp. 1515–1529, Jul. 2018.

[75] E. Markopoulos, A. D. Nordholm, S. Illiade, P. Markopoulos, J. Faraclas, and M. Luimula, "A certification framework for virtual reality and metaverse training scenarios in the maritime and shipping industry," *Creativity, Innov. Entrepreneurship*, vol. 31, pp. 36–47, Jan. 2022.

[76] A. K. Upadhyay and K. Khandelwal, "Metaverse: The future of immersive training," *Strategic HR Rev.*, vol. 21, no. 3, pp. 83–86, Jun. 2022.

[77] O. Hajjami and S. Park, "Using the metaverse in training: Lessons from real cases," *Eur. J. Training Develop.*, vol. 2023, pp. 1–21, Jun. 2023.

[78] M. Hawkins, "Virtual employee training and skill development, workplace technologies, and deep learning computer vision algorithms in the immersive metaverse environment," *Psychosociolog. Issues Hum. Resource Manage.*, vol. 10, no. 1, pp. 106–120, 2022.

[79] M. A. I. Mozumder, T. P. T. Armand, S. M. I. Uddin, A. Athar, R. I. Sumon, A. Hussain, and H.-C. Kim, "Metaverse for digital anti-aging healthcare: An overview of potential use cases based on artificial intelligence, blockchain, IoT technologies, its challenges, and future directions," *Appl. Sci.*, vol. 13, no. 8, p. 5127, Apr. 2023.

[80] J. M. Román-Belmonte, E. C. Rodríguez-Merchán, and H. De la Corte-Rodríguez, "Metaverse applied to musculoskeletal pathology: Orthoverse and rehabverse," *Postgraduate Med.*, vol. 5, pp. 1–9, Feb. 2023.

[81] T. F. Tan, Y. Li, J. S. Lim, D. V. Gunasekeran, Z. L. Teo, W. Y. Ng, and D. S. Ting, "Metaverse and virtual health care in ophthalmology: Opportunities and challenges," *Asia–Pacific J. Ophthalmol.*, vol. 11, no. 3, pp. 237–246, May 2022.

[82] R. Sharma, M. Mittal, G. Battineni, and F. Amenta, "Applications of metaverse for improving healthcare at sea," *Int. Maritime Health*, vol. 74, no. 2, pp. 129–130, Jun. 2023.

[83] I. Skalidis, O. Müller, and S. Fournier, "The metaverse in cardiovascular medicine: Applications, challenges, and the role of non-fungible tokens," *Can. J. Cardiol.*, vol. 38, no. 9, pp. 1467–1468, Sep. 2022.

[84] V. S. Arikatla, M. Tyagi, A. Enquobahrie, T. Nguyen, G. H. Blakey, R. White, and B. Paniagua, "High fidelity virtual reality orthognathic surgery simulator," *Proc. SPIE*, vol. 10576, pp. 253–259, Mar. 2018.

[85] Y. Kim, H. Kim, and Y. O. Kim, "Virtual reality and augmented reality in plastic surgery: A review," *Arch. Plastic Surg.*, vol. 44, no. 3, pp. 179–187, May 2017.

[86] F. Aïm, G. Lonjon, D. Hannouche, and R. Nizard, "Effectiveness of virtual reality training in orthopaedic surgery," *Arthroscopy, J. Arthroscopic Rel. Surgery*, vol. 32, no. 1, pp. 224–232, Jan. 2016.

[87] A. Ayoub and Y. Pulijala, "The application of virtual reality and augmented reality in oral & maxillofacial surgery," *BMC Oral Health*, vol. 19, no. 1, pp. 1–8, Dec. 2019.

[88] J. S. Yoo, D. S. Patel, N. M. Hrynewycz, T. S. Brundage, and K. Singh, "The utility of virtual reality and augmented reality in spine surgery," *Ann. Transl. Med.*, vol. 7, no. S5, p. S171, Sep. 2019.

[89] L. Noben, S. M. T. A. Goossens, S. E. M. Truijens, M. M. G. van Berckel, C. W. Perquin, G. D. Slooter, and S. J. van Rooijen, "A virtual reality video to improve information provision and reduce anxiety before cesarean delivery: Randomized controlled trial," *JMIR Mental Health*, vol. 6, no. 12, Dec. 2019, Art. no. e15872.

[90] C. W. Lee, "Application of metaverse service to healthcare industry: A strategic perspective," *Int. J. Environ. Res. Public Health*, vol. 19, no. 20, p. 13038, Oct. 2022.

[91] T. A. Naqishbandi, E. S. Mohamed, and G. Veronese, "Metaverse!: Possible potential opportunities and trends in e-healthcare and education," *Int. J. E-Adoption*, vol. 15, no. 2, pp. 1–21, Jan. 2023.

[92] U. Zaman, "Editorial: Metaverse going beyond adoption: The next frontier for global healthcare," *Frontiers Public Health*, vol. 11, May 2023, Art. no. 1194285.

[93] J. Thomason, "Metahealth-how will the metaverse change health care?" *J. Metaverse*, vol. 1, no. 1, pp. 13–16, 2021.

[94] Y. Zeng, L. Zeng, C. Zhang, and A. S. K. Cheng, "The metaverse in cancer care: Applications and challenges," *Asia–Pacific J. Oncol. Nursing*, vol. 9, no. 12, Dec. 2022, Art. no. 100111.

[95] P. Bhattacharya, A. Verma, V. K. Prasad, S. Tanwar, B. Bhushan, B. C. Florea, D. D. Taralunga, F. Alqahtani, and A. Tolba, "*Game-o-Meta*: Trusted federated learning scheme for P2P gaming metaverse beyond 5G networks," *Sensors*, vol. 23, no. 9, p. 4201, Apr. 2023.

[96] S. Tayal, K. Rajagopal, and V. Mahajan, "Virtual reality based metaverse of gamification," in *Proc. 6th Int. Conf. Comput. Methodologies Commun. (ICCMC)*, Mar. 2022, pp. 1597–1604.

[97] S. Jian, X. Chen, and J. Yan, "From online games to 'metaverse': The expanding impact of virtual reality in daily life," in *Proc. Int. Conf. Hum.-Comput. Interact.* Cham, Switzerland: Springer, 2022, pp. 34–43.

[98] A. Jungherr and D. B. Schlarb, "The extended reach of game engine companies: How companies like epic games and unity technologies provide platforms for extended reality applications and the metaverse," *Social Media Soc.*, vol. 8, no. 2, 2022, Art. no. 20563051221107641.

[99] D. Swarbrick, B. Seibt, N. Grinspun, and J. K. Vuoskoski, "Corona concerts: The effect of virtual concert characteristics on social connection and *Kama Muta*," *Frontiers Psychol.*, vol. 12, Jun. 2021, Art. no. 648448.

[100] F. An Nur, I. Wenerda, N. Fatonah, and Y. Palupi, "Virtual concert as the new lifestyle during COVID-19," *Jurnal Spektrum Komunikasi*, vol. 10, no. 3, pp. 215–223, Sep. 2022.

[101] P. S. Devindriati Kusuma, "Children virtual concert in the COVID-19 pandemic," *J. Music Sci., Technol., Ind.*, vol. 3, no. 2, pp. 247–260, Oct. 2020.

[102] S. Oh, K. Chung, I. Aliyu, M. Hahn, I.-K. Jeong, C.-R. Yu, T.-W. Um, and J. Kim, "XDN-based network framework design to communicate interaction in virtual concerts with metaverse platforms," *Appl. Sci.*, vol. 13, no. 17, p. 9509, Aug. 2023.

[103] D. Gursoy, S. Malodia, and A. Dhir, "The metaverse in the hospitality and tourism industry: An overview of current trends and future research directions," *J. Hospitality Marketing Manage.*, vol. 31, no. 5, pp. 527–534, Jul. 2022.

[104] A. Pestek and M. Sarvan, "Virtual reality and modern tourism," *J. Tourism Futures*, vol. 7, no. 2, pp. 245–250, Jun. 2021.

[105] R. Yung, C. Khoo-Lattimore, and L. E. Potter, "Virtual reality and tourism marketing: Conceptualizing a framework on presence, emotion, and intention," *Current Issues Tourism*, vol. 24, no. 11, pp. 1505–1525, Jun. 2021.

[106] D. Buhalis, D. Leung, and M. Lin, "Metaverse as a disruptive technology revolutionising tourism management and marketing," *Tourism Manage.*, vol. 97, Aug. 2023, Art. no. 104724.

[107] F.-J. Martínez-Cano, R. Lachman, and D. Patil, "Film practices in the metaverse: Methodological approach for prosocial VR storytelling creation," in *The Future of Digital Communication*. Boca Raton, FL, USA: CRC Press, 2023, pp. 105–119.

[108] M. Qu, Y. Sun, and Y. Feng, "Digital media and VR art creation for metaverse," in *Proc. 2nd Asia Conf. Inf. Eng. (ACIE)*, Jan. 2022, pp. 48–51.
[109] M. D. A. Mohamad, "Sports in the metaverse," in *Metaverse Applications for New Business Models and Disruptive Innovation*. Hershey, PA, USA: IGI Global, 2023, pp. 150–168.
[110] S. Hwang and G. Koo, "Art marketing in the metaverse world: Evidence from South Korea," *Cogent Social Sci.*, vol. 9, no. 1, Dec. 2023, Art. no. 2175429.
[111] L.-H. Lee, Z. Lin, R. Hu, Z. Gong, A. Kumar, T. Li, S. Li, and P. Hui, "When creators meet the metaverse: A survey on computational arts," 2021, *arXiv:2111.13486*.
[112] J. Hutson and P. Hutson, "Museums and the metaverse: Emerging technologies to promote inclusivity and engagement," Lindenwood Univ., Saint Charles, MO, USA, Tech. Rep., 2023.
[113] Z. Lv, W.-L. Shang, and M. Guizani, "Impact of digital twins and metaverse on cities: History, current situation, and application perspectives," *Appl. Sci.*, vol. 12, no. 24, p. 12820, Dec. 2022.
[114] M. Kang, X. Wang, H. Wang, J. Hua, P. de Reffye, and F.-Y. Wang, "The development of AgriVerse: Past, present, and future," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 53, no. 6, pp. 3718–3727, Jun. 2023.
[115] A. Nguyen, E. Windfeld, M. Francis, G. Lhermie, and K. Kim, "A virtual farm tour for public education about dairy industry," in *Proc. IEEE Conf. Virtual Reality 3D User Interface Abstr. Workshops (VRW)*, Mar. 2023, pp. 438–441.
[116] M. Ulagammai and R. N. Moorthy, "An augmented reality based intelligent precision agriculture using cascade advancement technique," in *Proc. 7th Int. Conf. Trends Electron. Informat. (ICOEI)*, Apr. 2023, pp. 303–307.
[117] A. Schütz, K. Kurz, and G. Busch, "Virtual farm tours—Virtual reality glasses and tablets are suitable tools to provide insights into pig husbandry," *PLoS ONE*, vol. 17, no. 1, Jan. 2022, Art. no. e0261248.
[118] S. Kumari, P. Raghuram, V. G. Venkatesh, and Y. Shi, "Future perspectives on progressive farming with adoption of virtual reality technology for sustainable quality in agriculture," *TQM J.*, vol. 34, no. 2, pp. 250–279, Feb. 2022.
[119] M. Xi, M. Adcock, and J. McCulloch, "Future agriculture farm management using augmented reality," in *Proc. IEEE Workshop Augmented Virtual Realities Good*, Mar. 2018, pp. 1–3.
[120] J. Huuskonen and T. Oksanen, "Augmented reality for supervising multirobot system in agricultural field operation," *IFAC-PapersOnLine*, vol. 52, no. 30, pp. 367–372, 2019.
[121] W. Hurst, F. R. Mendoza, and B. Tekinerdogan, "Augmented reality in precision farming: Concepts and applications," *Smart Cities*, vol. 4, no. 4, pp. 1454–1468, Dec. 2021.
[122] J. Huuskonen and T. Oksanen, "Soil sampling with drones and augmented reality in precision agriculture," *Comput. Electron. Agricult.*, vol. 154, pp. 25–35, Nov. 2018.
[123] E. Anastasiou, A. T. Balafoutis, and S. Fountas, "Applications of extended reality (XR) in agriculture, livestock farming, and aquaculture: A review," *Smart Agricult. Technol.*, vol. 3, Feb. 2023, Art. no. 100105.
[124] V. Ponnusamy, S. Natarajan, N. Ramasamy, C. Clement, P. Rajalingam, and M. Mitsunori, "An IoT-enabled augmented reality framework for plant disease detection," *Revue d'Intell. Artificielle*, vol. 35, no. 3, pp. 185–192, Jun. 2021.
[125] S. Hollensen, P. Kotler, and M. O. Opresnik, "Metaverse—The new marketing universe," *J. Bus. Strategy*, vol. 44, no. 3, pp. 119–125, Apr. 2023.
[126] Y. Toraman and B. B. Geçit, "User acceptance of metaverse: An analysis for e-commerce in the framework of technology acceptance model (TAM)," *Sosyoekonomi*, vol. 31, no. 55, pp. 85–104, 2023.
[127] B. Rathore, "Metaverse marketing: Novel challenges, opportunities, and strategic approaches," *Eduzone, Int. Peer Reviewed/Refereed Academic Multidisciplinary J.*, vol. 7, no. 2, pp. 72–82, 2018.
[128] H. Jeong, Y. Yi, and D. Kim, "An innovative e-commerce platform incorporating metaverse to live commerce," *Int. J. Innov. Comput., Inf. Control*, vol. 18, no. 1, pp. 221–229, Feb. 2022.
[129] D. Chakraborty, A. K. Kar, and D. Dennehy, "Metaverse in e-commerce industry: Current trends and future prospects," *Electron. Commerce Res.*, vol. 10, pp. 1–2, Aug. 2023.
[130] I. Cheah and A. S. Shimul, "Marketing in the metaverse: Moving forward—What's next?" *J. Global Scholars Marketing Sci.*, vol. 33, no. 1, pp. 1–10, Jan. 2023.
[131] T. Hennig-Thurau, D. N. Aliman, A. M. Herting, G. P. Cziehso, M. Linder, and R. V. Kübler, "Social interactions in the metaverse: Framework, initial evidence, and research roadmap," *J. Acad. Marketing Sci.*, vol. 51, no. 4, pp. 1–25, 2022.
[132] W. Hamidouche, L. Bariah, and M. Debbah, "Immersive media and massive twinning: Advancing towards the metaverse," 2023, *arXiv:2307.01522*.
[133] L. Jiaxin and G. Gongjing, "Socializing in the metaverse: The innovation and challenge of interpersonal communication," in *Proc. 8th Int. Conf. Humanities Social Sci. Res.*, in Advances in Social Science, Education and Humanities, 2022, pp. 2128–2131.
[134] H.-W. Lee, S. Kim, and J.-P. Uhm, "Social virtual reality (VR) involvement affects depression when social connectedness and self-esteem are low: A moderated mediation on well-being," *Frontiers Psychol.*, vol. 12, Nov. 2021, Art. no. 753019.
[135] Y. A. Jeon, "Reading social media marketing messages as simulated self within a metaverse: An analysis of gaze and social media engagement behaviors within a metaverse platform," in *Proc. IEEE Conf. Virtual Reality 3D User Interface Abstr. Workshops (VRW)*, Mar. 2022, pp. 301–303.
[136] G. Murtas, G. Pedeliento, and F. Mangiò, "Luxury fashion brands at the gates of the web 3.0: An analysis of early experimentations with NFTs and the metaverse," *J. Global Fashion Marketing*, vol. 2023, pp. 1–25, Aug. 2023.
[137] A. Joy, Y. Zhu, C. Peña, and M. Brouard, "Digital future of luxury brands: Metaverse, digital fashion, and non-fungible tokens," *Strategic Change*, vol. 31, no. 3, pp. 337–343, May 2022.
[138] E. Mogaji, Y. K. Dwivedi, and R. Raman, "Fashion marketing in the metaverse," *J. Global Fashion Marketing*, vol. 2023, pp. 1–16, Aug. 2023.
[139] J.-Y. Dai and L. Zhao, "Happiness and fashion culture of smart kidswear from the perspective of metaverse," in *Proc. 10th Int. Conf. Orange Technol. (ICOT)*, 2022, pp. 1–4.
[140] C. Chrimes and R. Boardman, "The opportunities & challenges of the metaverse for fashion brands," in *The Garment Economy: Understanding History, Developing Bus. Models, and Leveraging Digital Technologies*. Cham, Switzerland: Springer, 2023, pp. 389–410.
[141] L. Giraldi, "The metaverse as an opportunity for the development of fashion design," *Fashion Highlight*, vol. 1, no. 1, pp. 68–77, Jul. 2023.
[142] A. Trujillo and C. Bacciu, "Toward blockchain-based fashion wearables in the metaverse: The case of decentraland," 2023, *arXiv:2307.01322*.
[143] S. Cobben, "Designing a new customer experience for fashion in the metaverse," Delft Univ. Technol., Delft, The Netherlands, Tech. Rep., 2022.
[144] M. Wang and C. Hu, "Development of fashion design system based on virtual reality technology," in *Proc. 2nd Int. Conf. Comput. Technol. Media Converg. Design*, 2022, pp. 101–109.
[145] A. S. M. Sayem, "Digital fashion innovations for the real world and metaverse," *Int. J. Fashion Design, Technol. Educ.*, vol. 15, no. 2, pp. 139–141, May 2022.
[146] S. Periyasami and A. P. Periyasamy, "Metaverse as future promising platform business model: Case study on fashion value chain," *Businesses*, vol. 2, no. 4, pp. 527–545, Nov. 2022.
[147] Y. X. Lee, "Application of metaverse in the real estate industry," Ph.D. thesis, Real Estate Manag. (Honors), Tunku Abdul Rahman Univ. College, Kuala Lumpur, Malaysia, 2023.
[148] J. Hutson, G. Banerjee, N. Kshetri, K. Odenwald, and J. Ratican, "Architecting the metaverse: Blockchain and the financial and legal regulatory challenges of virtual real estate," *J. Intell. Learn. Syst. Appl.*, vol. 15, no. 1, pp. 1–23, 2023.
[149] L. Ante, F.-P. Wazinski, and A. Saggu, "Digital real estate in the metaverse: An empirical analysis of retail investor motivations," *Finance Res. Lett.*, vol. 58, Dec. 2023, Art. no. 104299.
[150] E. Fioretto, "Real estate in the metaverse," Polytech. Univ. Milan, Milan, Italy, Tech. Rep., 2022.
[151] V. Nakavachara and K. Saengchote, "Does unit of account affect willingness to pay? Evidence from metaverse LAND transactions," *Finance Res. Lett.*, vol. 49, Oct. 2022, Art. no. 103089.
[152] A. Azmi, R. Ibrahim, M. A. Ghafar, and A. Rashidi, "Metaverse for real estate marketing: The impact of virtual reality on satisfaction, perceived enjoyment and purchase intention," Res. Square, Durham, NC, USA, Tech. Rep., 2023.

[153] S. B. Far and A. I. Rad, ''Applying digital twins in metaverse: User interface, security and privacy challenges,'' *J. Metaverse*, vol. 2, no. 1, pp. 8–15, 2022.

[154] M. Letafati and S. Otoum, ''On the privacy and security for e-health services in the metaverse: An overview,'' *Ad Hoc Netw.*, vol. 150, Nov. 2023, Art. no. 103262.

[155] M. Adil, H. Song, M. Khurram Khan, A. Farouk, and Z. Jin, ''5G/6G-enabled metaverse technologies: Taxonomy, applications, and open security challenges with future research directions,'' 2023, *arXiv:2305.16473*.

[156] Z. Chen, J. Wu, W. Gan, and Z. Qi, ''Metaverse security and privacy: An overview,'' in *Proc. IEEE Int. Conf. Big Data (Big Data)*, Dec. 2022, pp. 2950–2959.

[157] S. Qamar, Z. Anwar, and M. Afzal, ''A systematic threat analysis and defense strategies for the metaverse and extended reality systems,'' *Comput. Secur.*, vol. 128, May 2023, Art. no. 103127.

[158] C. Chen, Y. Li, Z. Wu, C. Mai, Y. Liu, Y. Hu, Z. Zheng, and J. Kang, ''Privacy computing meets metaverse: Necessity, taxonomy and challenges,'' 2023, *arXiv:2304.11643*.

[159] P. Kürtünlüoğlu, B. Akdik, and E. Karaarslan, ''Security of virtual reality authentication methods in metaverse: An overview,'' 2022, *arXiv:2209.06447*.

[160] A. Riahi Sfar, E. Natalizio, Y. Challal, and Z. Chtourou, ''A roadmap for security challenges in the Internet of Things,'' *Digit. Commun. Netw.*, vol. 4, no. 2, pp. 118–137, Apr. 2018.

[161] S. Tariq, A. Abuadbba, and K. Moore, ''Deepfake in the metaverse: Security implications for virtual gaming, meetings, and offices,'' 2023, *arXiv:2303.14612*.

[162] C. H. Smith, J. Molka-Danielsen, J. Rasool, and J.-B. Webb-Benjamin, ''The world as an interface: Exploring the ethical challenges of the emerging metaverse,'' Univ. Hawaii, Honolulu, HI, USA, Tech. Rep., 2023.

[163] P. Calvo, ''Metaverse: Ethical challenges of the tokenisation of the economy,'' *Filosofia Unisinos*, vol. 24, Oct. 2023, Art. no. e24106.

[164] H. Huang, Q. Zhang, T. Li, Q. Yang, Z. Yin, J. Wu, Z. Xiong, J. Zhu, J. Wu, and Z. Zheng, ''Economic systems in metaverse: Basics, state of the art, and challenges,'' 2022, *arXiv:2212.05803*.

[165] Q. Wang, R. Li, Q. Wang, and S. Chen, ''Non-fungible token (NFT): Overview, evaluation, opportunities and challenges,'' 2021, *arXiv:2105.07447*.

[166] W. Rehman, H. E. Zainab, J. Imran, and N. Z. Bawany, ''NFTs: Applications and challenges,'' in *Proc. 22nd Int. Arab Conf. Inf. Technol. (ACIT)*, Dec. 2021, pp. 1–7.

[167] H. Huang, X. Zeng, L. Zhao, C. Qiu, H. Wu, and L. Fan, ''Fusion of building information modeling and blockchain for metaverse: A survey,'' *IEEE Open J. Comput. Soc.*, vol. 3, pp. 195–207, 2022.

[168] Q. Yang, Y. Zhao, H. Huang, Z. Xiong, J. Kang, and Z. Zheng, ''Fusing blockchain and AI with metaverse: A survey,'' *IEEE Open J. Comput. Soc.*, vol. 3, pp. 122–136, 2022.

[169] Y. Fu, C. Li, F. R. Yu, T. H. Luan, P. Zhao, and S. Liu, ''A survey of blockchain and intelligent networking for the metaverse,'' *IEEE Internet Things J.*, vol. 10, no. 4, pp. 3587–3610, Feb. 2023.

[170] I. F. Akyildiz, H. Guo, R. Dai, and W. Gerstacker, ''Mulsemedia communication research challenges for metaverse in 6G wireless systems,'' 2023, *arXiv:2306.16359*.

[171] J. Yu, A. Alhilal, P. Hui, and D. H. K. Tsang, ''6G mobile-edge empowered metaverse: Requirements, technologies, challenges and research directions,'' 2022, *arXiv:2211.04854*.

[172] K. A. Awan, I. Ud Din, A. Almogren, and B.-S. Kim, ''Enhancing performance and security in the metaverse: Latency reduction using trust and reputation management,'' *Electronics*, vol. 12, no. 15, p. 3362, Aug. 2023.

[173] X. Zhang, X. Huang, H. Yin, J. Huang, S. Chai, B. Xing, X. Wu, and L. Zhao, ''LLAKEP: A low-latency authentication and key exchange protocol for energy Internet of Things in the metaverse era,'' *Mathematics*, vol. 10, no. 14, p. 2545, Jul. 2022.

[174] L. Chang, Z. Zhang, P. Li, S. Xi, W. Guo, Y. Shen, Z. Xiong, J. Kang, D. Niyato, X. Qiao, and Y. Wu, ''6G-enabled edge AI for metaverse: Challenges, methods, and future research directions,'' *J. Commun. Inf. Netw.*, vol. 7, no. 2, pp. 107–121, Jun. 2022.

[175] A. M. Aslam, R. Chaudhary, A. Bhardwaj, I. Budhiraja, N. Kumar, and S. Zeadally, ''Metaverse for 6G and beyond: The next revolution and deployment challenges,'' *IEEE Internet Things Mag.*, vol. 6, no. 1, pp. 32–39, Mar. 2023.

[176] T. Q. Duong, D. Van Huynh, S. R. Khosravirad, V. Sharma, O. A. Dobre, and H. Shin, ''From digital twin to metaverse: The role of 6G ultra-reliable and low-latency communications with multi-tier computing,'' *IEEE Wireless Commun.*, vol. 30, no. 3, pp. 140–146, Jun. 2023.

[177] Z. Wang, J. Liu, and W. Zhu, ''Edge intelligence-empowered immersive media,'' *IEEE MultimediaMag.*, vol. 30, no. 2, pp. 8–17, Apr. 2023.

[178] P. Rospigliosi, ''Adopting the metaverse for learning environments means more use of deep learning artificial intelligence: This presents challenges and problems,'' *Interact. Learn. Environ.*, vol. 30, no. 9, pp. 1573–1576, Oct. 2022.

[179] S. Zeng, Z. Li, H. Yu, Z. Zhang, L. Luo, B. Li, and D. Niyato, ''HFedMS: Heterogeneous federated learning with memorable data semantics in industrial metaverse,'' *IEEE Trans. Cloud Comput.*, vol. 11, no. 3, pp. 3055–3069, Jul. 2023.

[180] L. U. Khan, I. Yaqoob, K. Salah, C. Seon Hong, D. Niyato, Z. Han, and M. Guizani, ''Machine learning for metaverse-enabled wireless systems: Vision, requirements, and challenges,'' 2022, *arXiv:2211.03703*.

[181] V. Stafford, ''Zero trust architecture,'' *NIST Special Publication*, vol. 800, p. 207, Aug. 2020.

[182] P. Krishnan, K. Jain, R. Buyya, P. Vijayakumar, A. Nayyar, M. Bilal, and H. Song, ''MUD-based behavioral profiling security framework for software-defined IoT networks,'' *IEEE Internet Things J.*, vol. 9, no. 9, pp. 6611–6622, May 2022.

[183] K. Ruth, T. Kohno, and F. Roesner, ''Secure multi-user content sharing for augmented reality applications,'' in *Proc. 28th USENIX Secur. Symp.*, 2019, pp. 141–158.

[184] D. Zou, J. Zhao, W. Li, Y. Wu, W. Qiang, H. Jin, Y. Wu, and Y. Yang, ''A multigranularity forensics and analysis method on privacy leakage in cloud environment,'' *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1484–1494, Apr. 2019.

[185] R. Imamguluyev, N. Umarova, and R. Mikayilova, ''Navigating the ethics of the metaverse: A fuzzy logic approach to decision-making,'' in *Proc. Int. Conf. Intell. Fuzzy Syst.* Cham, Switzerland: Springer, 2023, pp. 53–60.

[186] R. Cheng, S. Chen, and B. Han, ''Towards zero-trust security for the metaverse,'' *IEEE Commun. Mag.*, early access, May 29, 2023, doi: 10.1109/MCOM.018.2300095.

[187] I. U. Din, K. A. Awan, and A. Almogren, ''Secure and privacy-preserving trust management system for trustworthy communications in intelligent transportation systems,'' *IEEE Access*, vol. 11, pp. 65407–65417, 2023.

[188] H.-J. Kwon, A. E. Azzaoui, and J. H. Park, ''MetaQ: A quantum approach for secure and optimized metaverse environment,'' *Hum.-Cent. Comput. Inf. Sci*, vol. 12, p. 42, Jan. 2022.

[189] J. Zhu, P. Ni, and G. Wang, ''Activity minimization of misinformation influence in online social networks,'' *IEEE Trans. Computat. Social Syst.*, vol. 7, no. 4, pp. 897–906, Aug. 2020.

[190] R. García, A. Cediel, M. Teixidó, and R. Gil, ''Semantics and non-fungible tokens for copyright management on the metaverse and beyond,'' *ACM Trans. Multimedia Comput., Commun., Appl.*, vol. 2023, pp. 1–20, Feb. 2023.

[191] M. K. Hari, A. Agrawal, R. Bhatia, A. Bhatia, and K. Tiwari, ''T-PASS: A blockchain-based NFT enabled property management and exchange system,'' in *Proc. Int. Conf. Inf. Netw. (ICOIN)*, Jan. 2023, pp. 140–145.

[192] M. Shen, H. Liu, L. Zhu, K. Xu, H. Yu, X. Du, and M. Guizani, ''Blockchain-assisted secure device authentication for cross-domain industrial IoT,'' *IEEE J. Sel. Areas Commun.*, vol. 38, no. 5, pp. 942–954, May 2020.

[193] Y. Wang, Z. Su, and M. Yan, ''Social metaverse: Challenges and solutions,'' 2023, *arXiv:2301.10221*.

[194] M. Li, J. Weng, J.-N. Liu, X. Lin, and C. Obimbo, ''Toward vehicular digital forensics from decentralized trust: An accountable, privacy-preserving, and secure realization,'' *IEEE Internet Things J.*, vol. 9, no. 9, pp. 7009–7024, May 2022.

[195] Z. Guan, Z. Wan, Y. Yang, Y. Zhou, and B. Huang, ''BlockMaze: An efficient privacy-preserving account-model blockchain based on zk-SNARKs,'' *IEEE Trans. Dependable Secure Comput.*, vol. 19, no. 3, pp. 1446–1463, May 2022.

[196] S. Qu, Y. Kang, and J. Lee, ''Efficient multi-modal fusion with diversity analysis,'' in *Proc. 29th ACM Int. Conf. Multimedia*, 2021, pp. 2663–2670.

[197] B. Falchuk, S. Loeb, and R. Neff, ''The social metaverse: Battle for privacy,'' *IEEE Technol. Soc. Mag.*, vol. 37, no. 2, pp. 52–61, Jun. 2018.

[198] Y. Han, D. Niyato, C. Leung, D. In Kim, K. Zhu, S. Feng, S. Xuemin Shen, and C. Miao, "A dynamic hierarchical framework for IoT-assisted metaverse synchronization," 2022, *arXiv:2203.03969*.
[199] R. Liu, Z. Liu, J. Liu, and X. Fan, "Searching a hierarchically aggregated fusion architecture for fast multi-modality image fusion," in *Proc. 29th ACM Int. Conf. Multimedia*, Oct. 2021, pp. 1600–1608.
[200] M. Xu, Y. Guo, Q. Hu, Z. Xiong, D. Yu, and X. Cheng, "A trustless architecture of blockchain-enabled metaverse," *High-Confidence Comput.*, vol. 3, no. 1, Mar. 2023, Art. no. 100088.
[201] Y.-J. Liu, H. Du, D. Niyato, G. Feng, J. Kang, and Z. Xiong, "Slicing4Meta: An intelligent integration architecture with multi-dimensional network resources for metaverse-as-a-service in web 3.0," *IEEE Commun. Mag.*, vol. 61, no. 8, pp. 20–26, Aug. 2023.
[202] S. K. Tang and J.-H. Hou, "Designing a framework for metaverse architecture," in *Proc. 27th CAADRIA Conf.*, vol. 2, 2022, pp. 445–454.
[203] Z. Wang, J. Liu, and W. Zhu, "Edge intelligence empowered immersive media: Challenges and approaches," *IEEE MultimediaMag.*, vol. 30, no. 2, pp. 8–17, Apr. 2023.
[204] M. Xu, W. C. Ng, W. Y. B. Lim, J. Kang, Z. Xiong, D. Niyato, Q. Yang, X. Shen, and C. Miao, "A full dive into realizing the edge-enabled metaverse: Visions, enabling technologies, and challenges," *IEEE Commun. Surveys Tuts.*, vol. 25, no. 1, pp. 656–700, 1st Quart., 2023.
[205] W. Yu, T. J. Chua, and J. Zhao, "Asynchronous hybrid reinforcement learning for latency and reliability optimization in the metaverse over wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 7, pp. 2138–2157, Jul. 2023.
[206] D. Van Huynh, S. R. Khosravirad, A. Masaracchia, O. A. Dobre, and T. Q. Duong, "Edge intelligence-based ultra-reliable and low-latency communications for digital twin-enabled metaverse," *IEEE Wireless Commun. Lett.*, vol. 11, no. 8, pp. 1733–1737, Aug. 2022.
[207] L. Qi, S. Dou, Z. Guo, C. Li, Y. Li, and T. Zhu, "Low control latency SD-WANs for metaverse," in *Proc. IEEE 42nd Int. Conf. Distrib. Comput. Syst. Workshops (ICDCSW)*, Jul. 2022, pp. 266–271.
[208] J. Cao, X. Zhu, S. Sun, Z. Wei, Y. Jiang, J. Wang, and V. K. N. Lau, "Toward industrial metaverse: Age of information, latency and reliability of short-packet transmission in 6G," *IEEE Wireless Commun.*, vol. 30, no. 2, pp. 40–47, Apr. 2023.
[209] F. Guo, F. R. Yu, H. Zhang, H. Ji, V. C. M. Leung, and X. Li, "An adaptive wireless virtual reality framework in future wireless networks: A distributed learning approach," *IEEE Trans. Veh. Technol.*, vol. 69, no. 8, pp. 8514–8528, Aug. 2020.
[210] A. F. R. Guarda, N. M. M. Rodrigues, and F. Pereira, "Adaptive deep learning-based point cloud geometry coding," *IEEE J. Sel. Topics Signal Process.*, vol. 15, no. 2, pp. 415–430, Feb. 2021.
[211] M. Jamshidi, S. Sargolzaei, S. Foorginezhad, and O. Moztarzadeh, "Metaverse and microorganism digital twins: A deep transfer learning approach," *Appl. Soft Comput.*, vol. 147, Nov. 2023, Art. no. 110798.
[212] Y. J. Park, H. Ro, J.-H. Byun, and T.-D. Han, "Adaptive projection augmented reality with object recognition based on deep learning," in *Proc. 24th Int. Conf. Intell. User Interfaces, Companion*, Mar. 2019, pp. 51–52.
[213] E. Oliveira, P. Galvao de Barba, and L. Corrin, "Enabling adaptive, personalised and context-aware interaction in a smart learning environment: Piloting the iCollab system," *Australas. J. Educ. Technol.*, vol. 37, no. 2, pp. 1–23, May 2021.
[214] L. Rosenberg, "Regulation of the metaverse: A roadmap: The risks and regulatory solutions for largescale consumer platforms," in *Proc. 6th Int. Conf. Virtual Augmented Reality Simulations*, Mar. 2022, pp. 21–26.
[215] H. Zhang, G. Luo, Y. Li, and F.-Y. Wang, "Parallel vision for intelligent transportation systems in metaverse: Challenges, solutions, and potential applications," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 53, no. 6, pp. 3400–3413, Jun. 2022.
[216] J. Kang, D. Ye, J. Nie, J. Xiao, X. Deng, S. Wang, Z. Xiong, R. Yu, and D. Niyato, "Blockchain-based federated learning for industrial metaverses: Incentive scheme with optimal AoI," in *Proc. IEEE Int. Conf. Blockchain (Blockchain)*, Aug. 2022, pp. 71–78.
[217] H. Moudoud and S. Cherkaoui, "Federated learning meets blockchain to secure the metaverse," in *Proc. Int. Wireless Commun. Mobile Comput. (IWCMC)*, Jun. 2023, pp. 339–344.
[218] M. A. P. Putra, S. M. Rachmawati, M. Abisado, and G. A. Sampedro, "HFTL: Hierarchical federated transfer learning for secure and efficient fault classification in additive manufacturing," *IEEE Access*, vol. 11, pp. 54795–54807, 2023.
[219] T. T. C. K. Zhang, L. F. Toso, J. Anderson, and N. Matni, "Meta-learning operators to optimality from multi-task non-IID data," 2023, *arXiv:2308.04428*.
[220] Q. Li, Y. Diao, Q. Chen, and B. He, "Federated learning on non-IID data silos: An experimental study," in *Proc. IEEE 38th Int. Conf. Data Eng. (ICDE)*, May 2022, pp. 965–978.
[221] C. Chen, K. Z. K. Zhang, Z. Chu, and M. Lee, "Augmented reality in the metaverse market: The role of multimodal sensory interaction," *Internet Res.*, Aug. 2023.
[222] U. R. Saxena and T. Alam, "Role-based access using partial homomorphic encryption for securing cloud data," *Int. J. Syst. Assurance Eng. Manage.*, vol. 14, no. 3, pp. 950–966, Jun. 2023.
[223] C. D. Schuman, S. R. Kulkarni, M. Parsa, J. P. Mitchell, P. Date, and B. Kay, "Opportunities for neuromorphic computing algorithms and applications," *Nature Comput. Sci.*, vol. 2, no. 1, pp. 10–19, Jan. 2022.
[224] M. Chehimi, O. Hashash, and W. Saad, "The roadmap to a quantum-enabled wireless metaverse: Beyond the classical limits," in *Proc. 5th Int. Conf. Adv. Comput. Tools Eng. Appl. (ACTEA)*, Jul. 2023, pp. 7–12.
[225] R. Soltani, M. Zaman, R. Joshi, and S. Sampalli, "Distributed ledger technologies and their applications: A review," *Appl. Sci.*, vol. 12, no. 15, p. 7898, Aug. 2022.
[226] S. B. Othman, F. A. Almalki, C. Chakraborty, and H. Sakli, "Privacy-preserving aware data aggregation for IoT-based healthcare with green computing technologies," *Comput. Electr. Eng.*, vol. 101, Jul. 2022, Art. no. 108025.

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