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SURVEY

Metaverse Key Requirements and Platforms Survey

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ABSTRACT The growing interest in the metaverse has led to an abundance of platforms, each with its own unique features and limitations. This paper's objective is two-fold. First, we aim at providing an objective analysis of requirements that need to be fulfilled by metaverse platforms. We survey a broad set of criteria including interoperability, immersiveness, persistence, multimodal and social interaction, scalability, level of openness, configurability, market access, security, and blockchain integration, among others. Second, we review a wide range of existing metaverse platforms, and we critically evaluate their ability to meet the requirements listed. We identify their limitations, which must be addressed to establish fair, trustworthy, and interactive experiences within the metaverse ecosystem. Looking forward, we highlight the need for further research and development in areas such as decentralization, improved security and privacy measures, and the integration of emerging technologies like blockchain and AI, as essential building blocks for a resilient and secure metaverse.

INDEX TERMS Metaverse, security, blockchain, decentralization, interoperability, persistence, extended reality (XR), artificial intelligence, virtual reality (VR), connectivity, content generation, open-source, scalability, privacy, ethics, accessibility, avatar.

I. INTRODUCTION

The term 'metaverse' originated in Neal Stephenson's 1992 science fiction novel Snow Crash, where it was introduced as a vast virtual environment running parallel to the physical world [1]. In this digital realm, individuals could engage with one another via their virtual avatars. The concept of a virtual environment parallel to the physical world has evolved to encompass a wide range of interpretations, including universal and shared digital media networks [2], a sustainable [3], persistent [4], collective space in virtuality [5], with opportunities for social [6], creative [7], collaborative [8], immersive [9], and interactive experiences [10].

Although there is no one universally accepted definition of the Metaverse, Dionisio et al. described it as an immersive realistic environment that enables ubiquitous access and identity, interoperability, and scalability [11], while Wright et al. defined it as an extensive 3D virtual world that can support many people at the same time [6]. The metaverse is sometimes cited as the next generation of the internet, and as such is often defined as a collection of immersive digital spaces that are connected and shared across a variety of devices [2], [12]. According to Lee et al. [13], their understanding of the metaverse involves a computer-generated setting that combines elements of the physical world and the digital one. This is made possible through the merging of Internet and Web technologies, along with Extended Reality (XR). The current definition of the term metaverse typically pertains to a virtual world that is highly immersive and where individuals come together to *socialize, play, and work* [14].

The existing definitions of the metaverse highlight significant characteristics that are crucial for creating a persistent, immersive, interoperable virtual and augmented world. We define the Metaverse as "the universe of persistent Digital Twins (DT)", where a DT is a virtual representation of any living and non-living entities [15]. We also emphasize that the metaverse is not just a vast and immersive virtual world, but also a secured one, providing a safe environment

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for users to explore, interact, and create. We believe that the metaverse can be a space where communities can connect and interact, enabled by an open infrastructure that fosters creativity, collaboration, and innovation. For a seamless and realistic experience in the metaverse, a highly reliable network, scalable and interactive platforms that integrate AR, VR, web technologies, and security measures such as blockchain, are indispensable.

Additionally, we recognize that the metaverse offers a vibrant virtual economy that allows individuals and businesses to participate in commerce and trade, generating new opportunities and value for its participants. We emphasize that security and decentralization play a crucial role in ensuring the safety and fairness of transactions within this economy. Furthermore, the advancement of technology can facilitate the building of an accessible metaverse. Additionally, open-source platforms may democratize access to the high-powered computers and servers needed to create metaverse technologies, allowing individuals and businesses to participate in various domains [16]. Open-source allows more people to contribute to the creation of metaverse environments and experiences, which results in more diverse business models.

The convergence of Web3 and the metaverse represents a pivotal juncture in the evolution of digital experiences. Web3's decentralized architecture, rooted in ownership and privacy, seamlessly aligns with the metaverse's vision of user empowerment and interconnected virtual realms [17]. Through blockchain's immutable ledger and tokenization, users gain control over digital assets and identities, fostering trust and transparency within immersive environments [18]. Web3's emphasis on interoperability can bridge the gap between disparate metaverse platforms, enabling fluid movement of avatars and data [19].

This survey serves as a walk-through of the current open-source metaverse platforms and game engines, their main features, what technologies and devices they support, and their advantages and limitations. These reflect the progress and advancement of research and development in many applications and areas associated with both industry and academia. Ultimately, our objective is to assess existing metaverse platforms, identify their limitations, and bridge the gap between theory and practice to create an efficient and secure metaverse for the greater good.

We aim to answer the following research questions (RQs):

- RQ1: What are the Metaverse Key Requirements?
- RQ2: To what extent were these Key Requirements fulfilled within the existing Platforms?
- RQ3: What are the Gaps, Challenges, and Limitations? And how to tackle it?

RQ1 delves into the foundational elements that constitute the backbone of an effective metaverse. We aim to comprehensively identify and articulate the core requisites that must be present for a metaverse to offer a compelling and immersive experience for users and developers. By defining these requirements, we seek to establish a fundamental framework that can guide the development and evaluation of metaverse platforms. In RQ2 we quantify the degree to which these requirements are fulfilled to provide a critical evaluation of the metaverse platforms and highlight areas that require improvement or innovation. We focus on identifying shortcomings and seek to understand the underlying causes and complexities associated with these challenges in RQ3. Additionally, we aim to propose strategies and solutions for addressing these challenges, thereby contributing to the development of a more effective metaverse.

The remainder of the paper is organized as follows: Section II describes the existing literature and their contributions, while Section III delves into the metaverse requirements, providing a comprehensive analysis of their essential components. In Section IV, an overview of existing metaverse platforms and developer tools is presented, highlighting their unique features and functionalities. Section V critically discusses the limitations, and challenges, and suggests avenues for future work and further research in the field of metaverse development. Finally, in Section VI, a conclusive summary and insights are presented in the form of a conclusion.

II. RELATED WORKS

In the realm of metaverse exploration, several notable survey papers have laid the foundation for understanding the evolving landscape of the metaverse, its requirements, and its distinctive features. Our survey paper builds upon the insights offered by these seminal works while emphasizing the unique focus on metaverse requirements. In this section, we present a number of survey articles that explore the evolution of the metaverse, while summarizing their contributions.

Fig. 1 shows the significant growth in the number of publications related to only ''metaverse'' over the last years, reflecting the high level of attention and interest in this emerging technology. The publications were selected through a systematic search process using databases such as Web of Science, Scopus, and PubMed. The search query used the term ''metaverse'' across the title, abstract, and keywords fields to ensure comprehensive coverage of relevant articles. After gathering the search results, the number of publications per year was assessed to understand the trend and growth of research related to the metaverse. To account for the current year, 2023, the survey focused on the publications available until August 2023. The data collected up to that point was extrapolated to estimate the total number of publications for the entire year.

Among these studies, Lee et al. [13] emphasize the role of emerging technologies such as Extended Reality (XR), 5G, and Artificial Intelligence (AI). They present a comprehensive framework for metaverse development, focusing on enabling technologies (e.g., XR, AI, Blockchain) and user-centric factors (Avatar, Content Creation, Virtual Economy, Security, etc.), and proposes a research agenda to advance the metaverse. A comprehensive survey by Wang et al. [20] examines the security and privacy challenges

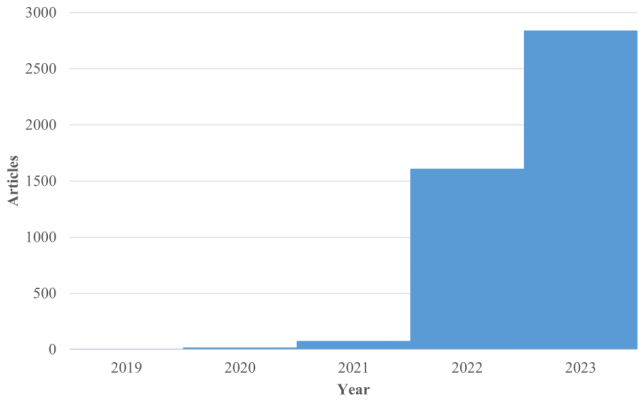

FIGURE 1. Metaverse-related publications' growth from 1996 to July 2023, based on Scopus, Web of Science, and Pubmed. The 2023 publication count was extrapolated proportionally to represent the entire year.

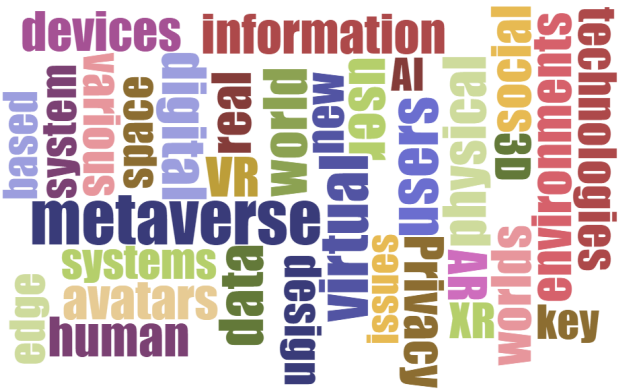

FIGURE 2. Word cloud frequency of keywords from metaverse-related survey articles [13], [20], [21], [22].

associated with the metaverse, detailing threats across various aspects. It offers insights into countermeasures and future research directions for creating a secure and privacy-preserving metaverse, while also discussing key characteristics and enabling technologies. Another study highlights the ongoing race to establish Metaverse infrastructure and emphasizes the implications for education while proposing a unified vision for leveraging the Metaverse in education, discussing key concepts of XR, MR, VR, AR, and Meta-education, historical context, and how they can offer immersive and equal global learning experiences [21]. The main contributions of the survey article by Wang et al. [22] include a description of the Metaverse's development across countries, international organizations, and publications; an introduction of its defining characteristics; and a proposal of a five-part technical framework encompassing communication, management, common technology, VR object connection, and VR space convergence. Dwivedi et al. [23] offers a balanced view of the transformative potential of the metaverse, highlighting benefits and challenges across multiple disciplines and areas of society, and exploring the socio-economic impact, sustainability, security, and privacy perspectives.

As companies increasingly embrace technology, the imperative to secure their data against cyber threats gains prominence, necessitating robust network security measures to facilitate technology adoption. The focus of the study [24] on evaluating security solution providers using the DEA SBM method highlights its pivotal role in identifying the most efficient players in the blockchain security arena, serving as a tool for decision-makers and investors seeking to enhance both company operations and the competitive edge of the security sector within the landscape of security and technology. Another study presents a comprehensive analysis of the efficiency of the cybersecurity industry in enhancing security features for wireless communication systems using data envelopment analysis window analysis and the Malmquist index approach [25]. It also explores the potential for performance improvement and technological advancement in the cybersecurity sector over four years, highlighting certain limitations and suggesting avenues for future research, including the consideration of alternative input and output components and the exploration of various data envelopment analysis models.

We generated a word cloud for the concept of "metaverse" by analyzing a large volume of text data related to this topic. In this process, we visualized frequently occurring words using the Drive World Cloud software by combining the most cited survey papers on Metaverse. As can be seen from Fig.2, this technique allowed us to visually highlight and prioritize the most relevant and prominent terms associated with the metaverse.

In summary, while the aforementioned survey papers contribute significantly to the understanding of various aspects of immersive technologies and metaverse ecosystems, our paper distinctly focuses on metaverse requirements, existing platforms, game engines, and developer tools, providing a comprehensive overview of the critical elements necessary for the successful design, development, and deployment of metaverse ecosystem.

III. METAVERSE REQUIREMENTS

Metaverse Standards Forum, Khronos Group, IEEE SA's Metaverse Standards Committee, and World Metaverse Council are groups leading the charge on developing the metaverse compatibility standard and protocols via the formation of consortiums and the facilitation of discussions centered on interoperability and decentralization [26], [27]. There are many features that build the core of the metaverse platform, being an interconnected structure as defined by Meta [12]. To evaluate existing Metaverse platforms and tools, various criteria have been established, where Fig. 3 shows the taxonomy of criteria that will be thoroughly described in this section.

The selection and prioritization of criteria into "Must-have", "Should-have" and "Good-to-have" criteria are based on the fundamental necessities required to create a

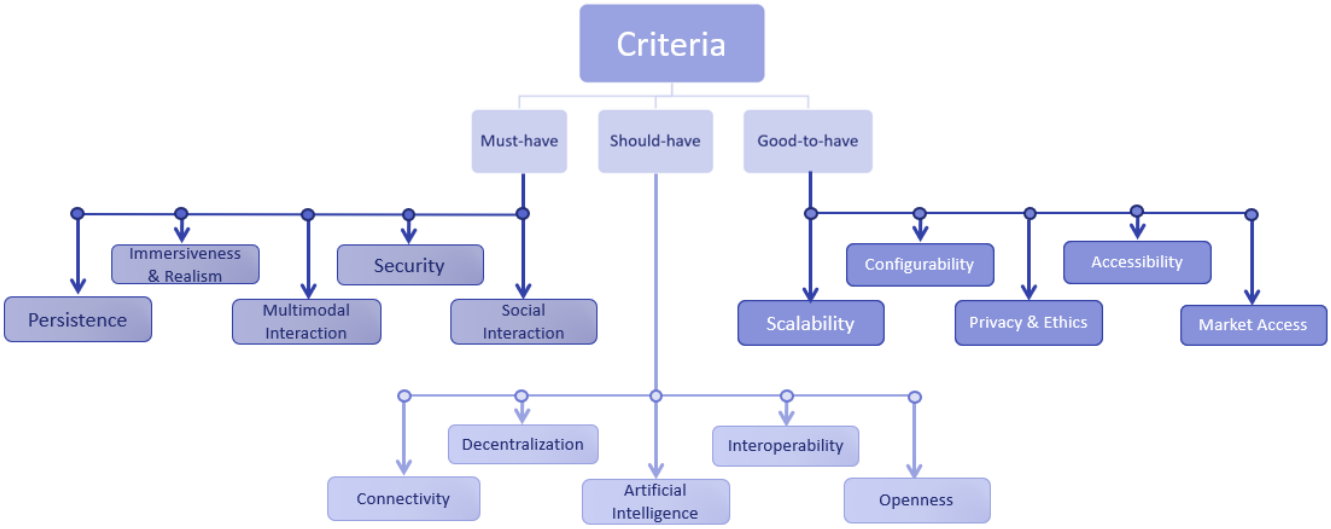

FIGURE 3. Metaverse key requirements.

functional metaverse ecosystem that aligns with existing literature and industry standards.

The ''Must-have'' criteria, including persistence, immersiveness and realism, multimodal interaction, security, and social interaction, are deemed essential because they form the foundational pillars of a successful metaverse. Without these core attributes, it is challenging for any metaverse to provide users with a compelling and immersive experience.

The ''Should-have'' criteria, such as connectivity, interoperability, decentralization, openness, and AI, are considered vital as they greatly enhance the metaverse's capabilities and adaptability to different use-case scenarios. These criteria are important for achieving a more advanced and adaptable metaverse experience.

Lastly, the ''Good-to-have'' criteria, encompassing scalability, application configurability, market access, accessibility, privacy, and ethics, are included to provide important features and convenience for users. While they may not be universally mandatory, they enhance the overall user experience and cater to diverse user preferences and needs.

Note that these classifications are to the best of our knowledge. While they provide a structured framework for evaluation, we acknowledge that in specific use-case scenarios or as the metaverse landscape evolves, the relative importance of these criteria may shift, and what is considered a ''Good-to-have'' today could become a ''Must-have'' in the future.

A. THE MUST-HAVE CRITERIA

1) PERSISTENCE

Avatars and digital twins are ways for users to have a virtual experience and feel a sense of belonging in the metaverse [15]. Persistence means that for those avatars or digital twins, the state is preserved even when the user is not actively connected to the metaverse, thus ensuring continuity and consistency in how the users' avatars and digital twins evolve over time. It also means that for metaverse spaces and virtual worlds that users access, the space remains unchanged until users themselves bring a change to that space. This ensures that users experience consistency within the metaverse, such is the case for physical real spaces. While current platforms exhibit a degree of persistence through avatar aesthetics and environment personalization, this can be considered local persistence; however, it falls short of fully meeting the overarching criterion of sustained persistence as envisioned.

Our comprehensive search across publishers like Scopus and Web of Science focused on the concept of persistence in the metaverse, and the findings indicate a notable gap in research dedicated specifically to this aspect of metaverse platforms or technologies. Surprisingly, no papers have been found that directly address the issue of persistence in the metaverse. This absence of research suggests that no platform has been able to fully meet the necessary requirements for persistence, likely due to the lack of in-depth exploration and understanding in this area.

2) IMMERSIVENESS AND REALISM

The transition of the metaverse has emerged into the diverse synergy of communication media including graphics, 3D virtual environments, and text, that led to immersion and realism of new technologies becoming a necessity (Jaynes 2003 metaverse). The user immersiveness in the metaverse can be defined with a combination of several factors, including the level of sensory immersion (AR/VR), and the level of interactivity [28]. A high level of sensory immersion, such as through the use of VR/AR/MR technology, allows the user to feel more immersed in the virtual world. Interactivity, such as the ability to move, touch, and interact with objects in the environment, increases the sense of presence and realism.

- **Virtual Reality (VR)** is a technology that immerses users in a virtual environment, creating a sense of presence and engagement that can enhance the level

of immersion in the metaverse. VR devices often use head-mounted displays, and motion sensor to simulate a realistic and interactive experience [29], [30]. By supporting VR headsets, the metaverse can provide a more seamless and interactive experience that feels more like a natural extension of the user's own body [31].

- **Augmented Reality (AR)** overlays digital elements onto the real world while adding contextual information to physical spaces, augmenting the user's perception and creating a more realistic and immersive experience in the metaverse [32], [33], [34], [35]. Various devices including handheld touch-screen devices, projectors, and wearables are capable of delivering AR overlays and digital entities, although AR headsets offer advantages in user attention and hands-free interaction [13].
- **Mixed Reality (MR)** combines elements of both virtual and augmented reality to create a more seamless integration of digital and physical worlds [36], [37], [38]. MR is often achieved using optical see-through and video-see-through types of technologies, and MR display tools fall into four categories: head-mounted, handheld, monitor-based, and projection-based devices [39].
- **Extended Reality (XR)** covers all types of reality technology, including VR, AR, and MR. XR technologies are designed to create immersive experiences that blend physical and digital environments in new and innovative ways. By combining elements of different reality technologies, XR can be tailored to suit a wide range of use cases and applications, from gaming and entertainment to education and training [40]. However, it encounters obstacles including limited adoption due to cost and accessibility issues, as well as sensory input constraints [22].
- **Holograms** serve as an additional entry point into the metaverse. 3D holographic communication technology can enhance realism and immersion by employing various technologies. The use of holograms in the Metaverse, rendered and displayed through HMDs with added parallax, enables interactive and immersive experiences, fostering improved perceptual quality and emotional engagement, such as making eye contact during meetings and generating a digital projection of the physical individual rather than a purely fictional portrayal [41]. While He et al. proposes a new three-dimensional holographic communication system for the metaverse based on 3D communication technology that involves four main components: display, transmission, hologram generation, and capture [42].
- **Large Display Technologies** like projectors, holography, and touchscreens, also play a role in creating immersive experiences in the metaverse. They offer different ways to display digital content, such as large ceiling interactive projectors that create an expansive display [43], wearable pico projectors for portable and flexible display [44], and holographic displays for 3D images [45]. Additionally, touchscreens enhance user interaction with digital content, thereby increasing immersion levels [46].
- **Flat Screen Support**: Flat screens enable users to observe, interact with, and participate in the metaverse for individuals who are not immersed in virtual reality [47].

3) MULTIMODAL INTERACTION

A metaverse with good multimodal interaction should allow for multiple forms of input and feedback, including gesture, voice, and haptic, to name a few [11], [28]. This enables a more natural and intuitive experience, as the user can interact with a virtual world in ways that are similar to how they interact with the real world [48].

- **Haptics** integration and telepresence are significant for creating immersive and engaging experiences in the metaverse by enabling users to experience physical sensations in virtual environments. Haptic can provide users with tactile feedback such as the feeling of touch or pressure, or kinesthetic feedback such as motion or resistance. At the same time, telepresence technologies can create a sense of being present in a remote location [49], [50].
- **Audio/Visual**: In a dynamic and vibrant social virtual context, audio is critical for navigation and conversation. High-quality audio can create a sense of spatial presence, while visual technologies such as high-resolution displays and 3D graphics can enhance the user's sense of immersion [51]. Marquardt et al. demonstrate the importance of audio and vibrotactile feedback in guiding users through dense information spaces on head-worn devices, achieving high accuracy with minimal deviations in search and information localization, resulting in superior performance and faster search times compared to visual cues [52].
- **Taste, Smell Feedback** are emerging modalities in the field of virtual reality, with the potential to develop more profound and deep Metaverse experiences [32]. Research has made progress in incorporating taste and smell experiences in virtual environments [53], [54], [55], exploring the taste intensity of food with a saltiness enhancer based on a cathodal current for virtual sensations primarily in salty and sour flavors [56], developing digital systems for delivering ambient scents and thermal/tactile cues [57], and exploring synchronized audiovisual content for multisensory tasting experiences [58], [59]; however, challenges arise from the preference for unpleasant odors in immersion, limiting widespread consumer adoption.
- **IoT/Wearable Support**: By incorporating various sensors and actuators, such as smart speakers or wearables, users can interact with the virtual environment in ways that mimic real-life experiences. This creates a more engaging and personalized experience [60]. Additionally, more seamless integration of real-world data and interactions that can be achieved through

IoT devices, enables the metaverse to become a more integrated part of our daily lives [28].

4) SECURITY

As the metaverse becomes more immersive, with users spending more time and engaging in various activities, it creates opportunities for cybercriminals to exploit vulnerabilities and gain unauthorized access to sensitive information [61]. Therefore, implementing robust security plays a significant role in ensuring users' trust, safety, and privacy [20]. One technology that can enhance metaverse security is blockchain, which offers a decentralized and tamper-proof system for storing and transferring data [62].

- **Security Protocols enabled by Blockchain Technology**: Blockchain is a decentralized and secure technology that is transforming the way we digitize and interact with the world, including the metaverse. Its tamper-proof, transparent ledger secures transactions and data storage, making it suitable for preserving digital assets and building confidence in virtual environments. However, blockchain's data storage capacity and network maintenance requirements limit its metaverse application [63]. Therefore, blockchain will need scaling solutions to secure the metaverse as it increases in complexity and size [62], [64].
- **Privacy** such as data harvesting and surveillance, are still present, making it necessary for metaverse platforms to prioritize privacy by implementing policies and technologies that limit data collection and sharing [65]. Additionally, data-driven consent mechanisms can address users' privacy concerns based on individual preferences [66].

5) SOCIAL INTERACTION

Since metaverses can host social meetings and other activities, usability, and interaction mechanisms are important criteria for evaluating them [13]. Easy-to-use metaverses with straightforward interaction mechanisms can boost user engagement, happiness, and adoption, making them more appealing and engaging social spaces [67]. Multilingual support ensures that metaverse users from different languages can participate in social activities [68].

- **Multilingual Support**: The Metaverse should support multiple languages [68]
- **Chat Support**: By enabling social interaction, the Metaverse has the potential to enhance well-being by providing a platform for users to connect with others and form meaningful relationships, as well as a space for sharing knowledge, experiences, and resources.

B. THE SHOULD-HAVE CRITERIA

1) CONNECTIVITY

Connectivity enables users to interact with each other and with the virtual environment seamlessly. Good connectivity in a metaverse is achieved with low latency, high bandwidth, and reliable network infrastructure [69]. Low latency ensures that there is minimal delay between user actions and the corresponding response in the virtual world, while high bandwidth allows for the transmission of high-quality audio and video. Reliable network infrastructure ensures that users connect to the metaverse consistently and without interruptions.

- **Edge and Cloud** Edge computing can help with data privacy and security, as sensitive information can be processed and stored locally rather than being sent to a central server [70]. It can help reduce latency and improve performance, while cloud computing provides a centralized infrastructure for managing virtual environments and supporting social interactions [63].
- **Network Infrastructure**: To allow real-time interactions and increased connectivity, the network infrastructure for the Metaverse must prioritize high throughput and low latency [13]. Furthermore, the development of digital twins and metaverse capabilities may rely heavily on 5G's ability to transmit time-sensitive data [71].

2) DECENTRALIZATION

Decentralization is a multifaceted attribute essential for the development of the metaverse. By dispersing authority and control, decentralization empowers users with greater user control and ownership over their activities and assets, thereby cultivating enhanced security and privacy. Notably, decentralization is pivotal in diminishing the vulnerability associated with a single point of failure, ensuring robust data protection, fortifying resistance against censorship, and fostering an environment of unparalleled transparency [72], [73]. Decentralized technologies like Decentralized Autonomous Organizations (DAOs) provide the necessary building blocks for a successful metaverse, allowing users to securely access and manage their information without relying on third-party intermediaries [23].

3) ARTIFICIAL INTELLIGENCE

Artificial intelligence (AI) is an essential component of the metaverse ecosystem, and its integration is critical to its success. The large amount of sophisticated metaverse data that can be used for AI applications provide greater user interaction and decision-making [13].

- **Machine Learning (ML)/Deep Learning (DL)**: AI is rapidly transforming the way we experience video games by simulating intelligent behavior that mimics that of real-life players. Additionally, AI can be used to support intelligent decision mechanisms [74]. This can facilitate providing avatars with a degree of autonomy, and enable them to perform tasks or participate in activities even when their users are not present, providing a more dynamic and interactive environment [75], [76].
- **Computer Vision (CV)**: By leveraging computer vision techniques, virtual worlds can simulate realistic visual representations of physical spaces, objects, and people, providing users with a sense of presence. Environments localization and mapping for representation and

interaction, [77], [78], Human pose and eye tracking for avatars representation and control [79], [80], [81], [82], Scene understanding with semantic segmentation, object detection, depth estimation, and action recognition [83], [84], [85], [86], [87], [88], [89] and Image enhancement [90], face detection [91] are common CV tasks among many others in the metaverse.

- **Natural Language Processing (NLP)**: addresses the primary challenge of human language understanding and making virtual assistants more intelligent. NLP allows chatbots to understand human conversations with varying dialects and undertones by capturing the syntactic and semantic relationships of preceding words and units. LLMs with advanced architecture can handle multiple sentence-based tasks such as sentiment prediction and question type classification, while NLP's feature extraction capabilities improve the reliability and flexibility of virtual assistant units in the metaverse, particularly in sentiment analysis and recognition [92].
- **Biosignal Processing**: The use of AI in biosignal processing has significant potential in the enriching metaverse experience. With the help of advanced biosensors, this digital world will be able to accurately interpret and respond to our physical, emotional, and mental states [93], [94].
- **Non-Player Characters (NPCs)**: will be an integral part of the Metaverse. They contribute to the immersive and interactive nature of the virtual environment by providing intelligent and responsive entities within the world. NPCs are designed to simulate human-like behavior, interactions, and decision-making, often utilizing artificial intelligence algorithms [68], [95]. NPCs in the Metaverse encompass aspects of AI such as behavior simulation, NLP, machine learning (ML), pathfinding, navigation, decision-making, and goal-setting among others. With its ability to outperform other AI algorithms, reinforcement learning enables one to learn from previous experiences in the game and adapt their behavior accordingly [96].
- **Content Generation**: With the ability to autonomously create diverse forms of content, including text, images, audio, and video, AI-driven generative technologies are bridging gaps in metaverse development [97]. Additionally, metaverses should have a rich library of multimodal content representation and learning, complex persona modeling, and storytelling capabilities that link entities together. The length of scenarios and scenario generation should also be considered [13].

4) INTEROPERABILITY

To guarantee that many technologies deployed in the metaverse are compatible with one another, the foundation includes hardware, protocols, and standards. This is the core of interoperability [11], which is the capacity to move virtual digital objects and avatars throughout the entire metaverse, creating challenges in fast service authorization, compliance auditing, and multi-source data fusion, particularly due to heterogeneity in virtual worlds' hardware, communication, and software [20]. This requires having unified standards within the foundational structure.

- **Standards**: ISO/IEC 23005 (MPEG-V) serves as the initial standardized framework for networked virtual environments in the metaverse, aiming to establish seamless information exchange, simultaneous reactions, and interoperability between real and virtual worlds [98], while the ISO/IEEE 11073 standards provide efficient interoperability for health services by enabling communication between personal health devices and managers, offering real-time plug-and-play functionality for health data exchange [60].

5) LEVEL OF OPENNESS OF THE SOURCE CODE

Openness has been recognized as an important factor in the success of the metaverse. The degree of openness, specifically the availability of open-source software, is an essential criterion for determining the sustainability of a metaverse [11]. Open-source availability allows for greater transparency, collaboration, and innovation within the metaverse community. It will enable developers to build on existing work and create new features and applications, leading to a more robust and vibrant virtual environment. Moreover, the availability of open-source software can foster interoperability and standardization across various metaverse platforms, ultimately benefiting both users and developers.

- **Documentation**: While metaverse platforms offer open access to source code, the absence of documentation poses challenges for users seeking to comprehend platform functionality and fully utilize its features, underlining documentation's significance in facilitating replication and understanding [99], [100]. Clear and comprehensive documentation provides insights into project functionality, usage guidelines, better decision making, and collaborative contributions within the open-source community [101].
- **Licensed**: While all open-source licenses have a minimum requirement for openness, there are significant differences in the freedoms and restrictions provided by each license. For example, while some licenses like the public domain offer the greatest degree of freedom by waiving all rights to the software, other licenses like BSD offer more limited freedoms by requiring attribution and other conditions. The GNU license, on the other hand, places more restrictions on the use and distribution of the software. As such, it is essential to carefully consider the specific license being used when evaluating the openness of an open-source project [102].
- **Closed**: virtual worlds or online platforms that are owned and operated by a single company or organization and their source code is not available for public inspection or modification [103].

C. THE GOOD-TO-HAVE CRITERIA

1) APPLICATION CONFIGURABILITY

Application configurability refers to the degree to which users can customize and adapt an application to their needs and preferences. In the context of a metaverse, configurability can enhance user experience and increase engagement [104].

- **Specific Domain** refers to the ability to tailor the metaverse platforms, tools, and content to specific industries or use cases [68]. For instance, a virtual training platform might allow the customization of training modules, assessments, and feedback mechanisms [105], and a virtual conference platform might have configurable office features [106].
- **General Configurability** refers to the metaverse's ability to be adapted to various settings and use cases that allows for flexibility and tailoring to specific industry requirements or individual user preferences. By enabling customization at both the domain-specific and general levels, the Metaverse can better serve the needs of different industries and users, while also fostering a vibrant and collaborative virtual community [68].

2) SCALABILITY

A seamless, immersive, and engaging experience for users while accommodating future growth and expansion can be achieved through scalable technologies [11]. The metaverse should be able to accommodate a high number of concurrent users and avatars interacting in real-time while maintaining stable network connections, low latency, and high frame rates [13]. Additionally, complex and dynamic scenes with advanced physics, lighting, and visual effects without compromising performance should be supported in the metaverse.

- **Concurrent Users/Avatars**: number of maximum users [11], [107], [108].
- **Scene Complexity**: number of objects in a particular locality and their behavior and appearance complexity level [11], [107], [108].
- **User/Avatar Interaction**: addressing challenges in terms of the need for large-scale real-time, continuous, and distributed interaction, simultaneous visualization from multiple endpoints, and the utilization of several simulation engines that possess varying operational characteristics are essential for scaling virtual worlds [11], [107], [108].

3) PRIVACY AND ETHICS

Due to the potential threats posed by continuous device sensing in MR, XR, users' privacy, security, and safety could be compromised [109]. The metaverse's societal resemblance creates governance complexities, necessitating regulations, and policies for user behavior management [110]. Crucial to the metaverse are privacy-enhancing technologies for protecting sensitive data and the implementation of ethical design to encourage positive interactions and resolve conflicts. Mitigating ethical challenges involves utilizing utilitarian decision-making to prevent data breaches and promoting transparency to enhance user awareness and data security. Implementing thorough disclosure policies and privacy guidelines can guide responsible data use and ethical behavior within the metaverse [111].

4) ACCESSIBILITY

In order to create a more inclusive and fair metaverse that caters to everyone, proper measures need to be implemented. The metaverse should be accessible to all individuals, regardless of their socioeconomic status or physical abilities. Accessibility issues are raised concerning people with physical or sensory disabilities [112]. Another example of accessibility issue has been highlighted in [112] that most VR headsets have been designed specifically for middle-aged adults. This means that older adults may have an issue accessing the metaverse wearing headsets not designed for their age group.

In the metaverse, individuals can interact and engage with others from different backgrounds, cultures, and locations, and therefore it is important to ensure that the metaverse is equitable to all its users [113].

5) MARKET ACCESS

Metaverse commerce is a novel and rapidly growing concept that encompasses various trading activities within virtual environments, such as user-to-user, business-to-user, and business-to-business transactions. The ability of users and developers to monetize their activities and creations within the metaverse is essential for the long-term viability and sustainability of the virtual environment [114]. Market access is an important criterion for evaluating the success of a metaverse and it can take numerous forms, including virtual goods sales, advertising, and sponsorship, and can provide users with new opportunities to generate income and support the growth of the metaverse [115].

Non-Fungible Tokens (NFTs) play a significant role in the metaverse market access by enabling ownership and trade of unique digital assets within virtual environments [116]. NFTs provide a way to represent ownership and authenticity of digital items, such as virtual real estate, artworks, collectibles, and more, which can be utilized and traded across various metaverse platforms [117]. However, it's worth noting that there are potential risks associated with NFTs, as observed in their price volatility and susceptibility to the cryptocurrency market, which could impact metaverse commerce and require careful consideration [118].

IV. EXISTING METAVERSE PLATFORMS AND DEVELOPER TOOLS OVERVIEW

In order to provide a comprehensive view of the various platforms and tools available for building the Metaverse, Tables 1-3 have been included to offer a detailed overview of the open-source platforms and closed-source platform, as well as development tools and engines, that are commonly used in creating the metaverse. Without evidence or reliable

TABLE 1. Evaluating Must-have Criteria Vs. Existing Platforms.

			Must-have				
Platform	**Number of users**	**Avatars**	**Persistence**	**Immersiveness**	**Multimedia Interaction**	**Security**	**Social interaction**
Vircadia	400+	Human-like	*	VR	Audio Visual	✓	Chat
Mozilla Hubs	–	Cartoon-like	*	All	Audio Visual	All (except blockchain)	Chat
Decentraland	300 000	Human-like	*	VR	Audio Visual	✓	Chat
Webaverse	–	Cartoon-like	*	VR	Audio Visual	✓	Chat
JanusWeb	–	Cartoon-like	–	VR	Audio Visual	–	Chat
Fortnite	350 million	Human-like	*	–	Audio Visual	All (except blockchain)	✓
Roblox	200 million	Cartoon-like	*	VR	Haptic Audio Visual	All (except blockchain)	✓
Minecraft	141 million	Cartoon-like	*	VR	Audio Visual	All (except blockchain)	✓
Second Life	64.7 million	Human-like	–	VR	Haptic Audio Visual IoT	All (except blockchain)	✓
Sandbox	4.5 million	Cartoon-like	*	–	Audio Visual	✓	Chat
Spatial.io	2 million	Human-like	*	VR	Audio Visual	✓	✓*
Meta's Horizon Worlds	300 000	Human-like	*	All	Haptic Audio Visual	All (except blockchain)	Chat
Somnium Space	–	Human-like	*	VR	* Haptic Audio Visual	✓	Chat
Microsoft Mesh	–	Human-like	*	VR	Audio Visual	All (except blockchain)	Chat

✓ - all and/or most of the criterion is met, **–** interprets that no information can be found, ***** - work in progress, and check the section overview for more details.

sources, any claims about the capabilities or potential of such technology would be purely speculative. Therefore, it is crucial to note that a dash mark in the tables represents a lack of information, and despite our best efforts to find all available data, it may indicate that the technology in question is either not yet available for use or has not been fully developed. Additionally, a checkmark in the tables is based upon a thorough evaluation process encompassing data derived from platforms' official websites, whitepapers, and documentation, alongside our empirical observations following the installation and exploration of the platforms.

Columns in the tables describe a specific requirement as described in the previous section, and evaluate how each platform meets that requirement. It is crucial to acknowledge that accessibility criteria are addressed in different ways across various platforms. This is due to the presence of

TABLE 2. Evaluating Should-have And Good-to-have Criteria Vs. Existing Platforms.

	Should-have					Good-to-have				
Platform	**Connect.**	**Decentr.**	**Artificial Intelligence**	**Interoper.**	**Level of Openness**	**Scalab.**	**Application Configur.**	**Privacy & Ethics**	**Accessib.**	**Market access**
Vircadia	✓	✓	–	✓	Open Apache 2.0 Licensed Documented	✓	✓	*	–	–
Mozilla Hubs	✓	–	Custom avatars	✓	* Mozilla Public License 2.0 Documented	✓	✓	*	–	–
Decentraland	✓	✓	*	*	Open Apache 2.0 Licensed	✓	✓	*	–	✓
Webaverse	–	✓	NPCs	✓	* MIT Licensed Documented	✓	✓	–	–	✓
JanusWeb	–	✓	–	✓	Open MIT Licensed Documented	✓	✓	–	–	–
Fortnite	✓	–	AI Patrol Path Node	–	Closed	✓	–	*	–	–
Roblox	✓	–	–	–	* MIT, Apache Licensed	✓	✓	*	–	✓
Minecraft	✓	–	AI experim. platform	–	Closed	✓	✓	*	–	✓
Second Life	✓	–	NLP	✓	* GNU LGPL Licensed Documented	✓	✓	*	–	✓
Sandbox	✓	✓	*	✓	* MIT Licensed	✓	✓	*	–	✓
Spatial.io	✓	*	3D Avatar generation	✓	Closed	✓	✓	*	–	✓
Meta's Horizon Worlds	–	–	AI voice command prototype	*	Closed	✓	✓	*	–	*
Somnium Space	*	✓	–	*	Closed	✓	–	*	–	✓
Microsoft Mesh	✓	–	–	*	Closed	✓	–	*	–	–

✓ - all and/or most of the criterion is met, – interprets that no information can be found, * - work in progress and check the section overview for more details.

numerous initiatives, including but not limited to the creation of a virtual community for disabled individuals in Second Life, accessibility simulations offered by Omniverse, and instructions, as well as accessible design packages developed by several companies. Further detailed descriptions of such initiatives can be found in this section.

TABLE 3. Evaluating criteria vs. Existing game engines and developer tools.

Game Engine Dev. Tool	Must-have		Should-have			Good-to-have	
	Immersive.	Multimodal Interaction	AI	Interoper.	Level of Openness	Scalability	Application Configurability
Unity 3D Engine	✓	Haptic Audio Visual	ML Agents	✓	Reference only Licensed Documented	✓	General custom.
Unreal Engine	✓	Haptic Audio Visual IoT	NPCs	✓	EULA Licensed Documented	✓	General custom.
Ethereal Engine	✓	Audio Visual	Agents	✓	MIT Licensed Documented	✓	General custom.
Babylon.js	✓	Haptic Audio Visual	Agents Navigation	–	Apache 2.0 Licensed Documented	✓	General custom.
Blender	VR	Haptic Audio Visual	*	✓	GNU GPL 3.0 Licensed Documented	–	General custom.
Nvidia Omniverse	✓	Haptic Audio Visual IoT	CV Plugins	✓	BSD-3-Clause Licensed	✓	General custom.

✓ - all and/or most criterion is met, – interprets that no information can be found, * - work in progress; check the section overview for more details.

A. METAVERSE PLATFORMS

1) VIRCADIA

Vircadia is a decentralized open-source software that facilitates the creation and sharing of virtual reality (VR) and desktop environments [119] and it was released in 2021. Users can create and upload their own content, including 3D models, animations, and scripts, to build their own virtual spaces. Vircadia also supports real-time voice and text chat, allowing users to communicate with each other while immersed in virtual environments. It incorporates social capabilities, such as avatar interactions, spatialized audio, and interactive physics. The platform is designed to be user-friendly, with support for a wide range of VR devices, including Oculus, HTC Vive, and Windows Mixed Reality headsets.

The persistence of the Vircadia domain server is characterized by continuous, real-time saving of the world's state to disk [120]. Additionally, users have the option to save the state as a snapshot whenever desired. Furthermore, to ensure data security and integrity, the persisted state undergoes regular backups through a rolling schedule.

After installing and testing Vircadia, we have observed that the web platform is currently in its early alpha stage, with many features still under development. Some functionalities such as login and exploring places are still being worked on. We also found out that the current version of Vircadia on their code repository has been deprecated, and a newer version is currently in development. However, the good news is that both the server and client are open and configurable, and the Iamus metaverse server can be packaged and run as a Docker image.

Additionally, Vircadia supports creating and sharing various types of content such as images, web, scripts, 3D models, particles, zones, materials, text, shapes, and lights. It also supports full-body avatars. It has a well-documented and growing ecosystem, and it's supported on different platforms such as Linux, Windows, and Android. While Vircadia doesn't support blockchain out of the box, it is possible to develop custom solutions to integrate blockchain technology. Overall, our observations indicate that Vircadia is a promising platform for creating and sharing immersive experiences and we look forward to seeing its continued growth and development. Regarding privacy in Vircadia, according to its privacy policy, it connects certain services to its servers for initial setup, requiring data collection upon registration/login for normal software operation; users can enable crash logging, which transfers information while prioritizing data removal, and opt into an eye-tracking feature that doesn't collect raw data but affects observable avatar actions [121].

2) MOZILLA HUBS

Mozilla Hubs is a social virtual reality (VR) platform that was released in 2018, and it allows users to create and join immersive 3D spaces and environments [122]. Developed by Mozilla, this platform is designed to be user-friendly, where users can interact with each other in real-time within these virtual spaces, using avatars to represent themselves and voice chat to communicate. They can also share and interact with various media, including images, videos, and 3D models. It can be used for a variety of purposes, such as socializing, education, meetings, and events.

One of Hubs' most notable features is its emphasis on privacy and security. All virtual spaces within Hubs are encrypted and users have complete control over access to

their space and the permissions granted to others. As per their privacy policy, Mozilla Hubs collects and shares information within rooms, including account data for features like avatars, room names and URLs, voice data, and chat messages; photos, videos, and objects are stored temporarily and deleted within 72 hours or can be pinned; technical, interaction, error, and website analytics data are used for improvement [123]. Regarding the accessibility in Mozilla Hubs, developers can follow guidelines and considerations to create accessible virtual reality experiences in Hubs, ensuring everyone can participate in the virtual world [124]. Concerning the level of openness, its client is open-source but the server is closed-source. Persistence in Mozilla Hubs allows networked instantiated entities to be saved and maintained across client disconnections and reconnections through pinning and the use of built-in functions for creating, updating, and deleting entity states in the database.

Our observation of Mozilla Hubs reveals that the web version provides limited functionality and only offers a demo version. There are various subscription options available for Mozilla Hubs: starter (free) with 10 guest capacity and 500MB asset storage, personal with 20 guest capacity and 2GB asset storage, and professional early access with 50 guest capacity, 25GB asset storage, and additional features like custom domains and access to Mozilla's codebase. Additionally, there is a third subscription option called Business, which provides custom solutions. The client-side code available on GitHub enables users to create their own rooms, customize their environment, and decorate their avatars. Another thing we have noted is that Hubs only supports half-body avatars. It is also possible to run private servers through AWS or DigitalOcean.

3) DECENTRALAND

Decentraland, a virtual reality platform released in 2020 and powered by the Ethereum blockchain, allows users to create, experience, and monetize their own virtual reality content and applications. Decentraland has its own cryptocurrency, MANA, which is used as the primary currency for buying and selling virtual assets and participating in the platform's economy.

In Decentraland, users can create and own their own virtual plots of land, known as LAND, which are represented as non-fungible tokens (NFTs) on the Ethereum blockchain. The platform operates on a decentralized model, meaning that all content and transactions are recorded on the blockchain, and users have complete control over their virtual assets. On the AI integration, Decentraland Decentralized Autonomous Organization (DAO) has approved a grant proposal to fund the development of DCLBuilderAI, an AI tool that creates scenes and other assets through natural language prompts [125].

Decentraland's Privacy Policy outlines data collection, use, and sharing, emphasizing data security measures for user data and users' privacy rights, where collected information is used to analyze trends, improve, personalize the experience, and communicate with users. Meanwhile, aggregated and anonymized data may be shared with third parties for necessary functions, and aggregated data might be shared for various purposes. Decentraland's Code of Ethics emphasizes values of integrity, responsibility, respect, and pioneering, requiring employees to conduct operations with honesty, compliance with laws, financial integrity, reporting, confidentiality, environmental care, and more, while maintaining a commitment to diversity, equal opportunity, and safety in the workplace, with breaches subject to serious consequences and compliance overseen by the Compliance Team.

On the interoperability improvement, Decentraland is working with other metaverses [126]. For example, Metaverse Fashion Week 2023 will take place in Decentraland and will bridge Decentraland with other virtual worlds, with a focus on digital-physical crossovers and more support for brands [127].

Based on an exploration of Decentraland's documentation, it was found that the virtual world is persistent, allowing continuous access to scenes with no startup or ending phase, and the game mechanics should be designed to facilitate the participation of players joining or leaving at any time [128]. Additionally, entity ownership and file storage are tied to Ethereum accounts, with content servers retaining the latest version and potentially keeping old versions based on their individual settings.

Having installed and explored the Decentraland Desktop client ourselves, which is currently available in the Beta version on Windows, we discovered various features it offers. One notable aspect is the ability to engage in gameplay as a registered user with a digital wallet or as a guest. For new users, there are introductory tasks designed to provide a smooth onboarding experience, allowing them to familiarize themselves with the platform's mechanics and functionalities.

However, the information will be locally stored in case of exploring Decentraland as a guest. While guest users have the freedom to traverse the virtual world, customize their avatar, and engage in conversations with other users, they will be unable to receive daily rewards, and seamlessly log in across multiple devices using the same guest ID and avatar without a digital wallet. According to the documentation provided on the Decentraland website, deploying your own transactions server in Decentraland involves setting up a server that communicates with the Ethereum blockchain and the Decentraland smart contracts. This allows users to handle transactions and interactions within the virtual world. [129].

4) WEBAVERSE

Webaverse constitutes an open-source decentralized platform aimed at facilitating the creation, sharing, and trading of virtual reality experiences, games, and assets [130]. This platform harnesses the potential of WebXR technology, allowing users to construct and personalize their own three-dimensional virtual spaces. Although the exact release date is not available, it was actively in development in 2021.

Webaverse's underlying infrastructure is built on a blockchain network, facilitating security, transparency, and decentralization. Additionally, the platform provides developers with the means to generate and market their own virtual assets, such as 3D models, animations, and sound effects, utilizing the Webaverse Software Development Kit (SDK). It is notable that the NFT Discord Bot simplifies user interaction with the Webaverse Ethereum sidechain in Discord servers, enabling them to trade and manage their inventory and storefront across multiple servers without the need for prior crypto knowledge.

Regarding persistence, Webaverse allows creators to drag-and-drop various assets such as images, 3D models, avatars, and scripts in real-time to showcase and monetize their creations, while users can buy parcels of land that serve as persistent spaces for embedding content, with in-world items persistently living within these LAND parcels [131].

Our installation and testing of the Webaverse client through their GitHub repository was successfully performed following their installation guide. However, the provided Discord invitation did not grant us access or facilitate community support. Additionally, it was observed that the most recent changes in the GitHub repository were made in December 2022.

5) JANUSWEB

JanusWeb is an open-source web framework of JanusVR, which enables developers to construct social virtual reality experiences [132]. JanusWeb's user interface makes it simple to design and develop immersive 3D environments that can be accessed on PC, mobile, and VR devices. Moreover, JanusWeb provides real-time collaboration capabilities, allowing users to collaborate across all devices and work together to build a shared virtual experience. JanusWeb allows users to import 3D models in standard file formats such as Collada, OBJ, and glTF. While the precise release date remains undisclosed, it was in active development throughout 2021.

Based on our experience with JanusWeb, we observed that it is a versatile web browser that allows for easy switching between scenes in both VR and AR. It can be used without requiring a login and provides the ability to view room sources, make changes, and view in debug mode. Additionally, JanusWeb facilitates browsing and building content using Janus Markup Language (JML) on VESTA, a social platform for 3D content creators to showcase their creations and get feedback through the use of JanusWeb. Despite the code repository not being updated recently, integrating a 3D WebVR portal onto any 2D webpage in a webspace is still possible using JanusWeb's widget generator [133]. JanusWeb has a client and server available in its code repository, and we were able to ensure that the connection is possible.

6) FORTNITE

Fortnite, developed by Epic Games in 2017, offers different versions of gameplay experiences. One of the versions they offer allows players to design their own worlds and battle arenas.

Epic Games has implemented security measures, including two-factor authentication (2FA), parental controls, and a reporting system to address inappropriate behavior [134]. In terms of accessibility, Fortnite offers various features such as control remapping, adjustable text size, and visual/audio cues for in-game events [135]. Additionally, some of the games include visual sound effects to assist players with hearing impairments.

In Fortnite, the Save Point device allows players to save their progress, location, resources, and stats, enabling them to leave the game and return later without starting over, providing persistence for various game aspects across multiple sessions [136]. Epic Games' privacy policy, applied to Fortnite and other Epic Services, collects information provided by users, automatic usage data, and data from third parties to operate, improve, customize, analyze, and promote their services, while allowing users certain choices and controls over their personal information based on their geographical location, with measures to protect security and data privacy in an administrative, technical, and physical levels [137]. Another important aspect of their privacy policy is the measures taken for children's privacy, such as following legal obligations like COPPA and requesting age-related information, requiring parental consent for access, providing controls for parents, and utilizing Kids Web Services for verification.

Based on our experiences, Fortnite is a video game that provides interactive, cross-platform gameplay and features a virtual economy. It shows the potential to evolve into an ecosystem for the metaverse, going beyond the traditional definition of a game. Interestingly enough, despite Fortnite's success in amassing a large audience, the company currently has no plans to integrate VR experience into the game.

7) ROBLOX

Roblox was founded in 2004 and has since become one of the largest gaming platforms in the world, with over 214 million active users as of 2023. Users can create games using the Roblox Studio software, which allows them to create 3D environments, add interactive objects and characters, and program game mechanics using Lua scripting [138]. Games created by users can be published on the platform and played by other users, creating a vast library of games for players to choose from, enabling developers to monetize their creations, with a virtual economy that allows players to purchase virtual items and currency using real money. Regarding the level of openness, only certain projects of Roblox are open-source. Concerning accessibility in Roblox, the company has partnered with an accessibility consulting company to conduct a full accessibility audit consisting of automated and manual testing on their website [139].

Roblox's privacy policy outlines how they handle personal information, allowing users to control and manage identifiable data, including usage, collection, and sharing,

and highlighting user rights based on location and age, while emphasizing their commitment to children's privacy; it also covers payment processing, content moderation, third-party integrations, location-based services, and data usage for improving user experience and safety, all in compliance with relevant laws and policies [140].

Regarding persistence in Roblox, the legacy Data Persistence (DP) service was deprecated in 2014 and completely sunset on June 1, 2021, with developers, now encouraged to use the stable and continually improving DataStore service for persistent data storage across different servers in a game experience. It allows storage of data that needs to persist between sessions, such as items in a player's inventory or skill points [138].

In addition, Roblox has declared that it is in the process of developing a platform that will grant its users access to generative artificial intelligence tools for creating content [141]. It also has a substantial community of developers who frequently contribute to open-source projects [142].

Based on our experience of installing and testing the Roblox Metaverse, this platform offers a wide range of games and customizable avatars. It is worth highlighting that what distinguishes Roblox from traditional gaming platforms is its emphasis on being a creator-driven platform, enabling users to actively participate in content creation and shaping their virtual experiences.

8) MINECRAFT

Minecraft, originally released in 2011, has since undergone significant evolution, incorporating metaverse-like elements. The game is currently under the management of Mojang Studios, a subsidiary of Xbox Game Studios, itself a division of Microsoft. Microsoft Research developed Project Malmo as an advanced AI research tool that utilizes Minecraft as a platform to address fundamental AI research challenges [143]. By combining deep reinforcement learning, cognitive science, and other AI concepts, the modded Java version of Minecraft provides an experimental environment for intelligent agents to perceive and interact with the game's surroundings. Moreover, Minecraft features a Marketplace where players can purchase Minecoins using real money, enabling them to access a wide range of community-created content, including skins, textures, intricately-crafted worlds, and adventures [144]. In terms of accessibility, Minecraft's Accessibility menu offers several features such as accessible navigation, narration, speech-to-text, and chat text formatting. Recently, new accessibility options have been introduced, including a contrasted achievement screen, adjustable font size, narration, and navigation options, configurable audio channels, and updated ore patterns for players with difficulty reading colors [145].

Minecraft follows Microsoft's privacy policy, which encompasses the collection of user data, its utilization for product improvement, personalization, advertising, and business operations, and offers user control through tools and contact methods, adhering to specific regulations for child data and aligning with Microsoft's enterprise offerings, all in compliance with relevant laws [146].

In Minecraft, persistence is ensured through periodic world saves, storing terrain, structures, player inventories, and more, allowing players to continue from where they left off, and backup systems are commonly utilized to safeguard against corruption or revert to previous world states, while modded Minecraft expands persistence with custom data storage for additional game elements.

Minecraft is not available as a completely free-to-play game. We were able to install and test specific free-trial editions, such as Minecraft Education, which is being adopted into school curricula in some countries [147]. This captivating educational tool exhibits the potential for fostering increased engagement and participation among the younger generation. Upon installing and playing Minecraft Education Edition, we discovered the game's interface is intuitive and user-friendly, allowing for easy navigation and exploration. From historical landmarks to scientific experiments, it offers an interactive and collaborative platform for learning across various disciplines. Also, it is possible to host games locally to join forces with other learners, working together to solve problems and complete complex tasks.

9) SECOND LIFE

Second Life, a metaverse created by Linden Lab in 2003, is a versatile platform that offers users opportunities to create, explore and interact in a virtual environment [148]. Its range of features includes avatar creation and customization, virtual economy participation, and the ability to construct and design virtual spaces. Second Life has been used for diverse purposes, ranging from socializing and gaming to education and virtual events. However, it is worth noting that the available information on its interoperability is from 2008 [149], and it is unclear whether it aligns with recent findings on interoperability standards by the Metaverse Standards Forum and World Economic Forum [150].

Concerning accessibility, Second Life offers individuals with disabilities new experiences, that may not be available in the physical world. These include the use of a text-based viewer to navigate the virtual environment through a third-party viewer, allowing limited vision and visually impaired users to explore and enjoy a range of activities [151]. Also, there is a Virtual Ability island, a virtual community in Second Life, which offers support for people with disabilities through an accessible virtual environment and tools, communication, and design principles [152].

Second Life's privacy policy outlines the terms for accessing the virtual world environment offered by Linden Research, Inc. (Linden Lab), encompassing the collection and use of personal and anonymous information, which may be used to create aggregate information, and the various purposes for which this data is processed, including services provision, communication, marketing, improvement, and compliance, as well as the sharing of information with third parties, specific provisions for young adults and children

accessing the services, and incorporating technical, physical, and organizational security safeguards, ongoing vulnerability monitoring, and data breach procedures for the protection of collected data [153].

Regarding the level of openness, there is an available client source code of Second Life, while the source code for the server software is not publicly available and is owned by the company [148].

10) SANDBOX

The sandbox metaverse represents a virtual world platform that allows users to create, share, and monetize their own gaming experiences and social spaces [154]. It was launched in 2012 as a large-scale sandbox game designed to be an open and decentralized platform but with an added layer of interconnectivity and player-driven content creation.

In The Sandbox Game (TSB), persistence allows players to save their last custom avatar design, ensuring they don't lose it when equipping another avatar, but the game is not a single persistent world. Regarding the privacy aspects, the privacy policy of TSB states how they collect, use, and disclose personal information through their websites, email communications, and offline interactions, using it for providing services, marketing, and analytics, sharing with affiliates and third-party providers as needed. This information includes various types of personal data such as name, email address, postal address, username, crypto wallet address, social media handle, IP address, in-game activity, and more. The privacy policy states that the services are not directed at individuals under the age of 18 [155].

Through firsthand engagement with the sandbox metaverse, we had the opportunity to construct and design personalized virtual environments, games, and experiences using a set of creation tools provided by the platform. Users can share their creations with others, and even monetize them by trading for the platform's native cryptocurrency, SAND. Moreover, the Sandbox game is working on integrating AI to improve the user experience in the Metaverse. AI is being used for moderation to reduce profanity and toxicity among players' conversations, and for self-expression through partnering with Kinetix [156]. The game has partnered with Scenario with the goal of developing AI tools for text-to-visual generative asset creation in video games. Concerning the level of openness, the Sandbox platform embraces partial openness by offering selected projects as open-source.

11) SPATIAL.IO

Spatial.io, established in 2016, provides a comprehensive platform for building immersive and collaborative spatial computing experiences that can be accessed on a variety of devices and run in a range of contexts, from gaming and entertainment to education and training [157]. After we explored, the platform, it is clear that the platform provides users with the ability to create virtual rooms using Unity and Spatial Studio. Users can join and invite others to join virtual rooms, where they interact with each other in real-time. Spatial.io uses blockchain to create a decentralized system for storing data about users' avatars that can be easily shared with other users. Regarding social interaction, Spatial also offers an upgraded version called Spatial+ which includes additional features such as hosting tools, token gating, overflow groups/instancing, live speech translation, and unlimited storage [158].

According to the Spatial Systems Privacy Policy, Spatial.io collects various types of information, including personal data such as account details, communications, virtual space content, teleconferencing data, and automatic data like IP addresses and device information. This information is used for purposes such as providing services, marketing, research, security, and analytics. Users can share content and profiles, have privacy choices, and have rights to access, correct, delete, and control their data, with data retention extending as needed for legitimate purposes and compliance with laws [157].

In Spatial.io, the persistence feature is facilitated by the Data Store system, allowing users to save state for their experiences, such as inventory items, XP, and levels, on a per-user basis; Spatial Park, a highlighted area within Spatial.io, serves as an official example of the platform's persistence capabilities, as stated on their website. This environment is characterized by its persistence, remaining consistently open and available for users to engage in collaborative activities and social interactions [159].

12) META'S HORIZON WORLDS

Horizon Worlds, released in 2021, is an online video game and game creation system that uses virtual reality technology and is currently only available on Meta VR headsets. Developed and published by Meta Platforms, the game allows players to interact with each other in various worlds where they can participate in events, games, and social activities. On the interoperability level, some effort is shown as Meta Platforms plans to connect Horizon Worlds and Crayta, another virtual platform, in a way that will enable cross-platform interoperability [160]. Concerning market access, they are testing new tools that enable Horizon Worlds creators to earn money by selling virtual items and experiences within their worlds through the Horizon Worlds Creator Bonus program [161]. Regarding persistence, persistent player variables are a crucial aspect of Horizon Worlds. These variables typically refer to the data that is tied to individual users and is saved and retained across gaming sessions [162].

The Meta Privacy Policy governs privacy in Meta's Horizon Worlds, where they gather user-generated content, messages, interactions, purchases, and more to use for personalization, improvement, safety, and research purposes [163]. The supplementary privacy policy involves the collection of various categories of information for users of Meta

VR Products, including Meta Horizon. This encompasses data related to Meta Horizon Profiles (e.g., profile name, picture, interactions), physical characteristics and movements (e.g., headset position, audio data), device information, Meta VR Product activity (e.g., purchases, events attended), content creation, fitness information, gameplay statistics, envir onment details, camera and audio information, voice interactions, and information from third parties [164].

13) SOMNIUM SPACE

Somnium Space is a virtual reality world that operates on the Ethereum blockchain and encourages social interaction, creativity, and commerce and was launched in 2017. Regarding interoperability, they have partnered with HighFidelity and JanusVR on creating a network of interconnected VR worlds (OASIS) and developing an open standard for interoperability between these platforms (VRBA) [165]. Regarding connectivity, Somnium Space has formed partnerships with blockchain companies Polygon and OpenSea [165]. Somnium Space is also working on developing a haptic suit and glove in partnership with Teslasuit, that allows users to feel physical sensations in the VR world [166].

In Somnium Space, persistence refers to the platform's ability to maintain a continuous, single virtual reality world where users can buy land, build, import objects, use avatars, and create experiences without being split into sub-servers or instances, providing a seamless, immersive, and Ready Player One-like experience without loading screens [167].

Somnium Space's Privacy Policy ensures the privacy of visitors to their website and app, collecting non-personally identifiable information through log files, utilizing cookies and web beacons to enhance user experience, providing links to third-party privacy policies, emphasizing protection for children online, and granting European Union residents rights to access and manage their personal information [165].

Through installing and experiencing Somnium Space we discovered that the web version of the platform offers the ability to browse various environments, select full-body human-like avatars, engage in chat, walk or fly, and experience holograms that are created through web cameras. However, it does not provide the option to modify or create new environments. On the other hand, the desktop PC client itself serves as a versatile builder, allowing users to create and shape virtual environments. The platform offers a 2D feature for a third-person view and a VR experience for a first-person perspective. The home window provides essential information such as news, announcements, account details (username, karma level, avatar location), and Somnium Space's world map.

14) MICROSOFT MESH

Microsoft Mesh is a collaborative platform developed by Microsoft that was announced in 2021 and previewed in 2023. It enables establishing connections with others during meetings without requiring the use of video by incorporating avatars into the Microsoft Teams platform [168].

Users can visualize and annotate content together in a 3D shared space. In order to improve interoperability, Microsoft has partnered with Meta to deliver immersive experiences for the future of work and play, where people can connect and collaborate as if they were physically present, using Meta Quest devices [169]. In Mesh's futuristic vision, they aim to create a mixed reality experience, where virtual holographic avatars are capable of seamlessly interacting with physical objects that exist in the user's real-world environment [170]. Microsoft Mesh adheres to Microsoft's comprehensive privacy policy, which is akin to the privacy practices outlined for Minecraft.

Regarding the accessibility in Microsoft Mesh, the early preview stage accessibility package offers a set of tools and resources for developers to enhance their mixed reality applications with text-to-speech and UI navigation with assistive technologies, along with guidelines for designing accessible experiences and testing [171]. In Microsoft Mesh, persistence enables organizations to create metaverses and persistent virtual worlds that connect the physical and virtual realms by incorporating digital twins of people, places, and objects, facilitating collaborative interactions and immersive experiences over time.

B. GAME ENGINES

1) UNITY 3D ENGINE

Unity 3D is a game development engine that enables developers to create 2D and 3D games across various platforms, including PC, mobile, and virtual reality (VR) and augmented reality (AR) applications, including the creation of Metaverse environments [172]. The Unity 3D engine provides developers with a toolset for building immersive 3D environments with realistic physics, lighting, and sound effects. Unity 3D engine has a decentralization category in its asset store along with cross-platform compatibility that provides developers with the tools necessary to create engaging, interactive, and decentralized gaming experiences. This includes enabling game mechanics that allow players to create, earn, or obtain in-game resources that they can sell or trade [172]. Regarding accessibility, Unity 3D Engine offers instructions for accessible design to ensure that developers' creations are accessible to all users, including users with disabilities [173].

2) UNREAL ENGINE

Unreal Engine is a game engine developed by Epic Games. It provides a wide range of features and tools for game development, including advanced graphics, physics simulation, audio, animation, and scripting [174]. The engine's real-time rendering capabilities allow developers to create high-fidelity graphics and realistic environments that can be dynamically lit and rendered in real-time. Additionally, it supports a wide range of platforms and devices and AI tools. Game developers can create immersive game experiences with dynamic non-player characters that react and respond to the player's actions. Concerning accessibility, Unreal Engine

provides three plugins, Text To Speech, Screen Reader, and Slate Screen Reader, which help developers comply with CVAA requirements for limited vision users [174].

3) ETHEREAL ENGINE

It is built by Ethereal Engine, which is a company that specializes in creating a complete solution for building a metaverse [175]. Their solution includes an XR engine that powers virtual environments where users can create their own personalized avatars, games, social interactions, and other metaverse infrastructures. The XR engine is designed to provide a seamless and immersive experience for users by leveraging technologies such as virtual and augmented reality. The web framework of the solution is built on top of popular Javascript frameworks, making it easy to use for developers.

4) BABYLON.JS

Babylon.js is a 3D engine used for the creation of 3D games, simulations, and other interactive applications that run on the web. The framework is accessible to all due to its free and open-source nature, and it supports the development of native applications across multiple platforms [176]. Babylon.js was developed on JavaScript and web standards, and it combines 3D rendering capabilities and cross-platform compatibility. Regarding the accessibility in Babylon.js, users with visual impairments can utilize the screen reader feature which renders a scene tree that can be easily read [176].

C. DEVELOPER TOOLS

1) BLENDER

Blender is an open-source 3D computer graphics software used for creating animated films, visual effects, art, 3D printed models, motion graphics, interactive 3D applications, and computer games. It is available for Windows, macOS, and Linux operating systems [177].

Blender's features include 3D modeling, texturing, rigging and skinning, fluid and smoke simulation, particle simulation, animating, rendering, video editing, and compositing. Blender's user interface is customizable and can be configured according to the user's preference. It offers support for a wide range of file formats, including 3D models, images, and video files.

Regarding AI support, Blender may not have native AI tools, but there are third-party options available to integrate AI into the workflow. One such tool is Stability for Blender, developed by Stability AI [178] which integrates the utilization of Stable Diffusion's advanced image creation technology.

2) NVIDIA OMNIVERSE

NVIDIA Omniverse is a platform that enables collaborative design and simulation workflows across different industries [179]. It allows users to create and interact with complex 3D environments in real-time, using a variety of software tools and technologies. At its core, Omniverse is built on top of NVIDIA's RTX technology, which allows for real-time ray tracing and AI-accelerated rendering. This means that users can create high-fidelity graphics and complex simulations that are more accurate and realistic. Omniverse also includes a suite of tools and APIs that enable collaboration between different software applications and workflows. Regarding accessibility, Nvidia Omniverse's partnership with New York University enables real-time simulation of grip and mobility, enhancing the testing of inclusive design concepts to make them accessible to everyone [180].

V. DISCUSSION

The metaverse is a concept that envisions a shared, immersive virtual space where people can interact with each other and digital objects in a seemingly real way. While it offers immense potential for a wide range of applications, including entertainment, education, and social interaction, it is not without its challenges. In reviewing existing platforms, several key challenges have been identified that must be addressed to ensure the metaverse's success. In our exploration of existing platforms, we have identified key limitations that can significantly impact user experiences and hinder the development of a robust metaverse ecosystem.

In the metaverse, one of the primary challenges is ensuring the persistence of virtual assets and experiences, enabling data and creations to be securely stored and retained over time. As the metaverse continues to evolve and due to a lack of research in this regard, it becomes crucial for researchers and developers to investigate and address the challenges of persistence to create a more cohesive and immersive experience for users in this emerging digital frontier. Without such persistence, the metaverse risks becoming fragmented and unstable. For instance, consider a scenario where a user invests time and effort in constructing a virtual world, only to have it disappear due to inadequate data storage mechanisms. This lack of persistence can erode user trust and hinder long-term engagement within the metaverse.

The ability for virtual assets, environments, and interactions to persist over time enables users to build, shape, and revisit their virtual spaces with a sense of permanence, fostering a sense of ownership and attachment to their creations.

Another prominent challenge lies in addressing crucial aspects such as security, privacy, and ethical considerations due to the vast amount of data generated and shared within the metaverse. Robust security measures and protocols are required to protect user data and prevent unauthorized access, ensuring a safe and enjoyable metaverse experience for all users. Insufficient security measures can leave user data vulnerable to breaches, threatening the overall integrity of the metaverse. To illustrate, recent instances of cyberattacks on virtual spaces have exposed user information and led to significant disruptions. Blockchain technology can provide a secure and transparent way to manage user identification data and provide secure communication between users and

platform servers, offering a potential solution to these security challenges [181].

Children's safety should be ensured in the metaverse to protect them from exposure to inappropriate content, cyberbullying, and online predators to protect younger users and maintain a trustworthy metaverse environment. This includes measures to safeguard privacy and data protection for children using the platform.

Interoperability stands as a formidable challenge, with various companies and developers each shaping their own platforms and standards. The lack of universal standards may lead to isolated sectors within the metaverse, impeding inter-platform communication and user mobility. For example, users on one platform may encounter difficulties when interacting with those on another due to protocol incompatibility. Ensuring that these platforms can communicate with each other seamlessly is critical to the metaverse's success. This requires the development of common standards and protocols that can be adopted by all stakeholders [182].

Connectivity emerges as another critical concern, requiring substantial investments in infrastructure and technology. This includes high-speed internet connections, powerful servers, and advanced graphics capabilities to support the immersive experience. Ensuring that these technologies are accessible and affordable would facilitate a broader user base and widespread metaverse adoption.

Furthermore, metaverse platforms must prioritize the implementation of accessibility measures to create a universally inclusive environment. Currently, there is a noticeable gap in providing a fully accessible metaverse experience, with no platform at the moment supporting a fully accessible metaverse, which can be a significant obstacle for individuals with disabilities. Addressing this oversight in future development is essential to ensure that the metaverse is accessible and empowering for everyone. It is important to note that our accessibility evaluation focuses primarily on the availability of accessibility features, as we do not possess the expertise to provide an evaluation regarding the quality and effectiveness of these provided features.

Another key challenge for the metaverse pertains to issues of ownership, regulation, and dispute resolution. The metaverse will need to abide by clear and transparent rules to ensure that users' rights are protected and disputes are resolved fairly. For instance, in cases involving disputes over virtual property rights or transactions within the metaverse, the lack of a well-defined regulatory framework can lead to legal ambiguities, potentially eroding user trust. This will require the development of standards and protocols that enable the creation of new models for economic exchange.

Addressing these multifaceted challenges will require a collaborative and multi-disciplinary approach. The future of the metaverse pivots on the development of a shared vision that places paramount importance on enhancing user experiences, ensuring robust security measures, prioritizing accessibility, and upholding ethical considerations. It is crucial to note that our evaluation and technical comparison have been thorough, encompassing all available information from official documents and our first-hand experience through installations. However, we acknowledge that our assessment may not be exhaustive, and we do not claim it to be comprehensive. Given the evolving nature of metaverse platforms, continuous research and evaluation are imperative. Therefore, we anticipate the need for a future, updated evaluation to account for platform advancements, thus providing an updated version of this assessment.

VI. CONCLUSION

On a final note, we hope our paper offers a meaningful contribution to the metaverse research landscape. We have provided insights into the essential requirements and aspects that are pivotal for delivering an exceptional metaverse experience, benefiting both users and developers. By introducing the Metaverse Key Requirements Taxonomy and identifying 15 requirements categorized into must-haves, should-haves, and good-to-haves, we have established a fundamental framework for metaverse platforms to reach their full potential.

Our study represents a significant contribution by offering a comprehensive overview of 14 open-source and commercial metaverse platforms, along with two developer tools and four game engines essential for building metaverse ecosystems. Through an extensive evaluation, we have revealed the strengths and weaknesses of these platforms, empowering developers and stakeholders to make informed decisions in this evolving landscape.

We emphasize the important need for continued research and development efforts in areas such as decentralization, enhanced security, improved accessibility, and heightened interoperability. Looking ahead, our paper lays the groundwork for future work in advancing the metaverse. Further research can build upon our taxonomy and assessment methodologies to continually refine and expand our understanding of metaverse requirements and capabilities.

In conclusion, while our comprehensive analysis sheds light on the pivotal requirements for a successful metaverse experience, it is evident that none of the existing metaverse platforms have been able to fully satisfy all of these criteria. By addressing the identified limitations and focusing on our roadmap, developers and researchers can collectively shape a metaverse that is more immersive, inclusive, secure, and interconnected, ultimately defining the future of digital interaction and collaboration in this dynamic metaverse realm.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest that could potentially bias or influence the outcomes of this research. We affirm that this research was conducted solely for the purpose of advancing knowledge in the field and providing valuable insights to the academic and broader community.

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