This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2023.3281303

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.Doi Number

Unveiling the Metaverse: Exploring Emerging Trends, Multifaceted Perspectives, and Future Challenges

Mueen Uddin [1] (SMIEEE), Selvakumar Manickam [2], Hidayat Ullah[3], Muath Obaidat [4] and Abdulhalim Dandoush [1]

[1]College of Computing and Information Technology, University of Doha for Science and Technology, 24449, Doha, Qatar; mueen.malik@ieee.org; andul.halim@udst.edu.qa

[2]National Advanced IPv6 Centre (NAv6), Universiti Sains Malaysia, Gelugor, Penang 11800, Malaysia; selva@usm.my

[3]College of Management, Shenzhen University, Shenzhen, People's Republic of China; haadi_mallick@yahoo.com

[4]Department of Computer Science, City University New York, USA; muobaidat@ccny.cuny.edu

Corresponding author: Selvakumar Manickam (e-mail: selva@usm.my)

ABSTRACT The metaverse is an expanding network of digital spaces that are gaining popularity in the realm of virtual environments. By utilizing digital representations known as avatars, users can interact and engage with each other in an immersive and interconnected space. This paradigm shift in computing represents a merging of the physical and digital worlds, offering users an unprecedented level of interactivity and experience. Driven by advancements in technologies such as virtual and augmented reality, artificial intelligence, and other technologies, the metaverse is unlocking new avenues for human interaction and innovation. The metaverse presents a wide range of possibilities for the development of interactive experiences, including virtual social spaces, remote work, and novel forms of entertainment. However, it also faces significant challenges, including privacy and security concerns, issues of equitable access, and ethical and legal considerations. Establishing a robust legal and ethical framework is crucial to ensure that the metaverse is utilized for the greater good, such as promoting social connection and fostering creativity. The development and evolution of the metaverse are poised to shape the future of digital life and experience, offering new and exciting opportunities for human engagement and creativity. This review paper provides a comprehensive analysis of the foundational principles, safety measures, and confidentiality of the virtual world, including its overall design, characteristics, and potential security and privacy hazards. Our discussion aims to provide perspective on the challenges and opportunities presented by this emerging technology, and how we can leverage its potential while addressing any associated risks.

Keywords metaverse, the virtual universe, digital world, interconnected network, virtual environments, avatars, immersive technologies, artificial intelligence, privacy and security, equitable access.

I. INTRODUCTION

The notion of the metaverse has been around for nearly 30 years since the inception of the internet itself. However, it is only in recent times that the metaverse has undergone tremendous growth, largely driven by the development of 3D gaming. The recent growth of the metaverse can be largely attributed to advancements in hardware and software, such as graphic processing units (GPUs), wireless connection networks, and built-in sensors on the hardware side, as well as communication, computer vision, and language processing on the software side. These developments have enabled the creation of a virtual world that is more imaginative, effective, and in line with the visions of science fiction authors. Figure 1 in this paper illustrates the development of the metaverse, highlighting key events such as the inception of the internet and the creation of the first virtual world, Second Life. These milestones in the development of digital technology paved the way for the emergence of the metaverse as we know it today. In recent times, the metaverse has attracted many users, mainly due to its immersive experience and the ability to interact with people from all over the world in a virtual environment. The

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and
content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2023.3281303

future of the metaverse is thought to be a sprawling, interrelated network of virtual realms, where individuals can experience life, engage in employment, and have fun. It can revolutionize how we interact with each other, consume media, and even conduct business. Although the metaverse is still in its infancy, its prospects are vast, and the future appears to be prosperous for this novel and thrilling digital realm.

Metaverse, in recent history, has attracted a lot of attention from the research community, and a considerable amount of work has already been done on the fundamentals, structure, and applications of this technology. However, as this is still a growing technology, we need to address the issues that may arise from some of the characteristics of the metaverse, such as virtual worlds, scalability, persistence, synchronization, financial flexibility, decentralization, security, and interoperability. This study's main aim is to produce new insights and knowledge as well as learn more about the metaverse and the difficulties and challenges it may confront in the future in developing a safe and privacy-preserving communication medium. It's a fresh attempt at deciphering the metaverse and its future trends and perspectives. Moreover, this study also examines the possibilities of the Metaverse's expansion in many sectors using bibliometric analysis based on different publications.

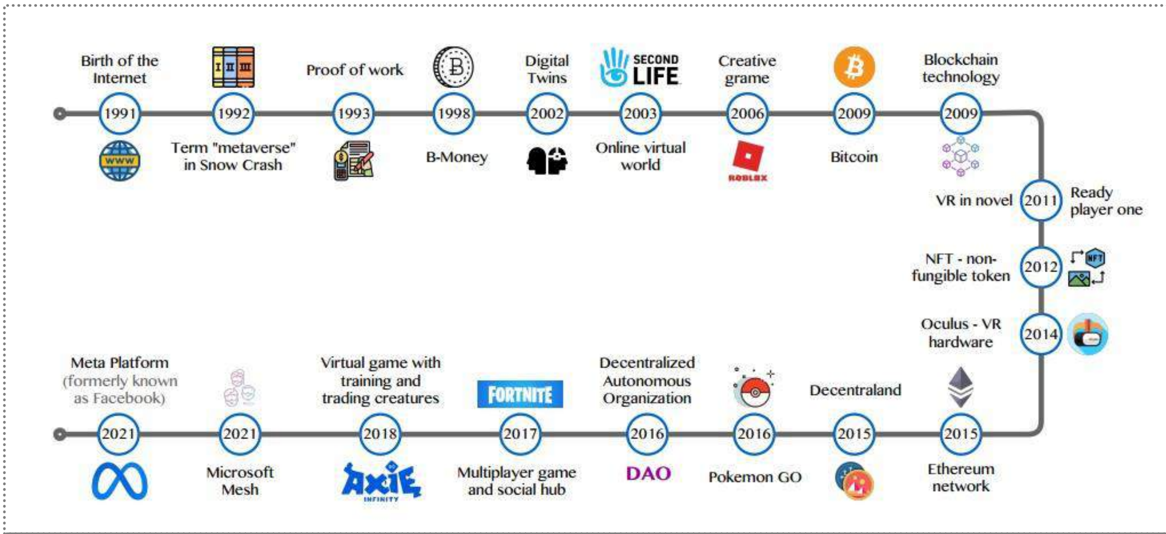

Fig. 1. A chronological outline of the evolution of the metaverse, highlighting key milestones from 1991 to 2021.

A. OUR CONTRIBUTIONS

This survey makes the following contributions:

- Elaborate on the fundamental concepts and intricacies of the metaverse, encompassing its comprehensive design, defining characteristics, advanced technologies facilitating its existence, and the latest and innovative examples of metaverse applications in existence today.
- Explore privacy and security issues in the metaverse from several different angles, including the administration of data, privacy, networks, economies, governance, and physical and social implications; authentication and access control; and outline the major difficulties that must be addressed.
- Indicate future metaverse research avenues for creating an efficient, private, and secure metaverse realm.

The contribution of our investigation of earlier comparable metaverse surveys is outlined in Table I.

TABLE I
A BRIEF COMPARISON OF OUR SURVEY WITH PREVIOUS WORKS

Year.	Refs.	Contribution
2020	[1]	Study of educational perspectives of the metaverse.
2021	[2]	Present the social benefit uses of the metaverse.
2021	[3]	Review of the metaverse's eight foundational technologies and the prospects it presents from its six user-centric factors
2021	[4]	Overview of the evolution of the metaverse in terms of governmental initiatives, commercial endeavors, infrastructures, enabling technologies, virtual reality, and the social metaverse.
2021	[5]	Examine digital art applications in the metaverse.
2022	[6]	Explore the potential applications of blockchain and AI in the creation of future metaverses.
2022	[7]	From six technological angles, discuss the significance of AI in the creation of the metaverse.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

2022	[8]	Investigate the ways users engage, launch, and showcase examples of utilization in the virtual world, as well as examine the fundamental elements, such as hardware, software, and content, that construct the
2022	[9]	Analyze the communication, networking, and computation in the edge-enabled metaverse.
2023	Ours	Present a comprehensive analysis of the foundational principles, safety measures, and confidentiality of the virtual world, including its overall design, characteristics, and potential security and privacy hazards. Delve into current issues, innovative solutions, and future avenues of study in establishing a

B. PAPER ORGANIZATION

The data for this study was sourced solely from various secondary sources, including books, journals, and online articles, such as those found on Google Scholar. The researchers conducted a meticulous search across different online platforms to gather relevant information and articles that support the study's objectives. The primary objective of this study is to deepen and enhance our understanding of the subject matter by thoroughly scrutinizing and synthesizing information sourced from secondary sources, thereby contributing to the expansion of knowledge in the field. A secondary objective of this study is to augment the existing body of knowledge and provide insights that may be valuable for future research in the field.

The introductory section provides a general overview of the topic and sets the stage for the subsequent sections. Section II highlights the overall approach for the research method. Section III covers the fundamental concepts of the metaverse, including its definition, the concept of avatars, and extended reality. It also explores the general architecture of the metaverse and the various stages of its development. This section also includes various hardware and software components that make up the metaverse, including head-mounted displays, input devices, and multi-modal content representation. Then, the various applications of the metaverse are explored in Section IV. Afterwards, the limitations and open challenges of the metaverse, including sustainability, hardware/software limitations, ethics, and security, are discussed in Section V. Lastly, an overview of the security challenges present in the implementation of the metaverse is provided in Section VI. Finally, the findings are summarized and the significance of the research is highlighted in this section.

II. RESEARCH METHOD

To gather reliable sources for our paper, we employed a combination of systematic literature review (SLR) [10] and hybrid-narrative literature review techniques. Our literature search was confined to studies and publications within the field of information systems and related disciplines that were relevant to the concepts of the Head-Mounted Display (HMD)-based on immersive virtual reality, Avatar, Extended Reality, immersive experience, digital twins, and Metaverse. Our exclusive method of obtaining references was through a comprehensive and rigorous examination of the relevant literature.

a. Explore related keyword combinations.
b. Locate and distinguish articles with relevant keyword phrases appearing in both the title and content of the paper.
c. Eliminate articles that contain relevant keywords but have no substantive connection to the realm of the Metaverse.
d. Group together the relevant papers

We performed a comprehensive search for relevant literature by exploring various online databases, including:

- ScienceDirect (https://www.sciencedirect.com/).
- ResearchGate (https://www.researchgate.net).
- IEEEXplore (https://ieeexplore.ieee.org).

We eliminated articles that were not pertinent, including those discussing VR hardware or software, prefaces, invitations to submit papers, special issue introductions, and book evaluations.

III. METAVERSE – FUNDAMENTALS

A. METAVERSE - FROM CONCEPTION TO ACHIEVING THE STATUS OF A GIANT IN THE GLOBAL MARKET

The term "metaverse," in which the prefix "meta" refers to "far off" and the suffix "verse" refers to "universe," was initially coined in 1992 by Neal Stephenson in one of his science fiction novels, "Snow Crash" [11] and was later given currency by Facebook founder Mark Zuckerberg when he announced the rebranding of his digital platform Facebook as "meta" in October 2021. In a broad sense, the term "metaverse" refers to the fifth generation and beyond the Internet world in which avatars can be used to represent participants who can interact with software programs and with one another in a virtual three-dimensional environment [12]. However, there is not a single, agreed, definition of the term, as various scholars have elaborated on this terminology in various ways. Some scholars describe it as an immersive 3D collaborative environment in which participants could perform cultural, economic, and social activities as well as interact with one another via avatars [13, 14]. While the other refers to it as a "virtual world" in which physical and geographic peculiarities of the physical world are mimicked and modeled to create a digital network space in which users are represented by avatars [15]. Additionally, the metaverse is often considered a fully enveloping, ultra-spatial, and self-sufficient digital and shared realm that blends the three domains of the digital, human, and physical spheres. [4]. Aside from the permanent virtual sites and structures in the digital realm, a variety of elements, including user identities, objects, and digital possessions, can be traded across virtual realms, sometimes even mimicking real life. [16]. The central thesis posits that, with the advent of the web and mobile internet, the metaverse is viewed as a thriving aspect of the next-generation internet. [17]. This digital world offers

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2023.3281303

people the chance to experience a separate life in the virtual realm and become part of the growing population of digital natives. Metaverse is perceived as a fresh frontier of the internet that provides a unique environment where individuals can interact and create in a completely new and exciting way. The potential of the metaverse is limitless, and it is poised to shape the future of the internet and human interaction.

In its totality and looking at the growth of the metaverse, it won't be an exaggeration to term it the next big advancement in the digital realm. and an heir to the modern-day internet [16]. Numerous major technology companies, including Unity, Bytedance, Tencent, NVIDIA, Microsoft, and Facebook, have already announced their involvement in the metaverse. Facebook has even gone so far as to rebrand itself as "meta". Microsoft has made a major investment in the metaverse, acquiring video game company Activision Blizzard for a staggering $68.7 billion as part of its efforts to extend its reach into the metaverse gaming world. These tech giants see the potential for the metaverse to revolutionize the digital world and are eager to be at the forefront of this new and exciting frontier [7]. Metaverse Seoul is creating a virtual ecosystem of communication for various municipal administrative fields, including culture, tourism, business, education, and public service. These developments provide a glimpse into the expanding metaverse universe, which is attracting not only online gaming giants, internet financial and business companies, and various social network platforms but also has the potential to extend to healthcare [18], education, simulation, and transportation [8], among other aspects of human life.

Furthermore, the metaverse industry is projected to experience substantial growth, with its value rising from USD 500 million in 2020 to an estimated USD 800 billion in 2024. Online gaming is expected to account for a significant portion of this revenue, representing roughly half of the global income generated by the metaverse.

B. METAVERSE – GENERAL ARCHITECTURE

The metaverse is an artificial world comprised of avatars controlled by users, digital assets, virtual environments, and other computer-generated components. Individuals, represented through their avatars, can interact, cooperate, and engage in social interactions with one another utilizing intelligent devices. Metaverse amalgamates the trichotomy of the physical, human, and digital realms, creating a unique and comprehensive environment for human interaction. Additionally, the metaverse's human world is portrayed as a digital arena where individuals can participate in a diverse range of pursuits and establish both psychological and social connections with each other. Through avatars and other digital representations, users can express themselves, communicate, and interact with others in a simulated environment that mimics the physical world.

The illustration of the metaverse in Figure 2 provides a graphical representation of the complex and extensive network that constitutes the metaverse's virtual universe. The physical space of the metaverse is made up of connected smart devices, objects, and sensors, like smart homes, wearable devices, and IoTs, that serve as the bridge between the digital and physical worlds. These devices and objects allow the metaverse to communicate with the real world, by collecting data, processing it, and transmitting it to the metaverse's network and computational systems. This enables a seamless transfer of data and ensures that the metaverse can respond to real-world events in real-time. Additionally, the network and computational systems of the metaverse allow for high-speed data transfer and processing, ensuring that the metaverse can keep pace with the rapid evolution of technology and the increasing demands of its users. Overall, the metaverse physical space plays a crucial role in creating an immersive and seamless experience for users, allowing them to interact with the digital world more naturally and intuitively. These smart objects and devices can be anything from virtual reality headsets to smartphones, and other internet-connected devices, which users interact with to engage with the virtual world. The network and computing infrastructure, on the other hand, provide the necessary support for the smooth functioning of the metaverse, enabling fast data transmission, low latency, and real-time interactions. IEEE 2888 [19] standards specify that the digital realm of the metaverse is constructed from a network of interrelated and dispersed virtual realms referred to as sub-metaverses.. Every sub-metaverse provides a distinct array of offerings, including social dating, gaming, virtual museums, and online concerts, to individuals represented through their avatars. In the proceeding segments, we shall delve into an extensive examination of the interconnectivity and correlation between the three realms, the building blocks that make up the metaverse, and the intricate mechanisms by which information is processed and circulated within the metaverse.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and
content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2023.3281303

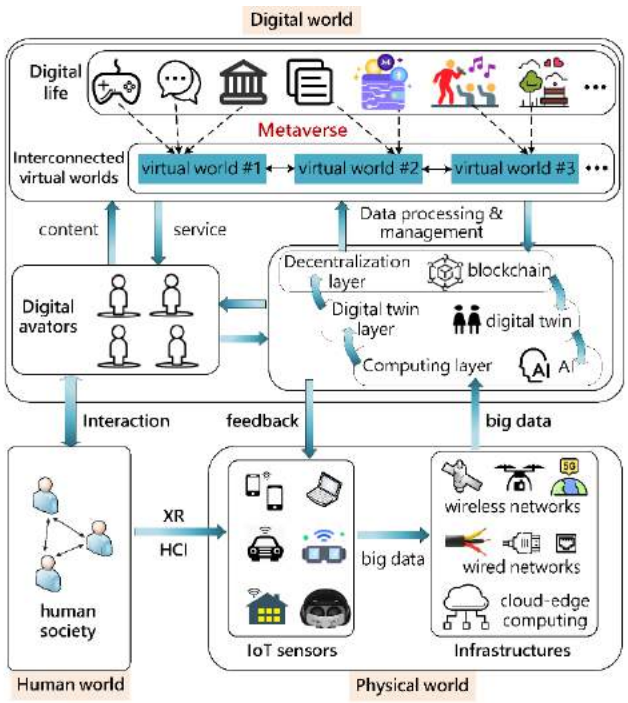

Fig. 2 The metaverse architecture is characterized by the combination of the human, physical, and digital realms [20].

1) **SOCIETY:** Metaverse is often seen as being centered around the needs and experiences of human users [21]. The human world is comprised of these users, along with their internal psychologies and social interactions. With the aid of advanced wearable devices such as VR/AR helmets, humans can interact with their digital avatars and control their movements within the metaverse. This allows them to engage in activities such as playing, working, socializing, and interacting with other avatars or virtual entities through human-computer interaction (HCI) and extended reality (XR) technologies, as depicted in the popular film, Ready Player One [22]. In this way, the metaverse offers a unique and immersive experience for human users, allowing them to fully engage with the virtual world in a previously impossible way.

2) **THE PHYSICAL WORLD** serves as a crucial support system for the metaverse, providing the necessary infrastructures such as sensing/control, communication, computation, and storage. These support systems enable the metaverse to effectively process and store multi-sensory data, Facilitating an effortless exchange of information and experiences between the virtual and physical domains through the integration of technology and human interaction. The sensing and control system, comprising intelligent devices, detectors, and regulators, enables comprehensive data acquisition from both the surrounding environment and human anatomy, as well as fine-tuned manipulation of technology. Interconnectivity is facilitated through a network infrastructure comprised of diverse wireless and wired networks, including Satellite communication networks, cellular communication networks, and unmanned aerial vehicle communication networks. Furthermore, the computing and data storage infrastructure provides substantial computing and storage capabilities, leveraging the synergies between cloud, edge, and end computing technologies. This support system allows the metaverse to function at its highest potential, providing users with a rich and immersive experience [23].

3) **INTERLINKED VIRTUAL SPACES** the digital world, as defined by ISO/IEC 23005 and IEEE 2888 standards [20], is comprised of multiple, interconnected virtual realms known as sub-metaverses. These sub-metaverses, in the digital world, offer a multitude of opportunities for users to engage in a variety of virtual experiences. By leveraging cutting-edge technologies such as artificial intelligence, extended reality, and human-computer interaction, individuals can engage in highly immersive and lifelike experiences with their digital counterparts and virtual surroundings. These virtual experiences can range from gaming and socializing to education and entertainment, providing users with a limitless world of possibilities. Furthermore, the interconnected nature of the sub-metaverses within the digital world enables users to seamlessly move between different virtual environments, creating a seamless and interconnected virtual world.

- **Avatars,** in the context of the metaverse, are digital counterparts of human users. They serve as the virtual representation of a user's presence in the metaverse, enabling them to interact with other digital entities. These avatars can take on various forms and shapes, ranging from human-like figures to animals, imaginary creatures, and more, depending on the metaverse application being used. Users have the flexibility to create multiple avatars for different purposes, each tailored to suit their specific needs and preferences.

- **Virtual environment** in Metaverse refers to the simulated, either real or fantastical, setting created using 3D digital elements and their characteristics. These virtual surroundings within the metaverse can have varying spatial and temporal dimensions, allowing users to experience an alternate reality, such as living in ancient times or visiting futuristic worlds. Furthermore, these virtual environments can

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

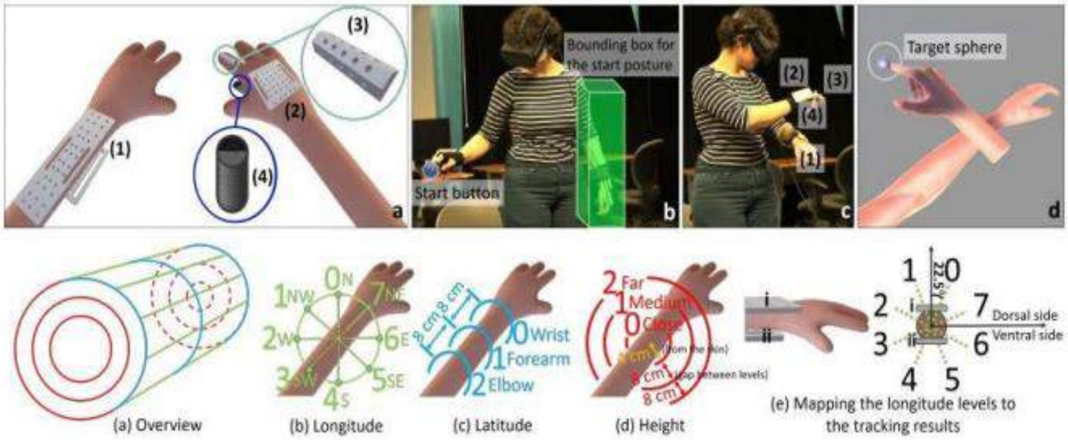

Fig. 3. An illustration of circular coordination and a zone for hand-based input devices [24]

be highly immersive and interactive, offering users a realistic and engaging experience. They can also be customized to match the user's preferences, allowing them to create and explore unique worlds. This level of customization and interactivity can lead to a greater sense of connection and immersion for the user, enhancing the overall experience in the metaverse. Additionally, virtual environments can serve as platforms for various activities, such as gaming, socializing, learning, and entertainment, creating a rich and diverse digital world for users to explore.

- **Virtual commodities**, including but not limited to digital art, skins, and virtual plots of land, are tradeable goods that are generated by Virtual Service Providers (VSPs) or individuals within the metaverse. The domain of virtual services within the metaverse is broad and encompasses a diverse range of fields and areas of interest, including the growing field of digital commerce, the use and adoption of digital currencies, the creation and implementation of virtual regulations, and the provision of social services and amenities, just to name a few. These virtual commodities hold value and can be bought, sold, and traded, much like physical commodities in the real world, and they play a crucial role in the growth and development of the metaverse as a thriving virtual economy.

4) **METAVERSE ENGINE** leverages real-world data to create, maintain and update the virtual world through AI, digital twin, blockchain, and XR and HCI (with a focus on brain-computer interaction). This enables users in physical environments to control their digital avatars through their senses and movements, participating in activities like racing, dating, and trading virtual goods. The virtual economy is generated through these activities and AI algorithms personalize avatar creation, render the metaverse and provide intelligent services. Digital twin technology uses AI-based big data analytics to simulate, digitize and mirror the real world, creating realistic virtual environments. Blockchain technology manages and monetizes digital twins and content, forming the economic and value system in the metaverse [20].

5) **IN-WORLD DATA TRANSFER** the human community is connected through social networks and shaped through shared activities and interaction between individuals. In the tangible realm, the Internet of Things (IoT) forms a crucial part in digitizing and transforming the physical space through its widespread sensors and actuators, transmitting, and analyzing IoT-generated data through network and computing systems. Within the digital realm, data from both the physical and human world is processed and administered by the metaverse engine, fostering the creation, and rendering of a large-scale metaverse and offering a variety of metaverse services. Moreover, users, portrayed as avatars, can create, and disseminate digital content across various sub-metaverses, driving the imaginative potential of the metaverse.

C. METAVERSE ENABLING SUBSYSTEMS

The metaverse is enabled by a variety of underlying technologies, six of which play a crucial role in its functioning. Figure 4 visualizes the enabling sub-systems for the metaverse. These technologies include:

1) INTERCONNECTIVITY With the ongoing improvement in Embedded technology, miniaturized

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

sensors, and XR technology, the way to access the metaverse is becoming more accessible through XR devices, like helmet-mounted displays (HMDs) [25]. Virtual reality, augmented reality, and mixed reality, which are included in XR technologies, are deeply integrated to provide a fully immersive, multi-sensory experience, as well as real-time interaction between users, avatars, and the virtual environment. This is achieved using front-projected holographic display, human-computer interaction (HCI) techniques, particularly brain-computer interface (BCI), and large-scale 3D modeling [26]. XR technology, which includes VR, AR, and MR, enables immersive and seamless experiences in the metaverse. Wearable XR devices, paired with indoor smart devices like digital cameras, allow for precise, human-specific sensory perception and comprehensive sensing of objects and the surrounding environment. This expands the interactivity between users and avatars to include a variety of interactive devices beyond mobile inputs. The use of real-time rendering and low-latency edge computing systems driven by AI can also help alleviate concerns such as dizziness related to wearing XR helmets.

Moreover, it is necessary to point out here that, although, the adoption of several essential technologies, including Virtual Reality (VR), Augmented Reality (AR), Computer Graphics, Internet, the internet of things (IoT), artificial intelligence (AI), and blockchain, are central to the metaverse. Yet it is also necessary to maintain the difference between the metaverse and these various independent technologies. Primarily, there are three main differences between the metaverse and AR and VR technologies. Firstly, the metaverse has a distinct focus on providing long-lasting, socially meaningful content as a service, while VR-related research is centered around physical rendering and implementation. Secondly, the use of AR and VR technologies is not a requirement for Metaverse, as the platform can still function as a Metaverse application even without support for VR and AR. And thirdly, to strengthen its social meaning, the Metaverse's scalable environment that can support numerous users is crucial. To successfully put into action a large-scale Metaverse, there are three essential components required: (1) advanced hardware, including high-performance GPUs and 5G connectivity, (2) the development of a recognition and expression model that leverages the parallel capabilities of the hardware, and (3) ready access to captivating and immersive content. [8].

2) **DIGITAL TWINS** The concept of a **digital twin** involves the creation of a highly detailed and aware digital representation of physical objects and systems [28]. It allows for the formation of digital replicas of actual physical entities [29], providing the ability to predict and optimize their virtual counterparts, and continuously learn and adapt within a virtual environment. In the virtual world of the metaverse, digital twins allow for accurate digital representations of objects and their characteristics by simulating complex physical processes and utilizing AI technology. This holds especially positive outcomes for crafting and presenting extensive metaverse landscapes. Furthermore, the incorporation of digital twins offers preventive upkeep and the ability to monitor accidents, thereby improving the effectiveness of the real world and reducing the risk of potential dangers. The digital twin of the metaverse serves as a mirror of the real world and its various counterparts aid in streamlining monitoring and operations within businesses [30].

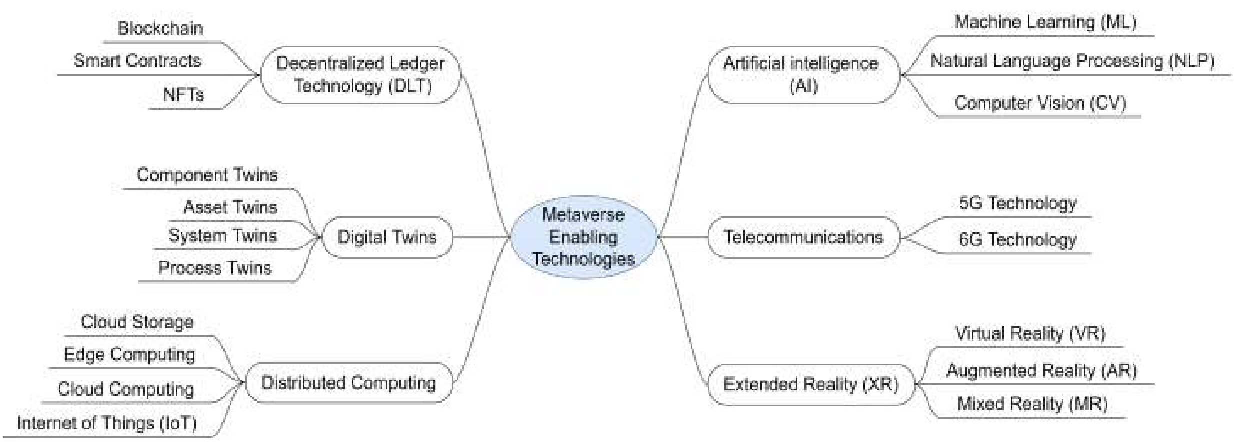

Fig. 4. Metaverse Enabling Technologies [27]

Digital Twins, with their distinct qualities, serve as a

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

crucial element in the construction of the metaverse, offering a gateway for users to access and engage with virtual world services. This feat is accomplished by constructing exact replicas of the real world, encompassing both the physical appearance and operational characteristics of objects, individuals, and environments.

3) **NETWORKING TECHNOLOGIES** the metaverse caters to a huge user base concerning widespread network connection via wireless networks. In recent years, various cutting-edge technologies have emerged to enhance the efficiency of networking systems and wireless communication, where AI has been utilized extensively across several levels of the network infrastructure [31].

Data Networking Technologies including 6G, IoT and software-defined networks (SDN), play a crucial role in facilitating a smooth and instantaneous exchange of information between the real and digital worlds, as well as among various sub-metaverses within the metaverse. The advancements in these technologies, such as B5G and 6G, provide numerous opportunities for ensuring reliable, real-time, and widespread communication for numerous metaverse devices, with enhanced mobility capabilities. With these technologies, the metaverse can be better connected and more accessible, leading to a more seamless and integrated experience for its users. [32]. The emerging trend of 6G's Space-Air-Ground Integrated Network (SAGIN) [33] holds immense potential for enabling seamless and widespread access to metaverse services. Software-Defined Networking (SDN) [34] enables efficient and adaptable management of complex metaverse networks by separating the control and data planes. This separation allows for the centralization of network management, providing greater scalability and flexibility in configuring the network to meet changing needs and demands. In a metaverse that utilizes SDN, physical devices and resources are controlled by a single centralized authority, using a standardized interface such as OpenFlow. This centralization allows for the dynamic allocation of resources, including computation, storage, and bandwidth, in response to the real-time requirements of various sub-metaverses. This results in a highly flexible and efficient metaverse infrastructure.

4) **BLOCKCHAIN** Typically, **blockchain** refers to a decentralized digital ledger that records transactions and assets in a secure network using cryptographic methods. This ledger offers prompt, common, and open information, which is saved in an unalterable and unbreakable format that can only be accessed by authorized network participants [35]. In a typical blockchain system, it's possible to monitor various activities such as payments, accounts, and other exchanges. However, within the virtual world known as the metaverse, vast amounts of data including digital content and videos captured by VR devices are often transmitted and stored in data centers without proper security and privacy measures, making them susceptible to cyber-attacks. Given these security and privacy concerns, blockchain, with its distinct characteristics, presents a viable solution for protecting data within the metaverse [36]. Over the past 10 years, various cutting-edge techniques for collecting, preserving, and distributing data have been suggested by integrating blockchain and AI in various fields to ensure maximum data privacy and security. These methods have demonstrated substantial promise for application in the metaverse.

D. STAGES OF METAVERSE DEVELOPMENT

Metaverse achieves the amalgam of virtual enhanced physical space with a constant virtual space via diversification of the latest emerging technologies [3] including smartphones, gaming PCs, AR glasses, VR headsets, and other gaming consoles. From a macro perspective, there are three stages into which the metaverse develops [3]:

- digital twins
- digital natives
- surreality.

The first stage creates a clone of the physical world, which is primarily made up of the broad and very concise digital twins of persons and objects in virtual settings to create a lifelike digital representation of the physical world. At this point in time, the actual world and the virtual world coexist as two distinct yet intertwined environments. The virtual components, such as the user's emotional state and physical actions, are meticulously modeled after their real-world counterparts, providing an experience that mimics reality in every way possible. In other words, the virtual parameters and activities are essentially a replication of the physical parameters and activities. This first stage is supplanted by the immersive 3D experience by augmented reality (AR) and VR in the second stage. A key aspect of this stage is the creation of original content where digital natives, represented by avatars, can generate new ideas and discoveries within virtual environments that may only exist in the digital realm. This approach lays the foundation for bridging the gap between the physical and digital realms and allows for the exploration of unique and innovative possibilities that are limited only by one's imagination. In the final stage, the metaverse reaches its full potential, evolving into a robust and self-sufficient alternate reality that seamlessly blends with and incorporates elements of the physical world. It becomes an enduring and dynamic environment, capable of sustaining itself and providing a rich

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

and immersive experience for users. As a result, the distinction between the physical and digital realms begins to blur, and the metaverse becomes a unique and integral part of our daily lives.

While 5th generation communication makes possible the creation of highly reliable and low latency connections for different metaverse gadgets including brain-computer interface (BCI), and other wearable sensors to allow interaction of user/avatar in the metaverse. Verification of the genuine ownership rights of metaverse assets is made possible in large part by blockchain and non-fungible tokens (NFT) [37].

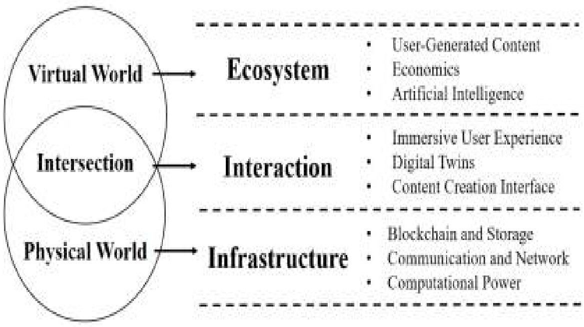

Fig. 5 The Metaverse's Three-Layer Architecture [2]

In Figure 5, the two circles on the left represent the virtual and physical worlds, with an intersection between the two. From bottom to top, the structure of these two circles corresponds to three layers in the central part of Figure 5.

IV. TECHNICAL APPLICATIONS FOR THE METAVERSE ECOSYSTEM

In this section, we present a comprehensive overview of notable prototypes that exist within the realm of metaverse applications in gaming, social experience, education, and health care. These prototypes serve as exemplars of the current state of technology in the virtual reality space, and they provide insight into the potential of what is to come.

1) **GAMING** The utilization of **games** has become essential in promoting the growth of the Metaverse and has been demonstrated to be the most well-received form of the platform in this emerging virtual reality. The popularity of games extends further than just providing entertainment, as they can also be used as a tool to tackle complex issues creatively. This has resulted in games being the most sought-after type of metaverse application, providing a captivating and interactive experience that appeals to a wide user base. With User-matching capabilities, technological advancements, and content flexibility, games are an ideal way to tap into the full potential of the Metaverse. They serve as a distinctive and all-encompassing platform for people to connect and present unlimited opportunities for imagination and invention.
Second Life is a sandbox game that provides players with a customizable 3D virtual world. As avatars, players can design and construct virtual structures, which they can then sell, as well as engage in various social activities. These activities may include art exhibitions, political meetings, and even visiting virtual embassies. Second Life offers a rich, immersive experience where players can express their creativity, interact with others, and participate in a variety of virtual events [38]. Roblox is an international gaming platform that allows players to design and develop their own games, as well as create custom items such as clothing and skins. This platform offers eight core components that are essential for the creation of a metaverse, including Depth of experience, diversity, identity, commerce, accessibility, seamless interaction, culture, and social connections. With its user-created content and comprehensive features, Roblox is poised to play a key role in shaping the future of virtual reality and the metaverse [39]. Adding to that Epic Games is responsible for the creation of Fortnite, a large-scale multiplayer online shooter game that enables players to construct various structures like buildings, bunkers, and even entire islands. The design of in-game items, such as skins, is exclusively controlled by the platform.
Research conducted by Baker *et al.* [40] found that agents in a hide-and-seek type of multi-agent competition can generate an educational program for automation that develops new techniques at various stages. On the other hand, Stanica *et al.* [41] presented INREX-VR, a state-of-the-art neurorehabilitation tool that employs virtual reality to promote self-improvement and competition. The tool records the real-time movements of users in interactive and game-like settings, executing intricate movements to assist in rehabilitation progress."

2) **SOCIAL EXPERIENCE** The Metaverse has the potential to completely transform our society, offering a range of immersive social experiences that would not be possible in the physical world. From virtual lifestyles to virtual shopping, dating, and communication, the Metaverse opens new avenues for social interaction. With the Metaverse, global travel becomes effortless, and even time and space travel could become a reality. The Metaverse has the potential to revolutionize our understanding of what is possible in the world of social applications.
In the recent past, the field of study concerning the Metaverse and its effects on society has seen a surge in interest. Papagiannidis *et al.* [42] conducted a comprehensive study on the relationship between the Metaverse and corporate social responsibility. They

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

analyzed the various ethical and policy-related issues that arise in this context and explored the impact that the Metaverse has on corporate behavior and decision-making. De Decker *et al.* [43] took a closer look at the potential of the Metaverse to aid in solving complex societal issues. They explored the use of the Metaverse as a means of addressing and resolving these problems, investigating the processes and methodologies that could be employed to achieve successful outcomes. Smart et al. [44] investigated the crucial aspects of social transformation within the Metaverse and the possibilities it offers for shaping the future. These studies paint a comprehensive picture of the potential effects of the Metaverse on society and its various facets.

With the rise of technology, the demand for virtual cultural experiences, such as visiting museums or watching performances, is growing. While online solutions offer the benefit of limitless capacity and greater accessibility, they still fall short in terms of the tangible sensory experiences that are present in physical events. Tang et al. [45] conducted a study to assess the effectiveness of using Metaverse as a tool for providing immersive educational library orientation services. The goal was to explore how this technology can be leveraged to create a more engaging and interactive experience for students, providing a comprehensive understanding of the library's resources and facilities. Choi and Kim et al. [46] researched enhancing museum visitors' experience by utilizing the combination of beacon technology and HMDs.

3) **EDUCATION** The utilization of Metaverse for audio and visual-based learning has enormous potential for widespread adoption and is considered a significant application of this technology. Experiential learning is crucial as it allows individuals to understand concepts and ideas tangibly and emotionally. The difference between reading about something and experiencing it first-hand is immense, making hands-on education a valuable tool in the acquisition of knowledge and skills. The sensation and emotions that accompany an experience leave a lasting impact and can aid in retaining information for a longer period. For instance, the intangible nature of radiation makes it challenging to grasp, leading one to hold a preconceived notion that it is simply hazardous. The Metaverse provides the ability to examine and experience the technical and scientific aspects of radioactivity, enabling a deeper understanding of its educational effects [47]. Sung et al. [48] conducted a study to evaluate the difference in immersion and educational impact between conventional static video presentations and the Metaverse method in marketing students. They utilized facial electromyography to assess the students' learning attitude, enjoyment, and performance and discovered that the Metaverse approach was more effective in enhancing the educational experience and fostering better learning outcomes. This research underscores the promising potential of the Metaverse for advancing education. Kemp et al. [49] evaluated the benefits and drawbacks of the virtual environment that accommodates multiple users for educational purposes and Collins et al. [50] conducted a research investigation on the methods of obtaining, engaging

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

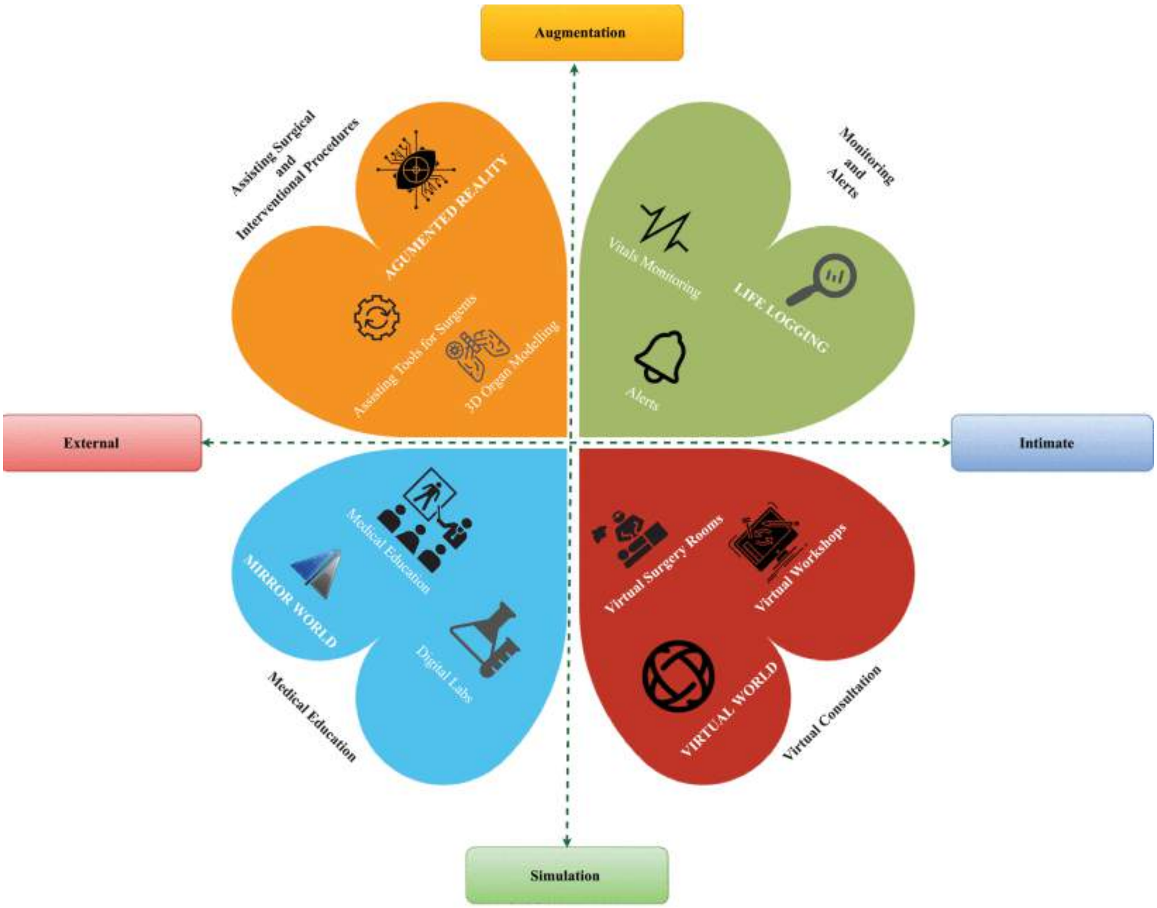

Fig. 6. The Four Pillars of Integrating the Metaverse into Healthcare [51]

with, and producing knowledge in higher education. Templeton et al. [52] explored the practical and educational aspects that must be considered by teachers in their pursuit of learning while Suzuki et al. [53] conducted a research study focused on the area of collaborative learning within the Internet of Things (IoT). The goal of this investigation was to examine the workings of collaboration among learners and identify ways to enhance it in the context of IoT-based learning. The concept of the Metaverse is being utilized in the realm of education, specifically within the framework of Problem-Based Learning (PBL). PBL is an approach to teaching and learning that involves students solving real-world problems and challenges as a means of acquiring new knowledge and skills. By incorporating Metaverse technology, the PBL method has been transformed into an immersive and interactive educational experience, providing students with a dynamic and engaging environment to explore and apply their learning [54, 55]. Barry et al. [56] assessed the instructional quality in the context of a Problem-Based Learning (PBL) task. He evaluated the quality of instruction by measuring the effect it had on students' emotions, specifically by monitoring the increase in the number of blinks, which is a common physiological indicator of emotional arousal. Additionally, he considered the presence of difficult questions, as they also have the potential to impact students' emotional stability. Khan et al. [57] presented a novel approach to performing outdoor safety training for children. This approach leverages the use of Virtual Reality (VR), the Kinect sensor, and the Unity game engine to create an interactive and immersive learning experience.

4) **HEALTH INDUSTRY** healthcare plays a vital role in promoting and sustaining the Physical, Mental, Social, and general well-being of the entire global population [58]. The concept of "MEDverse" refers to the incorporation of the metaverse into the medical field, a notion that was initially introduced in academic literature [59, 60]. the integration of the metaverse into the medical field offers immense potential to address the challenges faced by the healthcare sector. By leveraging the capabilities of the metaverse, healthcare providers can improve patient outcomes, enhance access to care, and increase efficiency in the delivery of medical services. The development of virtual healthcare environments will

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

not only provide a safe and accessible platform for patients, especially after the COVID-19 pandemic but it will also offer opportunities for medical professionals to collaborate, share knowledge, and advance the field of medicine. The four elements of incorporating the Metaverse into healthcare are illustrated in Figure 5.

In 2021, the SNU Hospital in Korea introduced a revolutionary smart operating room and metaverse environment. This innovative setup was employed to deliver comprehensive lung cancer surgery education to over 200 thoracic surgeons from various countries. The education was facilitated by utilizing high-resolution virtual reality cameras, which transmitted surgical scenes in a full 360° view, providing the surgeons with a fully immersive and interactive learning experience [61]. The Metaverse platform facilitates advanced surgical preparation by converting CT scans into 3D models that can be viewed with virtual reality headsets. This allows physicians to closely inspect, isolate, and manipulate specific body parts for precise surgical operations [62]. The Metaverse technology affords enhanced therapeutic options through prescription-based solutions, such as EaseVR. This innovative approach to treatment combines the use of virtual reality headsets and controllers with cognitive behavioral therapies [63, 64] to alleviate back pain in patients. In other words, EaseVR represents a convergence of cutting-edge technology and proven therapeutic techniques, offering a comprehensive solution for patients suffering from back pain.

The use of VR in the Metaverse has significant potential to revolutionize plastic surgery, allowing patients to preview the outcome of the procedure on virtual avatars. The Metaverse also offers benefits in radiology, with advanced capabilities in image visualization, improved training, and collaboration among radiologists [65]. The healthcare Metaverse also has the potential to enhance patient engagement through gamification, high-quality immersive content, and the use of digital twins to monitor health conditions [66]. The virtual dashboard helps patients to visualize health data, communicate with healthcare professionals, and achieve individualized care and treatment. The Metaverse requires a detailed understanding of human anatomy and the ability to use flexible and adjustable instruments for surgeries ranging from simple procedures to complex surgeries, such as removal of tumors and complicated spine surgeries.

V. CHALLENGES, AND OPEN RESEARCH

The advent of the metaverse holds immense potential for delivering breakthrough advancements across numerous domains in the future, however, it still faces numerous hurdles that require resolution. Despite advancements in the field, the virtual reality landscape remains relatively unchanged, requiring users to possess a set of technology including Virtual reality headsets, controllers, and powerful computers. Unfortunately, these devices come at a premium price, making accessibility a critical challenge in the realization of a thriving metaverse. In this section, we will present the most relevant challenges to adapting the Metaverse at a large scale.

Technical and Hardware Limitations, the Metaverse is not a separate and standalone ecosystem, it encompasses many technologies such as blockchain, AI, and head-mounted displays (HMDs) [82]. Since the Metaverse is very dependent on Augmented Reality (AR), mixed reality (MR) and virtual reality (VR) devices most of them are neither advanced to meet the need of the applications nor the user/avatar [83]. One of the primary challenges is the development of advanced head-mounted displays (HMDs) that provide an immersive and seamless experience. The HMDs must be ergonomic, lightweight, and capable of delivering high-quality visual, auditory, and haptic experiences. Additionally, they must be compatible with different types of input methods, such as motion, hand-based, sound, and speech recognition.

Another challenge is the development of motion input methods that accurately track and respond to users' movements in the virtual world. This requires the integration of advanced sensors and algorithms that can accurately detect and respond to users' gestures, body movements, and eye movements. Additionally, the development of hand-based input methods that provide users with a more natural and intuitive way of interacting with the virtual environment is crucial.

The capability for precise scene and object recognition presents a crucial challenge in the development of an immersive metaverse. The virtual world must have the ability to not only detect and recognize objects and scenes with accuracy but also respond dynamically to the actions and movements of users. Equally vital to the metaverse experience is the integration of advanced sound and speech recognition technologies, enabling users to communicate and interact with the virtual environment through natural language. The seamless integration of these cutting-edge algorithms and technologies is essential for enabling real-time responses to users' speech and sounds, further enhancing the overall experience within the virtual world.

Finally, the development of the advanced scene and object generation techniques is crucial for the creation of a vibrant and dynamic metaverse. The virtual world must be able to generate and render realistic and immersive environments, objects, and scenes in real-time, and must be able to respond to users' actions and movements. Similarly, a vast segment of the population is excluded from experiencing the virtual world due to the prohibitive cost of the required hardware, such as high-performance computers and specialized virtual reality headsets [67]. Last, Moving from embedded hardware in the user’s terminals (e.g., HTC Vive Cosmos headset for

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

VR) to the cloud should reduce the price of the terminals and allow for a large-scale usage of Metaverse as a user will pay as she/he goes according to cloud-based prices. The network infrastructure is making progress to enable such a shift to cloud computing-based Metaverse but a lot of work is still required mainly for 5G/6G Network slicing management [92, 93].

Lack of Standards and regulations across different applications for the Metaverse is another limitation of adapting the Metaverse on a large scale across domains [82].

Security and Privacy: The Metaverse ecosystem will collect a massive volume of data about the users/avatars such as biometrics, facial expressions, movement, and much more activities to name a few [83,89]. This information must be kept private and user's information must be protected from unauthorized access to comply with data protection acts such as General Data Protection Regulation (GDPR) [82]. Also, secure by design or built-in security provided through endogenous security theory is a promising solution to many security and privacy issues in the Metaverse [90]. This endogenous security theory provides self-evolution, and protection as well as autoimmunity competencies [90, 91]. Security and privacy concerns will be discussed in section VI.

Identity Theft: To establish the avatar's identity in the Metaverse is a challenge since threat actors can impersonate the identity of the avatar. Many factor authentication will be required to establish the user's identity and verify who s/he is such as speech recognition, eye retina scan and facial scans [83, 84].

Physical and Mental Health: avatars most likely will prefer to socialise within the Metaverse over the real world. This can create many health problems for the users such as mental issues, addiction to the virtual world, anxiety, depression and so on [82, 83, 84, 85]. It's already well known that people who will be more involved and engaged in the Metaverse world will be more susceptible to becoming antisocial, committing suicide, suffering from many physical health issues and having the tendency to emulate the behavior of others [84, 85, 86, 87]

Digital Currency and Payments: with a massive number of users/avatars there will be an online market that is worth billions of dollars of digital currency and cryptocurrencies, this will impose many questions on the safety and security of trading in the Metaverse [83, 84, 88].

Non-Fungible Tokens (NFTs): NFTs will play a key role in the Metaverse by being the cornerstone of the ecosystem [89]. The owner of the server where these NFTs reside is the controller of any transaction via the NFTs which means there is an integrity concern who is the actual owner of these assets with transactions through NFTs [89].

The Darkverse: this is even more serious than the dark web since the users are hidden behind the avatars and they have no index which is more challenging to regulate [89].

Sustainability of the Metaverse: to sustain steadiness continuity, a connection-based relation is a challenging task to maintain in low-specification devices [8]. Using an intermittent memory which enables users to access the Metaverse seamlessly as long as they desire. Saving user's experiences in memory has some limitations in capacity [8].

The Green Metaverse: the mature Metaverse should be green and energy efficient to preserve sustainability [90]. The collaboration among avatars/users can provide some solutions in terms of user-generated content (UGC), AI-generated content (AIGC) distribution, collaborative computation and networking [91].

VI. SECURITY and Privacy Issues

In this section, we will cover the security threats to Metaverse. We will discuss security threats and issues related to (a) authentication and access control, (b) cyber-attacks against the network and (c) privacy in the Metaverse.

A) Different threats arise against authentication in the Metaverse such as, (i) Identity theft in the virtual world has devastating consequences beyond just the loss of personal information. In the virtual universe, a user's digital identity encompasses their avatars, digital assets, social connections, and their entire digital existence. This makes it a more severe problem than conventional information security breaches. An example of this is the hack of 17 users on the Opensea NFT marketplace in 2022, which was caused by smart contract flaws and phishing attacks, leading to a significant financial loss of $1.7 million [20].

(ii) Impersonation attacks in the virtual realm are also a serious concern. In these types of attacks, a malicious actor can pretend to be a legitimate entity to gain unauthorized access to systems and services. This is made possible by the ease of assuming another person's digital identity in the virtual world. The process of verifying the identity of avatars, which involves evaluating visual cues like facial recognition, voice verification, and more, presents a greater challenge than traditional methods of identity authentication in the physical world [20, 68].

(iii) Avatar authentication concern, this is can be challenging to authenticate the avatar in the Metaverse such as voice, facial expressions, and video. In addition, threat actors can create AI bots that would be identical to an actual avatar which means more information is needed to authenticate and verify the identity of an avatar [20, 71].

(iv) Cross-trust data access, this issue arises from the need to authenticate uses from a cross-platform and cross-domain authentication of users [20, 72]. (v) Unsafe use of avatar's data. Data can be accessed by threat actors or by VSPs to better recognize the user via profiling to provide marketing services through advertising [20]. (vi) Unauthorized access to data, and the density nature of services that Metaverse will provide different ways of categorizing and profiling users/avatars. Some VSPs need to access avatars' activities in real-time. This

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and
content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2023.3281303

poses a threat because rouge VSPs may launch cyber-attacks to gain benefits via accessing data [20, 73, 74].

B) Many threats and attacks against the internet still hold for the Metaverse network since it's using the same network. We will discuss some of the most relevant threats in this sub-section.

(i) Distributed Denial of Service Attack DDoS. The Metaverse has so many IoT and wearable devices that can be part of a botnet controlled by a master to carry out a DDoS attack and make the network or the services unavailable [20,75]. Due to some constraints on the Blockchain, some of the threat actors can target NFTs that might be off the chain for some applications causing these NFTs unavailable in case of A DDoS attack [20, 76].

(ii) Sybil attack, threat actors may misuse stolen or impersonated identities to have a big impact on some services in the Metaverse such as voting services. In addition, threat actors can block some of the users by not permitting them from a blockchain Metaverse network [2].

(iii) Single-point of failure (SPoF) the centralized nature of the Metaverse architecture such as a cloud system makes things easier and more comfortable to deal with, but at the same time, it becomes a SPoF caused by a DDoS cyber-attack. Also, it can be prone to the SPoF caused by the damage of physical root servers and DDoS attacks [35]. Besides, it raises trust and transparency challenges in the trust-free exchange of virtual goods, virtual currencies, and digital assets across various virtual worlds in the Metaverse.

Social Engineering attacks: threat actors can use social engineering attacks such as psychological manipulation techniques to have avatars/users provide and disclose some sensitive information, these attacks in the Metaverse will be more subtle and more challenging to detect [89]. Threat actors can penetrate the Metaverse to compromise the identities of users, which is very difficult with the lack of legislation for law enforcement to intervene [82,83, 87,89]

C) Privacy in the Metaverse

Even though Metaverse provides a new experience and convenience to the users/avatars, this comes with a toll of many privacy issues concerning the users. The digital world will collect many sensitive and private information about the users/avatars such as habits, preferences, and location to name a few [89]. Information in transit and data at rest will have some serious consequences on the user's privacy, in this part, we will discuss the most relevant ones. (i) When information is in transit, plenty of private information that can be used to identify users is communicated over the wired and/or wireless medium. D*ata leaks when information is in transit* can occur even when the communication is encrypted to ensure confidentiality, threat actors can still gain access by eavesdropping on a certain channel or track avatars in the Metaverse by determining their location through differential attacks as well as interference cyber-attacks [20, 77]. (ii) *Data leaks in the cloud/edge* storing a massive amount of information about the users/avatars in the cloud and/or the edge devices can pose a threat to the privacy of users. For example, the adversary might carry differential attacks by sending continuous queries and can launch a DDoS attack to compromise the cloud/edge storage [20, 77, 78]. (iii) *Hacked or compromised end devices*, rouge end devices can pose a threat to the user's privacy. Since so many wearable sensors will be used by avatars to enable them to capture hand-gesture and make eye contact, express facial expressions, etc… in real-time, a substantial risk is that such wearable sensors can have a comprehensive assessment of who the avatars are, how they talk to express themselves, how they behave, and so on. Compromised or rouge wearables such as VR glasses can be an entry point for malware and such for data breaches [20, 79]. (iv) while *data is in the process* since there is a tremendous data aggregation and processing in the Metaverse to provide the experience of the virtual world as the reality, avatar's private information could be leaked [20, 80].

(v) *Pervasive data collection*: for the avatar to interact within the Metaverse, a pervasive avatar profiling is required to interact at a very fine granularity level [20, 81], this includes hand movement, eye contact, speech fingerprint, biometrics and facial expressions as well as avatar's movement and location tracking [20, 77, 81], this enables attackers to cause serious harm. To deliver seamless and personalized experiences, Virtual Service Providers in different sub-metaverses require real-time access to user/avatar profiles. However, some VSPs may engage in unauthorized access to this information through malicious means, such as exploiting buffer overflow vulnerabilities or tampering with access control lists, to monetize the data. This underlines the critical need for strong security measures to safeguard the privacy and data of users in the virtual world [69, 70].

In conclusion, the virtual world presents new and unique challenges in terms of security and privacy, especially with the increasing amount of sensitive personal information that is being generated. As the virtual universe continues to grow and evolve, robust security measures must be put in place to protect the privacy and data of users. This can help ensure that the virtual world remains a safe and secure place for individuals to interact, transact, and create digital experiences.

VII. CONCLUSION

This research carries out an in-depth exploration of the interrelated concepts of metaverse, avatar, and XR. The study begins by examining the three crucial components, hardware, software, and contents, which are indispensable to the functioning of the metaverse. The research then takes a comprehensive look at the present and future trends in metaverse technology, including user interaction, implementation, and applications.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

Additionally, the security and privacy issues inherent to the distributed metaverse architecture are thoroughly investigated, including the critical challenges that must be addressed to ensure the protection of personal information and secure transactions. The study highlights the importance of robust security measures and privacy preservation in the metaverse, given the potential risks and consequences of data breaches and identity theft.

In conclusion, the research provides a comprehensive overview of the metaverse, including its fundamental components, current and future trends, and security and privacy considerations. The study sheds light on the significance of the metaverse, not only as a rapidly growing technology but also as a transformative platform that has the potential to reshape the digital landscape and enhance human interaction and experience in the virtual realm.

REFERENCES

[1] J. Díaz, C. Saldaña, and C. Avila, "Virtual world as a resource for hybrid education," International Journal of Emerging Technologies in Learning (iJET), vol. 15, no. 15, pp. 94-109, 2020.

[2] H. Duan, J. Li, S. Fan, Z. Lin, X. Wu, and W. Cai, "Metaverse for social good: A university campus prototype," in Proceedings of the 29th ACM International Conference on Multimedia, 2021, pp. 153-161.

[3] L.-H. Lee et al., "All one needs to know about metaverse: A complete survey on technological singularity, virtual ecosystem, and research agenda," arXiv preprint arXiv:2110.05352, 2021.

[4] H. Ning et al., "A Survey on Metaverse: the State-of-the-art, Technologies, Applications, and Challenges," arXiv preprint arXiv:2111.09673, 2021.

[5] L.-H. Lee et al., "When creators meet the metaverse: A survey on computational arts," arXiv preprint arXiv:2111.13486, 2021.

[6] Q. Yang, Y. Zhao, H. Huang, Z. Xiong, J. Kang, and Z. Zheng, "Fusing blockchain and AI with metaverse: A survey," IEEE Open Journal of the Computer Society, vol. 3, pp. 122-136, 2022.

[7] 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," Engineering Applications of Artificial Intelligence, vol. 117, p. 105581, 2023.

[8] S.-M. Park and Y.-G. Kim, "A Metaverse: Taxonomy, components, applications, and open challenges," Ieee Access, vol. 10, pp. 4209-4251, 2022.

[9] M. Xu et al., "A full dive into realizing the edge-enabled metaverse: Visions, enabling technologies, and challenges," IEEE Communications Surveys & Tutorials, 2022.

[10] B. Kitchenham, O. P. Brereton, D. Budgen, M. Turner, J. Bailey, and S. Linkman, "Systematic literature reviews in software engineering–a systematic literature review," Information and software technology, vol. 51, no. 1, pp. 7-15, 2009.

[11] N. Stephenson, Snow crash: A novel. Spectra, 2003.

[12] K. Lippert, M. N. R. Khan, M. M. Rabbi, A. Dutta, and R. Cloutier, "A Framework of Metaverse for Systems Engineering," in 2021 IEEE International Conference on Signal Processing, Information, Communication & Systems (SPICSCON), 2021: IEEE, pp. 50-54.

[13] I. Nikolaidis, "Networking the Metaverses," IEEE Network, vol. 21, no. 5, 2007.

[14] D. Owens, A. Mitchell, D. Khazanchi, and I. Zigurs, "An empirical investigation of virtual world projects and metaverse technology capabilities," ACM SIGMIS Database: the DATABASE for Advances in Information Systems, vol. 42, no. 1, pp. 74-101, 2011.

[15] R. Schroeder, A. Huxor, and A. Smith, "Activeworlds: geography and social interaction in virtual reality," Futures, vol. 33, no. 7, pp. 569-587, 2001.

[16] M. A. Babu and P. Mohan, "Impact of the Metaverse on the Digital Future: People's Perspective," in 2022 7th International Conference on Communication and Electronics Systems (ICCES), 2022: IEEE, pp. 1576-1581.

[17] D. Grider and M. MAXIMO, "The metaverse: Web 3.0 virtual cloud economies," Grayscale Research, 2021.

[18] P. Bhattacharya, M. S. Obaidat, D. Savaliya, S. Sanghavi, S. Tanwar, and B. Sadaun, "Metaverse assisted telesurgery in healthcare 5.0: An interplay of blockchain and explainable AI," in 2022 International Conference on Computer, Information and Telecommunication Systems (CITS), 2022: IEEE, pp. 1-5.

[19] K. Yoon, S.-K. Kim, S. P. Jeong, and J.-H. Choi, "Interfacing cyber and physical worlds: Introduction to IEEE 2888 standards," in 2021 IEEE International Conference on Intelligent Reality (ICIR), 2021: IEEE, pp. 49-50.

[20] Y. Wang et al., "A survey on metaverse: Fundamentals, security, and privacy," IEEE Communications Surveys & Tutorials, 2022.

[21] L. Heller and L. Goodman, "What do avatars want now? posthuman embodiment and the technological sublime," in 2016 22nd International Conference on Virtual System & Multimedia (VSMM), 2016: IEEE, pp. 1-4.

[22] A. Genay, A. Lécuyer, and M. Hachet, "Being an avatar "for real": a survey on virtual embodiment in augmented reality," IEEE Transactions on Visualization and Computer Graphics, vol. 28, no. 12, pp. 5071-5090, 2021.

[23] C. Kai, H. Zhou, Y. Yi, and W. Huang, "Collaborative cloud-edge-end task offloading in mobile-edge computing networks with limited communication capability," IEEE Transactions on Cognitive Communications and Networking, vol. 7, no. 2, pp. 624-634, 2020.

[24] Z. Li, J. Chan, J. Walton, H. Benko, D. Wigdor, and M. Glueck, "Armstrong: An empirical examination of pointing at non-dominant arm-anchored uis in virtual reality," in Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, 2021, pp. 1-14.

[25] M. Sugimoto, "Extended reality (XR: VR/AR/MR), 3D printing, holography, AI, radiomics, and online VR Tele-medicine for precision surgery," in Surgery and Operating Room Innovation: Springer, 2021, pp. 65-70.

[26] C. Jaynes, W. B. Seales, K. Calvert, Z. Fei, and J. Griffioen, "The Metaverse: a networked collection of inexpensive, self-configuring, immersive environments," in Proceedings of the workshop on Virtual environments 2003, 2003, pp. 115-124.

[27] A. Musamih et al., "Metaverse in healthcare: Applications, challenges, and future directions," IEEE Consumer Electronics Magazine, 2022.

[28] N. H. Chu, D. T. Hoang, D. N. Nguyen, K. T. Phan, and E. Dutkiewicz, "Metaslicing: A novel resource allocation framework for metaverse," arXiv preprint arXiv:2205.11087, 2022.

[29] I. Yaqoob, K. Salah, M. Uddin, R. Jayaraman, M. Omar, and M. Imran, "Blockchain for digital twins: Recent advances and future research challenges," Ieee Network, vol. 34, no. 5, pp. 290-298, 2020.

[30] A. T. Kusuma and S. H. Supangkat, "Metaverse Fundamental Technologies for Smart City: A Literature Review," in 2022 International Conference on ICT for Smart Society (ICISS), 2022: IEEE, pp. 1-7.

[31] M. Chen, U. Challita, W. Saad, C. Yin, and M. Debbah, "Artificial neural networks-based machine learning for wireless networks: A tutorial," IEEE Communications Surveys & Tutorials, vol. 21, no. 4, pp. 3039-3071, 2019.

[32] H. Du, D. Niyato, C. Miao, J. Kang, and D. I. Kim, "Optimal targeted advertising strategy for secure wireless edge metaverse," in GLOBECOM 2022-2022 IEEE Global Communications Conference, 2022: IEEE, pp. 4346-4351.

[33] Y. Wang, Z. Su, J. Ni, N. Zhang, and X. Shen, "Blockchain-empowered space-air-ground integrated networks: Opportunities, challenges, and solutions," IEEE Communications Surveys & Tutorials, vol. 24, no. 1, pp. 160-209, 2021.

[34] K. Benzekki, A. El Fergougui, and A. Elbelrhiti Elalaoui, "Software-defined networking (SDN): a survey," Security and communication networks, vol. 9, no. 18, pp. 5803-5833, 2016.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

[35] T. R. Gadekallu et al., "Blockchain for edge of things: Applications, opportunities, and challenges," IEEE Internet of Things Journal, vol. 9, no. 2, pp. 964-988, 2021.

[36] A. Cannavo and F. Lamberti, "How blockchain, virtual reality, and augmented reality are converging, and why," IEEE Consumer Electronics Magazine, vol. 10, no. 5, pp. 6-13, 2020.

[37] R. Ratan and Y. Lei, "What is the metaverse? 2 media and information experts explain," The Conversation, 2021.

[38] N. Jennings and C. Collins, "Virtual or virtually U: Educational institutions in Second Life," International Journal of Educational and Pedagogical Sciences, vol. 1, no. 11, pp. 713-719, 2007.

[39] J. Han, J. Heo, and E. You, "Analysis of metaverse platform as a new play culture: Focusing on roblox and zepeto," in International Conference on Human-centered Artificial Intelligence, 2021, pp. 1-10.

[40] B. Baker et al., "Emergent tool use from multi-agent autocurricula," arXiv preprint arXiv:1909.07528, 2019.

[41] I.-C. Stanica, F. Moldoveanu, G.-P. Portelli, M.-I. Dascalu, A. Moldoveanu, and M. G. Ristea, "Flexible virtual reality system for neurorehabilitation and quality of life improvement," Sensors, vol. 20, no. 21, p. 6045, 2020.

[42] S. Papagiannidis, M. Bourlakis, and F. Li, "Making real money in virtual worlds: MMORPGs and emerging business opportunities, challenges and ethical implications in metaverses," Technological Forecasting and Social Change, vol. 75, no. 5, pp. 610-622, 2008.

[43] P. De Decker and S. Peterson, "Beyond Virtual or Physical Environments: Building a Research Metaverse A White Paper for NDRIO's Canadian Digital Research Needs Assessment," Canada: NDRIO, 2020.

[44] J. Smart et al., "A cross-industry public foresight project," Proc. Metaverse Roadmap Pathways 3DWeb, pp. 1-28, 2007.

[45] Y. Tang, "Help first-year college students to learn their library through an augmented reality game," The journal of academic librarianship, vol. 47, no. 1, p. 102294, 2021.

[46] M.-I. Dascalu, A. Moldoveanu, and E. A. Shudayfat, "Mixed reality to support new learning paradigms," in 2014 18th International Conference on System Theory, Control and Computing (ICSTCC), 2014: IEEE, pp. 692-697.

[47] H. Kanematsu, T. Kobayashi, D. M. Barry, Y. Fukumura, A. Dharmawansa, and N. Ogawa, "Virtual STEM class for nuclear safety education in metaverse," Procedia computer science, vol. 35, pp. 1255-1261, 2014.

[48] B. Sung, E. Mergelsberg, M. Teah, B. D'Silva, and I. Phau, "The effectiveness of a marketing virtual reality learning simulation: A quantitative survey with psychophysiological measures," British journal of educational technology, vol. 52, no. 1, pp. 196-213, 2021.

[49] J. Kemp and D. Livingstone, "Putting a Second Life "metaverse" skin on learning management systems," in Proceedings of the Second Life education workshop at the Second Life community convention, 2006, vol. 20: The University of Paisley CA, San Francisco.

[50] C. Collins, "Looking to the future: Higher education in the Metaverse," Educause Review, vol. 43, no. 5, pp. 50-52, 2008.

[51] R. Chengoden et al., "Metaverse for Healthcare: A Survey on Potential Applications, Challenges and Future Directions," IEEE Access, 2023.

[52] T. Templeton, "Getting real: Learning with (and about) augmented reality," Scan: The Journal for Educators, vol. 39, no. 10, pp. 6-15, 2020.

[53] S.-n. Suzuki et al., "Virtual Experiments in Metaverse and their Applications to Collaborative Projects: The framework and its significance," Procedia Computer Science, vol. 176, pp. 2125-2132, 2020.

[54] D. M. Barry et al., "International comparison for problem based learning in metaverse," The ICEE and ICEER, vol. 6066, 2009.

[55] H. Kanematsu, Y. Fukumura, N. Ogawa, A. Okuda, R. Taguchi, and H. Nagai, "Practice and evaluation of problem based learning in Metaverse," in EdMedia+ Innovate Learning, 2009: Association for the Advancement of Computing in Education (AACE), pp. 2862-2870.

[56] D. M. Barry et al., "Evaluation for students' learning manner using eye blinking system in Metaverse," Procedia computer science, vol. 60, pp. 1195-1204, 2015.

[57] N. Khan et al., "An adaptive game-based learning strategy for children road safety education and practice in virtual space," Sensors, vol. 21, no. 11, p. 3661, 2021.

[58] G. Salloum and J. Tekli, "Automated and personalized nutrition health assessment, recommendation, and progress evaluation using fuzzy reasoning," International Journal of Human-Computer Studies, vol. 151, p. 102610, 2021.

[59] A. Cerasa, A. Gaggioli, F. Marino, G. Riva, and G. Pioggia, "The promise of the metaverse in mental health: the new era of MEDverse," Heliyon, p. e11762, 2022.

[60] Y. Zeng, L. Zeng, C. Zhang, and A. S. Cheng, "The metaverse in cancer care: Applications and challenges," Asia-Pacific Journal of Oncology Nursing, p. 100111, 2022.

[61] H. Kang, "Sample size determination and power analysis using the G* Power software," Journal of educational evaluation for health professions, vol. 18, 2021.

[62] M. Taheri and D. Kalnikaite, "A study of how Virtual Reality and Brain Computer Interface can manipulate the brain," in 2022 The 5th International Conference on Software Engineering and Information Management (ICSIM), 2022, pp. 6-10.

[63] A. R. Javed et al., "Automated cognitive health assessment in smart homes using machine learning," Sustainable Cities and Society, vol. 65, p. 102572, 2021.

[64] A. R. Javed, M. U. Sarwar, S. ur Rehman, H. U. Khan, Y. D. Al-Otaibi, and W. S. Alnumay, "Pp-spa: privacy preserved smartphone-based personal assistant to improve routine life functioning of cognitive impaired individuals," Neural Processing Letters, pp. 1-18, 2021.

[65] A. Garavand and N. Aslani, "Metaverse phenomenon and its impact on health: A scoping review," Informatics in Medicine Unlocked, p. 101029, 2022.

[66] H. Hassani, X. Huang, and S. MacFeely, "Impactful Digital Twin in the Healthcare Revolution," Big Data and Cognitive Computing, vol. 6, no. 3, p. 83, 2022.

[67] G. Mileva, "A Deep Dive into Metaverse Marketing," Influencer Marketing Hub, 2021.

[68] P. Hu, H. Li, H. Fu, D. Cansever, and P. Mohapatra, "Dynamic defense strategy against advanced persistent threat with insiders," in 2015 IEEE Conference on Computer Communications (INFOCOM), 2015: IEEE, pp. 747-755.

[69] M. Xu, D. Niyato, J. Kang, Z. Xiong, C. Miao, and D. I. Kim, "Wireless edge-empowered metaverse: A learning-based incentive mechanism for virtual reality," in ICC 2022-IEEE International Conference on Communications, 2022: IEEE, pp. 5220-5225.

[70] J. Yu, Z. Kuang, B. Zhang, W. Zhang, D. Lin, and J. Fan, "Leveraging content sensitiveness and user trustworthiness to recommend fine-grained privacy settings for social image sharing," IEEE transactions on information forensics and security, vol. 13, no. 5, pp. 1317-1332, 2018.

[71] 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.

[72] J. D. N. Dionisio, W. G. Burns, III, and R. Gilbert, "3D virtual worlds and the metaverse: Current status and future possibilities," ACM Comput. Surveys, vol. 45, no. 3, pp. 1–38, Jul. 2013.

[73] M.Xu, D.Niyato, J.Kang, Z.Xiong, C.Miao, and D.I.Kim,"Wireless edge-empowered metaverse: A learning-based incentive mechanism for virtual reality," in Proc. IEEE Int. Conf. Commun. (ICC), 2022, pp. 5220–5225.

[74] J. Yu, Z. Kuang, B. Zhang, W. Zhang, D. Lin, and J. Fan, "Leveraging content sensitiveness and user trustworthiness to recommend fine-grained privacy settings for social image sharing," IEEE Trans. Inf. Forensics Security, vol. 13, no. 5, pp. 1317–1332, May 2018.

[75] E. Bertino and N. Islam, "Botnets and Internet of Things security," Computer, vol. 50, no. 2, pp. 76–79, Feb. 2017.

[76] "Key infrastructure of the metaverse: status, opportunities, and challenges of NFT data storage." Accessed: Feb. 2, 2022. [Online].

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

Available: https://www.hashkey.com/key-infrastructure-of- the-metaverse-status-opportunities-and-challenges-of-nft-data-storage/

[77] J.Wei, J. Li, Y. Lin, and J. Zhang, "LDP-based social content protection for trending topic recommendation," IEEE Internet Things J., vol. 8, no. 6, pp. 4353–4372, Mar. 2021.

[78] E. Bertino and N. Islam, "Botnets and Internet of Things security," Computer, vol. 50, no. 2, pp. 76–79, Feb. 2017.

[79] J. Shang, S. Chen, J. Wu, and S. Yin, "ARSpy: Breaking location-based multi-player augmented reality application for user location tracking," IEEE Trans. Mobile Comput., vol. 21, no. 2, pp. 433–447, Feb. 2022.

[80] X. Li, J. He, P. Vijayakumar, X. Zhang, and V. Chang, "A verifiable privacy-preserving machine learning prediction scheme for edge-enhanced HCPSs," IEEE Trans. Ind. Informat., vol. 18, no. 8, pp. 5494–5503, Aug. 2022.

[81] 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.

[82] Musamih, Ahmad, Ibrar Yaqoob, Khaled Salah, Raja Jayaraman, Yousof Al-Hammadi, Mohammed Omar, and Samer Ellahham. "Metaverse in healthcare: Applications, challenges, and future directions." IEEE Consumer Electronics Magazine (2022).

[83] G. Bansal, K. Rajgopal, V. Chamola, Z. Xiong and D. Niyato, "Healthcare in Metaverse: A Survey on Current Metaverse Applications in Healthcare," in IEEE Access, vol. 10, pp. 119914-119946, 2022, doi: 10.1109/ACCESS.2022.3219845.

[84] R. Kaur. (Feb. 2022). Challenges Faced by the Metaverse in Becoming a Reality. [Online]. Available: https://medium.datadriveninvestor.com/challenges-faced-by-the-metaverse-in-becoming-a-reality-d02219d29370

[85] D. Chen and R. Zhang, ''Exploring research trends of emerging technologies in health metaverse: A bibliometric analysis,'' SSRN Electron. J., Jan. 2022. [Online]. Available: https://ssrn.com/abstract=3998068, doi: 10.2139/ssrn.3998068.

[86] D.-I. D. Han, Y. Bergs, and N. Moorhouse, ''Virtual reality consumer experience escapes: Preparing for the metaverse,'' Virtual Reality, vol. 26, no. 4, pp. 1443–1458, Mar. 2022, doi: 10.1007/s10055-022-00641-7.

[87] R. A. Atis, ''Attachment theory and computer screen use: Addiction of the digital age family,'' Ph.D. dissertation, Pacifica Graduate Inst., Carpinteria, CA, USA, 2022.

[88] S. Mackenzie, ''Criminology towards the metaverse: Cryptocurrency scams, grey economy and the technosocial,'' Brit. J. Criminology, vol. 62, no. 6, pp. 1537–1552, Oct. 2022.

[89] Zefeng Chen, Jiayang Wu, Wensheng Gan, Zhenlian Qi, "Metaverse Security and Privacy: An Overview", IEEE International Conference on Big Data, 2022.

[90] Yuntao Wang et. al. " A Survey on Metaverse: Fundamentals, Security, and Privacy ", IEEE Communications Surveys & Tutorials, Vol. 25, No 1, 2023.

[91] Z. Zhou, X. Kuang, L. Sun, L. Zhong, and C. Xu, "Endogenous security defense against deductive attack: When artificial intelligence meets active defense for Online service," IEEE Commun. Mag., vol. 58, no. 6, pp. 58–64, Jun. 2020.

[92] M. Chahbar, G. Diaz, A. Dandoush, C. Cerin, and K. Ghoumid, A Comprehensive Survey on the E2E 5G Network Slicing Model, IEEE Transactions on Network and Service Management, 18(1), pp. 49–62, 9295415, 2021.

[93] A. Kammoun, N. Tabbane, G. Diaz, N. Achir, and A. Dandoush, Proactive Network Slices Management Algorithm Based on Fuzzy Logic System and Support Vector Regression Model, Lecture Notes in Networks and Systems, 97, pp. 386–397, 2020.

Mueen Uddin received PhD from the Universiti Teknologi Malaysia (UTM) in 2013. He is currently working as an Associate Professor of Data and Cybersecurity at the University of Doha for Science and Technology Qatar. Mueen has published more than 130 international journals and conference papers in highly reputed journals with a cumulative impact factor of over 300. His research interests include Blockchain, Cybersecurity, IoT security, and Network and Cloud Security.

Selvakumar Manickam is an Associate Professor and a Researcher with the National Advanced IPv6 Centre (NAv6), Universiti Sains Malaysia, working in cybersecurity, the Internet of Things, Industry 4.0, and Machine Learning. He has authored or co-authored more than 160 articles in journals, conference proceedings, and book reviews and has supervised 13 PhD students. He had ten years of industrial experience before joining academia. He is a member of technical forums at national and international levels. He also has experience building IoT, embedded, server, mobile, and web-based applications.

HIDAYAT ULLAH received master's degree from Preston University, Islamabad, Pakistan, in 2015. He currently pursued Ph.D. degree with the School of Communication and Information Engineering, at Shanghai University, Shanghai, China. He has authored 9 SCI-indexed articles in internationally renowned journals. His research interests mainly focused on big data, social media, environmental science, smart city, and urban planning, and Metaverse. He has been involved in several research projects, including projects of the National Natural Science Foundation of China and the Shanghai Science and Technology Commission. He was also a member of the Institute of Smart City, Shanghai University. He has been awarded the CSC Scholarship (China Scholarship Council) to study at Shanghai University. He has been awarded Turkiye Burslari scholarship in Istanbul Sabahattin Zaim University Istanbul Turkiye for his Post Doctoral certificate in 2021 and completed in 2023. He has the honor to Co-Chair the IEEE Conference ICALIP 2017.

Dr. Muath Obaidat is an Associate Professor of Computer Science and Information Security at John Jay College of Criminal Justice of the City University of New York and a member of the Center for Cybercrime Studies, Graduate Faculty in the Master of Science Digital Forensics and Cyber Security program and Doctoral faculty of the Computer Science Department at the Graduate School and University Center of CUNY. He has numerous scientific article publications in journals and respected conference proceedings. His research interests lie in the area of digital forensics, ubiquitous Internet of Things (IoT) security and privacy. His recent research crosscuts the areas wireless network protocols, cloud computing and security.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

Since July 2022, Abdulhalim is an Associate Professor in CCIT at UDST, Qatar. He is also an associated researcher at the L2TI institution of Sorbonne University and ESME Research Lab. Abdulhalim was the director of the expertise areas in Computing and Digital Technologies at ESME-Sudria in France, between 2015 and 2022. He obtained Master degree in Networking and a PhD in information technology from INRIA and UNSA in 2006 and 2010 respectively. He obtained an engineering degree in Electronics and Telecommunication from Tishreen University in 2022. He worked as Expert Engineer at INRIA within the Alstom-Transport Lab. His interests lie in the performance evaluation and optimization of network protocols and also the intelligent management of new-generation services. He was co-leading the ONF teaching brigade in 2017/2019. He worked at UNSA in France as an associate to research and teaching between 2006 and 2010 and as an assistant professor at the University of Tishreen in Syria and AASTMT in Egypt between 2011 and 2014.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4